Stock Assessment of eastern Bering Sea snow crab

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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 was presented in the draft May 2008 assessment. The estimated maturity provided some improvement in residual patterns, however, projected catches and biomass values were very similar to the base model and are not presented in this assessment. 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

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.

CIE reviewers recommended not changing growth or maturity over time simply to fit the length frequency data.

Growth and maturity are constant over time in the model as in previous assessments.

Changes to the Data

Catch and fishery length frequency data were also updated through the 2007/8 season. Survey abundance and length frequency data from 2008 were added to the model.

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 1,580 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 489 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. Model estimates of total mature biomass continued to decline to 348 million lbs in 2002, then increased to 556 million lbs in 2008. The 2007 observed survey total mature

biomass increased to 607.8 million lbs, about 66% of Bmsy. However, in 2008 observed survey total mature biomass declined to 509.4 million lbs (55% of Bmsy). The observed survey estimate of males greater than 101 mm increased from about 135 million in 2006 to 151 million in 2007, then declined to 117 million in 2008. In 2006 there was a high degree of uncertainty in the estimated large male (>101mm) numbers. The 2007 survey estimate of 151 million crab had lower uncertainty than in 2006 estimate, with an estimated 95% confidence interval +/-40%. Two large tows in 2007 accounted for about 46 million of the 151 million large males. In the 2008 survey the largest tow accounted for about 8 million of the 117 million large males. Model estimates of large males (>101mm) were about 96 million crab in 2006, 132 million in 2007 and 155 million in 2008.

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 2006 fishery was 37 million lbs, 36.4 million lbs in 2007 and 63 million lbs in the 2008 fishery.

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 2008/9-2013/14 was estimated using mature male biomass at the time of mating (February), fishing at the F35% and F40% control rules. Due to the decline in observed survey biomass in 2008, the trend in model estimated biomass is lower than estimated in the 2007 assessment. The 2008/9 mature male biomass at mating time is projected to be at 79% of B35% fishing at the F35% control rule and 84% of B35% fishing at the F40% control rule. Using a harvest control rule with B40% and F40%, the 2008/9 total catch was estimated at 59.7 million lbs (F = 0.40), with a retained catch of 49.7 million lbs. Using a harvest control rule with B35% and F35%, the 2008/9 total catch OFL was estimated at 77.3 million lbs (F = 0.55) with a retained catch of 64.7 million lbs.

F35%	OFL 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
Year								
2008/9	77.3	60.2	93.4	64.7	0.55	251.1	175.2	555.5

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 0% fishing at either the F35% or F40% control rules. The year of rebuilding to total survey biomass with fishing at the F40% control rule was estimated at 2020.

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 0.2%, fishing at F35%, and 5.3% fishing at F40%. Rebuilding to B35% using mature male biomass at mating time and fishing at F40% was estimated at 50% for the year 2015/16.

There is a high degree of uncertainty in future biomass and catch projections, and the projected OFLs and biomass may change when the next survey biomass is added to the model. The probability of rebuilding by 2010 is dependent on recruits estimated by the model and the trend in biomass in the last few years of the survey, while projections in later years will depend on the method of generating future recruitments. Biomass is expected to be slightly higher in 2009/10 to 2010/11, then decrease due to recent lower recruitment estimates and using autocorrelation to generate future recruitments in the projections. 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 retained catch for the 2007/8 fishery was 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).

The average size of retained crabs has remained fairly constant over time ranging between 105 mm and 118 mm, and most recently about 110 mm to 111 mm. The percent new shell animals in the catch has varied between 69% (2002 fishery) to 98% (1999), and was 87% for the 2005/6 fishery and 93% in the 2007/8 fishery. In the 2007/8 fishery 94% of the new shell males >101mm CW were retained, while 78% of the old shell males >101mm CW were retained. Only 3% of crab were retained between 78mm and 101 mm CW. The average weight of retained crab has varied between 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 biomass increased from 519 million lbs in 2006 to 607.8 million lbs in 2007, then decreased in 2008 to 509.4 million lbs.

The observed survey estimate of males greater than 101 mm increased from about 69 million in 2005 to 135 million in 2006, 151 million in 2007, then declined to 117 million in 2008. In 2006 there was a high degree of uncertainty in the estimated large male (>101mm) numbers, with the majority being caught in one tow. The 2007 survey estimate of 151 million crab has lower uncertainty than in 2006, with an estimated 95% confidence interval +/-40%. Two large tows in 2007 accounted for about 46 million of the 151 million large males. In the 2008 survey the largest tow accounted for about 8 million of the 117 million large males. Model estimates of large males (>101mm) were about 96 million crab in 2006 and 132 million in 2007 and 155 million in 2008.

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. and west of the Pribilof Islands between about 171 deg. W and 173 deg W.

Summer survey data from 2003 to 2007 show 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.

The spatial distribution of large male 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.

The spatial distribution of large male snow crab in the 2008 survey was farther south and east than in 2007 (Figures 18 and 18b). The 2008 summer survey estimated about 56% of large males below 58.5 deg N, higher than in previous years. About 53% of large new shell males were estimated to be south of 58.5 deg N. New shell crab were 66% of the large crab south of 58.5 deg N. There was one large tow of large males that occurred at 168 W 57N, farther east than has been observed in recent years. Also in 2008 the largest tows resulted in estimates of abundance of about 8 million crab (in a 20nm by 20nm square), while in 2007 the largest tows were about 20-25 million crab.

The difference between the summer survey distribution of large males and the fishery catch distribution indicates that survey catchability may be less than 1.0 and/or some movement occurs between the summer survey and the winter fishery. However, the exploitation rate on males south of 58.5 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.

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 2008 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 2008. Total discarded catch was estimated from observer data from 1992 to 2008(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 2008. 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	1978-2008 (Year when fishery actually occurred)
Discarded male and female crab pot fishery size frequency	1992-2008
Trawl fishery bycatch size frequencies by sex	1991-2007
Survey size frequencies by sex and shell condition	1978-2008
Retained catch estimates	1978-2008
Discard catch estimates from snow crab pot fishery	1992-2008 from observer data
Trawl bycatch estimates	1973-2007
Total survey biomass estimates and coefficients of variation	1978-2008

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 31 recruitment parameters estimated in the model, one for the mean recruitment, 30 for each year from 1979 to 2008 (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 using the average fraction mature based on chela height data and applied to all years of survey data to estimate mature survey numbers. 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

A full discussion of natural mortality estimation for snow crab was presented in the 2007 assessment (Turnock and Rugolo 2007). 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).

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 99th percentile of the distribution of ages in an unexploited population if observable. Under negative exponential depletion, the 99th percentile corresponding to age 20 of an unexploited population corresponds to a natural mortality rate of 0.23. 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. Both 2007 and 2008 were cold years.

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

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

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 961 million lbs in 1978 to the peak biomass of 1,580 million lbs in 1990. Biomass declined sharply after 1997 to about 348 million lbs in 2002, then increased to 556 million lbs in 2008 (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 2008 was estimated to be about 16.7% of the retained catch (with 50% mortality applied), similar to the average observed discards from 1992 to 2008 (15.5%) (Table 1 and Figure 31). Parameter estimates for the 50% discard mortality model are in Table 7. During the last five years (2004 to 2008 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). In the 2007/8 observed fishery discard mortality was similar to past years at about 15% of the retained catch.

Mature male and female biomass show similar trends (Table 3, Figures 32 and 34). Mature male biomass increased from 263 million lbs in 2006 to 330 million lbs in 2007, then continued to increase to 369 million lbs in 2008 (adjusted by survey selectivity). Observed survey mature male biomass increased from 331 million lbs (2006) to 385 million lbs (2007), then declined to 306 million lbs in 2008. Model estimates of mature female biomass increased from 180 million lbs in 2006 to 192 million lbs in 2007, then declined to 187 million lbs in 2008. Mature female biomass observed from the survey increased from 189 million lbs in 2006 to 223 million lbs in 2007, then declined to 204 million lbs in 2008. 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 40 by sex for shell conditions combined with residual plots in Figures 39 and 41. The model is not fit to crab by shell condition due to the inaccuracy of shell condition as a measure of shell age. Tagging results presented earlier indicate that the number of animals that are more than one year from molting may be underestimated by using shell condition as a proxy for shell age. However, an accurate measure of shell age is needed to improve the estimation of the composition of the catch that is extracted from the stock.

Differences between the observed and predicted survey length frequencies could be a result of spatial differences in growth due to temperature, or size at maturity. These would need to be investigated using a spatial model. Changing growth or maturity over time simply to fit the length frequency data was not recommended by the 2008 CIE reviewers. There also could be changes in survey catchability by area or between years that could contribute to 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 abundance estimates (Figure 42). The observed survey estimate of males greater than 101 mm increased from about 69 million in 2005 to 135 million in 2006, 151 million in 2007, the decreased to 117 million in 2008. The estimated 95% confidence interval for the observed survey large males in 2007 was +/-40% of the estimate. Model estimates of large males were about 96 million crab in 2006, 132 million crab in 2007 and 155 million crab in 2008.

Two main periods of high recruitment were estimated by the model, in 1981 (fertilization year) and in 1987-1988 (Figure 43). Recruits are 25mm to about 40 mm and may be about 4 years from hatching, 5 years from fertilization (Figure 44, 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 about average recruitment that has resulted in an increase in biomass in recent years. 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 45). 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 103.9 mm for males (shell condition combined, Figure 23). The size at 50% selected for the retained catch was 105.6 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 46 through 48. Fits to the trawl fishery bycatch size frequency data are in Figures 49 and 50.

Fishing mortality rates ranged from about 0.19 to 1.85 (Figure 51). 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, 0.53 for the 2006 and 0.49 for 2007, and 0.66 for 2008 (year fishery occurred).

Likelihood components included fits to the catch and survey length frequencies, catch and survey biomass values, recruitment constraint, constraint on fishing mortality values and fits and constraints on the estimation of the first year abundance by length (Table 8).

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 α = -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•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 54).

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

α = 0.1. F on the directed fishery is set to zero when mature male biomass is below 25% of B35% (Figure 54). 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 0.707, 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 317.7 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 0.56 and B40% at 363.0 million lbs.

B40% and B35% were estimated using average recruitment from1978 to 2008 and spawning biomass per recruit for males fishing at F40% or F35% respectively.

A measure of productivity can be estimated from the natural log of the ratio of recruitment to mature male biomass (Figures 57 and 58). 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 2008 have been above the F35% control rule except for six years (1979, 1984-1985, 1996-97, 2005) (Figure 54). The target F historically (pre-2000 fishery season) was about 1.1 which was exceeded in many years. The last three fishery seasons (2006-2008) F was estimated at 0.52, 0.49 and 0.66 all above the F35% control rule. The F in 2008 was above the F35% control rule in part due to a lower estimated abundance of large males and mature male biomass than the observed survey and the 2007 model estimates of abundance and biomass.

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 2013/14 fishery seasons (Table 6). The MMB in spring 2009 was estimated to be 251 million lbs, about 79% of B35% if a retained catch of 64.7 million lb is taken. The MMB in spring 2009/10 is estimated to be 256 million lbs, about 81% of B35%. The OFL using F35% total catch for 2008/9 was estimated at 77.3 million lbs (with a retained catch of 64.7 million lbs). The 2008/9 F40% total catch was estimated at 59.7 million lbs, with a retained catch of 49.7 million lbs. Total catch includes retained directed pot fishery, discard pot fishery (with 50% mortality of discards) and trawl bycatch (80% mortality). 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 0% in 2010, fishing at F35% or F40% (Table 6). The year of rebuilding to total survey biomass with fishing at the F40% control rule was estimated at 2020.

Under tier 3 management, the probability of rebuilding to B35% in 2010 is 0.2%, fishing at F35%, and 5.3% fishing at F40%. Rebuilding to B35% using mature male biomass at mating time and fishing at F40% was estimated at 50% for the year 2015/16.

Biomass is expected to be slightly higher in 2009/10 to 2010/11, then decrease due to recent lower recruitment estimates and using autocorrelation to generate future recruitments in the projections. There is a high degree of uncertainty in future biomass and catch projections, and the projected OFLs and biomass may change when the next survey biomass is added to the model. The probability of rebuilding by 2010 is dependent on recruits estimated by the model and the trend in biomass in the last few years of the survey, 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

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.

The model and observed biomass estimates are below the expected trends in biomass from the snow crab rebuilding plan for 2002 to 2008, due partly to the decrease in observed survey biomass in 2008 (Figures 55 and 56). 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. Projected catches estimated from the F35% and F40% control rule are lower than the expected values from the rebuilding. Future survey data and realized catches will result in changes to projected values.

Conservation concerns

- The Bering Sea snow crab survey estimates of total mature biomass in 2008 were 55% of the survey Bmsy (921.6 million lbs), down from the 2007 survey biomass. 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 be relatively flat, then decline.

- 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 funded by NPRB for the period 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 2007/8 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
2005/2006	36,974	9,965	46,939	5,311	12	42,297	2005	1,378
2006/2007	36,356	12,995	49,351	7,040	5	43,401	2006	385
2007/2008	63,000	18,560	78,560	13,408	66	76,364	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
2008	203.5	305.9	509.4	117

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	1,361	7,924	479	482	961	100	*	340	2.9
1979	1,324	6,764	567	458	1,025	121	640	289	4.1
1980	1,199	5,732	594	350	945	80	571	210	5.3
1981	1,076	4,863	541	281	822	51	529	197	5.1
1982	1,036	4,581	449	341	790	99	891	253	4.0
1983	1,063	5,364	378	408	786	153	1,863	309	3.2
1984	1,108	5,712	355	421	775	163	1,568	269	3.2
1985	1,174	6,435	356	384	740	138	2,047	219	3.5
1986	1,501	11,330	374	370	744	120	6,400	207	3.6
1987	1,824	11,307	501	441	943	149	2,511	242	3.9
1988	2,088	10,381	606	538	1,145	180	1,672	289	3.8
1989	2,246	8,692	629	703	1,332	236	779	416	3.1
1990	2,270	7,065	570	1,009	1,580	412	527	482	2.6
1991	1,920	6,551	483	978	1,461	415	1,467	458	2.4
1992	1,584	7,520	421	733	1,154	281	2,779	369	2.6
1993	1,416	7,652	422	522	944	172	2,018	288	3.0
1994	1,377	6,730	444	419	863	114	907	277	3.1
1995	1,412	5,311	434	487	921	148	165	350	2.8
1996	1,416	4,228	379	660	1,039	254	195	438	2.2
1997	1,255	3,340	307	728	1,036	310	202	362	2.1
1998	882	2,822	243	515	758	201	479	236	2.3
1999	601	2,709	201	288	489	86	710	213	2.2
2000	541	2,374	181	240	421	69	301	172	2.3
2001	508	2,095	164	212	376	60	279	145	2.4
2002	499	2,247	146	203	348	61	658	144	2.3
2003	536	2,847	136	221	358	79	1,128	166	2.1
2004	598	3,282	148	236	383	90	1,076	177	2.2
2005	655	3,161	170	240	410	89	612	167	2.5
2006	738	3,617	180	263	443	96	1,183	188	2.4
2007	792	3,067	192	330	522	132	275	218	2.3
2008	789	2,819	187	369	556	155	493	200	

*** 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 2008/9 to 2013/2014 fishery seasons. 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% (317.7 million lbs). F35% = 0.707, F40%= 0.56, B40%= 363.0 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											
2008/9	77.3	60.2	93.4	64.7	0.55	251.1	175.2	555.5	0.000	0.000	0.24
2009/10	81.9	54.6	116.6	69.1	0.57	255.9	183.0	553.4	0.000	0.000	0.24
2010/11	79.7	52.8	109.9	67.4	0.56	253.1	181.4	547.6	0.000	0.002	0.24
2011/12	67.5	44.6	96.0	57.6	0.52	239.3	166.2	533.8	0.001	0.002	0.22
2012/13	57.9	34.5	90.6	47.8	0.49	230.1	142.3	528.8	0.005	0.011	0.20
2013/14	71.2	31.9	151.6	58.0	0.52	251.1	159.2	578.9	0.041	0.104	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											
2008/9	59.7	45.3	73.6	49.7	0.40	266.9	175.2	555.5	0.000	0.000	0.18
2009/10	69.8	44.5	102.0	58.9	0.43	281.6	195.5	570.8	0.000	0.007	0.20
2010/11	70.9	46.3	99.6	60.2	0.43	283.3	199.9	573.7	0.000	0.053	0.20
2011/12	61.7	39.8	88.4	52.8	0.40	270.2	187.0	563.7	0.001	0.059	0.19
2012/13	53.3	31.8	84.4	44.4	0.38	259.5	162.7	558.5	0.007	0.091	0.17
2013/14	64.2	28.7	136.3	52.7	0.41	281.3	178.5	607.5	0.044	0.240	0.19

Table 7. 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	0.166
Fishery selectivity total males length at 50%	103.9
Fishery selectivity retention curve males slope	0.2535
Fishery selectivity retention curve males length at 50%	97.772
Pot Fishery discard selectivity female slope	0.305
Pot Fishery discard selectivity female length at 50%	70.619
Trawl Fishery selectivity slope	0.0676
Trawl Fishery selectivity length at 50%	120.0
Survey Q 1978-1981	1.0
Survey 1978-1981 length at 95% selected	48.35
Survey 1978-1981 length at 50% selected	28.25
Survey Q 1982-1988	0.953
Survey 1982-1988 length at 95% selected	68.02
Survey 1982-1988 length at 50% selected	43.15
Survey Q 1989-present	1.0
Survey 1989-present, length at 95% selected	43.67
Survey 1989-present length at 50% selected	33.14
Fishery cpue q	0.00104

Table 8. Likelihood values by component for the snow crab assessment model.

Likelihood Component	Likelihood value
recruitment	22.1
fishery length retained	-1795.4
fishery length total	761.4
fishery length female	122.3
length survey	4560.3
length trawl bycatch	216.7
Fishing mortality penalty	517.6
total catch biomass	41.7
retained catch biomass	37.5
female discard biomass	0.1
trawl bycatch	111.8
survey biomass	1467.8
initial year abundance by length	4.4
initial year abundance by length smooth constraint	71.0
total	6139.1

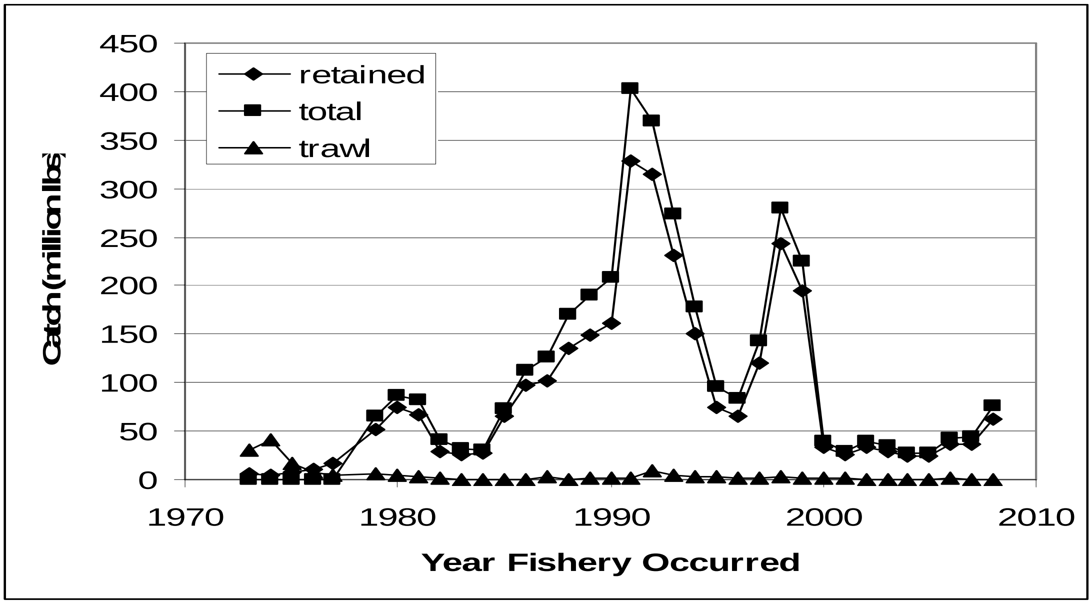

Figure 1. Catch (million lbs) from the directed snow crab pot fishery and groundfish trawl bycatch. Total catch is retained catch plus discarded catch after 50% discard mortality was applied. Trawl bycatch is male and female bycatch from groundfish trawl fisheries with 80% mortality applied.

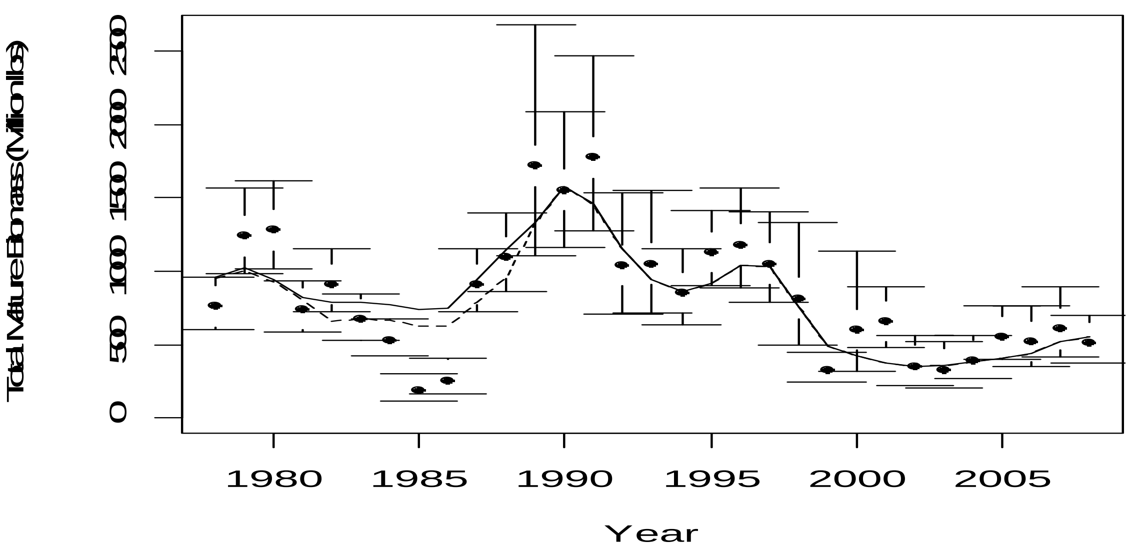

Figure 2. Population total mature biomass (millions of pounds, solid line), model estimate of survey mature biomass (dotted line) and observed survey mature biomass with approximate lognormal 95% confidence intervals.

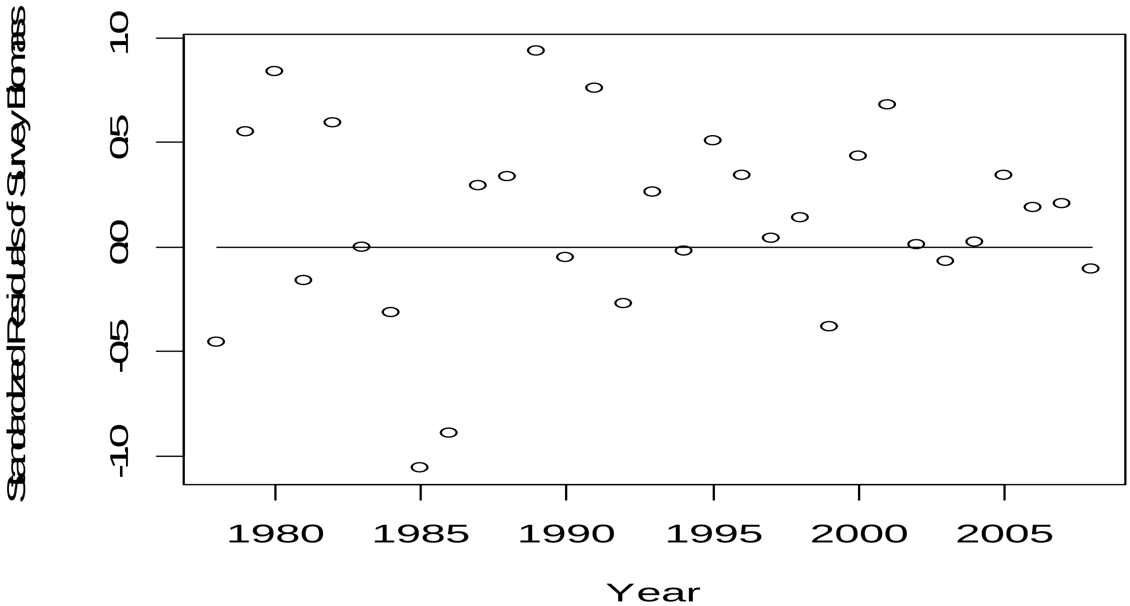

Figure 3. Standardized residuals for model fit to total mature biomass from Figure 2.

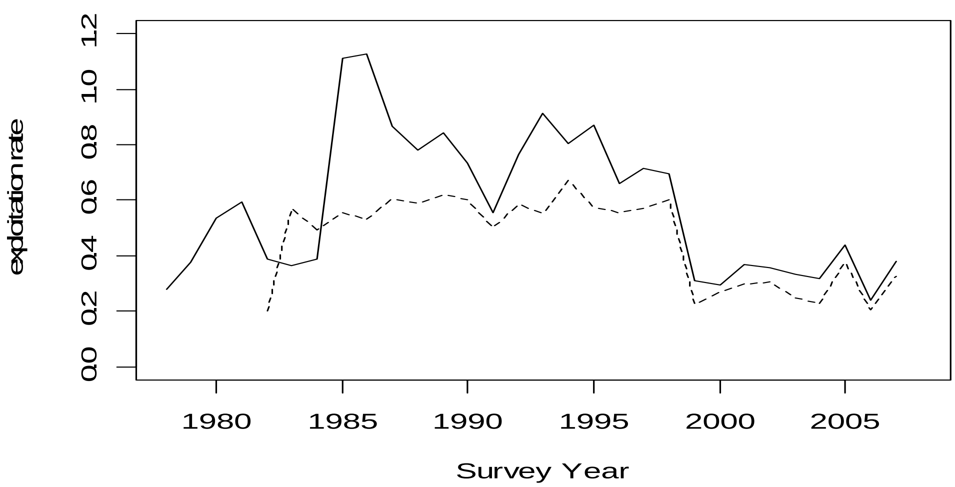

Figure 4. Exploitation rate estimated as the preseason GHL divided by the survey estimate of large male biomass (>101 mm) at the time the survey occurs (dotted line). The solid line is the retained catch divided by the survey estimate of large male biomass at the time the fishery occurs. Year is the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

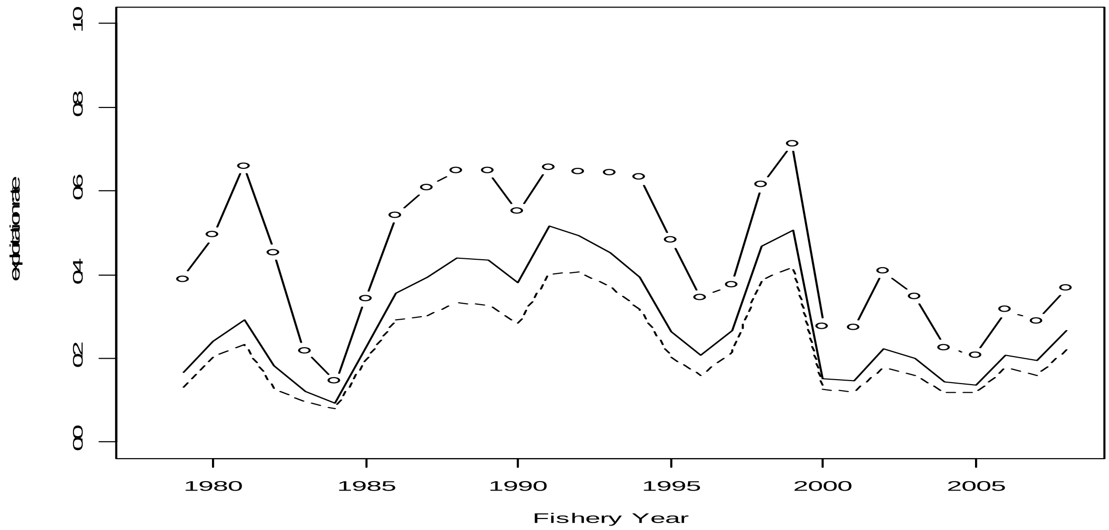

Figure 5. Exploitation fraction estimated as the catch biomass (total or retained) divided by the mature male biomass from the model at the time of the fishery (solid line and dotted line). The exploitation rate for total catch divided by the male biomass greater than 101 mm is the solid line with dots.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

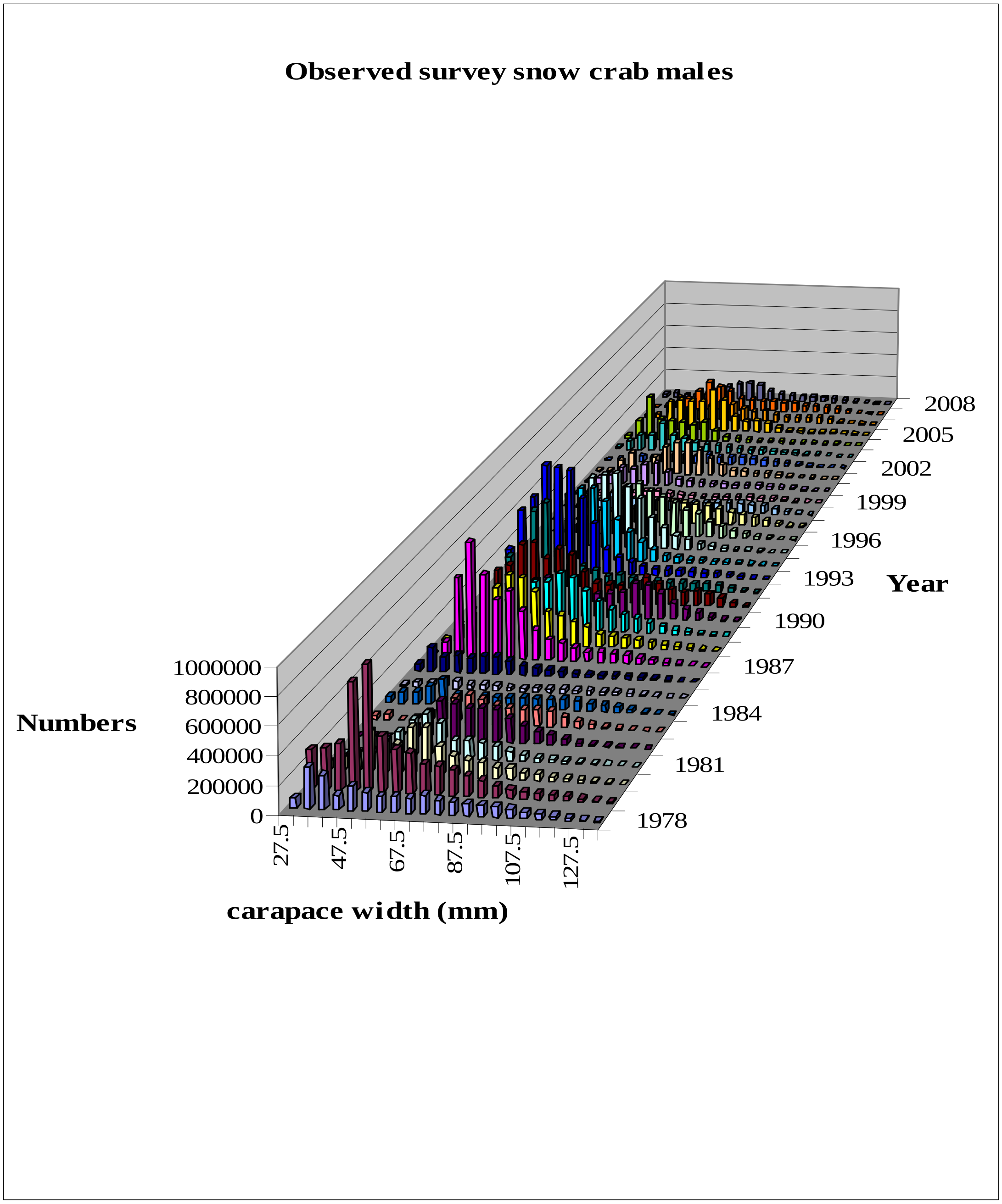

Figure 6. Observed survey numbers (1000’s of crab) by carapace width and year for male snow crab.

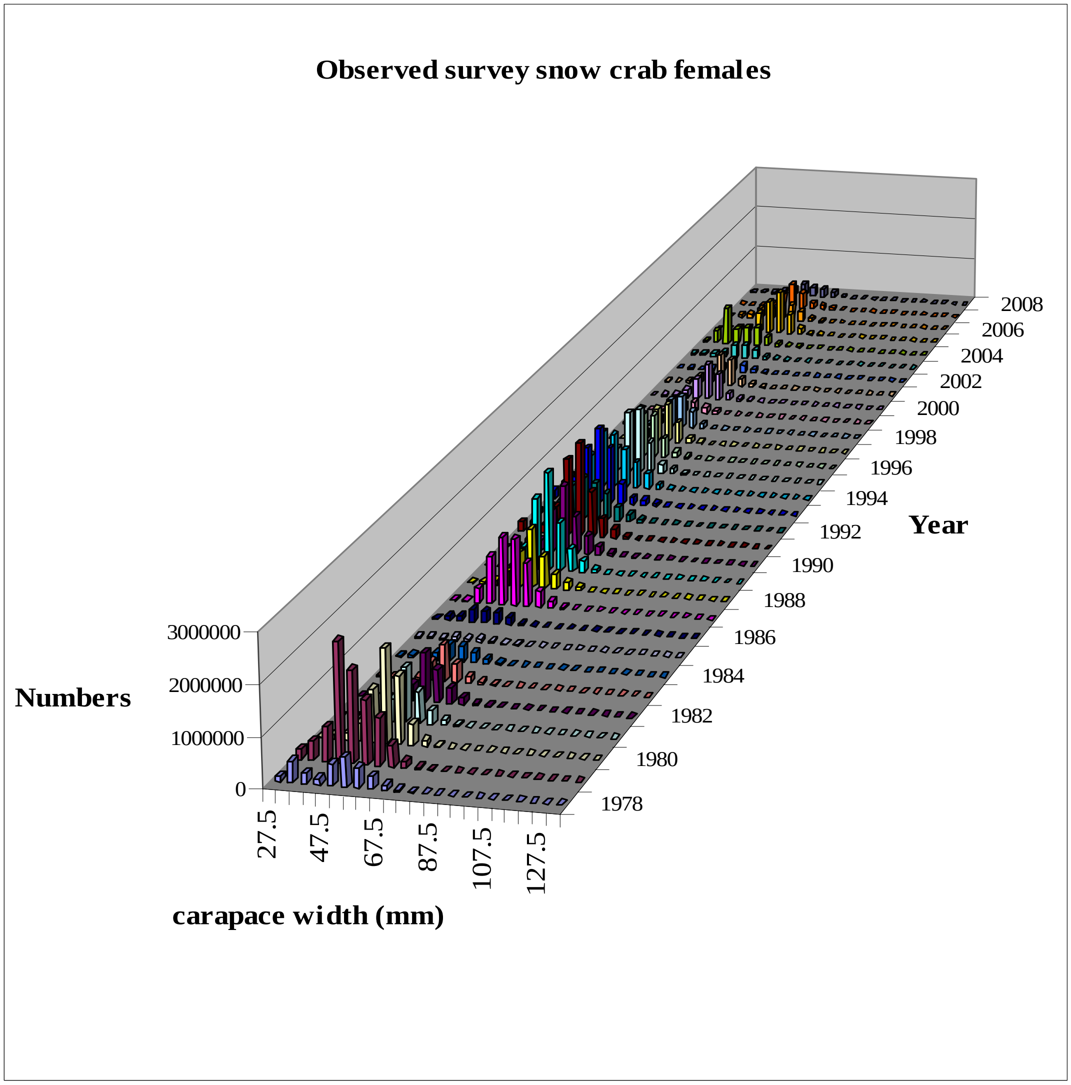

Figure 7. Observed survey numbers (1000's of crab) by carapace width and year for female snow crab.

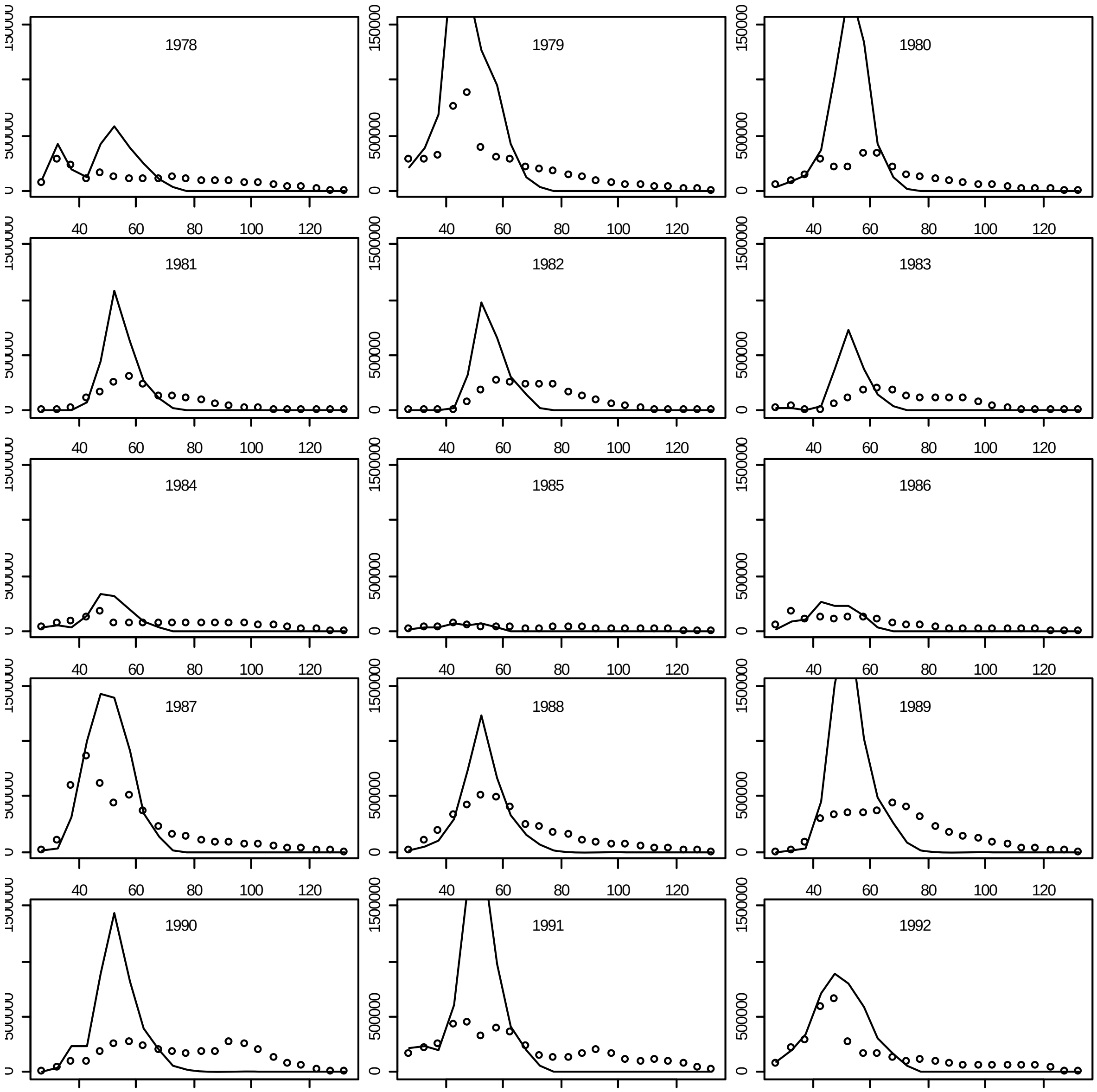

Figure 8. Observed survey numbers by length, males circles, females solid line.

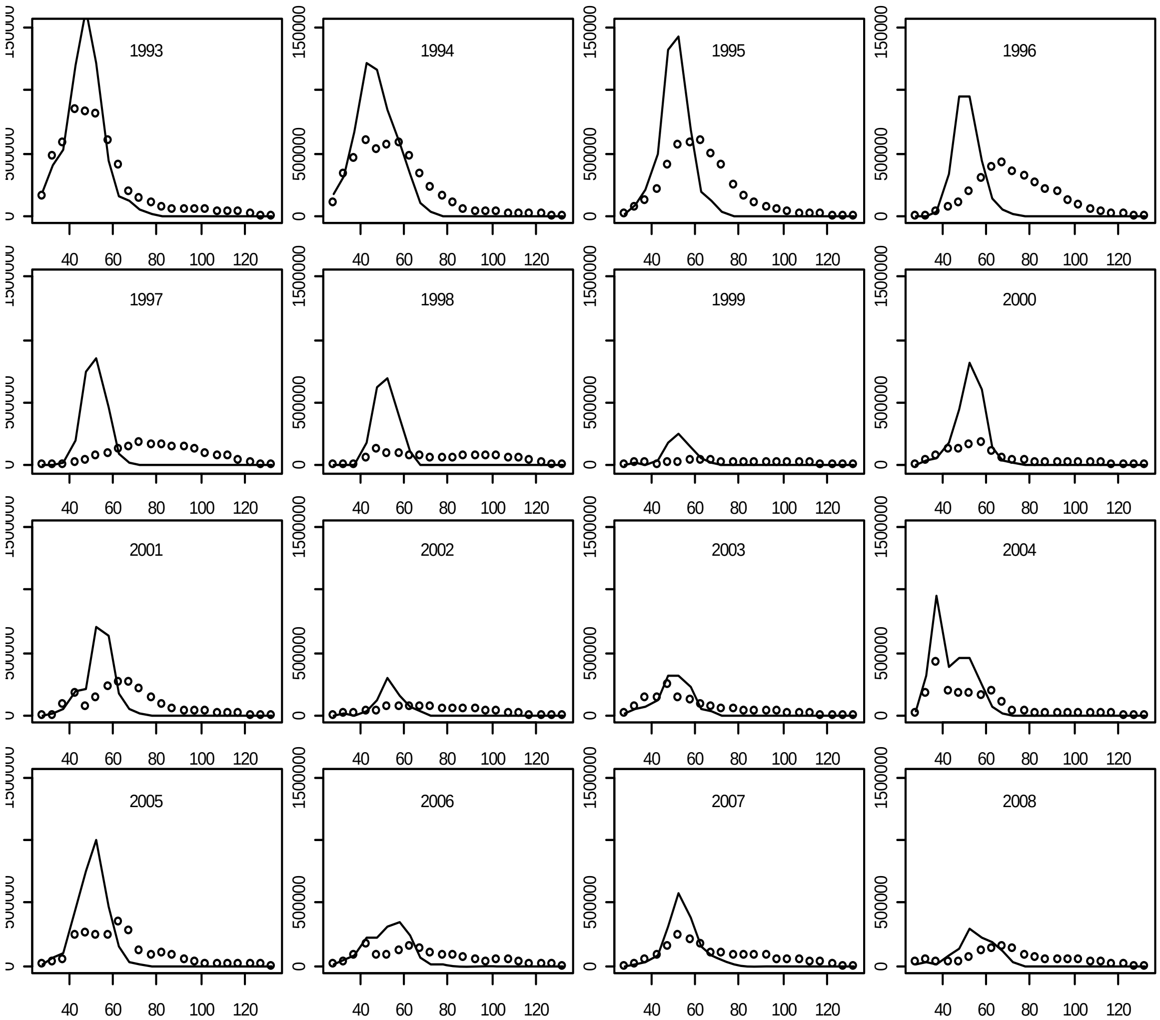

Figure 9. Observed survey numbers by length, males circles, females solid line.

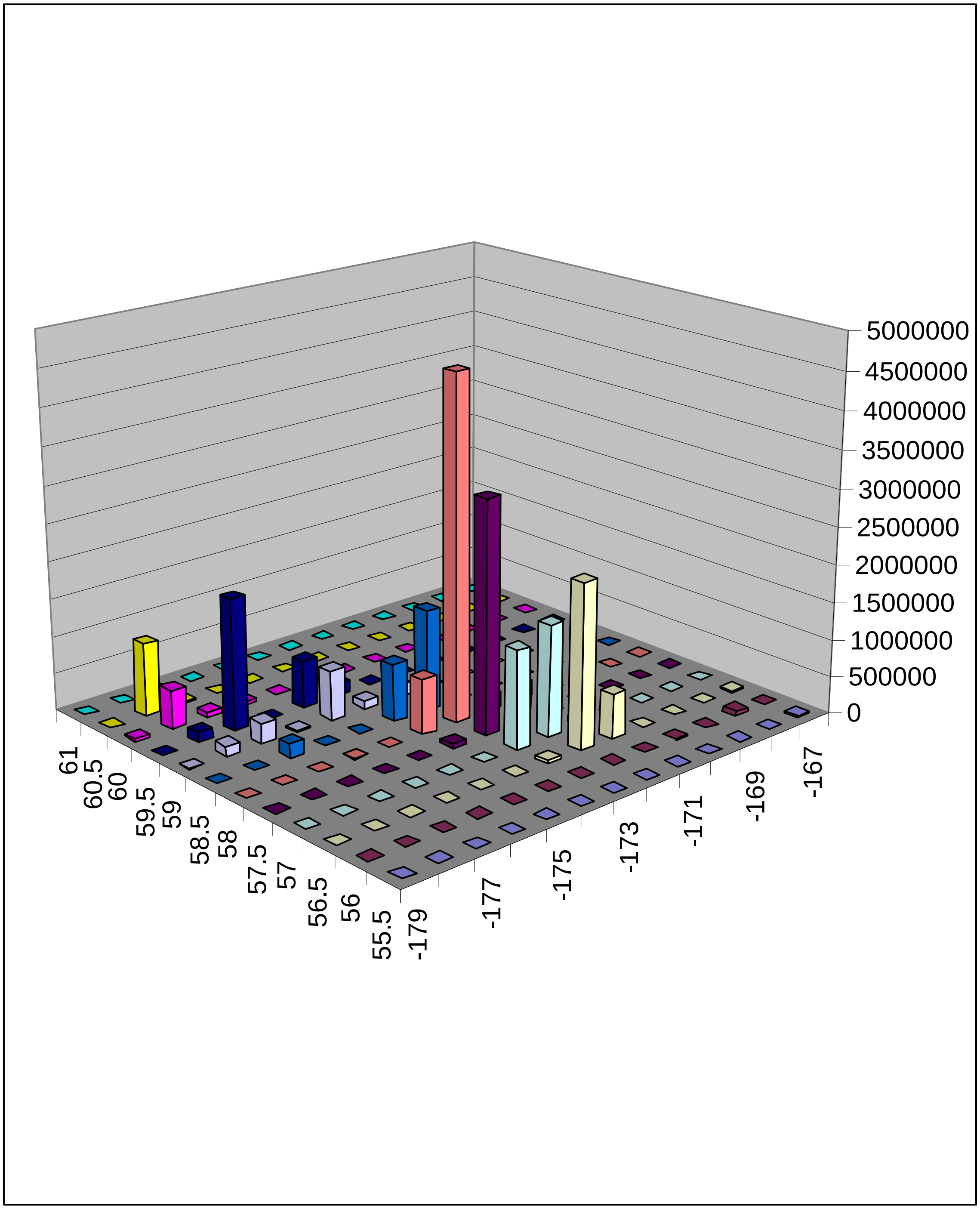

Figure 10. 2003 pot fishery retained catch in numbers by statistical area. Longitude in negative degrees. Areas are 1 degree longitude by 0.5 degree latitude.

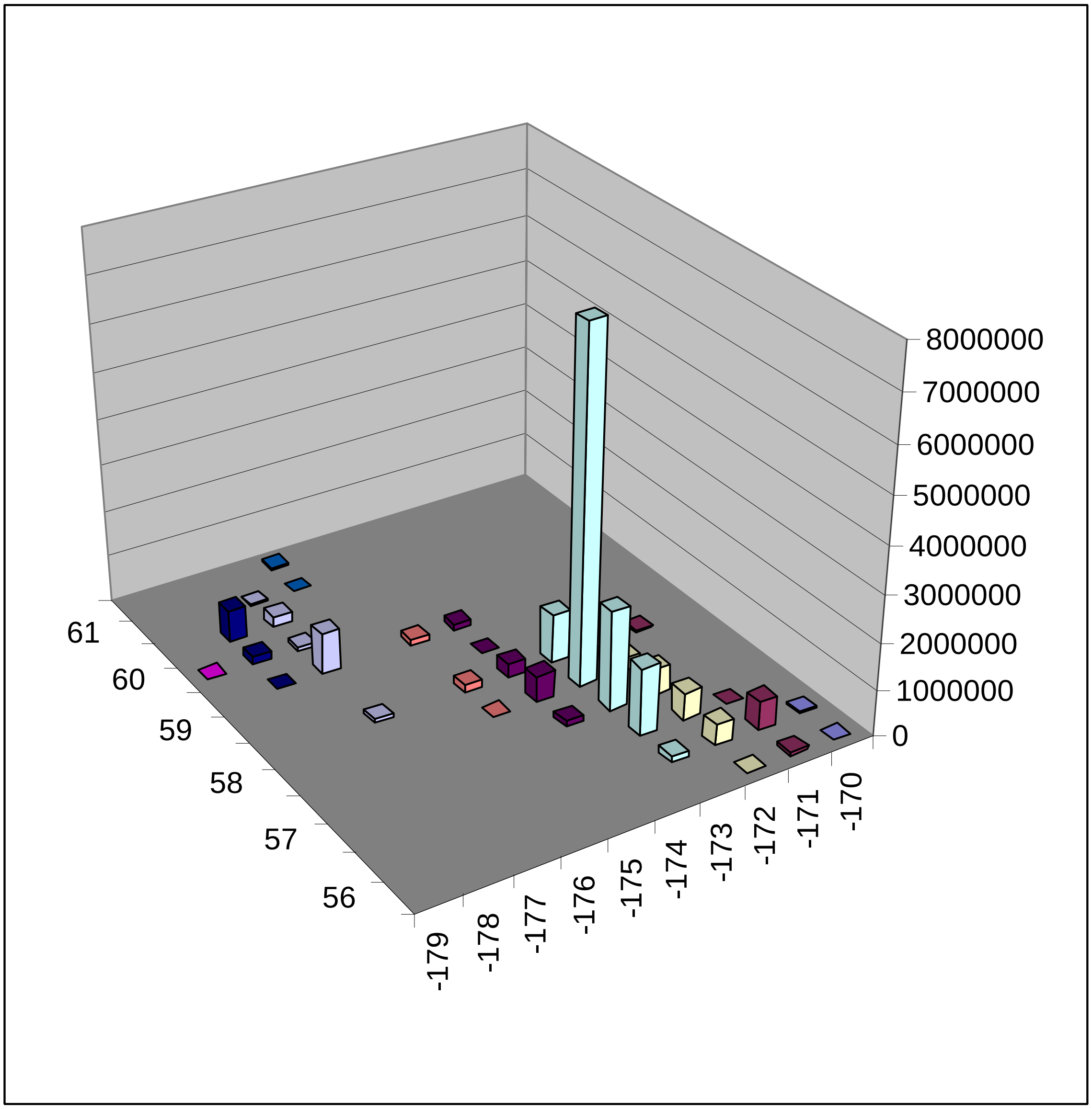

Figure 11. 2004 pot fishery retained catch in numbers by statistical area. Longitude in negative degrees. Areas are 1 degree longitude by 0.5 degree latitude.

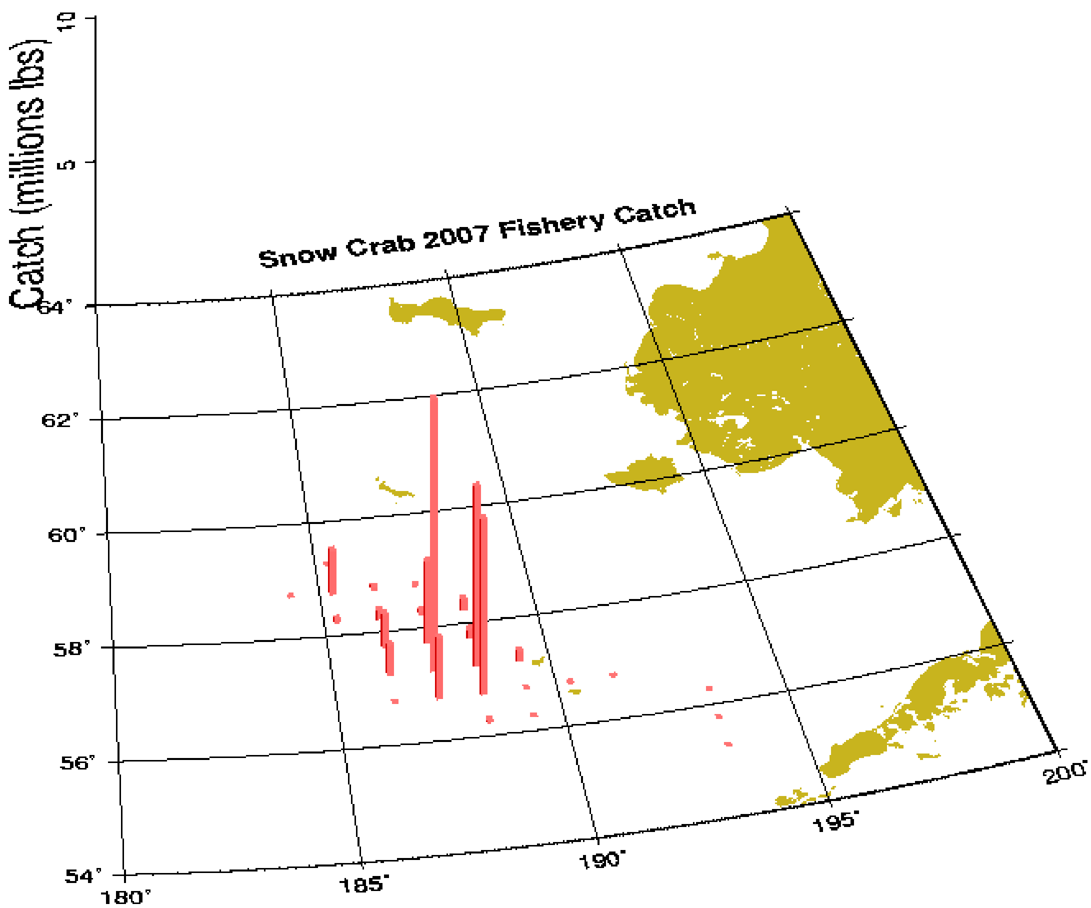

Figure 12. 2007 (2006 survey year) pot fishery retained catch(million lbs) by statistical area. Longitude increases from west to east (190 degrees = 170 degrees W longitude). Areas are 1 degree longitude by 0.5 degree latitude.

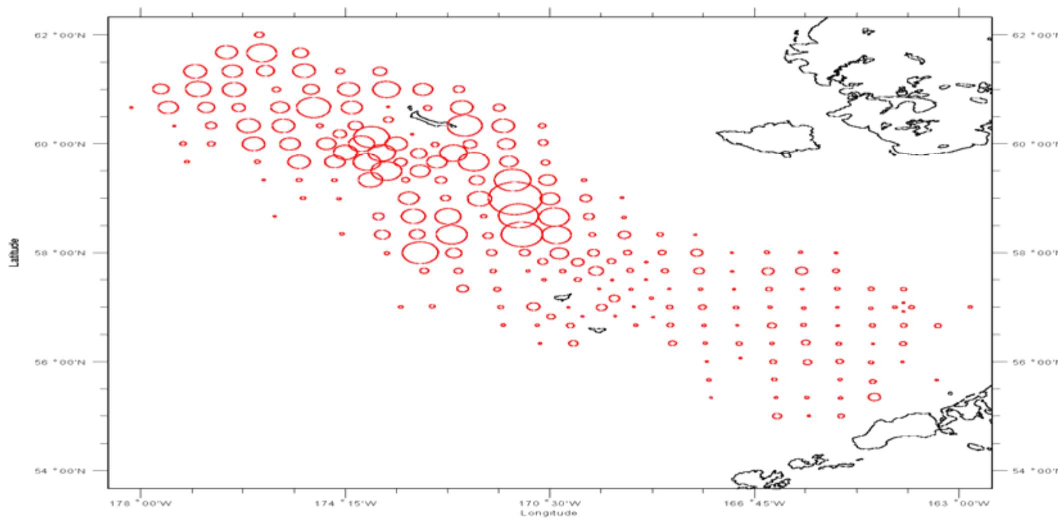

Figure 13. 2004 Survey abundance of males > 79 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle.

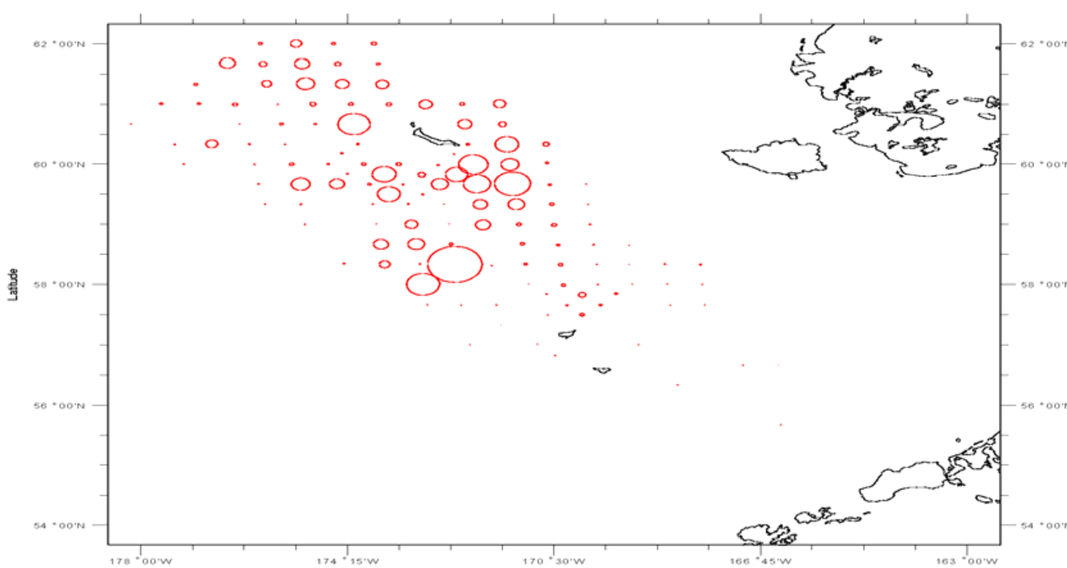

Figure 14. 2004 Survey abundance of females > 49 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle.

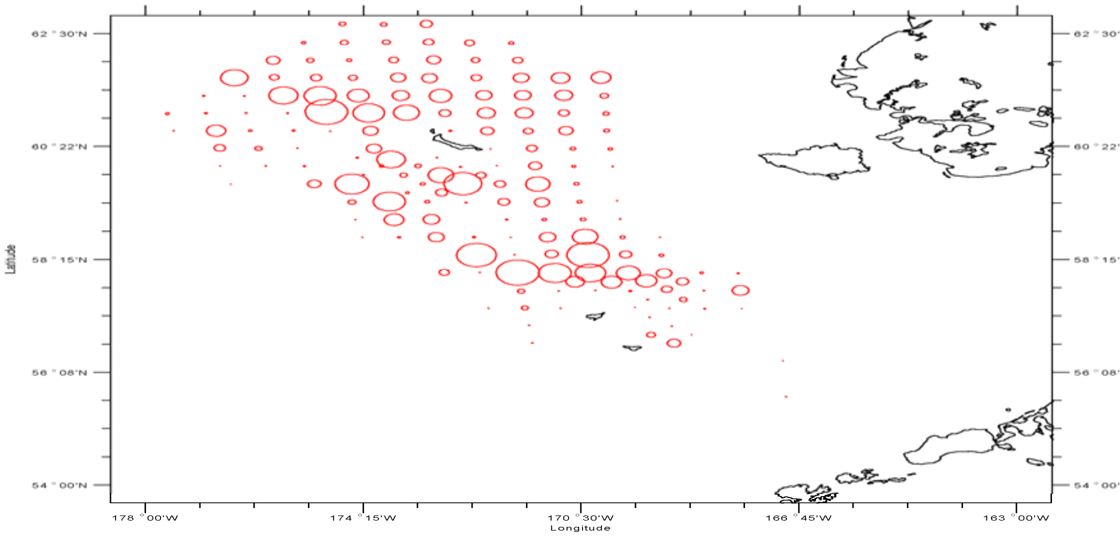

Figure 15. 2005 Survey abundance of females > 49 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle (not on the same scale as male abundance in Figure 54). Includes stations to the north of the standard survey area.

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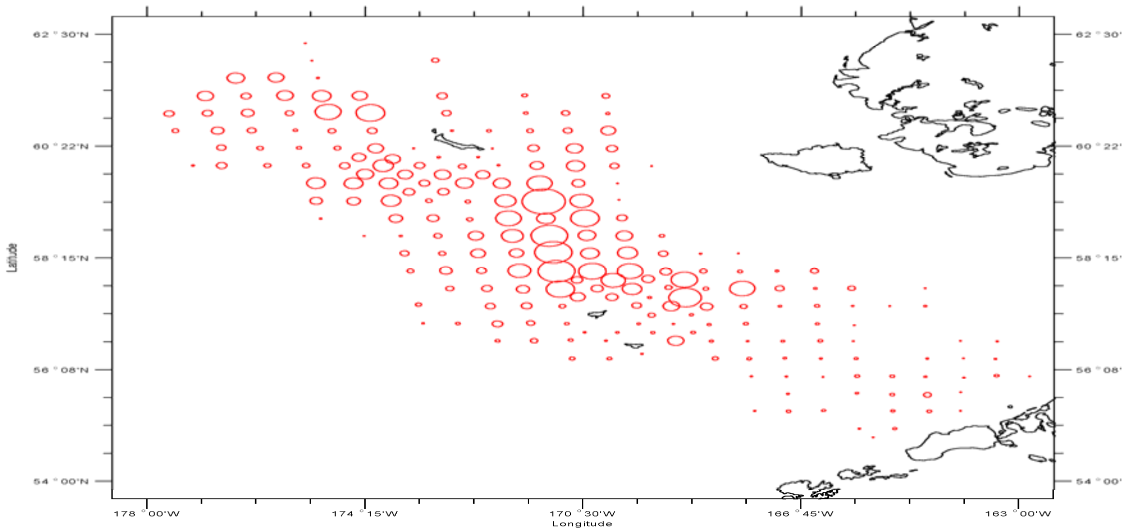

Figure 16. 2005 Survey abundance of males > 79 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle (not on same scale as female abundance in Figure 53).

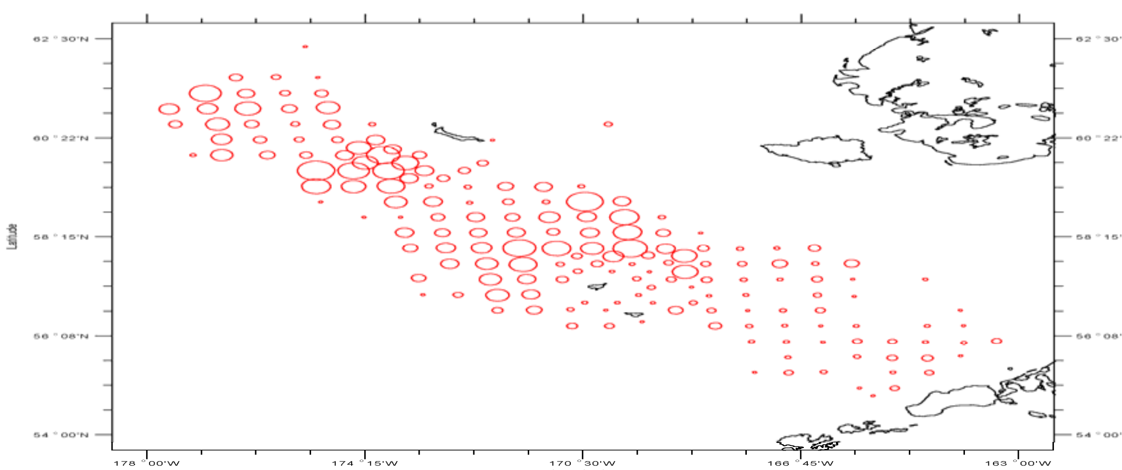

Figure 17. 2005 Survey abundance of males > 101 mm by tow. Abundance is proportional to the area of the circle.

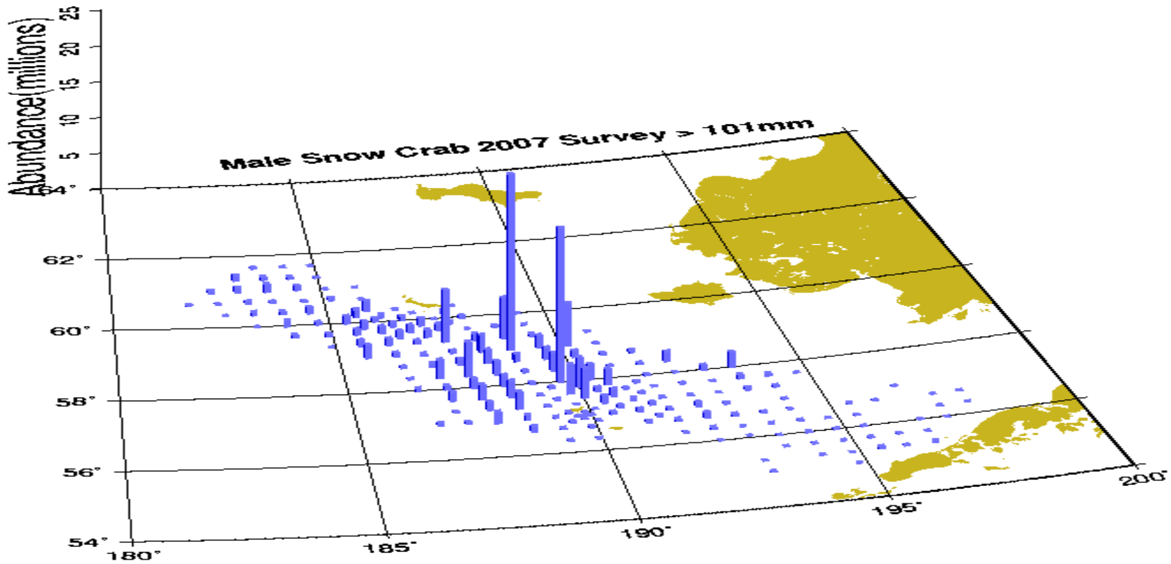

Figure 18. 2007 Survey abundance of males > 101 mm by tow. Abundance is in millions of crab.

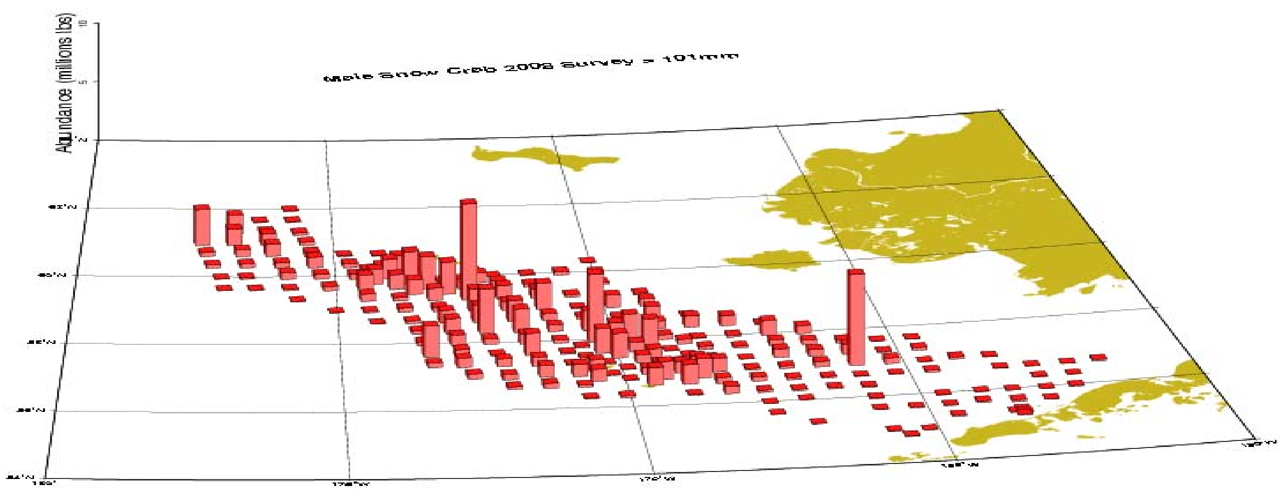

Figure 18b. 2008 Survey abundance of males > 101 mm by tow. Abundance is in millions of crab.

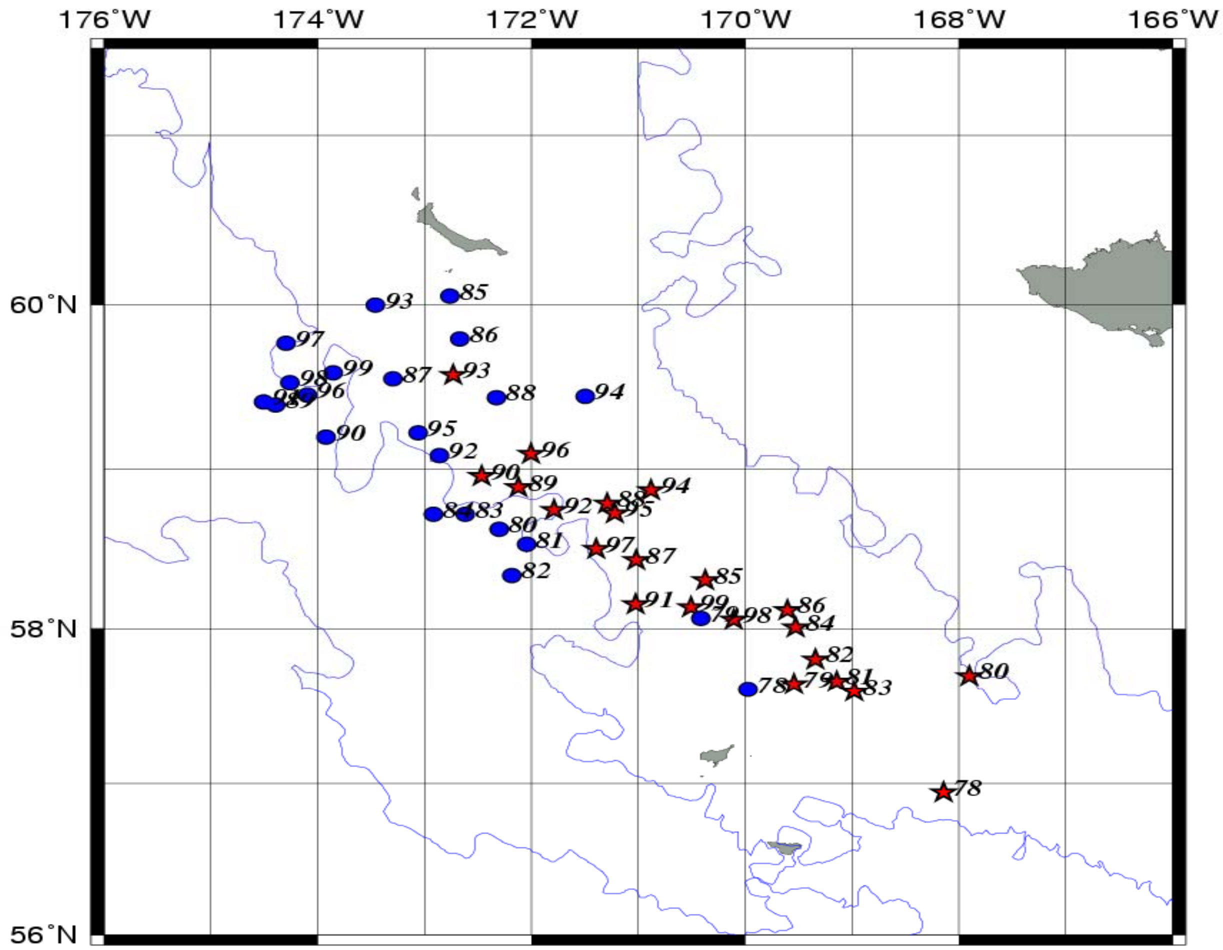

Figure 19. Centroids of abundance of mature female snow crabs (shell condition 2+) in blue circles and mature males (shell condition 3+) in red stars. Reprinted from Orensanz, Armstong and Ernst (in press).

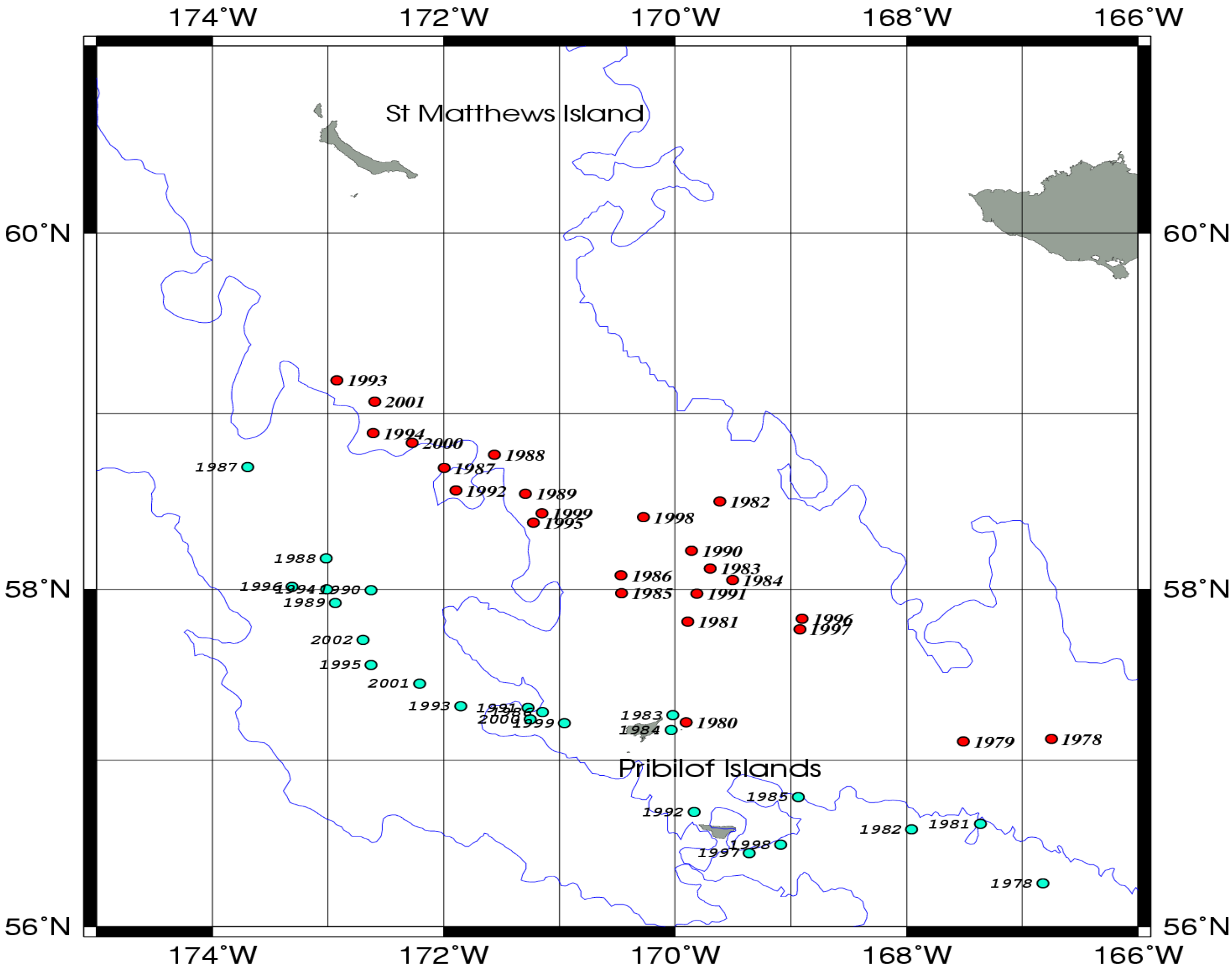

Figure 20. Centroids abundance (numbers) of snow crab males > 101 mm from the summer NMFS trawl survey (red) and from the winter fishery (blue-green), from Orensanz, Armstong and Ernst (in press).

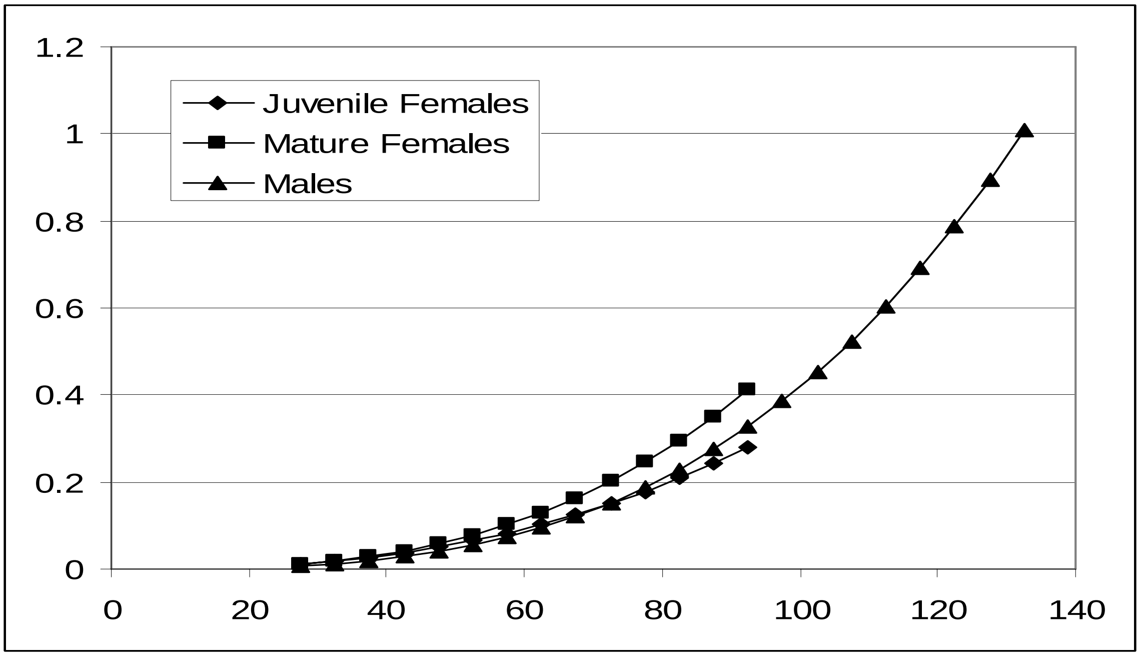

Figure 21. Weight (kg) – size (mm) relationship for male, juvenile female and mature female snow crab.

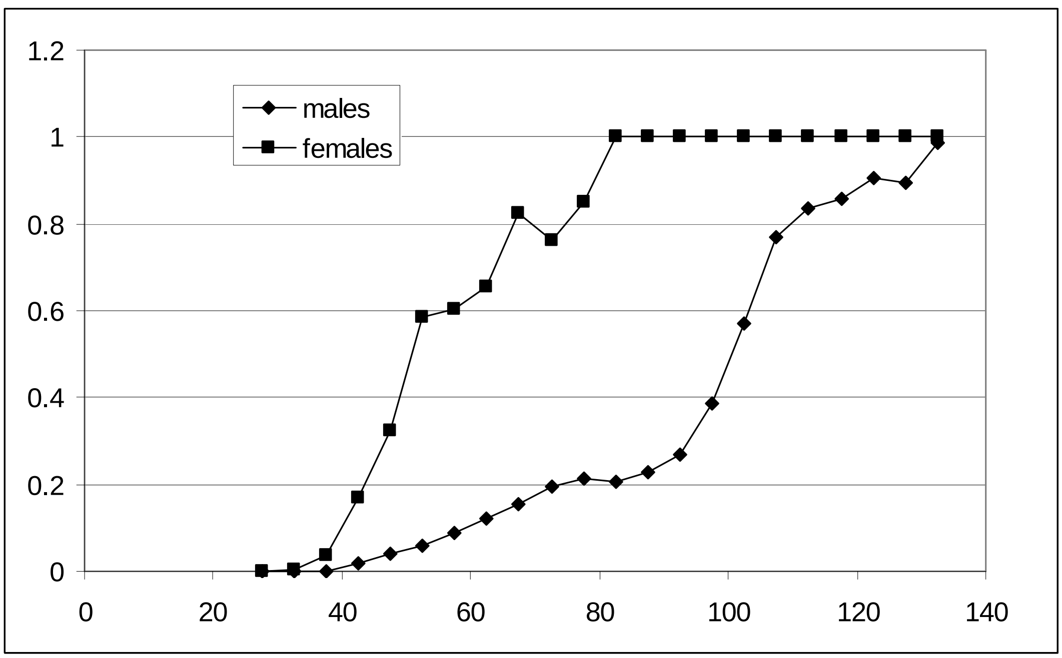

Figure 22. Probability of maturing by size for male and female snow crab (<u>not</u> the average fraction mature).

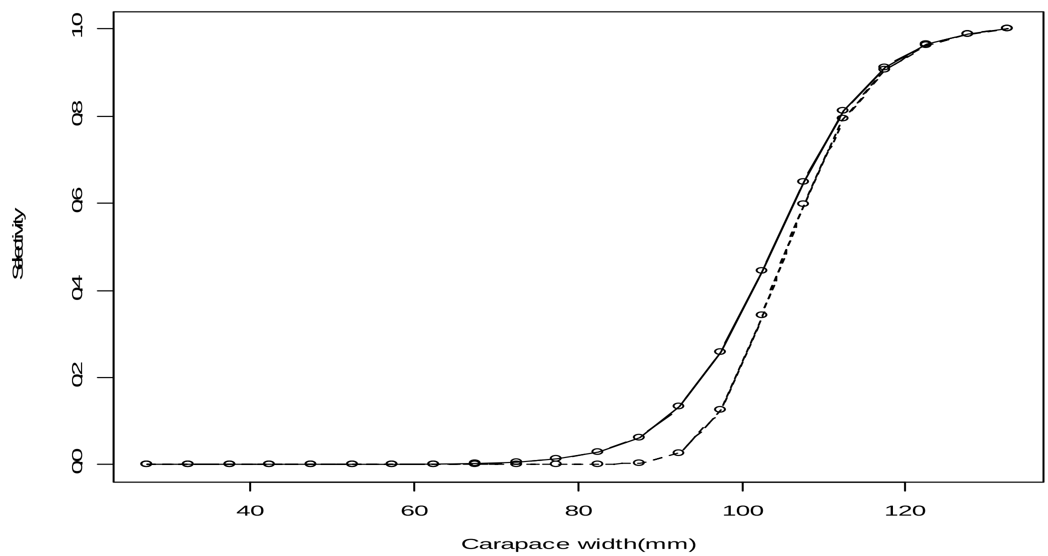

Figure 23. Selectivity curve for total catch (discard plus retained, solid line) and retained catch (dotted line) for combined shell condition male snow crab.

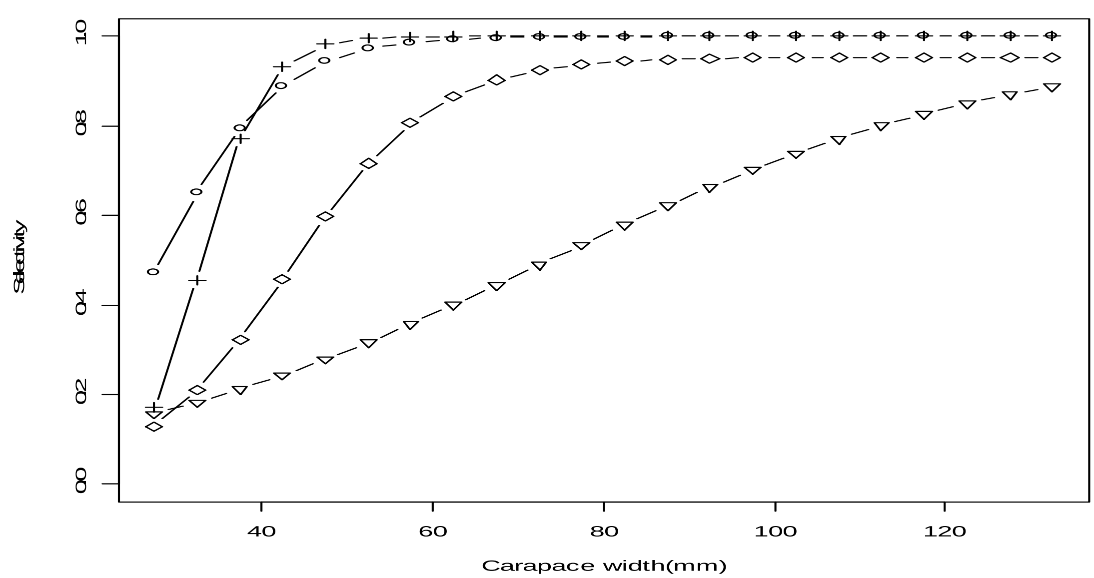

Figure 24. Survey selectivity curves for female and male snow crab estimated by the model for 1978-1981(solid line with circles), for 1982 to 1988 (solid line with diamonds), and 1989 to present (solid line with pluses). Survey selectivities estimated by Somerton and Otto (1998) are the solid line with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

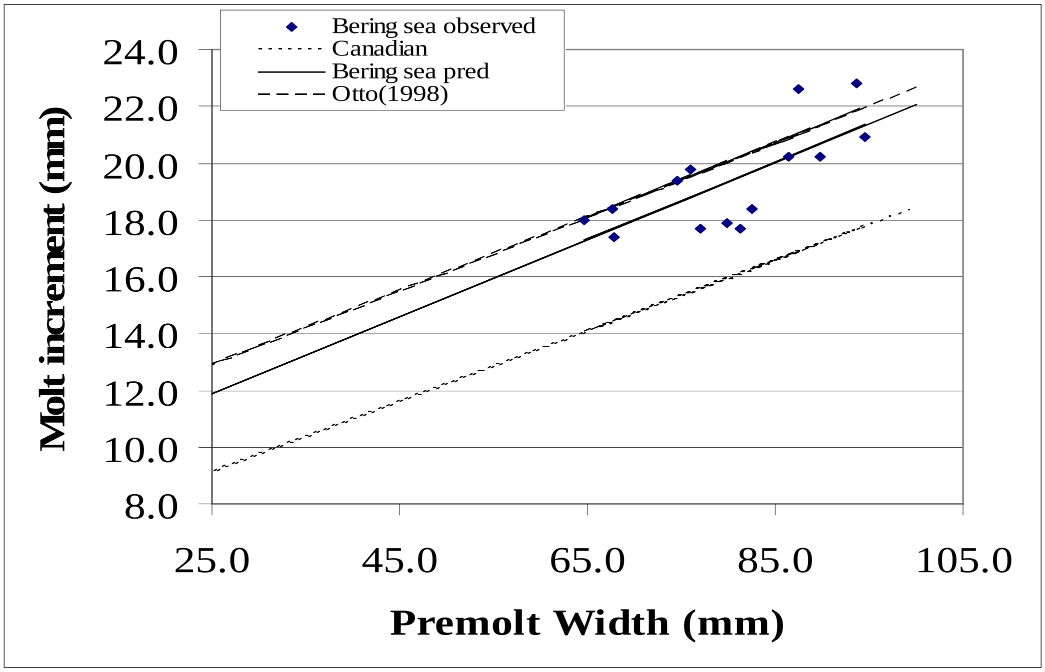

Figure 25. Growth increment as a function of premolt size for male snow crab. Points labeled Bering sea observed are observed growth increments from Rugolo (unpub data). The line labeled Bering sea pred is the predicted line from the Bering sea observed growth, which is used as a prior for the growth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

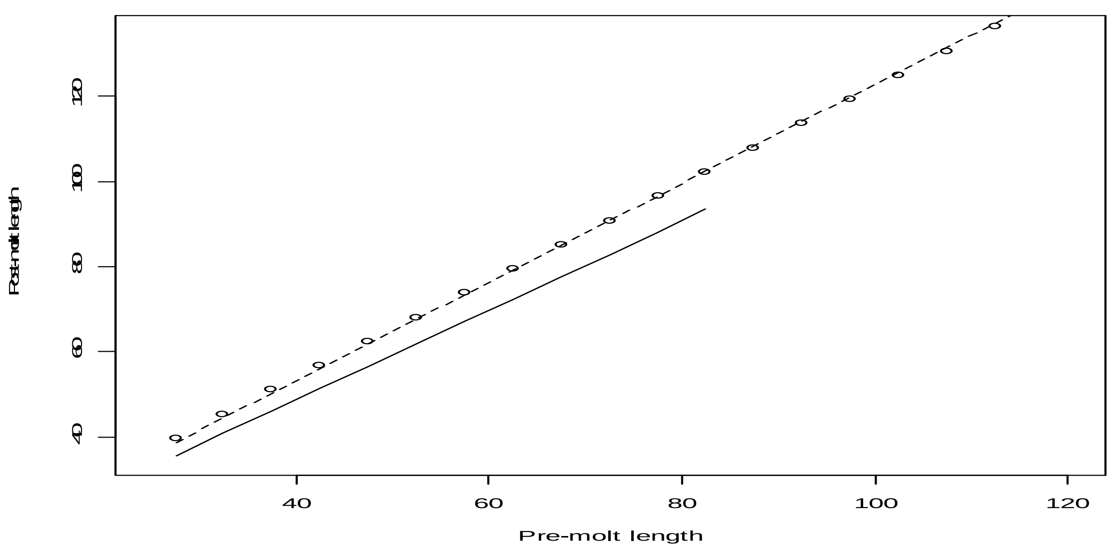

Figure 25. Growth(mm) for male(dotted line) and female snow crab (solid line) estimated from the model. Circles are the observed growth curve.

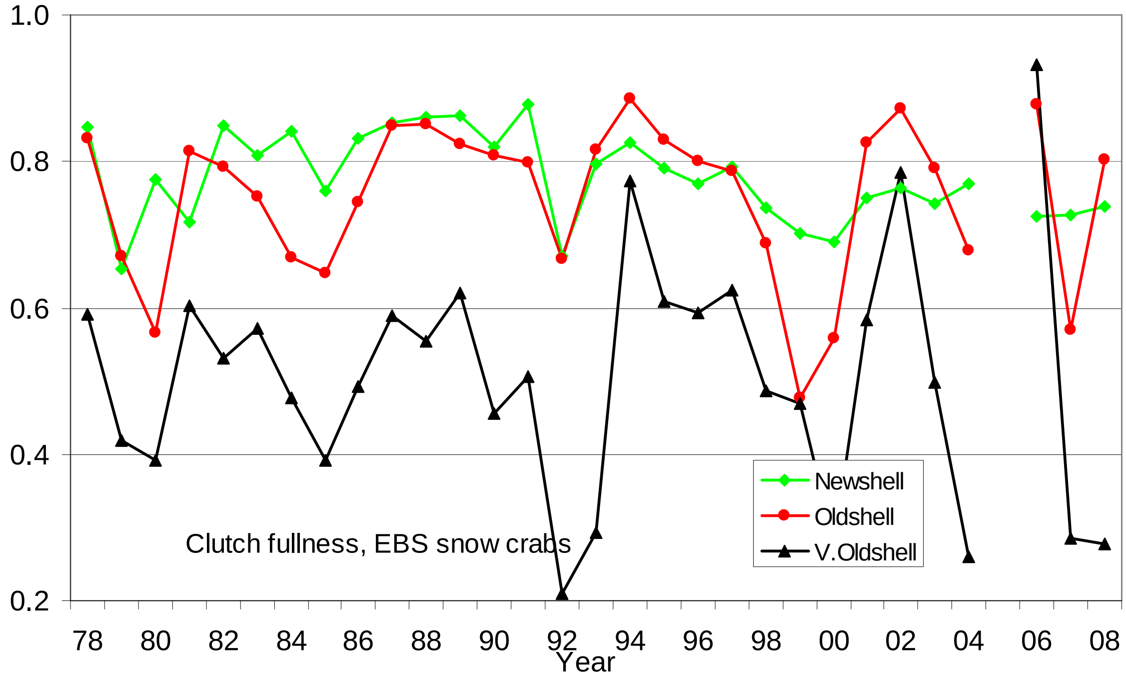

Figure 26. Clutch fullness for Bering sea snow crab survey data by shell condition for 1978 to 2008.

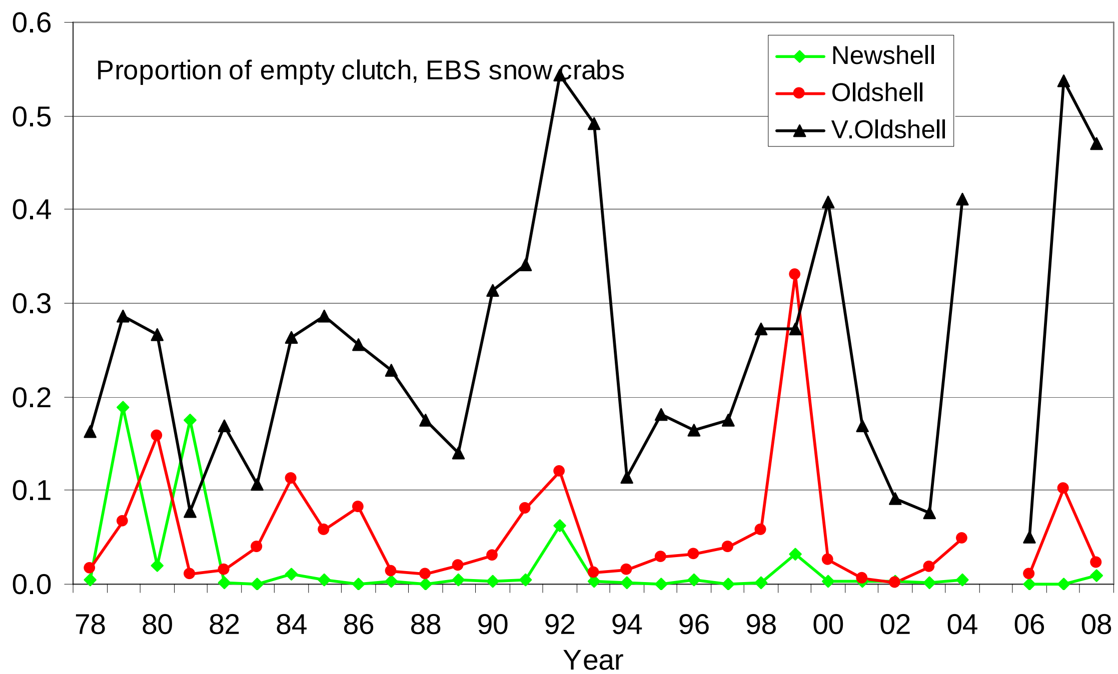

Figure 27. Proportion of barren females by shell condition from survey data 1978 to 2008.

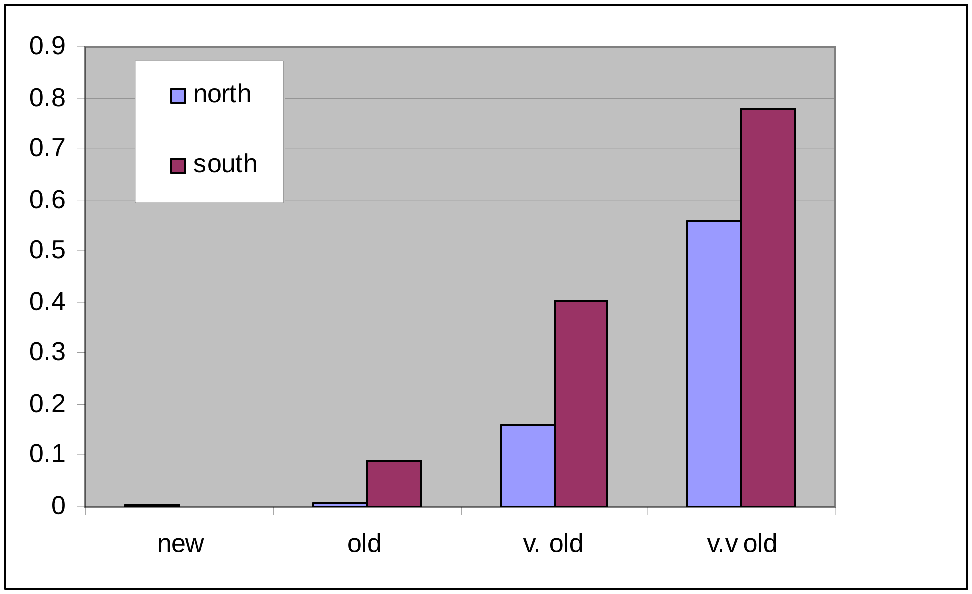

Figure 28. Fraction of barren females in the 2004 survey by shell condition and area north of 58.5 deg N and south of 58.5 deg N.

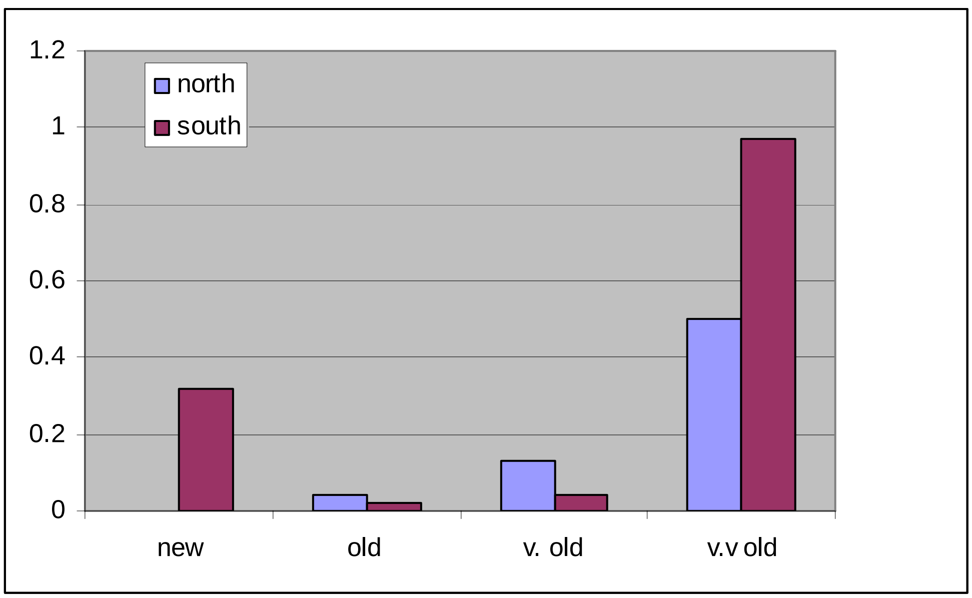

Figure 29. Fraction of barren females in the 2003 survey by shell condition and area north of 58.5 deg N and south of 58.5 deg N. The number of new shell mature females south of 58.5 deg N was very small in 2003.

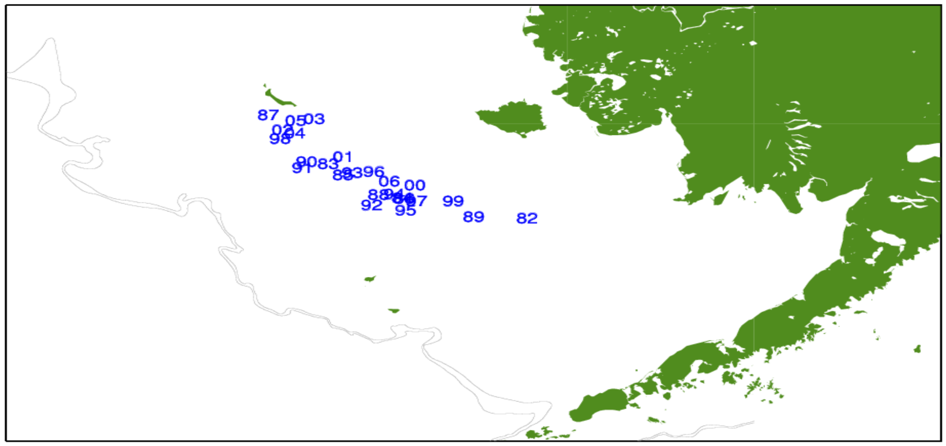

Figure 30. Centroids of cold pool (<2.0 deg C) from 1982 to 2006. Centroids are average latitude and longitude.

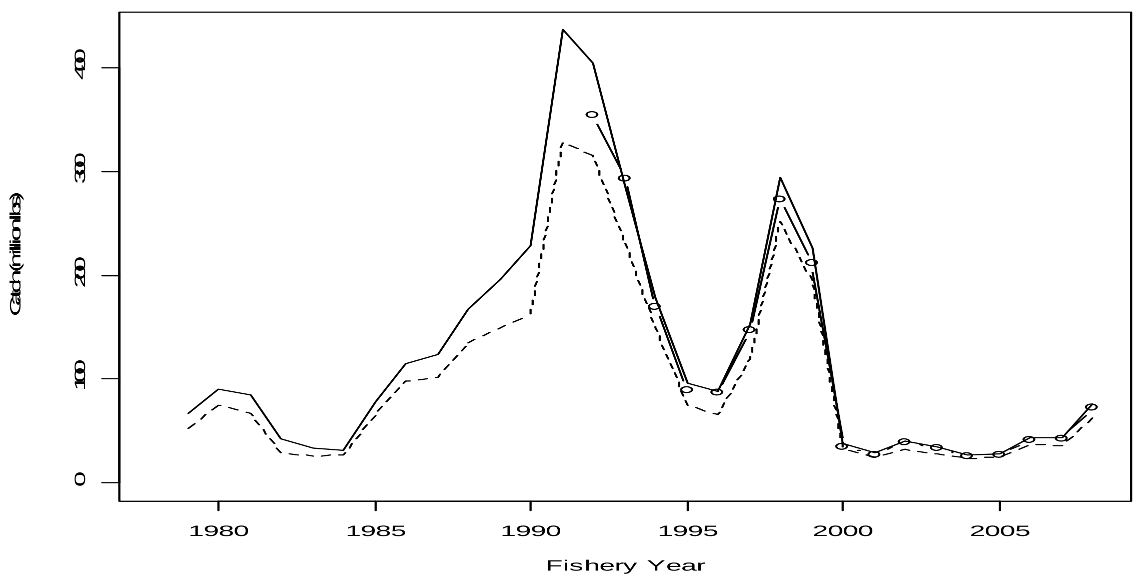

Figure 31. Estimated total catch(discard + retained) (solid line), observed total catch (solid line with circles) (assuming 50% mortality of discarded crab) and observed retained catch (dotted line) for 1979 to 2008 fishery seasons.

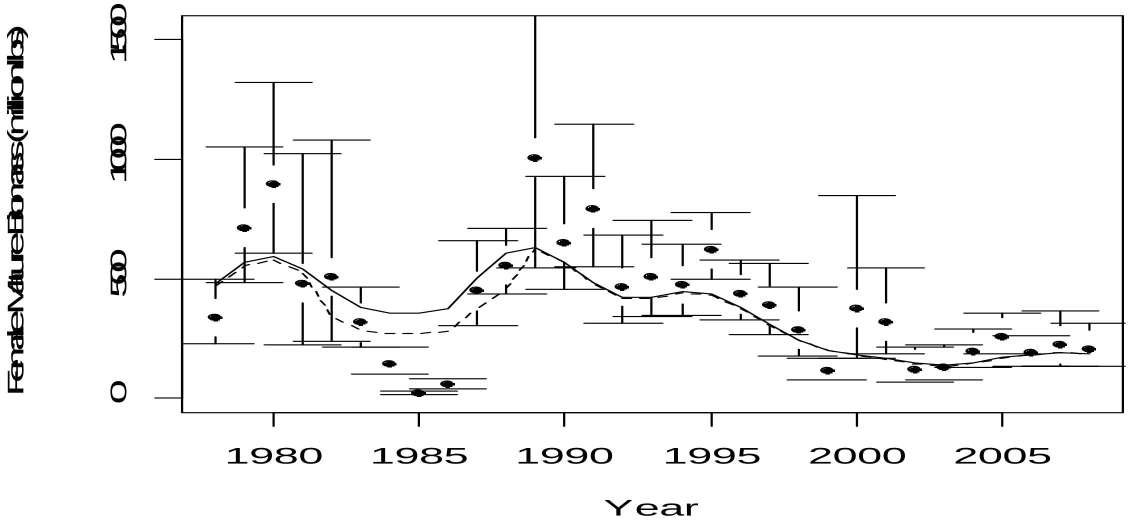

Figure 32. Population female mature biomass (millions of pounds, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

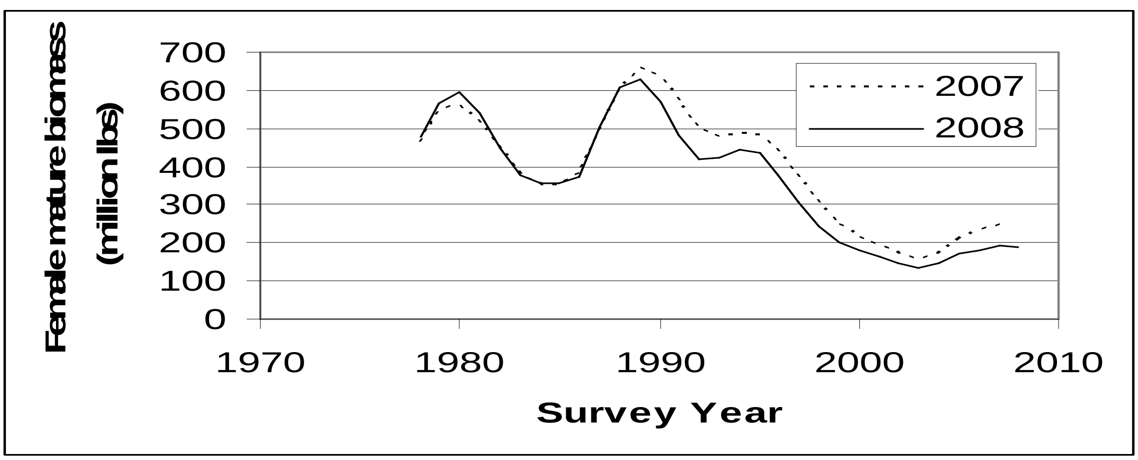

Figure 33. Population female mature biomass from the 2007 assessment and this assessment.

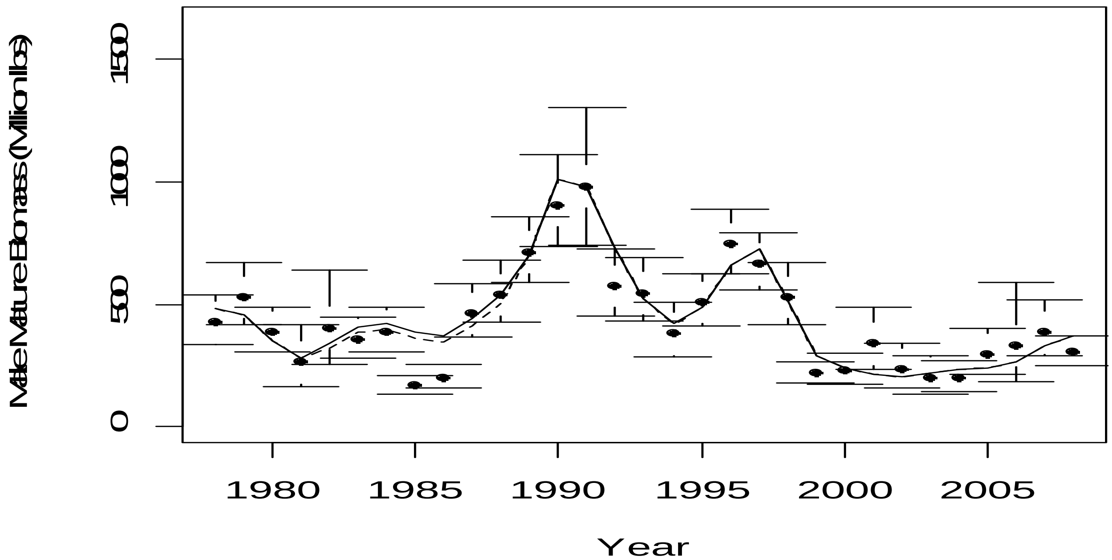

Figure 34. Population male mature biomass (millions of pounds, solid line), model estimate of survey male mature biomass (dotted line) and observed survey male mature biomass with approximate lognormal 95% confidence intervals.

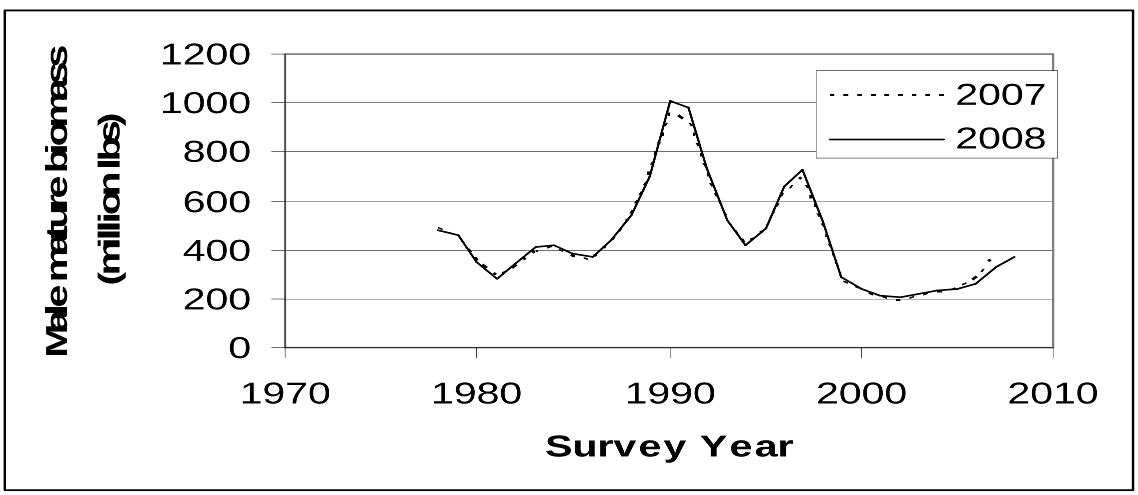

Figure 35. Population male mature biomass from the 2007 assessment and this assessment.

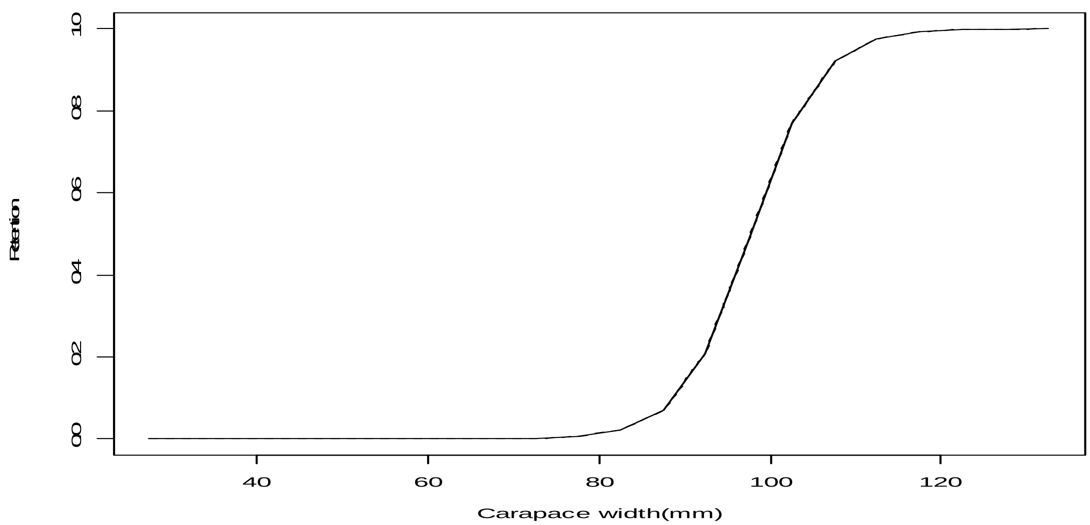

Figure 36. Model estimated fraction of the total catch that is retained by size for male snow crab combined shell condition.

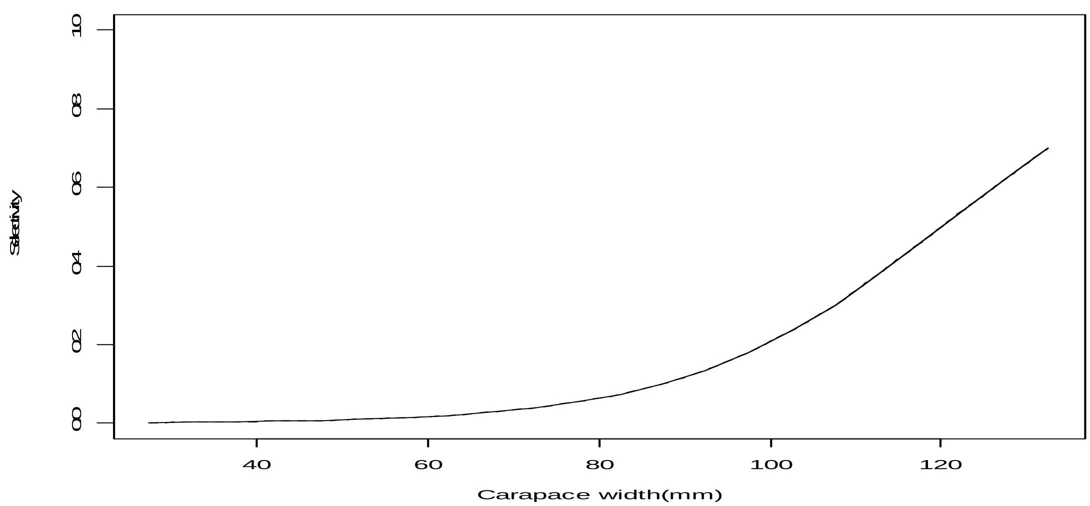

Figure 37. Selectivity curve estimated by the model for bycatch in the groundfish trawl fishery for females and males.

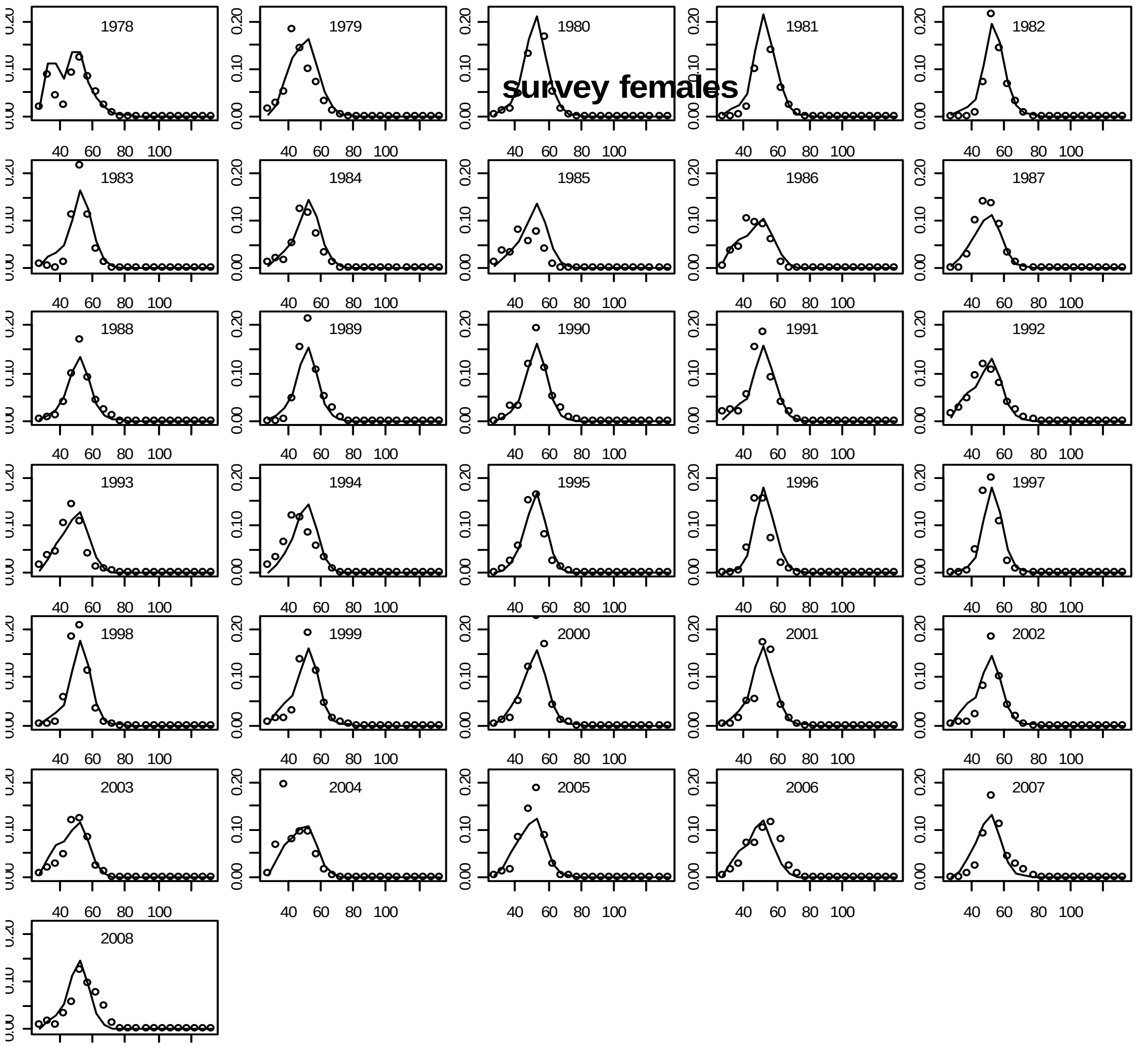

Figure 38. Model fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

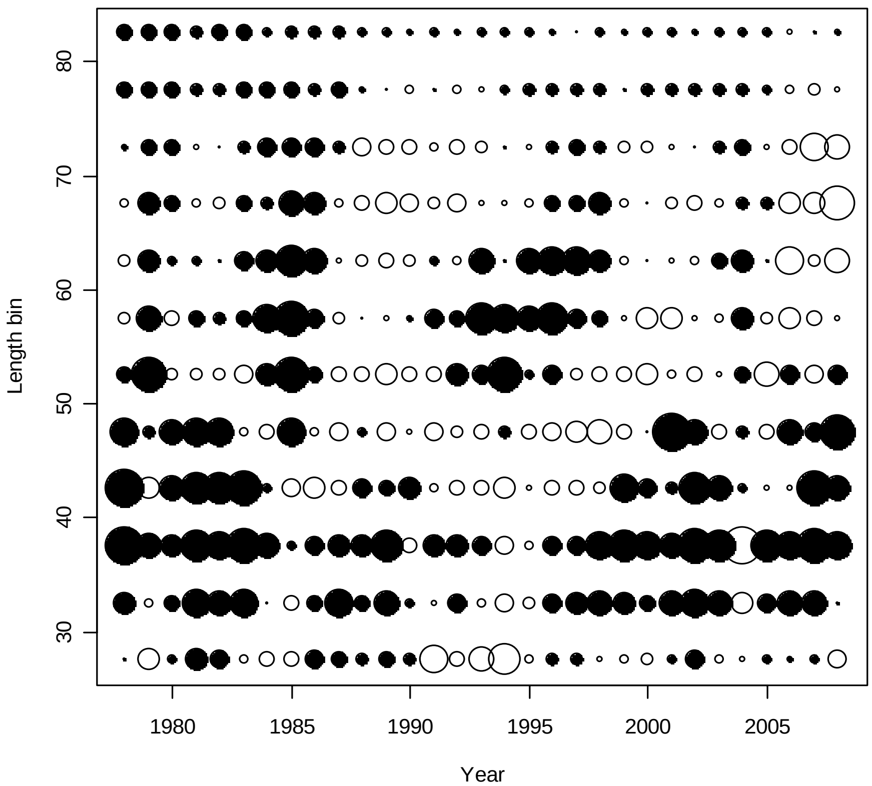

Figure 39. Residuals of fit to survey female size frequency. Filled circles are negative residuals.

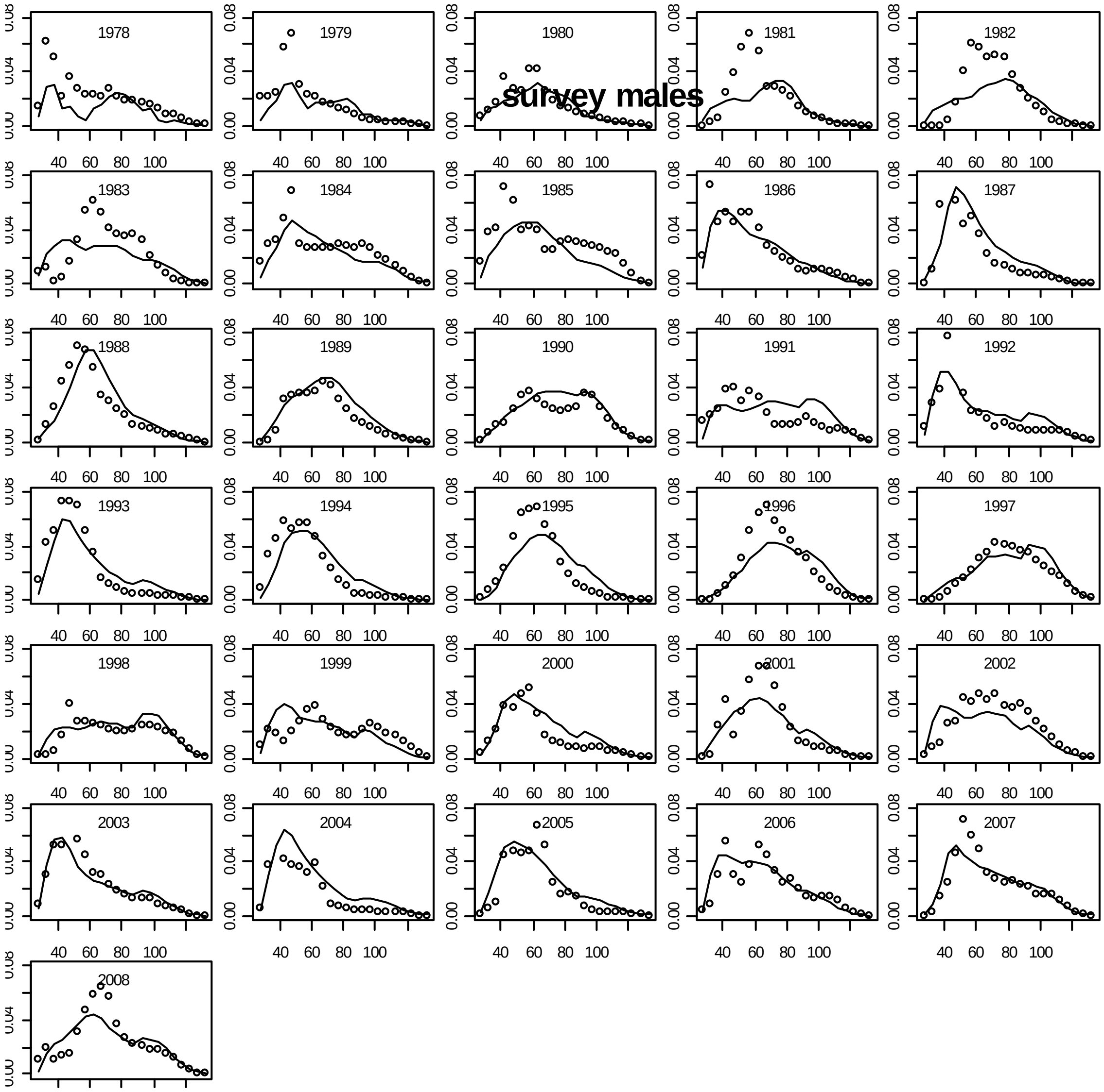

Figure 40. Model fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

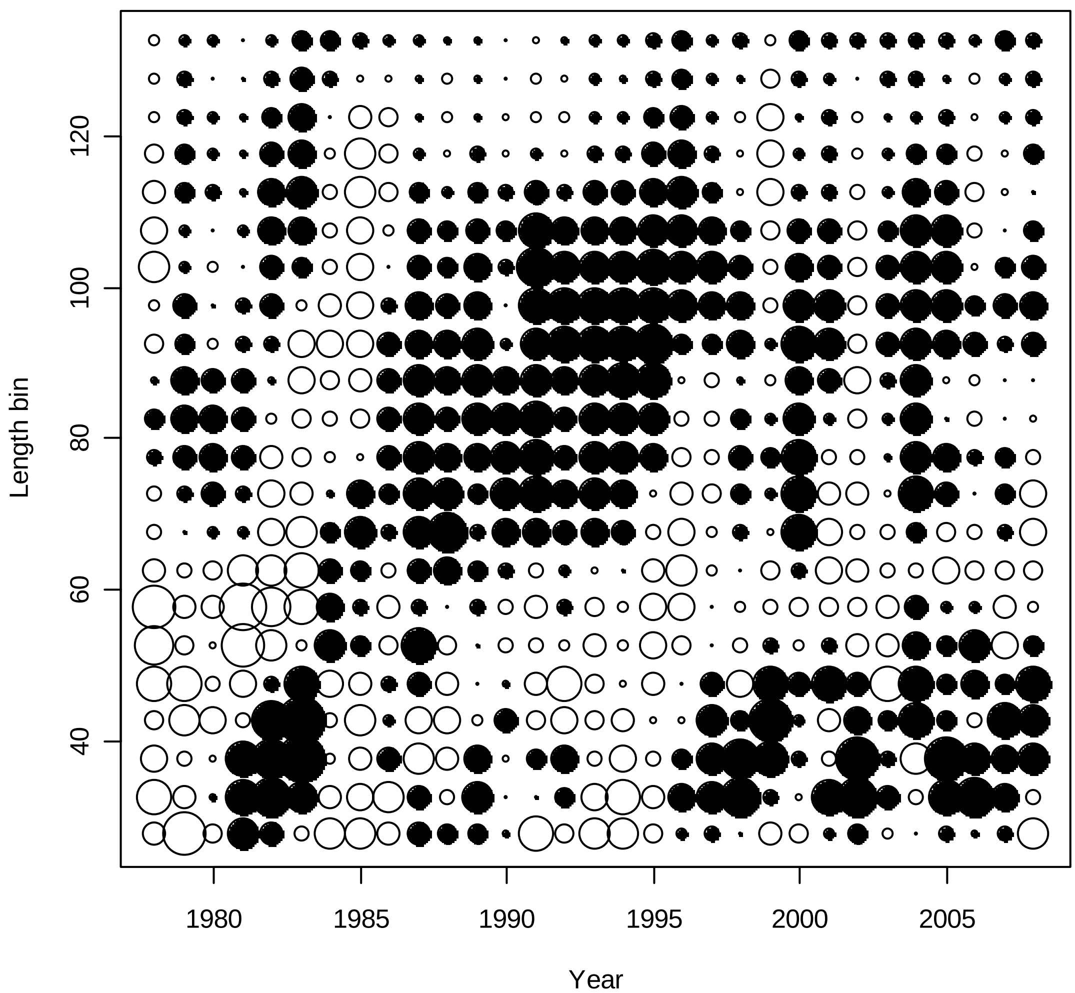

Figure 41. Residuals for fit to survey male size frequency. . Filled circles are negative residuals (predicted higher than observed).

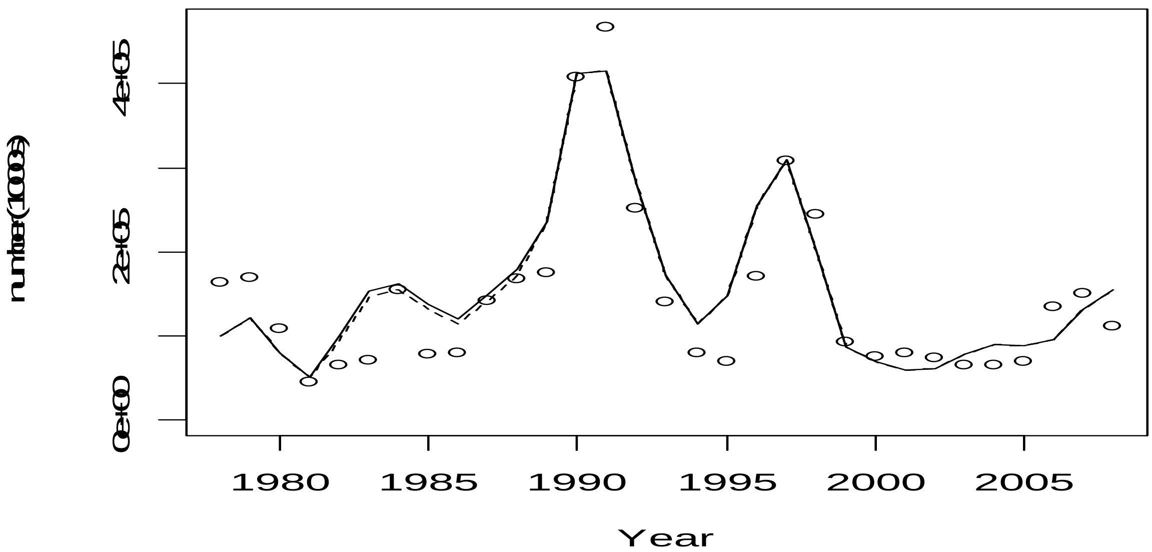

Figure 42. Observed survey numbers of males >101mm (circles), model estimates of the population number of males >101mm(solid line) and model estimates of survey numbers of males >101 mm (dotted line).

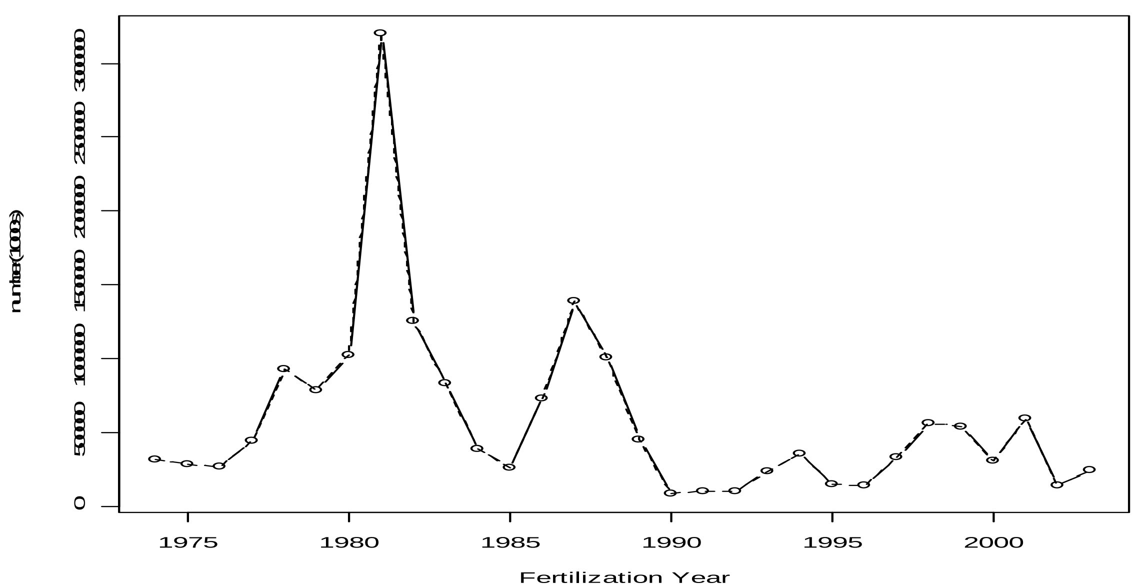

Figure 43. Recruitment to the model for crab 25 mm to 50 mm. Total recruitment is 2 times recruitment. Male and female recruitment fixed to be equal.

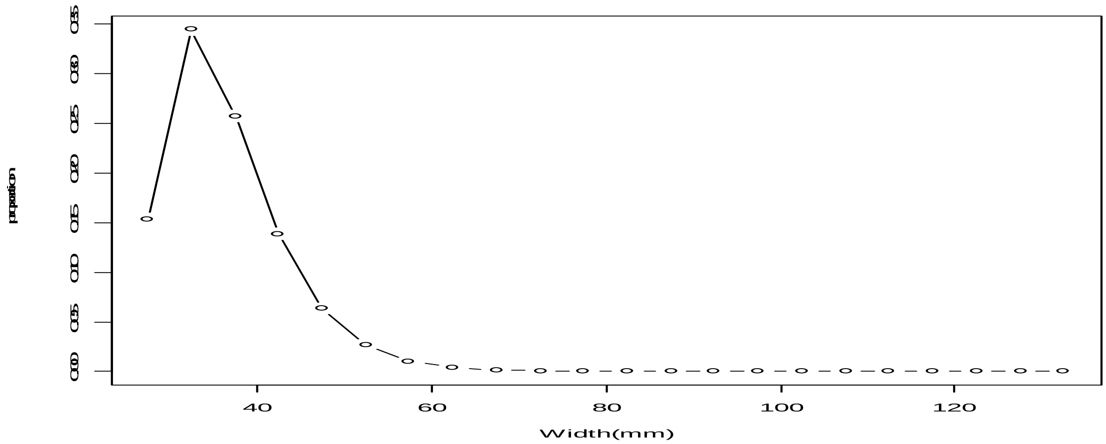

Figure 44. Distribution of recruits to length bins estimated by the model.

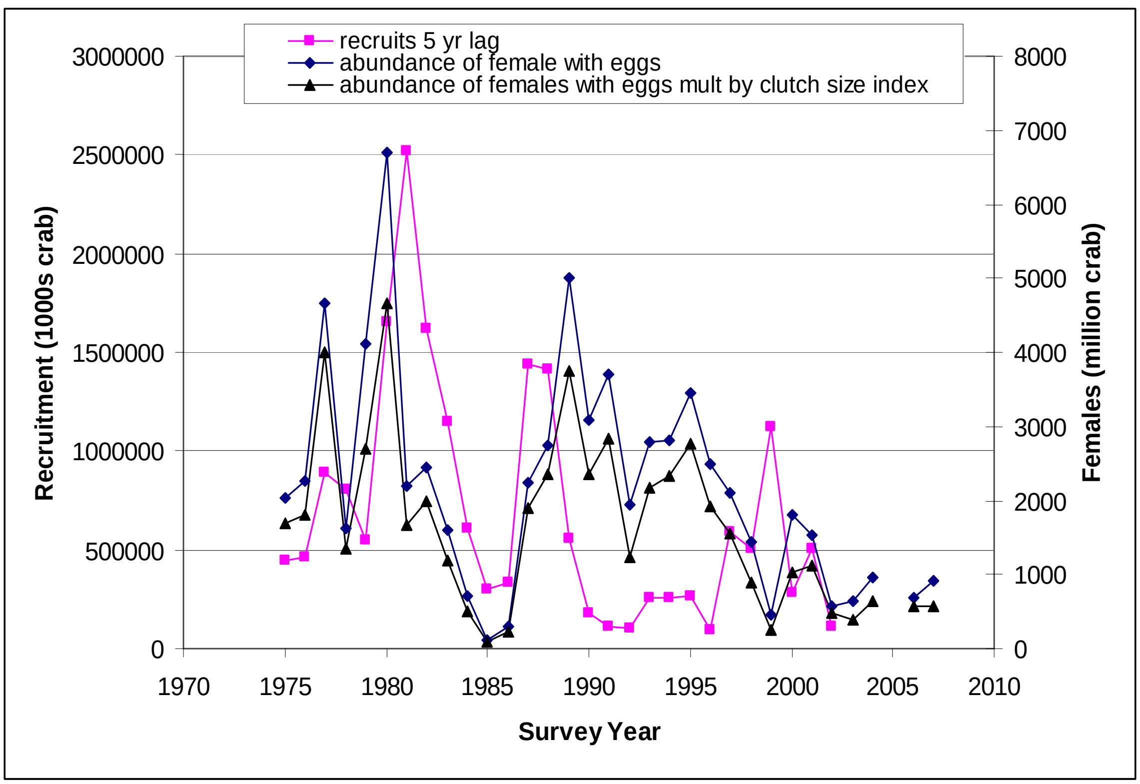

Figure 45. Model estimates of recruitment (fertilization year), survey abundance of females with eggs, and abundance of females with eggs multiplied by the fraction of full clutch from 1975 to 2007.

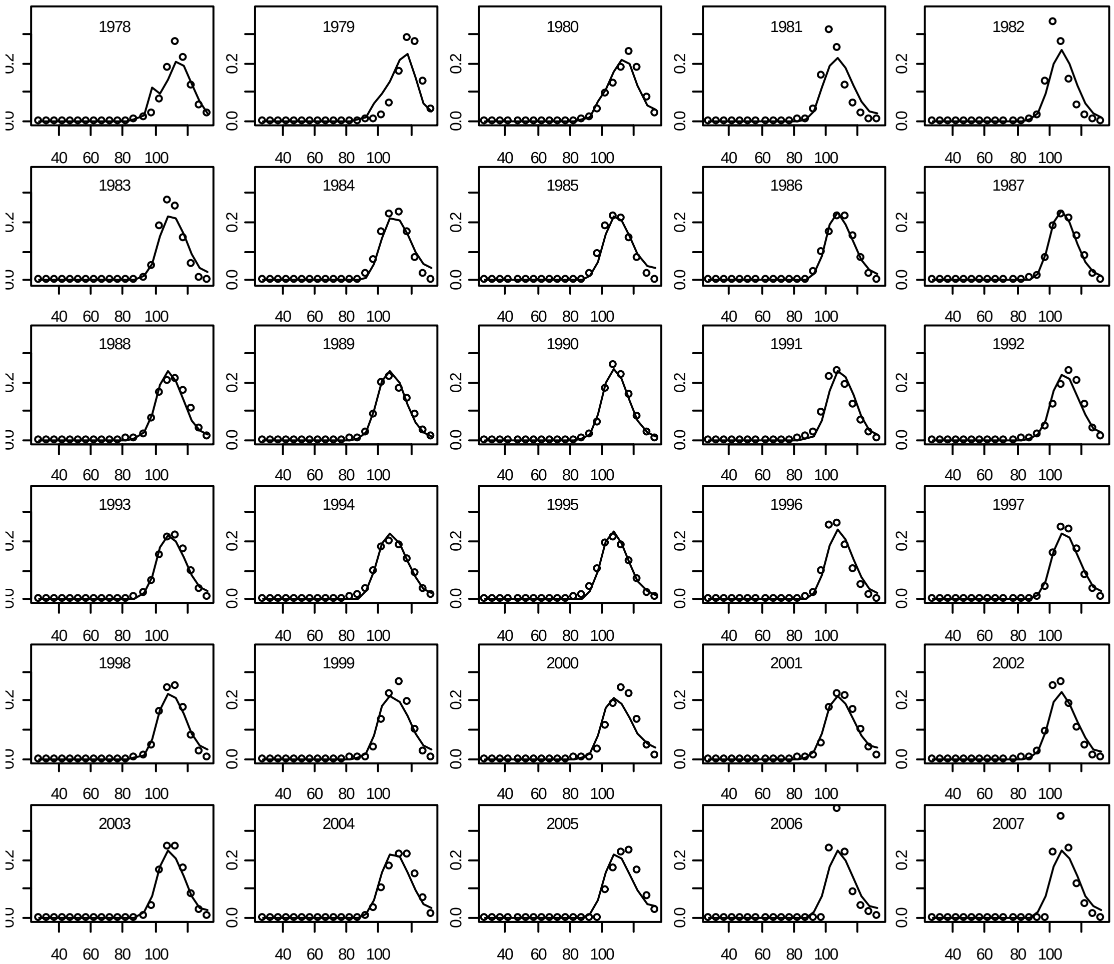

Figure 46. Model fit to the retained male size frequency data, shell condition combined. Solid line is the model fit. Circles are observed data. Year is the survey year.

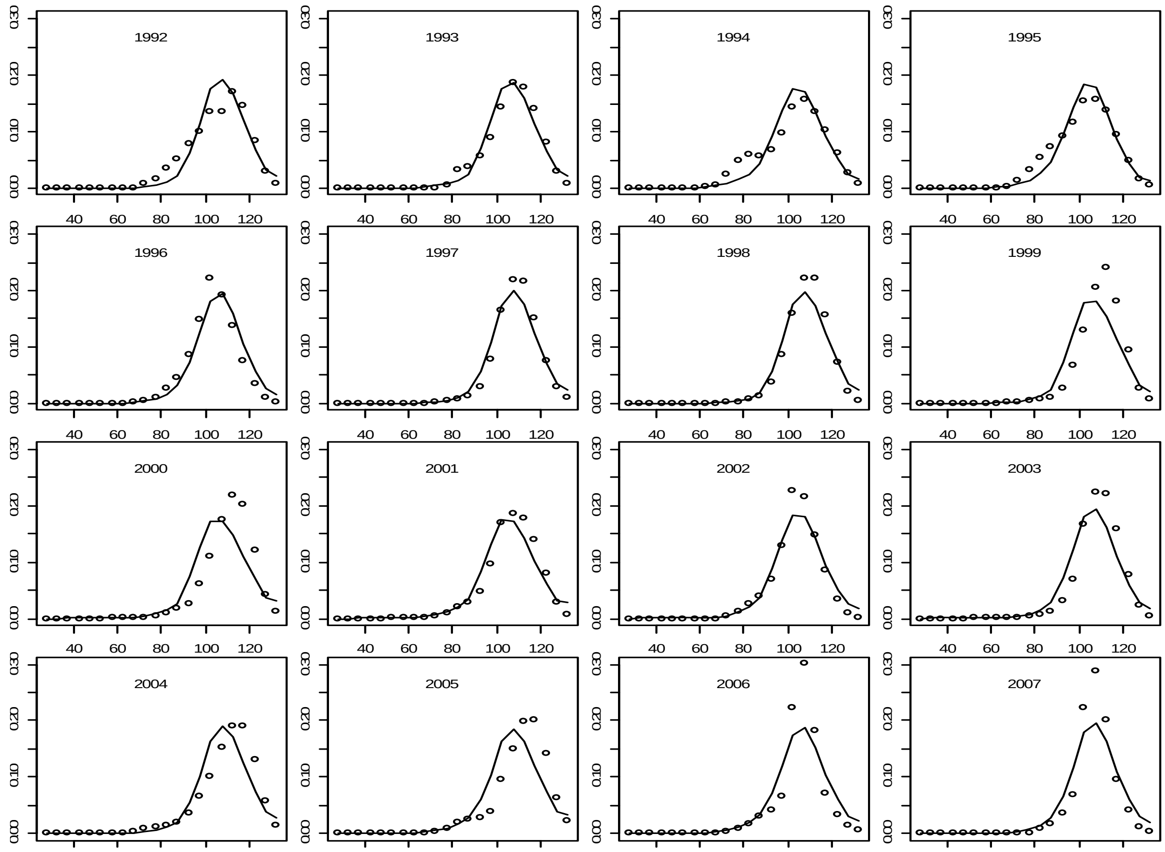

Figure 47. Model fit to the total (discard plus retained) male size frequency data, shell condition combined. Solid line is the model fit. Circles are observed data. Year is the survey year.

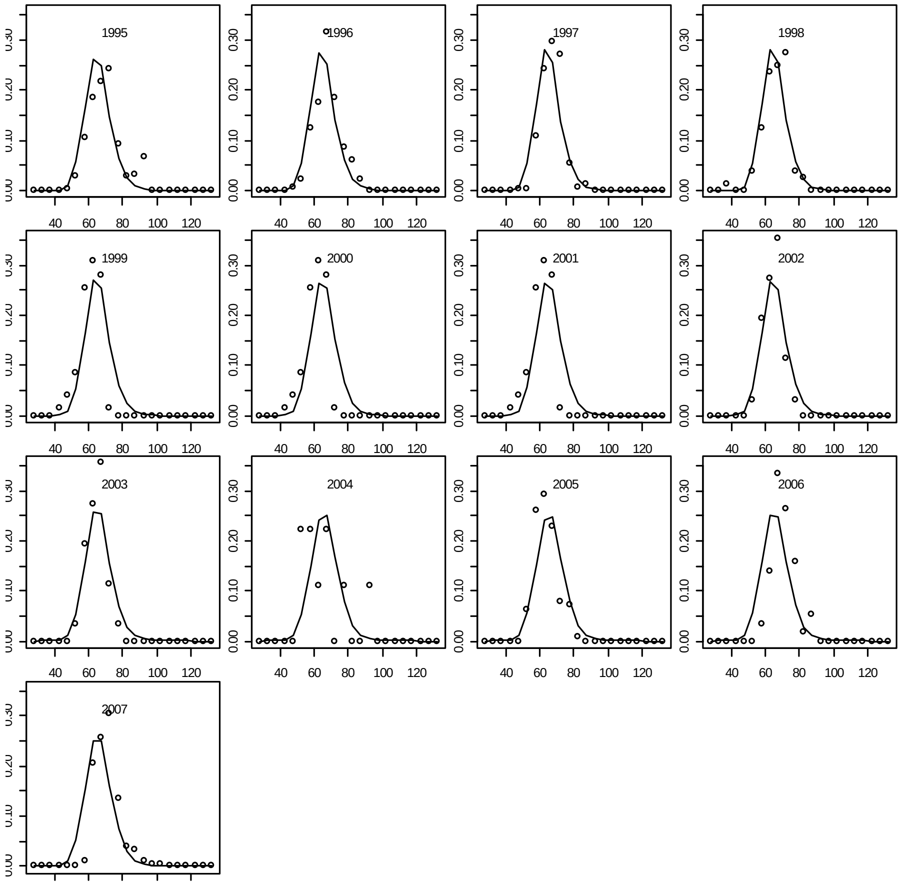

Figure 48. Model fit to the discard female size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

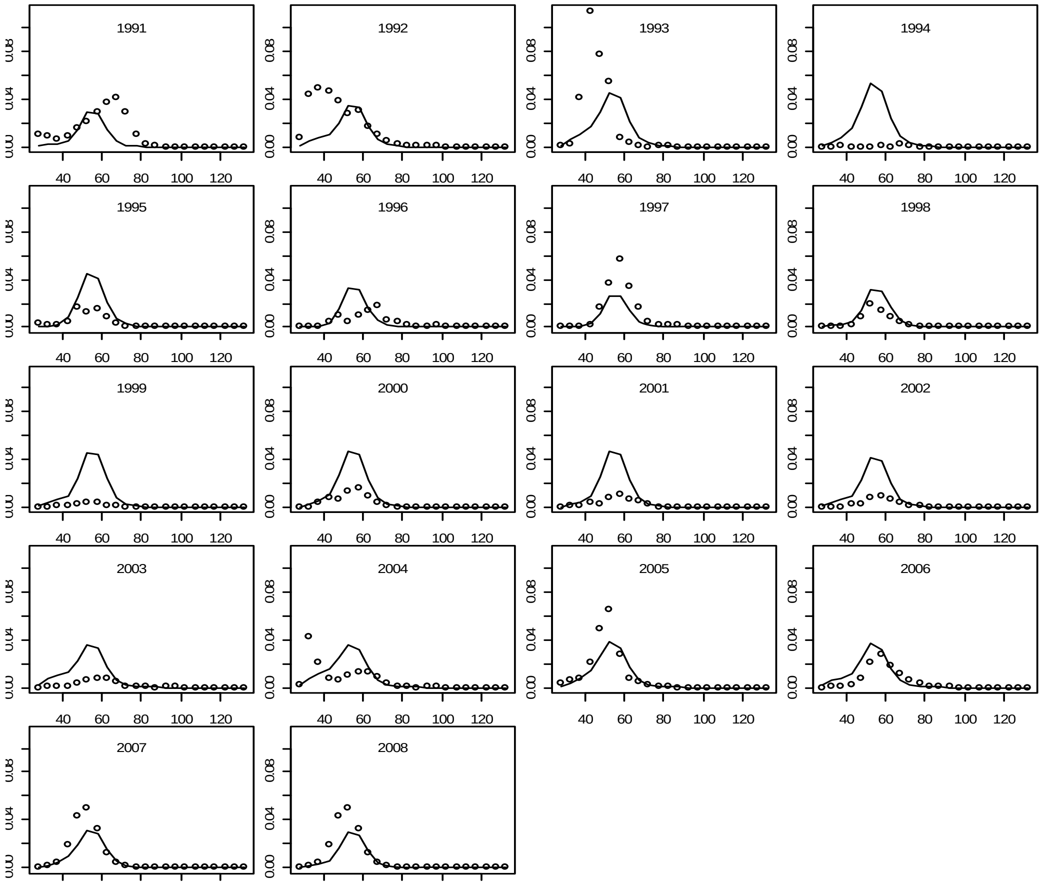

Figure 49. Model fit to the groundfish trawl discard female size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

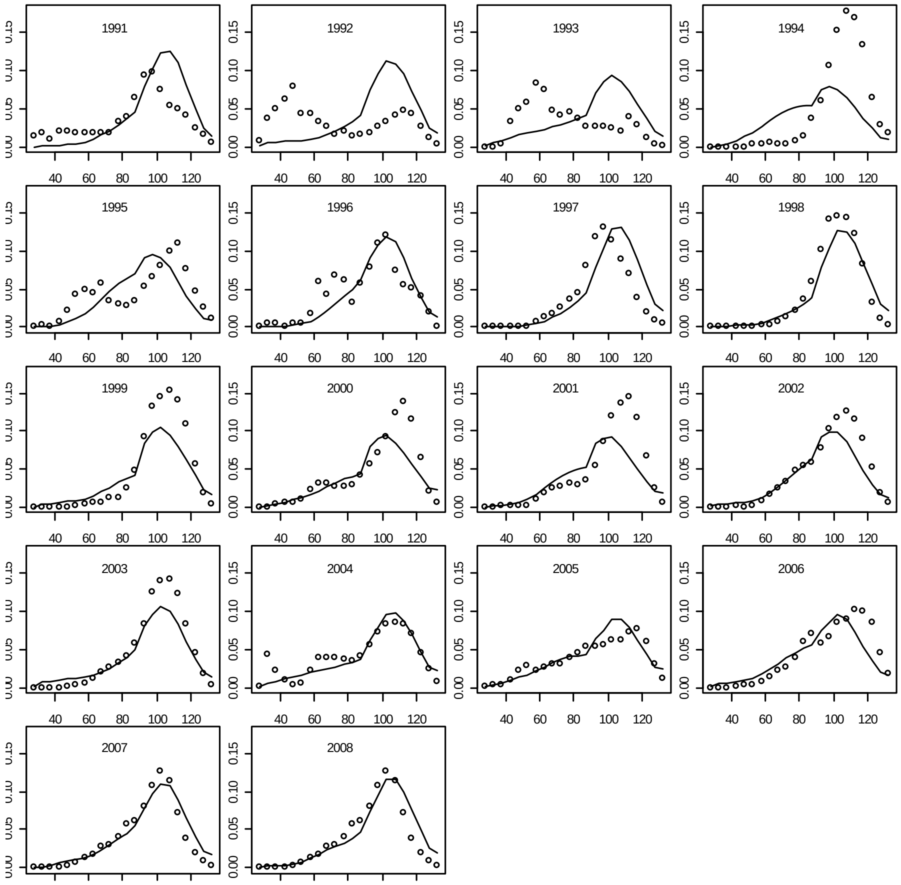

Figure 50. Model fit to the groundfish trawl discard male size frequency data. Solid line is the model fit. Circles are observed data.

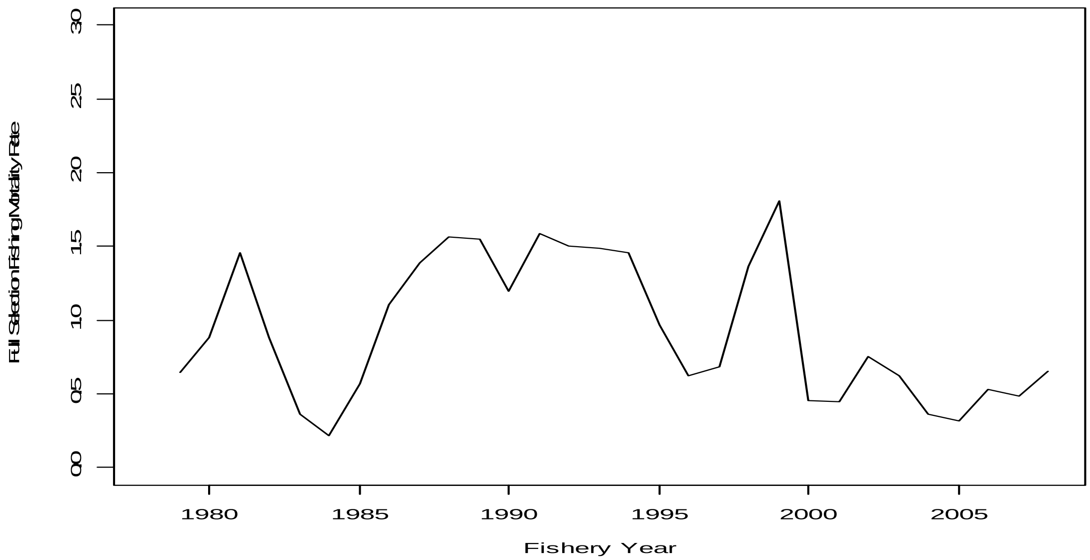

Figure 51. Full selection fishing mortality estimated in the model from 1979 to 2008 fishery seasons (1978 to 2007 survey years).

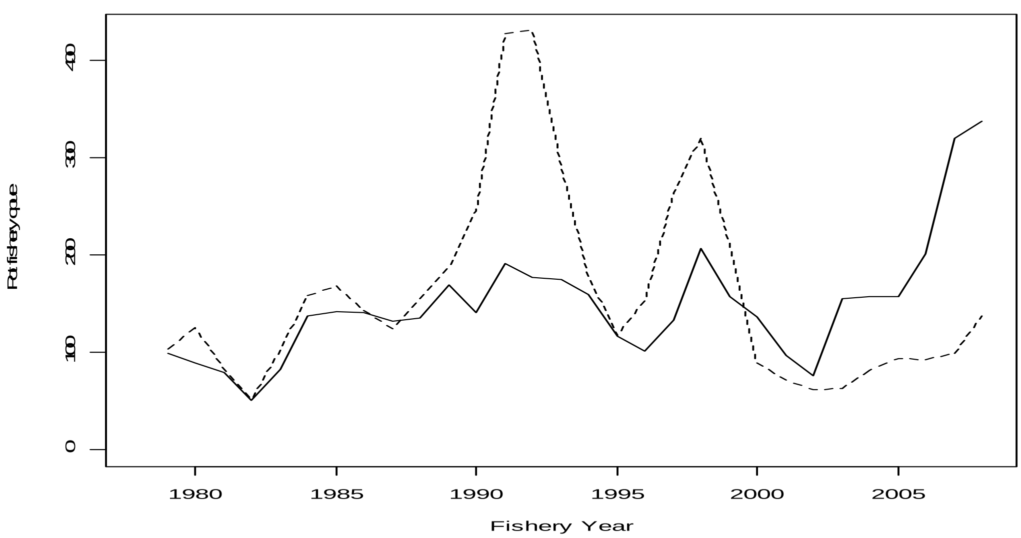

Figure 52. Fit to pot fishery cpue for retained males. Solid line is observed fishery cpue, dotted line model fit.

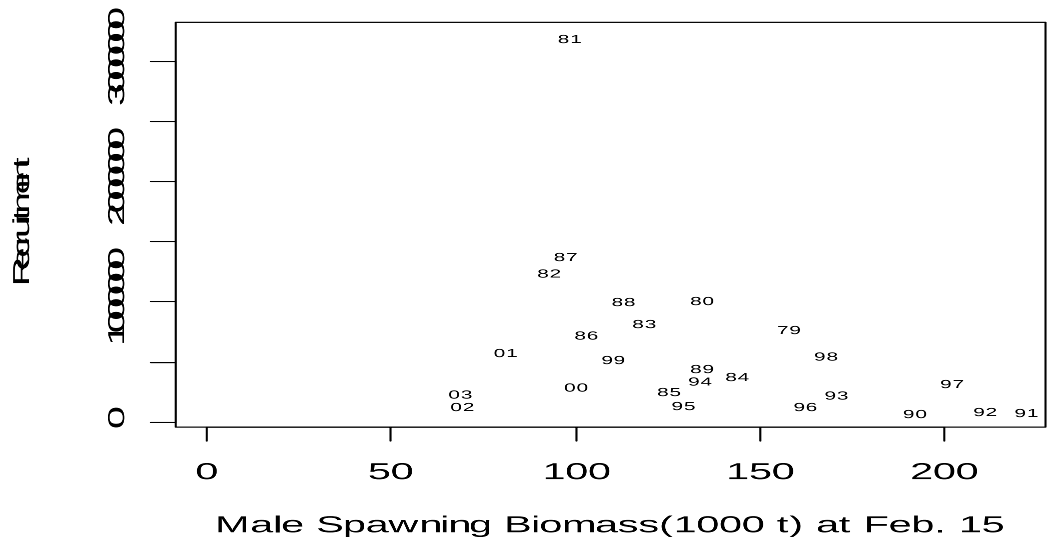

Figure 53. Spawner recruit estimates using male mature biomass at time of mating. Numbers are fertilization year assuming a lag of 5 years. Recruitment is half total recruits in thousands of crab.

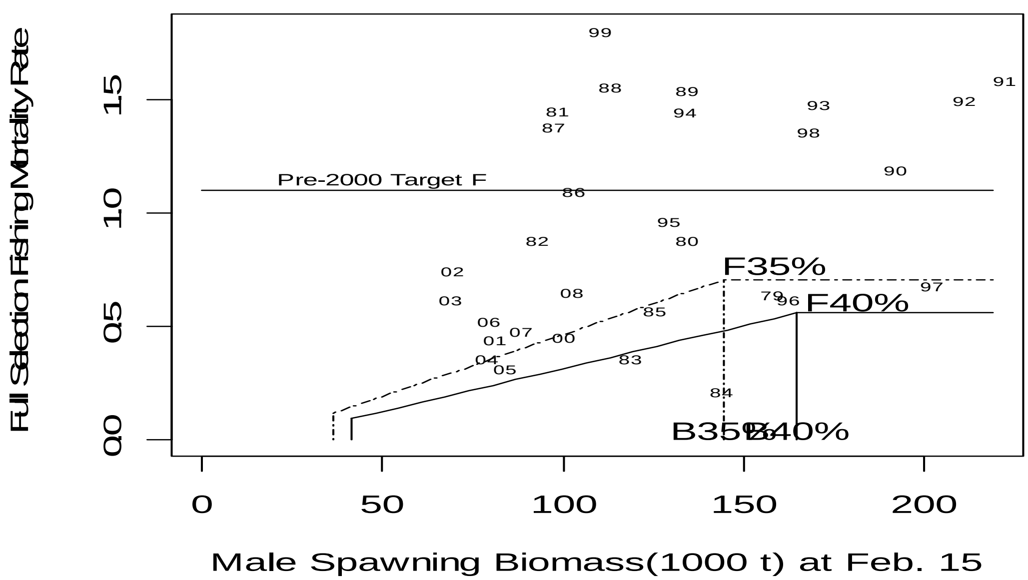

Figure 54. Harvest control rules. Two control rules are shown, one for F40% and one for F35% with alpha = 0.1. The pre-2000 target F of about 1.1 was the target F that resulted from the harvest strategy used before the 2000 fishery season. Vertical lines labeled B40% and B35% are estimated from the product of spawning biomass per recruit fishing at F40% or F35% respectively and mean recruitment from the stock assessment model.

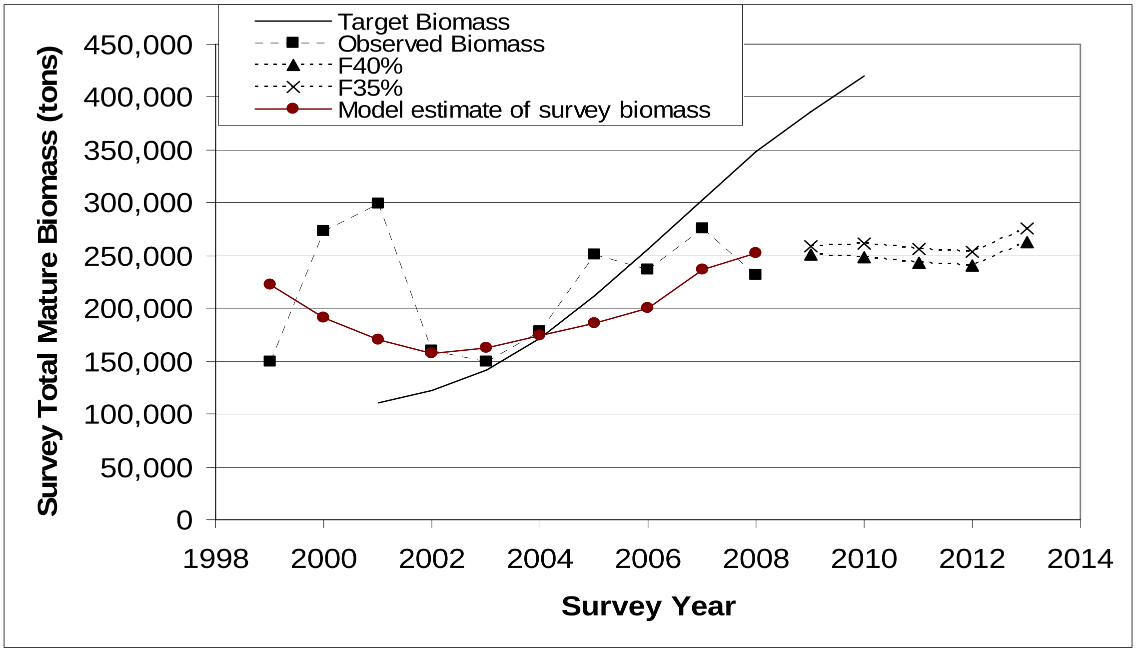

Figure 55. Target survey total mature biomass by year from rebuilding plan simulations, observed survey total mature biomass and model estimates of survey total mature biomass for the F40% and F35% harvest strategies. **2010 is 10 years from the start of the rebuilding plan**

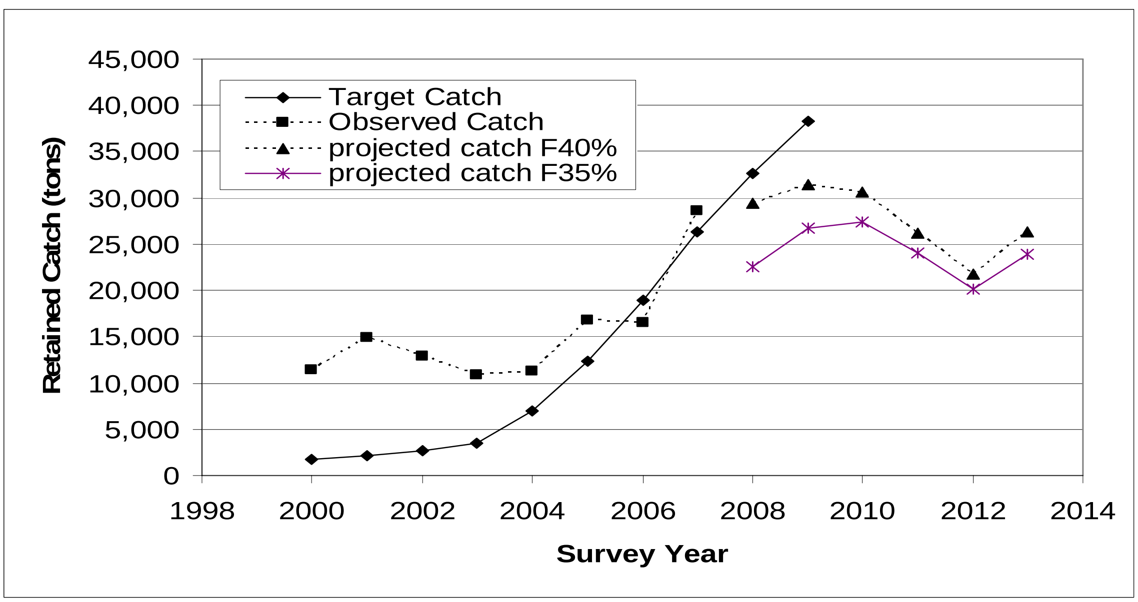

Figure 56. Target average retained catch by year from rebuilding plan simulations, observed retained catch for 2001 to 2007, and projected retained catch for 2008 to 2010 using the F40% and F35% harvest strategies.

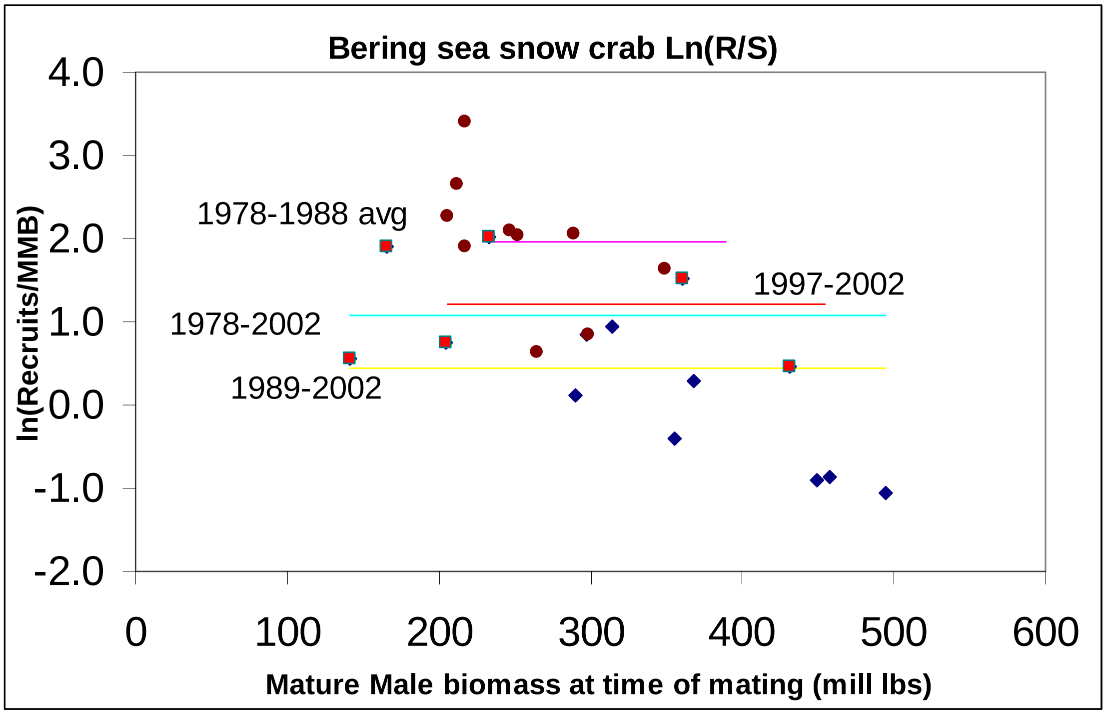

Figure 57. Productivity of snow crab (Ln(recruitment/mature male biomass at mating)) for different levels of mature male biomass at mating. Average values for various time periods are shown on the plot. Different symbols for MMB indicate which average they were included in.

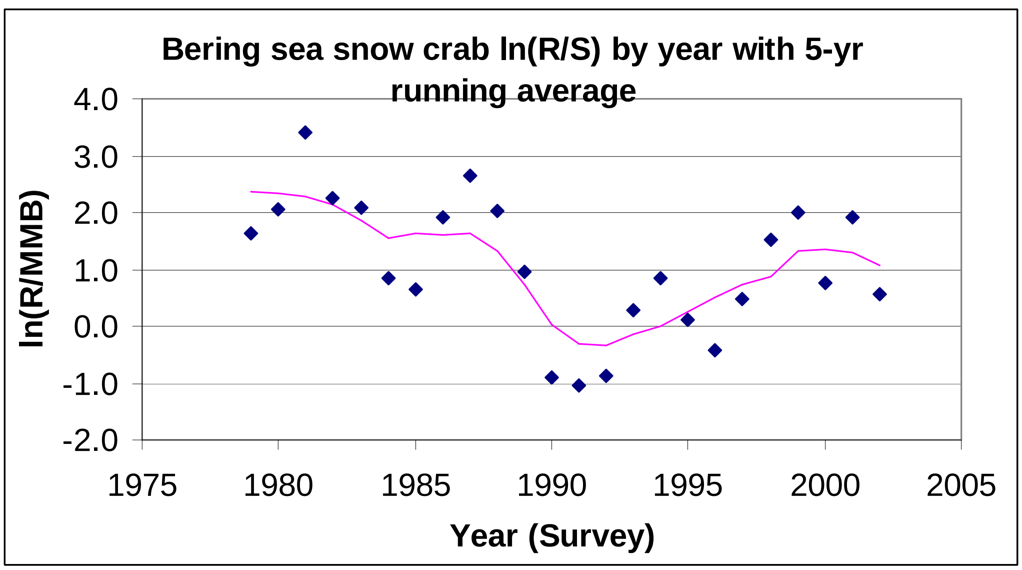

Figure 58. Productivity (ln(recruitment/Mature male biomass at mating)) from 1978 to 2002, with a 5-year running average.

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 $C_{t,s,l} = \sum_{s,l} (1 - e^{-F_{t,s,l} Sel_{t,s,l}}) e^{-M_s Cmid_t} N_{t,s,l}$ TRAWL BYCATCH $C_{t,s,l} = \sum_{s,l} (1 - e^{-F^{trawl}_{t,s,l} Sel^{trawl}_{t,s,l}}) e^{-M_s Cmid_t} N_{t,s,l}$	$1 \le t \le$ $1 \le l \le$	Catch taken as a pulse fishery at midpoint of catch(survey is considered start of the year).
$Nimmature_{new,t+1,s,l+1} =$ $(Nimmature_{new,t,s,l} e^{-Zimmat_{new,t,s,l}}) Gr_{s,l} (1 - \phi_{s,l})$ $Nmature_{new,t+1,s,l+1} =$ $(Nimmature_{new,t,s,l} e^{-Zimmat_{new,t,s,l}}) Gr_{s,l} (\phi_{s,l})$ $Nmature_{old,t+1,s,l+1} =$ $(Nmature_{new,t,s,l} e^{-Zmat_{new,t,s,l}}) + (Nmature_{old,t,s,l} e^{-Zmat_{old,t,s,l}})$	$1 \le t <$ $1 \le l \le$	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. $S_{surv,l} = q \frac{1}{1+e^{-a_{surv}(l-b_{surv})}}$			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.
ϕ_l	Proportion of immature crab that become mature at size l.
R_t	Recruitment in year t
R_0	Geometric mean value of recruitment
τ_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
ε_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
τ_t $1978 \le t \le 2008$, 31 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
ε_t $1978 \le t \le 2008$, 31 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).