Stock Assessment of eastern Bering Sea snow crab

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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 mature biomass of snow crab increased from the early 1980's to a peak in 1990 of about 1,841 million lbs. Biomass declined in the late 1990's to about 528 million lbs. in 1999. The stock was declared overfished in 1999 because the survey estimate of mature biomass was below the minimum stock size threshold (MSST). Model estimates of mature biomass continued to decline after 1999 and were estimated at 370 million lbs. in 2004. Survey biomass estimates were lower in the mid-1980's than current survey estimates, however, 2004 model estimates are at historic lows.

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, 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 was developed using a simulation model previous to the development of the current model (Zheng et al. 2002), that has been used to set the most recent GHL's. Retained catch in the 2004 fishery was 23.66 million lbs, about 14% above the GHL of 20.8 million lbs. The total catch was estimated at 27.54 million lbs (about 24 million crabs), which is an exploitation rate of 0.13 using the 2003 survey estimate of mature male abundance at the time the fishery occurs. The exploitation rate on mature male biomass for the total catch was 0.20.

Estimated discard (mostly undersized males and old shell males) in the directed pot fishery has averaged about 33% 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.

Three model scenarios were run for this stock assessment. Fmsy, Bmsy and the resulting catch estimates depend on the model scenario used, the steepness and R0 parameters of the spawner recruit curve, the assumptions about which males take part in mating, and the mating ratio (number of females that a male can fertilize in one mating season).

The stock is estimated to be at 32% of Bmsy in 2004. The total catch (retained plus discard mortality) for the 2005 season is estimated at 11.1 million lbs and the 2005 retained catch (GHL) is estimated at 8.6 million lbs. The 2005 GHL using the mature male survey biomass (143.7 mill lbs) is estimated at 15.8 mill lbs, using the current harvest strategy. Total catch (retained plus discard mortality) would be estimated at 21.0 mill lbs (assuming discard is 33% of retained catch).

Conservation concerns are that the stock is at its lowest level historically and that recruitment has been low for the past ten years. The stock is expected to decline in the future given past low recruitments. Survey biomass estimates were below the MSST in 1999, and have declined in the last three years (2002 to 2004).

Computing the GHL based on the complete survey biomass results in exploitation rates higher than the target rate on crabs in the southern area of the distribution. One solution would be to split the GHL 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 GHL from the portion of the stock where most of the catch is extracted. Another approach would be to compute a GHL that would result in the target harvest rate for the southern portion of the stock and increase that GHL according to the percent catch in the north. Splitting the GHL by area would result in about 28% (the average percent catch for 2003 and 2004) of the GHL south of 58.5 deg N and 72% north. If the total GHL is 15.8 mill lbs (calculated from the survey data) then the southern GHL would be 4.4 mill lbs and the northern GHL would be 11.4 mill lbs. The GHL could be calculated based on where the majority of the catch occurred. In 2003 and 2004 93% of the catch came from south of 60 deg N. The 2004 survey mature male biomass south of 60 deg N was 107.45 mill lbs which would result in a GHL (using the same exploitation rate used to get 15.8 mill lbs GHL) of 11.8 mill lbs. The third approach would be to compute the GHL for the southern region (south of 58.5 deg N) based on mature male biomass in the south. The GHL in the south would be 4.6 mill lbs (mature male biomass of 42.14 mill lbs). If 72% of the catch comes from the south, then the total GHL would be 6.4 mill lbs. This third method would result in maintaining the target harvest rate on mature males south of 58.5 deg N. The second method would result in maintaining the target harvest rate for mature male biomass south of 60 deg N.

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 (36.2 million lbs total catch), 28.3 million lbs of retained catch in 2003 (39 million lbs total catch), and 23.66 million lbs of retained catch in 2004 (27.54 million lbs total catch).

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. Trawl discard mortality was estimated at about 5.1 million lbs in 1974 then declined to less than 1 million lbs from 1976 to 1991. 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. Most discard for the period 1997 to 2002 in groundfish fisheries came from the (in order of catch) yellowfin sole trawl fishery, flathead sole trawl fishery, Pacific cod bottom trawl fishery, rock sole trawl fishery and the pacific cod hook and line and pot fisheries.

Size frequency data and catch per pot have been collected by observers on snow crab fishery vessels since 1992. Observer coverage was 10% on catcher vessels larger than 125 ft (since 2001), and 100% coverage on catcher processors (since 1992). In the 2002 fishery about 0.5% of the total pot lifts were observed (Neufeld and Barnard 2003).

The average size of retained crabs has remained fairly constant over time, between 105 mm and 118 mm, 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 95% to 98% for 1997 to 2001 fisheries. The average weight of retained crab has varied between 1.1 lbs (1983-1984) and 1.6 lbs(1979) and was about 1.3 lbs in the 2002 fishery.

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 opening laced with untreated cotton twine. 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 five-inch stretched mesh webbing or have no less than four circular rings of no less than three and three-quarter inches inside diameter. In the 2001 season the escapement for undersize crab was increased to at least eight escape rings of no less than four 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 five and one-quarter stretched mesh webbing. The size of the cotton laced panel to prevent ghost fishing was increased in 1991 to at least 18 inches in length.

ABUNDANCE AND EXPLOITATION TRENDS

Survey Biomass

Abundance is estimated from the annual Bering Sea bottom trawl survey conducted by NMFS (e.g., Stevens et al. 2000 for design and methods). Since 1989, the survey has sampled stations farther north than previous surveys. 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 estimated from the survey declined to a low of 180 million lbs in 1985, increased to a high of 1,657 million lbs in 1991, then declined to 294 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. The 2002 survey estimate of mature biomass was 314 million lbs, in 2003, 262 million lbs, and in **2004, 285 million lbs**. The total mature biomass includes mature females and morphometrically mature males. The term mature for male snow crab will be used here to mean morphometrically mature. Morphometric maturity for males refers to a change in chelae height, after which males are assumed to be effective at mating. Males are functionally mature at smaller sizes than when they become morphometrically mature.

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 (Snow crab rebuilding plan, 2000). The legal size limit for snow crab is 78 mm, however, the fishery generally accepts animals greater than 101 mm. The GHL divided by the survey abundance of male crab >101 mm was close to 58% for most years (Figure 5). 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.

The actual retained catch typically exceeded the GHL, resulting in exploitation rates for the retained catch (using survey numbers) ranging from about 60% to 100% for most years. The actual 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, which has been around 7 months since the late 1980's. The actual exploitation rate for the total catch (retained plus discard mortality), using the observed survey biomass, ranged from about 20% to over 100% (Figure 5). Catches were greater than the abundance estimates from the survey 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 75% (Figure 6). The exploitation fraction estimated by dividing the total catch by the model estimate of the crabs over 101 mm ranged from about 15% to 95% (Figure 6). The total exploitation rate on males > 101 mm was 65% to 85% for 1986 to 1994 and greater than 75% for 1998 and 1999 (year when fishery occurred).

The current harvest strategy uses a retained crab harvest rate on the mature male biomass of 0.1 at a 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). Bmsy is defined in the current crab FMP 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 (460 million lbs). The GHL is actually set as the number of retained crab allowed in the harvest, which is calculated by dividing the GHL in lbs by the average weight of a male crab > 101 mm. If the GHL in numbers is 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, when the fishery occurs 7 months after the survey.

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. Shell condition is recorded as soft shell (SC1) (less than three months from molting), new shell (SC2) (three months to less than one year from molting), old shell (SC3) (one year to several years from molting), very old shell (SC4) (greater than one year, but unknown age), and very very old shell (SC5) (greater than one year, but unknown age). Radiometric aging of shells from terminal molt male crabs (after the last molt of their lifetime) has recently shed light on how shell condition relates to 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 are shown in Figures 3 and 4.

ANALYTIC APPROACH

Data Sources

Catch data and size frequencies of retained crab from the directed snow crab pot fishery from 1978 to the 2004 season were used in this analysis. Observers were placed on directed crab fishery vessels starting in 1990. However, reliable size frequency data on the total catch (retained plus discarded) in the directed crab fishery were available from 1992 to 2004. Total discarded catch was estimated from observer data from 1992 to 2004(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 2004. The discard catch estimate was multiplied by the assumed mortality of discards from the pot fishery. In the model presented here mortality of discarded crab is assumed to be 100%. The estimated discards previous to 1992 may be underestimates due to the lack of escape mechanisms for undersized crab in the pots previous 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	1978-2004 (Year when fishery actually occurred)
Discarded male and female crab pot fishery size frequency	1992-2004
Trawl fishery bycatch size frequencies by sex	1990-2003
Survey size frequencies by sex and shell condition	1978-2004
Retained catch estimates	1978-2004
Discard catch estimates from snow crab pot fishery	1992-2004 estimated from observer data
Trawl bycatch estimates	1973-2003
Total survey biomass estimates and coefficients of variation	1978-2004

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 276 parameters estimated in the model (Table A.4). The 78 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 51 recruitment parameters estimated in the model, one for the mean recruitment, 25 for females and 25 for males, which were constrained to be similar. There were 55 fishery selectivity parameters, 50 of which were length at 50% selected parameters to allow changing fishery selectivities by year.

Molting probabilities for mature males and females were fixed at 0, resulting in mature animals ceasing to growth when they mature. Molting probabilities were fixed at 1.0 for immature females and were estimated for immature males. The intercept and slope of the linear growth function of postmolt relative to premolt size were estimated in the model using parmeters estimated from growth measurements for Bering sea snow crab as prior distributions (Table A.5). A gamma distribution was used in the growth transition matrix with the beta parameters estimated 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 new and old shell, immature and mature, and by sex. The model fits the size frequencies for the pot fishery catch by new and old shell and by sex.

Crabs over 25 mm CW (carapace width) were included in the model. There are 22 size bins of 5 mm each, from 25-29 mm to 130-135mm. In this report the term size as well as length will be considered synonymous with CW. Recruitment to the model was estimated separately for males and females. Recruits were distributed in the first few size bins using a two parameter gamma distribution with the parameters estimated in the model. Eighty-eight parameters were estimated for the initial population size composition of new and old shell males and females in 1978. Recruitment for males and females was constrained to be similar by adding a penalty to the likelihood. No spawner-recruit relationship was used in the population dynamics part of the model. Recruitment parameters were estimated in the model to fit the data.

The survey occurs in summer each year, however, in the model, the time of the survey is considered to be the start of the year (July). This results in the start of the year being July instead of January. The directed snow crab pot fishery has occurred generally in the winter months (January to February) over a short period of time, however in the early years the fishery occurred over a longer time period. The mean time of the fishery weighted by the catch was estimated for each year and the fishing mortality 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.

Weight - Size

The weight (kg) – size (mm) relationship was estimated from survey data, where weight = a* size^{b}. Female a= 0.00000253, b=2.56472, male a= 0.00000023, b=3.12948 (Figure 7).

Maturity

Maturity for females was determined by visual examination during the survey and used to determine the fraction of females mature by size for each year. Female maturity was determined by the shape of the abdomen, by the presence of brooded eggs or egg remnants. The average maturity curve which has a 50% value of about 49 mm with a slope of 0.16 (Figure 8), was used in the model to estimate mature female abundance and biomass.

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

One maturity curve for males was estimated and applied to all years in the model. A two-parameter logistic function was used that fit the fraction mature for larger new shell males well, resulting in size at 50% mature for new shell males of 88 mm CW with a slope of 0.12 (Figure 9). The separation of mature and immature males by chela height at small widths may not be accurate 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 recently taken 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, pers. comm.).

The average fraction mature for old shell males was used as the maturity curve for all years for old shell males. Maturity for old shell males is zero below 40 mm, increases from 83% at 45 mm to 95% at 115 mm.

Selectivity

Selectivity curves for the retained and total fishery catch were estimated as two-parameter ascending logistic curves. Fishery selectivities for new and old shell males are allowed to change by year by estimating one mean size at 50% selectivity parameter, with deviations for each year from 1978 to 2004. The yearly parameters are constrained by a penalty that results in a smooth trend in the parameters over time (Figures 10 and 11). The selectivities for the survey and trawl bycatch were estimated with two-parameter, ascending logistic functions. Survey selectivities were estimated using a two parameter logistic function that was equal for both 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 fixed at 1.0. 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.

Selectivities were estimated the same for new shell and old shell males for the total catch (retained plus discarded mortality) and separately for new and old shell for the retained catch. The probability of retaining crabs by size and 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.

Survey selectivities have been estimated for Bering Sea snow crab from underbag trawl experiments (Somerton and Otto 1999) (Figure 12). A bag underneath the regular trawl was used to catch animals that escaped under the footrope of the regular trawl. 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. 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 13). 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.). However, 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 14),

$$Width_{t+1} = a + b * width_t$$

The parameters a and b estimated from the observed growth data for Bering sea snow crabs were used as prior means for the growth parameters estimated in the model. 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. The Gamma distribution is,

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

Natural Mortality

Natural mortality is one of the most important parameters in a population dynamics model, and may have a large influence on optimal harvest rates. Natural mortality estimated in a population dynamics model may have high uncertainty and 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 due to uncertainty in natural mortality. The ability to estimate natural mortality in a population dynamics model is limited and depends on the how the true value varies over time as well as other factors (Fu and Quinn 2000, Schnute and Richards 1995).

In the 2003 snow crab SAFE, natural mortality has been assumed to be between 0.2 and 0.3 for males and females. A natural mortality of 0.3 would indicate a maximum age of about 14 years (Table 4)(Hoenig 1983). A maximum age of 20 years would result from an M of about 0.21 (Hoenig 1983). However, ISES uses a 5% rule for deriving a value of natural mortality, which would result in an M of 0.2 for a maximum observed age of 15 years (Anthony 1982). A natural mortality of 0.3 results in about 5% of animals remaining after 10 yrs of age. Research is currently underway to assess a method using lipofuscin for age determination (Se-Jong, et al. 1999). A maximum age of about 13 years for females and 19 years for males has been hypothesized for North Atlantic snow crab by Comeau, et al (1998) based on size frequency analysis and growth data. Sainte-Marie, et al (1995) estimated an age of about 9 years for a 95 mm male snow crab and 11 years for a 131 mm crab for a different sub-population of Atlantic snow crab than Comeau, et al (1998) using size frequency analysis and growth data. A maximum time at large of 8 years for tag returns of mature male snow crab in the North Atlantic has been recorded since tagging started about 1993 (Sainte-Marie, pers. comm.). Otto (1998) estimated natural mortality of male snow crab based on survey data and retained catches to be greater than 1.0. Otto (1998) overestimates M because the method assumed no time lapse between the survey and the fishery removals (during which natural mortality would be occurring) and no bycatch mortality. Otto (1998) also assumed survey selectivities were 1.0, shell condition is an accurate indicator of age since last molt (new shell less than one year, old shell crabs more than one, but less than two years from molting), and that new and old shell crabs were accurately categorized by shell condition. Zheng (unpub) investigated natural mortality of Bering Sea snow crab using a modeling approach, accounting for natural mortality between the time of the survey and the fishery. The snow crab fishery generally occurs over a short time span, about 7 months after the survey. Estimates of natural mortality ranged from 0.0 to 0.97, depending on assumptions made for molting probabilities, growth per molt and survey selectivities (Zheng unpub.).

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

Orensanz (unpub.) used radiometric techniques to estimate shell age from last molt (Table 4). The total sample size was 21 male crabs (a combination of Tanner and snow crab) from a collection of 105 male crabs from various hauls in the 1992 and 1993 NMFS Bering sea survey. Representative samples for the 5 shell condition categories were collected that made up the 105 samples. The oldest looking crab within shell conditions 4 and 5 were selected from the total sample of SC4 and SC5 crabs to radiometrically age (Orensanz, pers comm.). Shell condition (SC5) crab (very, very old shell) had a maximum age of 6.85 years (s.d. 0.58, 95% CI approximately 5.69 to 8.01 years). The average age of 6 crabs with SC4 (very old shell) and SC5, was 4.95 years. The range of ages was 2.70 to 6.85 years for those same crabs. Given the small sample size, crabs older than the maximum age of 7 to 8 years may be expected in the population.

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

Natural mortality was assumed to be 0.2 in the model run presented here.

SC2 animals (new shell) were 0.33 to 1.07 years old (mean 0.69 yrs (8.2 months)) from the radiometric samples. This indicates that either some animals molted in summer to fall (C.I. for 1.07 is, 0.49 to 1.66), or some animals that did not molt the year before were misclassified as new shell animals. If there is misclassification, then new shell animals may be overestimated, and old shell animals (SC3) underestimated in the survey data. If molting occurs from January to May, with peak molting in March (Rugolo, pers comm.), then animals classified as SC2 that are older than about 6-7 months radiometric age may actually have molted the spring of the previous year. Of the six SC2 crabs in the radiometric sample, four (67%) had radiometric ages greater than 7 months. The average age of soft shell crab (SC1) was 0.15 yrs, if the SC1 and SC2 animals are combined (as it is for estimating new shell animals for harvest purposes) the average age is lower than for SC2 alone (mean = 0.42 yrs). However, the SC3 (old shell) animals were 0.85 to 1.1 years old (mean 1.02 yrs). There was only one animal between 1.1 years and 4.2 years old, which was a SC5 crab, 2.7 years old. Some overlap of ages would be expected between SC3, and SC4 and SC5 animals, however, that did not occur in the sample, probably due to the small sample size.

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

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 recent data on hormone levels (Sherry Tamone, per. comm.) and findings from molt stage analysis via setagenesis (Lou Rugolo, pers. comm.). 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.

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 be retained for several weeks or months by snow crab (Rugolo, pers. comm..). 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 success. 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. Female stored sperm and clutch fullness varies with sex ratio (St. Marie 200?). 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 unmated 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 40 and 41). The highest levels of unmated 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. This indicates that the levels of exploitation occurring at the time may have resulted in not enough males for successful mating.

The fraction of barren females in the 2003 and 2004 survey south of 58.5 deg N was generally higher than north of 58.5 deg N (Figures 46 and 47). In 2004 the fraction barren females south of 58.5 deg N 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.

Female opilio in waters less than 1.5 deg C and colder have been determined to be biennial spawners in the Bering Sea (Lou Rugolo, pers. comm.). 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.

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 unmated females observed in the survey may not be an accurate measure of fertilization success because females may retain unfertilized eggs for months after extrusion. Rugolo (pers. comm.) sampled mature females from the Bering sea in winter and held them in tanks until their eggs hatched in March. 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. Any index of fertilized females using the visual inspection method of assessing clutch fullness and percent unmated females may be an overestimate of 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.

Spatial distribution of catch and survey abundance

In most years, the majority of the fishery catch has occurred south of 58.5 deg N., due to ice cover and proximity to port. In 2003, 66% of the catch was south of 58.5 deg N. (Figure 45), and in 2004 78% of the catch was south of 58.5 deg N. (Figure 44). 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.

In 2004 about 26 % of the survey abundance of male snow crab > 101 mm as well as the mature male biomass were south of 58.5 deg N.(Figure 50). About 53% of those males south of 58.5 deg N. were estimated to be new shell (which are preferred by the fishery). 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. The 2004 fishery retained about 19 million crab of which about 14.8 million were caught south of 58.5 deg south (about 78%). The 2003 survey estimate of new shell male crab > 101 mm was about 7.6 million south of 58.5 deg N. which would have been fished on in the 2004 fishery. In the 2004 survey about 9.5 million new shell males >101mm were estimated south of 58.5 deg N. This indicates that survey catchability may be less than 1.0 and/or some movement occurs between the summer survey and the winter fishery. However, the exploitation rate on males south of 58.5 deg N would have exceeded the target rate, possibly resulting in a depletion of males from the southern part of their range. Snow crab larvae drift north and east after hatching. Snow crab appear to move south and west as they age, however, no tagging studies have been conducted to estimate migration. High exploitation rates in the southern area may have resulted in a northward shift in snow crab distribution, due to lower egg production in the south from lower clutch fullness and higher percent barren females. The northward shift in mature females would result in lower productivity due to 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.

RESULTS

Three model scenarios were run, one with discard mortality at 100%, one with discard mortality at 50%, and one with discard mortality at 100% and survey selectivities fixed at values from Somerton and Otto (). 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 Zhou and Kruse (1998) and Shirley (1998), where 100% mortality occurred under temperature and wind conditions that may occur in the fishery. Even if damage did not result in short term mortality, immature crabs that are discarded may experience mortality during molting some time later in their life.

Model estimates in Tables 3 and 6 and in Figures 2 through 38 are from the base model with M=0.2. Parameter estimates for the base model with M=0.2 are in Table 6. The total mature biomass increased from about 699 mill lbs (328 mt) in 1978 to the peak biomass of 1,841 mill lbs in 1990. Biomass declined sharply after 1996 to about 370 mill lbs in 2004 (Table 3 and Figure 2). Mature biomass estimated by the model is currently the lowest level estimated from 1978 to the present. The model is constrained by the population dynamics structure, including natural mortality, the growth and selectivity parameters and the fishery catches. Given the population dynamics structure and the parameters used, the model cannot account for the catches removed from the population unless population biomass is larger than observed from the survey. 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. The model cannot fit the low survey abundance estimates in the mid-1980’s, fit the high survey abundance in the 1990’s, and extract the catches that occurred in the early 1990’s. Average discard catch mortality for 1978 to 2003 was estimated to be about 44% of the retained catch, a little higher than the observed discards from 1992 to 2003 (33%) (Table 1 and Figure 15). During the last four years (2000 to 2003 fishery seasons) model estimates of discard mortality averaged 34% of the retained catch. Estimates of discard mortality ranged from 14% of the retained catch to 69% of the retained catch.

Mature male and female biomass show similar trends (Table 3 and Figures 16 and 17). Mature male biomass was about the same from 2003 (192 mill lbs) to 2004 (196 mill lbs), while survey biomass decreased (161 mill lbs to 142 mill lbs). Mature female biomass decreased from 187 mill lbs in 2003 to 175 mill lbs in 2004. Mature female biomass observed from the survey increased from 101 mill lbs in 2003 to 144 mill lbs in 2004.

Fishery selectivities and retention curves were estimated using ascending logistic curves (Figure 10, 11 and 18). Selectivities for trawl bycatch were estimated as ascending logistic curves (Figure 19). Plots of model fits to the survey size frequency data are presented in Figures 20 to 26.

Survey selectivities for the period 1978 to 1981 were estimated at 50% at about 21 mm and reached 95% at about 30mm (Figure 12). This indicates that the survey net used previous to 1982 was more efficient than the present survey net. Survey selectivities for the period 1982 to 1988 were estimated at 50% at about 65 mm and reached 95% at 145 mm. These selectivities were the best fit determined by the model, which are close to the values estimated by Somerton and Otto (1998). Survey selectivities for the period 1989 to the present were estimated at 50% at about 19 mm and reached 95% 106 mm. The survey selectivities are multiplied by the population numbers by length to estimate survey numbers for fitting to the survey data. Molting probabilities for immature males declined from 100% at 25 to 60 mm, to about 60% at 130 mm (Figure 27)

The estimated number of males > 101mm generally follows the observed survey numbers except at the end of the time series from 1997 to 2004 where model estimates are lower than the survey estimates (Figure 28).

Two main periods of high recruitment were estimated by the model, in 1980-81 (fertilization year) and in 1987-1988 (Figure 29). Recruits are 25mm to about 40 mm and may be about 4 years from hatching, 5 years from fertilization (Figure 30, although age is unknown). Low recruitments were estimated for the last 11 years.

The size at 50% selected for the pot fishery varied between 93 mm and 105 mm for most years, and was about 103.5 mm in 2003 for males (Figure 11). Retention for old shell males was less than for new shell males (Figure 18 and 10). The fishery generally targets new shell animals with clean hard shells and all legs intact. Mortality of discarded crabs was assumed to be 100% in the model. The fits to the fishery size frequencies are in figures 31 through 35. Fits to the trawl fishery bycatch size frequency data are in figures 36 and 37.

Harvest Strategy and Guideline Harvest Levels

Fmsy and Bmsy for Bering sea snow crab was estimated using the model presented here. Effective spawning biomass was estimated the same as Siddeek(2003), assuming only old shell males take part in mating and mating ratio is 2. If the numbers of old shell mature males (NMM_O) at the time mating occurs (accounting for natural mortality and removing the catch from the numbers at survey time) is less than the numbers of mature females (NMF) at the time mating occurs, divided by the mating ratio (η = 2), then the female mature biomass (fspbio) is reduced to estimate effective female spawning biomass (efspbio),

$$efspbio = fspbio * \frac{NMM_O * \eta}{NMF}$$

If the number of old shell mature males at mating time is more than the numbers of mature females at the time mating occurs, divided by the mating ratio (2), then effective female spawning biomass is estimated to be equal to female spawning biomass, and the male mature biomass is reduced to estimate effective male spawning biomass,
If the numbers of old shell mature males (NMM_O) at the time mating occurs (accounting for natural mortality and removing the catch from the numbers at survey time) is more than the numbers of mature females (NMF) at the time mating occurs, divided by the mating ratio (η = 2), then the male mature biomass (mspbio) is reduced to estimate effective male spawning biomass (emspbio),

$$emspbio = mspbio * \frac{\frac{NMF}{\eta}}{NMM_O}$$

The effective female spawning biomass is added to the effective male spawning biomass to obtain total effective spawning biomass.

The parameters of the Beverton and Holt spawner recruit curve (steepness and R0) were estimated in a model separate from the population dynamics model using effective spawning biomass and recruits estimated from the population dynamics model for 1978 to 2004 (Figure 38),

$$\mathrm{Re}\,cruits = \frac{(0.8 * R0 * h * \gamma_0)}{0.2 * \gamma_0 * R0 * (1-h) + (h-.2) * \gamma_c}$$

γ_c is effective total spawning biomass, γ_0 is effective total spawning biomass per recruit at F=0, R0 is the recruitment that would occur when the stock is at the effective spawning biomass for F=0, and h is the steepness parameter (Gabriel et al. 1989, Dorn 2002). Steepness is the proportion of R0 that recruits when the stock is reduced to 20% of the unfished effective total spawning biomass. When steepness is 1.0, recruits are independent of stock biomass, when steepness is at the lower limit (0.2) recruits linearly increase with stock biomass.

A normal prior distribution was used for the steepness parameter with a mean of 0.52 (the steepness estimated for Bristol Bay red king crab, Siddeek, pers. comm.) and a relatively large standard deviation of 0.6. A normal prior distribution was also used for the R0 parameter (the recruitment at B0) with a mean equal to the average model recruitment when effective spawning biomass was above the median, and a cv of 0.6.

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 2004 fishery GHL. Bmsy is defined in the current crab FMP as the average total mature survey biomass for 1983 to 1997. MSST is defined as ½ Bmsy. The harvest strategy consists of a threshold for opening the fishery (MSST=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.

Under current FMP (Fishery Management Plan) definitions for MSY biomass (B_{MSY} = 921.6 million pounds TMB) and overfishing rate (F_{MSY} =M=0.3), the fishing mortality rate to apply to current mature male biomass (MMB), is determined as a function of TMB as,

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

for TMB ≥ 0.25*Bmsy and TMB<Bmsy, where α = -0.35, and,

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

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

- GHL_{max} = F•MMB.

The F determined from the harvest control rule was used as an exploitation rate on mature male biomass instead of as a fishing mortality rate for the GHL calculation. The use of the equation, GHL = F*MMB, assumes that fishery selectivities were 1.0 for all mature male crabs and that the mature male biomass at the time of the survey is equal to the average over the year and that fishing mortality and natural mortality occur simultaneously throughout the year. However, the biomass at the time the survey occurs is after growth and recruitment occurs and before the fishery, resulting in the maximum in the year. The convention of setting Fmsy = M is for setting the instantaneous fishing mortality rate at M, not the exploitation rate on the stock. For example, if Fmsy = M = 0.3, then the F to apply when TMB is at or above Bmsy would be 0.225 to obtain the total catch (retained plus discard). The exploitation rate corresponding to F = 0.225 would be (F *(1-exp(-Z))/Z) = 0.175, where Z=M+F, if the fishery and natural mortality occur simultaneously throughout the year. This results in an overestimation of the exploitation rate and the GHL by about 28.5%. The exploitation rate corresponding to a pulse fishery would be 0.167 on MMB at the time of the survey for an F = 0.225, an overestimation of 34.7%. If F = 0.1 (the value when TMB is at 25% Bmsy) the exploitation rate would be 0.079 on MMB at the time of the survey, a 26.6% overestimation of the GHL.

The use of the value of the harvest control rule as an exploitation rate on mature male biomass at the time of the fishery is consistent with the harvest strategy simulations (Zheng et al 2002), however, it still underestimates the true exploitation rate and cannot be compared to Fmsy, for example to determine overfishing.

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.

The existing harvest control rule is used here with estimates of Bmsy and Fmsy from the current model and α = -0.25 (Figure 39). An α = -0.25 results in an F of 40% of the maximum F at 25% of Bmsy, similar to the existing harvest strategy (Zheng et al 2002). The above formulation of the harvest control rule is the same as that used for North Pacific groundfish, except a value of 0.05 is used instead of -0.25 (BSAI SAFE 2002). Using a value of 0.05 as is used for groundfish means F will be zero when current biomass is 5% of Bmsy. The slope of the control rule is less for snow crab resulting in a relatively higher F than the groundfish control with α = 0.05, until current biomass is below 0.25 Bmsy, when F would be 0 for snow crab, but would still be greater than 0 for the groundfish rule (Figure 39). For the groundfish rule the maximum F applied when biomass is at or above Bmsy depends on the amount of information available about Fmsy.

The catch is estimated by the following equation,

$$catch = \sum_s \sum_l \left(1 - e^{-(F^*Sel_{S,i})}\right) w_l N_{S,l}\, e^{-M^*.62}$$

Where $N_{S,l}$ is the 2004 numbers at length(l) for mature males by shell condition(s) at the time of the survey estimated from the population dynamics model, M is natural mortality, 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 2004 total mature biomass, and w_l is weight at length. $Sel_{S,l}$ are the fishery selectivities by length and shell condition for the total catch (retained plus discard) or for the retained catch estimated from the population dynamics model averaged over the last three years (2002 to 2004 fishery seasons) (Figure 14).

Fmsy and 2005 catches as well as other reference points were estimated for each of the scenarios (Table 6). The Fmsy (full selection F) was 0.70 for the base model. The 2005 GHL was estimated at 8.6 mill lbs. The total catch for 2005 was estimated at 11.1 mill lbs.

For comparison, the GHL using the estimates of Fmsy = M = 0.3 and Bmsy = 921.6 mill lbs was calculated using 2004 survey biomass estimates. The survey biomass estimate for total mature biomass in 2004 was 285.2 mill lbs and mature male biomass was 141.5 mill lbs. The F for 2005 estimated from the harvest control rule with Fmsy = 0.3, Bmsy = 921.6 mill lbs and α = -0.35, was 0.11.

Using the F = 0.11 as an exploitation rate as has been used previously (F * MMB at survey time) would result in the 2005 GHL = 15.8 mill lbs. Total catch (retained plus discard mortality) would be estimated at 21.0 mill lbs using 33% discard.

Computing the GHL based on the complete survey biomass results in exploitation rates higher than the target rate on crabs in the southern area of the distribution. One solution would be to split the GHL 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 GHL from the portion of the stock where most of the catch is extracted. Another approach would be to compute a GHL that would result in the target harvest rate for the southern portion of the stock and increase that GHL according to the percent catch in the north. Splitting the GHL by area would result in about 28% (the average percent catch for 2003 and 2004) of the GHL south of 58.5 deg N and 72% north. If the total GHL is 15.8 mill lbs (calculated from the survey data) then the southern GHL would be 4.4 mill lbs and the northern GHL would be 11.4 mill lbs. The GHL could be calculated based on where the majority of the catch occurred. In 2003 and 2004 93% of the catch came from south of 60 deg N. The 2004 survey mature male biomass south of 60 deg N was 107.45 mill lbs which would result in a GHL (using the same exploitation rate used to get 15.8 mill lbs GHL) of 11.8 mill lbs. The third approach would be to compute the GHL for the southern region (south of 58.5 deg N) based on mature male biomass in the south. The GHL in the south would be 4.6 mill lbs (mature male biomass of 42.14 mill lbs). If 72% of the catch comes from the south, then the total GHL would be 6.4 mill lbs. This third method would result in maintaining the target harvest rate on mature males south of 58.5 deg N. The second method would result in maintaining the target harvest rate for mature male biomass south of 60 deg N.

Conservation concerns

- The Bering Sea snow crab model estimate of 2004 mature biomass is currently at its lowest level over the 25 year time period from 1978 to 2004.

- Survey biomass estimates have declined from a peak in 1991 to below 50% Bmsy in 1999 and additionally have declined over the past two years.

- Recruitment has been at low levels for the last 10 years (since 1994). The stock is expected to decline in the future due to the low recruitment.

- There is uncertainty in discard mortality due to low coverage of total pot lifts and only 10% coverage of catcher vessels which only started in 2001. Higher discard mortality would necessitate lower retained catches.

- Exploitation rates in the southern portion of the range of snow crab have been higher than target rates, possibly reducing reproductive output, and 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.

The lower number of mature old shell male crabs in the observed survey compared to what are expected in the model needs to be reconciled. Harvest rates and status of the stock are highly dependent on what the discrepancy is due to. The differences could be due to higher fishery discard mortality, higher natural mortality of mature animals, differential catchability of new and old shell animals in the survey, or the estimation of when maturity occurs, which determines when animals stop growing and subsequently move from new shell to old shell animals. In addition, the assignment of crabs to new and old shell condition used in the survey data may not be an accurate measure of time from the last molt.

Increased observer coverage is needed on catcher vessels in the directed snow crab fishery to improve estimates of discards. Field studies are needed to estimate mortality of discards in the winter snow crab pot fisheries where freezing temperatures and wind chill are important factors.

Some method of aging crab needs to be developed. Current research is being conducted using lipofuscin to age crabs and continued radiometric aging of shells of mature crabs is also being conducted (results may be available the end of 2004). However, at this time it is not known if the lipofuscin method will be successful, and radiometric aging is time consuming, so only small numbers of animals can be aged at present. 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).

Which males are effective at mating and how many females they can successfully mate with in a mating season is critical to 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 (Lou Rugolo, pers. comm.). 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.

There were 68 million male snow crab >101mm estimated from the 2004 survey, about 18 million were estimated in the area south of 58.5 deg N (26%). About 9.5 million of those males were estimated to be new shell (14% of the total). The 2003 survey estimated about 67 million male snow crab >101mm, about 16 million were estimated in the area south of 58.5 deg N (24%). About 7.6 million of those were estimated to be new shell (11% of the total). The 2003 fishery retained about 15 million crab south of 58.5 deg N (66% of the total catch). The 2004 fishery also retained about 15 million crab south of 58.5 deg N, however this was about 78% of the total retained catch of 19 million crab. The ice coverage in January 2003 and 2004 was farther north than in most years resulting in some catch being removed from the northern areas of the snow crab distribution. The exploitation rate on crabs south of 58.5 deg N has been higher than the target exploitation rate possibly resulting in a depletion of animals from the southern part of their range. As discussed earlier there has been a shift northward in the distribution of snow crab. Even if environmental conditions have influenced this northward shift, high exploitation rates in the southern area may have also resulted in a northward shift in snow crab distribution. One solution would be to split the GHL into two regions, north and south, according to the percent distribution of the survey estimate of large males from those regions. This northward shift in mature females has resulted in lower productivity due to 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.

Literature Cited

BSAI SAFE. 2002. Bering Sea and Aleutian Islands stock assessment and fishery evaluation for North Pacific Groundfish.

Comeau, M., Conan, G.Y. Robichaud., G., and Jones, A. 1991. Life history and population fluctuations of snow crab (Chionoecetes opilio) in the fjord of Bonne Bay on the west coast of Newfoundland, Canada—from 1983 to 1990. Can.Tech.Rep.Fish.Aquat.Sci. 1817.

Comeau, M., G.Y. Conan, F. Maynou, G. Robichaud,J. Therriault, and M. Starr. 1998. Growth, spatial distribution, and abundance of benthic stages of the snow crab (Chionoecetes opilio) in Bonne Bay, Newfoundland, Canada. Can.J. Fish. Aquat. Sci. 55: 262-279.

Anthony, V.C. 1982. The calculation of F0.1: a plea for standardization. NAFO SCR Doc. 82/VI/64. Serial NO. N557. 16pp.

Bering sea and Aleutian Islands Crab SAFE. 2002. North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

Crab FMP 1998. Bering Sea Crab Plan Team, North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

Dawe, E.G., D.M. Taylor, J.M. Hoenig, W.G. Warren, and G.P. Ennis. 1991. A critical look at the idea of terminal molt in male snow crab (*Chionoecetes opilio*). Can. J. Fish. Aquat. Sci. 48: 2266-2275.

Dorn, M.W. 2002. Advice on west coast rockfish harvest rates from Bayesian meta-analysis of stock-recruit relationships. North American Journal of Fisheries Management 22:280-300.

Fournier, D.A. and C.P. Archibald. 1982. A general theory for analyzing catch-at-age data. Can.J.Fish.Aquat.Sci. 39:1195-1207.

Fu and T.J. Quinn. 2000.

Gabriel, W.L., M.P. sissenwine, and W.J. Overholtz. 1989. Analysis of spawning biomass per recruit: an example for Georges Bank haddock. North American Journal of Fisheries Management 9:383-391.

Greiwank, A. and G.F. Corliss(eds). 1991. Automatic differentiation of algorithms: theory, implementation and application. Proceedings of the SIAM Workshop on the Automatic Differentiation of Algorithms, held Jan. 6-8, Breckenridge, CO. Soc. Indust. And Applied Mathematics, Philadelphia.

Hoenig, J. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull. 82: 898-903.

INPFC. 1969. Release and recovery information for united states king crab tags recovered by the Japanese in 1968. INPFC Document no. 1171.

Mcbride (1982). Tanner crab tag development and tagging experiments 1978-1982. In Proceedings of the International Symposium of the Genus Chionoecetes. Lowell Wakefield Fish. Symp. Ser., Alaska Sea Grant Rep. 82-10. University of Alaska, Fairbanks, Alaska. Pp. 383-403.

McMullen, J.C. and H.T. Yoshihara. 1969. Fate of unfertilized eggs in king crabs *Paralithodes camtschatica (Tilesius)*. Department of Fish and Game. Informational Leaflet 127. INPFC document no. 1151. 14pp.

Methot, R. D. 1990. Synthesis model: An adaptable framework for analysis of diverse stock assessment data. Int. N. Pac. Fish. Comm. Bull. 50:259-277.

Nevissi, A.E., J.M. Orensanz, A.J.Paul, and D.A. Armstrong. 1995. Radiometric Estimation of shell age in Tanner Crab, Chionoecetes opilio and C. bairdi, from the eastern Bering Sea, and its use to interpret indices of shell age/condition. Presented at the International symposium on biology, management and economics of crabs from high latitude habitats October 11-13, 1995, Anchorage, Alaska.

Neufeld, G and D.R. Barnard. 2003. Alaska department of fish and game summary of the 2001 mandatory shellfish observer program database for the general and cdq fisheries. Regional Information Report No. 4K03-2. Alaska Department of Fish and Game. 160pp.

Otto, R.S. 1998. Assessment of the eastern Bering Sea snow crab, Chionoecetes opilio, stock under the terminal molting hypothesis. In Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. Edited by G.S. Jamieson and A. Campbell. Can. Spec. Publ. Fish. Aquat. Sci. 125. pp. 109-124.

Paul, A.J. and J.M. Paul. 1995. Molting of functionally mature male *Chionoecetes bairdi* Rathbun (Decapoda: Majidae) and changes in carapace and chela measurements. Journal of Crustacean Biology 15:686-692.

Paul, A.J., J.M. Paul and W.E. Donaldson. 1995. Shell condition and breeding success in Tanner crabs. Journal of Crustacean Biology 15: 476-480.

Press, W.H., S.A. Teukolsky, W.T.Vetterling, B.P. Flannery. 1992. Numerical Recipes in C. Second Ed. Cambridge Univ. Press. 994 p.

Sainte-Marie, B., Raymond, S., and Brethes, J. 1995. Growth and maturation of the male snow crab, *Chionoecetes opilio* (Brachyura: Majidae). Can.J.Fish.Aquat.Sci. 52:903-924.

Sainte-Marie, B., J. Sevigny and M. Carpentier. 2002. Interannual variability of sperm reserves and fecundity of primiparous females of the snow crab (Chionoecetes opilio) in relation to sex ratio. Can.J.Fish.Aquat.Sci. 59:1932-1940.

Schnute, J. and L. Richards. 1995. The influence of error on population estimates from catch-age models. Can. J. Fish. Aquat. Sci. 52: 2063-2077.

Se-Jong, J., D.H. Secor, H.R. Harvey. 1999. Use of extractable lipofuscin for age determination of blue crab *Callinectes sapidus*. Marine Ecology Progress series. Vol 185: 171-179.

Shirley, T.C. 1998. Appendix D: Crab handling mortality and bycatch reduction. In: King and Tanner crab research in Alaska: Annual report for July 1, 1997 through June 30, 1998. Alaska Department of Fish and Game Regional Information Report No. 5J98-07.

Siddeek, M.S.M., B. Sainte-Marie, J. Boutillier and G. Bishop. 2003. Some reference points used in US and Canada crab fisheries and a comparison of a referential system estimated using a length-based method for snow crab (*Chionoecetes opilio*) and Dungeness crab (*Cancer magister*).

Somerton, D.A. 1981. Life history and population dynamics of two species of Tanner crab, Chionoecetes bairdi and C. opilio, in the eastern Bering Sea with implications for the management of the commercial harvest. Ph.D. dissertation. University of Washington, Seattle, Wash. 220 p.

Somerton, D.A. and R.S. Otto. 1999. Net effeciency of a survey trawl for snow crab, *Chionoecetes opilio*, and Tanner crab, *C. Bairdi*. Fish.Bull. 97:617-625.

Stevens, B.G., J.A. Haaga, R.A. MacIntosh, R.S. Otto, and L. Rugolo. 2000. Report to industry on the 2000 Eastern Bering Sea crab survey. AFSC Processed Report 2000-07.

Bering Sea snow crab rebuilding plan, 2000. Bering Sea Crab Plan Team, North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

Zheng, J., S. Siddeek, D. Pengilly, and D. Woodby. 2002. Overview of recommended harvest strategy for snow crabs in the Eastern Bering Sea. Regional Information Report No. 5J02-03. Alaska Department of Fish and Game. Juneau, Alaska.

Zheng, J. unpublished. Uncertainties of natural mortality estimates for Eastern Bering Sea snow crab, *Chionoecetes opilio*. Alaska Department of Fish and Game. Juneau, Alaska.

Zheng, J., G.H. Kruse, and D.R. Ackley. 2001. Spatial distribution and recruitment patterns of snow crabs in the eastern Bering Sea. Spatial Processes and management of marine populations. Alaska sea grant college program. AK-SG-01-02, 2001.

Zheng, J., G.H. Kruse, and M.C. Murphy. 1998. A size-based approach to estimate population abundance of Tanner crab, Chionoecetes bairdi, in Bristol Bay, Alaska. In Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. Edited by G.S. Jamieson and A. Campbell. Can. Spec. Publ. Fish. Aquat. Sci. 125. pp. 97-105.

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

Zhou, S. and G.H. Kruse. 1998. Appendix C: Crab handling mortality and bycatch reduction. In: King and Tanner Crab research in Alaska: Annual Report for July 1, 1997 through June 30, 1998. Alaska Department of Fish and Game Regional Information Report No. 5J98-07.

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. Discarded catch is the total estimate of discards which assumes 100% mortality. Discards from 1992 to 2002 were estimated from observer data.

Year fishery occurred	retained catch(1,000s of lbs)	Observed Discard male catch	Retained + discard male catch	Model estimate of male discard	Discard female 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			12,862	73	1978	5,422
1979-80	75,025			13,822	91	1979	4,331
1980-81	66,933			68,005	81	1980	3,150
1982	29,355			21,670	46	1981	1,314
1983	26,128			19,374	62	1982	535
1984	26,813			25,520	44	1983	689
1985	65,999			76,566	43	1984	732
1986	97,984			116,190	44	1985	628
1987	101,903			68,405	96	1986	2,699
1988	135,355			34,206	139	1987	8
1989	149,456			72,064	148	1988	968
1990	161,821			56,513	192	1989	1,124
1991	328,647			127,556	204	1990	860
1992	315,302	96,214	402,897	310,002	234	1991	9,401
1993	230,787	124,865	355,652	123,644	481	1992	4,552
1994	149,776	38,922	188,698	49,820	321	1993	2,892
1995	75,253	29,436	104,689	33,578	232	1994	3,219
1996	65,713	42,104	107,817	36,660	63	1995	1,794
1997	119,543	54,391	173,934	57,529	277	1996	2,063
1998	243,342	41,982	294,171	102,815	22	1997	2,884
1999	194,000	34,158	228,358	116,409	26	1998	2,146
2000	33,500	3,790	37,081	5,150	2	1999	788
2001	25,256	4,537	29,794	5,833	2	2000	611
2002	32,722	13,824	46,546	15,622	17	2001	
2003	28,307	9,938	38,245	14,706	3	2002	
2004	23,663	4,196	27,859	6,097	6	2003	

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

Year	Observed survey male mature biomass	Observed survey female mature biomass	Observed survey total mature biomass	Observed number of males > 101mm (millions)
1978	273.0	398.6	671.6	163.4
1979	584.9	443.9	1,028.9	169.1
1980	733.8	315.7	1,049.5	109
1981	391.8	200.7	592.5	45.4
1982	411.2	334.1	745.3	65
1983	260.2	319.0	579.2	71.5
1984	118.5	375.3	493.9	154.2
1985	17.4	162.4	179.8	78.2
1986	45.8	174.1	219.9	80
1987	365.7	372.0	737.7	141.9
1988	451.9	443.1	895.0	167.3
1989	825.6	604.1	1,429.7	175.4
1990	529.6	1,025.0	1,554.6	407.2
1991	650.3	1,006.6	1,656.9	466.6
1992	376.1	507.0	883.0	251.4
1993	416.3	334.5	750.7	140.8
1994	387.9	282.5	670.4	80.3
1995	514.1	360.2	874.3	69
1996	362.6	642.7	1,005.3	170.1
1997	322.7	762.7	1,085.4	308.5
1998	237.6	512.6	750.2	244
1999	93.4	200.4	293.8	92.2
2000	307.2	187.6	494.8	75.6
2001	258.9	255.7	514.6	79.4
2002	98.3	216.0	314.3	73.5
2003	101.1	160.5	261.7	61.2
2004	143.7	141.5	285.2	58.7

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. Recruitment is lagged 5 years to approximate fertilization year.

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, lag 5 yr to fertilization year)
1978	1,030	6,156	318	381	699	93	225
1979	1,062	5,652	430	394	823	110	871
1980	995	4,911	450	321	771	70	10,514
1981	902	4,361	421	255	675	40	1,272
1982	895	3,632	370	347	717	83	1,971
1983	958	5,348	325	414	738	128	1,148
1984	963	4,546	293	409	703	135	632
1985	946	4,427	274	326	600	99	685
1986	1,471	13,889	350	316	666	80	1,659
1987	1,822	12,458	560	434	994	149	3,294
1988	2,134	12,027	782	517	1,299	146	454
1989	2,324	10,788	828	730	1,558	166	207
1990	2,397	9,267	768	1,074	1,841	320	305
1991	2,039	7,855	684	967	1,650	281	246
1992	1,481	7,365	606	551	1,156	187	287
1993	1,330	8,968	560	367	928	124	499
1994	1,303	7,613	545	305	850	83	238
1995	1,387	6,327	522	397	918	94	315
1996	1,471	5,383	467	630	1,097	170	355
1997	1,369	4,485	401	765	1,165	252	457
1998	971	3,649	342	521	863	157	554
1999	622	3,199	296	232	528	47	
2000	570	2,827	260	216	476	42	
2001	535	2,604	231	206	438	39	
2002	499	2,444	206	193	400	34	
2003	479	2,419	187	192	379	39	
2004	484	2,510	175	196	370	42	

Table 4. Radiometric ages for male crabs for shell conditions 1 through 5.

				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. Estimated reference points, fishing mortality and catch for 2005 Bering Sea snow crab fishery. Biomass is in millions of lbs. Scenario 1 has survey selectivities estimated in the model and mortality on discarded crab at 100%. Scenario 2 has survey selectivities fixed at the Somerton and Otto () values and mortality on discarded crab at 100%. Scenario 3 has survey selectivities estimated in the model and mortality on discarded crab at 25%.

Scenario	1	2	3
Fmsy (overfishing)(full selection F)	0.70	0.915	1.06
F maximum (0.75*Fmsy)	0.525	0.686	0.793
Exploitation rate for total catch at Fmsy on MMB at time of the fishery	0.165	0.150	0.162
Exploitation rate for retained catch at Fmsy on MMB at time of the fishery	0.121	0.106	0.135
B0 total mature biomass at survey time	2,375	2,378	1,560
Bmsy total mature biomass at survey time	1,155	1,187	765
MSST total mature biomass at survey time (1/2 Bmsy)	578	594	383
MSY total catch	128	119	83
MSY retained catch	94	84	69
2004 model estimate of total mature biomass at survey time	370	567.3162	323
Percent of Bmsy for 2004 model estimate of total mature biomass at survey time	32%	48%	42%
R0 (billion crabs)	1.68	1.99	1.12
Steepness	0.61	0.591	0.60
F 2005 fishery	0.24	0.434	0.46
2005 Male mature biomass at time of fishery	173	276	176
2005 total catch(discard + retained)	11.1	22.4	14.1
2005 retained catch (GHL)	8.6	16.6	12.1
2005 total catch/male mature biomass at time of fishery	0.064	0.081	0.080
2005 retained catch/male mature biomass at time of fishery	0.050	0.060	0.069

Table 7. Parameters values for model, excluding recruitments, changing fishery selectivity and fishing mortality parameters.

Natural Mortality	0.2
Female intercept (a) growth	12.724
Male intercept(a) growth	8.748
Female slope(b) growth	1.000
Male slope (b) growth	1.180
Mean length of recruits	
Beta for gamma distribution of recruits	3.012
Beta for gamma distribution female growth	0.714
Beta for gamma distribution male growth	1.494
Immature male molting probability slope	0.049
Immature male molting probability length at 50% molting	152.006
Fishery selectivity total new and old shell slope	0.209
Fishery selectivity retention curve new shell slope	0.332
Fishery selectivity retention curve new shell length at 50%	97.364
Fishery selectivity retention curve old shell slope	0.232
Fishery selectivity retention curve old shell length at 50%	106.063
Pot Fishery discard selectivity female slope	1.005
Pot Fishery discard selectivity female length at 50%	130.000
Trawl Fishery selectivity female slope	1.005
Trawl Fishery selectivity female length at 50%	130.000
Trawl Fishery selectivity male slope	0.237
Trawl Fishery selectivity male length at 50%	68.865
Survey Q 1978-1981	1.000
Survey 1978-1981 length at 95% selected	30.000
Survey 1978-1981 length at 50% selected	20.796
Survey Q 1982-1988	1.000
Survey 1982-1988 length at 95% selected	145.208
Survey 1982-1988 length at 50% selected	64.582
Survey Q 1989-present	1.000
Survey 1989-present, length at 95% selected	105.531
Survey 1989-present length at 50% selected	19.311
Fishery cpue q	0.001245

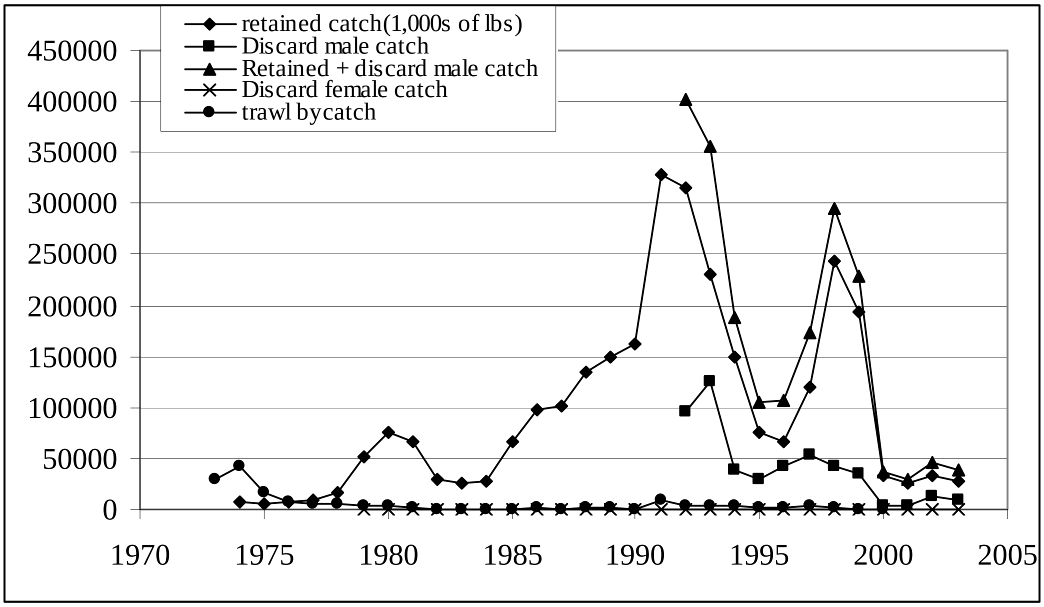

Figure 1. Catch (1,000s lbs) from the directed snow crab pot fishery and groundfish trawl bycatch. Retained and total catch are males only, female catch is the discard mortality from the directed pot fishery and trawl is male and female bycatch from groundfish trawl fisheries.

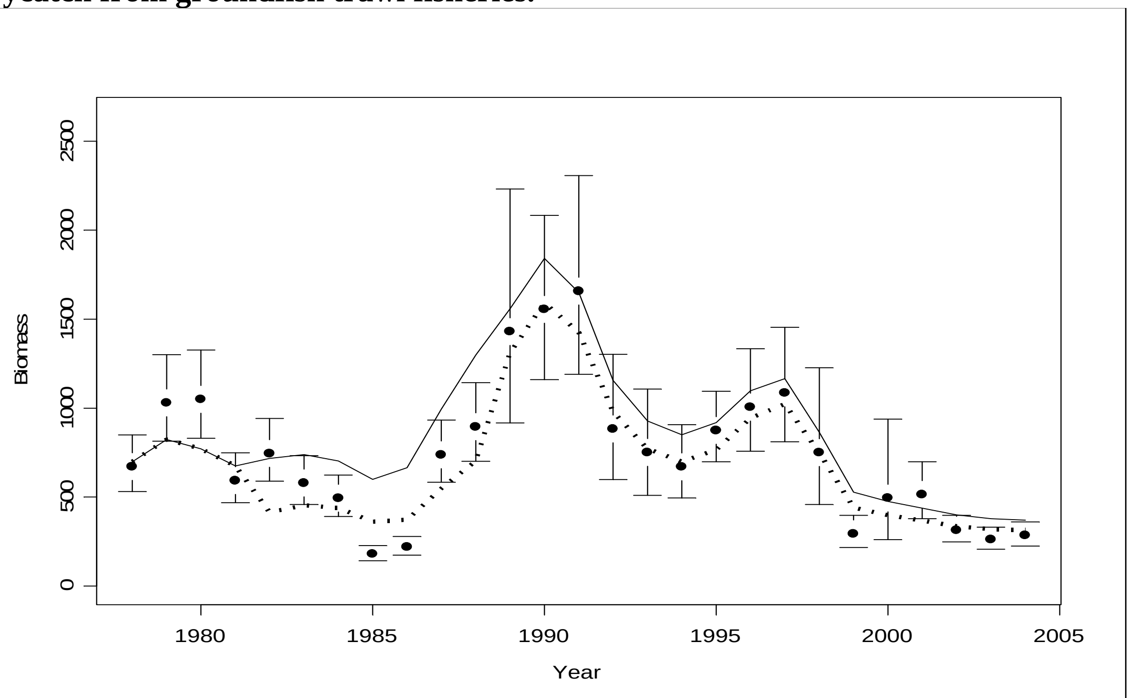

Figure 2. Population total mature biomass (millions of pounds, solid line), model estimate of survey mature biomass (dotted line) and observed survey mature biomass with approximate lognormal 95% confidence intervals.

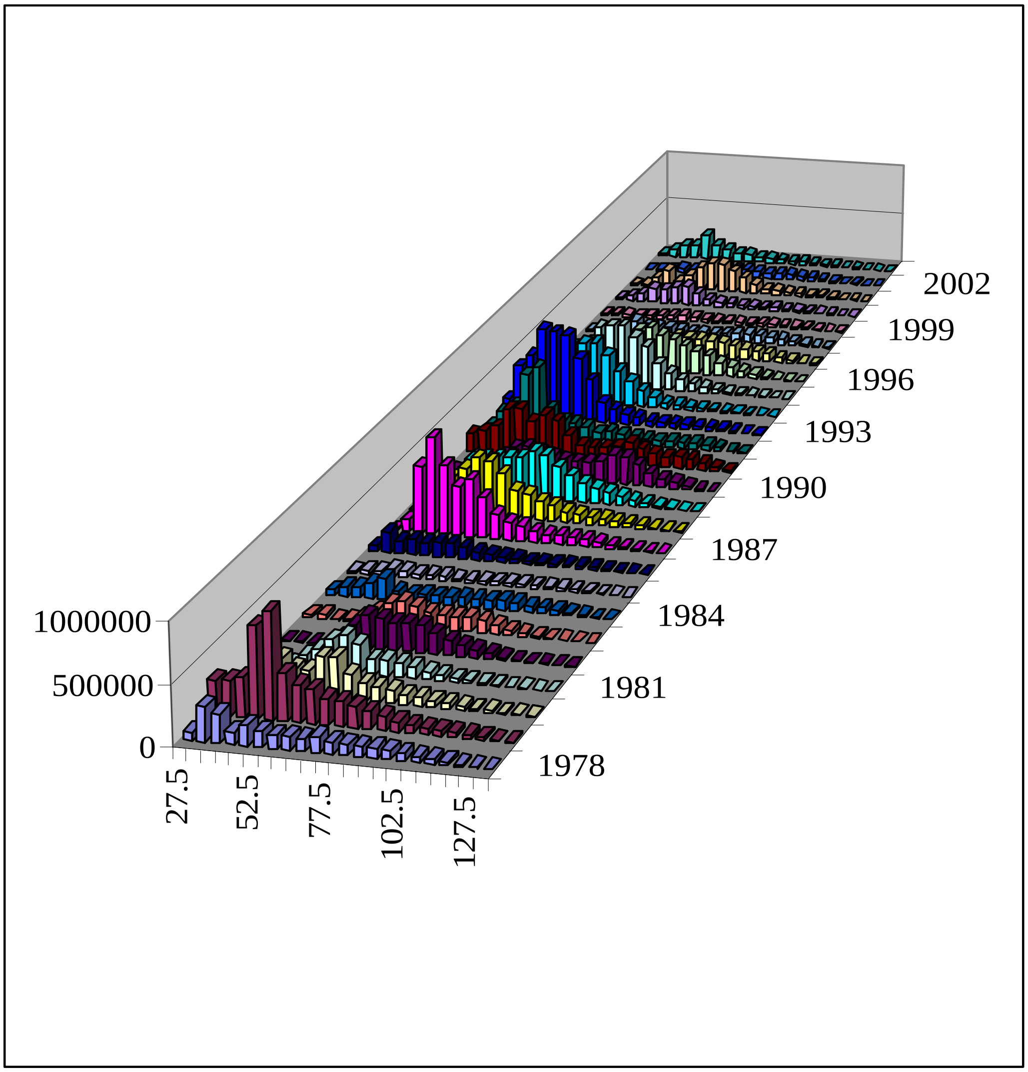

Figure 3. Observed survey numbers by carapace width and year for male snow crab.

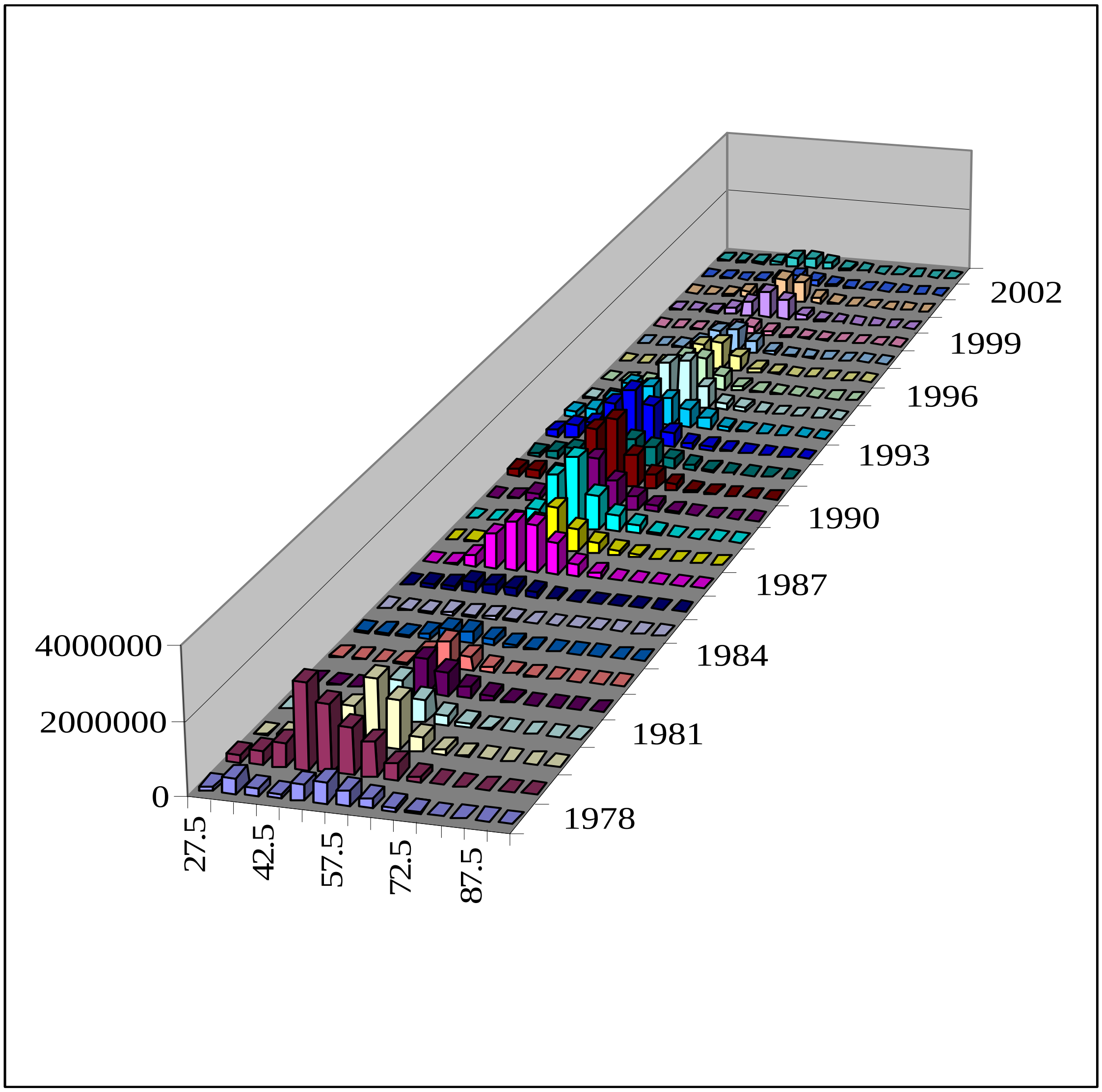

Figure 4. Observed survey numbers by carapace width and year for female snow crab.

Figure 5. Exploitation rate estimated as the preseason GHL divided by the survey estimate of large male biomass (>101 mm) at the time the survey occurs (dotted line). The solid line is the retained catch divided by the survey estimate of large male biomass at the time the fishery occurs. Year is the year the fishery occurred.

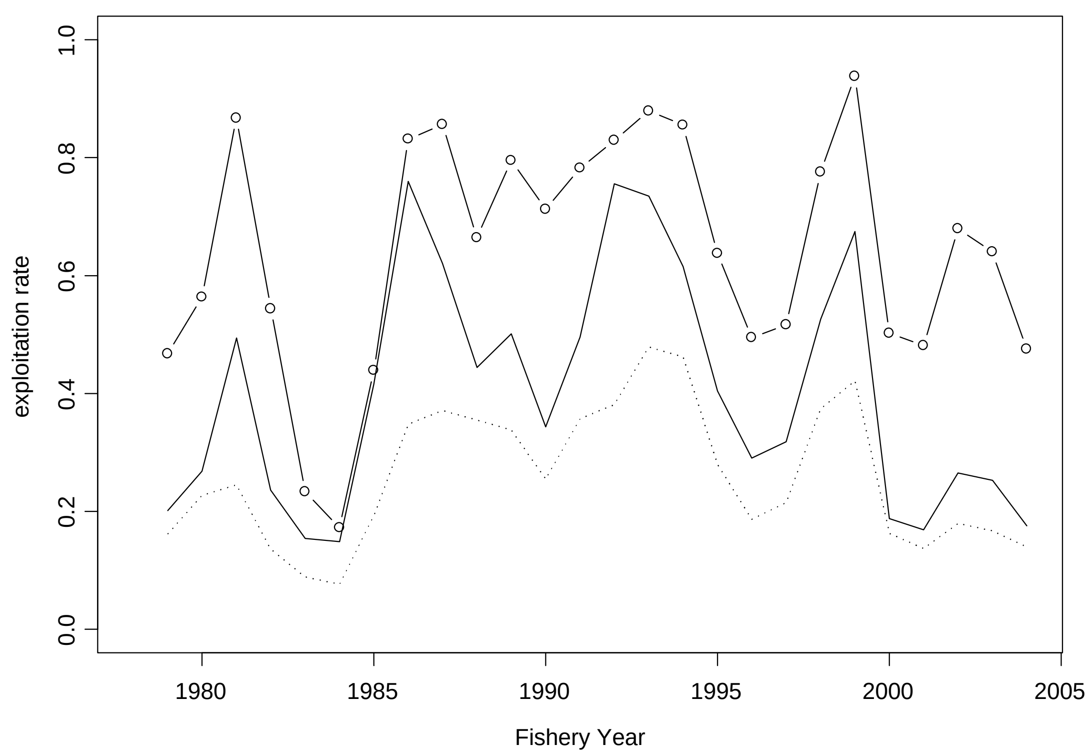

Figure 6. Exploitation fraction estimated as the catch biomass (total or retained) divided by the mature male biomass from the model at the time of the fishery (solid line and dotted line). The exploitation rate for total catch divided by the male biomass greater than 101 mm is the solid line with dots. Year is the year of the fishery.

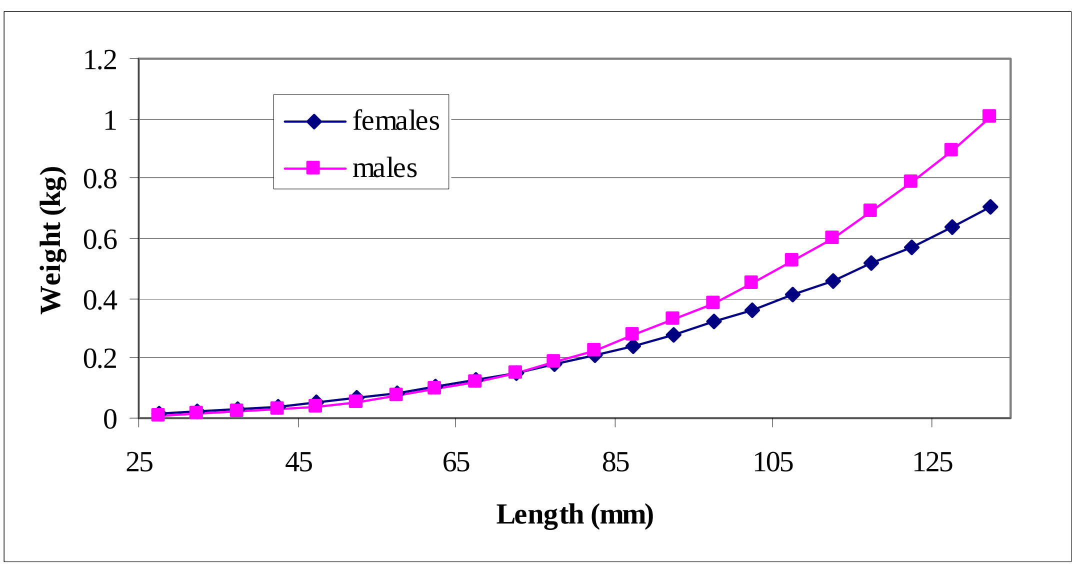

Figure 7. Weight (kg) – size (mm) relationship for male and female snow crab.

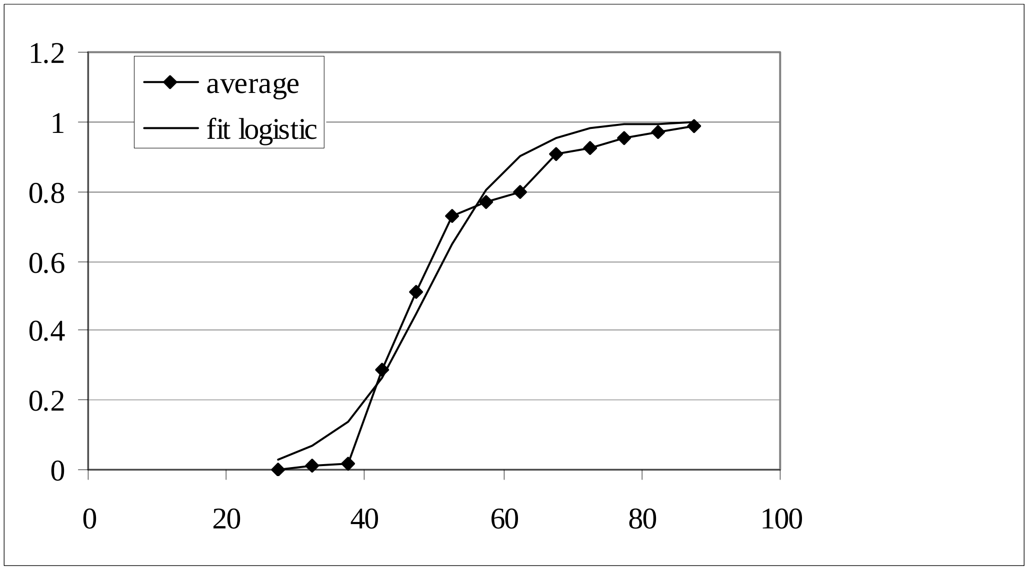

Figure 8. Average maturity for females from the survey 1978 to 2000 (not used in the model). Females were determined to be mature or immature based on visual examination in the survey. Line labeled logistic has a slope of 0.163 and size at 50% of 48.8 mm for comparison only.

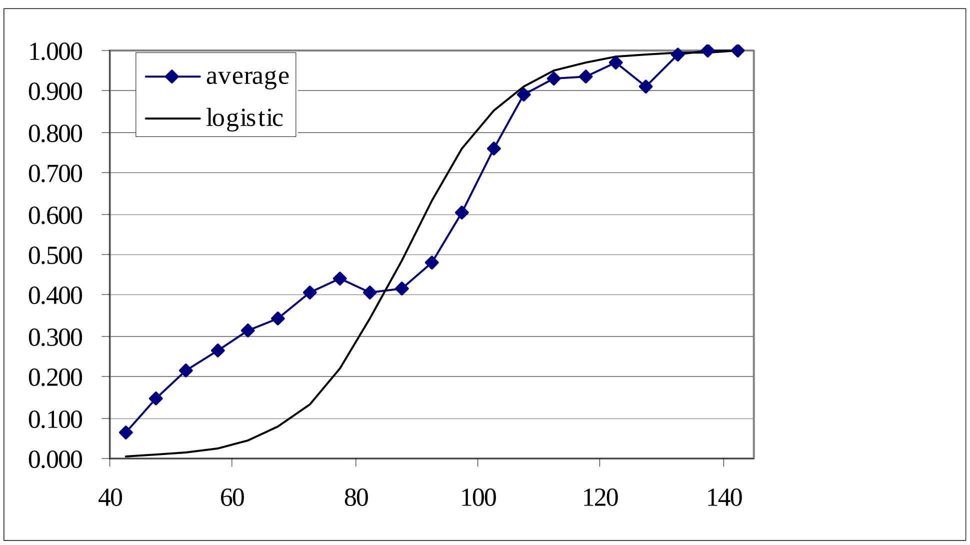

Figure 9. Maturity curve for new shell males. Line labeled average is the average maturity for new shell males from the survey 1989 to 2000. Line labeled logistic is the curve used in the model (slope 0.12, size at 50% 88.0mm).

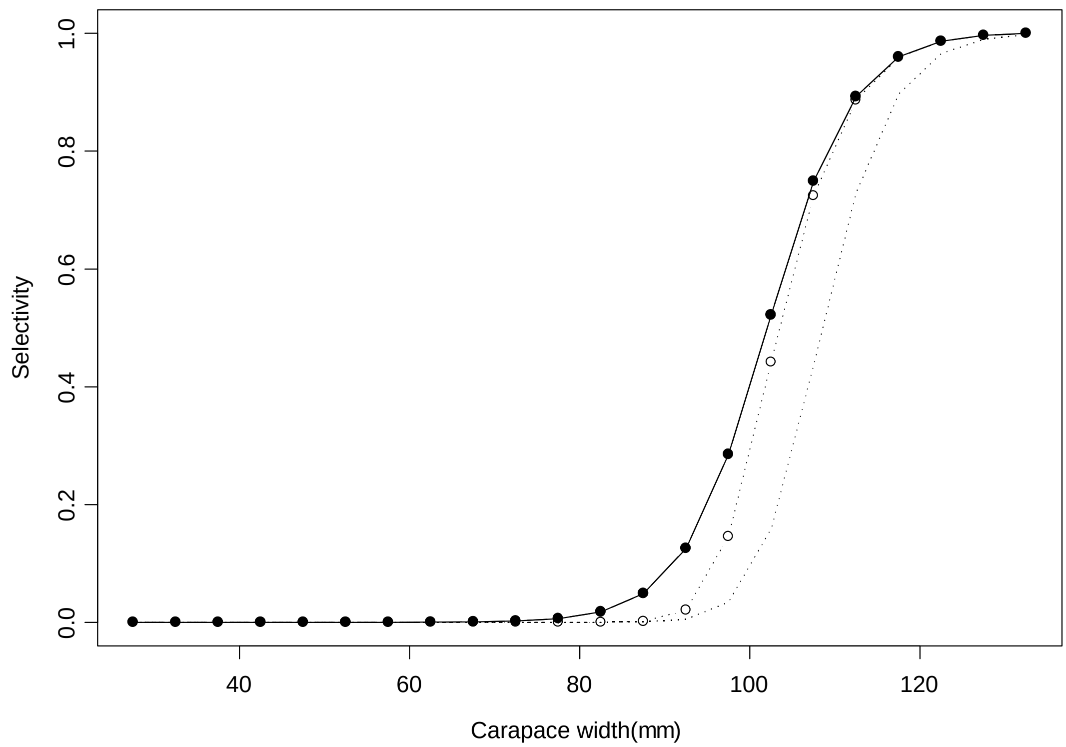

Figure 10. Selectivity curves for total catch (discard plus retained, new and old shell the same, solid line with filled circles) and retained catch of male snow crab by new (dotted line with open circles) and old shell condition (dotted line) averaged over the last three years (2002 to 2004 fishery seasons).

Figure 11. Size at 50% selected parameter for pot fishery selectivities of male crab 1978 to 2004.

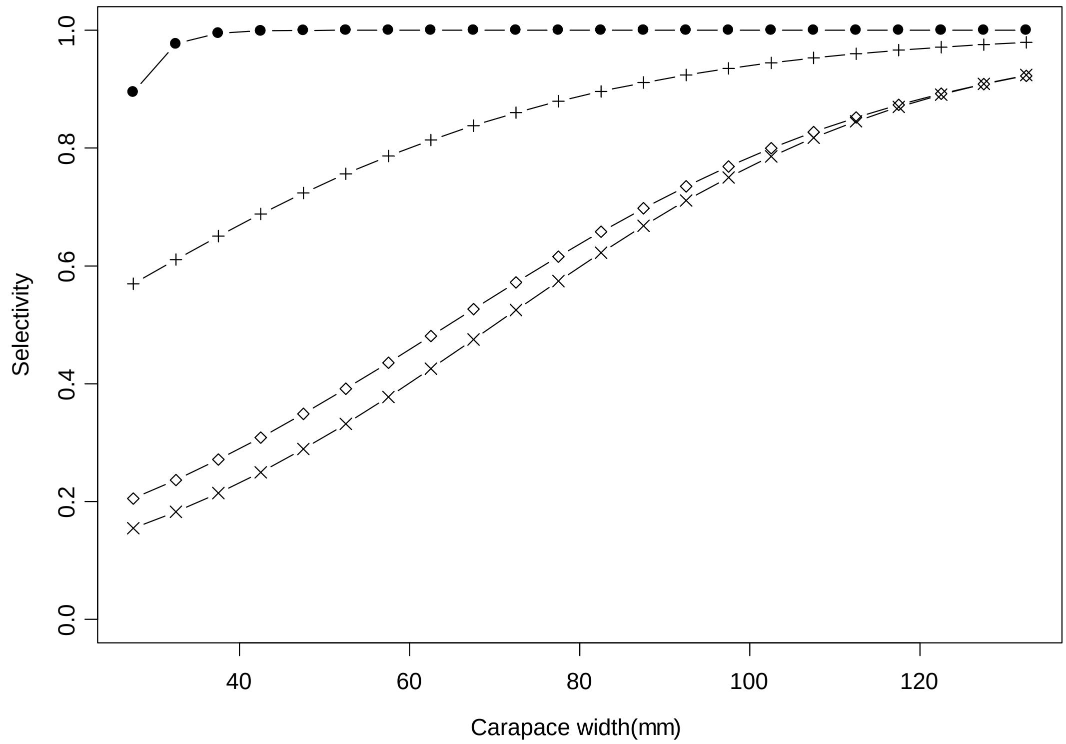

Figure 12. Survey selectivity curves for female and male snow crab estimated by the model for 1978-1981(solid line with circles), for 1982 to 1988 (solid line with diamonds), and 1989 to present (solid line with pluses). Survey selectivities estimated by Somerton and Otto (1998) are the solid line with crosses.

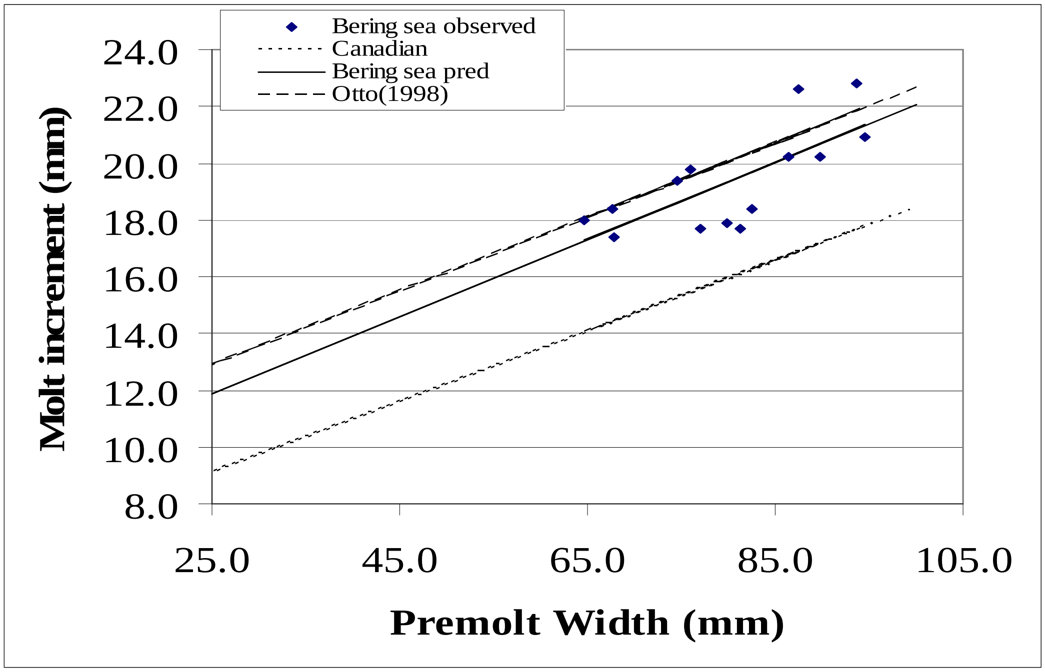

Figure 13. Growth increment as a function of premolt size for male snow crab. Points labeled Bering sea observed are observed growth increments from Rugolo (unpub data). The line labeled Bering sea pred is the predicted line from the Bering sea observed growth, which is used as a prior for the growth 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.

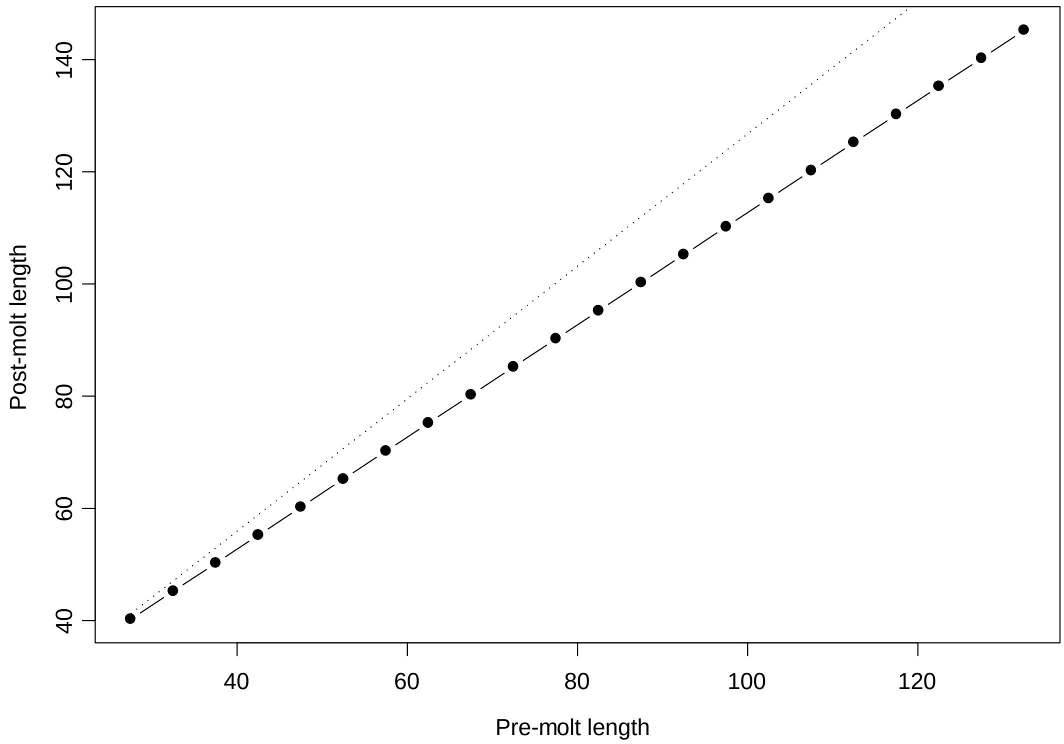

Figure 14. Growth(mm) for male(dotted line) and female snow crab (solid line with circles) estimated from the model.

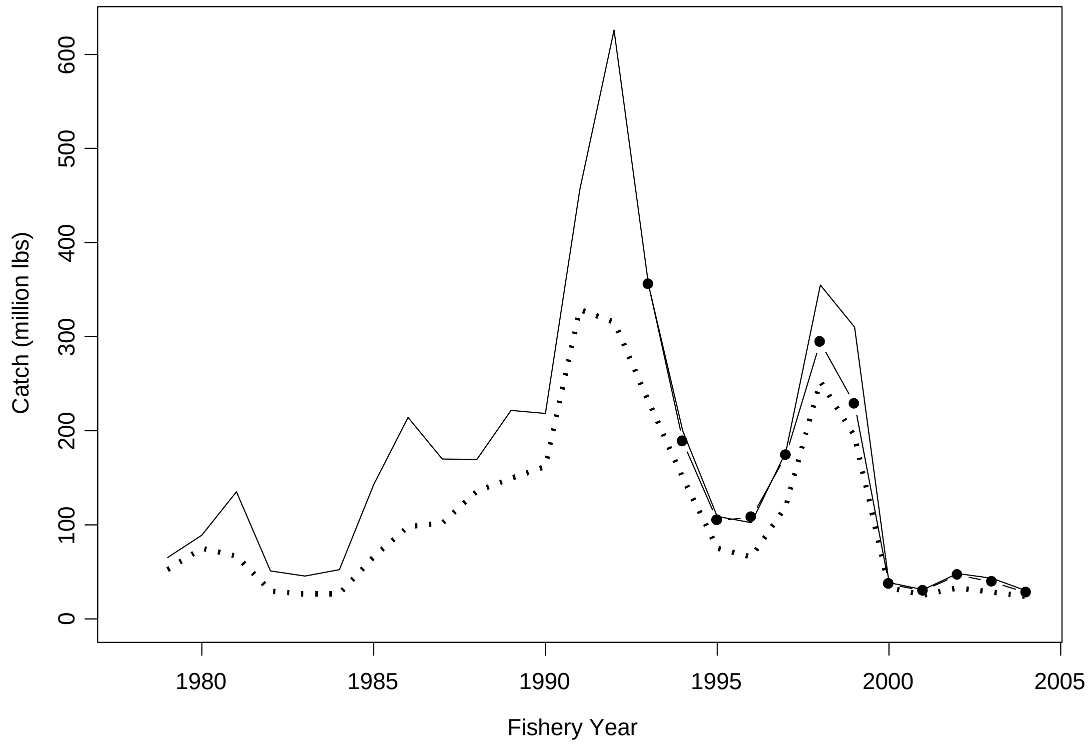

Figure 15. Estimated total catch(discard + retained) (solid line), observed total catch (solid line with circles) and observed retained catch (dotted line) for 1978 to 2004 fishery seasons.

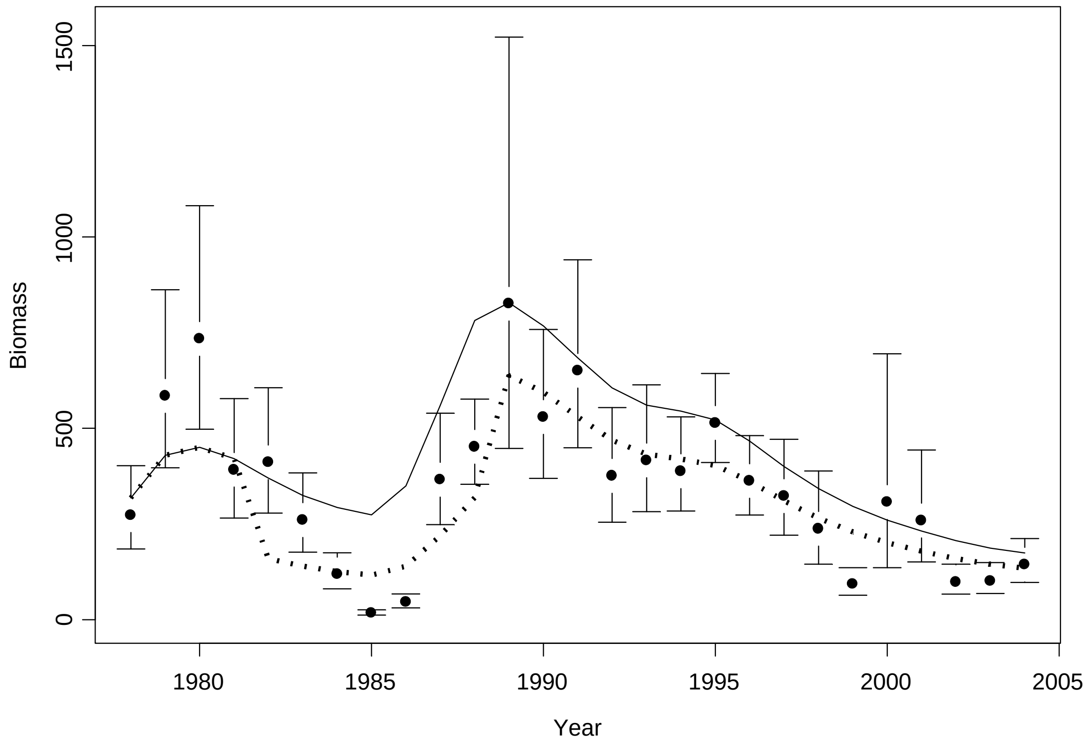

Figure 16. Population female mature biomass (millions of pounds, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

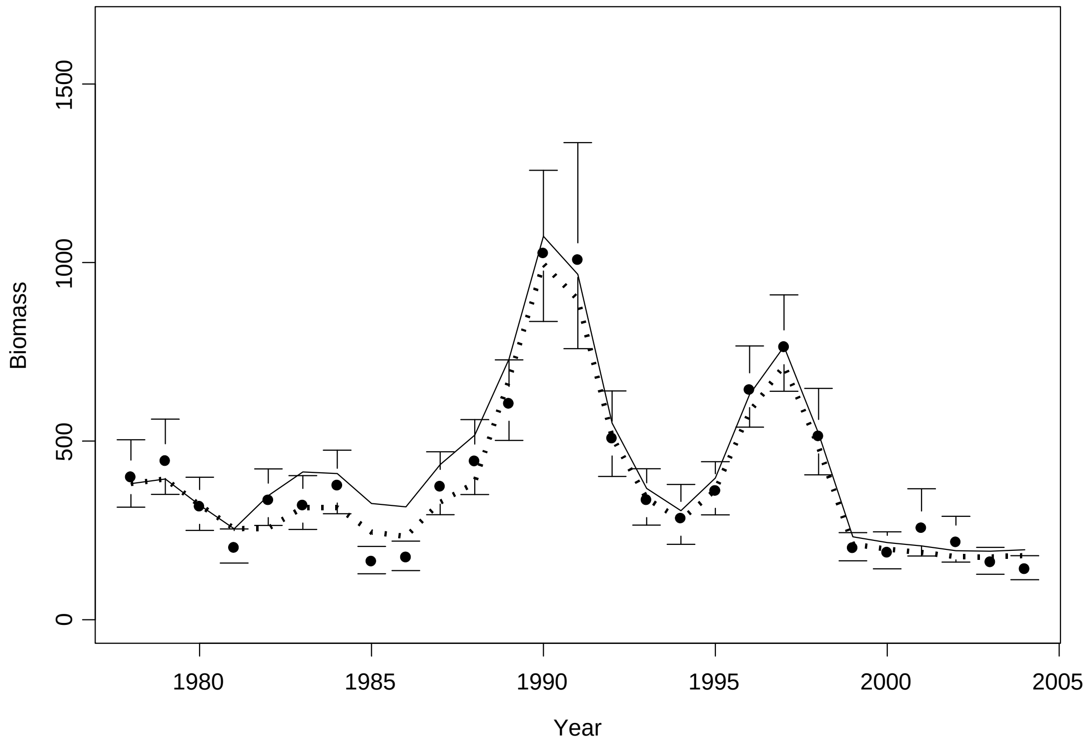

Figure 17. Population male mature biomass (millions of pounds, solid line), model estimate of survey male mature biomass (dotted line) and observed survey male mature biomass with approximate lognormal 95% confidence intervals.

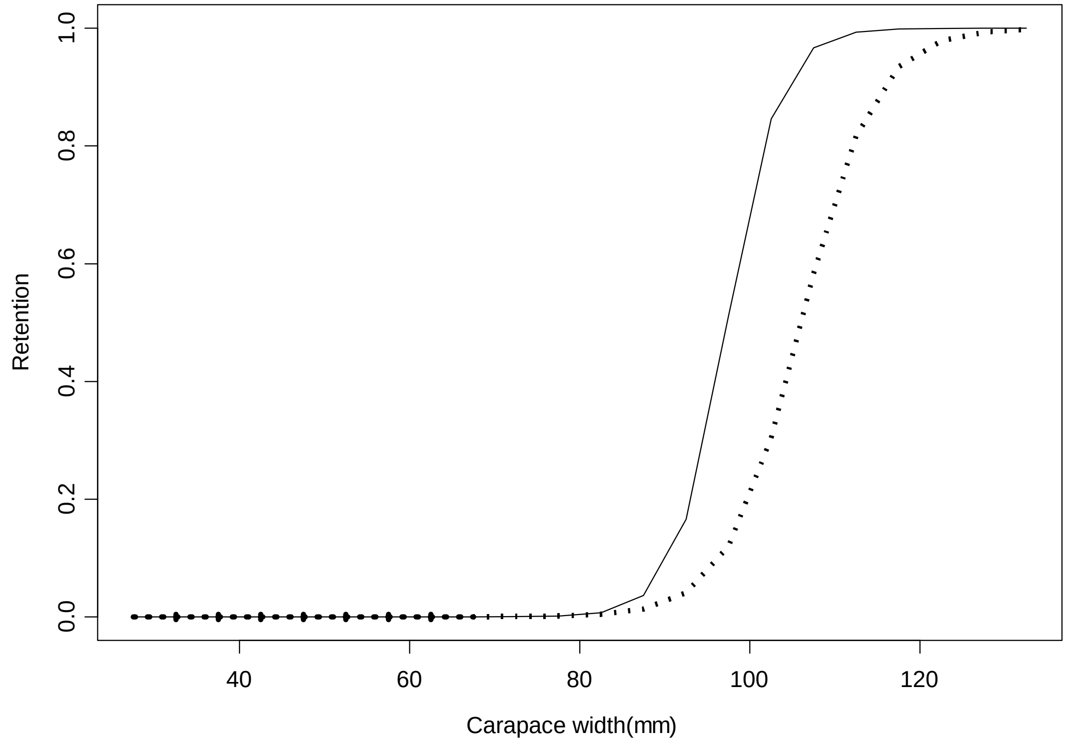

Figure 18. Model estimated fraction of the total catch that is retained by size for new(solid line) and old(dotted line) shell male snow crab.

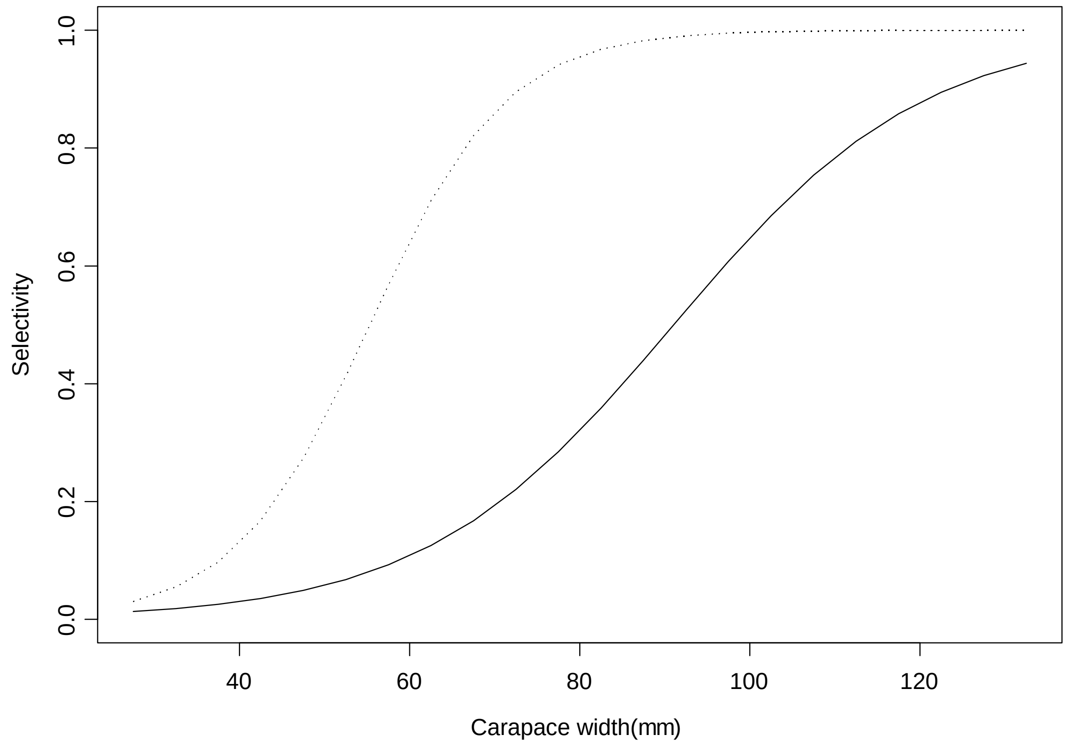

Figure 19. Selectivity curves estimated by model for the trawl fishery discard for females (solid line) and males (dotted line).

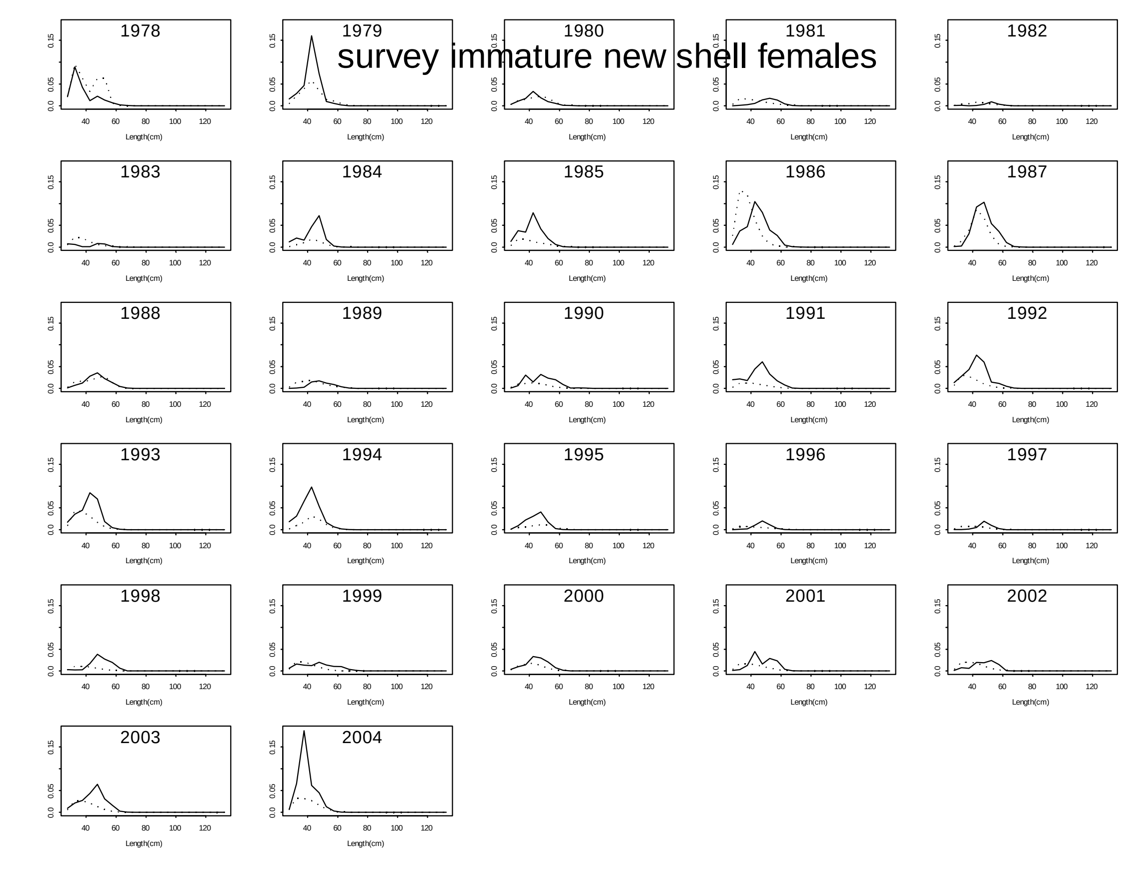

Figure 20. Model fit to the survey immature female new shell size frequency data. Dotted line is the model fit.

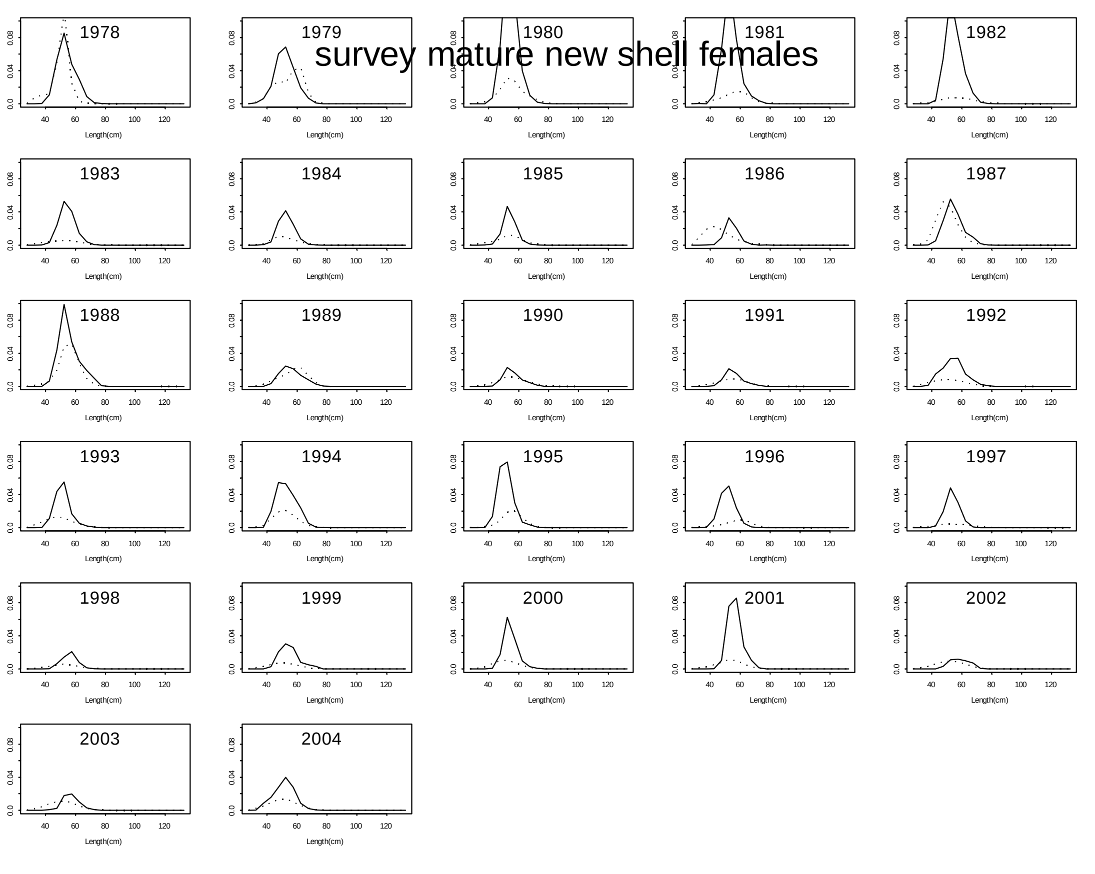

Figure 21. Model fit to the mature survey female new shell size frequency data. Dotted line is the model fit.

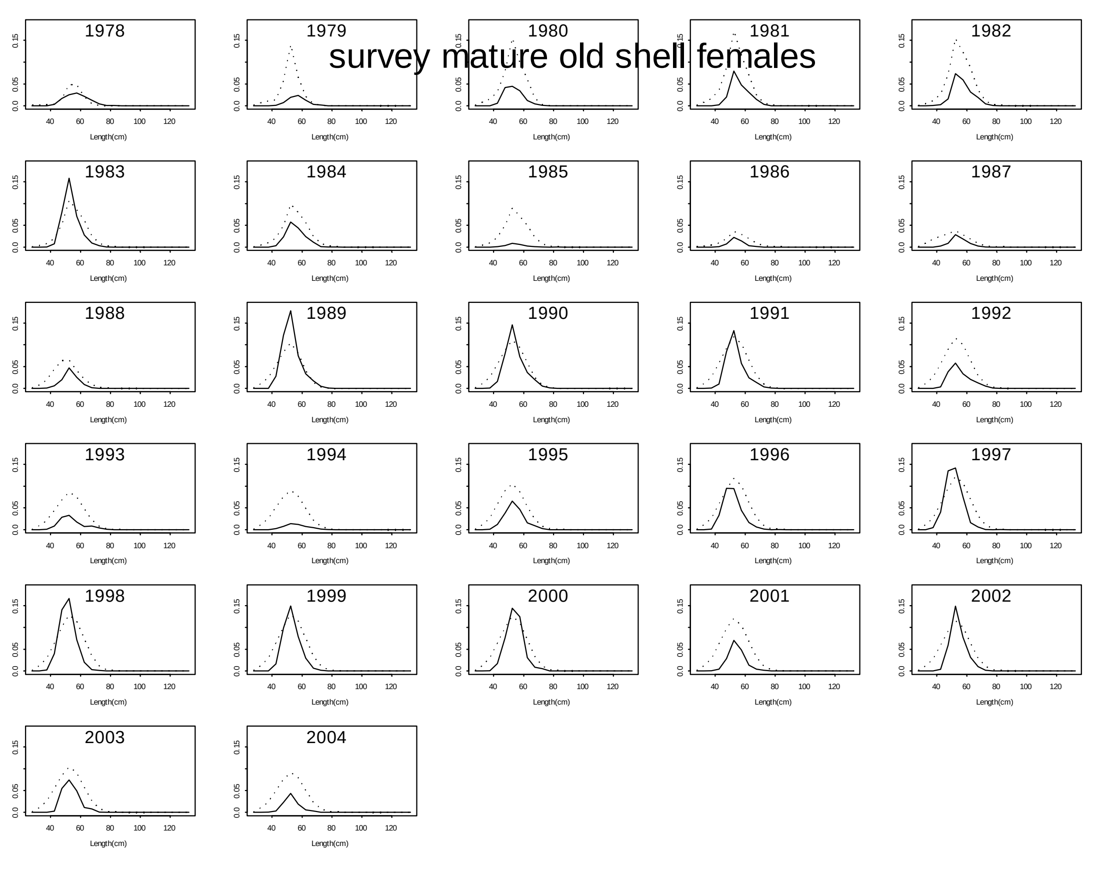

Figure 22. Model fit to the mature survey female old shell size frequency data. Dotted line is the model fit.

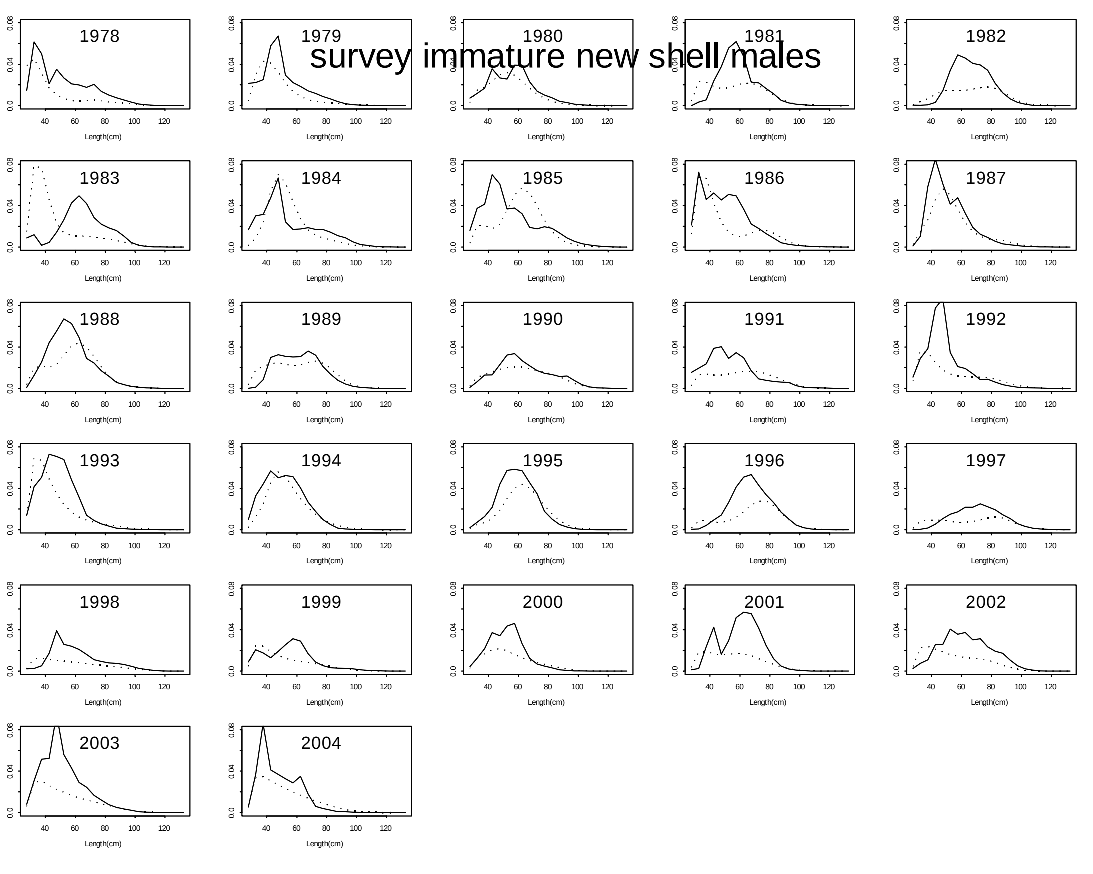

Figure 23. Model fit to the immature survey male new shell size frequency data. Dotted line is the model fit.

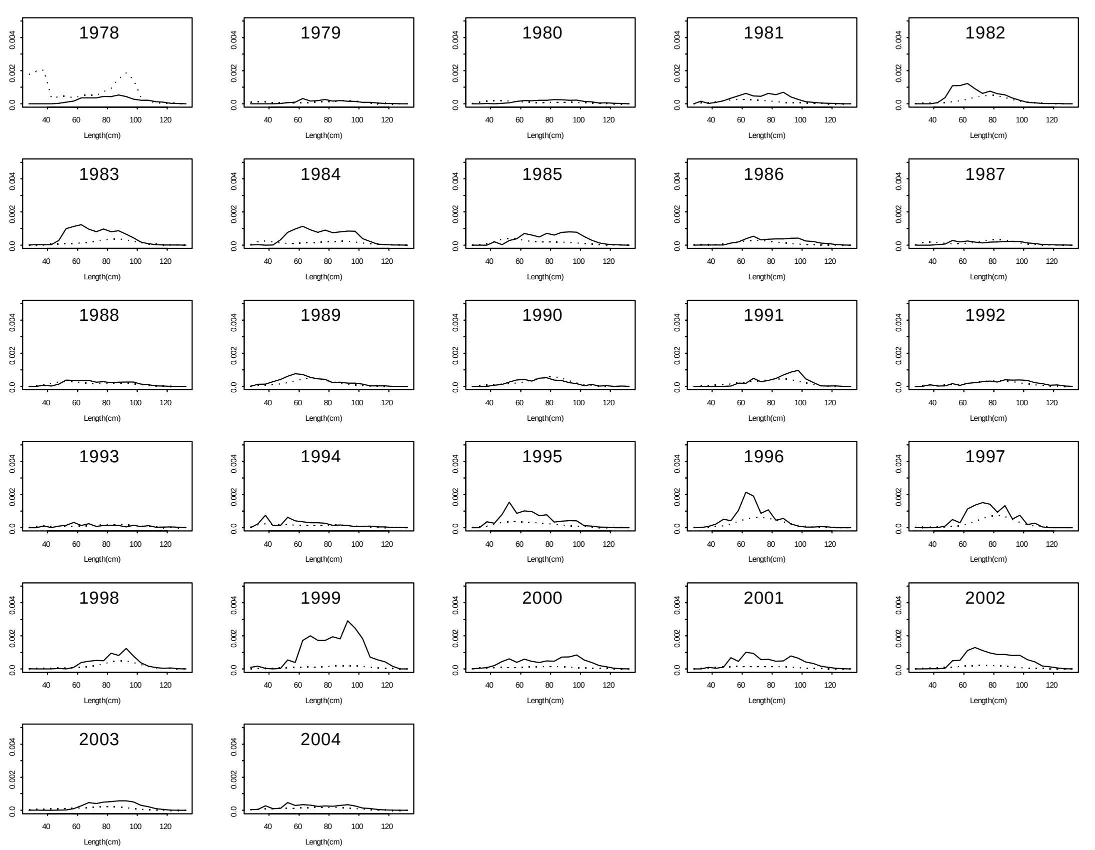

Figure 24. Model fit to the immature survey male old shell size frequency data. Dotted line is the model fit.

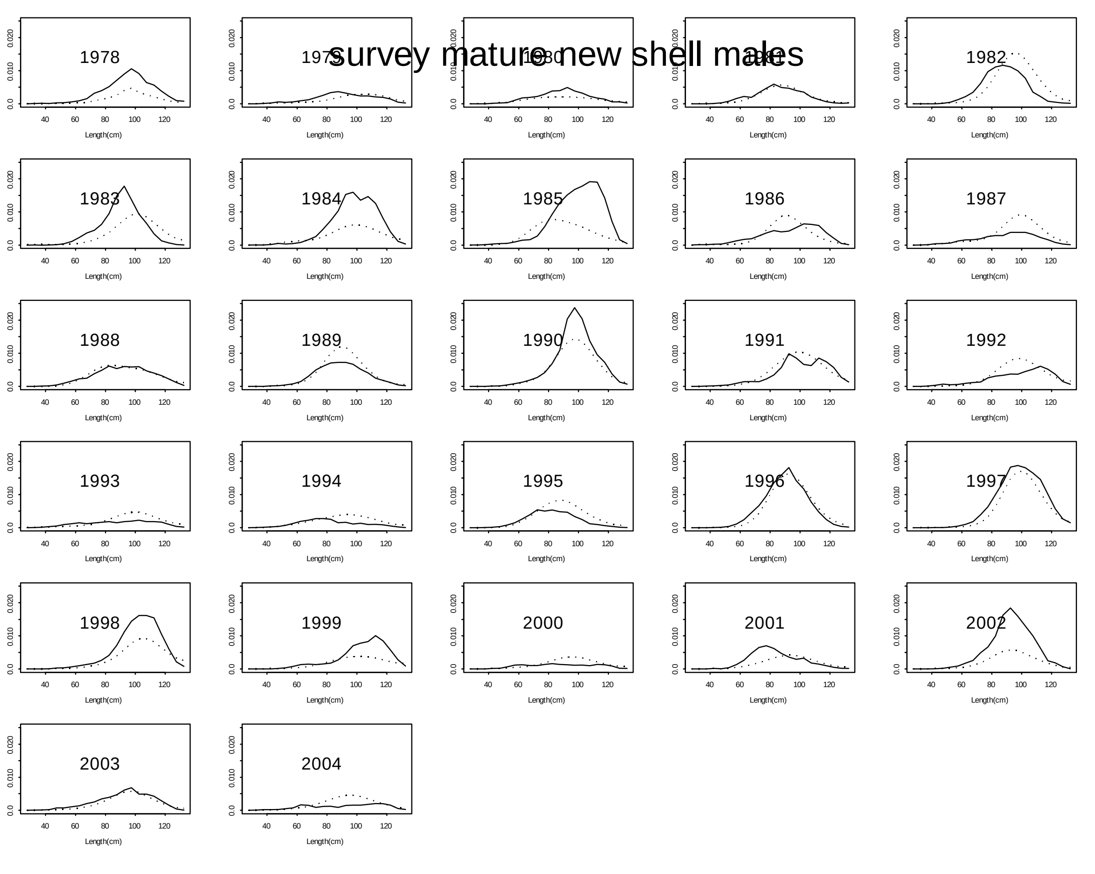

Figure 25. Model fit to the mature survey male new shell size frequency data. Dotted line is the model fit.

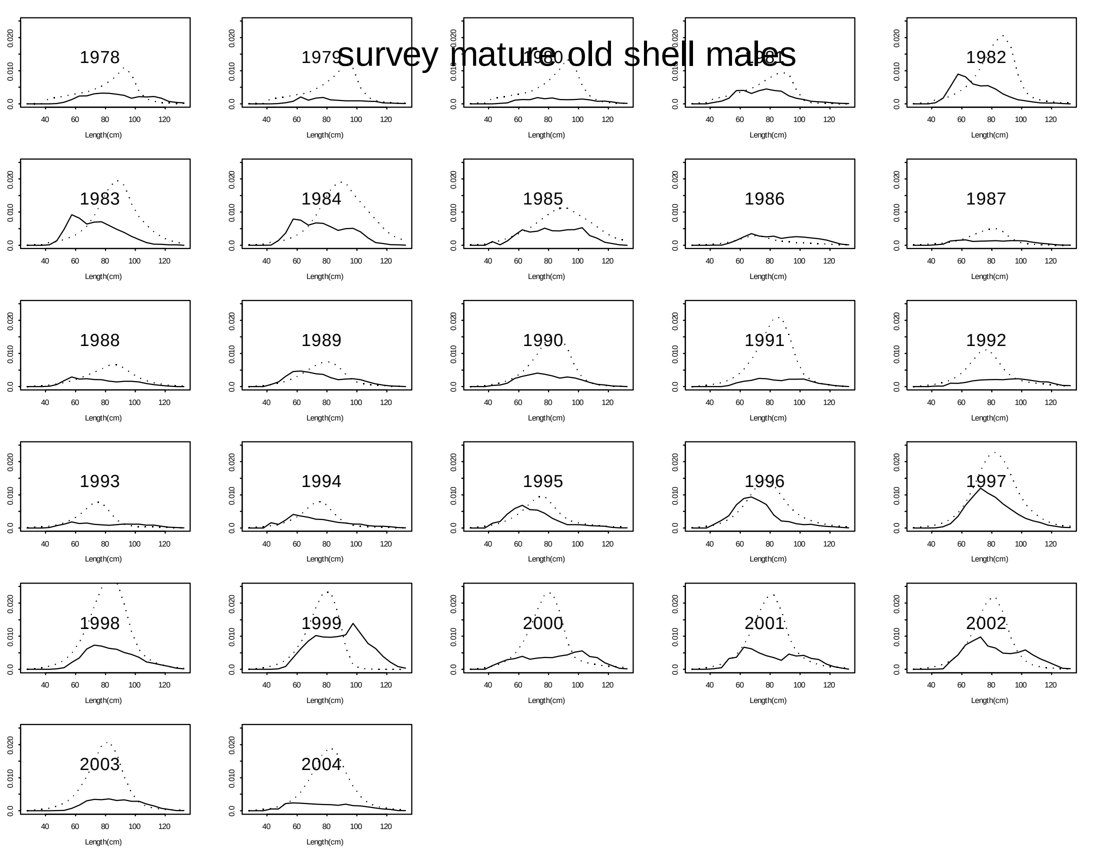

Figure 26. Model fit to the mature survey male old shell size frequency data. Dotted line is the model fit.

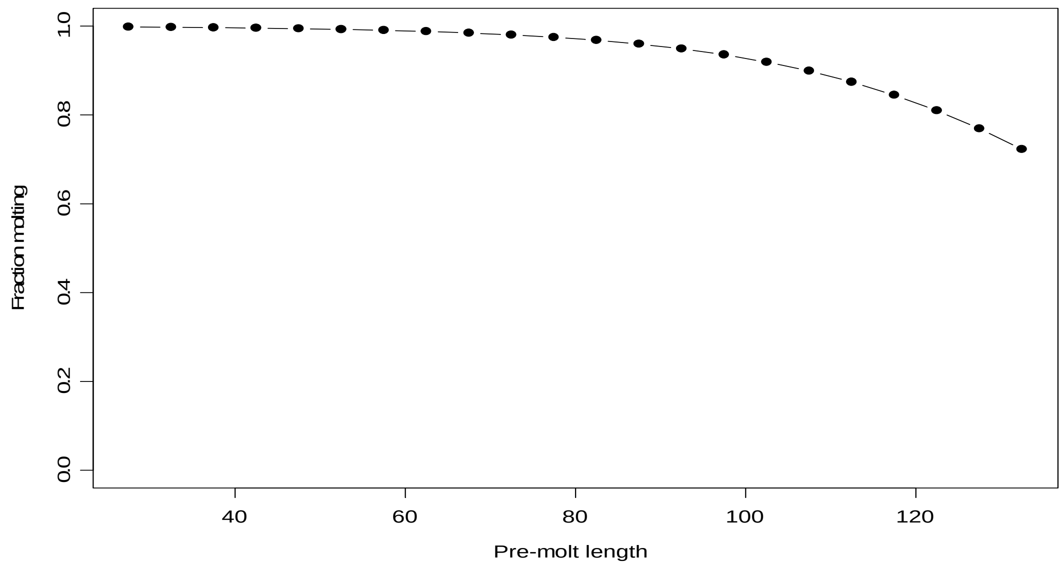

Figure 27. Molting probabilities for immature male crabs.

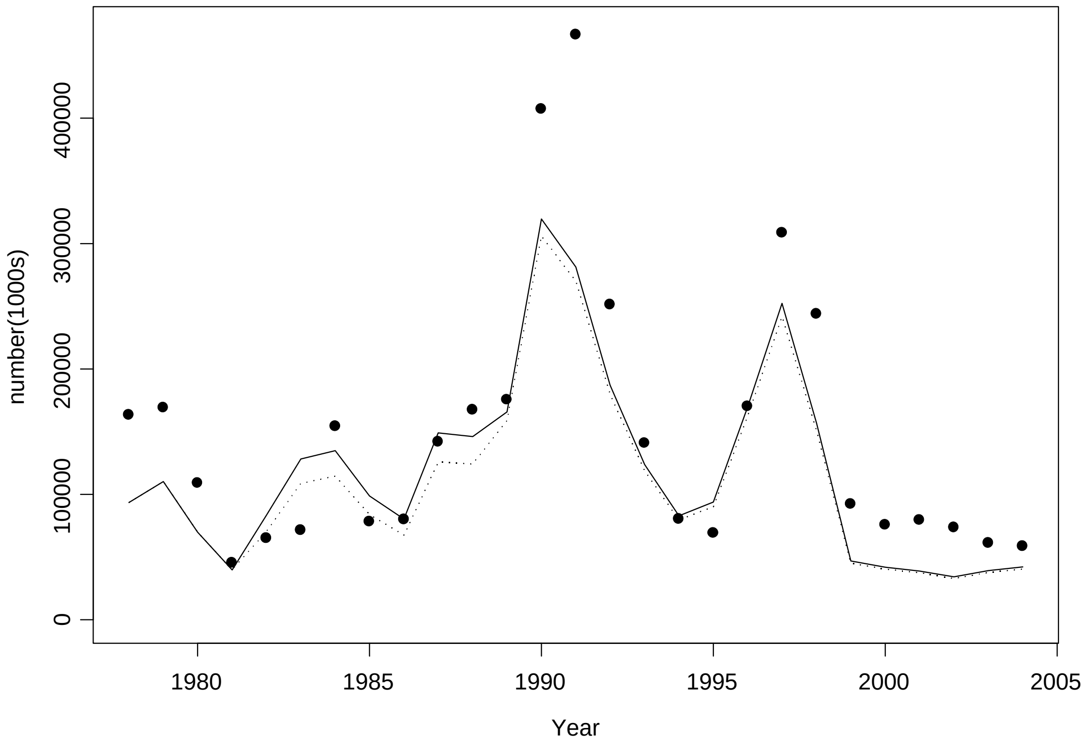

Figure 28. Observed survey numbers of males >101mm (circles) and model estimates of the population number of males >101mm(solid line) and model estimates of survey numbers of males >101 mm (dotted line).

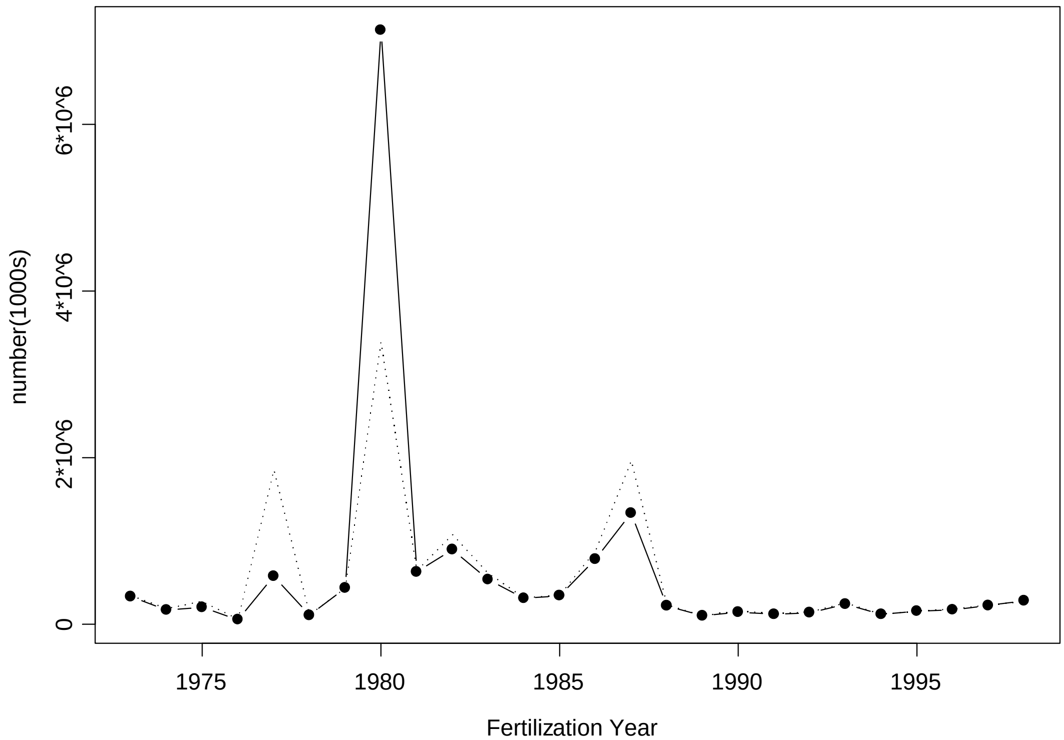

Figure 29. Recruitment to the model of male (dotted line) and female (solid line with dots) crab 25 mm to 50 mm.

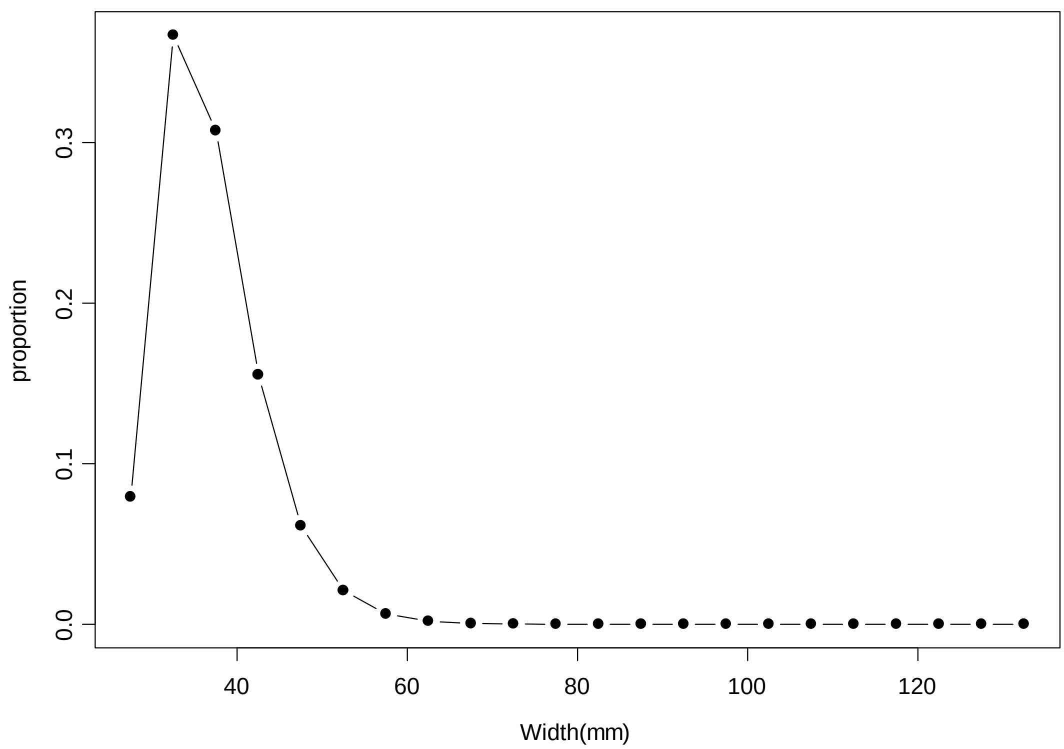

Figure 30. Distribution of recruits to length bins estimated by the model.

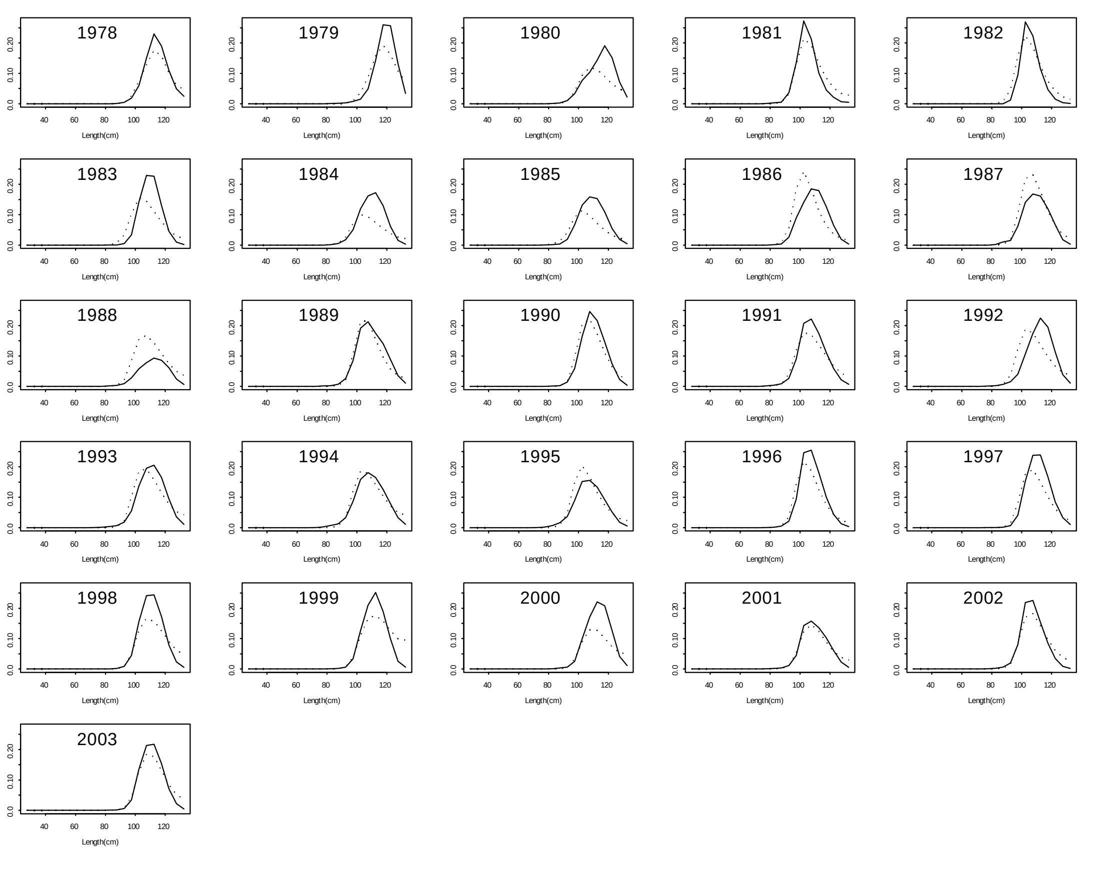

Figure 31. Model fit to the retained male new shell size frequency data. Dotted line is the model fit. Year is the survey year.

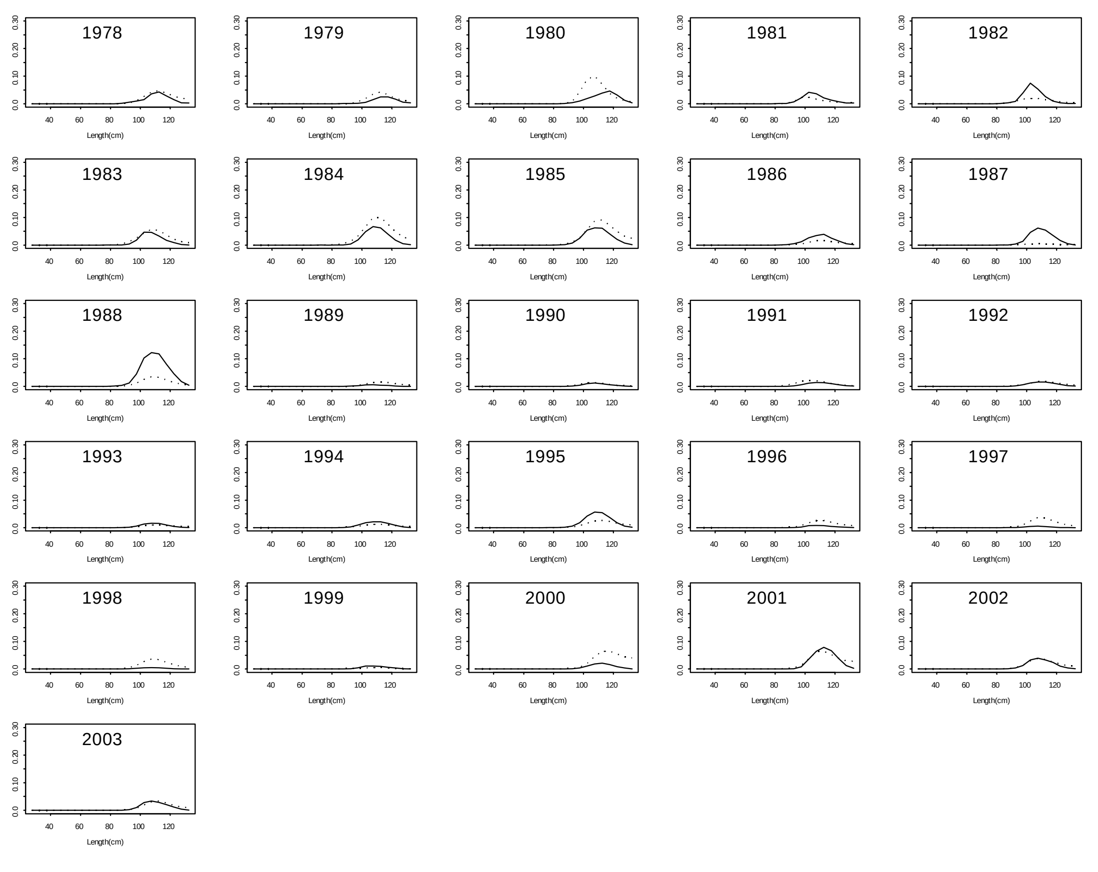

Figure 32. Model fit to the retained male old shell size frequency data. Dotted line is the model fit. Year is the survey year.

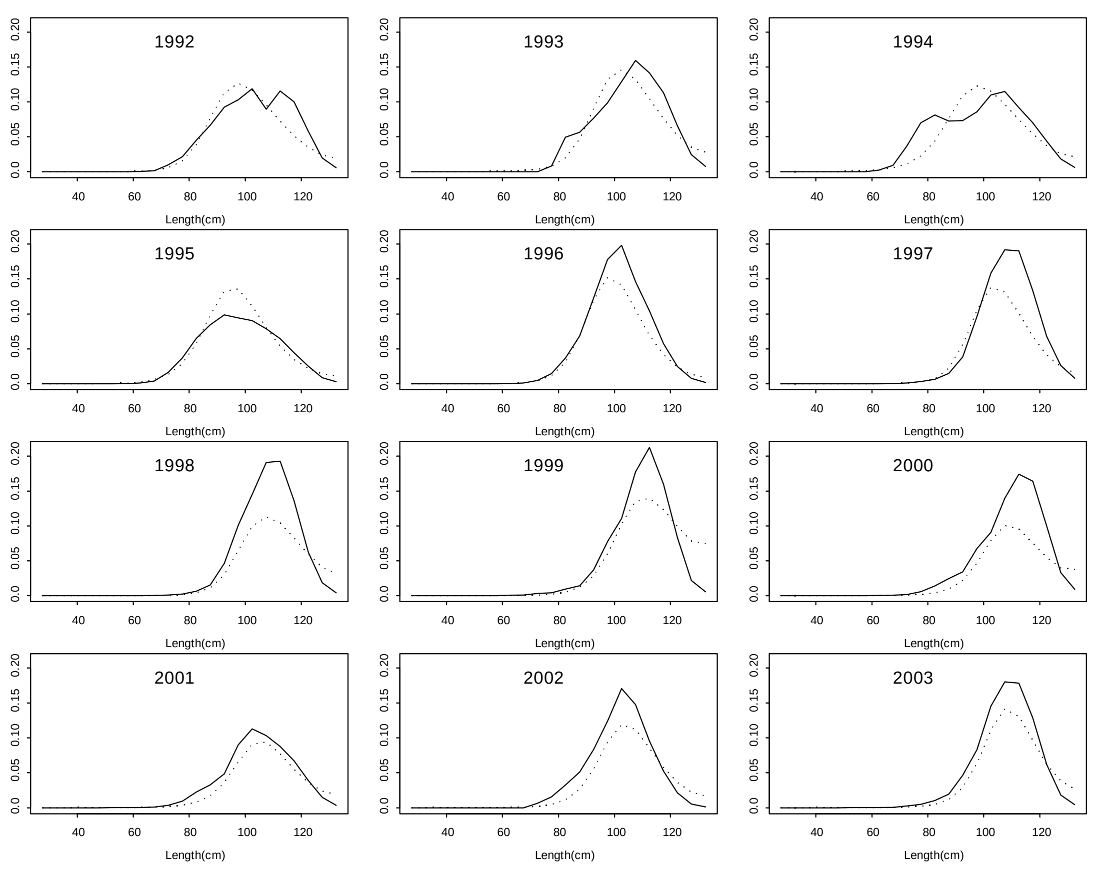

Figure 33. Model fit to the total (discard plus retained) male new shell size frequency data. Dotted line is the model fit. Year is the survey year.

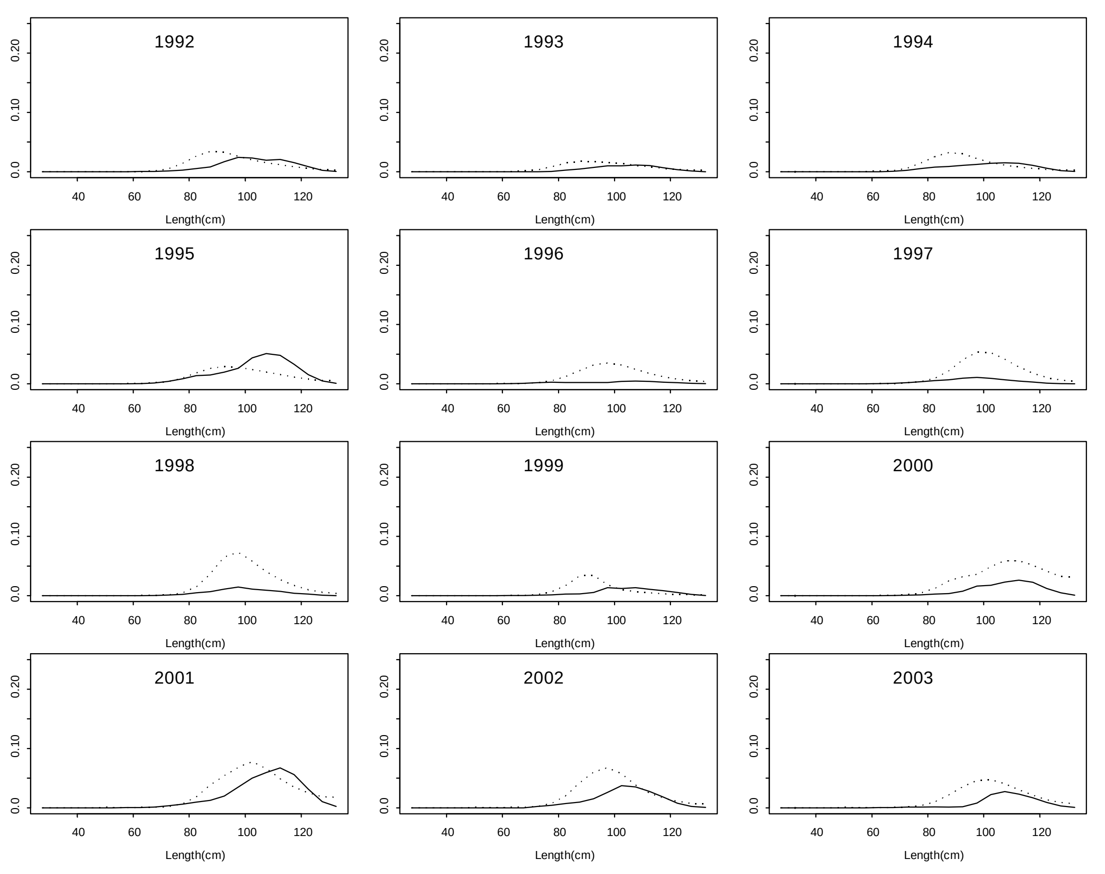

Figure 34. Model fit to the total (discard plus retained) male old shell size frequency data. Dotted line is the model fit. Year is the survey year.

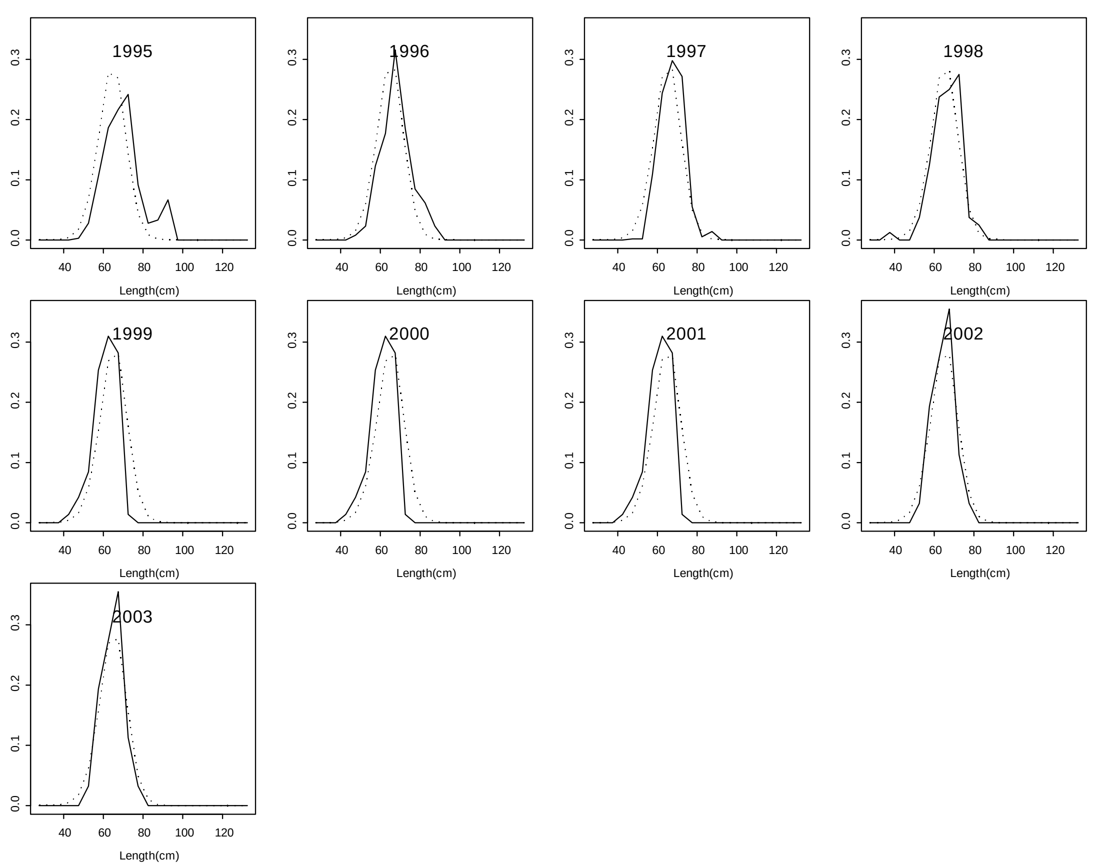

Figure 35. Model fit to the discard female size frequency data. Dotted line is the model fit. Year is the survey year.

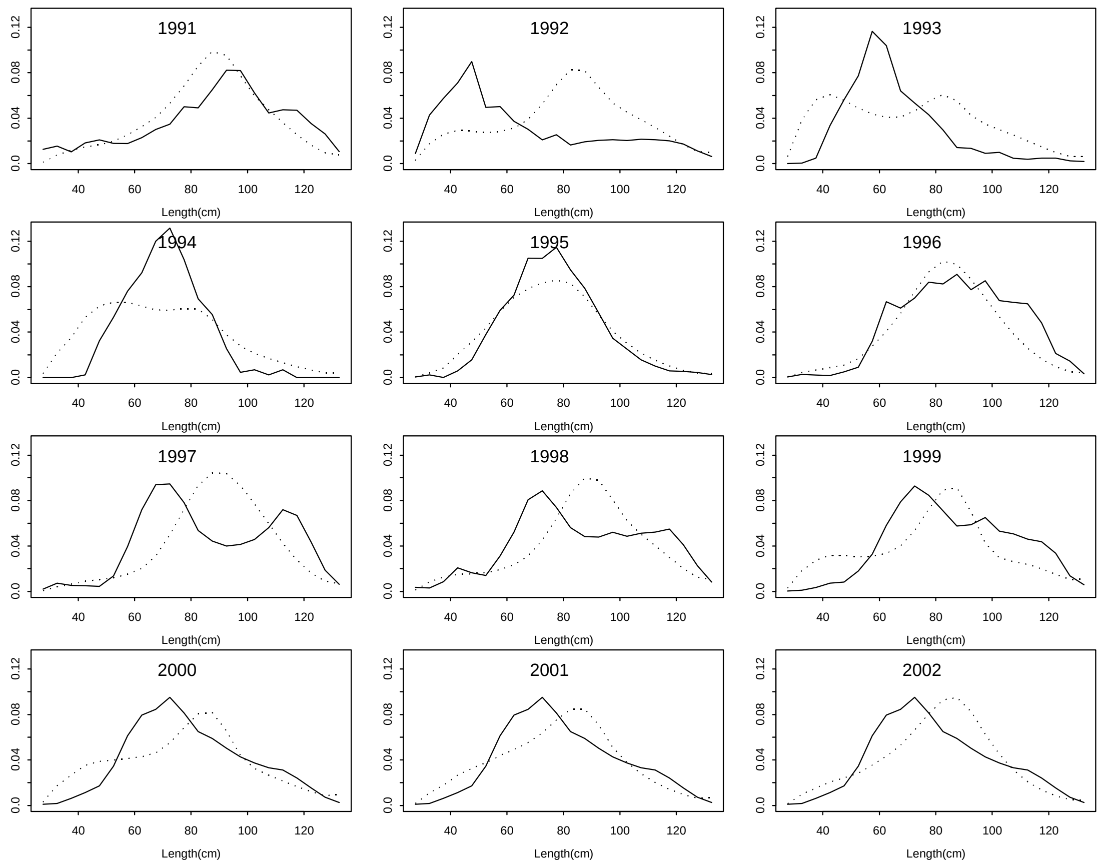

Figure 36. Model fit to the groundfish trawl discard male size frequency data. Dotted line is the model fit. Year is the survey year.

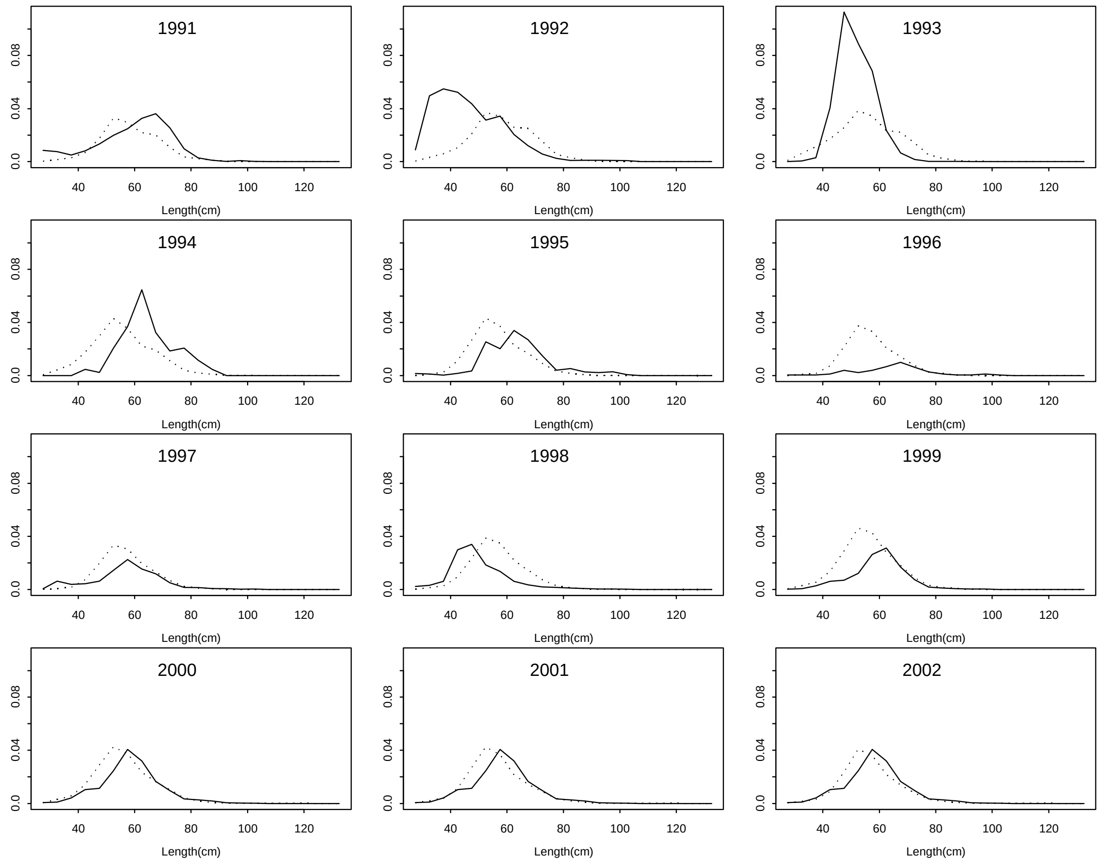

Figure 37. Model fit to the groundfish trawl discard female size frequency data. Dotted line is the model fit.

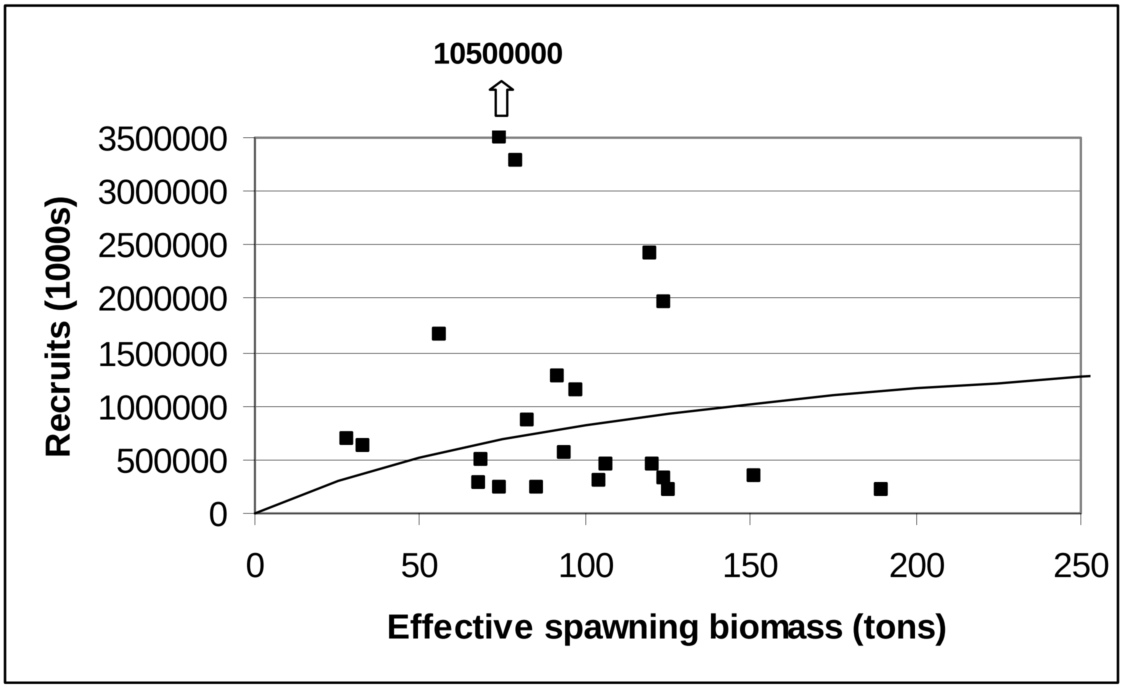

Figure 38. Spawner recruit curve using total effective spawning biomass at time of mating. Curve has a steepness parameter of 0.61 and R0 of 1.68 billion recruits.

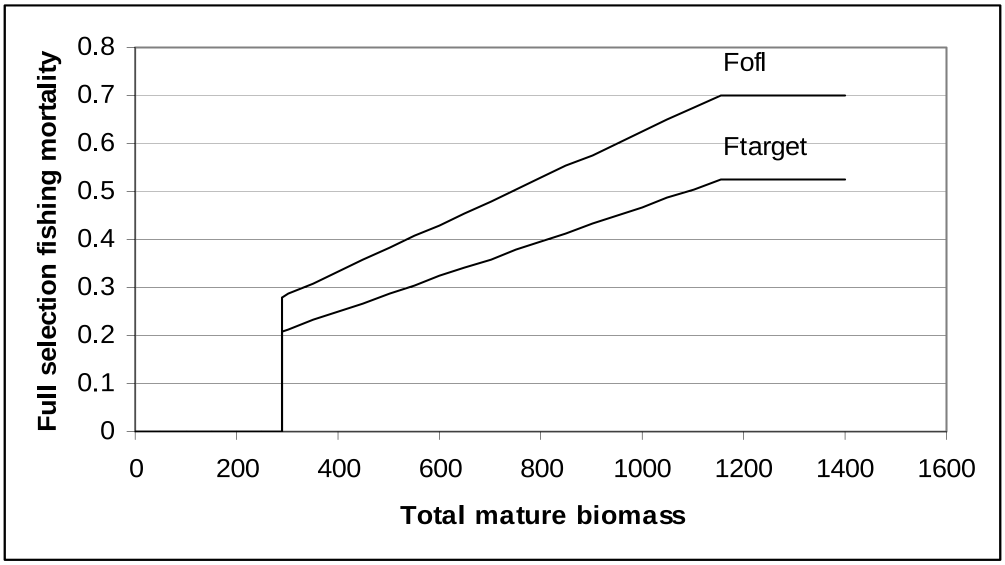

Figure 39. Harvest control rules. Line labeled Fofl is the overfishing harvest control rule using Fmsy = 0.7, Bmsy = 1155 million lbs and alpha = -0.25. Lower line labeled Ftarget is for target harvest control rule.

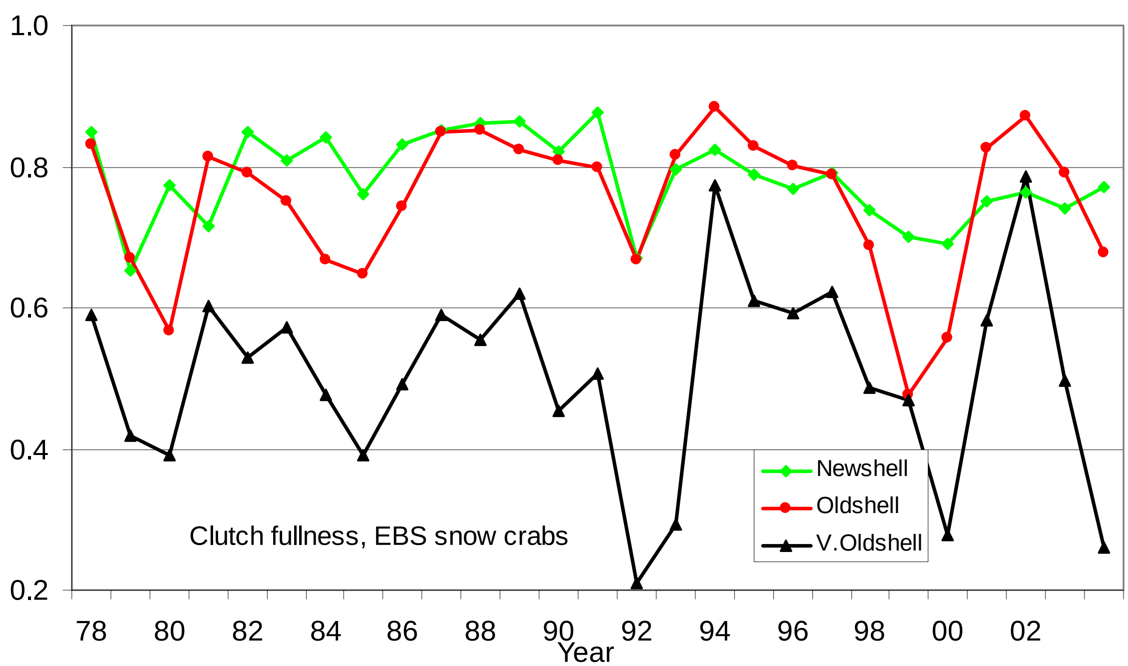

Figure 40.

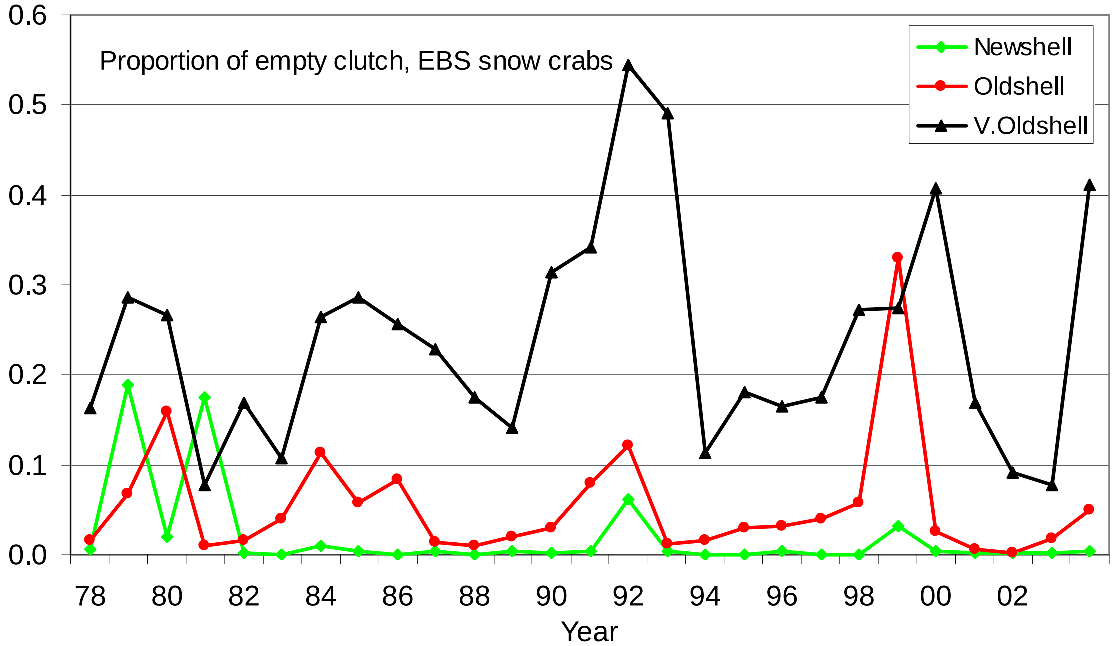
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Proportion of empty clutch, EBS snow crabs
Newshell
Oldshell
V.Oldshell
78
80
82
84
86
88
90
92
94
96
98
00
02
Year

Figure 41.

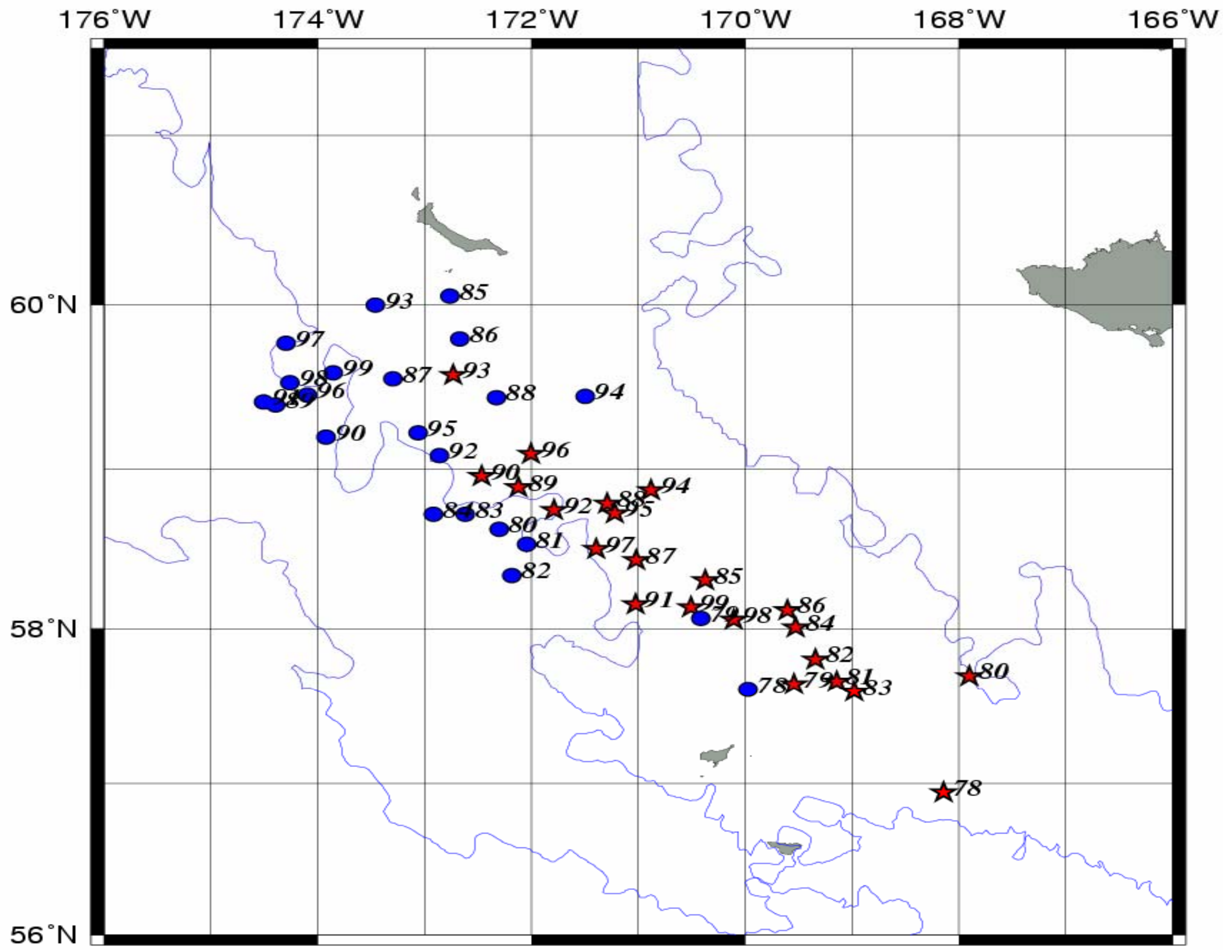

Figure 42. Centroids of abundance of mature female snow crabs (shell condition 2+) in blue circles and mature males (shell condition 3+) in red stars. Reprinted from Orensanz, Armstong and Ernst (in press).

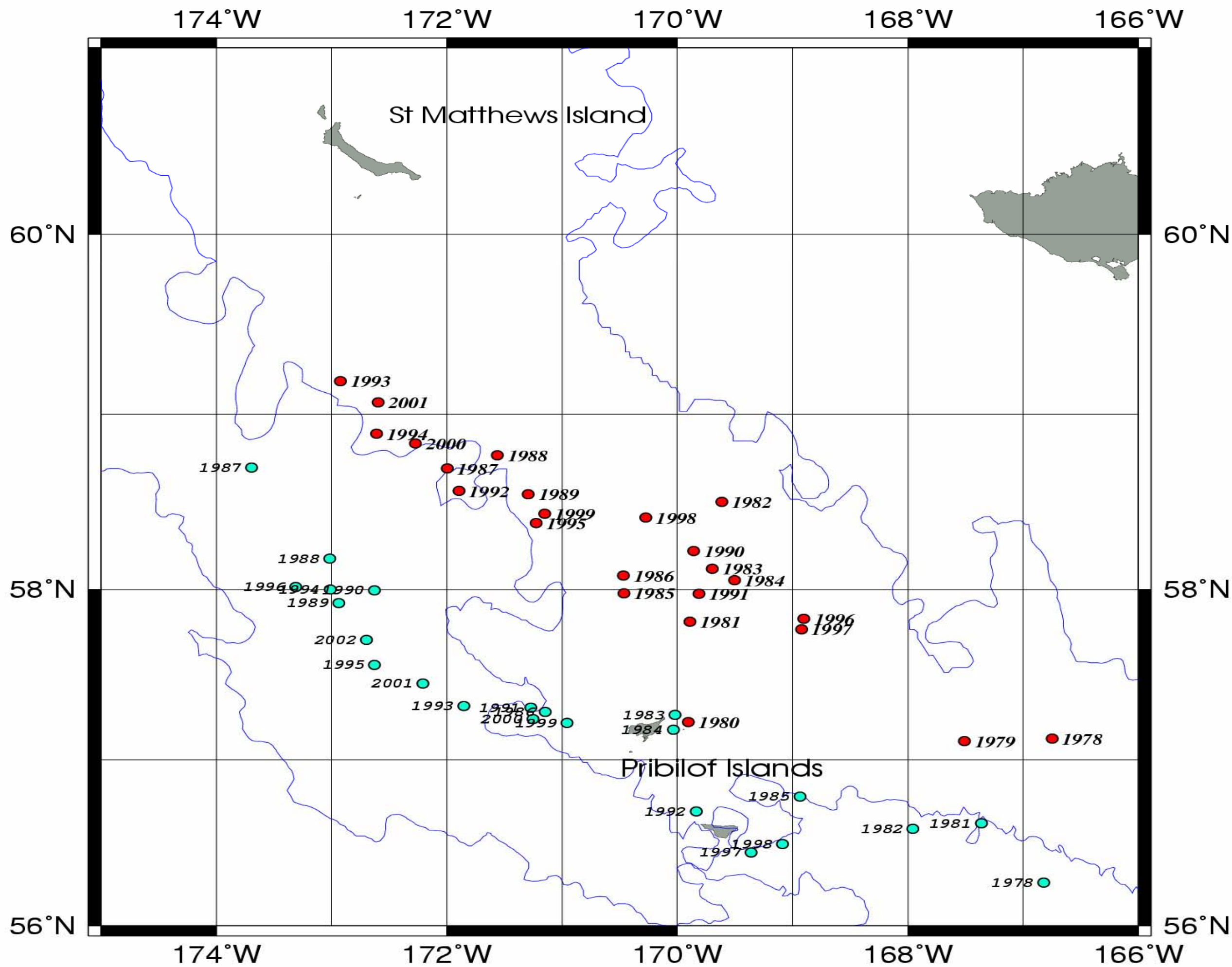

Figure 43. Centroids abundance (numbers) of snow crab males > 101 mm from the summer NMFS trawl survey (red) and from the winter fishery (blue-green).

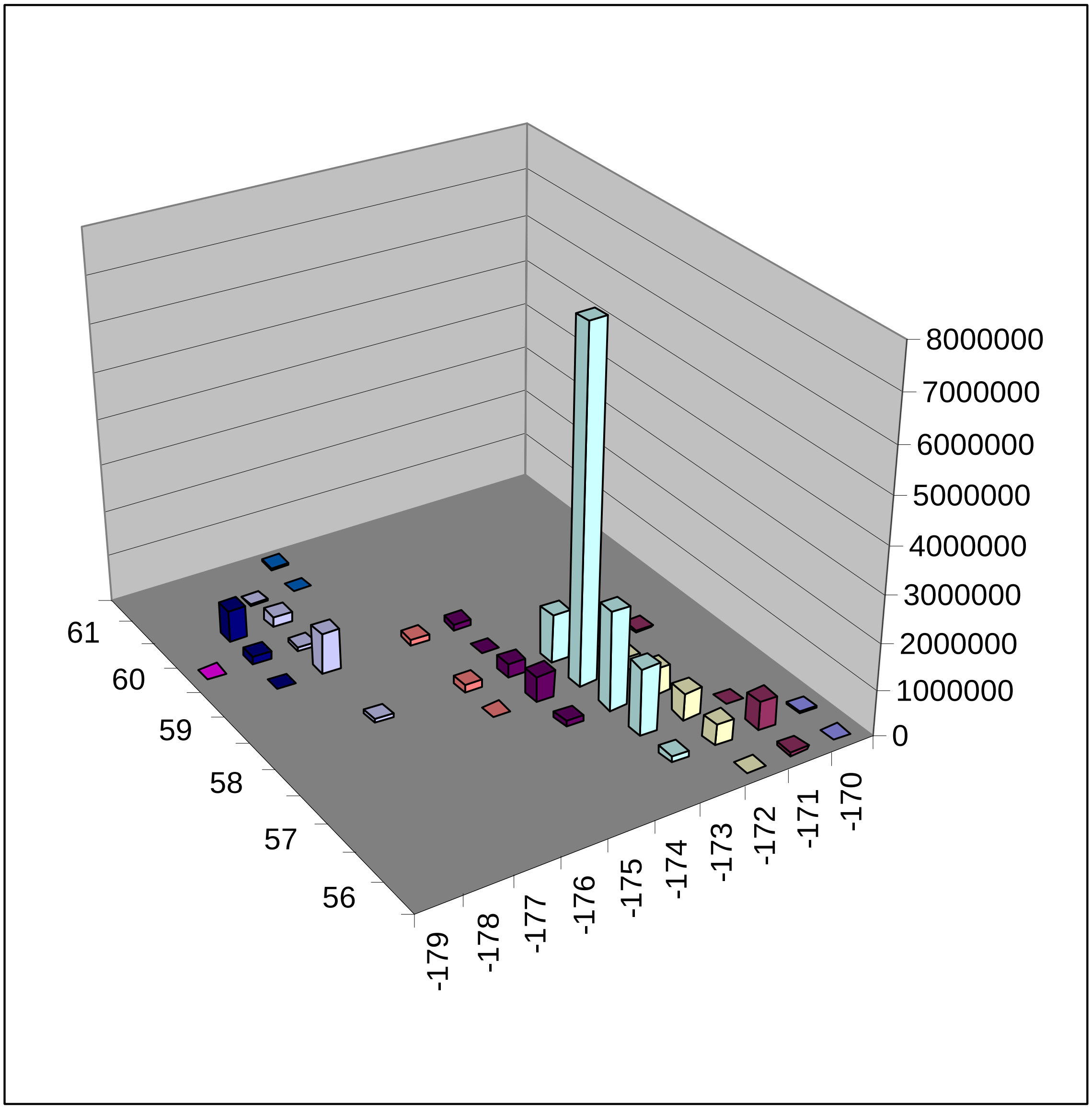

Figure 44. 2004 pot fishery retained catch in numbers by statistical area. Longitude in negative degrees. Areas are 1 degree longitude by 0.5 degree latitude.

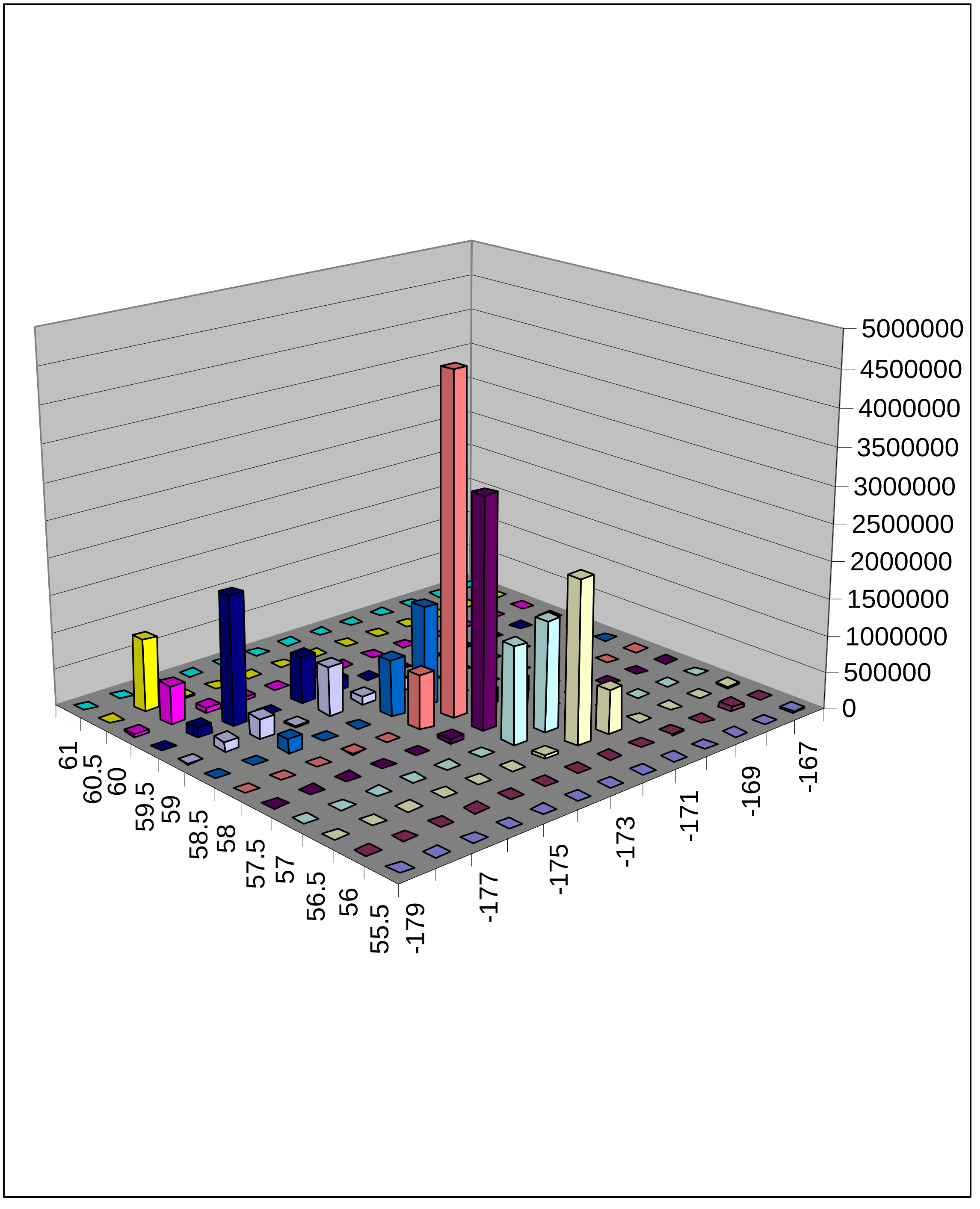

Figure 45. 2003 pot fishery retained catch in numbers by statistical area. Longitude in negative degrees. Areas are 1 degree longitude by 0.5 degree latitude.

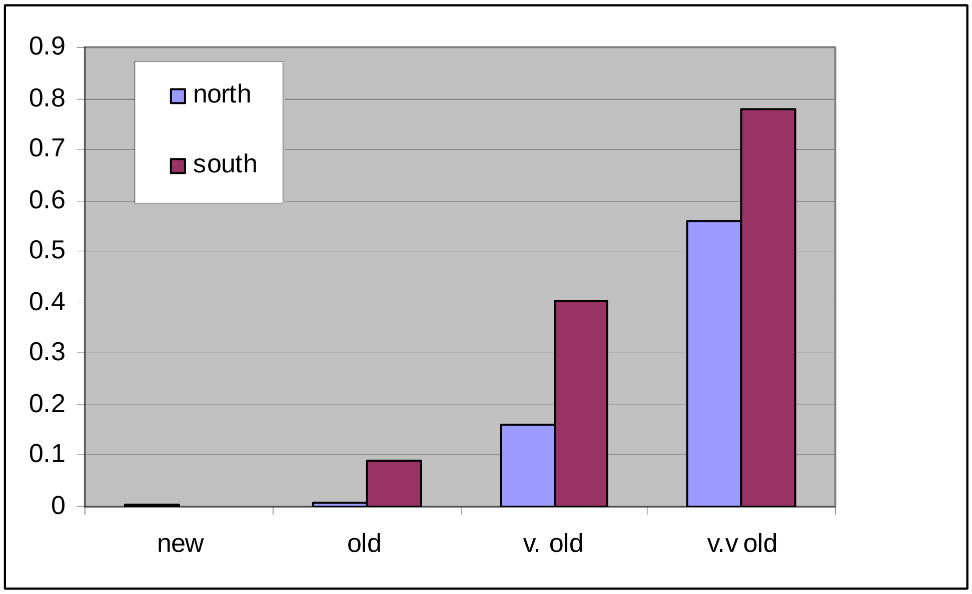

Figure 46. Fraction of barren females in the 2004 survey by shell condition and area north of 58.5 deg N and south of 58.5 deg N.

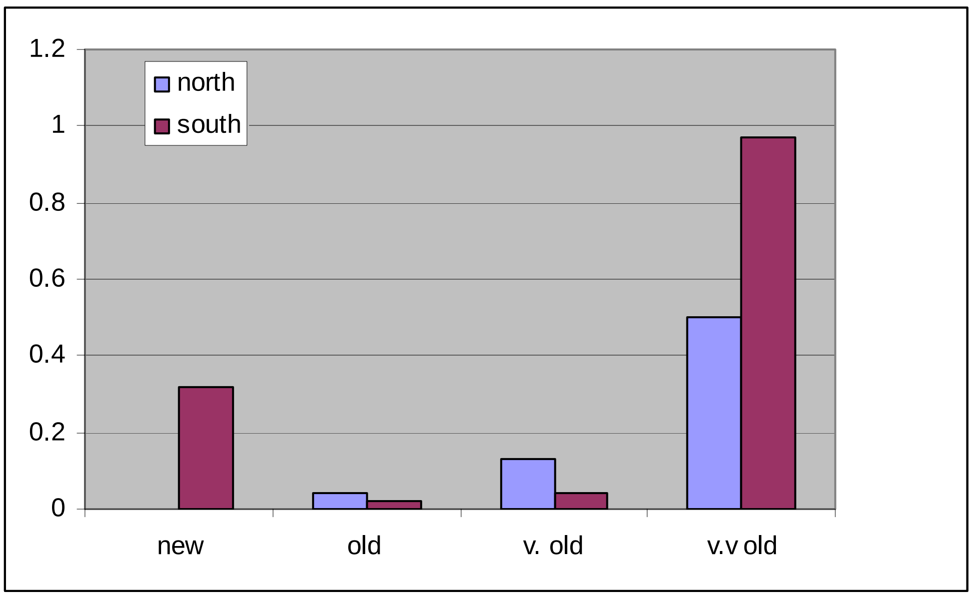

Figure 47. Fraction of barren females in the 2003 survey by shell condition and area north of 58.5 deg N and south of 58.5 deg N. The number of new shell mature females south of 58.5 deg N was very small in 2003.

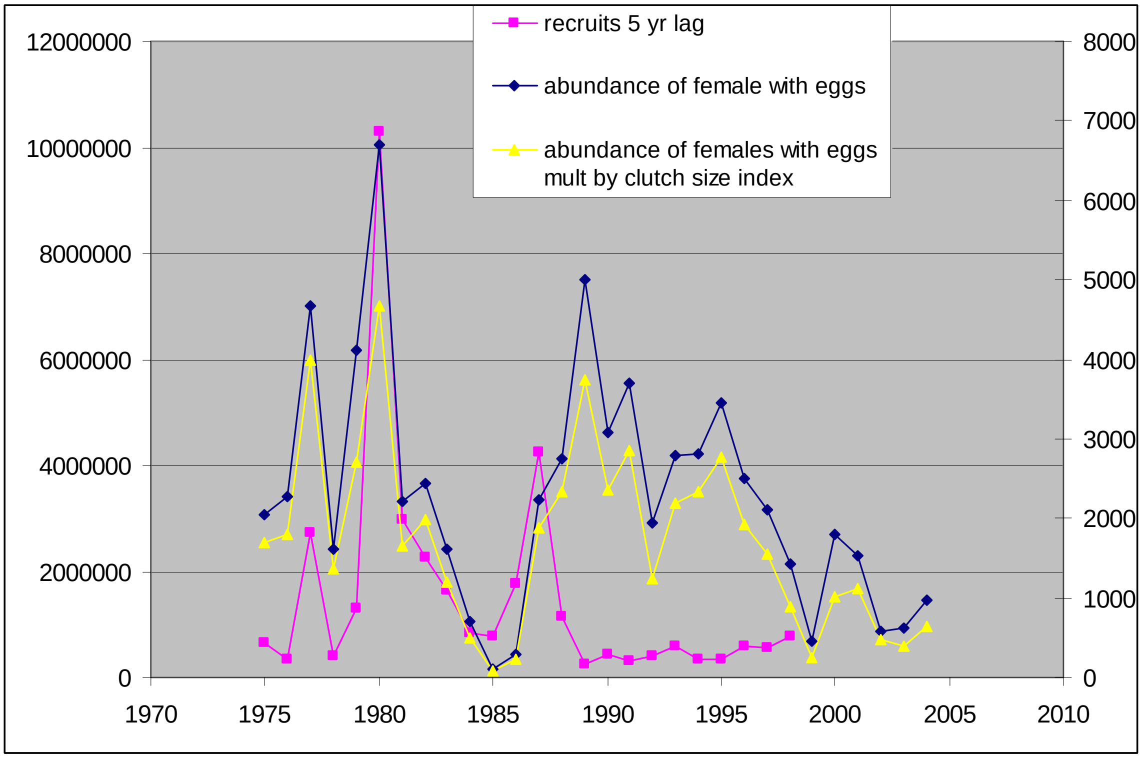

Figure 48. Model estimates of recruitment (fertilization year), survey abundance of females with eggs, and abundance of females with eggs multiplied by the fraction of full clutch from 1975 to 2004.

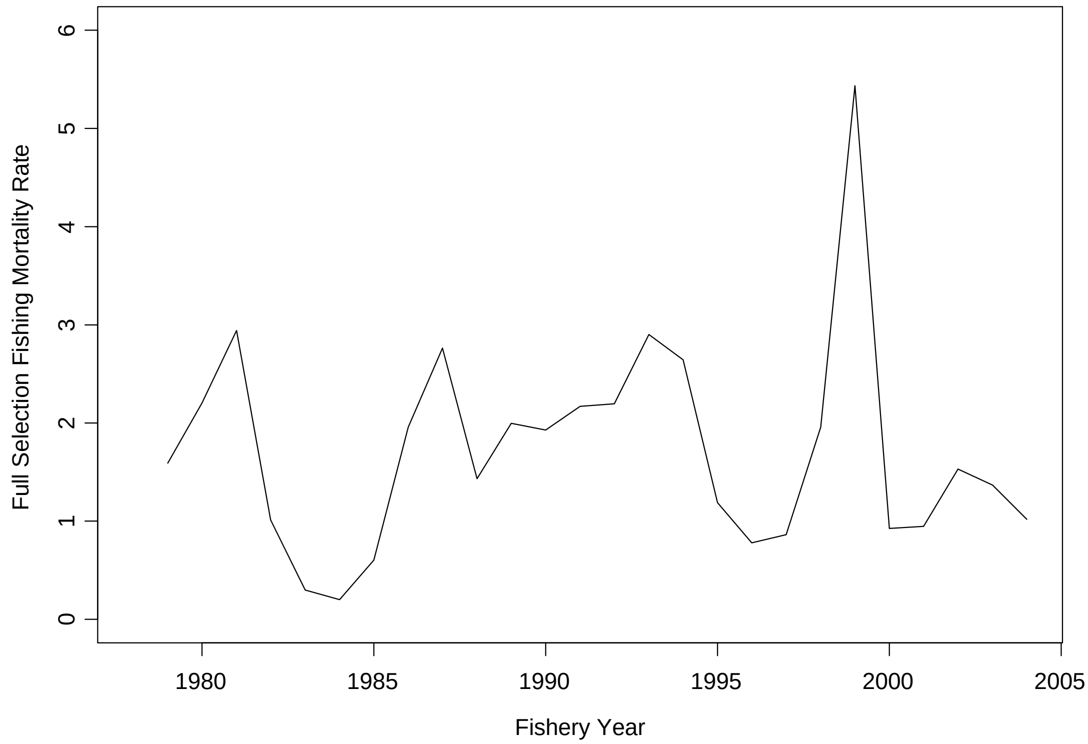

Figure 49. Full selection fishing mortality estimated in the model from 1978 to 2004.

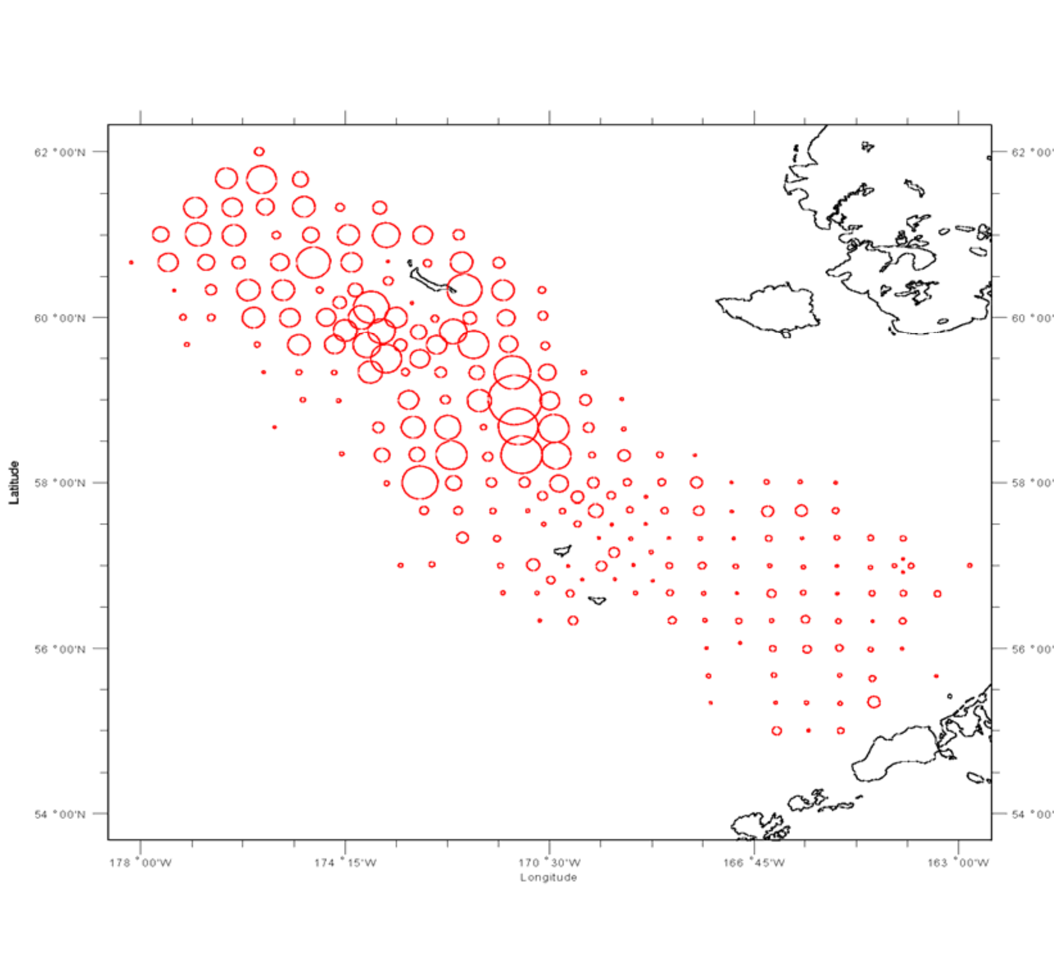

Figure 50. Survey abundance of males > 79 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle (not on same scale as female abundance in Figure 51).

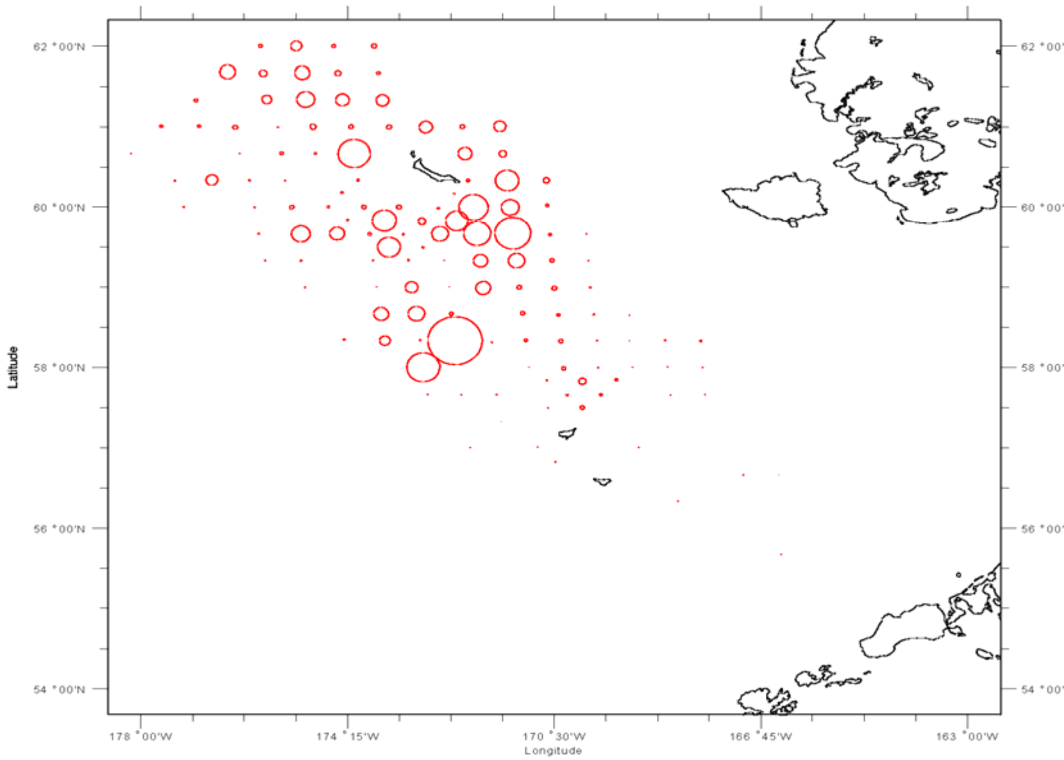

Figure 51. Survey abundance of females > 49 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle (not on the same scale as male abundance in Figure 50).

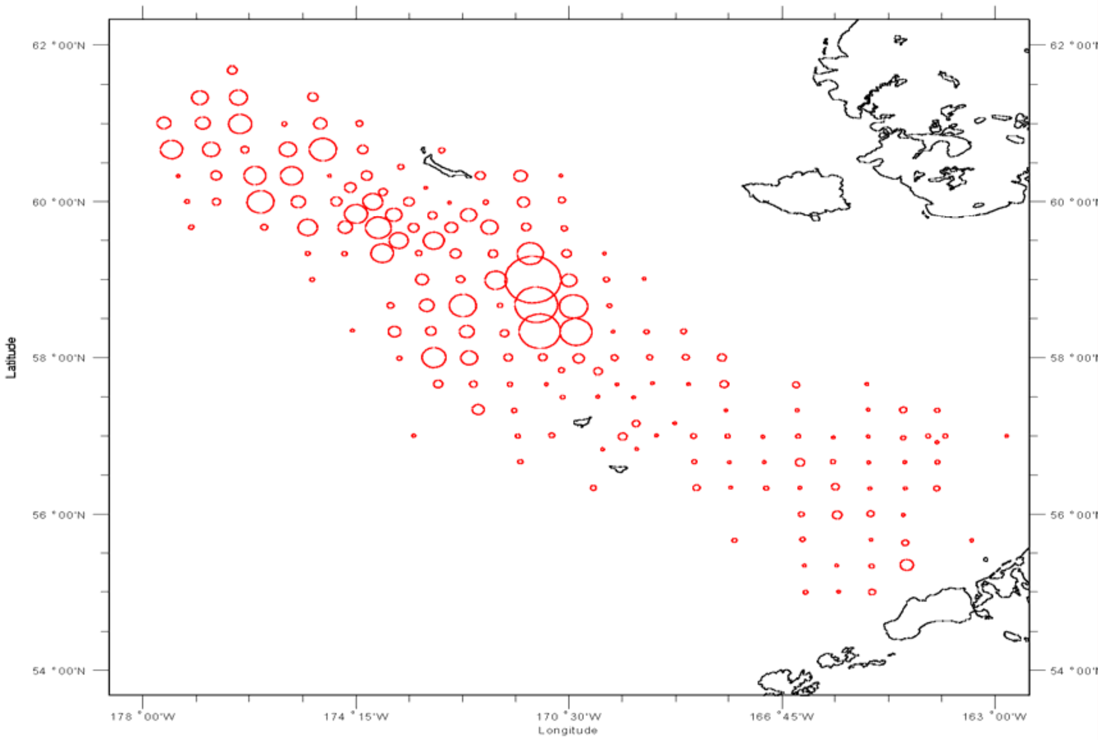

Figure 52. Survey abundance of males > 101 mm by tow. Abundance is proportional to the area of the circle.

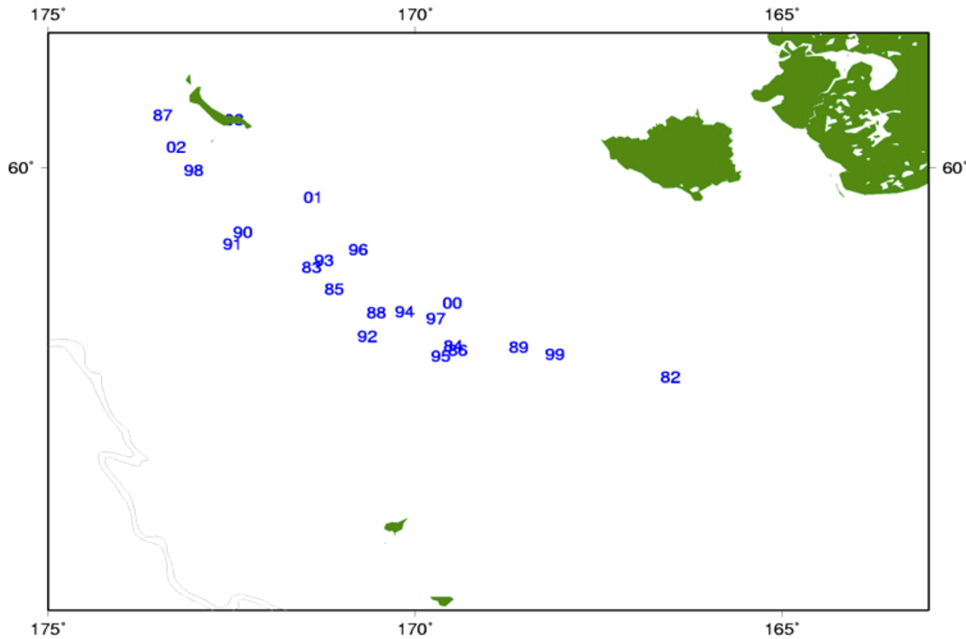

Figure 53. Centroids of cold pool (<2.0 deg C). Centroids are average latitude and longitude.

Appendix A.

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

$N_{s,t,1} = R_{s,t} = R_{0,s} e^{\tau_{s,t}}$	$\tau_{s,t} \sim N(0,\sigma_R^2$	Recruitment
TOTAL POT CATCH $C_{t,totalpotfishery,s,sh,l} = \sum_{mature,immature} \frac{F_{s,totalpotfishery,mat,sh,t,l}}{F_{s,mat,sh,t,l}} (1-e^{-F_{s,mat,sh,t,l}}) e^{-M_{s,mat,sh} Cmid_t} N_{s,mat,sh,t,l}$ RETAINED POT CATCH $C_{t,retainedfishery,s,sh,l} = \sum_{mature,immature} \frac{F_{s,retainedfishery,mat,sh,t}}{F_{s,mat,sh,t,l}} (1-e^{-F_{s,mat,sh,t,l}}) e^{-M_{s,mat,sh} Cmid_t} N_{s,mat,sh,t,l}$ TRAWL BYCATCH $C_{t,trawlfishery,s,sh,l} = \sum_{mature,immature} \frac{F_{s,ftrawlfishery,mat,sh,t,l}}{F_{s,mat,sh,t,l}} (1-e^{-F_{s,mat,sh,t,l}}) e^{-M_{s,mat,sh} Cmid_t} N_{s,mat,sh,t,l}$	$1 \le t \le$ $1 \le l \le$	Catch taken as a pulse fishery at midpoint of catch(survey is considered start of the year).
$Nimmature_{new,t+1,s,l+1} =$ $(Nimmature_{new,t,s,l} e^{-Zimmat_{new,t,s,l}}) Gr_{s,l} (1-\phi_{s,l})$ $Nmature_{new,t+1,s,l+1} =$ $(Nimmature_{new,t,s,l} e^{-Zimmat_{new,t,s,l}}) Gr_{s,l} (\phi_{s,l})$ $Nmature_{old,t+1,s,l+1} =$ $(Nmature_{new,t,s,l} e^{-Zmat_{new,t,s,l}}) + (Nmature_{old,t,s,l} e^{-Zmat_{old,t,s,l}})$	$1 \le t < T$ $1 \le l \le$	Numbers at size
$SB_{t,s} = \sum_{l=1}^{L} w_{s,l} (Nmature_{new,t,s,l} + Nmature_{old,t,s,l})$		spawning biomass by sex

Table A.1. continued.

$Z_{t,s,sh,l} = \sum_{fishery} F_{t,fishery,s,sh,l} + M$			Total Mortality
$C_{t,fishery} = \sum_{s}\sum_{sh}\sum_{l} C_{t,fishery,s,sh,l}$			Total Catch in numbers
$p_{t,sh,l} = C_{t,sh,l} / C_t$			proportion at size in the catch
$Y_t = \sum_{l=1}^{L} w_{t,l} C_{t,l}$			Catch biomass
$F_{t,fishery,s,sh,l} = s_{t,s,sh,l} F_{t,fishery}$			Fishing mortality
$F_{t,s,sh,l} = \sum_{fishery} F_{t,fishery,s,sh.l}$			Total F over all fisheries (total pot and trawl fisheries)
$S_{t,s,sh,l} = \frac{1}{1+e^{-a_{s,sh}(l-b_{t,s,sh})}}$			Fishery selectivity for total catch sex or shell condition s and size bin l. The 50% parameter changes over time.
$S_{male,t,sh,l} = \frac{1}{1+e^{-a_{male,sh}(l-b_{t,male,sh})}} \frac{1}{1+e^{-c_{sh}(l-d_{sh})}}$			Fishery selectivity for male retained catch by shell condition sh and size bin l is the selectivity for total catch multiplied by the retention curve

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
$MP_l = 1 - \frac{1}{1+e^{-a(l-b)}}$			Declining logistic for Molting probability by size
$SB_{s,t} = \sum_{s} \sum_{l=1}^{L} w_{s,l} s_{surv,l} N_{s,t,l}$			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 $\tau_{s,t} \sim N(0,\sigma_R^2)$
$\lambda\sum_{t}\left[\log(\frac{R_{male,t}}{R_{female,t}})\right]^2$	Sex ratio penalty
$\lambda\sum_{t=1}^{t=T-1}\left[\log(s_{50\%,sh,t+1}) - \log(s_{50\%,sh,t})\right]^2$	Constraint on size at 50% for fishery selectivity

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 2003
L	number of size classes (L =22)
W_l	mean body weight(kg) of crabs in size group l.
ϕ_l	proportion 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
$C_{t,l}$	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
$F_{t,s,sh,l}$	Instantaneous fishing mortality rate for size group l, sex s, shell condition sh, 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. There were 213 total parameters estimated in the model.

Parameter	Description
$\log(R_0)$	log of the geometric mean value of recruitment, one parameter
τ_t $1978 \le t \le 2002$, 25 parameters for each sex.	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 $1978 \le t \le 2002$, 25 parameters, one set for retained catch, one set for female discard, and one set for trawl bycatch equals 75 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(2 parameters new shell, 2 parameters old shell)	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(2 parameters male, 2 parameters female)	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
Size at 50% selected for fishery new and old shell 1978 to 2002, 2*25 paramaters plus 2 means	Changing fishery selectivity over time

Table A.5. Fixed parameters in the Admodel builder model.

Parameter	Description
M	Natural mortality
Q = 1.0 for 1982 to present surveys	Survey catchability
Parameters for the linear growth function, intercept a and slope b (2 parameters male, 2 parameters female). Standard deviation of size at the first size bin and standard deviation of size for the last size bin.	Growth parameters estimated from Bering sea snow crab data (14 observations).
Slope and 50% parameters of the declining logistic curve	molting probabilities for immature male crabs