Length-Based Stock Assessment Model of eastern Bering Sea Tanner Crab

Louis J. Rugolo and Benjamin J. Turnock
National Marine Fisheries Service
Alaska Fisheries Science Center
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Background

We report on the current status and performance of the Tanner crab stock assessment model (TCSAM). The TCSAM was presented for review at the Crab Modeling Workshop (Martel and Stram 2011), to the SSC in March 2011 and to the CPT in May 2011. Review findings and recommendations for model development from the Workshop, SSC and CPT are found in their respective meeting reports. The model has been extensively revised since the May 2011 CPT meeting. A section of this report will be devoted to the developments in the TCSAM since May 2011in accordance with recommendations of the CPT, SSC and Crab Modeling Workshop, which was reported in Rugolo and Turnock (2011)

We present the model to the CPT to consider its suitability for stock assessment and the rebuilding analysis. We formulated several model configurations to show the effects of principal changes to the model, and recommend a *Base Model* that attends to virtually all of the recommendations of the Crab Modeling Workshop, the SSC and plan team. The model is significantly improved over earlier intermediate versions seen by the Crab Modeling Workshop and SSC in March 2011, and by the CPT in May 2011. We propose that the *Base Model* currently represents the best available science, and a level of performance in modeling stock and fishery dynamics that may be acceptable to status of stock determination, OFL-setting and projection analysis. If the model is approved by the CPT in May 2012 and SSC in June 2012, it will apply to OFL-setting and stock status determination in the 2012/13 assessment cycle. If approved by the CPT and SSC in September 2011, it may be used in the analysis underlying the Tanner crab rebuilding plan.

Summary Overview

We formulated a length-based assessment model for Tanner crab to characterize the performance of the stock and to serve in estimating overfishing definitions. The model was initiated in 1950 to estimate recruitments to build the stock to fit initial observed survey biomass and length frequency estimates starting in 1974. Thirty-two 5mm length bins from the 25-29 mm bin to a cumulative plus-group bin at 180-184 mm are modeled. Fishery-independent estimates of biomass, population metrics and length frequency distributions used in the analysis were from NMFS trawl survey data for 1974-2011. We estimated biological characteristics of male and female crab such as weight-length relationships, maturity schedules and growth functions from extant survey and experimental data, and from the literature to complete model parameterization where necessary. All component fishery-dependent data on Tanner crab were employed. Retained catch data in the domestic and foreign fisheries were available for 1965-2010. Retained male length-frequency by shell condition (1981-2011) and discard length frequency (1991-2011) for male and female crab in the directed fishery were incorporated. Sex-specific length frequencies of discarded crab in the snow crab and Bristol Bay red king pot fisheries (1989-2011), and from groundfish fisheries (1973-2011) were used to characterize non-directed stock losses and fishery

performance. Mature male biomass at the nominal time of mating is the population metric used to gauge stock status relative to the limit reference point (B_{MSY} or proxy B_{MSY}) and to derive the overfishing limit (F_{OFL}) from the control rule. Male and female survey selectivity were estimated for three time periods (1974-1981, 1982-1987 and 1988-2011) to address evolving survey design and gear changes. Survey catchability was estimated for both sexes in all three periods. In the third period, a prior on Q of 0.88 was used to inform male and female selectivity based on the net selectivity experiment on Tanner crab (Somerton and Otto 1999). Fishery selectivity curves for the directed and all non-directed fleets were estimated for males and females over various periods. Post-release mortality for the pot discarded crab was set at 50%, and that for trawl discards set at 80%. Population dynamics in the model are separated by maturity status, shell condition class and sex. Estimated survey mature biomass is fit to observed mature biomass by sex, and survey length frequency is fit to immature and mature crab separately for each sex for the combined shell condition class. Model performance is evaluated by the fit to observed survey and fishery data. $B_{35\%}$ can be derived using model estimates of MMB over the reference period 1974-1980 representing the proxy B_{MSY}, or as the product of mean recruitment which gave rise to the reference biomass and spawning biomass per recruit fishing at $F_{35\%}$. The performance of the Tanner crab stock over the period of record has experienced a one-way trip from high biomass levels early-1970s to exceedingly low levels in the 1980s. The stock was under a rebuilding plan from 1999-2007, and the fishery closed in 1985-1986, 1997-2004 and 2011 due to conservation concerns. The eastern Bering Sea Tanner crab was declared overfished by NOAA Fisheries in 2010. A rebuilding plan must be implemented in 2012 for the 2012/13 fishing season.

A. INTRODUCTION

Tanner crab *Chionoecetes bairdi* is one of five species in the genus *Chionoecetes*. The common name for *C. bairdi* of "Tanner crab" (Williams et al. 1989) was recently modified to "southern Tanner crab" (McLaughlin et al. 2005). Prior to this change, the term "Tanner crab" has also been used to refer to other members of the genus, or the genus as a whole. Hereafter, the common name "Tanner crab" will be used in reference to "southern Tanner crab".

Tanner crabs are found in continental shelf waters of the north Pacific. In the east, their range extends as far south as Oregon (Hosie and Gaumer 1974) and in the west as far south as Hokkaido, Japan (Kon 1996). The northern extent of their range is in the Bering Sea (Somerton 1981a) where they are found along the Kamchatka peninsula (Slizkin 1990) to the west and in Bristol Bay to the east.

In the eastern Bering Sea (EBS), the Tanner crab distribution may be limited by water temperature (Somerton 1981a). *C. bairdi* is common in the southern half of Bristol Bay, around the Pribilof Islands, and along the shelf break, although sub-legal sized males (≤138 mm cw) and ovigerous and immature females of all sizes are distributed broadly from southern Bristol Bay northwest to St. Matthew Island (Rugolo and Turnock 2011a). The southern range of the cold water congener the snow crab, *C. opilio*, in the EBS is near the Pribilof Islands (Turnock and Rugolo 2011). The distributions of snow and Tanner crab overlap on the shelf from approximately 56° to 60°N, and in this area, the two species hybridize (Karinen and Hoopes 1971).

1. Stock Structure

Tanner crabs in the EBS are considered to be a separate stock distinct from Tanner crabs in the eastern and western Aleutian Islands (NPFMC 1998). The unit stock is that defined across the geographic range of the EBS continental shelf, and managed as a single unit (Figure 1). Somerton (1981a) suggests that clinal differences in some biological characteristics may exist across the range of the unit stock. These conclusions may be limited since terminal molt at maturity in this species was not recognized at the time of that analysis, nor was stock movement with ontogeny considered. Biological characteristics estimated

based on comparisons of length frequency distributions across the range of the stock, or on modal length analysis over time may be confounded as a result.

Despite the custom of setting management controls for this stock east and west of 166° W longitude, the unit stock of Tanner crab in the EBS comprises crab throughout the geographic range of the NMFS bottom trawl survey. We found no evidence that the EBS shelf is member to two distinct, non-intermixing, non-interbreeding stocks that can be assessed and managed separately.
Given understanding of the fidelity of the stock over its range and its availability to the fisheries, partitioning the total catch OFL may be possible to allow setting TACs or issuing of IFQs for the eastern and western area fisheries consistent with the total catch OFL.

B. FISHERY HISTORY

1. Management Unit

Fisheries have historically taken place for Tanner crab throughout their range in Alaska, but currently only the fishery in the EBS is managed under a federal fisheries management plan (NPFMC 1998). The plan defers certain management controls for Tanner crab to the State of Alaska (SOA) with federal oversight (Bowers et al. 2008). The state manages Tanner crab based on registration areas divided into districts. Under the plan, the state can adjust or further subdivide districts as needed to avoid overharvest in a particular area, change size limits from other stocks in the registration area, change fishing seasons, or encourage exploration (NPFMC 1998).

The Bering Sea District of Tanner crab Registration Area J (Figure 1) includes all waters of the Bering Sea north of Cape Sarichef at 54° 36' N lat. and east of the U.S.-Russia Maritime Boundary Line of 1991. This district is divided into the Eastern and Western Subdistricts at 173° W longitude. The Eastern Subdistrict is further divided at the Norton Sound Section north of the latitude of Cape Romanzof and east of 168° W longitude and the General Section to the south and west of the Norton Sound Section (Bowers et al. 2008).

In March 2011, the Alaska Board of Fisheries approved a new minimum size limit strategy for Tanner crab effective for the 2011/12 fishery. The previously minimum legal size limit was 5.5" (138 mm cw) throughout the Eastern Subdistrict. The new regulations established different minimum size limits east and west of 166° West longitude. That for the fishery to the east will be 4.8" (122 mm cw), and that to the west will be 4.4" (112 mm cw). The industry may self-impose retention of crab above 5.5" (138 mm cw) and 5" (127 mm cw) east and west of 166° West longitude, respectively.

The domestic Tanner crab pot fishery rapidly developed in the mid-1970s (Table 1, Figure 2). For stock biomass and fishery data tabled in this document, we adopt the convention that 'year' refers to the survey year (t), and fishery data are those subsequent to the survey (t+1) through prior to year t+1 – e.g., 2008/09 is the 2008 summer survey and the winter 2009 fishery. Other notation is explicit. United States landings were first reported for Tanner crab in 1968 at 0.46 thousand t taken incidentally to the EBS red king crab fishery (Table 1). Tanner crab was targeted thereafter by the domestic fleet and landings rose sharply in the early-1970s, reaching a high of 30.21 thousand t in 1977 (Table 1, Figure 2). Landings fell precipitously after the peak in 1977 through the early 1980s, and domestic fishing was closed in 1985 and 1986 due to depressed stock status. In 1987, the fishery reopened and landings rose again in the late-1980s to a second peak in 1990 at 18.19 thousand t, and then fell sharply through the mid-1990s. The domestic Tanner crab fishery closed between 1997 and 2004 as a result of conservation concerns regarding depressed stock status. The domestic Tanner crab fishery re-opened in 2005 and has averaged 0.77 thousand t retained catch between 2005-2009/10 (Table 1). Landings of Tanner crab in the Japanese pot and tangle net fisheries were reported between 1965-1978, peaking at 19.95 thousand t in 1969. The Russian tangle net fishery was prosecuted between 1965-1971 with peak landings in 1969 at 7.08

thousand t. Both the Japanese and Russian Tanner crab fisheries were displaced by the domestic fishery by the late-1970s (Table 1, Figure 2).

For the 2010/11 fishery, the SOA closed directed commercial fishing for Tanner crab. The SOA's harvest strategy for opening the fishing is 21 million pounds (9.5 thousand t) of mature female biomass in the Eastern Subdistrict at the time of the survey. The 2010 survey estimate of total mature female Tanner crab biomass was 15.1 million pounds (6.8 thousand t).

Discard and bycatch losses of Tanner crab originate from the directed pot fishery, non-directed snow crab and Bristol Bay red king crab pot fisheries, and the groundfish fisheries (Table 3). Discard mortalities 2were estimated using post-release handling mortality rates (HM) of 50% for pot fishery discards and 80% for groundfish fishery bycatch (NPFMC 2008). The pattern of total discard/bycatch losses is similar to that of the retained catch (Table 1). These losses were persistently high during the early-1970s; a subsequent peak mode of discard losses occurred in the early-1990s. In the early-1970s, the groundfish fisheries contributed significantly to total bycatch losses, although the combined crab pot fisheries are the principal source of contemporary non-retained losses to the stock. Tanner crab predicted (*Base Model*) retained catch plus non-directed losses of males and females (Table 6, Figure 12) reflect the performance patterns in the directed and non-directed fisheries. Total male catch rose sharply with fishery development in the early-1960s and reveals a bimodal distribution between 1965 and 1980 (Figure 12). Total male catch rose sharply after the directed domestic fishery reopened in 1987 and reached a peak of 40.08 thousand t in 1990. Total male and female catch fell sharply thereafter with the collapse of the stock and the fishery closure in 1997.

After the Tanner crab stock declined to low levels by the early-1980s, retained catches were low and variable. Since the re-opening in 2005, retained catch has routinely been below the total catch OFL. A specialized directed Tanner crab fishery has not developed since 2005 due to low quota sizes, and the majority of catch is taken incidentally in the Bristol Bay red king crab fishery and the snow crab fishery that hold Tanner shares. After the development of the domestic fleet in late-1970s, the contribution to total catch from a specialized directed fleet versus incidental catch by the snow and red king crab fisheries is not well understood and, unlike the snow crab and Bristol Bay red king crab fisheries with defined fishing practices (e.g., seasons, areas and gear), the current directed Tanner crab fishery is much less defined.

2. Exploitation Rates

The historical patterns of fishery exploitation on legal male biomass (LMB) and male mature biomass (MMB) were derived. The exploitation rate on LMB was estimated as the predicted retained catch biomass divided by the estimated legal male biomass at the time of the fishery, while that on MMB as the predicted total catch biomass (retained plus discard) divided by the estimated male mature biomass at the time of the fishery. The patterns of exploitation rates on LMB and MMB are similar over the period of record, 1969-2011 (Figure 13). Exploitation rates were high in the late-1970s to early-1980s and fell with stock condition through the mid-1980s, followed by a second period of prominent rates during the early-1990s. The pattern of fishery exploitation of this stock coincides with the modes of high catches in the late-1970s and the early-1990s. Exploitation rate on MMB and full-selection F peaked 0.45 and 1.45 in 1980 respectively, and closely followed the buildup of the second mode of biomass during the late-1980s to early-1990s. These high rates of exploitation on MMB and LMB exceed the mortality at M=0.23 for this stock; the EBS Tanner crab stock did not persist at sustainable levels subjected to these rates. Rugolo and Turnock (2011a) discuss the history of exploitation rates on the male Tanner crab stock based on observed survey data and conclude that these exceeded rates would be deemed biologically reasonable, and led to the erosion of stock biomass. Exploitation rates on mature and legal male biomass since the start of the rebuilding plan in 1998 have approximated 5-10% (Figure 13).

C. DATA

1. The Survey

The NMFS conducts an annual trawl survey in the EBS to determine the distribution and abundance of commercially-important crab and groundfish fishery resources (Chilton et al. 2011). The survey has been conducted since 1968 by the Resource Conservation and Engineering (RACE) Division of the Alaska Fisheries Science Center. In 1975, it was expanded into Bristol Bay and the majority of the Bering Sea continental shelf. Since 1988, 376 standard stations have been included in the survey covering a 150,776 nm^2 area of the EBS with station depths ranging from 20 to 150 meters depth. The annual collection of data on the distribution and abundance of crab and groundfish resources provides fishery-independent estimates of population metrics and biological data used for the management of target fishery resources. Crustacean resources targeted by this survey are red king crab (*Paralithodes camtschaticus*), blue king crab (*P. platypus*), hair crab (*Erimacrus isenbeckii*), Tanner crab (*Chionoecetes bairdi*) and snow crab *(C. opilio*). The sampling methodology specifies the majority of tows made at the centers of squares defined by a 20 x 20 nmi (37 x 37 km) grid (Chilton et al. 2011). Near St. Matthew Island and the Pribilof Islands, additional tows are made at the corners of squares that define high density sampling strata for blue king crab and red king crab.

The 83-112 eastern otter trawl (83 ft/25.3 m headrope and 112 ft/34.1 m footrope) has been the standard gear since 1982. Each tow is approximately 0.5 h in duration towed at 3 knots conducted in accordance with established NMFS groundfish bottom trawl protocols (Stauffer 2004). Between 1968-1981, the 400 eastern otter trawl was the survey gear deployed and towed for approximately 1.0 h at 2.0 knots. Crabs are sorted by species and sex, and then a sample of the catch measured to the nearest millimeter to provide a size-frequency distribution. Derived population metrics are indices of relative abundance and biomass and do not necessarily represent absolute abundance or biomass. They are most precise for large crabs, and are least precise for small crabs due to gear selectivity, and for females of some stocks due to behavior.

2. Data Sources

Estimates of Tanner crab stock biomass, population metrics and length frequencies from the trawl survey used in this assessment were based on area-swept calculations using measured net width spreads for 1974-2011. As recommended by the Crab Workshop (Martel and Stram 2011), 1969-1973 survey data are excluded from the analysis. The pre-1974 survey did not consistently sample Tanner habitat which resulted in variable and biased low biomass estimates and length frequency distributions. Each year from 1969-1973 represented a unique coverage ranging from 25% to 72% of the total Tanner distribution sampled since 1978 (Foy, pers. comm.). The male and female 5 mm length frequency abundance observed in the survey for 1969-2011 are shown in Figure 3 and Figure 4, respectively.

Size frequency data on retained Tanner crab in the directed fishery from 1981-1996 and 2005/06 to 2010/11 seasons were used in the analysis. Observers were placed on board directed crab vessels starting in 1990, and dockside sampling of the retained catch began in 1981. Length frequency data on the total catch and the retained catch in the directed fishery were available from 1991-2010/11 and 1981-2010/11 absent fishery closures. Retained catch data were available for 1974-2010/11. Total discard catch biomass was estimated from observer data from 1991 to 2010/11. The discard male catch was estimated from 1969-1990/91 in the model using the estimated fishery selectivity based on observer data from 1991-2010/11 and an applied post-release mortality rate of 50% for pot released crab. Male and female length frequency and catch biomass data in the snow crab fishery were available from 1989-2010/11. Male and female length frequency and catch biomass data in the Bristol Bay red king crab fishery were available from 1989-1993 and 1996-2010/11. Trawl discard catch biomass estimates and the length frequency of discard crab included in the model were from 1973 to 2010/11.

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

Data Component	Years
Retained length frequency by shell condition of male crab in directed fishery	1981-1996, 2005-2010/11
Total catch length frequency of male and female crab in directed fishery	1991/92-1996/97, 2005/06-2010/11
Male and female length frequency and catch in snow crab fishery	1989/90-2010/11
Male and female length frequency and catch in red king crab fishery	1989-1993, 1996-2010/11
Retained catch in directed fishery	1969-2010/11
Trawl discard catch and length frequency	1973-2010/11
Survey length frequency by sex and shell condition	1974-2011
Survey biomass estimates and coefficients of variation	1974-2011

D. LIFE HISTORY

1. Reproduction

In most majid crabs, the molt to maturity is the final or terminal molt. For *C. bairdi*, it's now accepted that both males (Tamone et al. 2007) and females (Donaldson and Adams 1989) undergo terminal molt at maturity. Females terminally molt from their last juvenile, or pubescent, instar usually while being grasped by a male (Donaldson and Adams 1989). Subsequent mating takes place annually in a hard shell state (Hilsinger 1976) and after extruding their clutch of eggs. While mating involving old-shell adult females has been documented (Donaldson and Hicks 1977), fertile egg clutches can be produced in the absence of males by using stored sperm from the spermathacae (Adams and Paul 1983, Paul and Paul 1992). Two or more consecutive egg fertilization events can follow a single copulation using stored sperm to self-fertilize the new clutch (Paul 1982, Adams and Paul 1983), however, egg viability decreases with time and age of the stored sperm (Paul 1984).

Maturity in males can be classified either physiologically or morphometrically. Physiological maturity refers to the presence or absence of spermataphores in the gonads whereas morphometric maturity refers to the presence or absence of a large claw (Brown and Powell 1972). During the molt to morphometric maturity, there is a disproportionate increase in the size of the chelae in relation to the carapace (Somerton 1981a). While many earlier studies on Tanner crabs assumed that morphometrically mature male crabs continued to molt and grow, there is now substantial evidence supporting a terminal molt for males (Otto 1998, Tamone et al. 2007). A consequence of the terminal molt in male Tanner crab is that a substantial portion of the population may never recruit to legal size (NPFMC 2007).

Although observations are lacking in the EBS, seasonal differences have been observed between mating periods for pubescent and multiparous females in the Gulf of Alaska and Prince William Sound. There, pubescent molting and mating takes place over a protracted period from winter through early summer, whereas multiparous mating occurs over a relatively short period during mid April to early June (Hilsinger 1976, Munk et al. 1996, and Stevens 2000). In the EBS, egg condition for multiparous Tanner

crabs assessed between April and July 1976 also suggested that hatching and extrusion of new clutches for this maturity status began in April and ended sometime in mid June (Somerton 1981a).

2. Fecundity

A variety of factors affect female fecundity including somatic size, maturity status (primiparous vs. multiparous), age post terminal molt, and egg loss (NMFS 2004a). Of these factors, somatic size is the most important, with estimates of 89 to 424 thousand eggs for females 75 to 124 mm cw respectively (Haynes et al. 1976). Maturity status is another important factor affecting fecundity with primiparous females being only ~70% as fecund as equal size multiparous females (Somerton and Meyers 1983). The number of years post maturity molt, and whether or not, a female has had to use stored sperm from that first mating can also affect egg counts (Paul 1984, Paul and Paul 1992). Additionally, older senescent females often carry small clutches or no eggs (i.e., barren) suggesting that female crab reproductive output is a declining function of age (NMFS 2004a).

The fraction of barren mature females by shell condition (Figure 5) and the fraction of mature females with clutches one-half full or less by shell condition (Figure 6) are shown. After 1991, 20-40% of new shell females brooded clutches less than or equal to 50% full, and in 2009 this number was approximately 23%. We developed a Egg Production Index (EPI) by female shell condition that incorporates observed clutch size measurements taken on the survey and fecundity by carapace width for 1976-2009 (Figure 7). Figure 7 also presents estimates of male and female mature biomass relative to the shell condition class EPIs in these years. Although male and female mature biomass increased after 2005, egg production does not increase proportionally to mature biomass.

3. Size at Maturity

We estimated the maturity at length schedules for male and female Tanner crab from extant NMFS trawl survey data. For females, egg and maturity code information collected on the survey from 1976-2009 was analyzed to estimate the maturity curves for new shell females, and for the aggregate class of females all shell conditions combined (Figure 8). $SM_{50\%}$ for females all shell classes combined was estimated to be 68.8 mm cw, and that for new shell females was 74.6 mm cw. For males, data from the special collection of morphometric measurements taken to the 0.1 mm in 2008 on the NMFS survey served to derive the classification rules between immature and mature crab based on chela allometry using the mixture-of-two-regressions analysis. We estimated classification lines between chela height and carapace width defining morphometric maturity for the unit Tanner crab stock, and for the sub-stock components east and west of 166^0 W longitude. These rules were then applied to historical survey data from 1990-2007 to apportion male crab to immature and mature population mature at length. We examined and found no significant differences between the classification lines of the sub-stock components (E and W of 166^0 W longitude), or between the sub-stock components and that of the unit stock classification line. $SM_{50\%,}$ for males all shell condition classes combined was estimated to be 91.9 mm cw, and that for new shell males was 104.4 mm cw (Figure 9). By comparison, Zheng (1999) in development of the current SOA harvest strategy used knife-edge maturity at >79 mm cw for females and >112 mm cw for males. The maturity curve for new shell females can be considered to represent the conditional probability of new shell immature females maturing given a representative sample of the length composition in the stock by shell condition class and no error in shell classification. For the *Base Model* run presented here, the probability of maturing by size for males and females was estimated in the model with the constraint to be a smooth function (Figure 14). For comparison, the probability of new shell immature males maturing used by Zheng in the Amendment 24 analysis of overfishing definitions is shown in which $SM_{50\%}$=130.9 mm cw (NPFMC 2007) (Figure 14). We allow the assessment model to estimate a smooth function for both sexes that represents the probability that a new shell immature crab will molt to maturity which is distinguished from the average fraction of new shell mature crabs in the stock.

4. Mortality

Due to the lack of age information, Somerton (1981a) estimated mortality separately for individual EBS cohorts of juvenile (pre-recruit) and adult Tanner crab. Somerton postulated that because of net selectivity, age five crab (mean cw=95 mm) were the first cohort to be fully recruited to the gear; he estimated an instantaneous natural mortality rate of 0.35 for this size class using catch curve analysis. Using this analysis with two different data sets, Somerton estimated natural mortality rates of adult male crab from the fished stock to range from 0.20 to 0.28. When using CPUE data from the Japanese fishery, estimates of M ranged from 0.13 to 0.18. Somerton concluded that M estimates of 0.22 to 0.28 estimated from models that used both the survey and fishery data were the most representative.

We examined empirical evidence for reliable estimates of oldest observed age for male Tanner crab. Unlike its congener the snow crab, information on longevity of the Tanner crab is lacking. We reasoned that longevity in a virgin population of Tanner crab would be analogous to that of the snow crab (Turnock and Rugolo 2011) given the close analogues in population dynamic and life-history characteristics, where longevity would be at least 20 years. Employing 20 years as a proxy for longevity and assuming that this age represents the upper 98.5th percentile of the distribution of ages in an unexploited population if observable, M is estimated to be 0.23 (Hoenig 1983). If 20 years is assumed to represent the 95% percentile of the distribution of ages in an unexploited stock, M is estimated to be 0.15. We adopted M=0.23 for both male and female Tanner crab in this analysis. This value corresponds with the range estimated by Somerton, and to the value used in the analysis to estimate new overfishing definitions which underlie Amendment 24 to the management plan (NPFMC 2007).

In the *Base Model*, we allow the model to estimate M mature male crab, mature female crab, and for immature crab pooled by sex. In model configurations with fixed natural mortality, M=0.23 for immature and mature male and female crab.

5. Growth

We derived growth relationships for male and female Tanner crab using data collected in the Gulf of Alaska near Kodiak (Munk pers. comm., Donaldson et al. 1981). Growth relationships were based on observed growth data for males to approximately 140 mm cw and for females to approximately 115 mm cw (Figure 10). Somerton (1981a) estimated growth for EBS Tanner crab based on modal size frequency analysis of Tanner crab in survey data assuming no terminal molt at maturity. This approach did not directly measure molt increments and Somerton's findings are constrained by not considering that the progression of modal lengths between years was biased since crab ceased growing after their maturity molt. We compared our growth per molt (gpm) relationships with those of Stone et al. (2003) for Tanner crab in southeast Alaska in terms of the overall pattern of gpm over the size range of crab. We found that the pattern of gpm for both males and females is characterized by a higher rate of growth to an intermediate size (90-100 mm cw) followed by a decrease in growth rate from that size thereafter (Figure 10). Such shaped growth curves are corroborated in work of Stone et al. (2003), Somerton (1981), Donaldson et al. (1981) and in the data of Munk. We modeled the relationship between pre-molt and post-molt size for males and females as a two parameter exponential function of the general form $y=ax^b$ where y=post-molt and x=pre-molt carapace width. The fitted growth relationship for males is $y=1.550x^{0.949}$, and that for females is $y=1.760x^{0.913}$.

Weight at Length

We derived weight at length relationships for male, immature female and mature female Tanner crab based on special collections of length and weight data on the summer trawl survey in 2006, 2007 and 2009 (Figure 11). The fitted weight (*kg*)-length (*mm cw*) relationship for males of shell condition classes 2 (SC2) through class 5 (SC5) inclusive is: $W=0.00016(cw)^{3.136}$. Those for immature (SC2) and mature (SC2-SC4) females are, respectively, $W=0.00064(cw)^{2.794}$ and $W=0.00034(cw)^{2.956}$.

E. MODEL DEVELOPMENT

In this section, we present developments in the TCSAM implemented since the May 2011 CPT meeting in accordance with recommendations of the CPT, SSC and Crab Modeling Workshop (Martel and Stram 2011). In the first section, we present comments of the CPT in May 2011 and the SSC in June 2011 on the model. In the second section, we present an annotated outline of the changes to the model since the May 2011 meeting. A separate review document (Rugolo and Turnock 2011b) of model changes including output and diagnostics was submitted to a small group of plan team members in July 2011. The purpose was to provide a preview of the status and performance of the model to elicit criticisms and recommendations for development prior to the September 2011 CPT meeting.

For the *Base Model (0)*, we estimated $B_{35\%}$=162.31 thousand t and $F_{35\%}$=0.574. The model estimate of 2010/11 MMB at mating (53.45 thousand t) represents $0.33B_{35\%}$. The proxy B_{MSY} used in the 2011 SAFE for OFL-setting under Tier-4 is estimated as the average observed MMB at the time of mating from survey data over the reference period 1974-1980 at 83,330 t (Rugolo and Turnock 2011). The bias-corrected proxy B_{MSY} based on adjusted MMB at mating following the method of Rugolo and Turnock (2011c) is 93,240 t. The bias-corrected proxy B_{MSY} is calculated after extraction of the F_{MSY} catch rather than the observed catch which is a more consistent benchmark regardless of whether observed catches were larger or smaller than the F_{MSY} catch. In the 2011 Tier-4 Tanner crab SAFE, Rugolo and Turnock (2011) estimated that after extraction of the total catch OFL, the resulting $MMB_{2011/12}/B_{MSY\ Proxy}$=0.28 using the bias-corrected proxy B_{MSY}, and 0.32 using the non-bias corrected proxy B_{MSY}.

By comparison, the average of the *Base Model(0)* estimated MMB at mating over 1974-1980 is 198,310 t. After extraction of the 2011/12 total catch OFL, the resulting MMB at mating in 2011 = 52,650 t which represents a ratio $MMB_{2011/12}/B_{MSY\ Proxy}$=0.27. This is comparable to the bias-corrected Tier-4 assessment results using the same reference period.

1. Responses to SSC and CPT Comments

June 2011 SSC Meeting

In their review of the 2011 draft crab SAFE report, the SSC made the following comments on eastern Bering Sea Tanner crab:

- *Authors Rugolo and Turnock developed a draft assessment in which they responded to changes suggested by the CPT and SSC in 2010, and to recommendations of the Crab Workshop (February 2011) and the SSC in April 2011. The CPT was encouraged by the changes and felt progress was being made, although the model is not yet ready for use in the stock assessment. The strategy is to continue improvements and evaluate it for assessment purposes in May 2012. Following a recommendation from the Crab Workshop, years 1969 through 1974 were not used for data quality reasons. The period 1974 through 1980 is now the period used for determining reference biomass; given the shortness of this period, the SSC recommends strongly that this time period be evaluated as intended by the authors.*
- *The main issues that have arisen in past (model) reviews were discussed:*
  - *Hybrids: concerned that misidentification of hybrids might have degraded data quality. However only 1 hybrid has been seen in the survey in the last 8 years of legal Tanner size. The authors did not think this is a significant issue in recent years.*
  - *Early bycatch data in groundfish fishery - specifically, why is bycatch estimated to be so high in 1973/74 and 1974/75. Concerns raised about misidentification of snow crabs. The authors are examining this issue.*
  - *Patterns in survey length frequency. (See model scenarios below)*
  - *Lack of fit to survey biomass between 1983 and 1987. (See model scenarios below)*
- *The following model scenarios were decided at the CPT meeting:*
  - *Estimate survey catchability, Q, to see if this improves survey biomass fit in mid 1980s.*
  - *Include the underbag data.*

  - *Estimate growth and natural mortality with priors (important since growth data is borrowed from Kodiak).*
  - *Try different selectivity periods based on fishery changes.*
  - *Try dynamic initial biomass estimation.*
- *The SSC agrees with this plan of action.*
- *The CPT would wants to use Tanner model for population projections despite its lack of approval for assessment. The SSC urges caution proceeding in this direction. It's more appropriate that a model is accepted for assessment and then used for the projection. The CPT requested the authors proceed with the rebuilding model for evaluation in September 2011 if it can produce plausible results. Rebuilding scenarios would include no catch, bycatch only, different percentages of $F_{35\%}$, and the SOA harvest strategy. Recruitment scenarios could include random, a spawner-recruit relationship (SRR) model, a SRR with autocorrelation, an SRR with periodic behavior, and others. The SSC will review these scenarios and the performance of the model in September, 2011.*

The TCSAM has been extensively revised since the May 2011 CPT meeting. We formulated several model configurations to show the effects of principal changes to the model, and recommend a *Base Model* that attends to virtually all of the recommendations of the Crab Workshop, the SSC and plan team. The model is significantly improved over earlier intermediate versions seen by the Crab Workshop and SSC in April 2011. In our view, the *Blease Model* represents the best available science and, while imperfect, a level of performance in modeling stock and fishery dynamics that may be acceptable to status of stock determination, OFL-setting and projection analysis. The CPT and SSC will review the model in September 2011. Approval of the model for assessment will be made at the May 2012 CPT and June 2012 SSC meeting under the Council process. If approved, the model will apply to OFL-setting and stock status determination in the 2012/13 assessment cycle.

The potential degradation of the Tanner retained catch by misidentification of hybrid crab was addressed. The early bycatch data in the groundfish fishery was validated. The *Base Model* estimates survey selectivity in the period (1982-1987) to improve survey biomass fit in the mid-1980s. The model estimates growth, natural morality on immature and mature male and female crab, and includes different directed and non-directed fishery selectivity periods to improve model performance.

May 2011 CPT Meeting

In their review of the draft 2011 SAFE, the CPT made the following comments and recommendations. Only comments on the assessment model are included here:

- *On the stock assessment model, the team encourages development and an update on the model in September 2011 focusing on model fits and to move forward as quickly as possible. Suggestions on the model by the team:*
  - *free up Q to address the residual pattern*
  - *include underbag data as it pertains to this assessment*
  - *free up as many parameters (e.g., growth, M) as possible perhaps – e.g., growth data are not from the Bering Sea*
  - *examine length compositions and other data sources to evaluate model fit to the survey data, particularly in the early years.*
  - *consider a large number of selectivity time-blocks to see what the data want, then explore if reasons to justify choices of selectivity time-blocks*
  - *examine dynamic B_0, i.e. what would have happened has the fishery never occurred*
- *The team discussed how to develop and analyze rebuilding plan alternatives in absence of a model. Without an approved assessment model, it's not possible to estimate the required pieces of a rebuilding plan: minimum time to rebuild, target time to rebuild, and harvest rate that would achieve rebuilding in the target time period. Or to evaluate different rebuilding options. The team will develop rebuilding plan alternatives in September 2011 as the structure of the alternatives will be driven by whether the assessment model can be used. The model could be used for initial projection of the time frame to rebuild*

and which can be updated as the model improves. The team recommended going forward with projection model focusing on recruitment; it should be possible to use the model to develop a rebuilding plan if the model is sufficiently close to acceptance in September.

The TCSAM has been extensively revised since the May 2011 CPT meeting and significantly improved over earlier intermediate versions seen by the Crab Workshop, SSC in April 2011 and CPT in May 2011. The CPT will review the model for the purpose of use in stock assessment and the rebuilding analysis. We recommend the *Base Model* as the best available science and a level of performance in modeling stock and fishery dynamics that may be acceptable to assessment and projection analysis. The authors will present the CPT results of a stock projection model run using the *Base Model* configuration as a case example of the utility of the model for rebuilding plan analysis.

In the *Base Model*, survey Q is freed in the three time periods and informed by the results of the underbag study. Male and female growth, and immature and mature male and female natural mortality are estimated. We examined the length compositions and all data to evaluate survey data fit, and modified the model accordingly. We implemented several selectivity time-blocks in the directed and non-directed fisheries to explore data fits and adopted time-blocks as required.

2. Model Development Outline Implemented Since May 2011

We implemented extensive revisions to the model seen by the Crab Modeling Workshop, SSC and plan team through May 2011. Model development addressed the author's identified needs as well as recommendations of these groups which can be found in their respective meeting reports.

Work performed can be grouped into two general categories: a) validation of data inputs to the model – directed and non-directed fishery catch and length composition components, and survey size frequency abundance and biomass estimates; and, b) revisions and extensions to the model code. Here, we present the work in these two categories.

a. Data Validation

Various actions were performed to be certain that all data components input to the model were correct ranging from routine data verification to data development.

i. Directed Fishery - Retained Catch

The directed fishery was closed in 1986-1987 and in 1997-2004 and prosecuted in different seasons over its history. For crab assessments, the CPT has adopted the convention of the biological year from 01 July in year t of the survey through 30 June in year t+1 of the fishery. For example, 2008/09 corresponds to the 2008 survey and the 2009 fishery. The issue was that the historical data notes these years differently with respect to the CPT convention. It was necessary to verify that the sequence of retained catch data was consistent with the biological and fishing years – largely, a house-keeping issue.

For the 1986-1987 closure, the fishery was closed in fishing years 1986 and 1987; the input data file correctly shows these as matching the CPT convention 1985/86 and 1986/87. The fishery was closed again 1997-2004; the data files obtained from the SOA shows these as 1997/98 through 2004/05. We verified that the nominal 1997-2004 closure corresponds to the survey year since fisheries didn't occur in January through March of 1998-2005.

The sequence of data input to the model was correct and consistent with year of the fishery, and unchanged relative to the May 2011 model.

ii. Directed Fishery – Retained Length Frequency Data

The retained length frequency data are derived from the Dockside Sampling Program that samples deliveries. The on-board Observer Program provides retained and not-retained LF data from the directed fishery and non-directed pot fisheries. No 1995 LF data were available from the dockside program. Previously, we used a 'dummy' record for the 1995 LF equal to the 1994 LF as a placeholder until this could be resolved.

For 1995, the on-board observer program contained data at five levels: female discard, new shell male retained, old shell male retained, new shell male not-retained, and old shell male not-retained. These data were for the QT (Western District, 173^0 W longitude) area only. We used the LF for new plus old shell retained males combined as the 1995 data record and set the fishery sample weight to n=1 for this year since these data are for QT area only, and of a different data type – i.e., on-board observer data versus a dockside sample of retained catch.

iii. Directed Fishery – Male Discard Data

[The following applies discussion applies to the directed fishery female discard catch LF, to the snow crab fishery male and female discard catch LF of Tanner crab, and to the Bristol Bay red king crab fishery male and female discard catch LF of Tanner crab. We cover it here in detail then by reference in discussions of other data elements.]

Length composition data are available from the Observer Program for 1991-1996 and 2005-2010. Estimates of total discard catch are available for 1992-1996 and 2005-2010. Previously, 1991 LF data were commented out which we sought to reconcile. We requested and obtained a complete data set of processed Observer Program data for 1991-2010. In recent years, we obtained subsets of these years from different authors, and one goal was to insure that we had a consistent data set generated with consistent protocols. Examination of these data revealed discrepancies in the lengths of male crab designated as being retained or not-retained in the directed fishery. E.g., new shell crab markedly larger than the minimum legal size limit were designated as not-retained, while crab considerably smaller than legal size were coded as retained.

The current "legal" codes in the database are: 0 = sublegal; 1=legal size, legally retained; 2=legal size, not-retained; 3=legal size, illegally retained; and 6=legal size, unknown retained status. There is also a set of sex codes, shell condition codes and missing data codes. The emphasis on the application of these codes evolved over the years and, for the two non-directed pot fisheries in years when the Tanner fishery was closed, there were discrepancies in the designation of a crab with code=1 or 2. The principal issue became one of representativeness of the sublegal and legal designations of the catch, and the ultimate disposition of crab not designated as being retained or not-retained – e.g., codes 0 and 6.

After extensive discussion with the SOA, we made several decisions regarding these data and their use in the model. Firstly, because of uncertainty in the pre-1993 LF data, they may be de-emphasized in model fits. Secondly, we shouldn't seek to resolve the Observer's observed male catch into the five categories (0, 1, 2, 3 and 6) but rather use these data to derive a total catch LF not a discard LF, and modify the logic of the model to fit the total catch LF only from the on-board program. The dockside samples catch deliveries and provides the LF of the retained catch. Lastly, we would develop a new time series of length composition of total male and female catch for 1991-2010. We requested and received a complete set of raw historical data files – i.e., unprocessed into the various categories.

With assistance from the SOA regarding interpretation of the codes for these data, and on changes in the application of these codes over time, we developed R-script, processed the raw data files

and generated 11 years of total catch 5 mm LF for males (old + new shell classes combined) and populated the 'dat' file. We revised the model code to use the new total catch LF versus discard LF and examined various sample size weights for these data with respect to model fit.

iv. Directed Fishery – Female Discard Data

Length composition data are available from the Observer Program for 1991-1996 and 2005-2010. Estimates of total discard catch are available for 1992-1996 and 2005-2010. Previously, 1991 LF data were commented out which we sought to reconcile.

For the reasons discussed in 2.a.iii (Directed Fishery – Male Discard Data), we generated a new 11-year time series of female discard catch 5 mm LF and populated the 'dat' file. Since female discard catch data start in 1992, the model doesn't need to fit the 1991 discard LF so, set n=1 for sample weight in 1991.

v. Snow Crab Fishery Discard Data

Both male and female Tanner crab discard LF data were available for 1991-2008/09. Male and female total discard catch data were available for 1992-2008/09. Both data series needed to be updated through the 2010/11 fishery.

For the reasons discussed in 2.a.iii (Directed Fishery – Male Discard Data), we obtained the raw Observer Program data files from 1991-2010/11 and generated a new 21-year time series of male and female discard catch 5 mm LF and populated the 'dat' file. Since female discard catch data start in 1992, the model doesn't need to fit the 1991 discard LF so, set n=1 for sample weight in 1991. We updated the 'dat' file with male and female total discard catch data for the 2009/10 and 2010/11 fisheries.

vi. Bristol Bay Red King Crab Fishery Discard Data

Both male and female Tanner crab discard LF data were available for 1989-1993 and 1996-2008/09. The red king crab fishery in Bristol Bay was closed in 1994-1995. Male and female total discard catch data were available for 1992-2010/11. Both data series needed to be updated through the 2010/11 fishery.

As discussed in A.3 (Directed Fishery – Male Discard Data), we obtained the raw Observer Program data files from 1989-2010/11 and generated a new 20-year time series of male and female discard catch 5 mm LF and populated the 'dat' file. We updated the 'dat' file with male and female total discard catch data for the 2010/11 fishery.

vii. Groundfish Fishery Discard Data

Formerly, male and female discard LF data were available for 1973-2007. These length composition data were derived from the Observer Foreign and Observer Domestic groundfish data bases although the source query could not be validated. On further examination, discrepancies were found in the length distribution of male crab discarded in the fishery during 1973-1985. There was a sharp drop-off in discarded sizes above 100 mm carapace width which was inconsistent with expectations and observations in other years.

We queried the Observer Foreign and Domestic data bases and generated a new time series of male and female 5 mm LF discard catch for 1973-2010. The Foreign data base dates from 1973-1990 and the Domestic data base from 1986-2010. The five years of overlap (1986-1990) were integrated as a weighted Domestic and Foreign LF discard catch based on the proportion of each fleet to the total groundfish catch while maintaining the male-female sex ratios in each 5 mm

length bin. The 'dat' file was populated with the new 1973-2010 series of 5 mm LF discard catch for males and females.

For the total discard catch data, recommendations from the Crab Modeling Workshop and SSC were to validate the time series data, particularly in the early period of record. The data series also needed to be updated with the 2009/10 bycatch data. We validated the historical total catch data of Tanner crab in the groundfish fisheries in the historical source references on file at the Center. Minor adjustments in the time series were necessary - principally from increasing the level of precision of the tabulated data which were rounded in some instances. We consulted with the ARO regarding 2009/10 bycatch estimate which had declined to approximately one-half of the previous 5-year average (2004-09). The decline was thought to be due to a shift in the cod quota to the B-season and a change in the mean weight per crab used in the expansions. The 'dat' file was populated with the new data.

b. Model Code Development

A variety of progressive modifications to the code were performed to address performance in specific areas, and to implement extensions in accordance with the author's work plan and recommendations of the Crab Modeling Workshop, SSC and CPT.

i. Survey Selectivity

The model through May 2011 estimated two selectivity periods: 1974-1981 and 1982-2010. For period-1 all three parameters of the logistic function for males and females were estimated. For period-2 males, Q was informed based on the 1999 Somerton and Otto underbag study (Q=0.88); the 50% parameter was estimated and the 95% parameter fixed. For females in period-2, the model estimated all three logistic parameters.

As seen in the results presented to the Crab Modeling Workshop in March 2011 and to the CPT in May 2011, the model has difficulty fitting the observed survey biomass over the 1982-1987. In this period, there is an inherent conflict between the observed survey biomass and length composition data. If the model is forced to fit survey biomass in these years, the full-selection fishing mortality rate increases to unrealistically high levels (~5.0) and, in some instances, the retained catch can exceed the available observed stock. This suggests that the survey estimates of biomass in these years was biased low.

There is strong indication that the survey selectivity in this intermediate period (1982-1987) differs from the preceding years (1974-1981) and later years (1988-2010). In the history of the bottom trawl survey, 1981 was a transition year where both the original 400 eastern trawl (1969-1981) and the new 83-112 trawl (1981-P) were fished. In 1981, each net sampled one-half of the survey area –the area was bifurcated east and west and each net sampled all the stations on one side of the line. In 1982, the 83-112 was adopted as the standard survey net.

During the intermediate period, there were changes in sampling protocols, in gear design, in equipment to measure net performance, in fishing vessels, and in deployment methods. After 1982, the survey examined net configurations and sampling protocols (e.g., warp lengths and tow speeds), and combinations of six different vessels were used over 1982-1988. One vessel in 1986 used a non-standard set of trawl doors which affected perceived net spread. Net mensuration gear and the approach to estimate net spread and distance fished evolved over time. SCANMAR was first tested in 1986 and implemented in 1988 to measure spread for all tows. Previously, starting in 1982, a single net spread value was input for all tows. Rose and Walters (1990) developed a mean net width-inverse scope regression which was used to reverse calculate the net spread for all tows pre-1988. Use of a standard scope table began in 1989. Starting in 1982, the distance

traveled by the trawl was estimated using Loran C and chart dividers, and the time fished was from brakeset to haulback although many of the data records in these years show exactly 30.0 minutes and 1.5 nmi (2.778 km) (i.e., 30.0 min x 3.0 knots) which implies that these were input and not actual measurements. Use of a Loran C Buroughs program to calculate distance fished began in 1988. One vessel used in this period was underpowered and may not have towed at 3.0 knots thereby overestimating area-swept.

Beginning in 1990 and continuing through the present, we see increasing precision in metrics of net performance and data quality on the survey. Some examples of changes implemented after 1982-1987 include: standard scope table (1989); Rose and Walters method used when net width values not recorded (1990); Branker depth/temperature logger (1992) for on-bottom evidence; West coast 'trawlgate' (1993) that marked a period of examining and standardizing survey protocols; Trident 'A-boats' *FV Arcturus* and *FV Alderberan* (1993) – well powered and standard design; standard setting and retrieval protocol (1994); distance fished using GPS stream data (1995); begin on-bottom to off-bottom protocol with bottom contact sensor (1995). We don't believe that it will be possible to quantify changes in survey selectivity outside the context of an assessment model for two reasons. First, this is a complex issue and, while it may be possible to surmise the directionality of the effect on Q of any particular change, the magnitude of any effect is elusive and that for the changes in aggregate even less certain. Second, this issue dates back 30 years and to where the data either are missing or, if recorded, don't lend themselves to analysis. It would be difficult to quantify the magnitude of these changes on survey selectivity external to a model that integrates measurement and observation error in fitting the survey data.

Based on our understanding of this history, we're resigned that there appears to be a period of the survey following the net change, as manifested in length composition and biomass data, which indicates that survey selectivity in the intermediate period (1982-1987) differs from that afterwards to the present. For the *Base Model*, we modified the code to estimate survey selectivity for three periods: period-1 (1974-1981), period-2 (1982-1987) and period-3 (1988-P). We note for reference that the snow crab assessment model also estimates survey selectivity for an intermediate period (1982-1988), albeit for different considerations regarding the extension of the survey to the north-western most range of snow crab inhabited predominately by immature male and mature female crab. The snow crab model fit to survey MMB in the 1980s benefits from this intermediate period even though the distribution of MMB occurs principally south of the extended range.

The *Base Model* estimates all three parameters (50%, 95% and Q) of the logistic function for both males and females in all three periods. For males in period-3, we inform Q based on the 1999 Somerton and Otto underbag study (Q=0.88).

Examination of the model performance revealed notable improvements in model fits to the survey MMB in the intermediate time period, and some improvement in the residual pattern of model fit to the survey male LF data.

ii. Directed Fishery Selectivity

The model through May 2011 estimated one directed fishery selectivity for males and females for all years. The questions we examined were twofold. First, is there evidence of changing fishery selectivity over time? Second, is a single fishery selectivity pattern representative of a characteristic fishing practice by a specialized Tanner fleet, particularly after the fishery re-opened in 2005 under rationalization?

After the Tanner crab stock fell to low levels by the early-1980s, retained catches were low and variable. Since the re-opening in 2005, retained catch has routinely been below the total catch OFL. A specialized directed Tanner crab fishery has not developed since 2005 due to low quota sizes, and the majority of catch is taken incidentally in the Bristol Bay red king crab fishery and the snow crab fishery that hold Tanner shares. After the development of the domestic fleet in late-1970s, the contribution to total catch from a specialized directed fleet versus incidental catch by the snow and red king crab fisheries is not well understood, particularly after 1980 when catches fell to low historical levels.

Unlike the snow crab and Bristol Bay red king crab fisheries with defined fishing practices (e.g., seasons, areas and gear), the directed Tanner crab fishery is much less defined. After 2005 in particular, it's apparent that a single fishery selectivity function is not representative of a partial recruitment pattern that can characterize a 'directed' fishery given the contribution to the catch by the various fleet components.

We examined a variety of scenarios for estimating directed fishery selectivity and formulated a *Base Model* to estimate both the retention function and the total selectivity. We initially allowed the model to estimate the 50% parameter of the logistic for all years and examined the temporal pattern in this parameter to suggest periods of selectivity. The initial model estimated 3 periods (1981-1991, 1992-1996 and 2005-2009) with one selectivity function estimated for period-1 and period-2, and annually varying selectivity estimated for period-3. After further examination of the fits to the retained LF, we set the *Base Model* to estimate the retention function and total selectivity according to:

- The retention function is estimated for two periods: period-1 (1981-1990) and period-2 (1991-2010). Retained LF data from the dockside sampling program start are available starting in 1981.
- Total selectivity is estimated for two periods: period-1 (1991-1996) and period-2 (2005-2010/11). For each period, a slope and mean (50%) parameter is estimated. For period-1 and period-2, a vector of annual deviations from the mean size at 50% selection is estimated. Total LF data from the observer program are available starting in 1991.

In the model, retained selectivity is the product of the retention function and total selectivity. Total selectivity is used prior to 1991 to estimate total catch with the assumption that the 1981-1990 retention function is representative of years prior to 1991.

We developed an alternative model configuration to remove the estimation of the annual deviations from the mean parameter for total selectivity to examine the effects on the likelihood of the annual estimation of total selectivity. Thus, 11 fewer parameters, one each for 1991-1996 and 2005-2010. Those results are reported in Rugolo and Tunock (2011b), Alt-2 in Table 9.

iii. Snow Crab Fishery Discard Selectivity

The model through May 2011 estimated one discard selectivity curve for males and females for all years. The questions we examined were twofold. First, is there evidence of changing discard selectivity over time? Second, should there be separate selectivity estimated in years that the Tanner fishery was closed (1986-1987, 1997-2004)?

We examined the discard length compositions over all years and related patterns in the LF fits to changes in snow crab fishing practices with respect to season, area and gear. For example, escape mechanisms were instituted in 1997 (5 rings), and in 2001 the number of required mechanisms increased to 8. We also examined the patterns in the residuals of the model fit to the discard LF

which supported a decision to implement different selectivity periods when the Tanner fishery was open and closed.

The *Base Model* configuration estimates snow crab fishery discard selectivity in three periods: period-1 (1989-1996), period-2 (1997-2004) and period-3 (2005-2010). In each period, one discard selectivity curve is estimated for males and females.

iv. Bristol Bay Red King Crab Fishery Discard Selectivity

The model through May 2011 was coded to estimate one discard selectivity curve for males and females for all years, although that was turned off due to data issues and an error in the code. The Bristol Bay red king crab fishery was closed in 1994 and 1995. The questions we examined were twofold. First, is there evidence of changing discard selectivity over time? Second, should there be separate selectivity estimated in years that the Tanner fishery was closed (1986-1987, 1997-2004)?

As discussed in 2.a.iii (Directed Fishery – Male Discard Data), we generated a new 20-year time series of discard catch 5 mm LF for male and female Tanner crab. We discovered the problem with the model not being able to estimate discard selectivity was in the estimation of fishing morality rates and the discard catch. The F deviation vector required redefinition to account for years when the red king crab fishery was closed so as to match the correct fishing year data.

We examined the discard length compositions over all years and related patterns in the LF fits to changes in red king crab fishing practices with respect to season, area and gear. We also examined the patterns in the residuals of the model fit to the discard LF which supported a decision of implementing different selectivity periods when the Tanner fishery was open and closed.

The *Base Model* configuration estimates Bristol Bay red king crab fishery discard selectivity in three periods: period-1 (1989-1996), period-2 (1997-2004) and period-3 (2005-2010). In each period, one discard selectivity curve is estimated for males and females.

v. Groundfish Fishery Discard Selectivity

The model through May 2011 estimated one discard selectivity curve for males and females over all years, 1973-2007. Discard length composition data for 1973-1985 were pooled for sexes, while sex-specific length compositions were available for 1986-2007. The questions we examined were threefold. First, is there evidence of changing discard selectivity over time? Second, should there be separate selectivity for the period of Foreign fishing (1973-1987) and for the remaining period (1988-2007) of Domestic fishing? Third, did implementation of groundfish fishery CAPS have an effect on fleet operations resulting in change in the discard LF?

We examined the length composition of discards over all years in an attempt to observe changes that may correspond to periods of selectivity. Under 2.a.vii (Groundfish Fishery Discard Data), we generated a new time series of male and female 5 mm LF discard catch for 1973-2010. We also examined the patterns in the residuals of the model fit to LF of discards which supported a decision of implementing different selectivity periods to address the combined effects of the shift from the Foreign to Domestic fleets, and for when the Tanner fishery was open and closed.

The *Base Model* configuration estimates groundfish fishery discard selectivity in three periods: period-1 (1973-1986), period-2 (1987-1996) and period-3 (1997-2010). In each period, one discard selectivity curve is estimated for males and females.

vi. Growth

The model through May 2011 used the *a* and *b* parameters of an exponential growth model empirically derived for males and females based on growth data collected near Kodiak Island in the Gulf of Alaska. Growth for males and females was fixed in the model over all years.

While we considered that the observed GOA data might suitably described the pre-molt and post-molt relationship, growth in eastern Bering Sea may be different - the frequency of molting of young immature crab might be different at colder ambient temperatures, and/or growth may not be constant over all years. Our goal was to free the model specification of growth. A broader issue was evidence of changing growth over time which is unresolved at this writing. We modified the code to implement the model estimation of male and female growth.

The *Base Model* configuration estimates the *a* and *b* parameters of exponential growth for males and females used in all years. Comparison of the estimated growth functions to those derived empirically from GOA data reveal that estimated growth is similar for male and slower for female Tanner crab over the range of sizes. This is consistent with slower growth in colder realms.

vii. Natural Mortality

In the model through May 2011, M was fixed for males and females at 0.23. Six M values were input to the model: immature M (male, female); mature new shell M (male, female) and mature old shell M (male, female). They could be set at different levels but were fixed.

To address recommendations from the Crab Modeling Workshop and SSC, we sought to examine the effect on model performance of M changing over time, different Ms on immature and mature crab, and different Ms on males and females. Ultimately, develop a profile on M.

We implemented alternative scenarios to estimate M in the model: 1) estimate immature M (pooled sexes) and mature M (pooled sexes); 2) estimate immature M (pooled sexes), mature male M and mature female M; 3) estimate annual immature M (pooled sexes), annual mature male M and annual mature female M with smooth constraint on annual deviations; and, 4) estimate annual immature M (pooled sexes) and annual mature M (pooled sexes). For each scenario, we examined the effect on the fit to the survey LF and biomass. Scenario-2 was preferred since, while argument can support a different natural mortality rates on mature males versus mature females given life-history and reproductive dynamics, immature male and female crab are likely subjected to similar ecological effects embodied in M.

The various model configurations were implemented progressively to evaluate model performance. For scenario-2 (estimated immature M pooled sexes, mature male M, mature female M), the progression was: a) estimate immature M conditional on mature M on males and females fixed at 0.23, resulting in immature M=0.262; b) estimate immature M and mature M on males conditional on mature female M fixed at 0.23, resulting in immature M=0.261, mature male M=0.210; c) estimate immature M pooled sexes, mature male M and mature female M, resulting in immature M=0.227, mature male M=0.247, and mature female M=0.326.

The *Base Model* configuration estimates M for immature crab (pooled sexes), M on mature males, and M on mature females.

Estimation of Annual M

As an initial experiment, the code was modified to estimate annual M for male crab (immature and mature pooled), and to estimate one M for immature females and one M for mature females. The purpose was to consider change in M over time or stanzas of mortality that could be related

to ecological effects. For males, M varied between 0.1-0.6 over all years, immature female M=0.272, and mature female M=0.314. This resulted in improved model fit to survey MMB, in a worse pattern in the residual fit to the survey male LF, and in the male and female survey selectivity in the early and intermediate periods declining sharply which resulted in increases in MMB and MFB to start the model.

Relating the pattern in annual M to moderating factors in the environment is an area of research in our mid-term planning once the model meets peer review.

viii. Recruitment Periods

The model through May 2011 estimated two recruitment periods each with a mean recruitment and vector of deviations: period-1 (1950-1968) and period-2 (1969-2010). These periods were the original configuration based on survey data starting in 1969. As the 1969-1973 survey data were dropped from the model, the code was modified so that the transition between the two periods coincided with the start of observed survey biomass in 1974. One question was how to best estimate recruitment in period-1 so as to modulate the occurrence of dominant recruitments generated by the model to fit the data.

We implemented two recruitment periods: period-1 (1950-1973) and period-2 (1974-2010). The mode estimates a mean recruitment and deviation vector for each period. To modulate inter-annual variation in recruitments estimated in period-1, we examined the effect of changes to the weight of the recruitment deviation penalty from 1.0 to 5.0, 10.0 and 50.0. This proved unsatisfactory as the model still estimated dominant recruitments in the early-1960s, and setting the weight penalty to high values, while it lessened the dominant mode, it dampened many of the period-1 recruitments.

Alternatively, we replaced the recruitment deviation penalty with a first-difference penalty in period-1 and tested various weights (0.25, 0.50 and 1.0) on that penalty. The resulting pattern of recruitments in period-1 were more satisfactory. Large dominant peaks in recruitment preceded or followed by recruitment drop-outs were eliminated. While the model estimated a mode of high recruitments in the 1960 fertilization year as expected, transitions of estimated recruitment between years was constrained. The first-difference penalty of the base model is 1.0.

The *Base Model* configuration estimates recruitment in period-1 (1950-1973) and period-2 (1974-2010) with a first-difference penalty used in period-1.

ix. Maturity

In the model through May 2011, and in the current model, a maturity function is estimated that defines the probability of an immature crab molting to maturity for males and females for all years. For females, we used the survey egg code data to input immature and mature crab at length in all years. For males, chela height and carapace width data are available for 1990-2010. Using results of a special collection in 2008 of refined male crab morphometric measurements to the 0.1mm, we developed a mixture-of-two regression analysis to derive the classification rule used to assign male crab into immature and mature sub-populations whose results were used to input immature and mature crab at length for all years. The survey did not collect chela height data in 1974-1989.

Using this classification rule, we derived the proportion of mature male crab at length by new and old shell classes for 1990-2007 at present. Two parameter logistic models were fit to the observed proportion mature at length in each year, and an overall mean logistic function of

maturity at length by shell class fit to the mean proportion mature for 1990-2007. This mean function is used to impute maturity status of males by shell class for all years 1974-2010.

Work on this element is incomplete at this writing. Two tasks are identified:

- Use the annual maturity functions (1990-2010) to assign male crab to mature and immature status by shell class rather than the mean maturity function. The overall mean will be used to impute maturity status for 1974-1989 which lack chela data.
- Examine annual maturity to consider if there's evidence of a change in maturity over time or stanzas of maturity. If so, implement annually changing maturity or periods of maturity.

In the *Base Model*, we lowered the smoothness penalty on maturity likelihood component for males from 5.0 to 1.0, and for females from 2.0 to 1.0 to make the estimated probability of maturing more responsive with the goal of improving fit to the survey LF. The resulting probability of maturing function for males and females had acceptable smoothness. The pattern of residuals in the fits to the survey LF showed no obvious improvement.

x. Male-Female Recruitment Estimation:

The current model does not distinguish between males and females in terms of recruitment. Thus, a 1:1 sex ratio of recruits is assumed that is distributed to the initial length bins. One question is to consider the effects on model performance of different sex ratios of recruitment with the goal of improving the residual patterns of fits to survey LF. Identified tasks are to implement different fixed male:female sex ratios at recruitment. Some considerations are the status quo (50:50), male dominated (75:25) and female dominated (75:25). Alternatively, estimate sex-specific recruitment annually, or over periods of time.

We modified the code to estimate recruitment separately for males and females to address the in fits to the survey LF. In that configuration, the model estimated a mean recruitment and deviation vector for two periods: period-1 (1950-1973) and period-2 (1974-2010). We observed no marked improvements survey LF residuals, and some odd outcomes in terms of predicted male and female mature biomass estimates and survey selectivity. This was an initial examination the issue of male-female recruitment estimation that requires further evaluation.

The *Base Model* configuration does not estimate male-female recruitment separately. It estimates a combined recruitment for two time periods (1950-1973 and 1974-2010), with a first-difference penalty on annual deviations from the mean in period-1.

F. MODEL CONFIGURATION – The Current Analysis

In this analysis, we present results of TCSAM that incorporates all revisions implemented since May 2011 as described in E (Model Development), including revisions resulting from the review comments of Rugolo and Turnock (2011b) submitted to select plan team members in July 2011.

We formulated a *Base Model(0)* that attends to virtually all of the recommendations of the Crab Modeling Workshop, the SSC and plan team. The *Base Model (0)* represents the best available science in our view, and a level of performance in modeling stock and fishery dynamics that may be acceptable to status of stock determination, OFL-setting and projection analysis. The *Base Model* represents all revisions *i-vii* to the input data described in 2.a (Data Validation), and all code revisions *i-x* described in 2.b (Model Code Development). We formulated six model configurations in addition to the *Base Model(0)* to show the effects on performance of principal changes to the model since May 2011.

In summary, the specification of the ***Base Model (0)*** is:

i. Survey Selectivity:
All three parameters of the logistic function are estimated for both males and females in 3 periods, 1974-1981, 1982-1987, and 1988-2011.

ii. Directed Fishery Selectivity:
A retention function and total selectivity are estimated in 2 periods: retention function (1981-1990 and 1991-2010); total selectivity (1991-1996 and 2005-2010/11) with annual varying maen (50%) in periods 1991-1996 and 2005-20010/11.

iii. Snow Crab Fishery Discard Selectivity:
Selectivity is estimated in 3 periods, 1989-1996, 1997-2004 and 2005-2010/11. In each period, one selectivity curve for males and females.

iv. Bristol Bay Red King Crab Fishery Discard Selectivity:
Selectivity is estimated in 3 periods, 1989-1996, 1997-2004 and 2005-2010/11. In each period, one selectivity curve for males and females.

v. Groundfish Fishery Discard Selectivity:
Selectivity is estimated in 3 periods, 1973-1986, 1987-1996 and 1997-2007. In each period, one selectivity curve for males and females.

vi. Growth:
The *a* and *b* parameters of exponential growth for males and females are estimated, all years.

vii. Natural Mortality:
Immature M (pooled sexes), mature male M and mature female M are estimated, all years.

viii. Estimation of Annual M:
Does not estimate annual M.

ix. Recruitment Periods:
Estimates recruitment in 2 periods, 1950-1973 and 1974-2011 with a first-difference penalty in the early period.

x. Maturity:
A maturity function that defines the probability of an immature crab molting to maturity for males and females is estimated, all years.

xi. Male-Female Recruitment Estimation:
Does not estimate male-female recruitment separately.

Specifications for all seven model configurations presented in this analysis are defined:

Model 0: *Base Model*

Model 1: *Base Model* modified such that survey selectivity is estimated in 2 periods (1974-1981 and 1982-2011).

Model 2: *Base Model* modified such that annual varying Q is estimated.
The 50% and 95% logistic parameters are estimated in each of 3 periods (1974-1981, 1982-1987 and 1988-2011). One overall average Q is estimated for the time-series with a vector of annual deviations in Q (1974-2011).

Model 3: *Base Model* modified such that survey selectivity is estimated in 2 periods (1974-1981 and 1982-2011) plus M is estimated in 2 periods: (1=1974-1981 + 1988-2011; 2=1982-1987) as in *Base Model*

Model 4: *Base Model* modified such that male and female growth are fixed to empirical functions based on GOA data.

Model 5: *Base Model* modified such that M is fixed at 0.23.

Model 6: *Base Model* modified such that fishery selectivity is estimated in only 1 period (all years) for the directed Tanner fishery, the Bristol Bay red king crab fishery, the snow crab fishery, and the groundfish fishery.

Model:	Specification
0	Base Model
1	Base Model *but* 2 survey selectivity periods (1974-1981, 1982-2011)
2	Base Model *but* annual varying Q
3	Base Model *but* survey selectivity in 2 periods (1974-1981, 1982-2011) plus M estimated in 2 periods (1=1974-1981 + 1988-2011; 2=1982-1987)
4	Base Model *but* fixed growth
5	Base Model *but* fixed M=0.23
6	Base Model *but* 1 fishery selectivity estimated all years for: directed, red king crab, snow crab and groundfish fisheries

G. MODEL APPROACH

In this analysis, we developed a length-, sex-, maturity- and shell condition-structured model to characterize stock performance and serve the basis of estimating overfishing definitions. The model structure was developed following the methods of Fournier and Archibald's (1982) 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 to find the objective function via a quasi-Newton function minimization routine (e.g., Press et al. 1992). The model implementation language (ADModel Builder) gives simple and rapid access to these routines and provides the ability to estimate the variance-covariance matrix for all parameters of interest.

The model estimates recruitments beginning in 1950 to build the stock to fit initial observed survey data biomass and length frequency estimates beginning in 1974. This results in 20 additional recruitment parameters. There are 32, 5mm length bins in the model starting from 25-29 mm up to a cumulative bin at 180-184 mm.

1. Recruitment

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

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

where,

R_0^l Mean recruitment

pr_l Proportion of recruits for each length bin

τ_t Recruitment deviations by year.

Recruitment numbers are estimated equal for males and females in the model.

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

$$N^s_{t,l} = (1 - \phi^s_l) \sum_{l=l_1}^{l'} \psi^s_{l',l} \; e^{-Z^s_{l'}} N^s_{t-1,l'}$$

$\psi^s_{l',l}$ growth transition matrix by sex, pre-molt and post-molt length bins which defined the fraction of crab of sex *s* and pre-molt length bin *l*', that moved to length bin *l* after molting,

$N^s_{t,l}$ abundance of immature crab in year *t*, sex *s* and length bin *l*,

$N^s_{t-1,l'}$ abundance of immature crab in year *t-1*, sex s and length bin *l*',

$Z^s_{l'}$ total instantaneous mortality by sex *s* and length bin *l*',

ϕ_l^s fraction of immature crab that became mature for sex *s* and length bin *l*,
l' pre-molt length bin,
l post-molt length bin.

2. Growth

Growth was modeled using a fixed non-linear exponential function to estimate the mean post-molt carapace width (*Y*) given the mean pre-molt carapace width (*X*) (Figure A-8),

$$Y_{t+1} = aX_t^b$$

Parameters values used in the model and whether parameters were estimated in the model, excluding recruitments and fishing mortality parameters are listed in Table A-5.

Assignment to length bins was made using a two-parameter gamma distribution with mean equal to the growth increment by sex and length, over the 25-185 mm CW range, and a beta parameter which determines the variance,

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

where,
$\alpha_{s,l'}$ expected growth interval for sex *s* and size *l'* divided by the shape parameter β,
$\psi_{l',l}^s$ growth transition matrix for sex, *s* and length bin *l'* (pre-molt size), and post-molt size *l*.

The Gamma distribution was,

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

where *l* is the length bin, β was set equal to 0.75 for both males and females as estimated from growth data on EBS Tanner and king crab due to the scant amount of growth data available for snow crab.

3. Maturity

The probability of an immature crab becoming mature by size was applied to the post-molt size. Crab that matured and underwent their terminal molt in year *t* were mature new shell (SC2) by definition during their first year of maturity. The abundance of newly mature crab ($\Omega_{t,l}^s$) in year *t* is given by,

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

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

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

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

4. Male Mature Biomass

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

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

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

5. Catch

Catch of male Tanner crab was taken as a pulse fishery on February 15 (0.62 y) after the beginning of the assessment year (July 1),

$$\hat{C}_t = \sum_l (1 - e^{-(F_{red} * Sel_l^{red} + F_{snow} * Sel_l^{snow} + F_{tanner} * Sel_l^{tanner} + F_{trawl} Sel_l^{trawl})} w_l N_{t,l}^{males} e^{-M0.62}$$

F_{tanner}	full selection fishing mortality (y^{-1}) determined from the control rule using biomass including assessment error,
F_{trawl}	fishing mortality (y^{-1}) for trawl bycatch fixed at 0.01 (average *F*),
F_{red}	fishing mortality (y^{-1}) for red king crab fishery trawl bycatch,
Sel_l^{tanner}	directed fishery selectivity for shell condition and length bin *l* for male crab,
Sel_l^{red}	red king bycatch fishery selectivity for shell condition and length bin *l* for male crab,
Sel_l^{snow}	snow bycatch fishery selectivity for shell condition and length bin *l* for male crab,
Sel_l^{trawl}	trawl bycatch fishery selectivity for shell condition and length bin *l* for male crab,
w_l	mean weight of male crab in length bin *l*,
$N_{t,l}^{males}$	numbers by length for shell condition class and length bin *l*,
M	instantaneous natural mortality rate.

6. Selectivity

The selectivity curves for the total catch, the retention curve, catch in the red king crab fishery, catch in the snow crab fishery, and catch in the groundfish fisheries, were estimated as two-parameter ascending logistic curves,

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

Where *a* is slope and *b* is length at 50% selectivity. Separate selectivity curves for males and females were estimated for the directed, snow and red king crab fisheries.

The probability of retaining crabs by size in the directed fishery with combined shell condition was estimated as an ascending logistic function. The selectivities for the retained catch were estimated by multiplying a two parameter logistic retention curve (same logistic equation as the total selectivity) by the selectivities for the total catch,

$$S_{ret,l} = (selectivity\ total)(retention)$$

The selectivities for the survey were estimated with three-parameter, ascending logistic functions (Survey selectivities in Figure A-14).

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

Survey selectivities were estimated for 3 periods, 1974-1981, 1982-1987, and 1988-2011 to address evolving survey design and gear changes as discussed (*see* 2.b.i. Survey Selectivity). The spatial coverage of the survey was standardized in 1978 with the exception of the addition of some stations in the northwestern survey area, well outside the distribution of EBS Tanner crab. Years 1974-1981 were considered to have similar coverage of the Tanner crab distribution. Years prior to 1974 had unique coverage temporally and spatially relative to Tanner crab and not included in the analysis as recommended by the Crab Modeling Workshop (Martel and Stram 2011). All three parameters (50%, 95% and Q) of the logistic function for both males and females are estimated in the three periods. For males in period-3, we inform Q based on the 1999 Somerton and Otto underbag study (Q=0.88).

7. Likelihood Equations

Weighting values (λ) for each likelihood equation are shown in Table 10.

Catch biomass for the directed fishery, snow crab fishery, red king crab fishery and groundfish fishery is assumed to have a normal distribution,

$$\lambda \sum_{t=1}^{T} \left[(C_{t,fishery}) - (\hat{C}_{t,fishery}) \right]^2$$

There are separate likelihood components for the retained catch, discard in the directed fishery, discard in the snow crab fishery, discard in the red king crab fishery and groundfish bycatch.

The robust multinomial likelihood is used for length frequencies from the survey and the catch (retained and total) for the fraction of animals by sex in each 5mm length interval. The number of samples

measured in each year is used to weight the likelihood. However, since thousands of crab are measured each year, the sample size was set at 200.

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

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

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

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

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

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

Recruitment deviations likelihood equation is (t is year),

$$\lambda \sum_{t=1}^{T} \tau_t^2$$

First difference constraint on early recruitments (years (t) from 1950 to 1973)

$$\sum_{t=1}^{T} (first\ differences(\tau_t))^2$$

Smooth constraint on probability of maturing by sex and length

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

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

Fishery CPUE in average number of crab per pot lift (currently not fit in the model),

$$\sum_{t=1}^{tf}\left[\frac{\log(CPUE_t)-\log(\hat{C}PUE_t)}{sqrt(2)*s.d.(\log(CPUE_t))}\right]^2$$

Penalties on fishing mortality deviations,

$$\lambda\sum_{t=1}^{T}\varepsilon_t^2$$

Growth parameters likelihood,

$$0.5(\frac{\tau-\mu}{\sigma})^2$$

M penalty, sd = 0.05,

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

Penalty on survey Q for period 1989-persent (3 period model) or 1982-present (2 period model), sd = 0.05, prior is from underbag experiment,

$$0.5(\frac{Q-0.88}{\sigma})^2$$

Constraint on annual survey Q deviations (when estimated),

$$\lambda\sum_{t=1}^{T}\varepsilon_t^2$$

Snow crab and red king crab fisheries discard catch of Tanner crab for years when discard data are not available was estimated from the relationship between the retained catch of snow crab (or red king crab) and the bycatch of Tanner crab in the directed snow crab (or red king crab) fishery for years with observer data,

$$R=mean\left[\frac{F_{Tanner\,bycatch}}{\mathrm{Re}tained\ Directed\ catch}\right]$$

Fishing mortality for Tanner crab bycatch for years when no observer data are available is estimated using R above with the retained catch of snow crab (or red king crab, C_R),

$F = R\ C_R$

A first difference penalty on annual deviations in the size at 50% selected for the total male catch in the directed Tanner fishery,

$$\sum_{t=1}^{T} (\textit{first differences}(\tau_t))^2$$

In *Base Model (0)*, a total of 295 parameters for the 38 years of data (1974-2011) were estimated in the model (Table 8). The 97 fishing mortality parameters (one for the directed fishery deviations, 1970-2011, and one mean value), one set for the snow crab fishery, 1992-2011, one set for the red king crab fishery, 1992-2011, and one set for the trawl fishery bycatch, 1973-2011) estimated in the model were constrained so that the estimated catch fit the observed catch closely. There were 62 recruitment deviation parameters estimated in the model, 2 mean recruitments in 2 periods (male and female recruitment were fixed to be equal). There were 62 fishery selectivity parameters. Male and female survey selectivity was estimated for 3 periods resulting in 18 parameters estimated. A total of 64 parameters were estimated for the probability of maturing smooth constrained functions.

Molting probabilities for mature males and females were fixed at 0, i.e., growth ceases at maturity which is consistent with the terminal molt paradigm (Otto 1998, Tamone et al. 2005). Molting probabilities were fixed at 1.0 for immature females and males. The a and b parameters of the exponential model of post-molt size relative to pre-molt size describing growth of male and female were estimated in the model. A gamma distribution was used in the growth transition matrix with the beta parameters fixed at 0.75 for males and females. We modeled the variance of the distribution of post-molt size given pre-molt size bin using growth data on male and female GOA Tanner crab and found that a beta of 0.75 resulted in good approximation of the distribution of post-molt sizes over all size bins.

The model separates male and female crab into mature, immature, new shell and old shell for the population dynamics. The model estimate of survey mature biomass is fit to the observed survey mature biomass time series by sex. The model fits the size frequencies of the survey by immature and mature separately for each sex and shell condition combined. The model fits the size frequencies for the pot fishery catch by sex.

Crabs 25 mm cw and larger were included in the model, divided into 32 size bins of 5 mm each, from 25-29 mm to a plus group at 180-184 mm. In this report the term size as well as length will be considered synonymous with cw. Recruits were distributed in the first few size bins using a two parameter gamma distribution with the parameters estimated in the model. The alpha parameter of the distribution was fixed at 11.5 and the beta parameter fixed at 4.0. No spawner-recruit relationship was used in the population dynamics part of the model; annual recruitments were estimated in the model to fit the data.

The NMFS trawl survey occurs in summer each year, generally in June-August. In the model, the time of the survey (July) is considered to be the start of the year rather than January. The modern directed Tanner crab pot fishery has occurred generally in the winter months (January to February) over a contracted time period. In contrast, in the early years the fishery occurred over a more protracted period of time. Natural mortality is applied to the population from the time the survey occurs until the fishery occurs, then catch is extracted instantaneously. The fishing mortality was applied as a pulse fishery at the mean time for that year. After the fishery, growth and recruitment take place in spring, with the remainder of losses due to natural mortality through the end of the year.

8. Discard mortality

Pot fishery discard mortality was assumed to be 50% for this assessment. The fishery for snow crabs occurs in winter when low temperatures and wind may result in freezing of crabs on deck before they are returned to the sea. Short-term mortality may occur due to exposure, which has been demonstrated in laboratory experiments by Zhou and Kruse (1998) and Shirley (1998), where 100% mortality occurred under temperature and wind conditions that may occur in the fishery. Even if damage did not result in short term mortality, immature crabs that are discarded may experience mortality during molting some time later in their life.

9. Projection Model Structure

Variability in recruitment, as well as assessment error, was simulated with temporal autocorrelation. Recruitment was generated from a Beverton-Holt stock-recruitment model,

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

$spr_{F=0}$	mature male biomass per recruit fishing at F=0. $B_0 = spr_{F=0}\ R_0$,
B_t	mature male biomass at time t,
h	steepness of the stock-recruitment curve defined as the fraction of R_0 at 20% of B_0,
R_0	recruitment when fishing at F=0,
σ_R	standard deviation for recruitment deviations, estimated at 0.86 from the assessment model.

The temporal autocorrelation error (ε_t) was estimated as,

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

ρ_R	temporal autocorrelation coefficient for recruitment, set at 0.6.

Recruitment variability and autocorrelation were estimated using recruitment estimates from the stock assessment model. R_0 and steepness were estimated such that $F_{35\%} = F_{MSY}$ and $B_{35\%} = B_{MSY}$ using a Beverton-Holt stock recruitment relationship.

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

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

$B_t^{'}$	mature male biomass in year t with assessment error input to the harvest control rule,
B_t	mature male biomass in year t,
ρ_I	temporal autocorrelation for assessment error, set at 0.6 (estimated from the recruitment time series),

σ_I standard deviation of φ, which determines the magnitude of the assessment error, set at the estimate of variance of ending biomass from the assessment model plus additional uncertainty.

Assessment error in mature male biomass resulted in fishing mortality values applied to the population that were either higher or lower than the values without assessment error. The autocorrelation was assumed to be the same value as that estimated for recruitment. Assessment autocorrelation was used to more closely approximate the process of estimating a biomass time series from within a stock assessment model. The variability in biomass of the simulated population resulted from the variability in recruitment and variability in full selection *F* arising from implementation error on biomass. Uncertainty in initial numbers by length was added using a lognormal distribution with cv of ending biomass from the assessment model. The population dynamics equations were identical to those presented for the assessment model in the model structure section of this assessment.

Appendix A presents an example of a rebuilding analysis using results of the *Base Model (0)* fishing at the full F_{OFL}, at $0.75F_{OFL}$ and at F_{OFL}=0 with only the groundfish fishery discard mortality.

10. New Size Limits Strategy and Fishery Selectivity

In March 2011, the Alaska Board of Fisheries approved a new minimum size limit strategy for Tanner crab that will be in effect for the 2011/12 fishery. The previously minimum legal size limit was 5.5" (138 mm cw) throughout the Eastern Subdistrict. The new regulations established different minimum size limits east and west of 166^0 West longitude. That for the fishery to the east will be 4.8" (122 mm cw), and that to the west will be 4.4" (112 mm cw). The industry may self-impose retention of crab above 5.5" (138 mm cw) and 5" (127 mm cw) east and west of 166^0 West longitude, respectively.

For future stock status, since we have no observed data on fishery performance under these proposed regulatory changes, we would initially approximate east-west fishery selectivities and the resultant catch splits in the projection model framework. As a first-order approximation, we would take the current fishery selectivity curve based on 138 mm cw size limit and shifted the curve by the difference between 138 mm and the proposed minimum size limit in each area – i.e., by 16 mm east of 166^0 W longitude and by 26 mm west of 166° W longitude. Alternatively, we could consider the minimum size limits that the industry is purported to self-impose to adjust the current fishery selectivity curve. Both the retained and total fishery selectivity curves would be shifted in this manner. The split in the catch east-west would be approximated by the proportion of the abundance of crab observed in the 2010 survey east and west of 166^0 W longitude.

H. RESULTS

Table 1 provides the fishery history of observed retained catch in the domestic and foreign Tanner crab fisheries from 1965/66 to 2010/11. The total biomass of discard catch of Tanner crab in the domestic pot fisheries and groundfish fisheries for 1973/74 through 2010/11 is shown in Table 2. Table 3 presents the observed survey female, male and total spawning biomass, and observed abundance of legal male crab (≥ 138 mm cw) for 1974-2011. *Base Model (0)* estimates of predicted retained and discard catch of Tanner crab by sex in the directed fishery for 19674/75 through 2009/10 is shown in Table 4. Table 5 shows the discard catch in the non-directed pot and groundfish fisheries by sex estimated in the *Base Model (0)* for 19674/75 through 2010/11. The *Base Model (0)* predicted total (retained plus discard) Tanner crab catch biomass from the directed and all non-directed fisheries combined for years 19674/75 through 2010/11 is presented in Table 6. *Base Model (0)* estimates of population biomass and abundance, male, female and total mature biomass, abundance of legal males, recruitment to the population, male mature biomass at mating and full-selection fishing mortality rates are presented in Table 7. Table 8 provides the parameter values and whether the parameters were estimated in the model, excluding recruitments and fishing mortality parameters for *Base Model (0)*. Table 9 shows the likelihood values by component for *Model (0)* through *Model (6)*, and Table 10 presents the weighting factors for the likelihood equations used for all models. The values of natural morality (M) estimated or fixed for *Model (0)* through *Model (6)* are shown in Table 11.

***Base Model (0)*:**

Figure 12 presents predicted retained male catch and predicted retained plus discarded catches of male Tanner crab in the directed fishery, and total male catch in all fisheries combined. Mature male biomass declined sharply from its high in 1974 to the mid-1980s, increased modestly to a secondary mode in 1990, then declined thereafter through the early-2000s (Table 7, Figure 15). The model does not fit the increasing survey biomass trend in 2005-2008 but better fits the 2009-2011 observed biomass. The increasing trend in 2005-2008 was driven principally by hot-spot tows which inflated total biomass estimates (Rugolo and Turnock 2008). Exploitation rates on legal and mature male biomass demonstrated two peaks: the first in the late-1970s through early-1980s and the second in the mid-1990s (Figure 13).

Estimated total selectivity for combined shell condition male Tanner crab in the directed fishery was estimated in three periods (1981-1990, 1991-1996 and 2005-2010) (Figure 16). The estimated fraction of total catch retained by size for male crab in the directed fishery for all shell condition classes combined estimated in three periods (1981-1990, 1991-1996 and 2005-2010) is presented in (Figure 17. All three parameters (50%, 95% and Q) of the logistic function for male (Figure 18) and female (Figure 19) survey selectivity was estimated in three periods (1974-1981, 1982-1987 and 1988-2011) and, for males in period-3, we inform Q based on the 1999 Somerton and Otto underbag study (Q=0.88). Male and female Tanner crab fishery selectivity in the Bristol Bay red king crab fishery (Figure 20) and in the snow crab fishery (Figure 21) was estimate in three periods (1989-1996, 1997-2004 and 2005-2011). Selectivity of Tanner crab in the groundfish fisheries was estimated for three periods (1973-1986, 1987-1996 and 1997-2010) (Figure 22).

Model fits to mature male biomass and to mature female biomass are shown in Figure 15 and Figure 23 respectively. The model fits the observed male mature biomass well over the time-series with the exception of 2005-2008 as noted. Observed female mature biomass is relatively more variable than MMB and the model does not fit these female data as well in the late-1970s and early-1980s.

Model fits to the survey length frequencies for males and females including observed survey biomass are shown in Figure 24 and Figure 26 respectively. Residuals of model fits to the male survey length frequencies are shown in Figure 25, and those for mature females in Figure 27. A summary plot of the model fit to the survey length frequencies for males and females over all years is shown in Figure 28.

Observed survey numbers of legal males and model estimates of the population of legal males and of the survey number of legal males are shown in Table 7.

The relationships of pre-molt length to post-molt length for male and female Tanner crab estimated in the model are shown in Figure 29. Figure 30 illustrates the estimated recruitment to model of crab 25 mm to 50 mm by fertilization year. The distribution of recruits by carapace width to the model is shown in Figure 31. Model fits to the retained male size frequency data in the 1981-2009 directed fishery, and the summary fit to the retained male size frequencies over all years are shown in Figure 32 and Figure 33 respectively. The model fits to the total male size frequency data for 1981-2009 in all fisheries combined, and the summary fit to the total male size frequencies over all years are shown in Figure 3 and Figure35 respectively. Figure 36 presents the summary fit to the discard female size frequency data in the directed fishery. Figures 37 through 39 present the summary model fits to the size frequencies of male and female Tanner crab discards in the snow crab fishery, in the Bristol Bay red king crab fishery and in the EBS groundfish fisheries.

Full-selection fishing mortality rates varied from near zero to 2.1 (Figure 40, Table 7). Full-selection fishing mortality rates concur with a history of excessive exploitation, averaging 0.98 (1977/78-1981/82) peaking in 1980/81 at 1.45, and averaging 1.12 (1990/91-1994/95) peaking in 1992/93 at 2.08 coincident with peak extraction of catch and decline in stock biomass. Figure 41 shows realized instantaneous fishing morality rate vs. male mature biomass at mating by fishing year and the *Base Model (0)* where $F_{35\%}$=0.574 and $B_{35\%}$=162.31 thousand t. The pattern of recruitment to the model vs. male mature biomass is illustrated in Figure 42. Figure 43 presents the trajectory of estimated male mature biomass at the time of mating from 1974-2011. From the high biomass in 1974, MMB at mating has demonstrated a one-way trip of sharply declining biomass through 2000 and remaining at low levels thereafter. A modest mode of MMB was observed in the late-1980s to early-1990s, peaking in 1990 (Figure 43, Table 7), but this peak represented only approximately 25% of the male mature biomass estimated in 1974-1980. The male size frequencies from 1974-2011 (Figure 24) reveals a contraction of the distribution and a length shift to smaller sizes coincident with the decline; the modest increase in biomass associated with the 1990 mode is seen in the progression of lengths from 1987 through 1992. Inspection of the metrics of stock and fishery performance of Tanner crab over the history from 1974-2011 indicate a severe stock decline.

Alternative Model Scenarios:
For the additional six model configurations, we present a select group of seven representative figures representative of model performance. For females, these are the estimated population of mature female biomass with model fit to survey mature biomass, the model fit to the survey size frequency data, and the residual plot of model fit to the survey size frequency data. We repeat this set of three figures for males. Lastly, the summary plot of the model fit to the survey male and female size frequency data. On a case-specific basis, figures representing special features of a model are also shown – e.g., the plots of the male and female survey selectivity for two periods in *Model (1)*, or the figure of annual varying Q for *Model (2)*. It would be impractical to present the full set of figures as shown for the *Base Model (0)* for the additional six model configurations.

Model (1):
Model fits to mature male biomass and to mature female biomass along with the respective model estimated population of mature biomass is shown in Figure 44 and Figure 48. Figure 45 and Figure 49 show the model fit to the survey size frequencies for females and males respectively, including the observed survey biomass data. Residuals of model fits to the female survey size frequency data are shown in Figure 46, and those for mature males in Figure 50. The summary plot of the model fit to the survey size frequencies for females and males over all years is shown in Figure 47. Since *Model (1)* estimates survey selectivity in only two periods, Figure 51 shows the fitted survey selectivity curves for males, and Figure 52 shows that for females over these periods.

Model (2):
Model fits to mature male biomass and to mature female biomass along with the respective model estimated population of mature biomass is shown in Figure 53 and Figure 57. Figure 54 and Figure 58 show the model fit to the survey size frequencies for females and males respectively, including the observed survey biomass data. Residuals of model fits to the female survey size frequency data are shown in Figure 55, and those for mature males in Figure 59. The summary plot of the model fit to the survey size frequencies for females and males over all years is shown in Figure 56. The plot of model estimates of annual survey selectivity (Q) for *Model (2*) is shown in Figure 60.

Model (3):
Model fits to mature male biomass and to mature female biomass along with the respective model estimated population of mature biomass is shown in Figure 61 and Figure 65. Figure 62 and Figure 66 show the model fit to the survey size frequencies for females and males respectively, including the observed survey biomass data. Residuals of model fits to the female survey size frequency data are shown in Figure 63, and those for mature males in Figure 67. The summary plot of the model fit to the survey size frequencies for females and males over all years is shown in Figure 64. Since *Model (3)* estimates survey selectivity in only two periods, Figure 68 shows the fitted survey selectivity curves for males, and Figure 69 shows that for females over these periods.

Model (4):
Model fits to mature male biomass and to mature female biomass along with the respective model estimated population of mature biomass is shown in Figure 70 and Figure 74. Figure 71 and Figure 75 show the model fit to the survey size frequencies for females and males respectively, including the observed survey biomass data. Residuals of model fits to the female survey size frequency data are shown in Figure 72, and those for mature males in Figure 76. The summary plot of the model fit to the survey size frequencies for females and males over all years is shown in Figure 73.

Model (5):
Model fits to mature male biomass and to mature female biomass along with the respective model estimated population of mature biomass is shown in Figure 77 and Figure 81. Figure 78 and Figure 82 show the model fit to the survey size frequencies for females and males respectively, including the observed survey biomass data. Residuals of model fits to the female survey size frequency data are shown in Figure 79, and those for mature males in Figure 83. The summary plot of the model fit to the survey size frequencies for females and males over all years is shown in Figure 80.

Model (6):
Model fits to mature male biomass and to mature female biomass along with the respective model estimated population of mature biomass is shown in Figure 84 and Figure 88. Figure 85 and Figure 89 show the model fit to the survey size frequencies for females and males respectively, including the observed survey biomass data. Residuals of model fits to the female survey size frequency data are shown in Figure 86, and those for mature males in Figure 90. The summary plot of the model fit to the survey size frequencies for females and males over all years is shown in Figure 87.

Since *Model (6)* estimates one sex-specific fishery selectivity curve over all years for the directed fishery, and the non-directed snow crab, Bristol Bay red king crab and groundfish fisheries, we present the estimated fishery selectivity curves and the summary plots of the model fits to the retained or discard catch in these fisheries. Figure 91 shows the selectivity curves estimated for discard catch of Tanner crab in the snow crab fishery. Discard catch of male and female Tanner crab in the Bristol Bay red king crab fishery is shown in Figure 92, and that in the EBS groundfish fisheries in Figure 93. Figure 94 shows the estimated total selectivity of male Tanner crab in the directed fishery, and the estimated fraction of total male catch retained in the directed fishery is shown in Figure 95. The summary fit to the discards of male

and female Tanner crab in the snow crab fishery is shown in Figure 96. Figure 97 and Figure 98 show the summary fit to the discards of male and female Tanner crab in the Bristol Bay red king crab fishery and in the groundfish fisheries, respectively. Figure 99 shows the summary fit to the total discard plus retained male size frequency data for all shell condition classes combined. The summary fit to the retained male size frequency data for all shell condition classes combined is shown in Figure 100.

1. State of Alaska Harvest Strategy Prior to 2011/12

The SOA harvest strategy (Zheng and Kruse 2000) in effect prior to the change in 2011/12 was: Let MFB_t be the estimate of mature female biomass in the Eastern Subdistrict (i.e., the waters of the Bering Sea District east of 173^0 W longitude) at the time of the survey in year t defined as the estimated biomass of females > 79 mm carapace width (cw), MFB_{t-1} be the estimate of mature female biomass in the Eastern Subdistrict at the time of the survey in the previous year (t-1), $MMMA_t$ be the molting mature male abundance in each area east and west of 166^0 W longitude within the Eastern Subdistrict at the time of the survey in year t defined as the estimated abundance of all new-shell males > 112-mm cw plus 15% of the estimated abundance of old-shell males > 112-mm cw, $ELMA_t$ be the exploitable legal male abundance in each area east and west of 166^0 W longitude within the Eastern Subdistrict at the time of the survey in year t defined as the estimated abundance of all new-shell legal males ≥ 138 mm cw plus 32% of the estimated abundance of old-shell legal males ≥ 138 mm cw, W_t be the average weight of legal males in the Eastern Subdistrict east or west of 166^0 W longitude in year t estimated by applying a weight-length relationship to the survey size-frequency data for legal (≥ 138 mm cw) males, HG_{COMP} be the total allowable catch computed for each area east and west of 166^0 W longitude in the Eastern Subdistrict, HG_{CAP} be the capped total allowable catch derived for each area east and west of 166° W longitude in the Eastern Subdistrict. In applying the control rule, [i] a separate HG is determined as the minimum of the HG_{COMP} and the HG_{CAP} for each area east and west of 166^0 W longitude, and [ii] the HG of legal males in each area east or west of 166^0 W longitude in the Eastern Subdistrict is capped at 50% of the exploitable legal male abundance.

The control rule for the HG during year t in each area east and west of 166^0 W longitude in the Eastern Subdistrict is as follows: (mp=million pounds).

1. If $MFB_{t-1} < 21.0$ mp and $MFB_t < 21.0$ mp, then $HG_{COMP}=0$ and $HG_{CAP}=0$.
2. If $MFB_{t-1} < 21.0$ mp and 21.0 mp $\leq MFB_t < 45.0$ mp, then $HG_{COMP}=0.05MMMA_tW_t$ and $HG_{CAP}=0.25ELMA_tW_t$.
3. If $MFB_{t-1} < 21.0$ mp and $MFB_t \geq 45.0$ mp, then $HG_{COMP}=0.1MMMA_tW_t$ and $HG_{CAP}=0.25ELMA_tW_t$.
4. If $MFB_{t-1} \geq 21.0$ mp and $MFB_t < 21.0$ mp, then $HG_{COMP}=0$ and $HG_{CAP}=0$.
5. If $MFB_{t-1} \geq 21.0$ mp and 21.0 mp $\leq MFB_t < 45.0$ mp, then $HG_{COMP}=0.1MMMA_tW_t$ and $HG_{CAP}=0.5ELMA_tW_t$.
6. If $MFB_{t-1} < 21.0$ mp and $MFB_t \geq 45.0$ mp, then $HG_{COMP}=0.2MMMA_tW_t$ and $HG_{CAP}=0.5ELMA_tW_t$.

In March 2011, the Alaska Board of Fisheries approved a new minimum size limit strategy for Tanner crab effective for the 2011/12 fishery. The previously minimum legal size limit was 5.5” (138 mm cw) throughout the Eastern Subdistrict. The new regulations established different minimum size limits east and west of 166° West longitude. That for the fishery to the east will be 4.8” (122 mm cw), and that to the west will be 4.4” (112 mm cw). The industry may self-impose retention of crab above 5.5” (138 mm cw) and 5” (127 mm cw) east and west of 166° West longitude, respectively. The operational framework of the thee new regulations will be incorporated in stock projections.

2. Overfishing Control Rule

Amendment 24 to the NPFMC fishery management plan (NPFMC 2007) introduced revised the definitions for overfishing for EBS crab stocks. The information provided in this assessment is sufficient to estimate overfishing limits for Tanner crab under Tier 3b. The OFL control rule for Tier 3b is based on spawning biomass-per-recruit reference points (NPFMC 2007).

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

where,

B_t	mature male biomass at time of mating in year t
B_{REF}	proxy for B_{MSY} defined as mature male biomass at time of mating resulting from fishing at F_{REF} (proxy F_{MSY})
F_{REF}	F_{MSY} proxy defined as the fishing mortality that reduces mature male biomass at the time of mating-per-recruit to specified percent of its unfished level
α	fraction of B_{REF} where the harvest control rule intersects the x-axis if extended below β
β	fraction of B_{REF} below which directed fishing mortality is 0

The total catch, including all bycatch of both sexes from all fisheries, is estimated by the following equation,

$$catch = \sum_f \sum_s \sum_l \frac{F_{f,s,l}}{F_{tot,s,l}}(1-e^{-(F_{tot,s,l})})w_{s,l}N_{s,l}\,e^{-M*.62}$$

where, $N_{S,l}$ is the 2011 numbers in length bin *l* and sex *s* at the time of the survey estimated from the population dynamics model, M_s is natural mortality by sex, 0.62 is the time elapsed (in years) from when the survey occurs to the fishery, F_{tot} is the value estimated from the OFL control rule using the 2011 mature male biomass projected forward to the time of mating time (February 2011), $F_{f,s,l}$ is partial value for each directed and non-directed fishery component in length bin *l* by sex, and $w_{s,l}$ is the mean weight in length bin *l* by sex. Fishery selectivity by length for the total catch (retained plus discard) and retained catch estimated from the population dynamics model (Figures 16 and 17).

3. B_{MSY} Proxy $B_{35\%}$

For the *Base Model (0)*, we estimated $B_{35\%}$=162.31 thousand t and $F_{35\%}$=0.574. The model estimate of 2010/11 MMB at mating (53.45 thousand t) represents $0.33B_{35\%}$. The proxy B_{MSY} used in the 2011 SAFE for OFL-setting under Tier-4 is estimated as the average observed MMB at the time of mating from survey data over the reference period 1974-1980 at 83,330 t (Rugolo and Turnock 2011). The bias-corrected proxy B_{MSY} based on adjusted MMB at mating following the method of Rugolo and Turnock (2011c) is 93,240 t. The bias-corrected proxy B_{MSY} is calculated after extraction of the F_{MSY} catch rather than the observed catch which is a more consistent benchmark regardless of whether observed catches were larger or smaller than the F_{MSY} catch. In the 2011 Tier-4 Tanner crab SAFE, Rugolo and Turnock (2011) estimated that after extraction of the total catch OFL, the resulting $MMB_{2011/12}/B_{MSY\ Proxy}$=0.28 using the bias-corrected proxy B_{MSY}, and 0.32 using the non-bias corrected proxy B_{MSY}.

By comparison, the average of the *Base Model(0)* estimated MMB at mating over 1974-1980 is 198,310 t. After extraction of the 2011/12 total catch OFL, the resulting MMB at mating in 2011 = 52,650 t which represents a ratio $MMB_{2011/12}/B_{MSY\ Proxy}$=0.27. This is comparable to the bias-corrected Tier-4 assessment results using the same reference period.

The Tanner crab stock experienced a one-way trip from high biomass levels in the late-1960s and early-1970s to low levels in the 1980's to the present. The performance of stock and fishery reveal that the Tanner crab experienced a severe stock decline over the period of record. The stock was declared overfished in 2010 by the NOAA Fisheries and in need of a rebuilding plan (Rugolo and Turnock 2010). The historical bimodal distribution in male mature biomass (Figure 15) reflects that of the attendant directed fisheries (Figure 13) with peak modes in the early- and late-1970s and early-1990s, and depressed stock status subsequent to these modes. Full-selection fishing mortality rates estimated in the model concur with a history of excessive exploitation (Figure 40, Table 7) averaging 0.98 (1977/78-1981/82) peaking in 1980/81 at 1.45, and averaging 1.12 (1990/91-1994/95) peaking in 1992/93 at 2.08 coincident with peak extraction of catch and decline in stock biomass. If the $F_{35\%}$ OFL control rule established by Amendment 24 had been in effect from 1974/75-2010/11, in approximately one-half of the 44 years, the realized F would have exceeded the overfishing limit (Figure 41). Fishing mortality rates on male Tanner crab have often exceeded the F_{OFL}, however, this did not constitute overfishing in the past because Amendment 24 was implemented in 2008.

Recruitment to the model of crab 25 mm to 50 mm cw fluctuated widely from 1950-2006 displaying a prominent period of moderately high recruitment in the early-to-mid-1960s (Figure 31). These recruitments gave rise to the peak male mature biomass levels in the early-1970s. Recruitments to the stock following the precipitous decline in stock biomass from the 1970s have been low and insufficient to maintain the stock at levels observed pre-1980 or provide for stock growth.

The EBS Tanner crab stock was under a rebuilding plan for 1999-2009 and the directed fishery closed from 1997 to 2004 as a result of severely depressed stock status. Under the former BSAI King and Tanner Crab fishery management plan (NPFMC 1998) and overfishing definitions, the Tanner crab stock was above the B_{MSY} level indicative of a restored stock for the second consecutive year in 2007 and declared rebuilt. As note, the increase in observed biomass in 2005-2008 was driven principally by hot-spot tows that inflated total biomass estimates (Rugolo and Turnock 2008). It was doubtful that MMB increased as suggested by estimated survey biomass. MMB declined in 2008-2010 from the apparent 2007 level and the stock was declared overfished in 2010 (Rugolo and Turnock 2010) and deemed in need of a rebuilding plan.

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Table 1. Eastern Bering Sea Tanner crab retained catch in the United States pot, the Japanese tangle net and pot, and the Russian tangle net fisheries, 1965/66-2010/11.

	Eastern Bering Sea *Chionoecetes bairdi* Retained Catch (1000T)			
	US Pot	Japan	Russia	Total
Year				
1965/66		1.17	0.75	1.92
1966/67		1.69	0.75	2.44
1967/68		9.75	3.84	13.60
1968/69	0.46	13.59	3.96	18.00
1969/70	0.46	19.95	7.08	27.49
1970/71	0.08	18.93	6.49	25.49
1971/72	0.05	15.90	4.77	20.71
1972/73	0.10	16.80		16.90
1973/74	2.29	10.74		13.03
1974/75	3.30	12.06		15.24
1975/76	10.12	7.54		17.65
1976/77	23.36	6.66		30.02
1977/78	30.21	5.32		35.52
1978/79	19.28	1.81		21.09
1979/80	16.60	2.40		19.01
1980/81	13.47			13.43
1981/82	4.99			4.99
1982/83	2.39			2.39
1983/84	0.55			0.55
1984/85	1.43			1.43
1985/86	0			0
1986/87	0			0
1987/88	1.00			1.00
1988/89	3.15			3.18
1989/90	11.11			11.11
1990/91	18.19			18.19
1991/92	14.42			14.42
1992/93	15.92			15.92
1993/94	7.67			7.67
1994/95	3.54			3.54
1995/96	1.92			1.92
1996/97	0.82			0.82
1997/98	0			0
1998/99	0			0
1999/00	0			0
2000/01	0			0
2001/02	0			0
2002/03	0			0
2003/04	0			0
2004/05	0			0
2005/06	0.43			0.43
2006/07	0.96			0.96
2007/08	0.96			0.96
2008/09	0.88			0.88
2009/10	0.60			0.60
2010/11	0			0

Table 2. Eastern Bering Sea Tanner crab discards (1000 t) in the domestic pot fisheries and groundfish fisheries, 1973/74-2010/11. No discard mortality applied.

	Discards (1000 t) of Tanner Crab by Fishery						
	Tanner Crab		Snow Crab		Red King Crab		Groundfish
Year	Male	Female	Male	Female	Male	Female	♀+♂
1973/74							17.737
1974/75							24.450
1975/76							9.410
1976/77							4.700
1977/78							2.776
1978/79							1.868
1979/80							3.395
1980/81							2.114
1981/82							1.472
1982/83							0.449
1983/84							0.672
1984/85							0.646
1985/86							0.397
1986/87							0.650
1987/88							0.638
1988/89							0.464
1989/90							0.672
1990/91							0.945
1991/92							2.543
1992/93	10.986	1.787	25.759	1.787	1.188	0.029	2.760
1993/94	6.831	1.814	14.530	1.814	2.967	0.198	1.758
1994/95	3.130	1.270	7.124	1.271	0.000	0	2.096
1995/96	2.762	1.760	4.797	1.759	0.000	0	1.525
1996/97	0.236	0.091	0.833	0.229	0.027	0.004	1.594
1997/98	0	0	1.750	0.226	0.165	0.003	1.180
1998/99	0	0	1.989	0.175	0.119	0.003	0.935
1999/00	0	0	0.695	0.145	0.076	0.004	0.631
2000/01	0	0	0.146	0.022	0.067	0.002	0.742
2001/02	0	0	0.323	0.011	0.043	0.002	1.185
2002/03	0	0	0.557	0.037	0.062	0.003	0.719
2003/04	0	0	0.193	0.026	0.056	0.003	0.424
2004/05	0	0	0.078	0.014	0.048	0.003	0.675
2005/06	0.286	0.027	0.968	0.043	0.042	0.002	0.621
2006/07	1.243	0.322	1.462	0.169	0.026	0.003	0.717
2007/08	2.100	0.100	1.872	0.102	0.056	0.009	0.695
2008/09	0.431	0.014	1.119	0.050	0.270	0.004	0.533
2009/10	0.071	0.002	1.324	0.014	0.150	0.001	0.321
2010/11	0	0	1.344	0.016	0.033	0.001	0.217

Table 3. Observed survey female, male and total spawning biomass (1000 t) and observed abundance of legal male crab ≥ 138mm (million crab), 1974-2011.

Observed Survey Mature Male and Female Biomass and Legal Male Abundance				
Year	Mature Biomass (1000 t)			Male ≥ 138 mm (10^6 crab)
	Male	Female	Total	
1974	212.01	55.76	267.77	87.53
1975	265.07	38.76	303.83	151.45
1976	152.09	45.99	198.08	86.07
1977	130.41	47.59	177.99	68.49
1978	80.62	26.43	107.06	37.65
1979	47.82	20.43	68.25	21.33
1980	86.33	70.42	156.76	28.53
1981	50.67	45.24	95.91	10.14
1982	49.67	64.76	114.43	6.82
1983	29.04	20.72	49.76	4.70
1984	26.15	14.72	40.87	6.19
1985	11.71	5.68	17.39	3.54
1986	13.18	3.49	16.67	2.27
1987	24.18	5.27	29.46	5.73
1988	59.51	25.57	85.08	15.60
1989	101.48	25.47	126.96	32.73
1990	103.17	36.36	139.52	42.93
1991	110.82	45.56	156.37	33.89
1992	108.12	27.76	135.88	39.65
1993	62.12	11.91	74.03	18.22
1994	44.55	10.37	54.92	14.81
1995	33.86	13.44	47.30	9.45
1996	27.32	9.80	37.12	8.56
1997	11.07	3.53	14.60	3.24
1998	10.56	2.31	12.87	1.97
1999	12.40	3.81	16.21	2.07
2000	16.45	4.17	20.63	4.60
2001	18.20	4.61	22.81	5.97
2002	18.23	4.48	22.71	5.94
2003	23.71	8.35	32.06	6.31
2004	25.56	4.70	30.26	4.50
2005	43.99	11.62	55.61	10.41
2006	66.89	15.79	82.68	13.36
2007	72.63	13.33	85.97	10.90
2008	59.70	11.33	71.03	14.39
2009	37.60	8.22	45.82	6.91
2010	36.14	5.44	41.59	8.01
2011	46.30	8.67	54.97	13.68

Table 4. *Base Model (0)* predicted retained and discard catch (1000 t) by sex in the directed Tanner crab pot fishery, 1974/75-2010/11.

Directed Fishery Predicted Retained and Discard Catch Biomass (1000 t)				
Year	Retained	Discard Catch		Total
	Male Catch	Male	Female	Male Catch
1974/75	15.23	6.88	0.39	22.11
1975/76	17.65	7.58	0.44	25.23
1976/77	30.01	13.99	0.83	43.99
1977/78	35.51	19.86	1.25	55.37
1978/79	21.07	13.84	0.95	34.91
1979/80	18.93	15.28	1.21	34.21
1980/81	13.38	17.15	1.55	30.52
1981/82	5.00	6.68	0.50	11.67
1982/83	2.43	1.82	0.12	4.25
1983/84	0.62	0.31	0.02	0.92
1984/85	1.46	0.57	0.03	2.02
1985/86	0	0	0	0
1986/87	0	0	0	0
1987/88	1.00	0.39	0.02	1.38
1988/89	3.14	1.47	0.08	4.61
1989/90	11.05	5.54	0.32	16.59
1990/91	18.10	10.20	0.66	28.30
1991/92	14.31	10.26	0.68	24.57
1992/93	15.09	6.83	1.43	21.92
1993/94	7.31	4.02	0.73	11.33
1994/95	3.18	2.14	0.22	5.32
1995/96	1.66	1.80	0.08	3.46
1996/97	0.55	0.58	0.02	1.13
1997/98	0	0	0	0
1998/99	0	0	0	0
1999/00	0	0	0	0
2000/01	0	0	0	0
2001/02	0	0	0	0
2002/03	0	0	0	0
2003/04	0	0	0	0
2004/05	0	0	0	0
2005/06	0.33	0.39	0.01	0.71
2006/07	0.86	0.86	0.02	1.72
2007/08	0.95	1.11	0.02	2.06
2008/09	0.82	0.34	0.02	1.17
2009/10	0.57	0.04	0.03	0.61
2010/11	0	0	0	0

Table 5. *Base Model (0)* predicted discard catch (1000 t) by sex in the non-directed domestic pot and groundfish fisheries by sex, 1974/75-2010/11.

Non-Directed Fishery Predicted Discard Catch Biomass (1000 t)					
Year	Snow Crab Fishery		Red King Crab Fishery		GF Fishery
	Male	Female	Male	Female	Male + Female
1974/75	0.99	0.11	5.36	1.4E-02	19.56
1975/76	0.64	0.07	5.60	1.5E-02	7.53
1976/77	0.90	0.10	5.64	1.6E-02	3.76
1977/78	0.88	0.10	4.50	1.4E-02	2.24
1978/79	1.12	0.14	3.96	1.4E-02	1.52
1979/80	3.24	0.43	3.27	1.3E-02	2.71
1980/81	5.14	0.62	2.88	1.3E-02	1.71
1981/82	5.11	0.57	0.97	3.8E-03	1.21
1982/83	2.18	0.24	0.99	3.2E-03	0.53
1983/84	1.65	0.19	1.18	3.4E-03	0.65
1984/85	1.36	0.16	0	0	0.63
1985/86	2.86	0.34	0	0	0.48
1986/87	4.12	0.48	0.85	2.1E-03	0.61
1987/88	4.87	0.53	0.78	1.9E-03	0.58
1988/89	7.19	0.76	0.82	2.0E-03	0.48
1989/90	7.91	0.88	0.83	2.2E-03	0.59
1990/91	8.09	0.94	0.72	2.2E-03	0.76
1991/92	13.94	1.75	0.58	2.0E-03	1.99
1992/93	12.73	1.78	0.22	8.0E-04	2.17
1993/94	7.25	1.10	0.16	6.0E-04	1.40
1994/95	3.62	0.58	0	0	1.69
1995/96	2.57	0.45	0	0	1.25
1996/97	0.65	0.12	0.08	3.2E-04	1.34
1997/98	0.89	0.35	0.05	1.9E-06	0.91
1998/99	0.59	0.21	0.04	1.4E-06	0.55
1999/00	0.16	0.05	0.04	1.2E-06	0.27
2000/01	0.15	0.04	0.04	1.2E-06	0.40
2001/02	0.23	0.06	0.05	1.3E-06	0.86
2002/03	0.37	0.09	0.05	1.4E-06	0.56
2003/04	0.32	0.08	0.06	1.6E-06	0.39
2004/05	0.24	0.06	0.08	2.1E-06	0.54
2005/06	0.46	0.12	0.06	2.2E-07	0.50
2006/07	0.71	0.18	0.07	2.9E-07	0.59
2007/08	0.95	0.24	0.09	3.2E-07	0.61
2008/09	0.70	0.18	0.09	3.3E-07	0.51
2009/10	0.72	0.17	0.10	3.3E-07	0.38
2010/11	0.67	0.15	0.1	3.2E-07	0.31

Table 6. *Base Model (0)* predicted total (retained + discard) Tanner crab catch biomass (1000 t) in the directed and non-directed fisheries, 1973/74-2010/11. Post-release discard mortality rates applied (0.50=pot and 0.80=groundfish).

Year	Total Catch Biomass (1000 t)	
	Male	Female
1973/74	38.24	10.29
1974/75	35.23	4.29
1975/76	52.42	2.83
1976/77	61.86	2.48
1977/78	40.75	1.86
1978/79	42.08	3.00
1979/80	39.40	3.04
1980/81	18.36	1.69
1981/82	7.68	0.62
1982/83	4.08	0.54
1983/84	3.70	0.51
1984/85	3.10	0.58
1985/86	5.27	0.78
1986/87	7.32	0.84
1987/88	12.85	1.09
1988/89	25.63	1.50
1989/90	37.49	1.98
1990/91	40.08	3.43
1991/92	35.95	4.29
1992/93	19.44	2.53
1993/94	9.79	1.65
1994/95	6.65	1.15
1995/96	2.54	0.81
1996/97	1.40	0.81
1997/98	0.90	0.48
1998/99	0.33	0.18
1999/00	0.39	0.24
2000/01	0.71	0.49
2001/02	0.70	0.37
2002/03	0.58	0.28
2003/04	0.59	0.33
2004/05	1.48	0.39
2005/06	2.80	0.50
2006/07	3.40	0.56
2007/08	2.22	0.45
2008/09	1.62	0.39
2009/10	0.93	0.31

Table 7. *Base Model (0)* estimates of population biomass and abundance, male, female and total mature biomass, abundance of legal (≥ 138mm) males, recruitment to the population, male mature biomass at mating, and full-selection fishing mortality rate. (Biomass in 1000 t, abundance in 10^6 crab).

Year	Population ≥ 25mm		Mature Biomass (1000 t)			Males ≥ 138 mm	R > 25-30mm	MMB @Mating	Full-Selection
	1000 t	10^6 crab	Female	Male	Total	10^6 crab	10^6 crab	1000 t	F
1974/75	733.68	3094.22	132.72	455.71	588.43	176.82	140.29	350.53	0.19
1975/76	629.12	2581.37	113.80	401.79	515.59	157.62	719.92	308.95	0.21
1976/77	552.26	3376.84	97.94	345.55	443.49	131.85	378.90	245.00	0.42
1977/78	468.09	3327.86	82.86	276.62	359.48	98.12	314.30	177.47	0.73
1978/79	393.55	3158.92	70.62	202.32	272.94	62.24	54.18	134.48	0.69
1979/80	357.98	2533.62	66.72	156.61	223.33	41.71	28.08	95.19	1.06
1980/81	335.03	1968.74	70.16	128.12	198.28	25.27	114.77	76.54	1.45
1981/82	319.29	1687.62	72.89	130.16	203.05	23.94	54.73	97.41	0.42
1982/83	310.85	1377.22	69.33	162.32	231.65	45.87	400.83	132.66	0.10
1983/84	299.92	1847.46	59.71	181.72	241.44	64.71	233.46	152.04	0.03
1984/85	277.59	1899.08	48.56	175.04	223.60	70.18	252.00	146.40	0.03
1985/86	259.60	1984.42	40.70	152.11	192.81	62.86	291.31	127.58	0.00
1986/87	257.56	2133.66	38.39	132.06	170.44	53.77	194.38	108.83	0.01
1987/88	265.85	2054.18	41.19	123.20	164.39	47.88	139.27	99.97	0.04
1988/89	278.11	1875.32	45.43	128.71	174.14	47.30	75.37	100.41	0.11
1989/90	280.29	1593.04	48.00	138.13	186.13	52.24	44.69	96.58	0.37
1990/91	260.15	1289.32	48.49	132.42	180.91	48.36	12.41	80.66	0.73
1991/92	219.81	967.18	46.10	113.39	159.49	36.92	10.95	63.54	0.83
1992/93	168.26	691.30	40.05	89.03	129.08	28.19	7.82	45.16	2.08
1993/94	116.78	473.80	31.64	62.11	93.75	17.32	22.22	36.16	1.38
1994/95	84.47	365.07	24.36	46.71	71.07	12.91	36.34	30.98	0.56
1995/96	63.92	328.89	18.39	36.83	55.22	11.07	16.89	25.21	0.27
1996/97	48.19	270.67	13.62	27.55	41.17	9.10	53.97	20.85	0.14
1997/98	40.53	308.88	10.42	21.59	32.01	7.43	20.40	16.92	0.05
1998/99	36.18	276.25	8.32	17.61	25.93	6.20	84.57	14.15	0.04
1999/00	36.77	381.52	7.34	15.92	23.26	5.51	76.93	13.30	0.02
2000/01	40.60	453.11	7.12	16.59	23.70	5.78	205.35	13.79	0.03
2001/02	49.84	766.93	7.34	18.09	25.43	6.54	48.38	14.72	0.05
2002/03	58.14	701.97	8.14	19.85	27.99	7.18	84.59	16.35	0.03
2003/04	69.81	722.23	9.97	23.05	33.02	8.32	143.77	19.25	0.02
2004/05	85.57	856.18	13.09	29.02	42.12	9.93	45.46	24.35	0.02
2005/06	99.79	764.60	16.45	39.15	55.60	13.28	33.04	32.27	0.05
2006/07	109.50	663.33	18.31	51.01	69.32	18.27	31.01	41.23	0.08
2007/08	112.12	575.36	18.90	58.93	77.83	23.33	36.47	47.41	0.07
2008/09	109.13	514.36	18.97	61.08	80.06	24.56	149.06	50.21	0.06
2009/10	107.49	693.17	17.94	63.26	81.20	25.46	152.89	52.65	0.09
2010/11	105.45	845.41	15.79	63.46	79.25	27.16	101.82	53.45	0.01
2011/12	103.77	867.03	14.01	59.02	73.04	26.26	-	49.08	-

Table 8. *Base Model (0)* parameter values and whether parameters were estimated in the model, excluding recruitments and fishing mortality parameters.

Parameter	Value	S.Deviation	Estimated?
Natural Mortality - immature male and female	0.224	0.01	Y
Natural Mortality - mature male	0.249	0.01	Y
Natural Mortality - mature female	0.327	0.01	Y
Female (a) parameter of exponential growth	1.82	0.12	Y
Female (b) parameter of exponential growth	0.90	0.01	Y
Male (a) parameter of exponential growth	1.62	0.08	Y
Male (b) parameter of exponential growth	0.94	0.01	Y
Alpha for gamma distribution of recruits	11.5		N
Beta for gamma distribution of recruits	4.0		N
Beta for gamma distribution female growth	0.75		N
Beta for gamma distribution male growth	0.75		N
Fishery selectivity total male slope - 1991-1996	0.12	0.01	Y
Fishery selectivity total male slope - 2005-2010	0.14	0.01	Y
Fishery selectivity total male length at 50%, 1991	134.80	0.02	Y
Fishery selectivity total male length at 50%, 1992	146.33	0.01	Y
Fishery selectivity total male length at 50%, 1993	144.69	0.02	Y
Fishery selectivity total male length at 50%, 1994	138.64	0.02	Y
Fishery selectivity total male length at 50%, 1995	126.00	0.02	Y
Fishery selectivity total male length at 50%, 1996	121.60	0.02	Y
Fishery selectivity total male length at 50%, 2005	121.89	0.01	Y
Fishery selectivity total male length at 50%, 2006	124.47	0.02	Y
Fishery selectivity total male length at 50%, 2007	115.60	0.02	Y
Fishery selectivity total male length at 50%, 2008	133.88	0.01	Y
Fishery selectivity total male length at 50%, 2009	157.33	0.01	Y
Fishery retention curve males slope, 1991-1996	0.69	0.08	Y
Fishery retention curve males length at 50%, 1991-1996	137.96	0.27	Y
Fishery retention curve males slope, 2005-2010	2.00	3.45	Y
Fishery retention curve males length at 50%, 2005-2010	137.56	0.97	Y
Directed Fishery discard selectivity female slope	0.17	0.01	Y
Directed Fishery discard selectivity female length at 50%	111.62	1.69	Y
Snow crab male selectivity slope ascending, 1989-1996	0.08	0.01	Y
Snow crab male selectivity length at 50% ascending, 1989-1996	104.30	3.97	Y
Snow crab male selectivity slope descending, 1989-1996	0.21	0.01	Y
Snow crab male selectivity length at 50% descending, 1989-1996	83.20	0.75	Y
Snow crab male selectivity slope ascending, 1997-2004	0.17	0.01	Y
Snow crab male selectivity length at 50% ascending, 1997-2004	84.59	1.31	Y
Snow crab male selectivity slope descending, 1997-2004	0.33	0.06	Y
Snow crab male selectivity length at 50% descending, 1997-2004	87.96	1.09	Y
Snow crab male selectivity slope ascending, 2005-2010	0.10	0.02	Y
Snow crab male selectivity length at 50% ascending, 2005-2010	129.68	2.87	Y
Snow crab male selectivity slope descending, 2005-2010	0.23	0.02	Y
Snow crab male selectivity length at 50% descending, 2005-2010	92.97	0.77	Y
Snow crab fishery female selectivity slope, 1989-1996	0.17	0.03	Y
Snow crab fishery female selectivity length at 50%, 1989-1996	136.61	1.44	Y
Snow crab fishery female selectivity slope, 1997-2004	0.15	0.01	Y
Snow crab fishery female selectivity length at 50%, 1997-2004	104.81	1.60	Y

Table 8. (continued)

Parameter	Value	S.Deviation	Estimated?
Snow crab fishery female selectivity slope, 2005-2010	0.29	0.04	Y
Snow crab fishery female selectivity length at 50%, 2005-2010	138.77	0.91	Y
Red king crab fishery male selectivity slope, 1989-1996	0.24	0.01	Y
Red king crab fishery male selectivity length at 50%, 1989-1996	114.69	2.58	Y
Red king crab fishery male selectivity slope, 1997-2004	0.18	0.00	Y
Red king crab fishery male selectivity length at 50%, 1997-2004	147.22	20.15	Y
Red king crab fishery male selectivity slope, 2005-2010	0.20	0.00	Y
Red king crab fishery male selectivity length at 50%, 2005-2010	156.24	23.03	Y
Red king crab fishery female selectivity slope, 1989-1996	0.27	0.03	Y
Red king crab fishery female selectivity length at 50%, 1989-1996	118.24	0.88	Y
Red king crab fishery female selectivity slope, 1997-2004	0.11	0.01	Y
Red king crab fishery female selectivity length at 50%, 1997-2004	127.16	1.85	Y
Red king crab fishery female selectivity slope, 2005-2010	0.07	0.00	Y
Red king crab fishery female selectivity length at 50%, 2005-2010	146.10	4.71	Y
Groundfish Fishery male selectivity slope, 1973-1986	0.05	0.01	Y
Groundfish Fishery male selectivity length at 50%, 1973-1986	59.58	4.24	Y
Groundfish Fishery male selectivity slope, 1987-1996	0.01	0.00	Y
Groundfish Fishery male selectivity length at 50%, 1987-1996	250.01	0.03	Y
Groundfish Fishery male selectivity slope, 1997-2010	0.07	0.00	Y
Groundfish Fishery male selectivity length at 50%, 1997-2010	102.16	2.76	Y
Groundfish Fishery female selectivity slope, 1973-1986	0.12	0.02	Y
Groundfish Fishery female selectivity length at 50%, 1973-1986	47.80	1.91	Y
Groundfish Fishery female selectivity slope, 1987-1996	0.03	0.01	Y
Groundfish Fishery female selectivity length at 50%, 1987-1996	79.10	14.42	Y
Groundfish Fishery female selectivity slope, 1997-2010	0.07	0.00	Y
Groundfish Fishery female selectivity length at 50%, 1997-2010	88.75	2.58	Y
Survey Q 1974-1981 – male	0.50	0.00	Y
Survey 1974-1981 length at 95% of Q – male	90.00	0.00	Y
Survey 1974-1981 length at 50% of Q – male	53.78	1.65	Y
Survey Q 1982-1988 – male	0.17	0.01	Y
Survey 1982-1988 length at 95% of Q – male	120.00	0.00	Y
Survey 1982-1988 length at 50% of Q – male	12.97	18.47	Y
Survey Q 1989-2010 – male	0.87	0.04	Y
Survey 1989-2010 length at 95% of Q – male	107.94	22.99	Y
Survey 1989-2010 length at 50% of Q – male	13.31	8.57	Y
Survey Q 1974-1981 – female	1.00	0.00	Y
Survey 1974-1981 length at 95% of Q – female	148.14	7.29	Y
Survey 1974-1981 length at 50% of Q – female	83.76	2.55	Y
Survey Q 1982-1988 – female	0.62	0.10	Y
Survey 1982-1988 length at 95% of Q – female	200.01	0.01	Y
Survey 1982-1988 length at 50% of Q – female	95.60	6.30	Y
Survey Q 1989-2010 – female	0.63	0.03	Y
Survey 1989-2010 length at 95% of Q – female	120.00	0.00	Y
Survey 1989-2010 length at 50% of Q – female	-50.00	0.00	Y
Fishery cpue q	0.00055		N

Table 9. Likelihood values by component for the Tanner crab assessment model shown for *Base Model (0),* and *Model (1)* through *Model (6)*.

Likelihood Component	Likelihood Value						
	Model 0	*Model 1*	*Model 2*	*Model 3*	*Model 4*	*Model 5*	*Model 6*
recruitment deviations	1.6	1.3	2.3	1.4	2.0	1.7	1.3
probability of maturity smooth constraint	2.0	1.9	2.1	1.9	2.0	1.9	1.8
Survey q penalty	12.0	32.9	0.0	37.8	22.5	47.8	7.8
F penalty	30.6	29.2	25.7	28.3	31.3	30.9	26.7
retained length	106.6	126.7	76.9	123.2	95.3	95.5	170.6
total directed length	67.6	69.4	54.5	68.5	61.0	63.7	230.1
female directed length	63.6	61.6	59.6	60.9	66.7	64.6	57.2
survey length	320.2	378.5	253.6	352.6	319.3	362.5	355.3
groundfish fishery length	271.8	287.0	278.0	289.7	281.9	296.0	473.8
snow fishery length	572.5	597.2	572.8	597.0	593.3	568.8	663.8
red king fishery length	1268.4	1314.6	1255.3	1315.9	1265.4	1266.4	1421.6
survey biomass	201.1	245.6	11.5	244.7	207.8	241.8	180.8
fishery cpue	-	-	-	-	-	-	-
directed fishery male discard catch	4.7	4.3	5.0	4.3	5.1	4.9	14.9
directed fishery male retained catch	11.6	13.1	11.7	12.9	13.2	12.6	37.1
directed fishery female discard catch	11.6	11.7	12.3	11.6	12.8	12.1	7.9
groundfish fishery male + female catch	3.1	1.8	1.4	1.8	3.3	2.2	2.0
snow fishery male + female catch	16.7	16.5	13.2	16.4	18.0	20.1	68.1
red king fishery male + female catch	19.3	18.7	13.3	18.4	19.0	18.6	19.9
natural mortality penalty	37.1	34.7	10.9	47.4	51.7	0.0	50.9
survey Q deviation penalty	-	-	34.3	-	-	-	-
Total Likelihood	3024.1	3248.6	2698.3	3236.5	3071.8	3113.2	3792.2

Table 10. Weighting factors for likelihood equations for *Base Model (0),* and *Model (1)* through *Model (6)*. Sample sizes for all length components were set at 200.

Likelihood Component	Weight
retained + discard male catch, male and female discards in snow and red king fisheries	10.0
directed fishery female discards	10.0
groundfish catch	10.0
total catch length composition	1.0
retained catch length composition	1.0
female directed fishery length composition	0.5
survey length composition	1.0
groundfish fishery length composition	0.5
snow and red king fishery length composition	1.0
survey biomass	1.0
recruitment deviations	1.0
directed fishing mortality deviations	0.1
snow fishing mortality deviations	0.5
red king crab fishing mortality deviations	3.0
trawl fishing mortality deviations	0.5
fishery cpue	0
natural mortality penalty standard deviation	0.05
growth penalty male a standard deviation	0.025
growth penalty male b standard deviation	0.1
growth penalty female a standard deviation	0.1
growth penalty female b standard deviation	0.025
penalty on first-difference early recruitment	1.0
penalty on second-difference maturity probability males	0.5
penalty on second-difference maturity probability females	1.0
penalty on survey Q annual deviations	2.0
survey Q standard deviation penalty	0.05

Table 11. Natural mortality rates on immature male and female (pooled), mature female and mature male Tanner crab estimated in *Base Model (0)* through *Model (6)*. M is fixed at 0.23 in *Model (5)*.

	Natural Mortality Rate (M)			
Category	*Model 0*	*Model 1*	*Model 2*	*Model 3*
				Period-1
Immature (M-F)	0.224	0.241	0.232	0.276
Mature (F)	0.327	0.316	0.273	0.310
Mature (M)	0.249	0.271	0.261	0.273
				Model 3
	Model 4	*Model 5*	*Model 6*	Period-2
Immature (M-F)	0.228	0.230	0.264	0.186
Mature (F)	0.343	0.230	0.340	0.242
Mature (M)	0.261	0.230	0.243	0.241

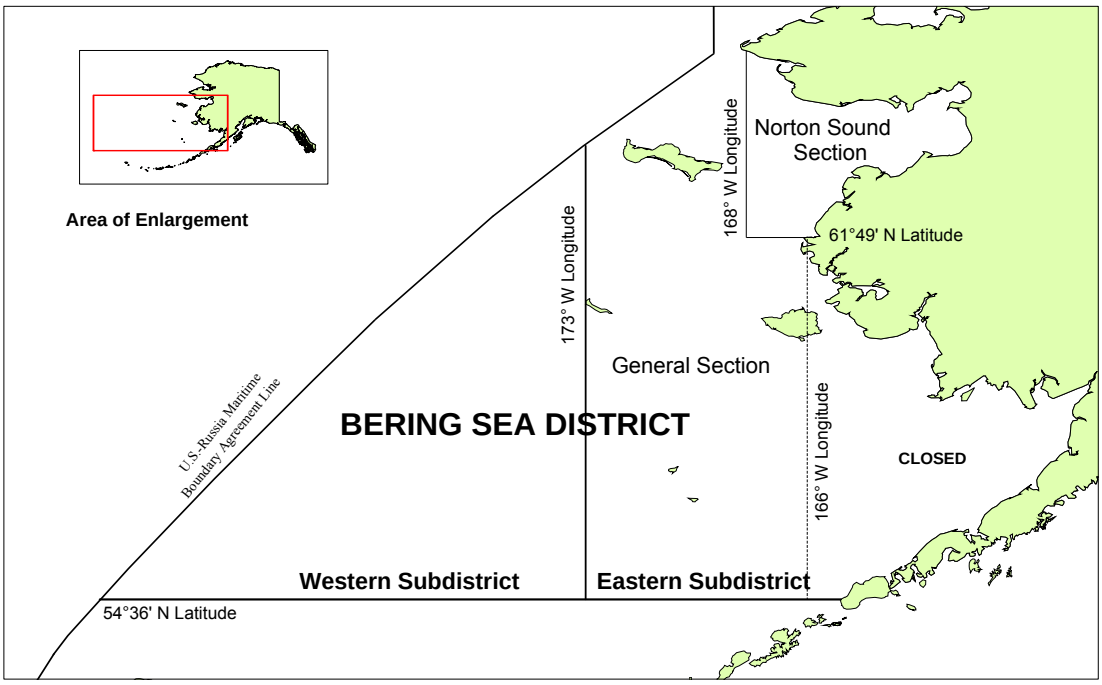


Figure 1. Eastern Bering Sea District of Tanner crab Registration Area J including subdistricts and sections (From Bowers et al. 2008).

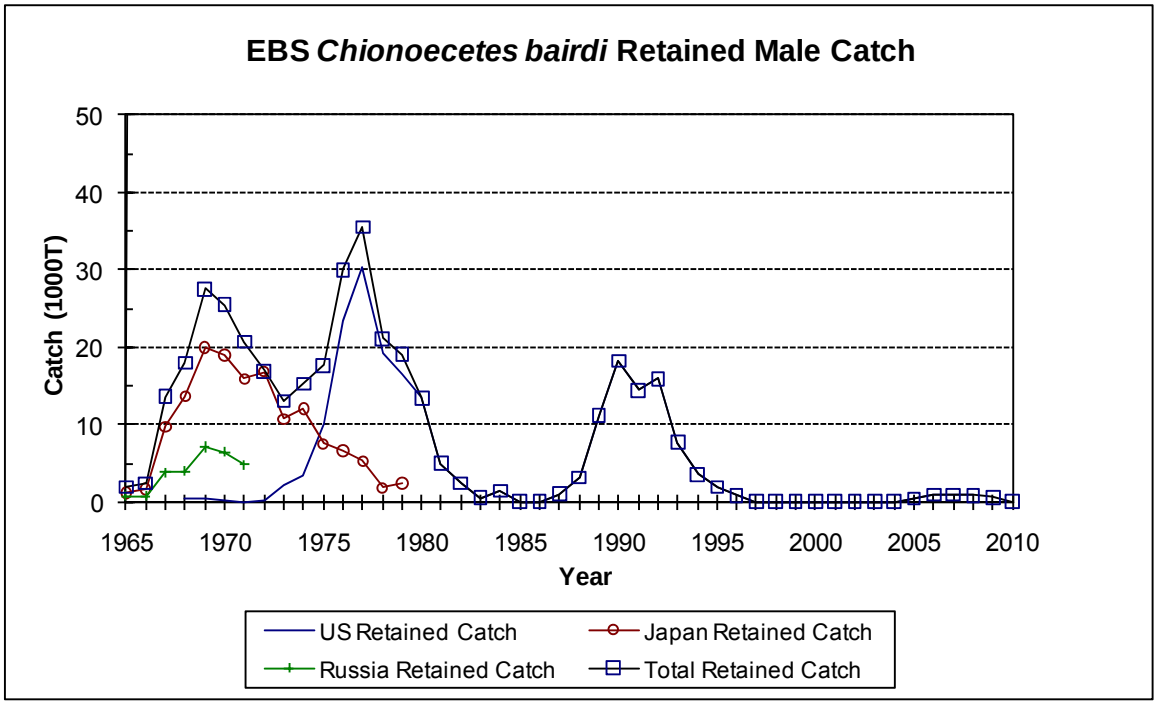


Figure 2. Eastern Bering Sea *C. bairdi* retained male catch in the directed United States, Russian and Japanese fisheries, 1965/66-2010/11.

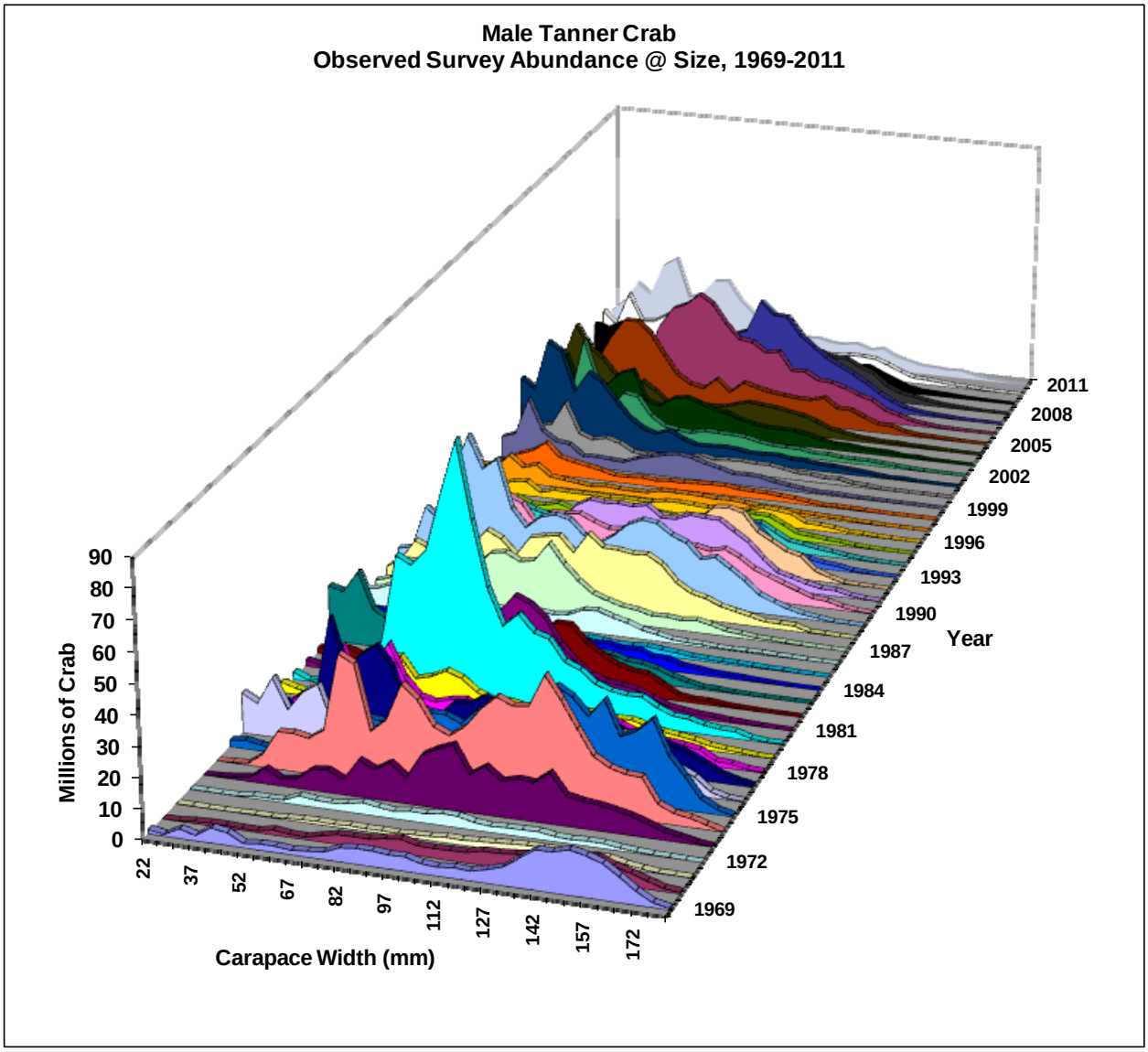


Figure 3. Observed male Tanner crab survey abundance (millions of crab) by carapace width for 1969/70 to 2010/11.

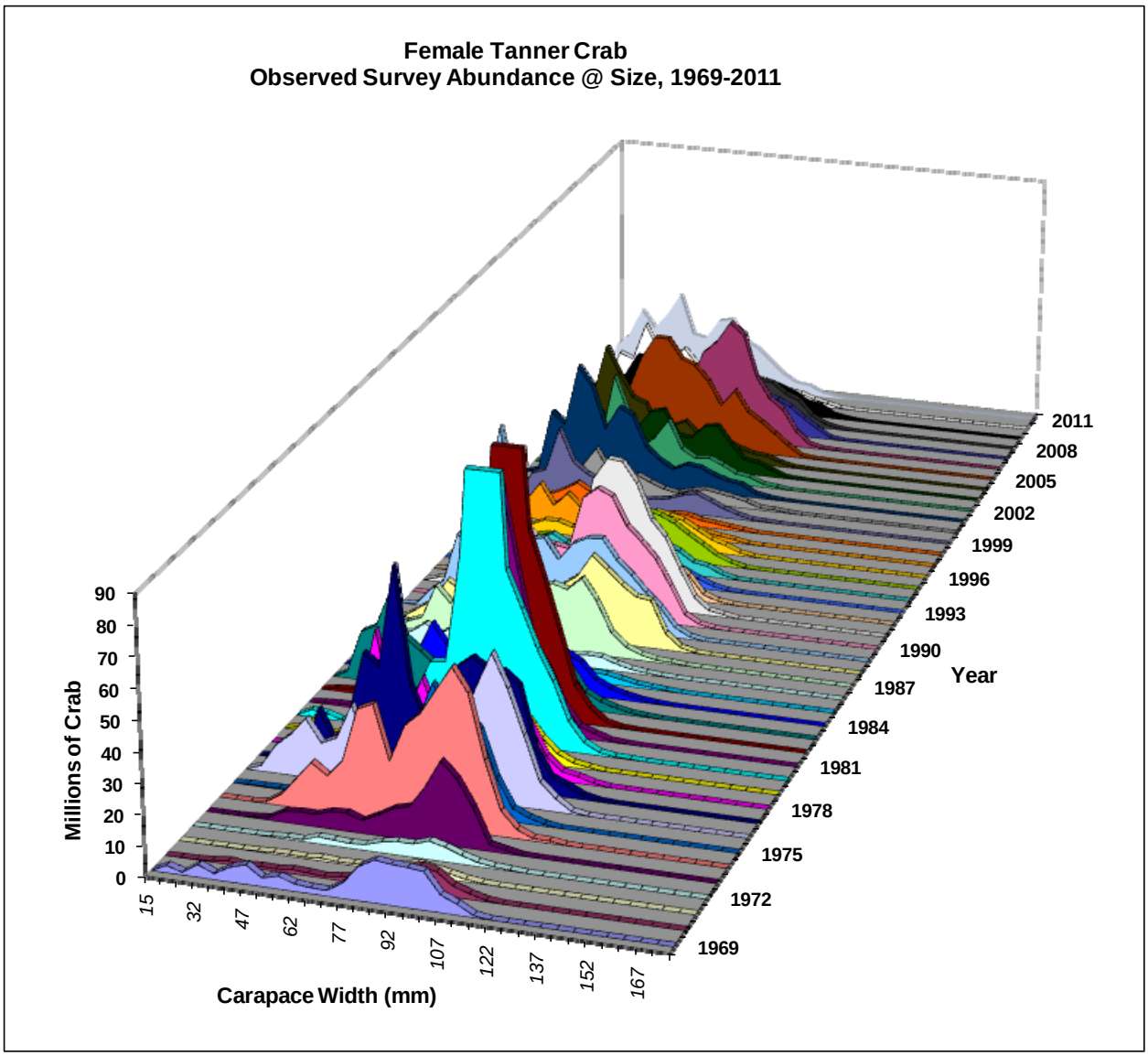


Figure 4. Observed female Tanner crab survey abundance (millions of crab) by carapace width for 1969/70 to 2010/11.

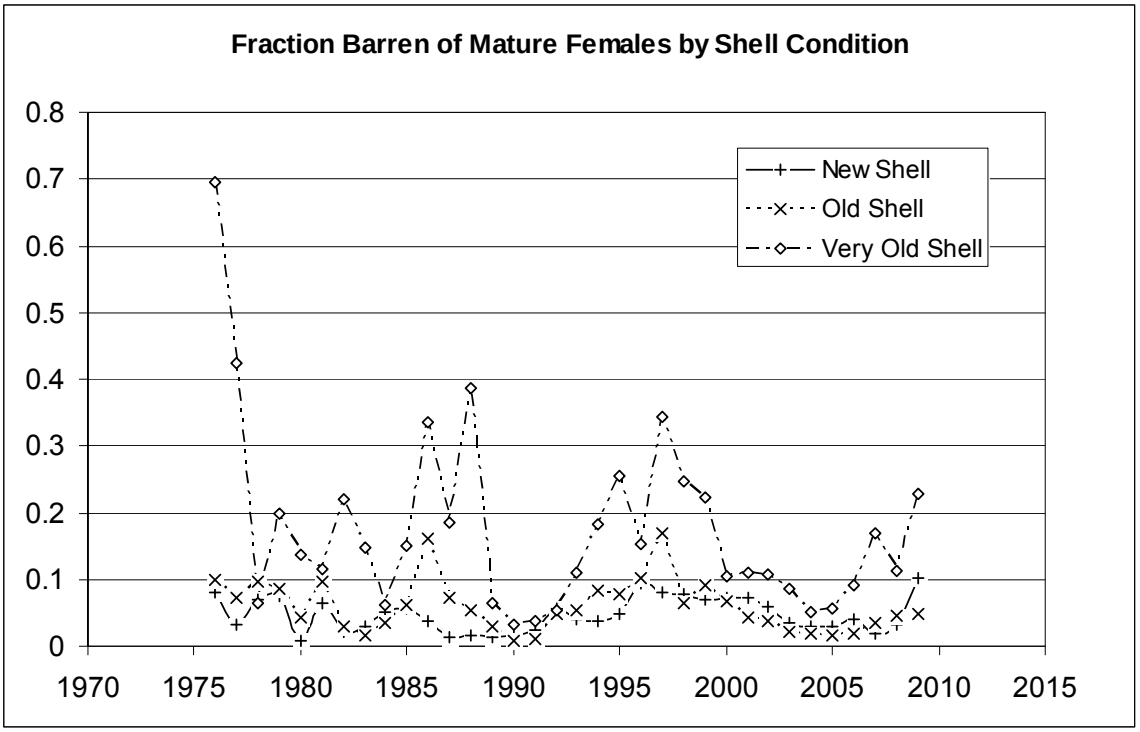


Figure 5. Proportion of female Tanner crab with barren clutches by shell condition from survey data for 1976/77 to 2009/10.

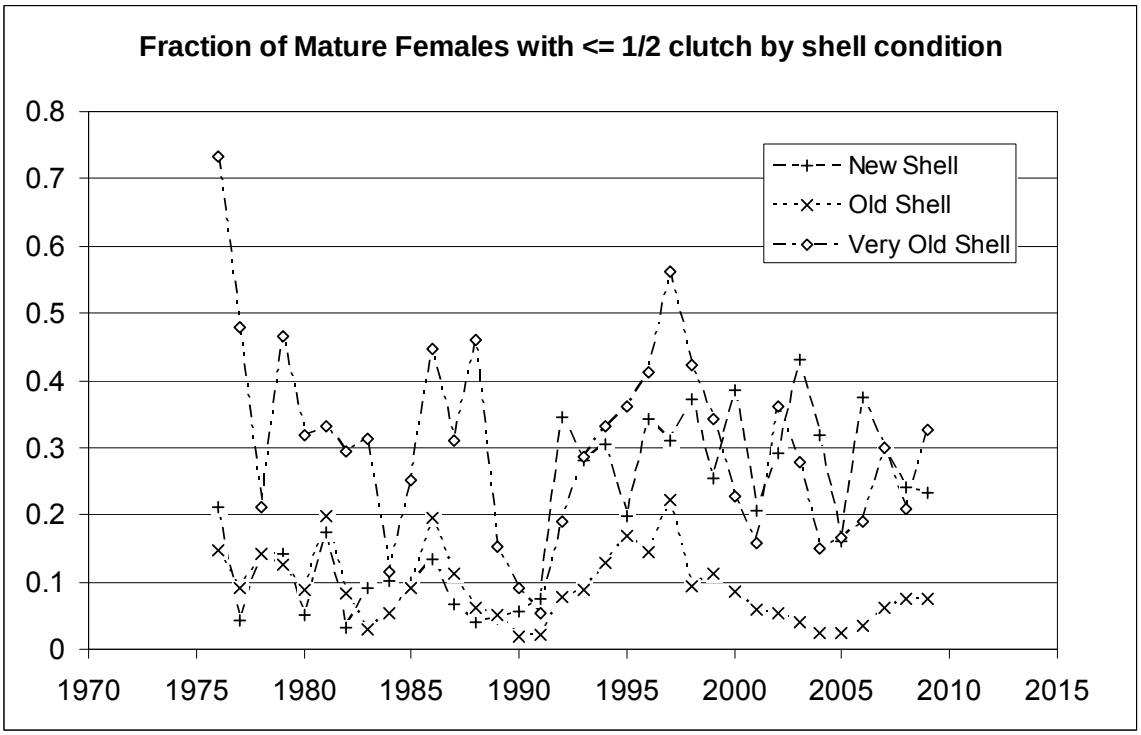


Figure 6. Proportion of female Tanner crab with less than or equal to one-half full clutch by shell condition from survey data 1976/77 to 2009/10.

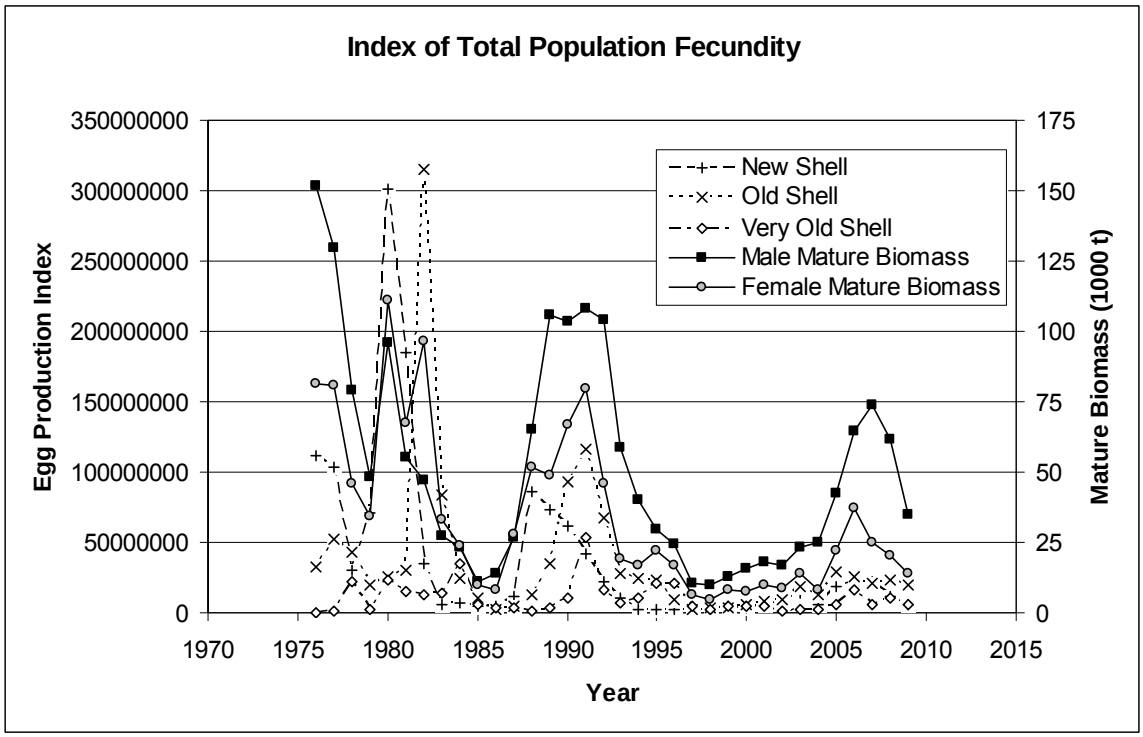


Figure 7. Tanner crab female egg production index (EPI) by shell condition, survey estimate of male mature biomass (1000 t), and survey estimate of female mature biomass (1000 t) from survey data for 1976/77 to 2009/10.

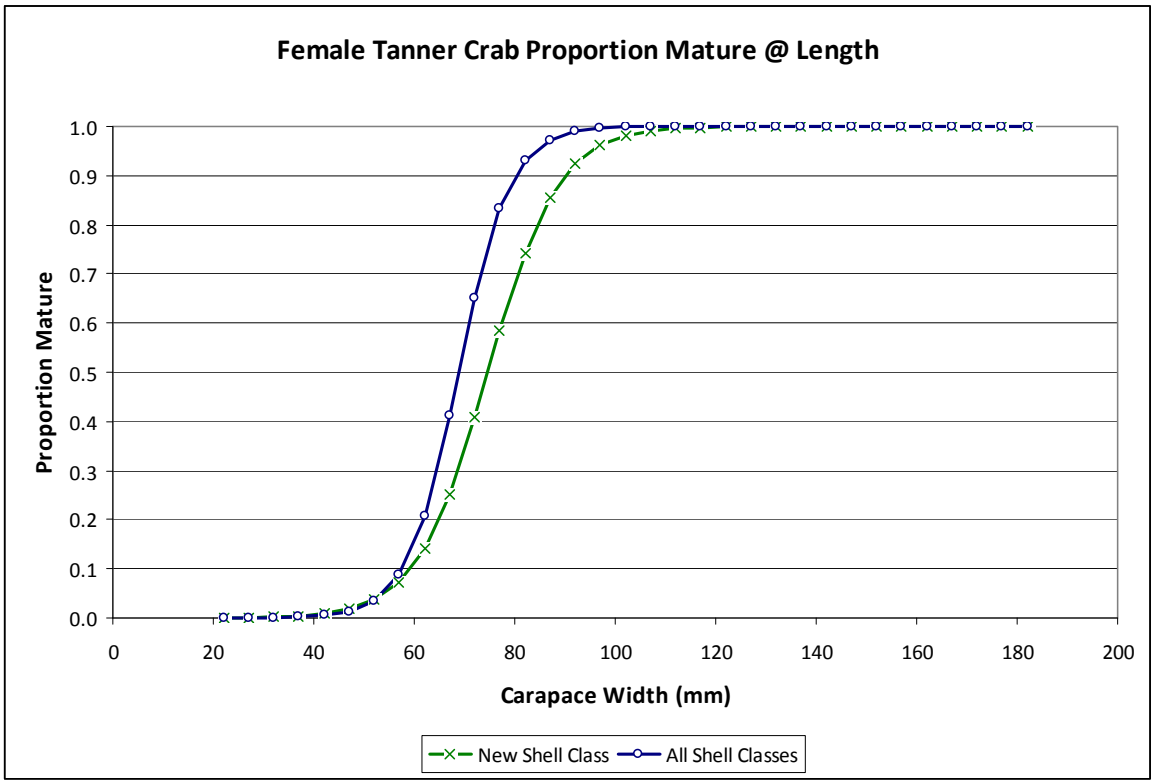


Figure 8. Fitted logistic functions of proportion mature in the stock for new shell and old shell female Tanner crab based on egg code classification of new and old shell crab in 1976-2009 survey data.

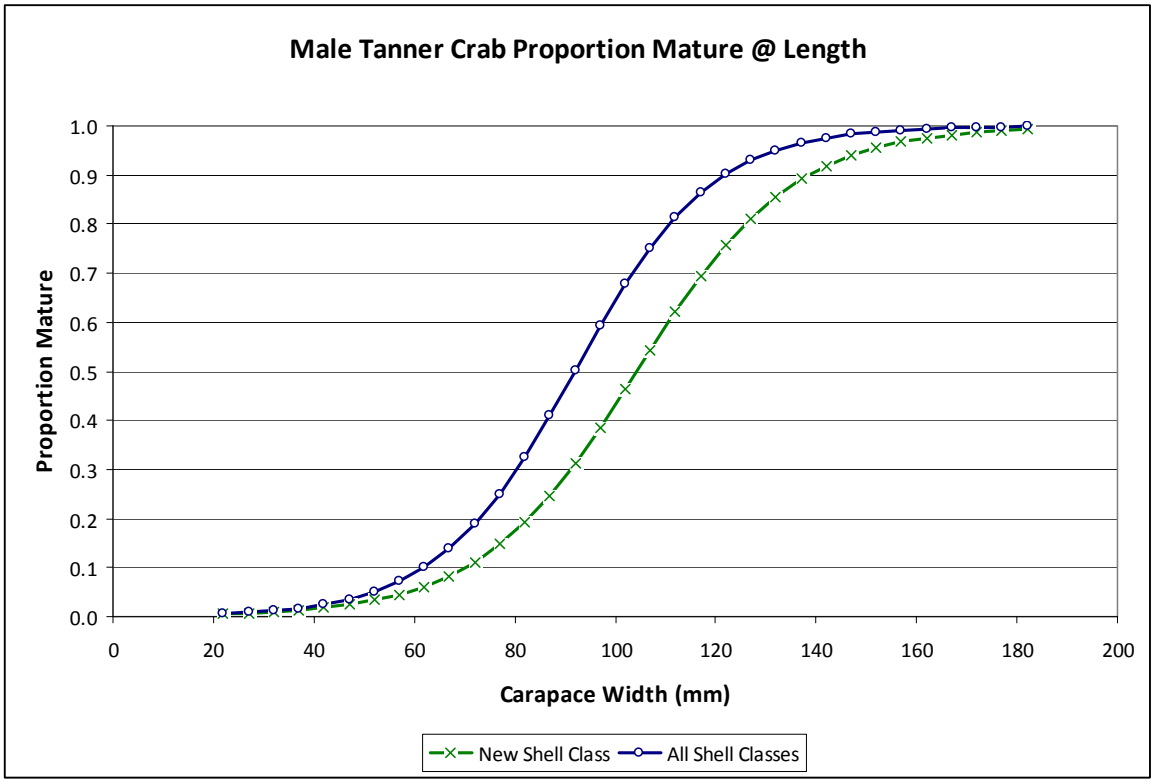
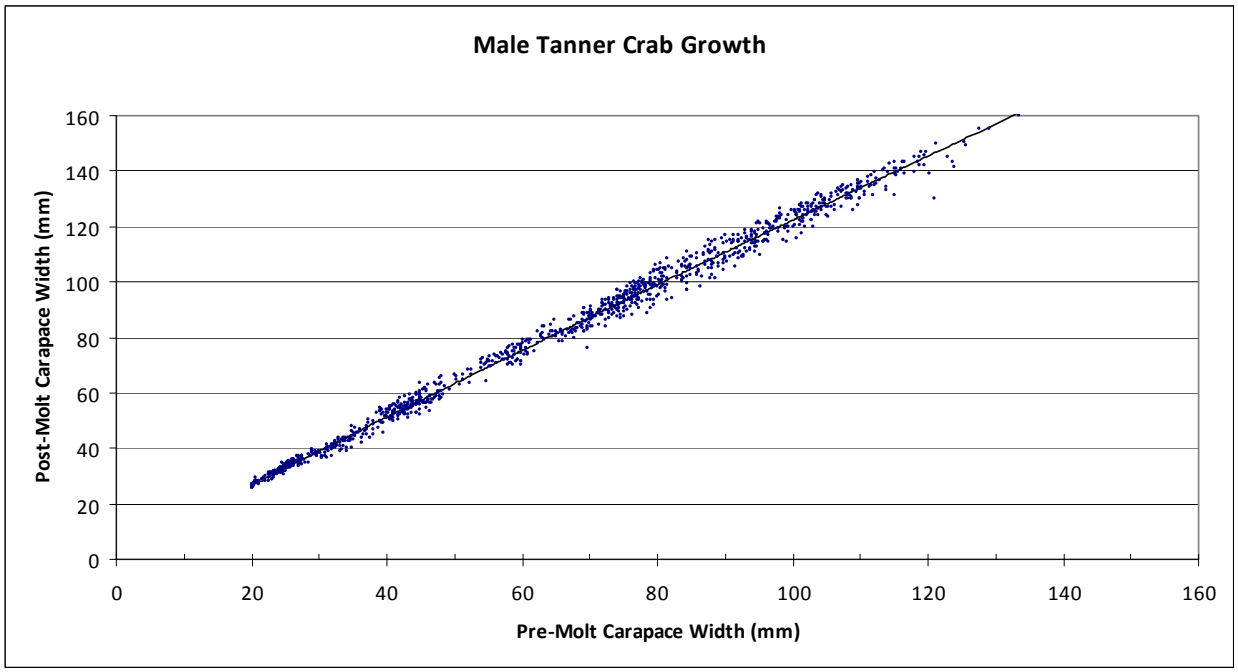


Figure 9. Fitted logistic functions of proportion mature in the stock for new shell and old shell male Tanner crab based on classification of new and old shell crab in 1990-2007 survey data.

(a)



(b)

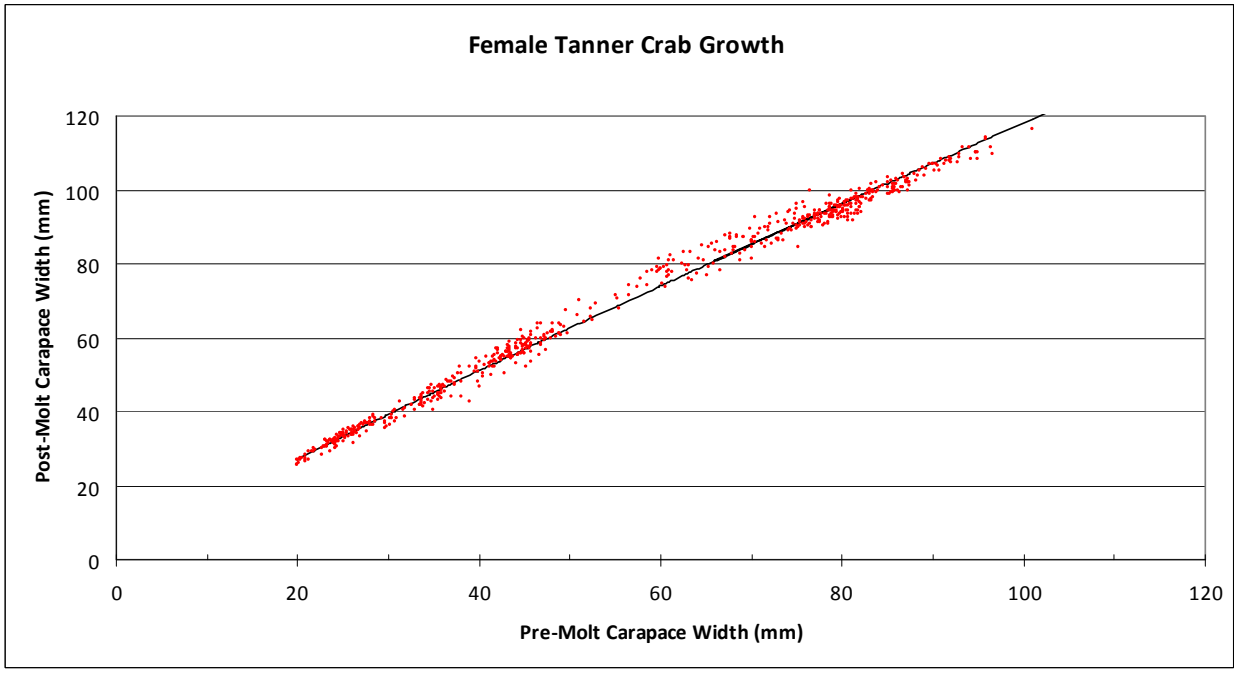


Figure 10. Growth of male (a) and female (b) Tanner crab as a function of premolt size. Estimated by Rugolo and Turnock 2010 based on data from GOA Tanner crab (Munk, unpublished data).

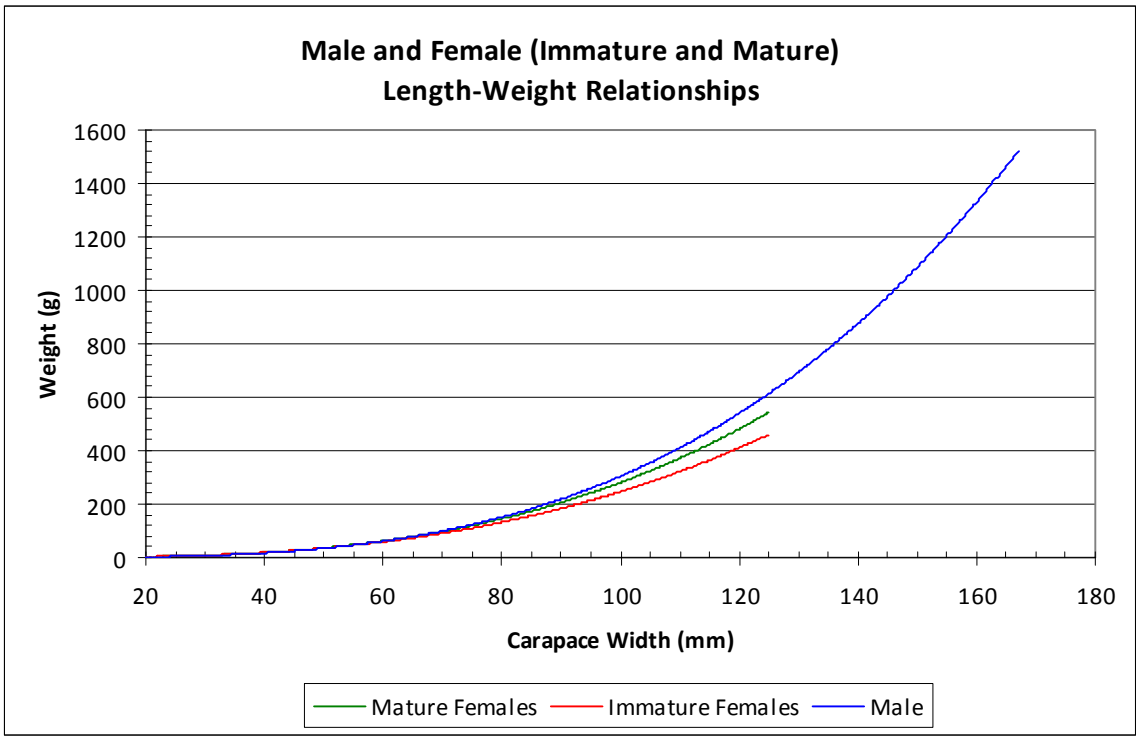


Figure 11. Weight (kg) – size (mm) relationship for male (top), mature female (middle) and immature female (bottom) Tanner crab.

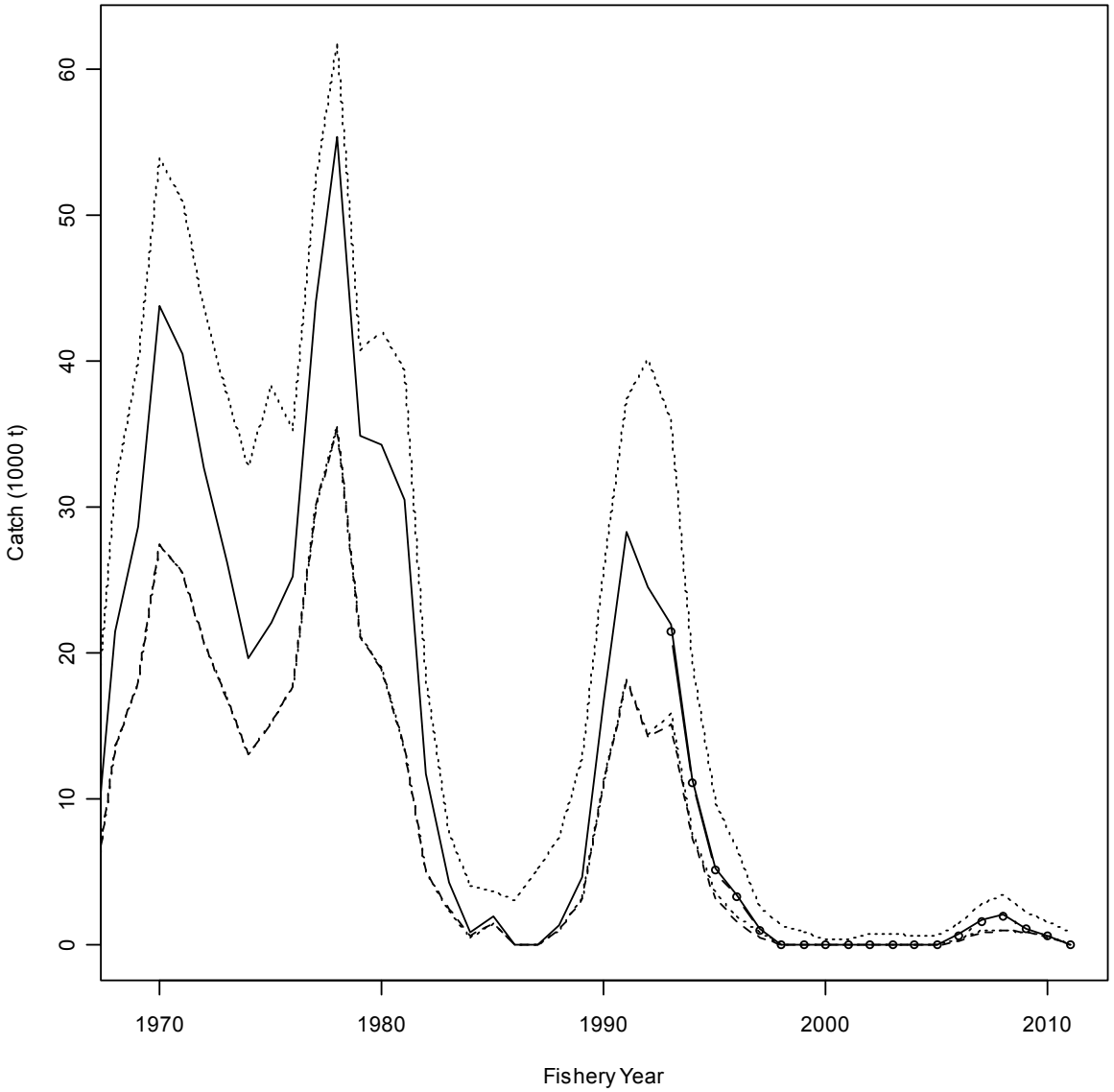


Figure 12. *Base Model (0)* predicted catch history of male Tanner crab catch by survey year. [solid line=predicted retained plus discard catch in the directed fishery; dashed line=predicted retained catch in the directed fishery; dotted line=predicted total male catch from all sources].

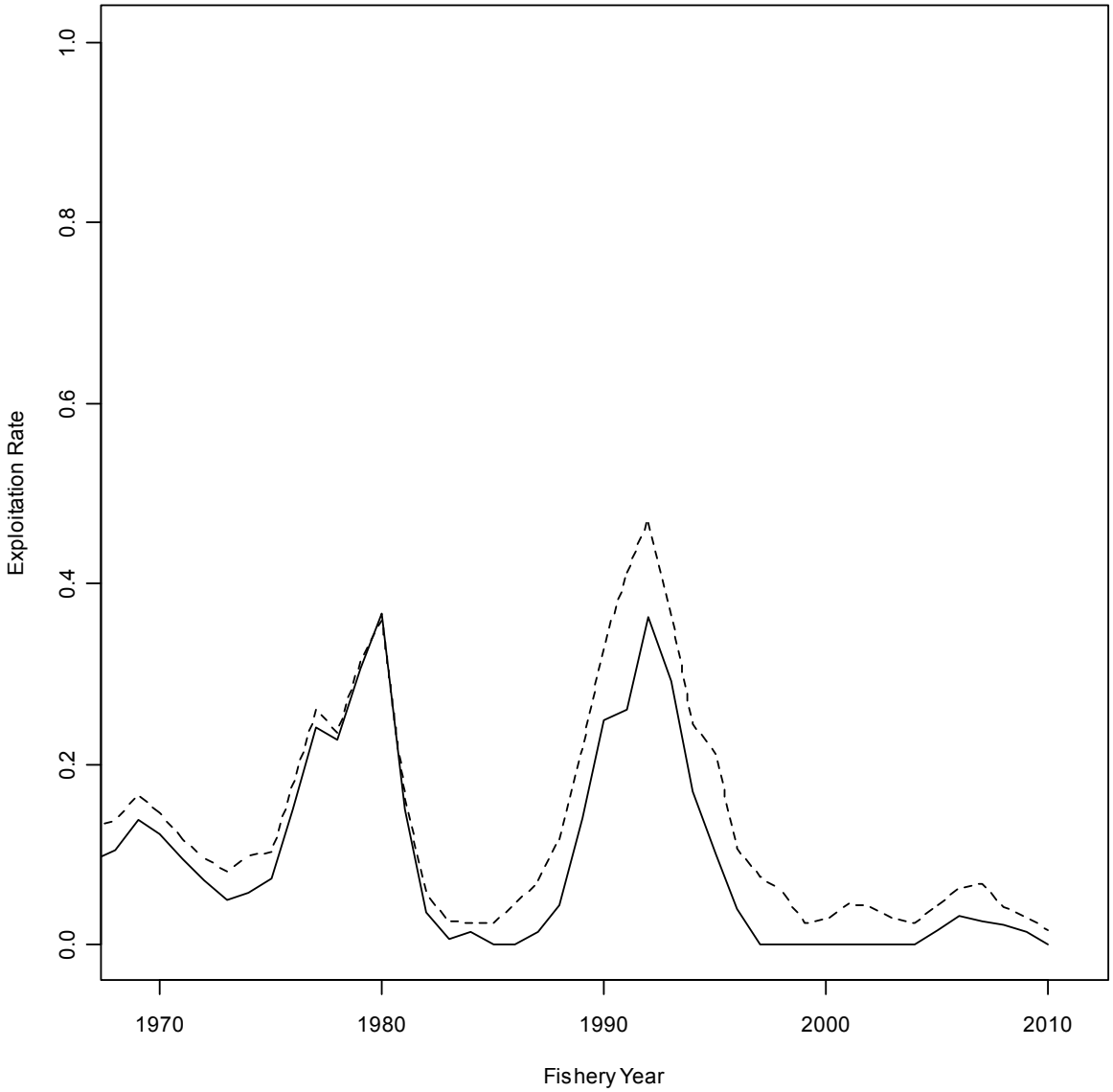


Figure 13. . *Base Model (0)* exploitation fraction estimated as the predicted catch biomass of legal males in all fisheries divided by the estimated legal male biomass at the time of the fishery (solid), and the predicted total catch (retained plus discard) divided by the estimated male mature biomass at the time of the fishery (dotted). Year is the year of the fishery.

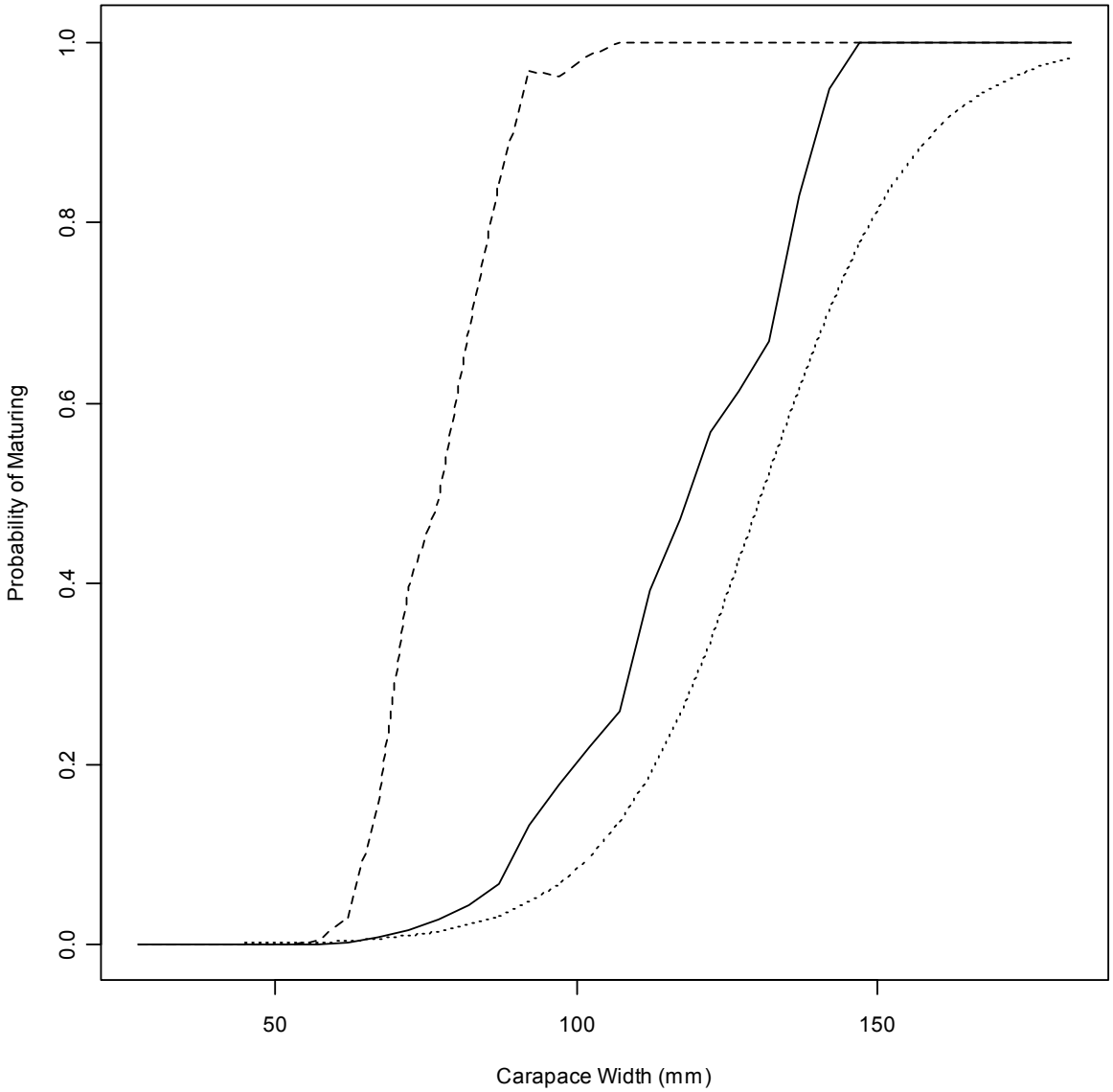


Figure 14. *Base Model (0)* estimate of probability of maturing by size for male (solid) and female (dashed) Tanner crab (not average fraction mature), and male probability of maturing by size used in Amendment #24 OFL analysis (dotted) (NPFMC 2007).

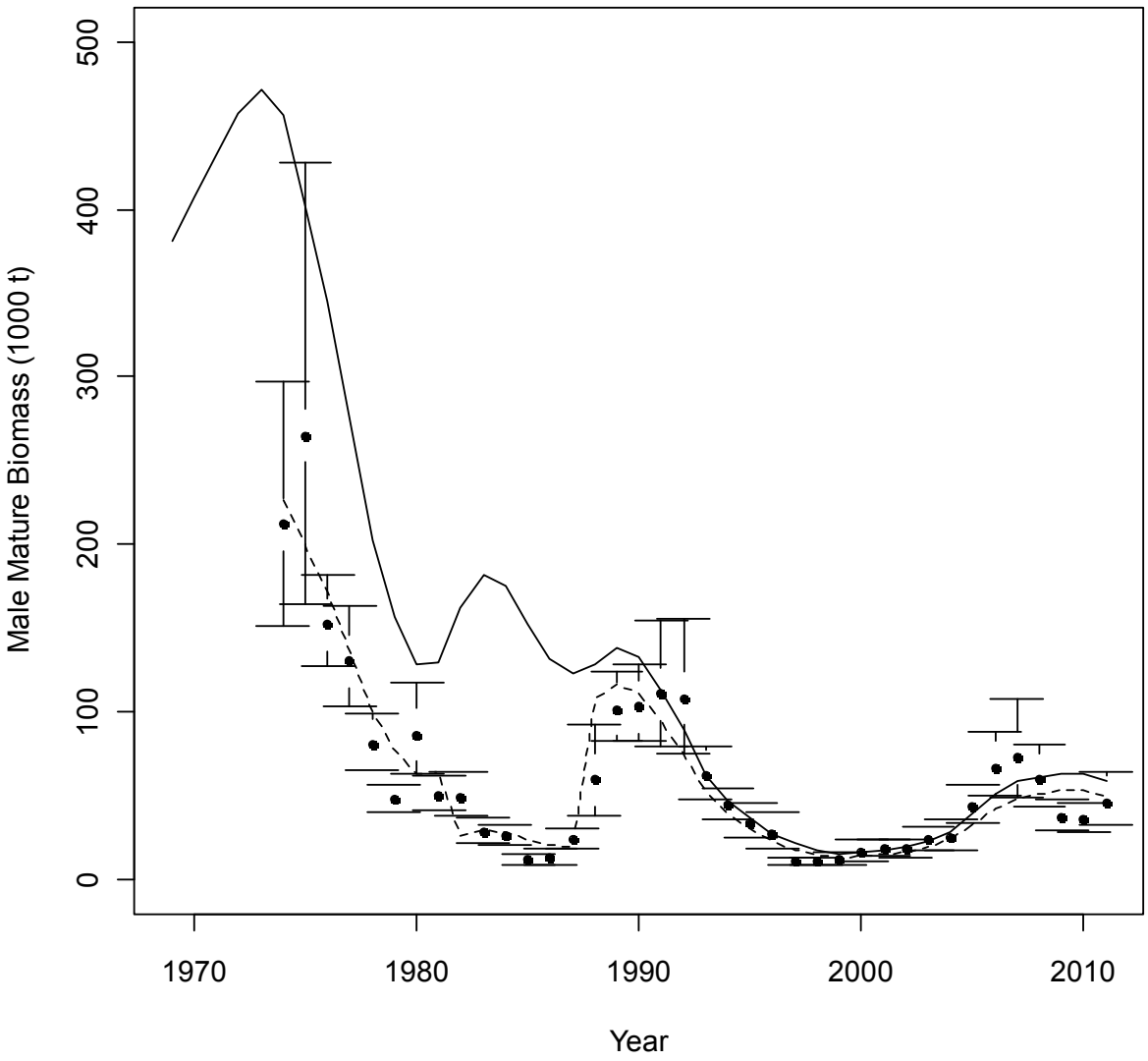


Figure 15. *Base Model (0)* population mature male biomass (1000 t, solid line) at the time of the survey, model estimate of survey mature biomass (dotted line) and observed survey mature male biomass with approximate lognormal 95% confidence intervals.

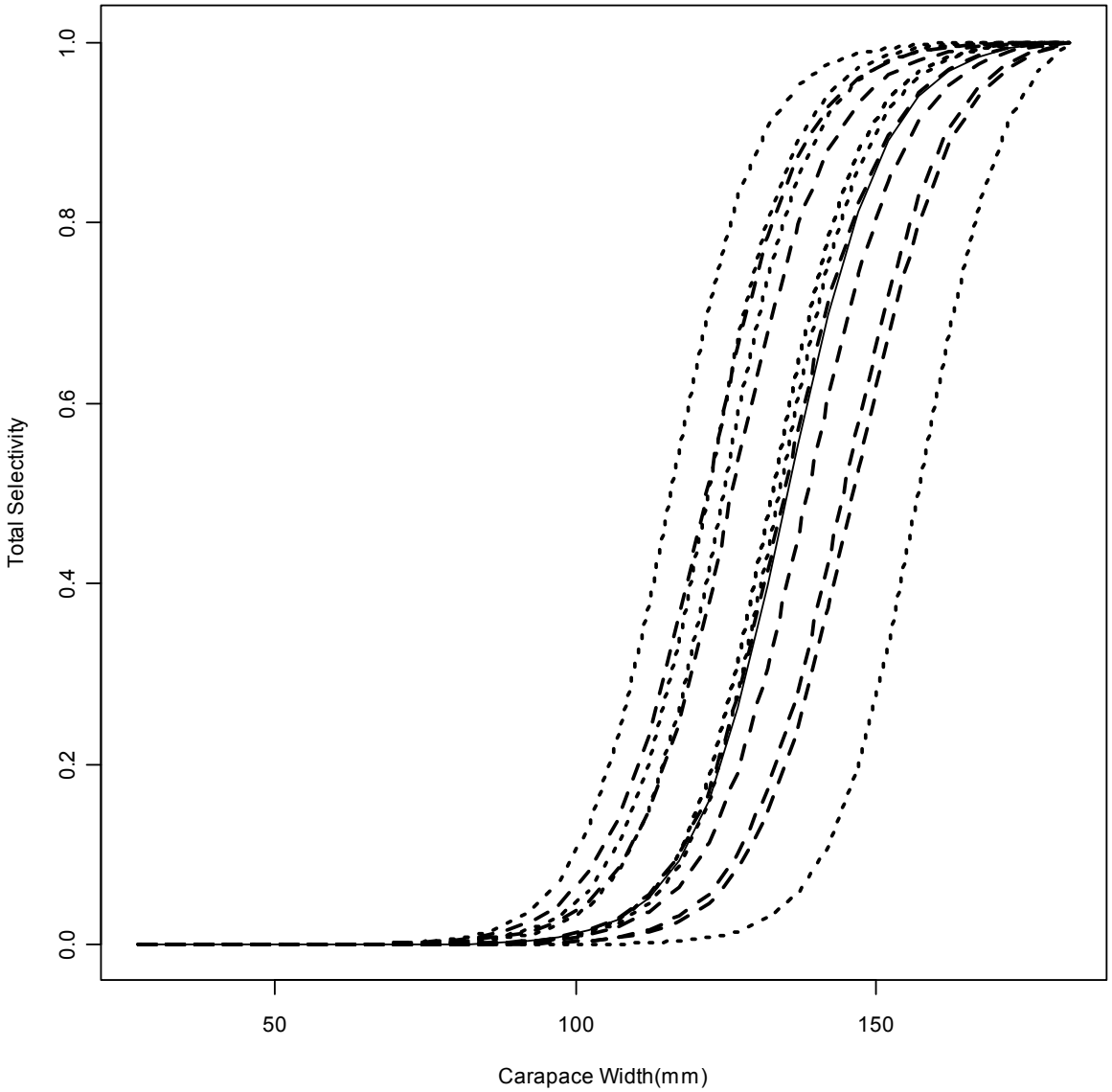


Figure 16. *Base Model (0)* estimated total selectivity for combined shell condition male Tanner crab in the directed fishery for 3 periods: period-1 (1981-1990) fixed selectivity (solid line), period-2 (1991-1996) annual selectivity (series of dashed lines), and period-3 (2005-2010) annual selectivity (series of dotted lines). Lines from left to right: 2007, 2005, 1996, 2006, 1995, 2010, 2008, 1991, 1981-1990 (solid), 1994, 1993, 1992 and 2009.

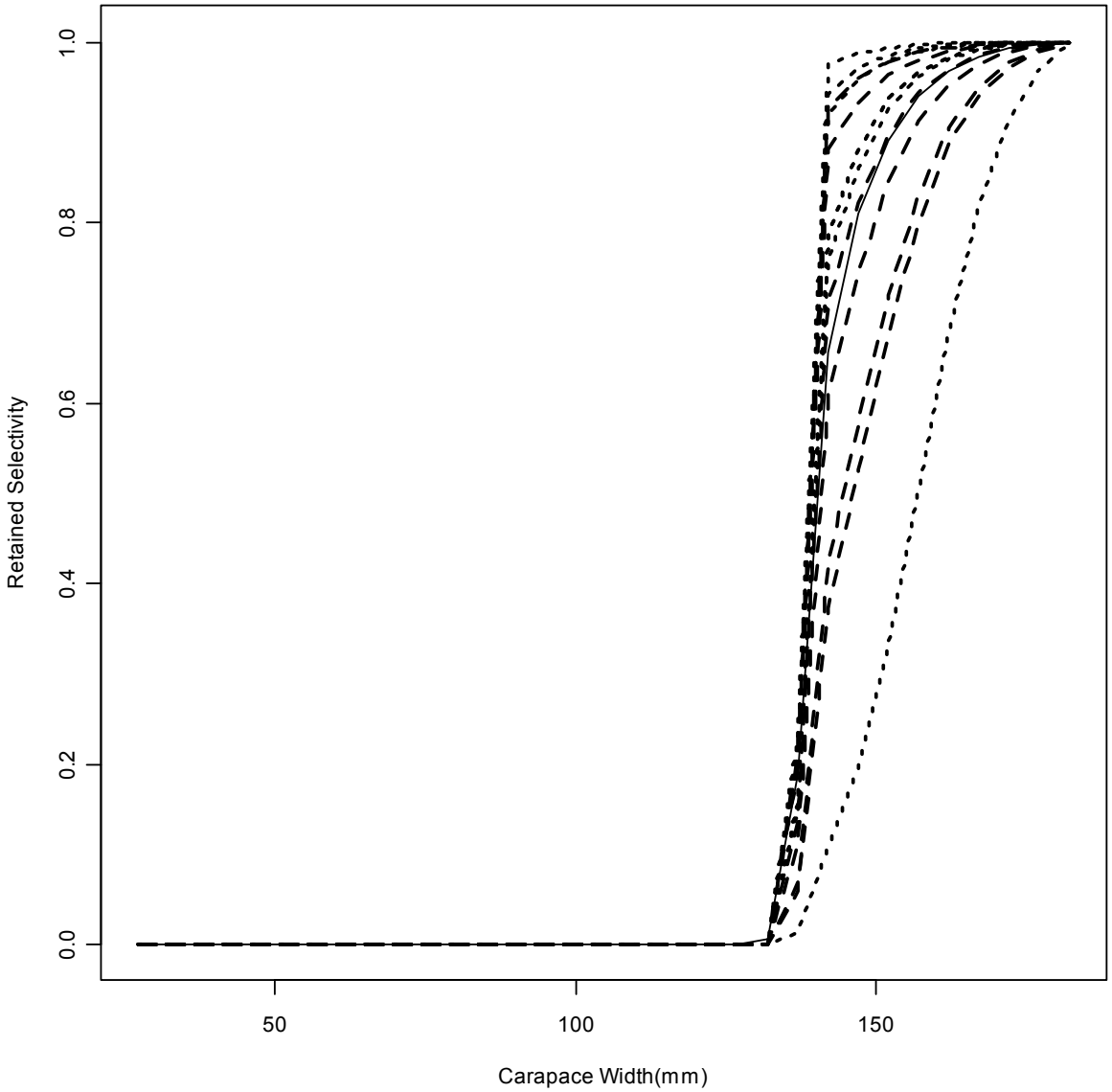


Figure 17. *Base Model (0)* estimated fraction of total catch retained by size for male crab in the directed fishery, all shell conditions combined for 3 periods: period-1 (1981-1990) fixed selectivity (solid line), period-2 (1991-1996) annual selectivity (series of dashed lines), and period-3 (2005-2010) annual selectivity (series of dotted lines). Lines from left to right: 2007, 2005, 1996, 2006, 1995, 2010, 2008, 1991, 1981-1990 (solid), 1994, 1993, 1992 and 2009. The retention function is multiplied by the total directed male selectivity to estimate the directed fishery retained selectivity.

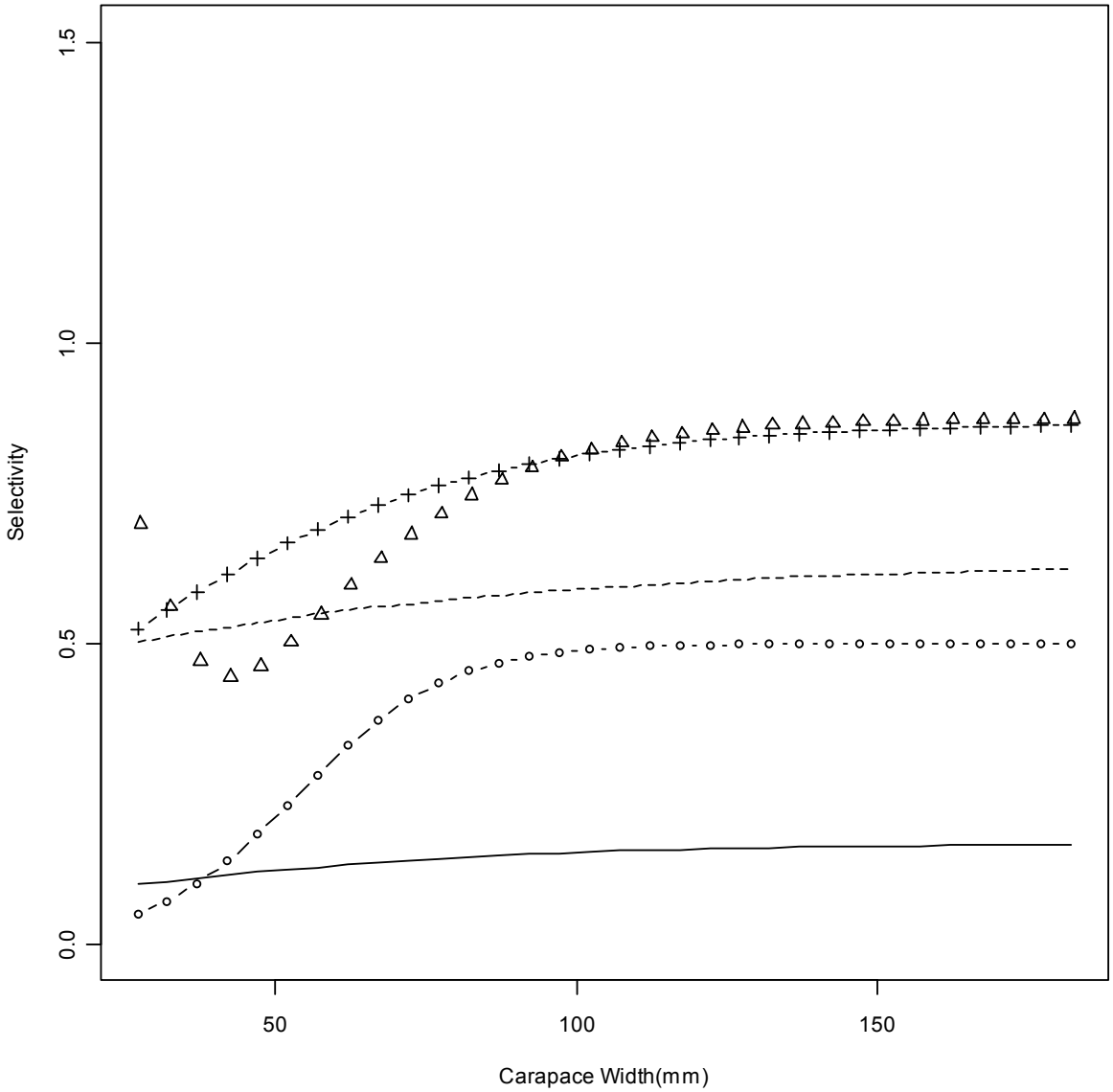


Figure 18. *Base Model (0)* survey selectivity curves for male Tanner crab estimated for 1974-1981 (dashed line with circles), 1982-1987 (solid line) and 1988-P (dashed line with pluses). Survey selectivity estimated by Somerton and Otto (1998) are triangle symbols, and female selectivity for 1988-2011 is dashed line for reference.

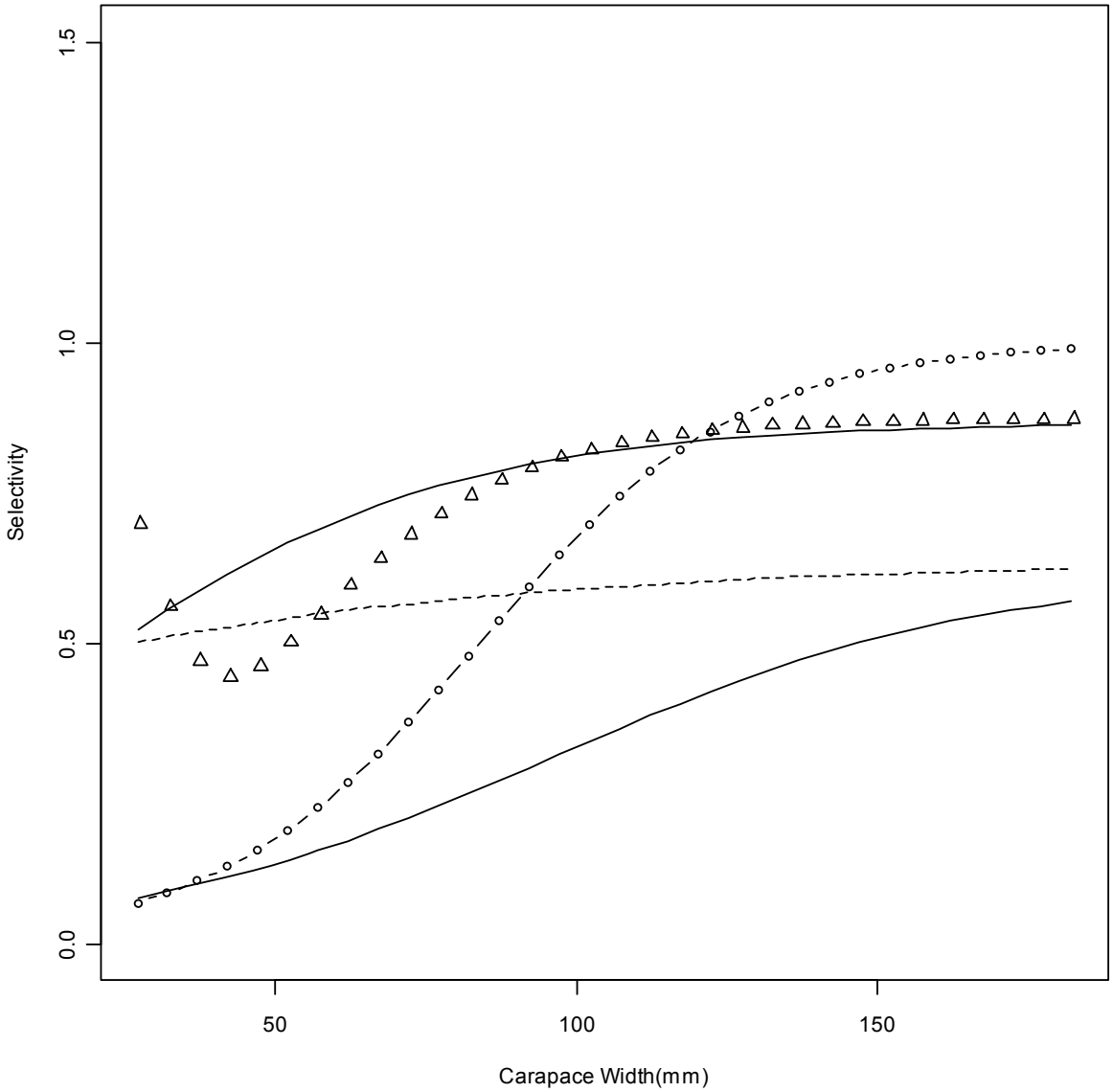


Figure 19. *Base Model (0)* survey selectivity curves for female Tanner crab estimated for 1974-1981 (dashed line with circles), 1982-1987 (lower solid line) and 1988-P (dashed line). Survey selectivity estimated by Somerton and Otto (1998) are triangle symbols, and male selectivity for 1988-2011 is upper solid line for reference.

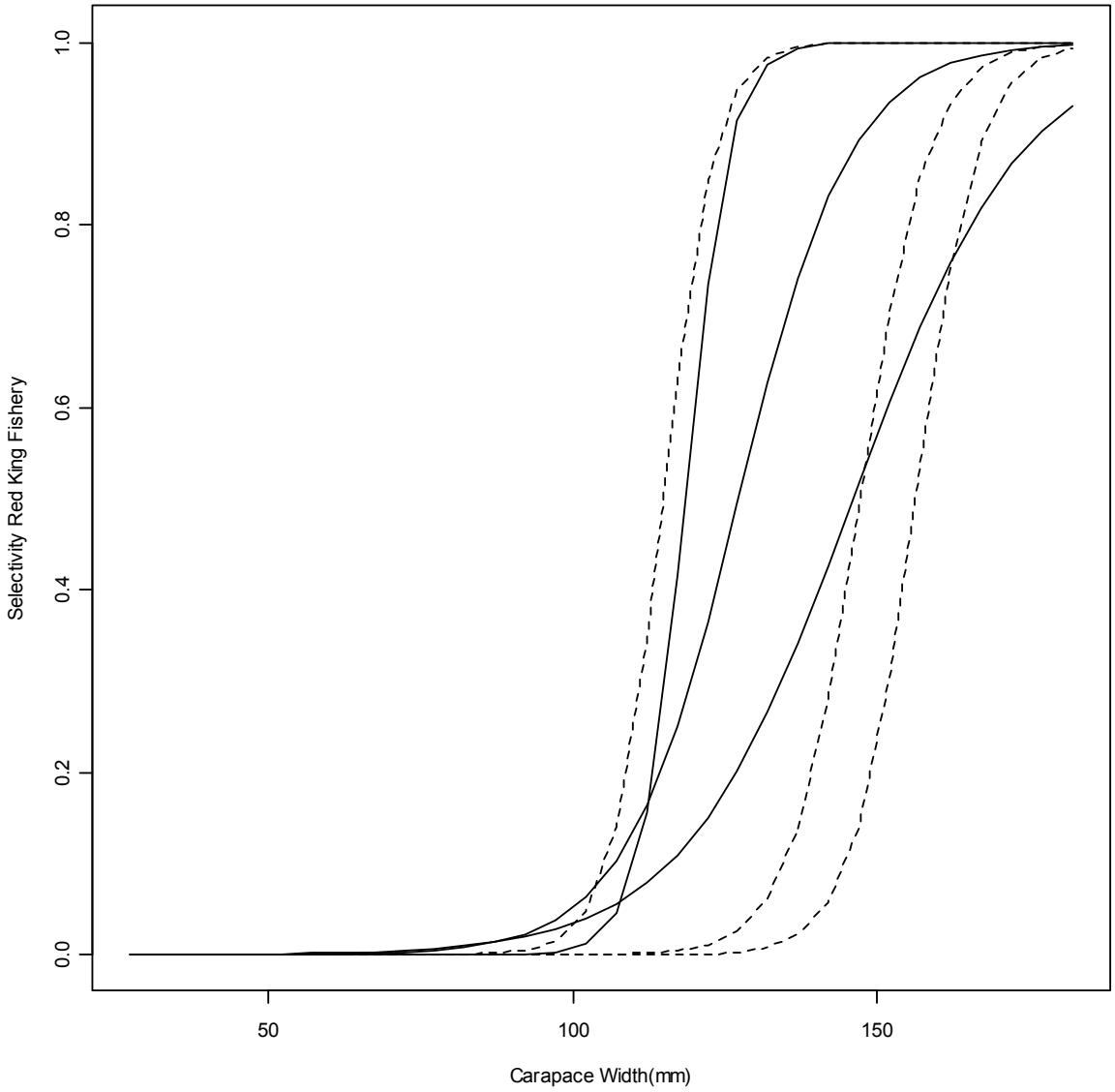


Figure 20. *Base Model (0)* selectivity curve estimated by the model for bycatch in the Bristol Bay red king crab fishery for females (dashed) and males (solid) for three periods: period-1 (1989-1996), period-2 (1997-2004) and period-3 (2005-P). The male and female curves for the three time periods are in chronological order from left to right – i.e., earliest to left, intermediate in center, and most recent to right.

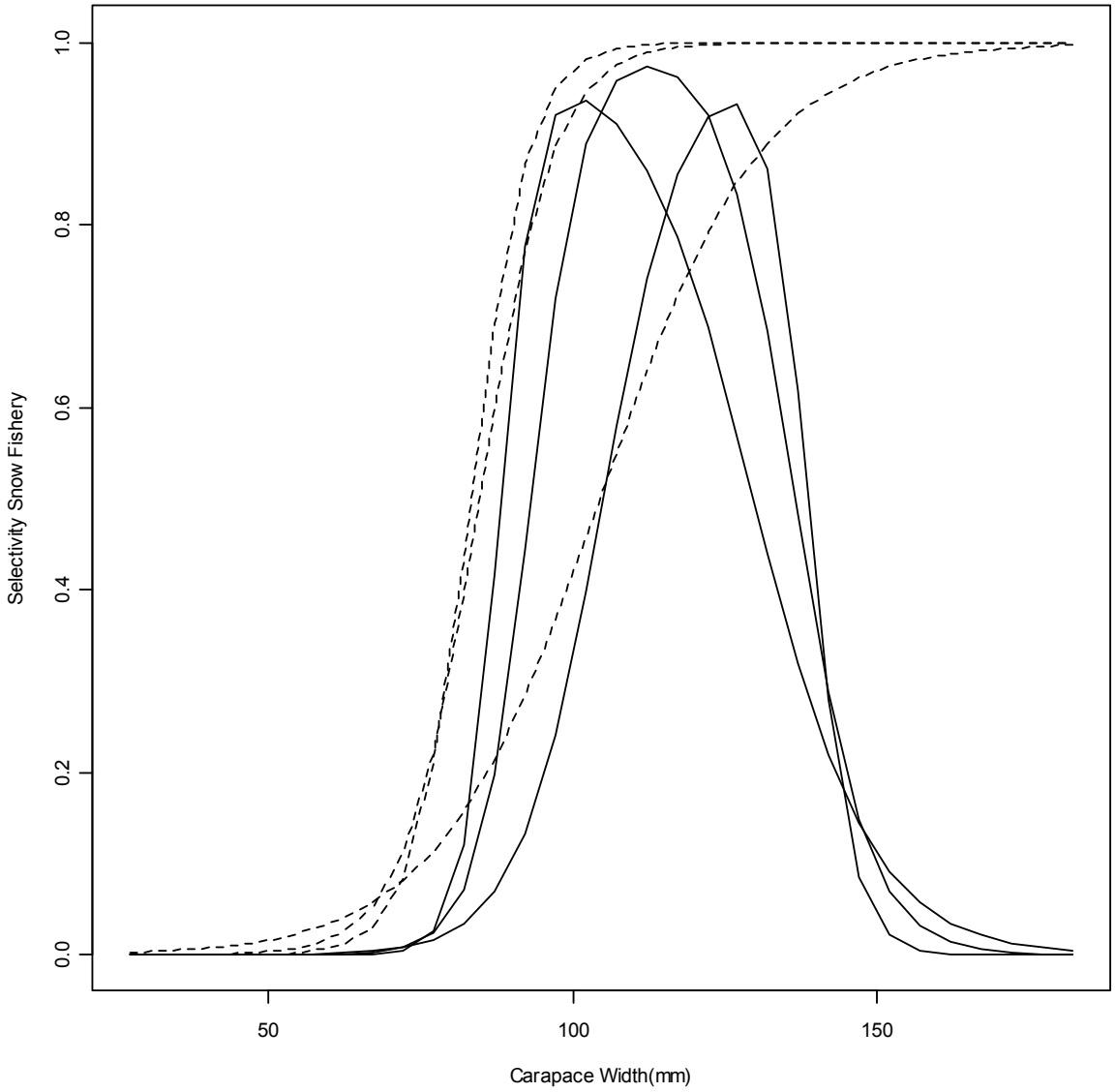


Figure 21. *Base Model (0)* selectivity curve estimated by the model for bycatch in the snow crab fishery for females (dashed) and males (solid) for three periods: period-1 (1989-1996), period-2 (1997-2004) and period-3 (2005-P). The curves for males: period-1 (left), period-2 (center) and period-3 (right). Curves for females: period-1 (right), period-2 (left) and period-3 (center).

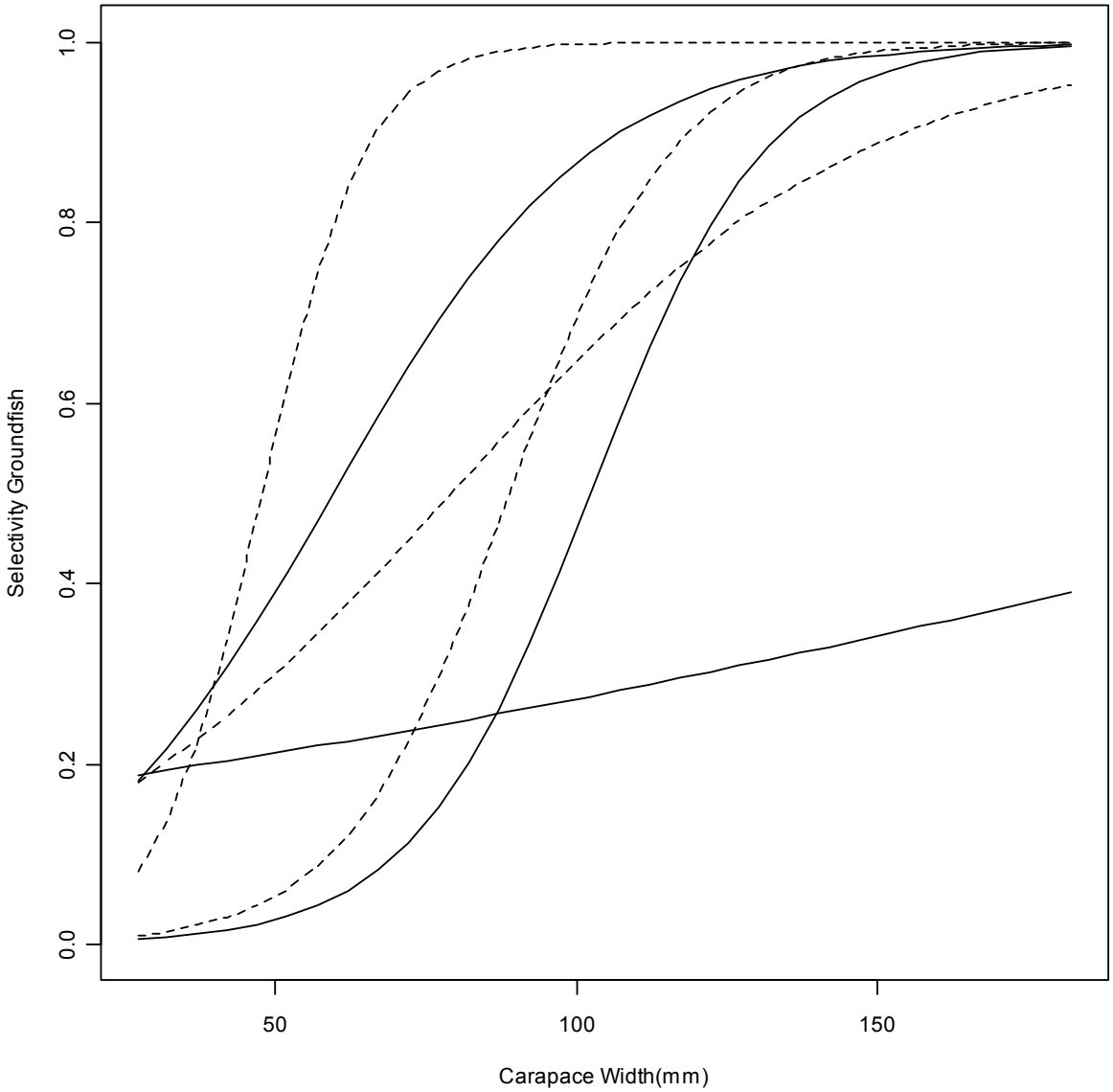


Figure 22. *Base Model (0)* selectivity curve estimated by the model for bycatch of males (dashed) and females (solid) in the groundfish fishery for three periods: period-1 (1973-1986), period-2 (1987-1996) and period-3 (1997-P). The curves for males: period-1 (left), period-2 (center) and period-3 (right). Curves for females: period-1 (left), period-2 (right) and period-3 (center).

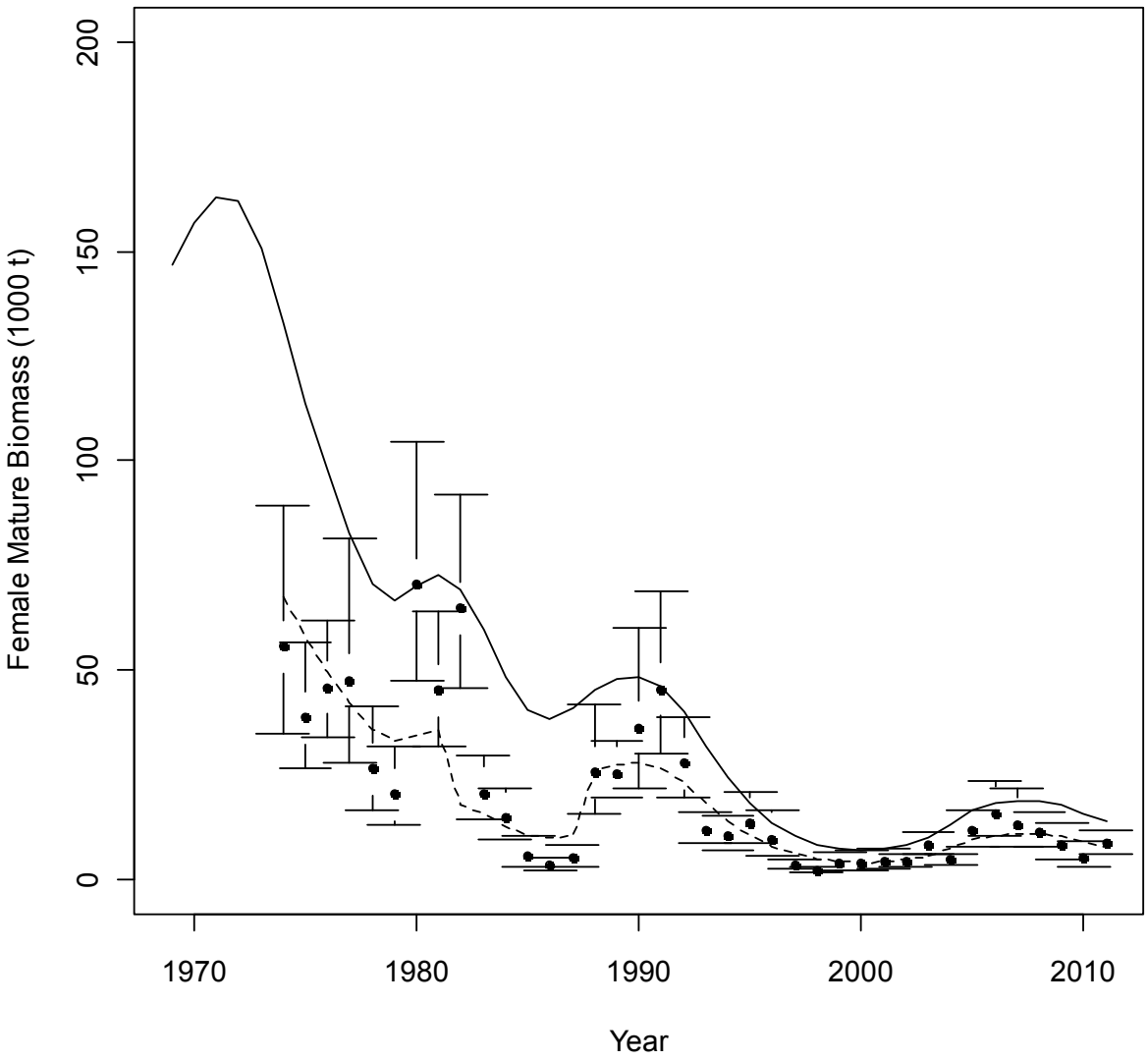


Figure 23. *Base Model (0)* population female mature biomass (1000 t, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

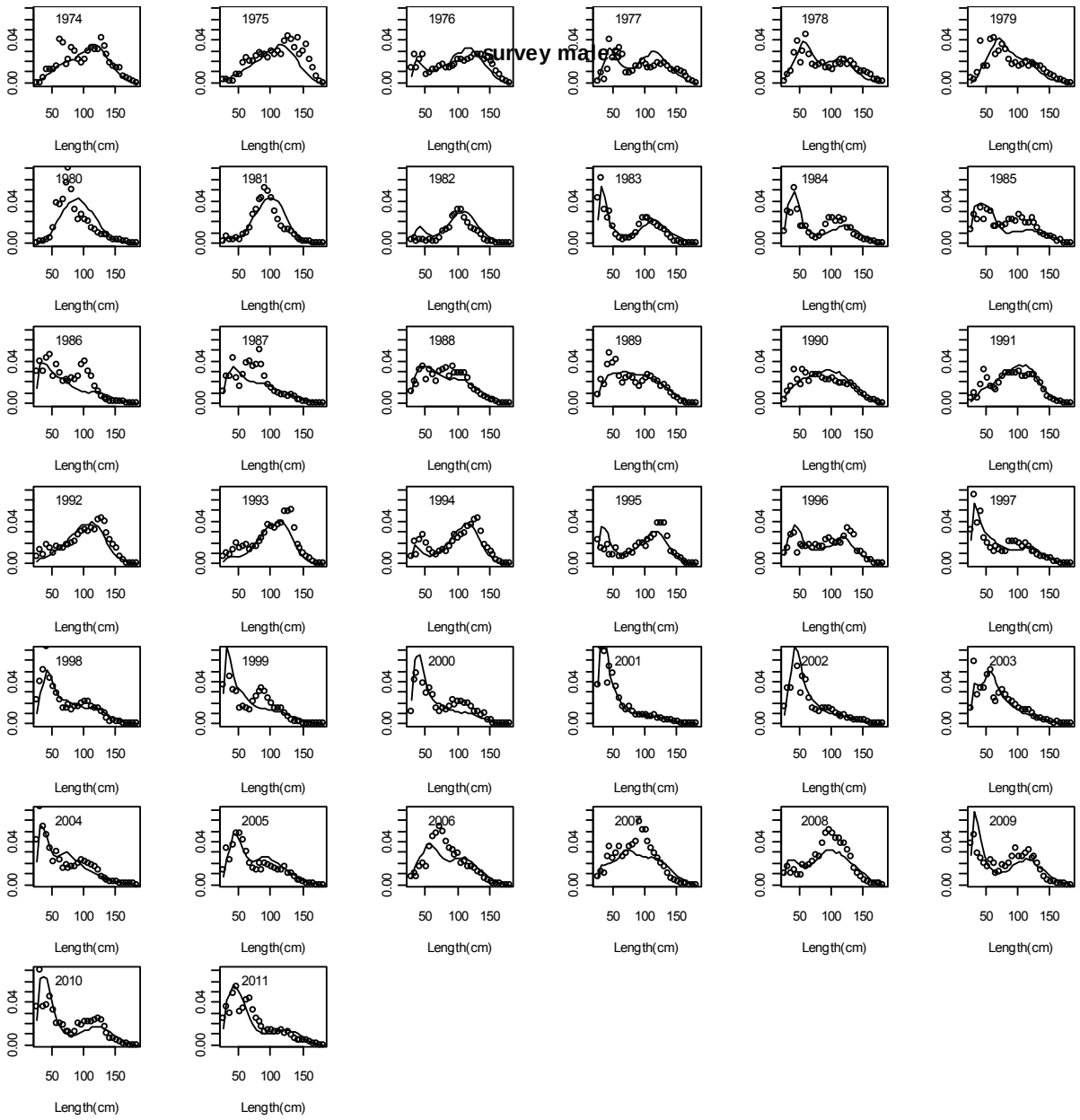


Figure 24. *Base Model (0)* fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

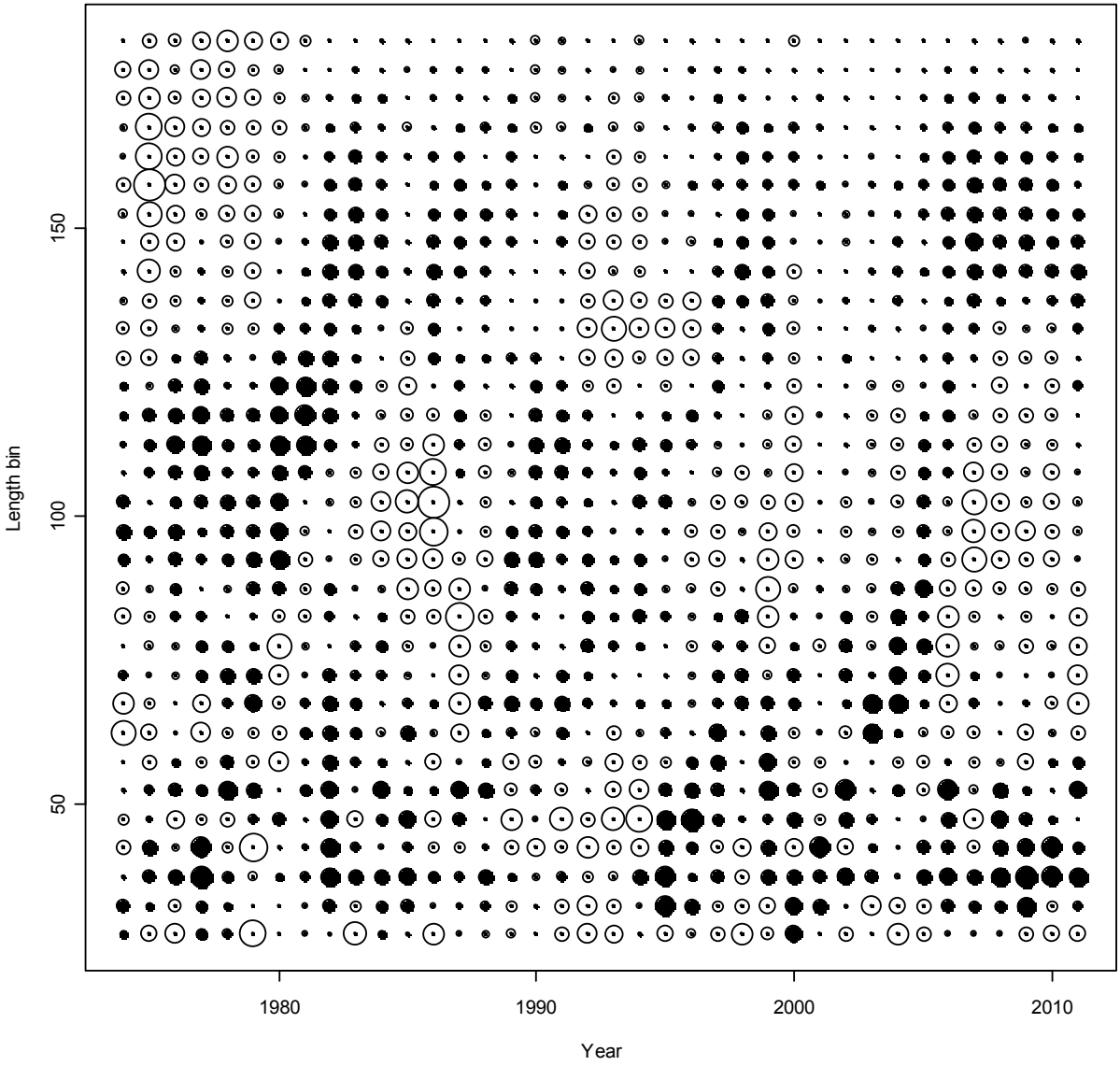


Figure 25. *Base Model (0)* residuals of the model fit to the survey male size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

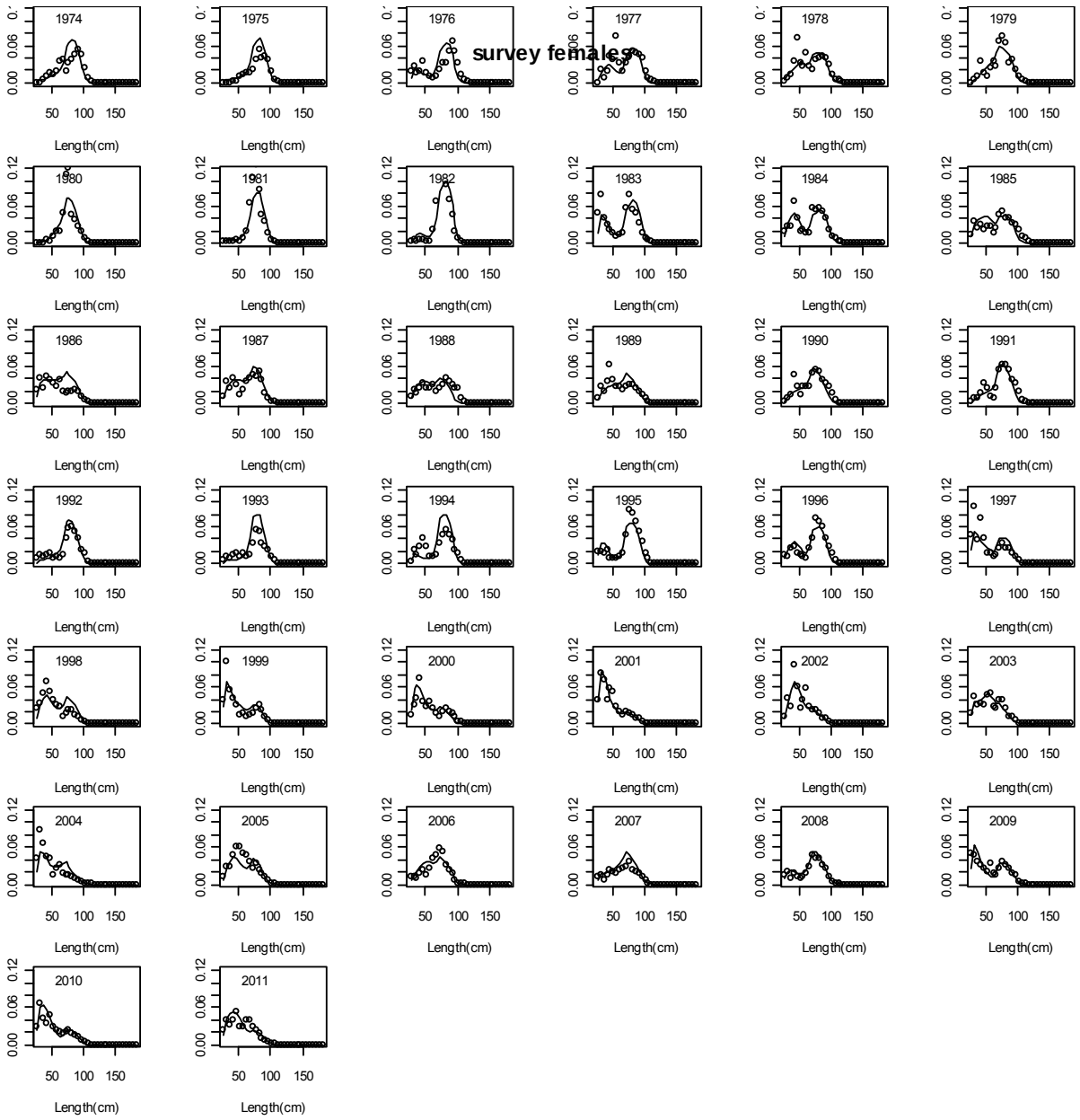


Figure 26. *Base Model (0)* fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

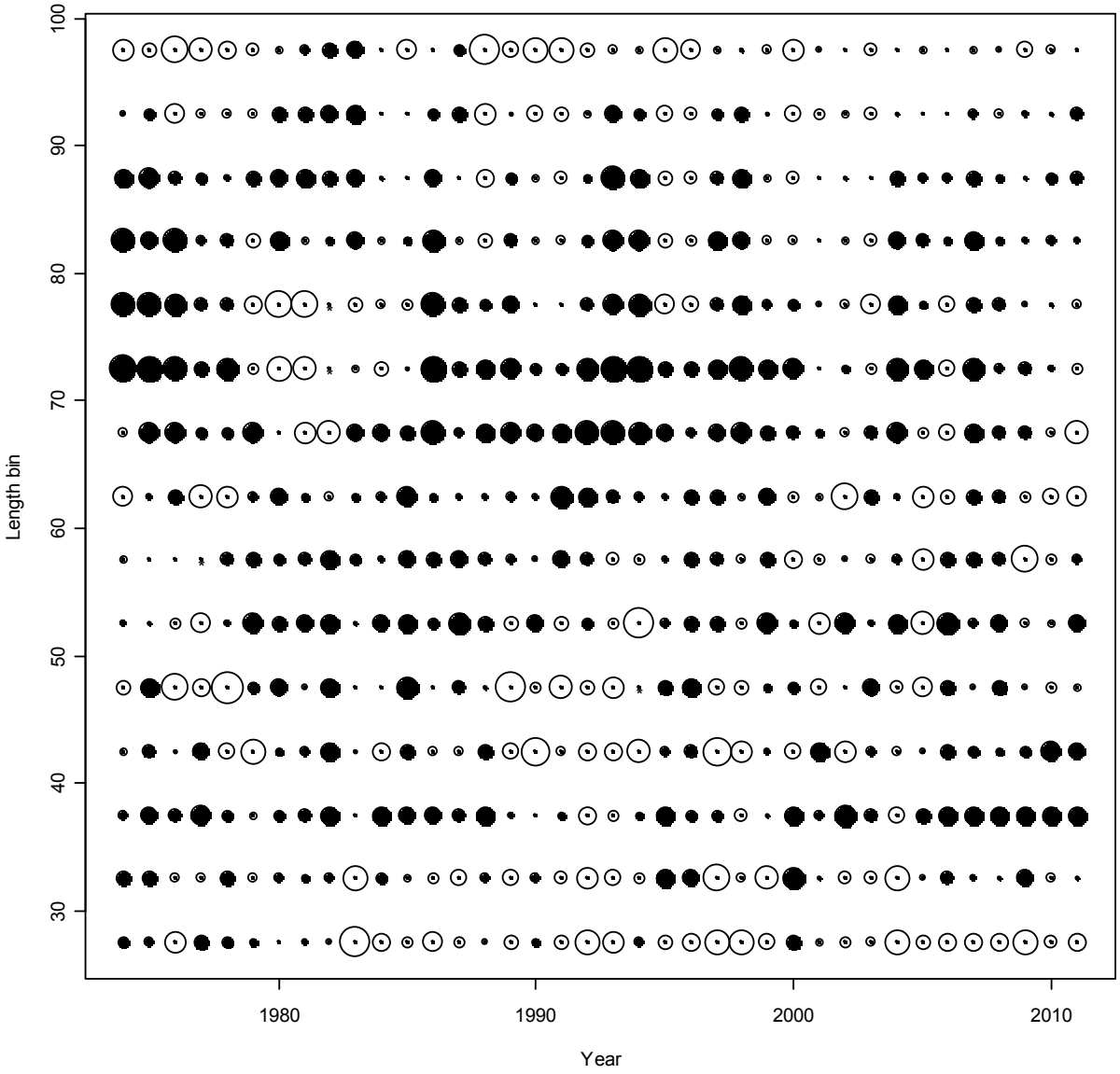


Figure 27. *Base Model (0)* residuals of the model fit to the survey female size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

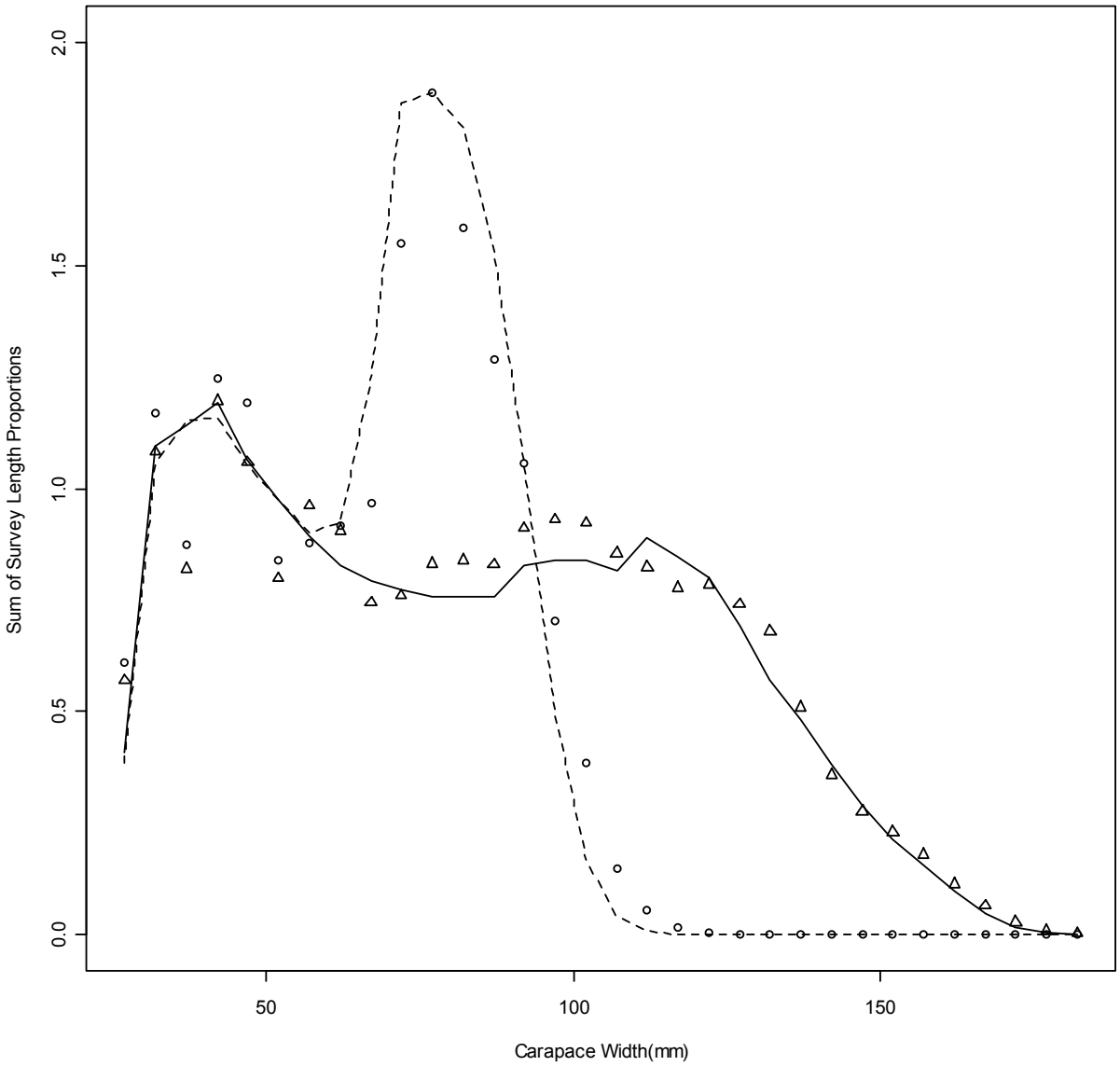


Figure 28. *Base Model (0)* summary fit to the survey male (solid line) and female (dotted line) size frequency data, all shell conditions combined. Symbols are observed data.

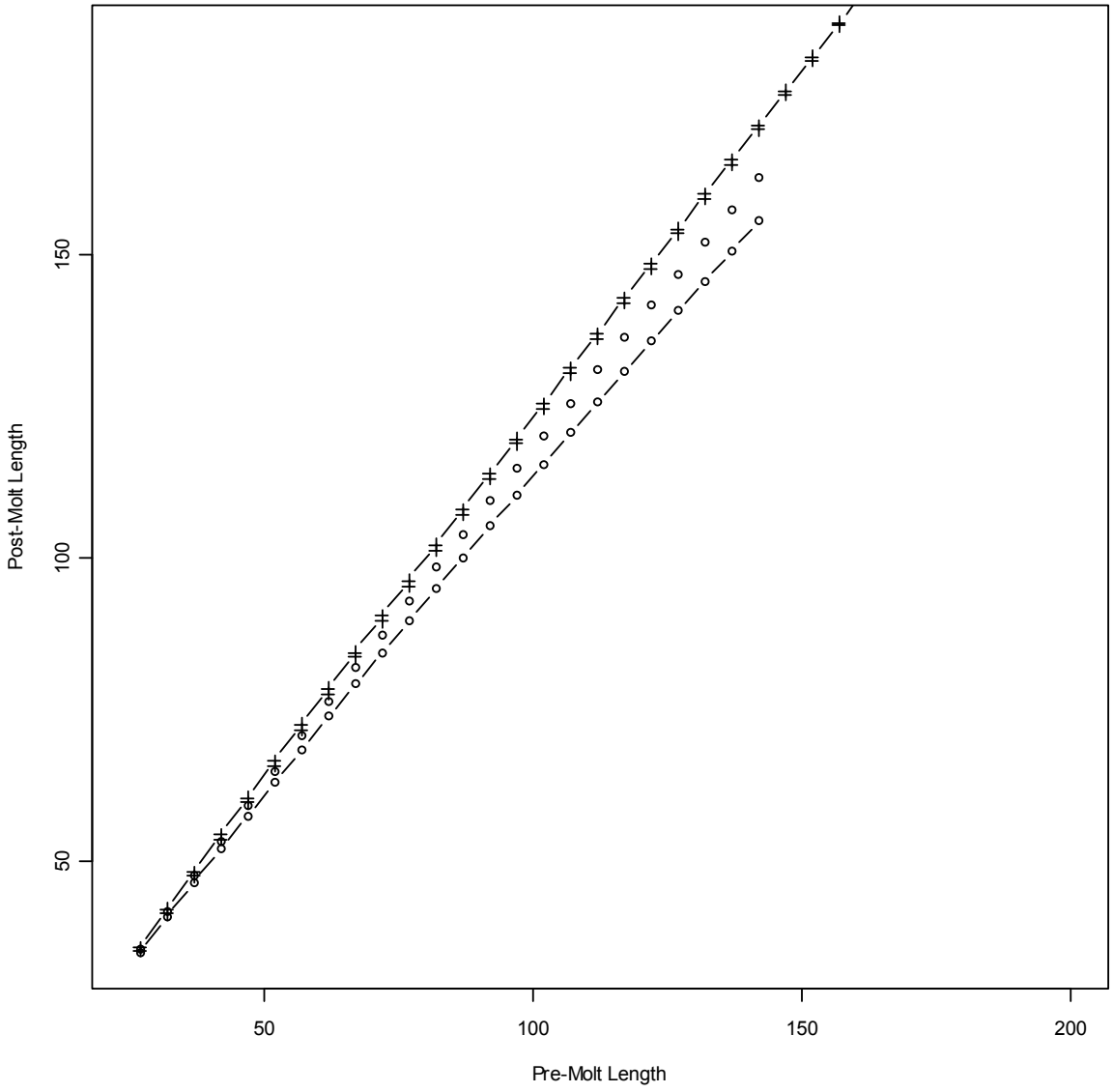


Figure 29. *Base Model (0)* estimated relationships of pre-molt length to post-molt length (mm cw) for male (dashed with pluses) and female (dashed with circles) eastern Bering Sea Tanner crab. The empirically-derived growth relationships for male (pluses) and female (circles) based on data collected near Kodiak Island in the Gulf of Alaska are shown for reference.

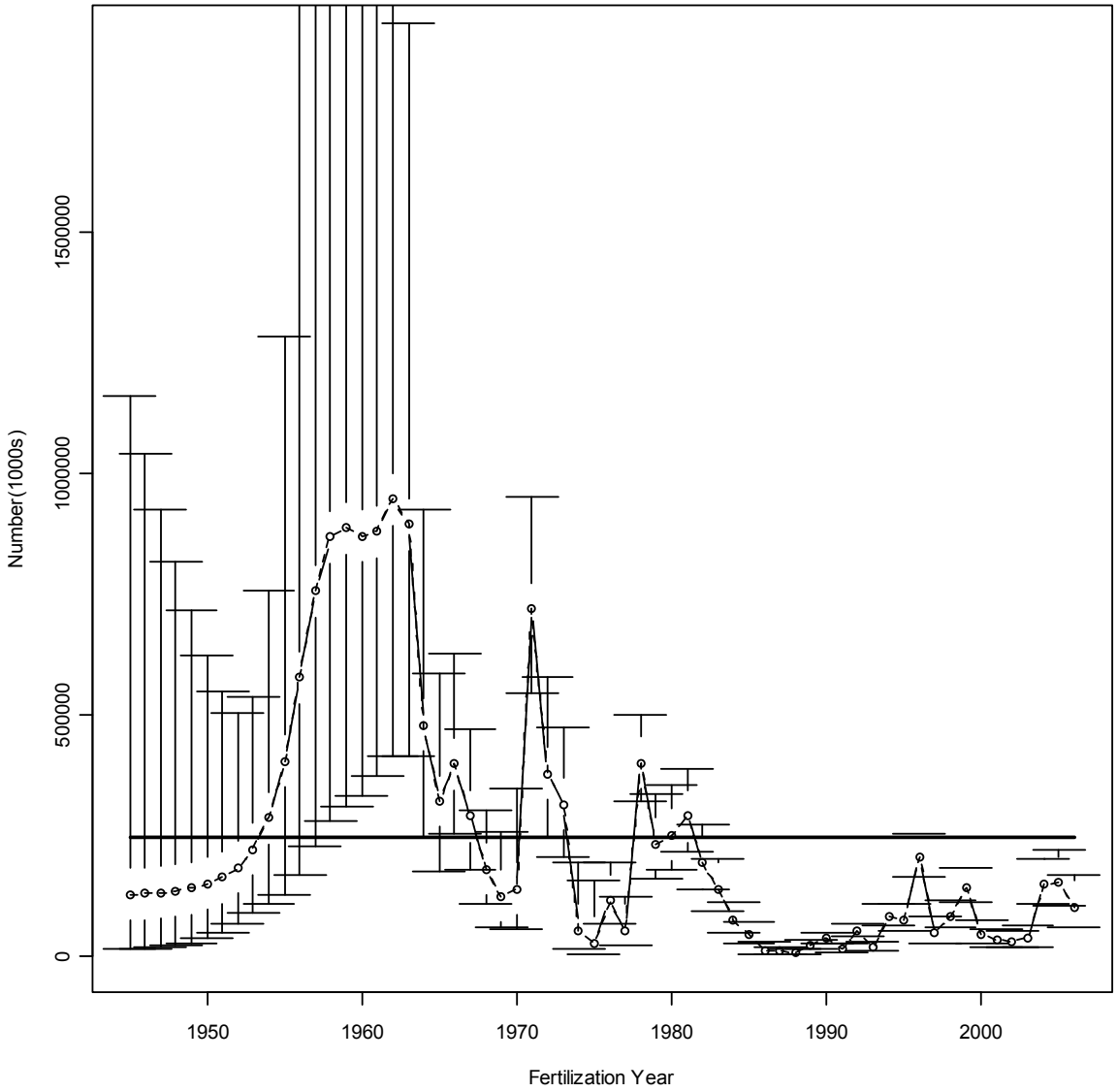


Figure 30. *Base Model (0)* recruitment to model of crab 25 mm to 50 mm by fertilization year. Total recruitment is 2 times recruitment in the plot given that male and female recruitment is set to be equal. Solid horizontal line is average recruitment.

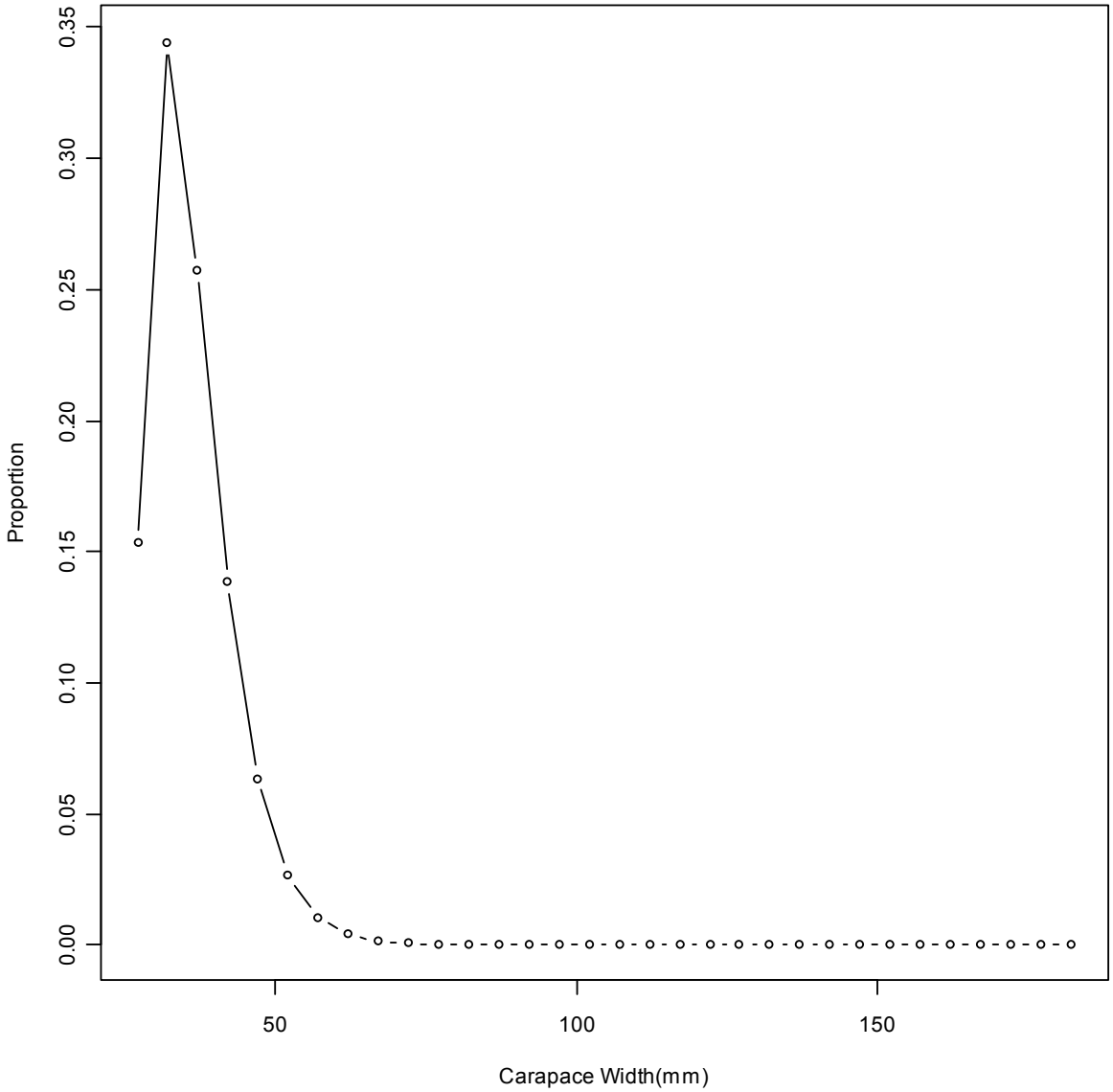


Figure 31. *Base Model (0)* distribution of recruits to length bins estimated by the model.

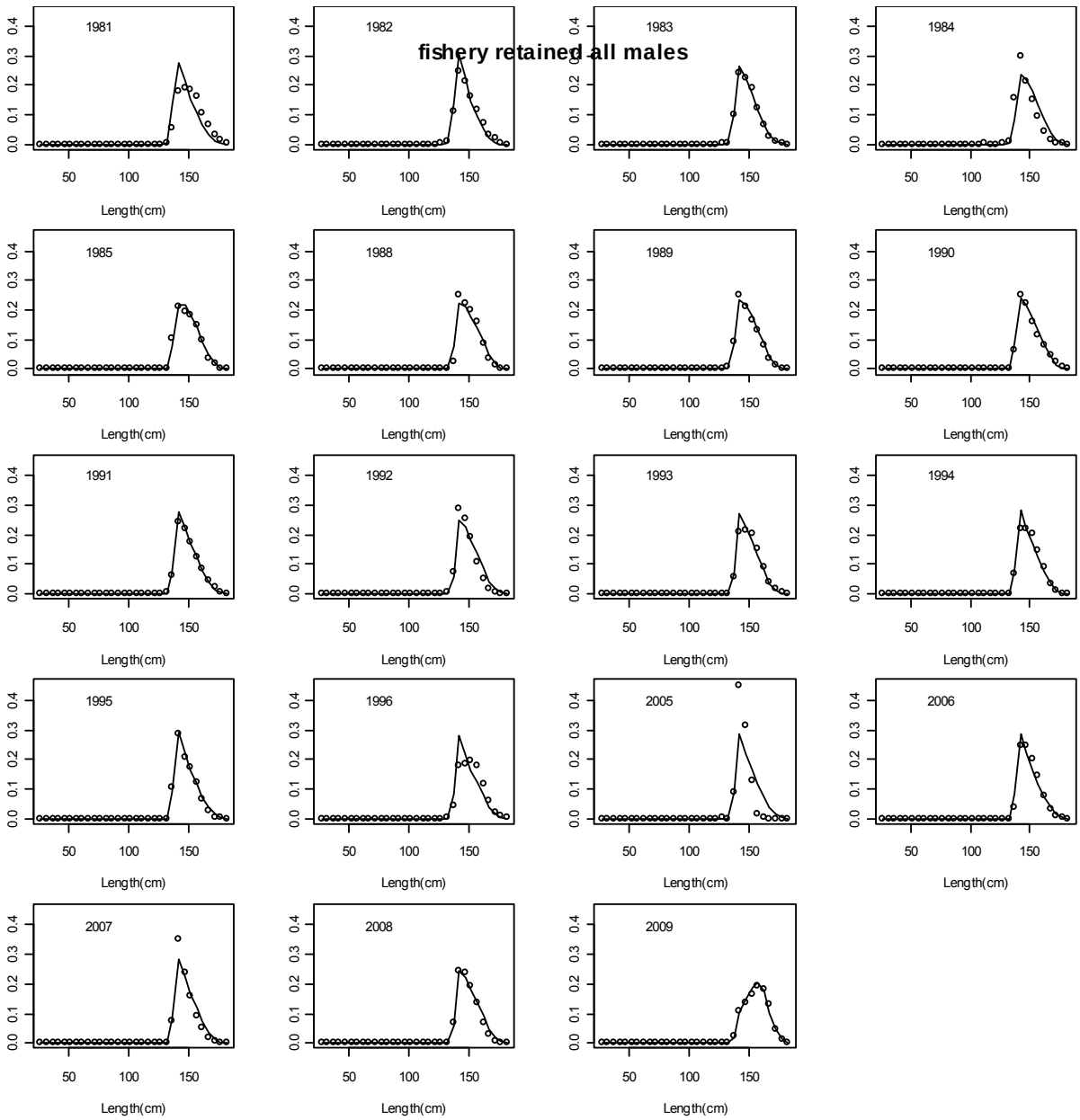


Figure 32. *Base Model (0)* fit to the retained male size frequency data in the directed fishery, shell condition combined. Circles are observed data.

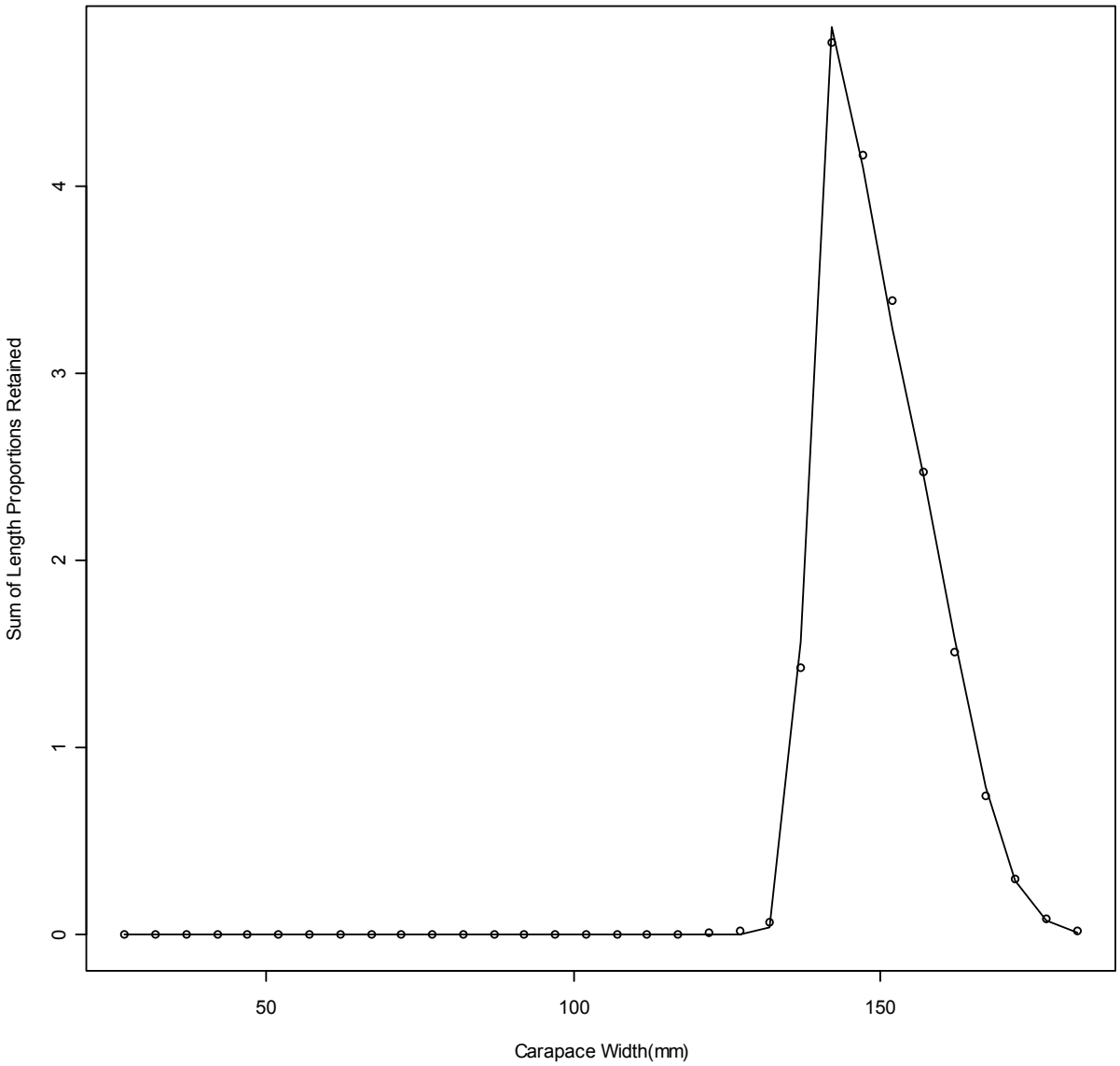


Figure 33. *Base Model (0)* summary fit to the retained male size frequency data, shell condition combined. Solid line is the model fit. Circles are observed data.

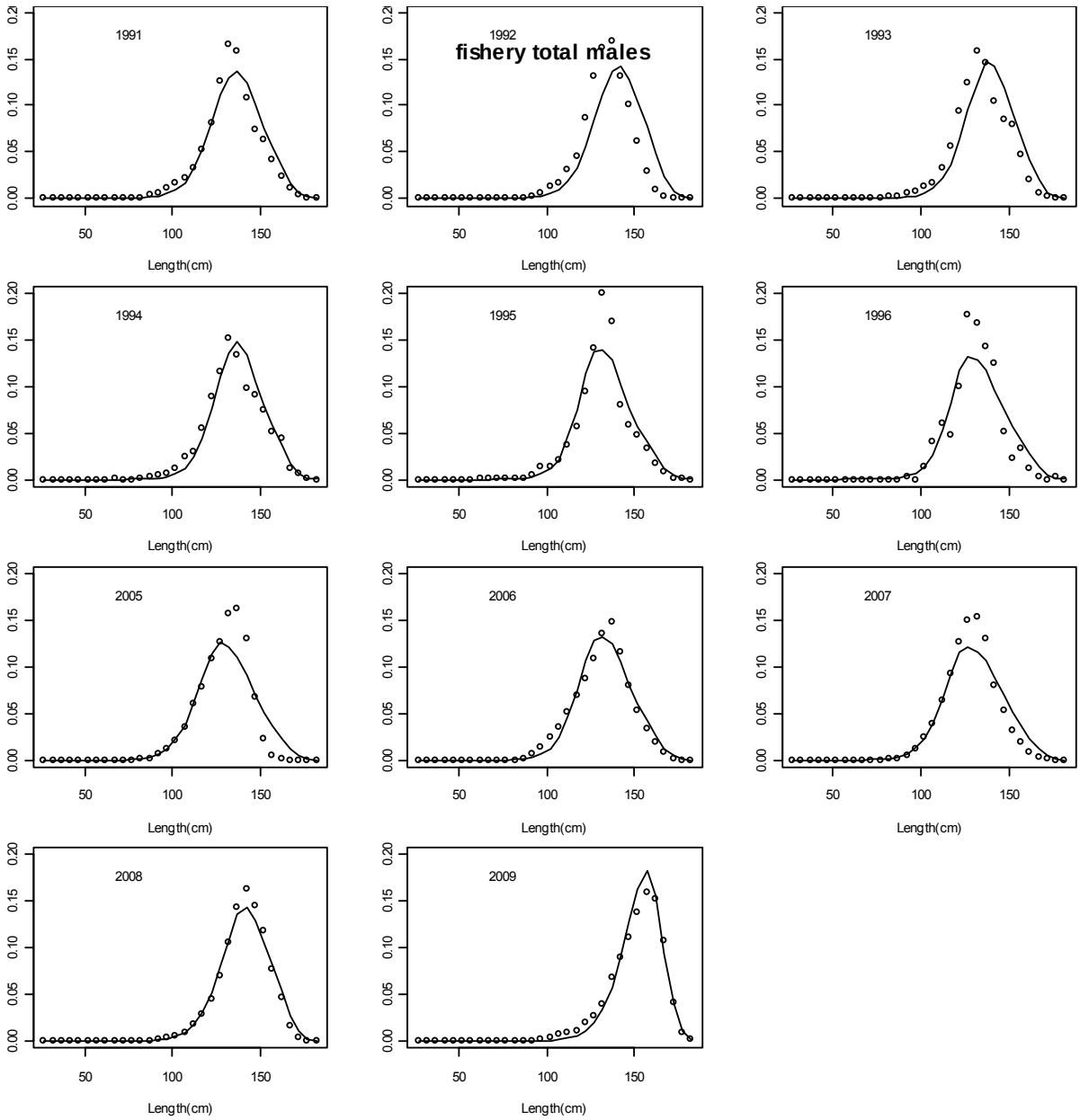


Figure 34. *Base Model (0)* fit to the total (discard plus retained) male size frequency data in all fisheries combined, shell condition combined. Circles are observed data.

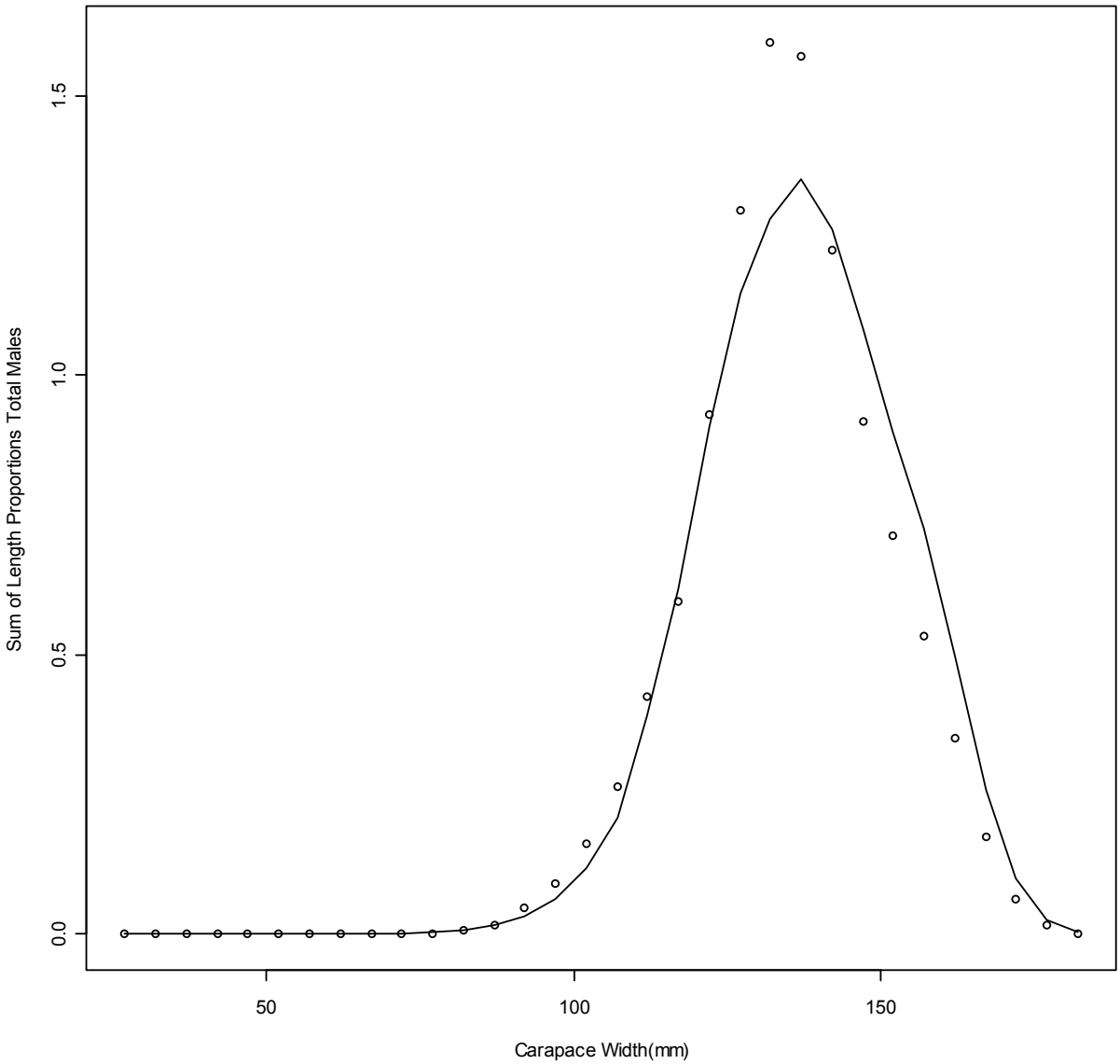


Figure 35. *Base Model (0)* summary fit to the total (discard plus retained) male size frequency data, shell condition combined. Solid line is the model fit. Circles are observed data.

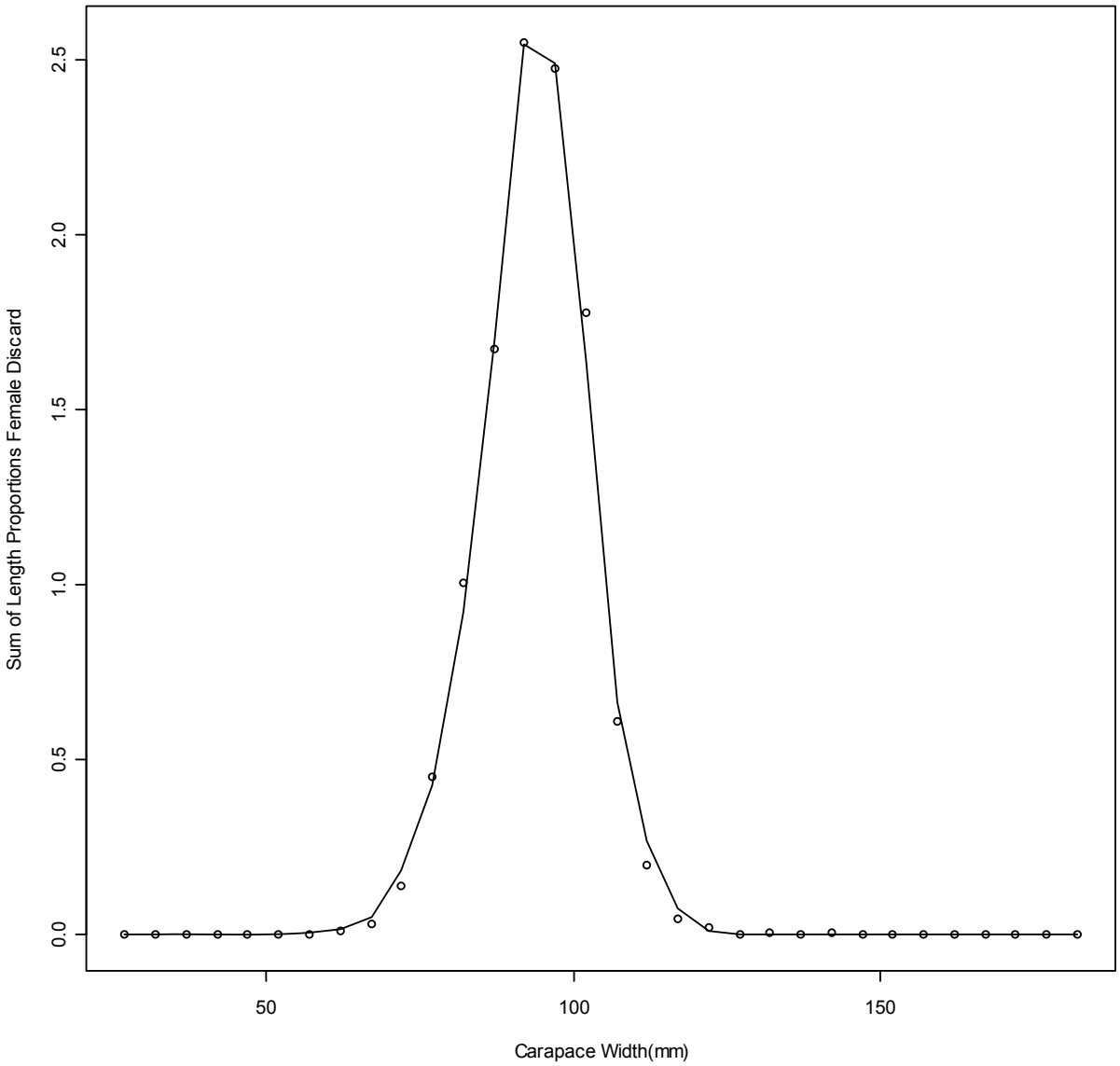


Figure 36. *Base Model (0)* summary fit to the discard female size frequency data in the directed fishery. Solid line is the model fit. Circles are observed data.

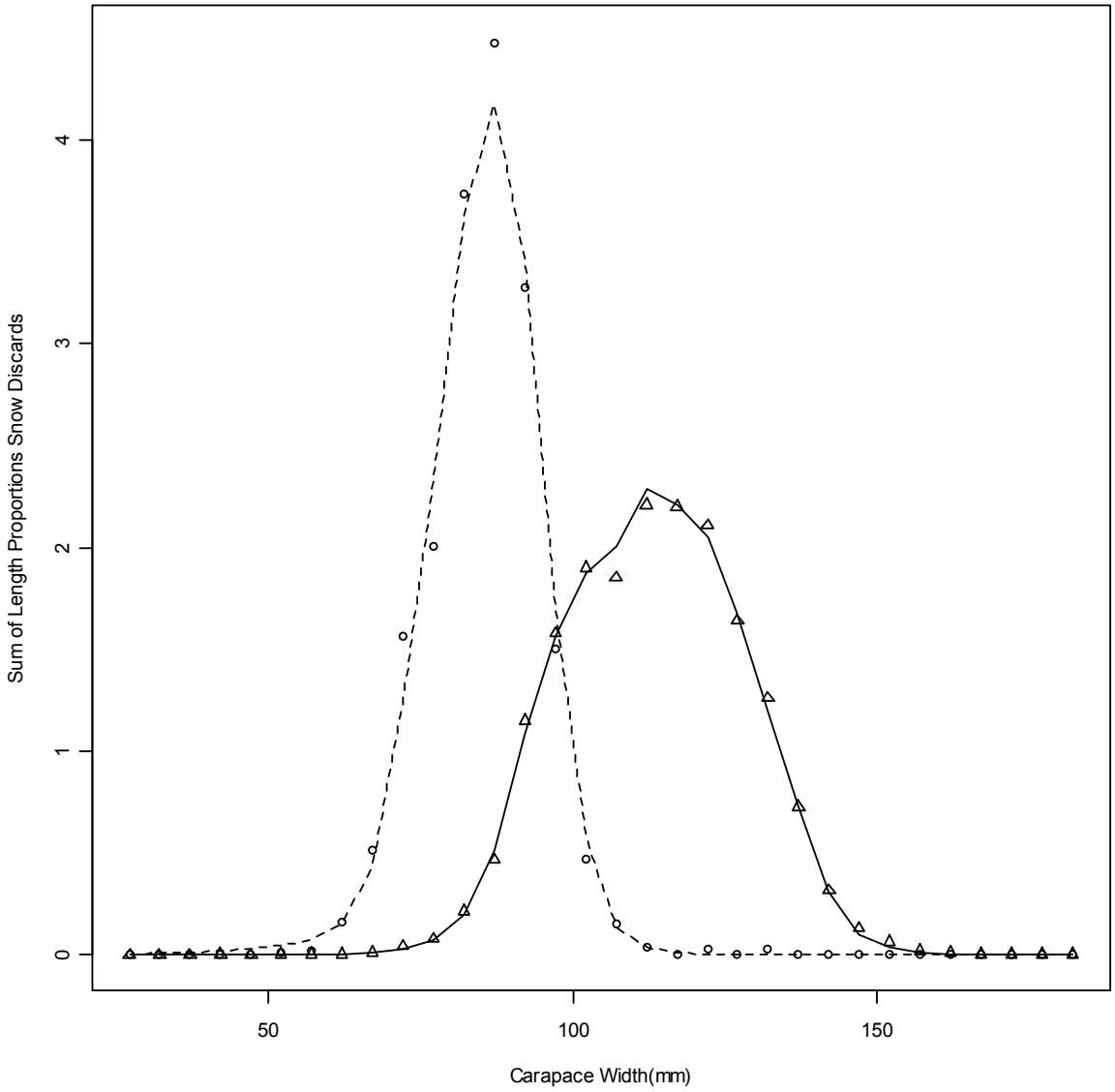


Figure 37. *Base Model (0)* summary fit to the discards in the snow crab fishery for males (solid line) and females (dotted line) size frequency data. Symbols are observed data.

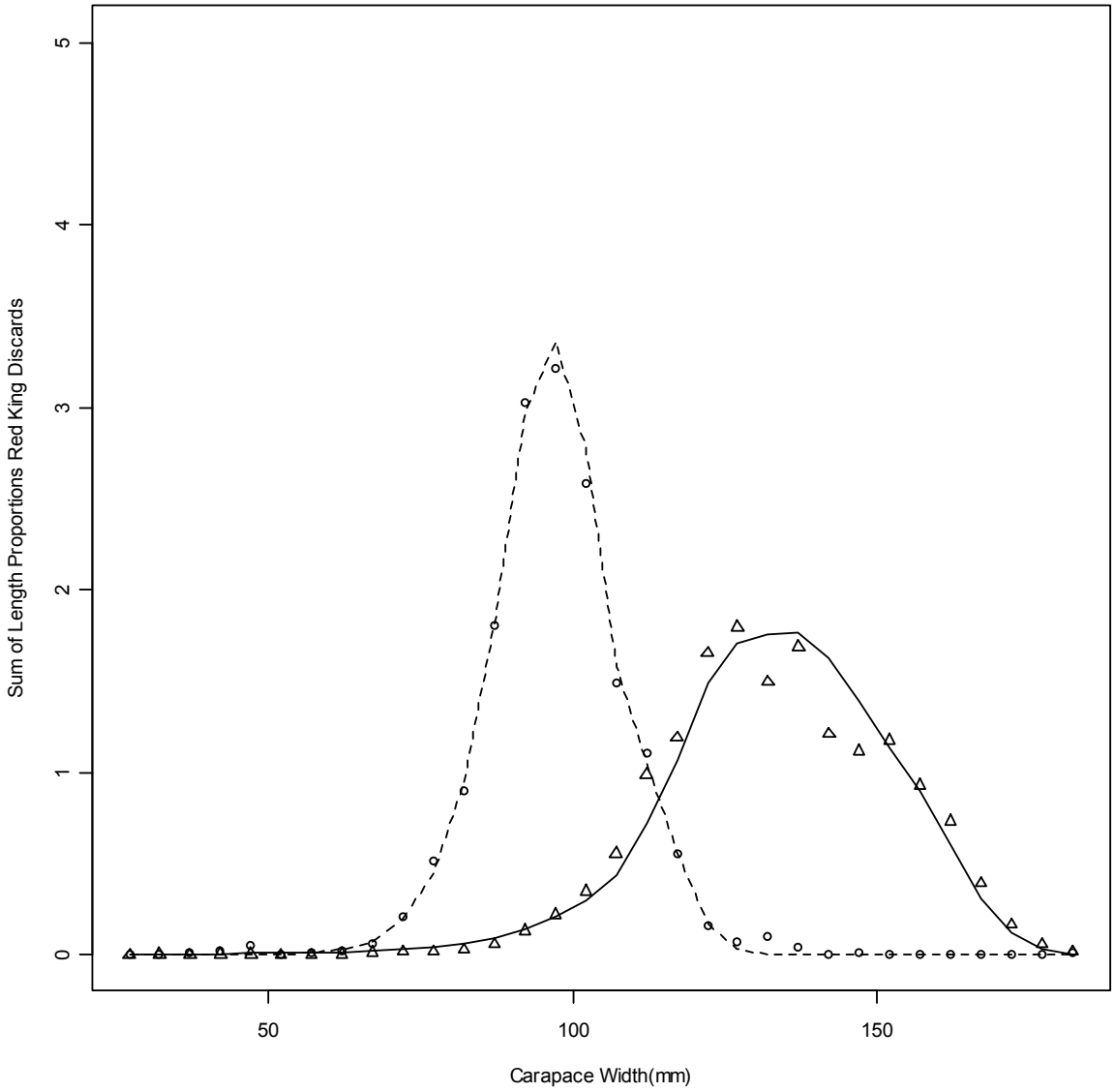


Figure 38. *Base Model (0)* summary fit to the discards in the Bristol Bay red king crab fishery for males (solid line) and females (dotted line) size frequency data. Symbols are observed data.

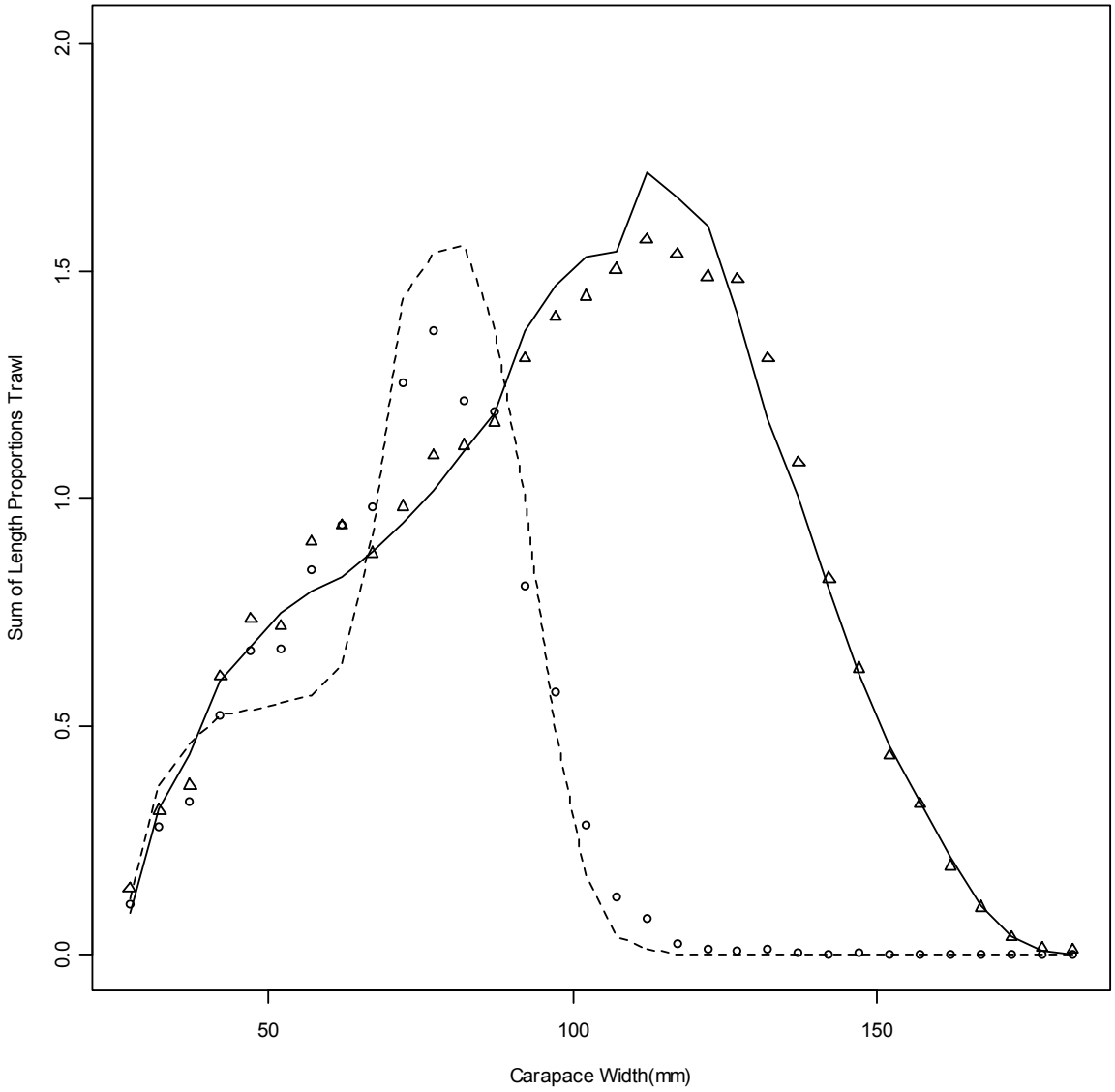


Figure 39. *Base Model (0)* summary fit to the discards in the eastern Bering Sea groundfish fisheries for males (solid line) and females (dotted line) size frequency data. Symbols are observed data.

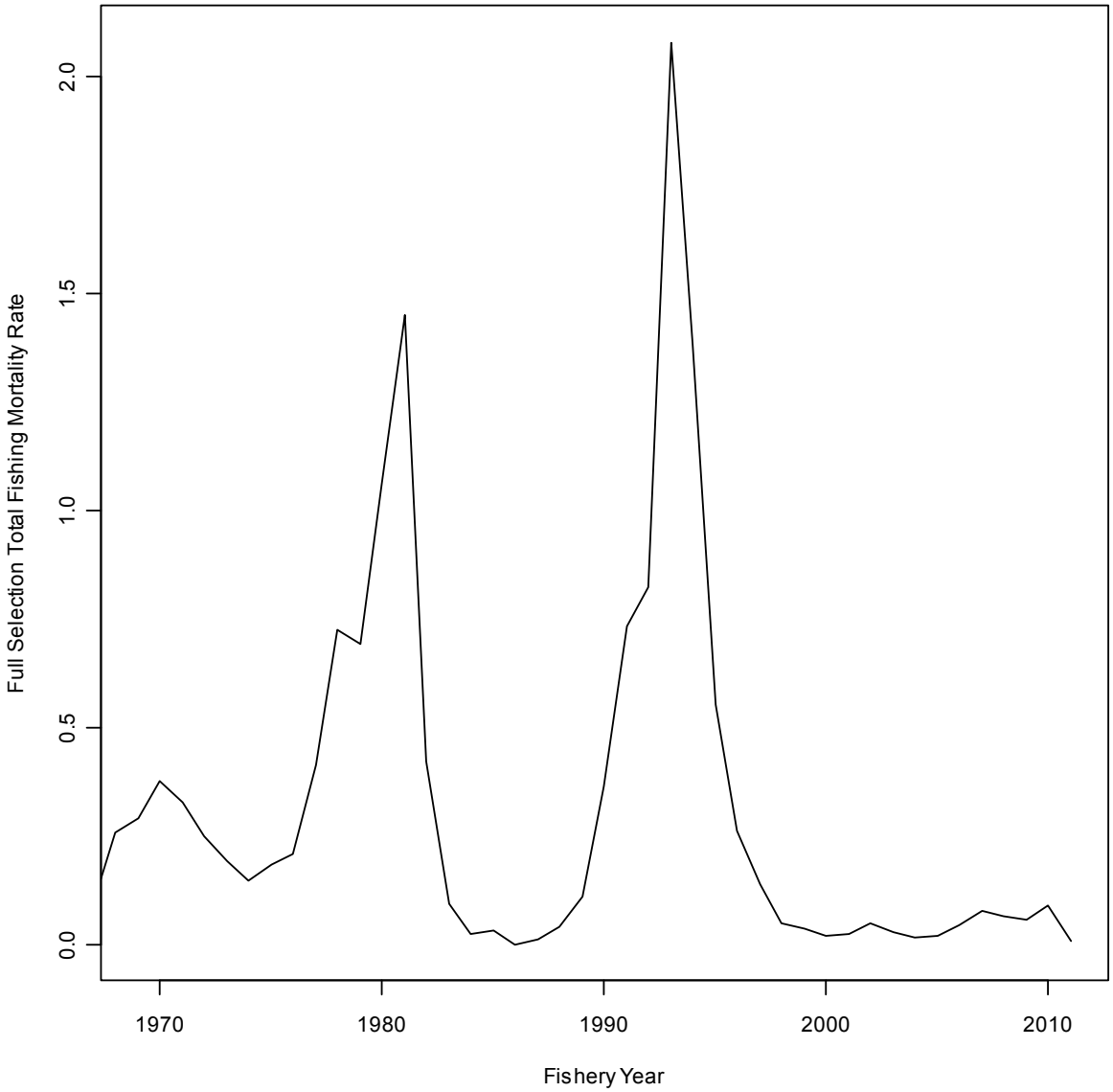


Figure 40. *Base Model (0)* full-selection total fishing mortality rates estimated in the model from 1970 to 2011 fishery seasons (1969 to 2010 survey years).

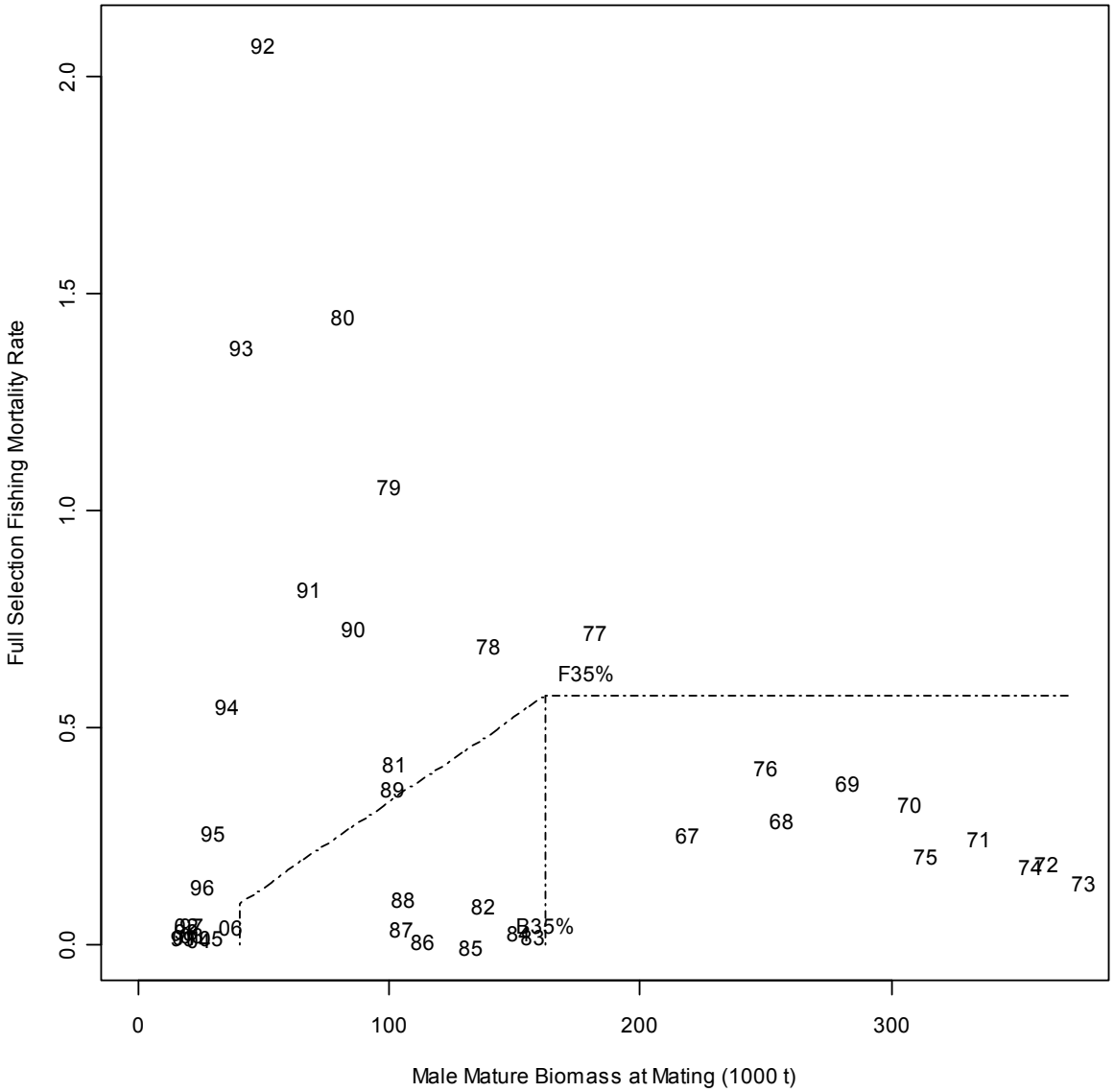


Figure 41. Full-selection fishing mortality versus male mature biomass at mating in fishing years 1967-2010/11. The *Base Model (0)* OFL control rule where $F_{35\%}$=0.574 and $B_{35\%}$=162.31 thousand t.

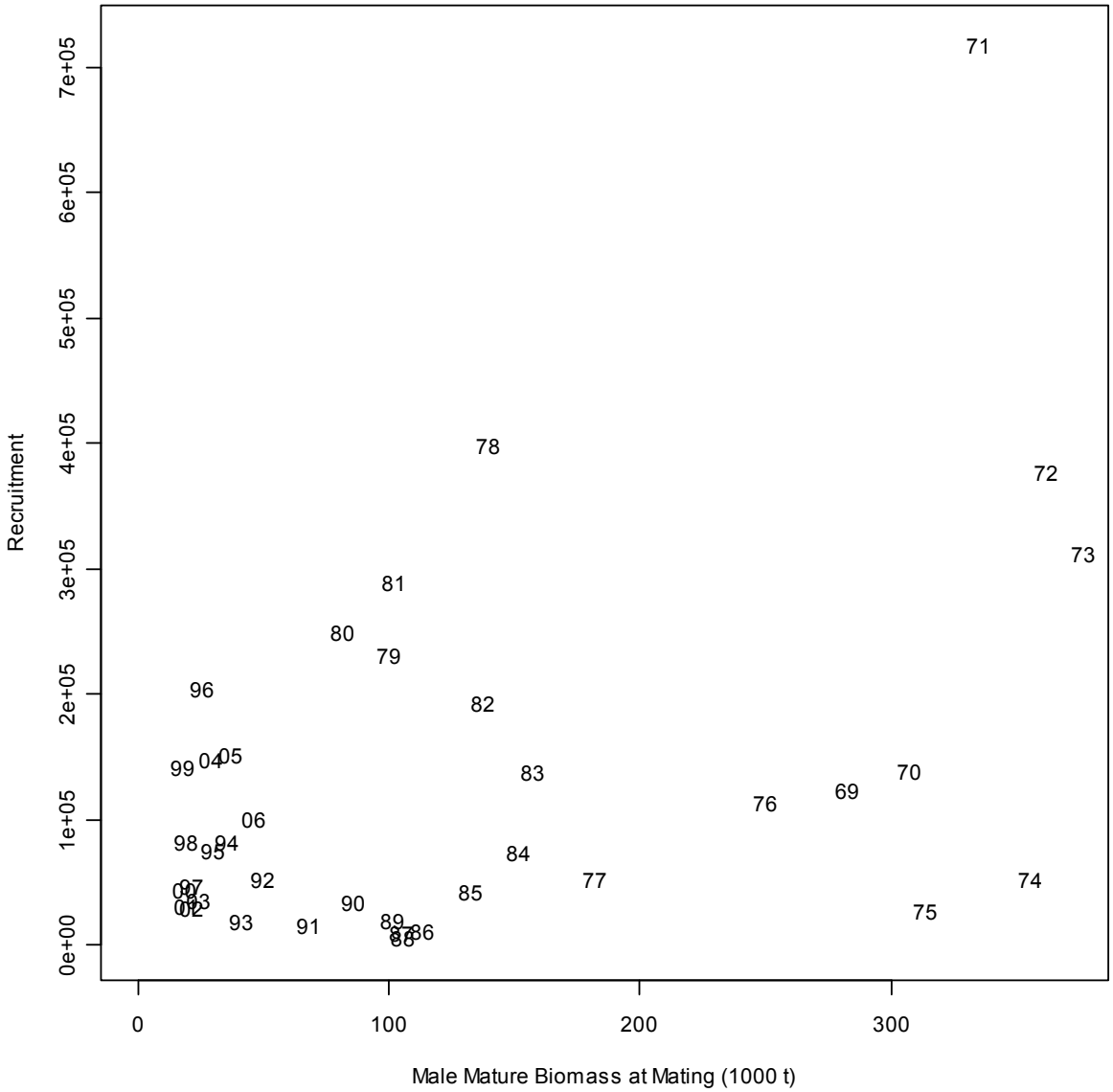


Figure 42. *Base Model (0)* recruitment (1000 crab) vs. male mature biomass at time of mating (1000 t). Two digit year numbers are fertilization year lagged 5 years. Recruitment is one-half of total recruits.

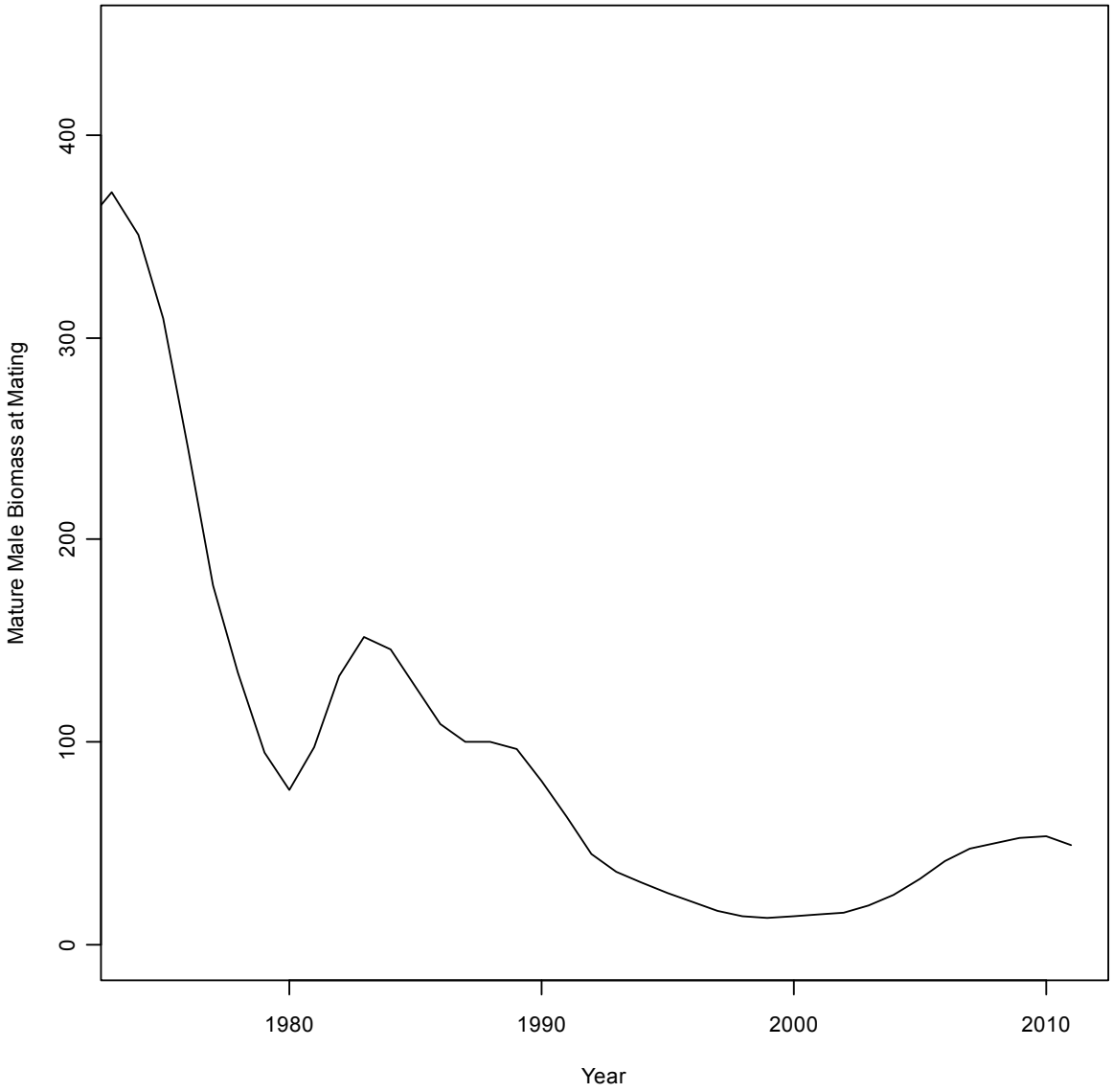


Figure 43. *Base Model (0)* time-trajectory of mature male biomass at the time of mating for EBS Tanner crab (1000 t) for years 1974-2011.

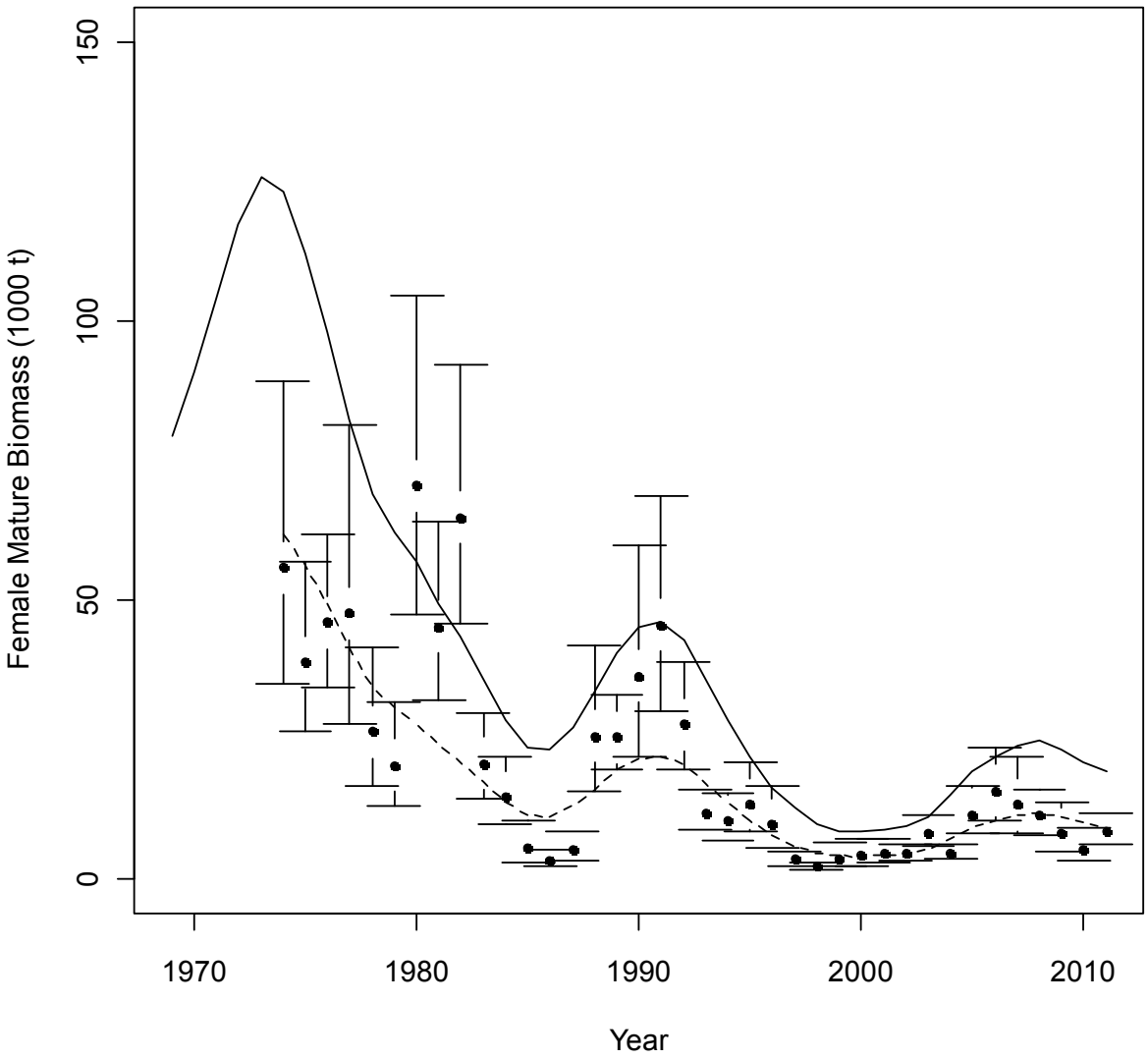


Figure 44. *Model (1)* population female mature biomass (1000 t, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

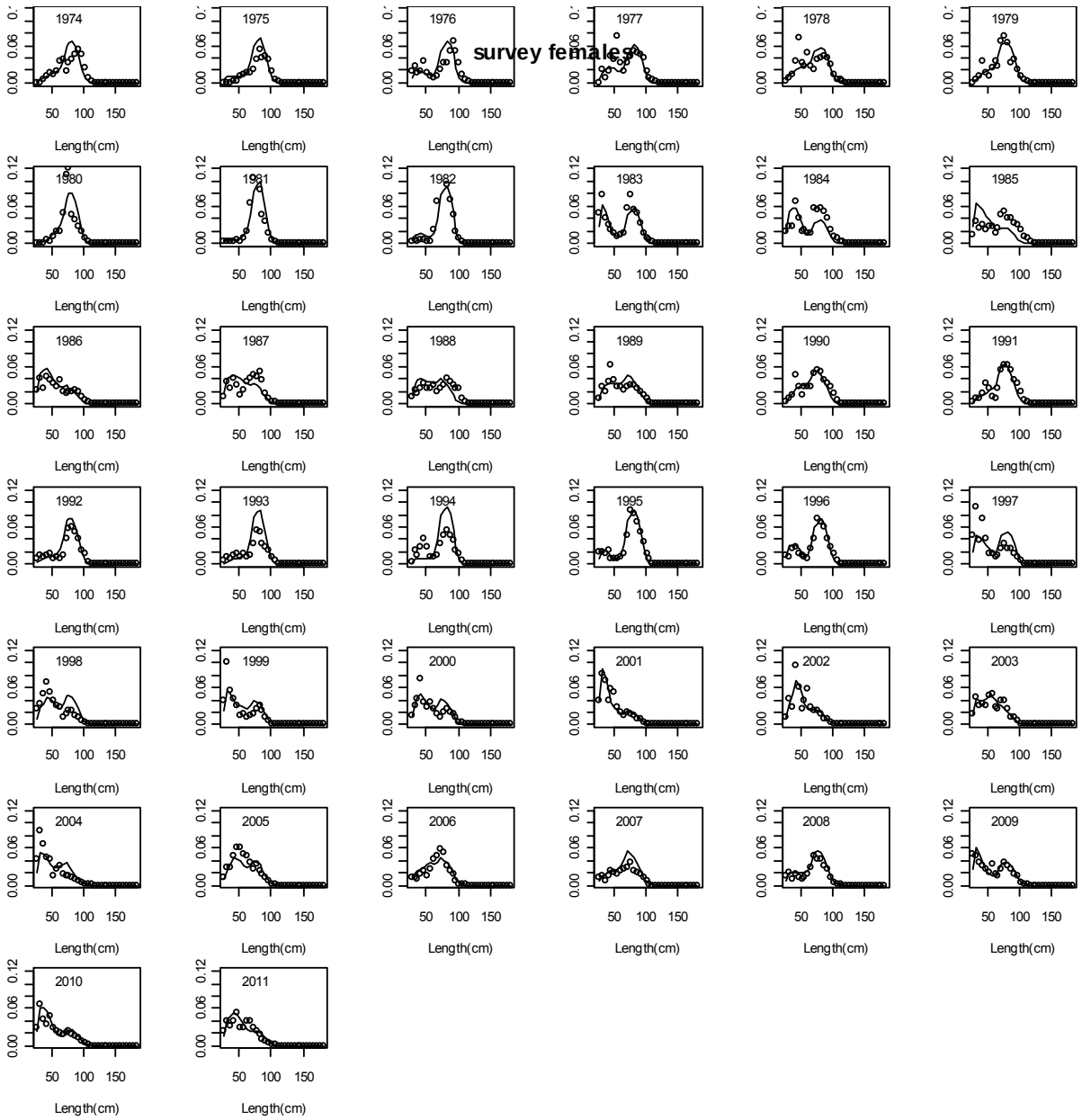


Figure 45. *Model (1)* fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

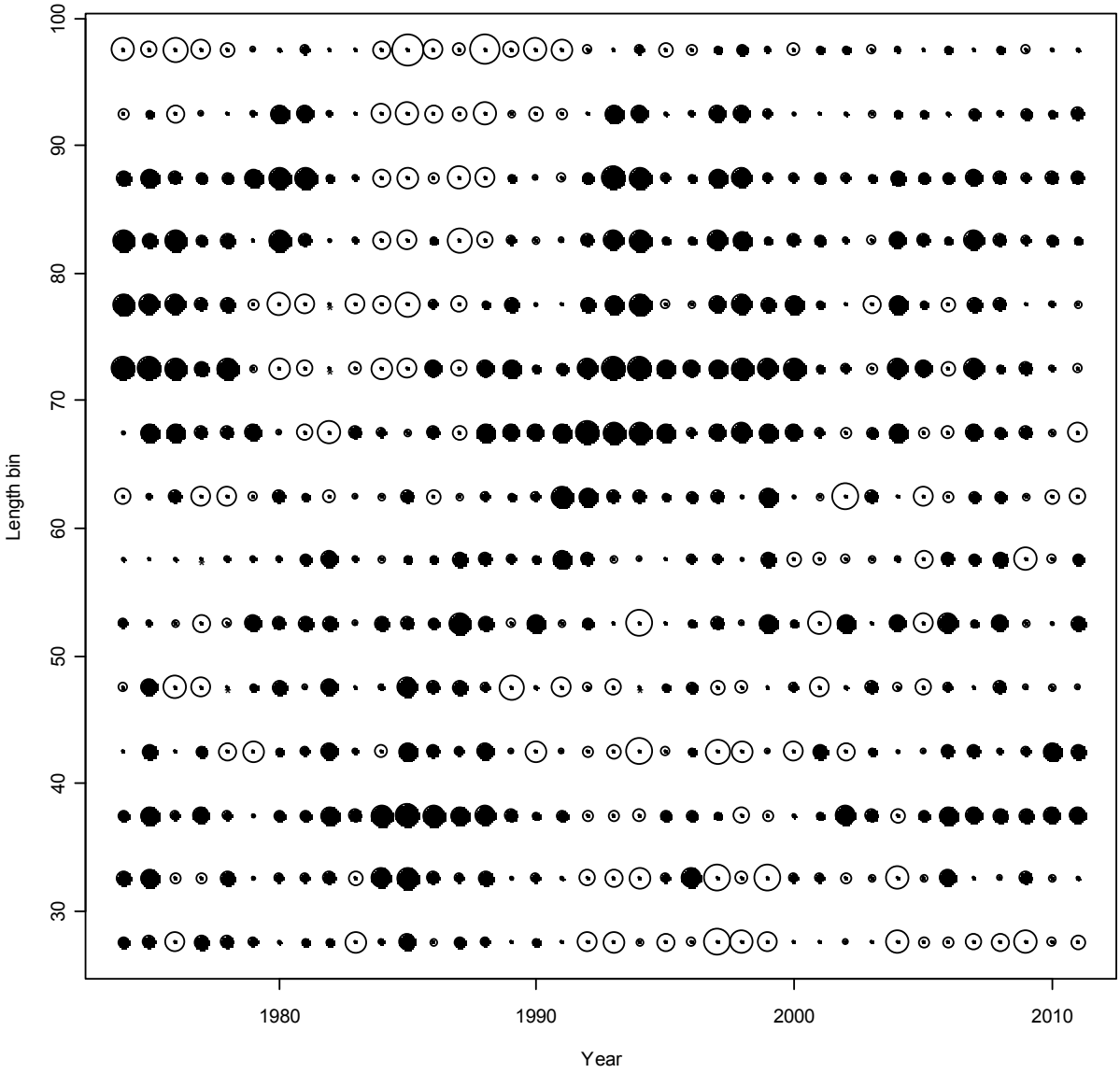


Figure 46. *Model (1)* residuals of the model fit to the survey female size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

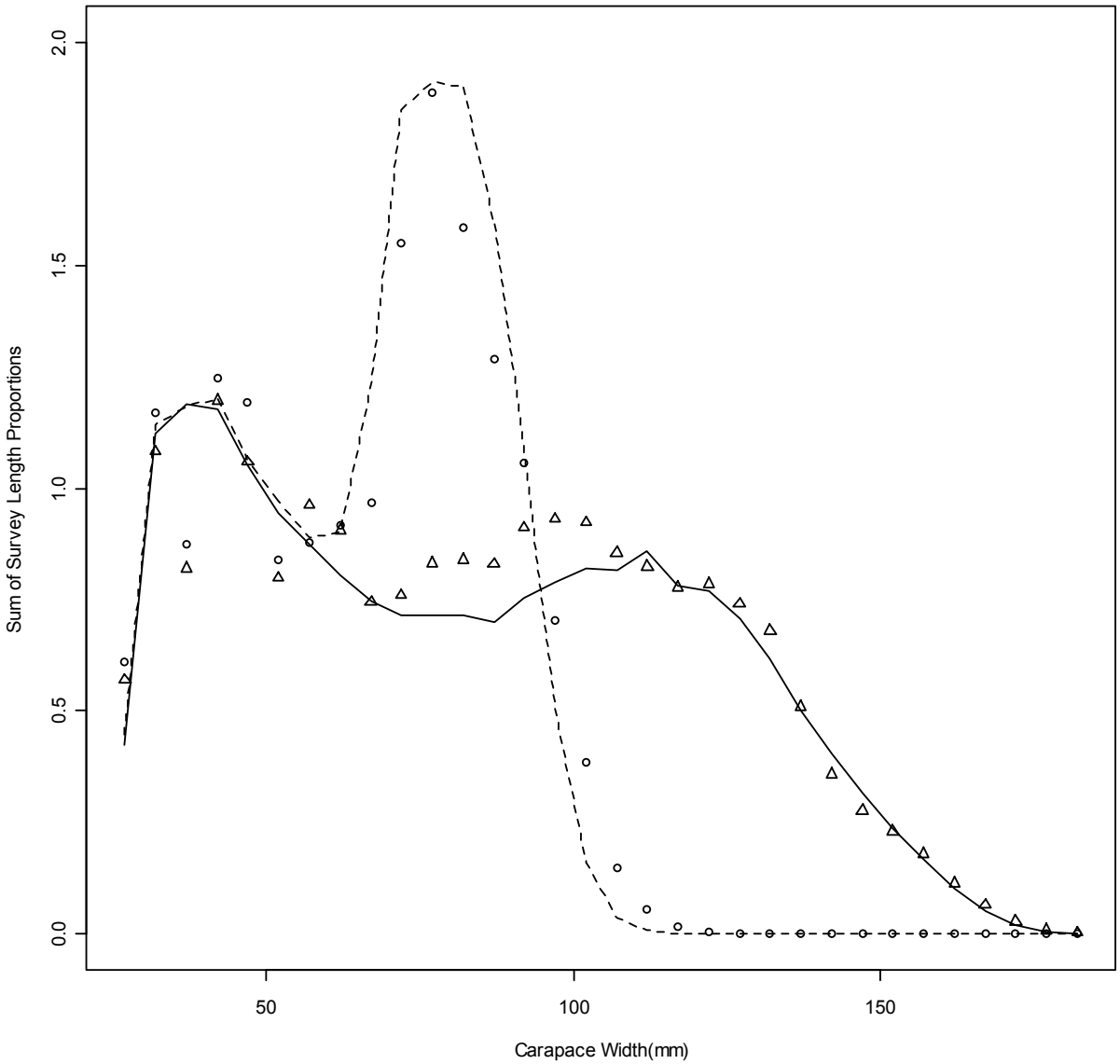


Figure 47. *Model (1)* summary fit to the survey male (solid line) and female (dotted line) size frequency data, all shell conditions combined. Symbols are observed data.

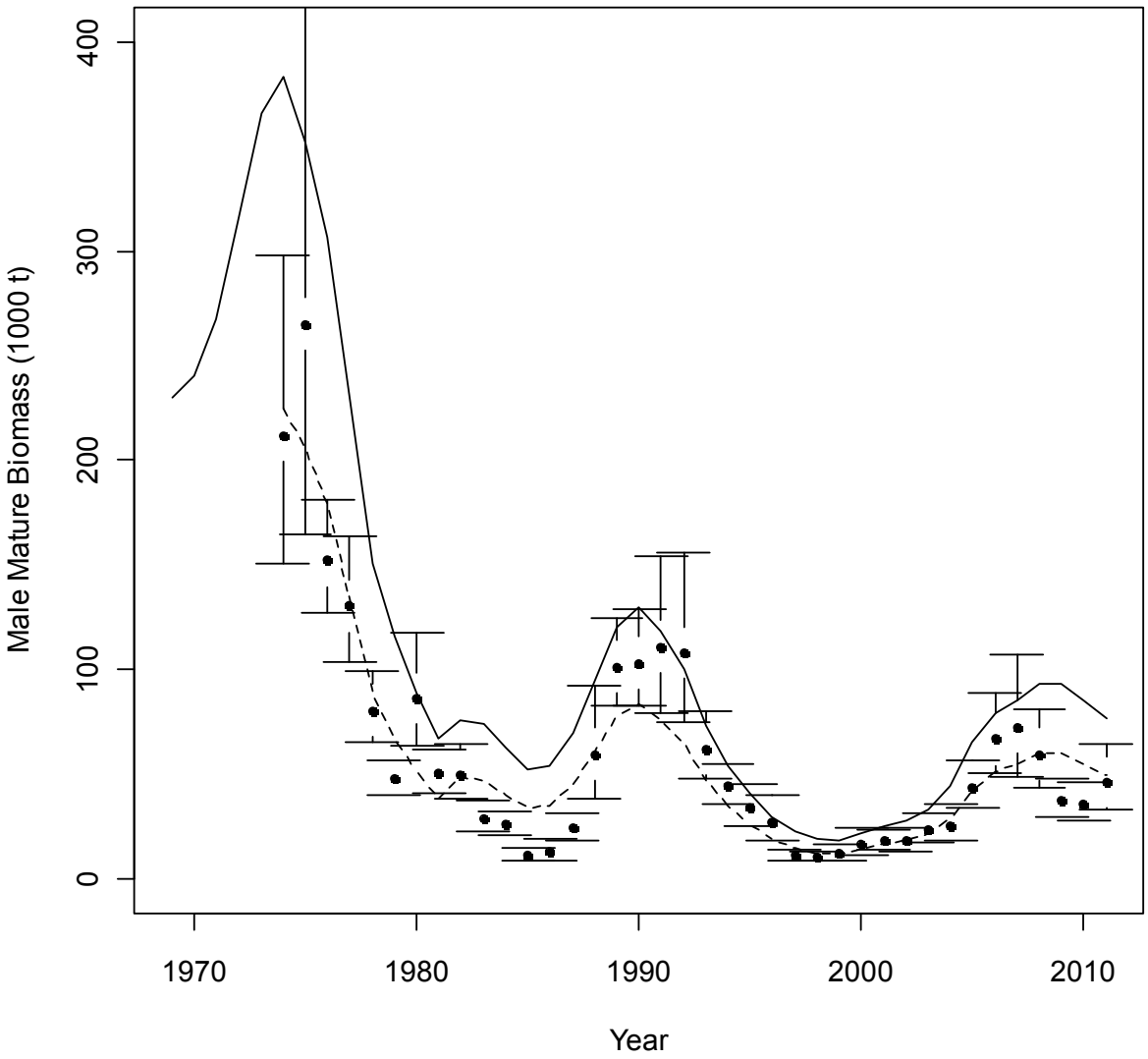


Figure 48. *Model (1)* population mature male biomass (1000 t, solid line) at the time of the survey, model estimate of survey mature biomass (dotted line) and observed survey mature male biomass with approximate lognormal 95% confidence intervals.

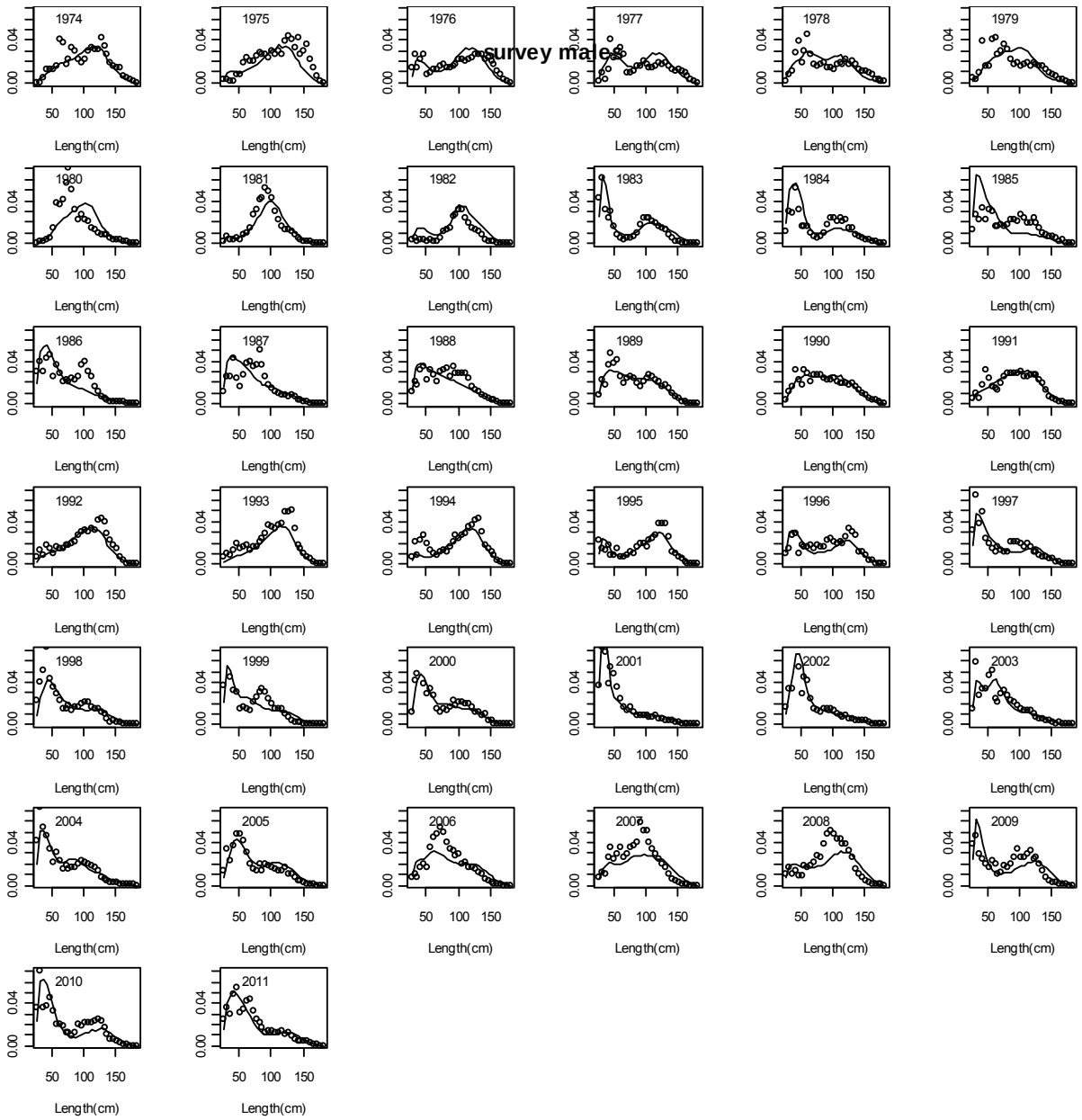


Figure 49. *Model (1)* fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

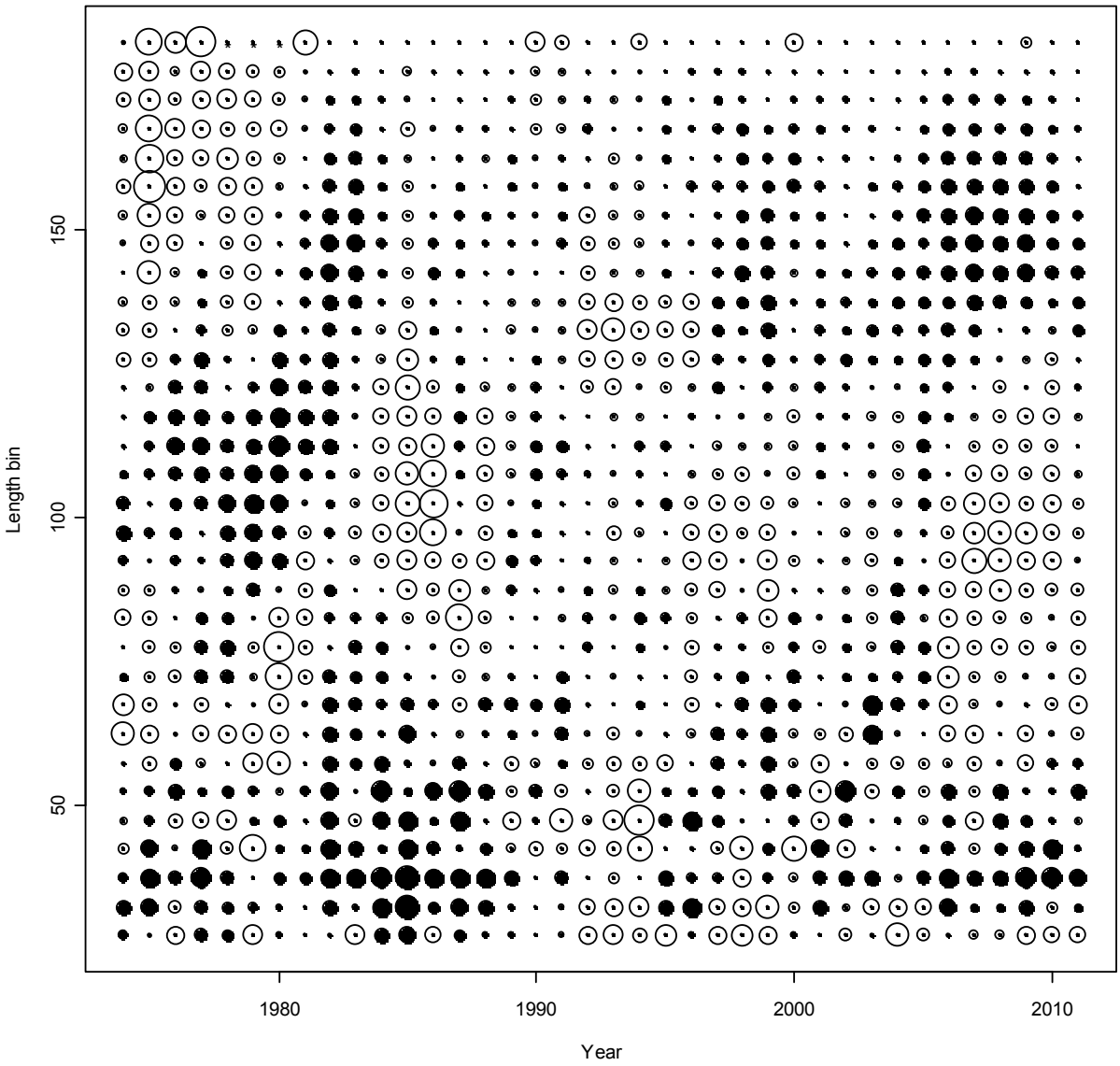


Figure 50. *Model (1)* residuals of the model fit to the survey male size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

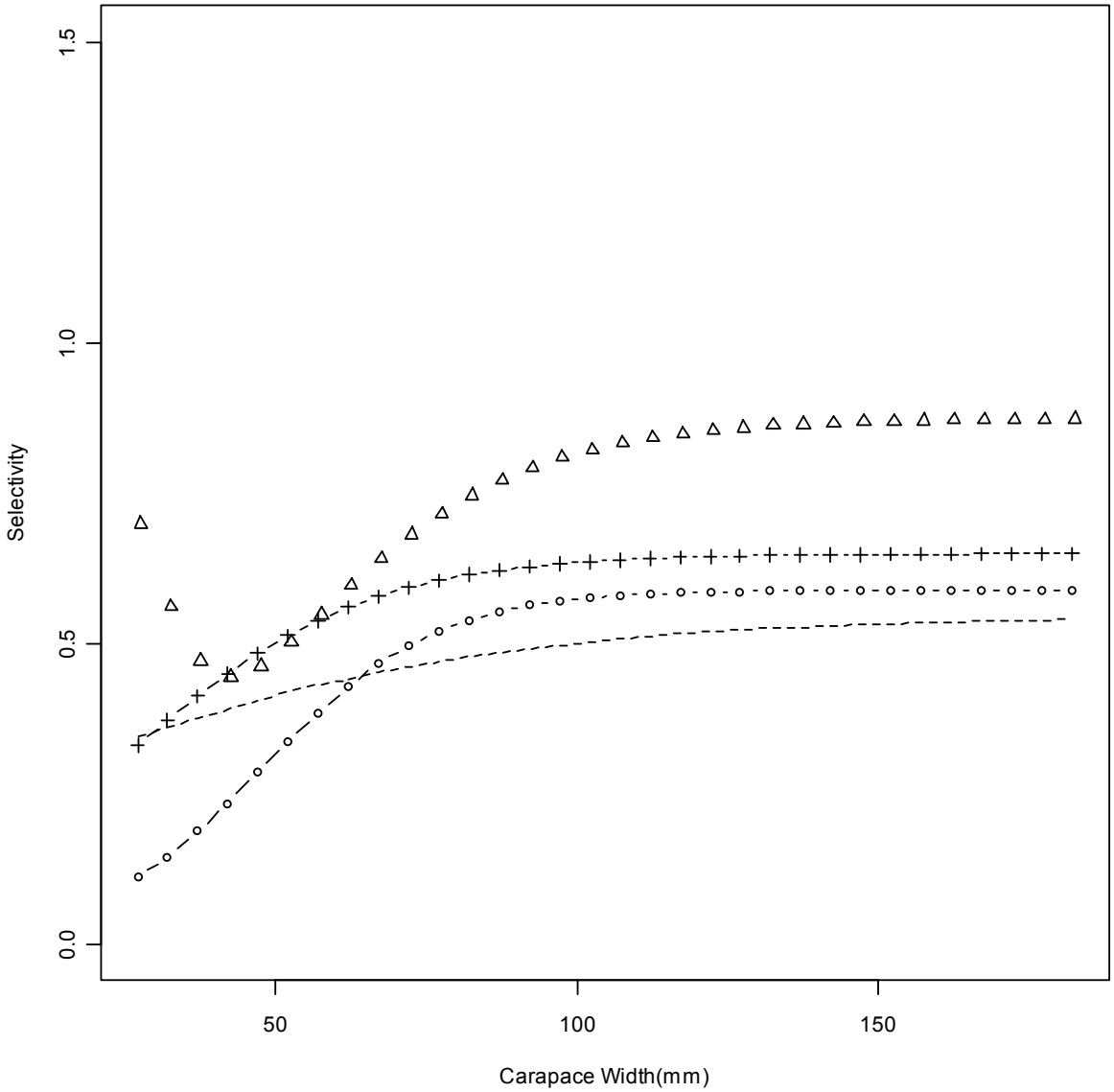


Figure 51. *Model (1)* survey selectivity curves for male Tanner crab estimated for 1974-1981 (dashed line with circles), and 1982-2011 (dashed line with pluses). Survey selectivity estimated by Somerton and Otto (1998) are triangle symbols, and female selectivity for 1982-2011 is dashed line for reference.

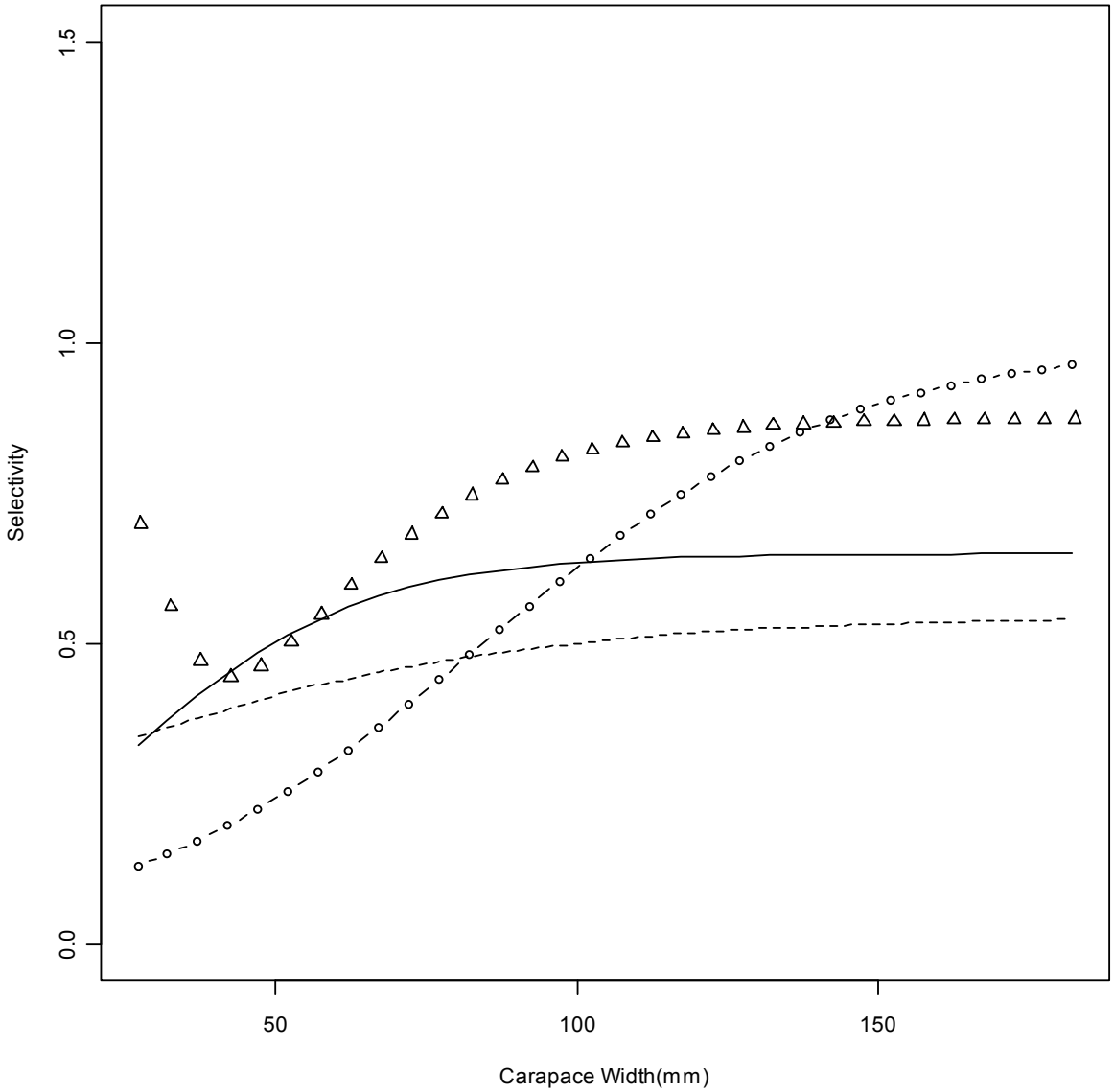


Figure 52. *Model (1)* survey selectivity curves for female Tanner crab estimated for 1974-1981 (dashed line with circles) and 1982-2011 (dashed line). Survey selectivity estimated by Somerton and Otto (1998) are triangle symbols, and male selectivity for 1982-2011 is solid line for reference.

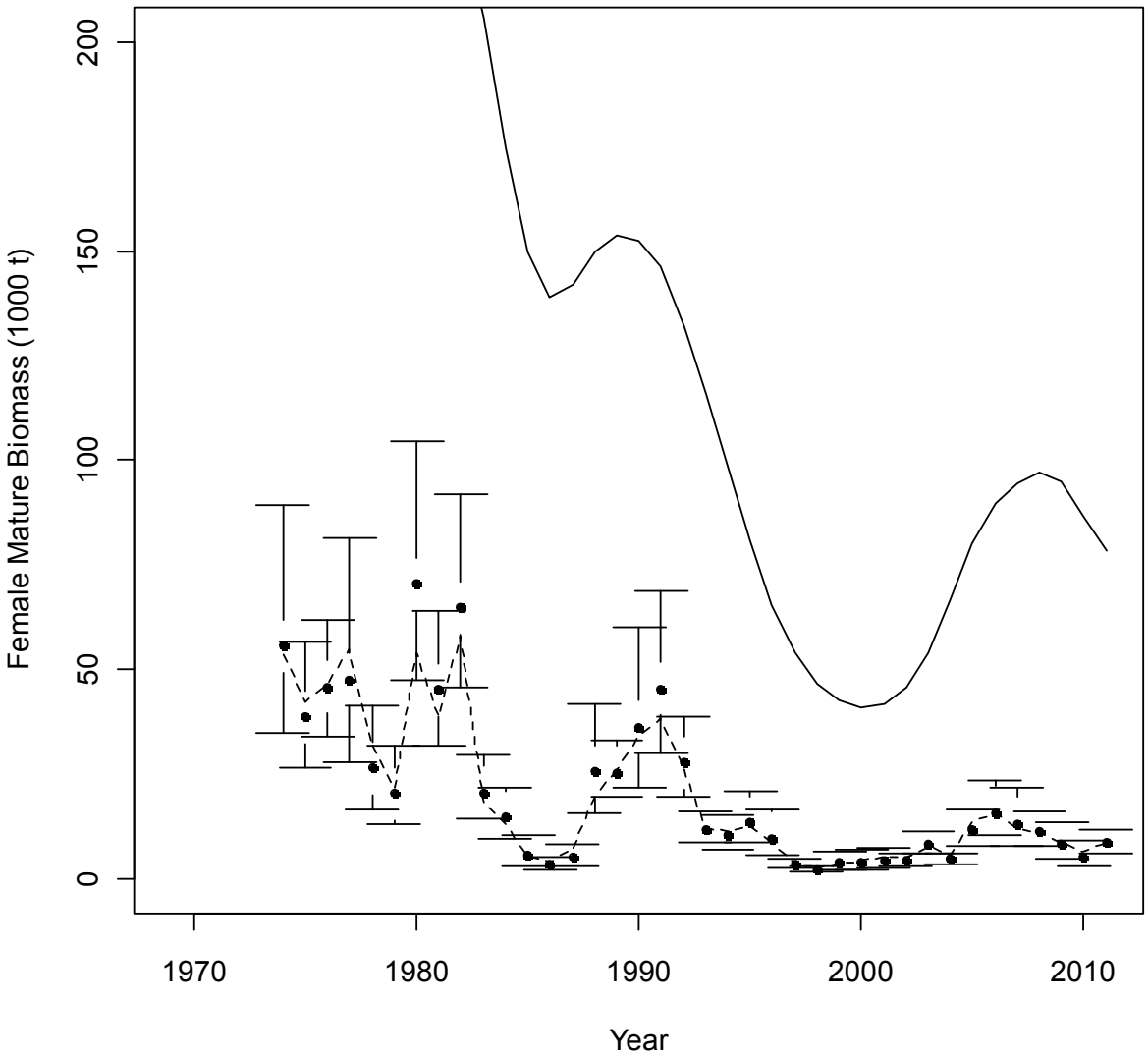


Figure 53. *Model (2)* population female mature biomass (1000 t, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

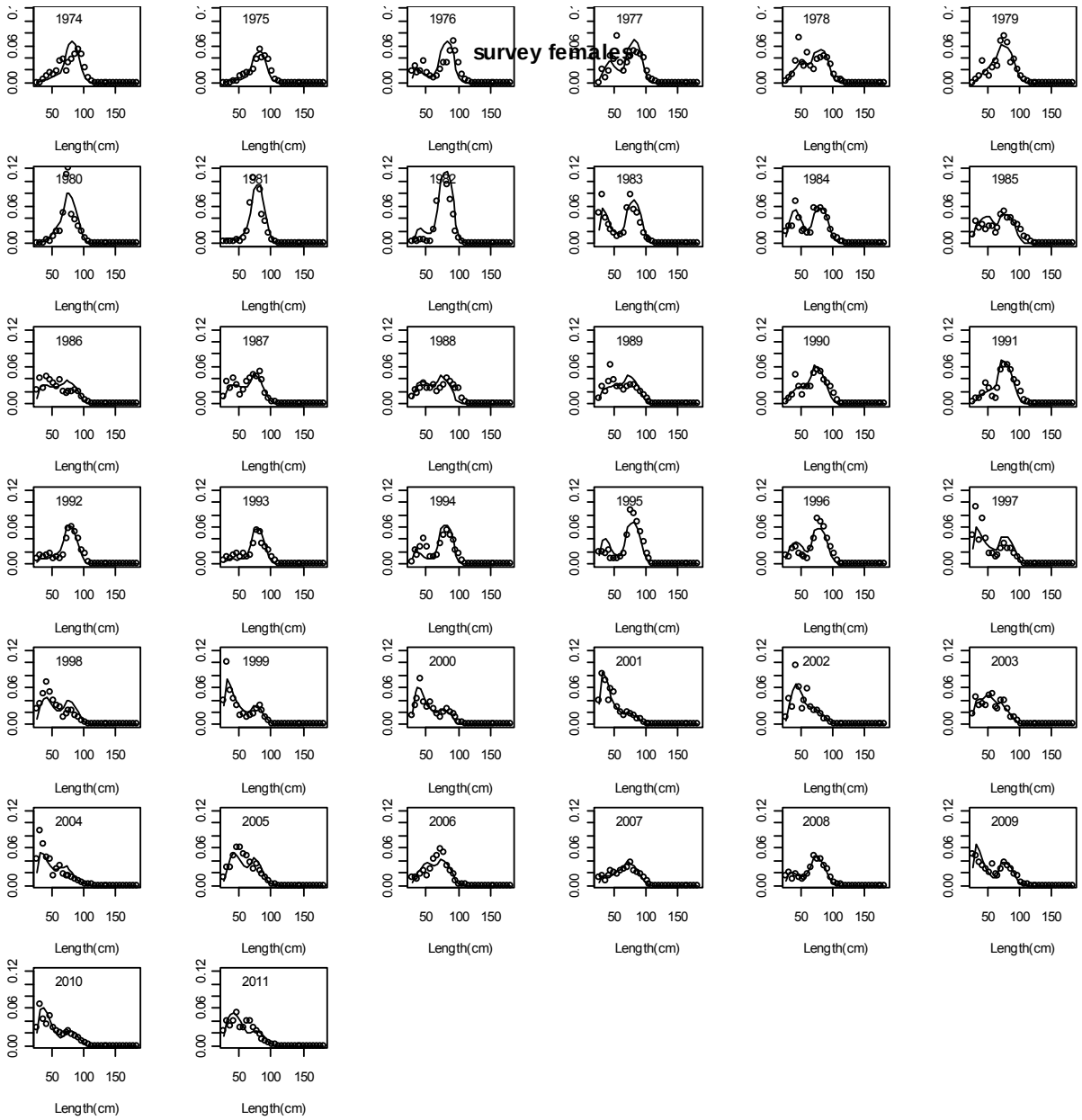


Figure 54. *Model (2)* fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

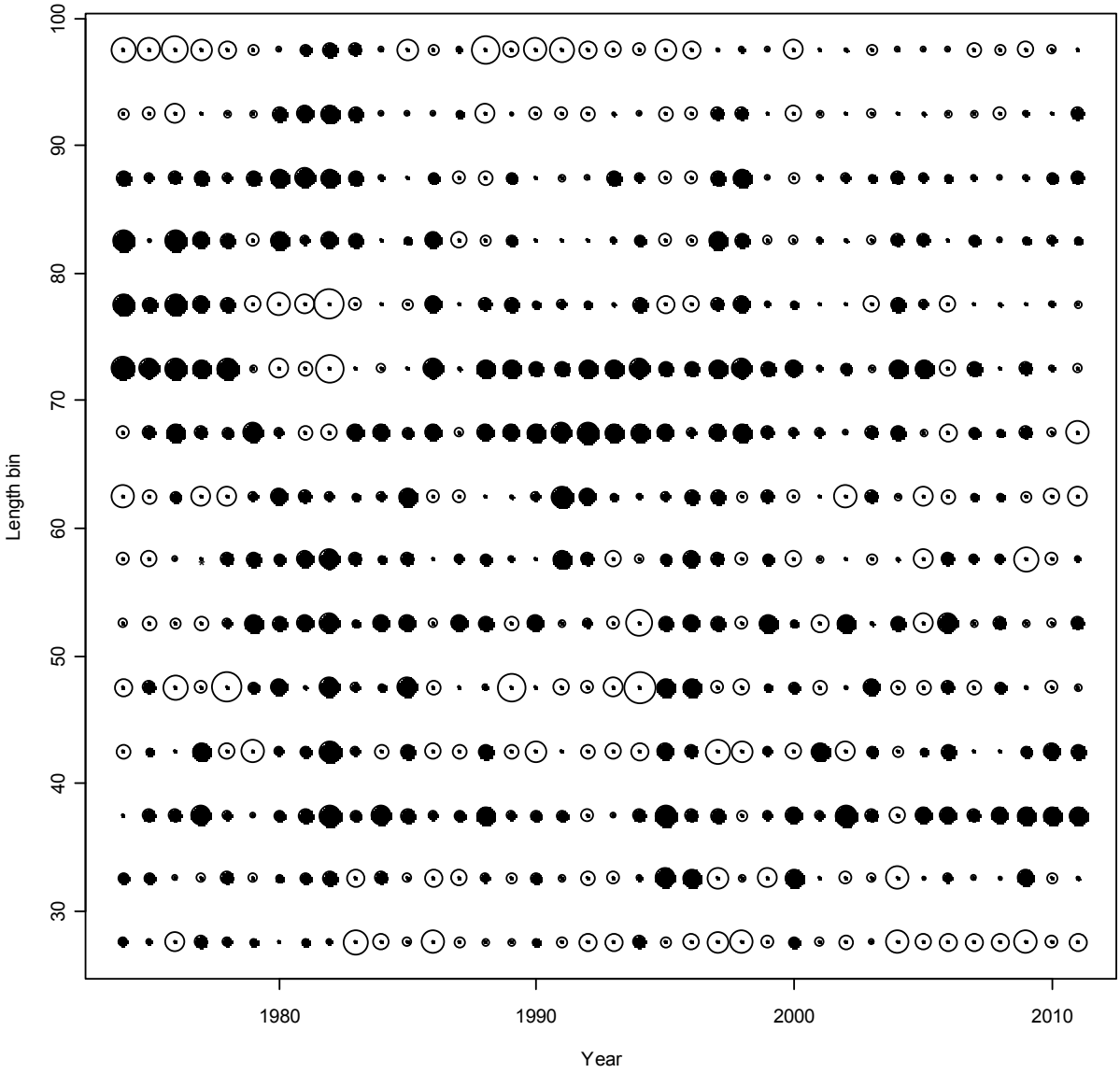


Figure 55. *Model (2)* residuals of the model fit to the survey female size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

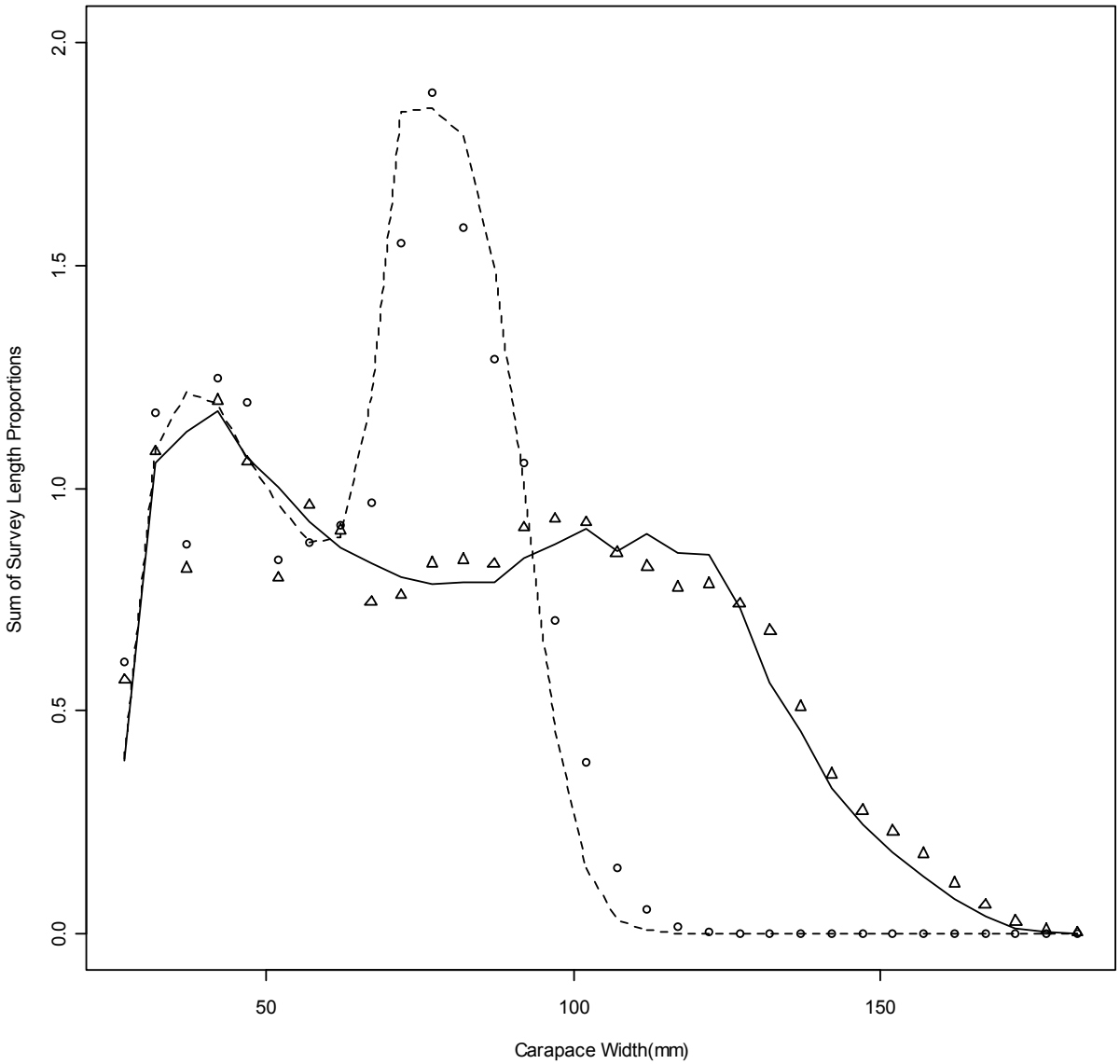


Figure 56. *Model (2)* summary fit to the survey male (solid line) and female (dotted line) size frequency data, all shell conditions combined. Symbols are observed data.

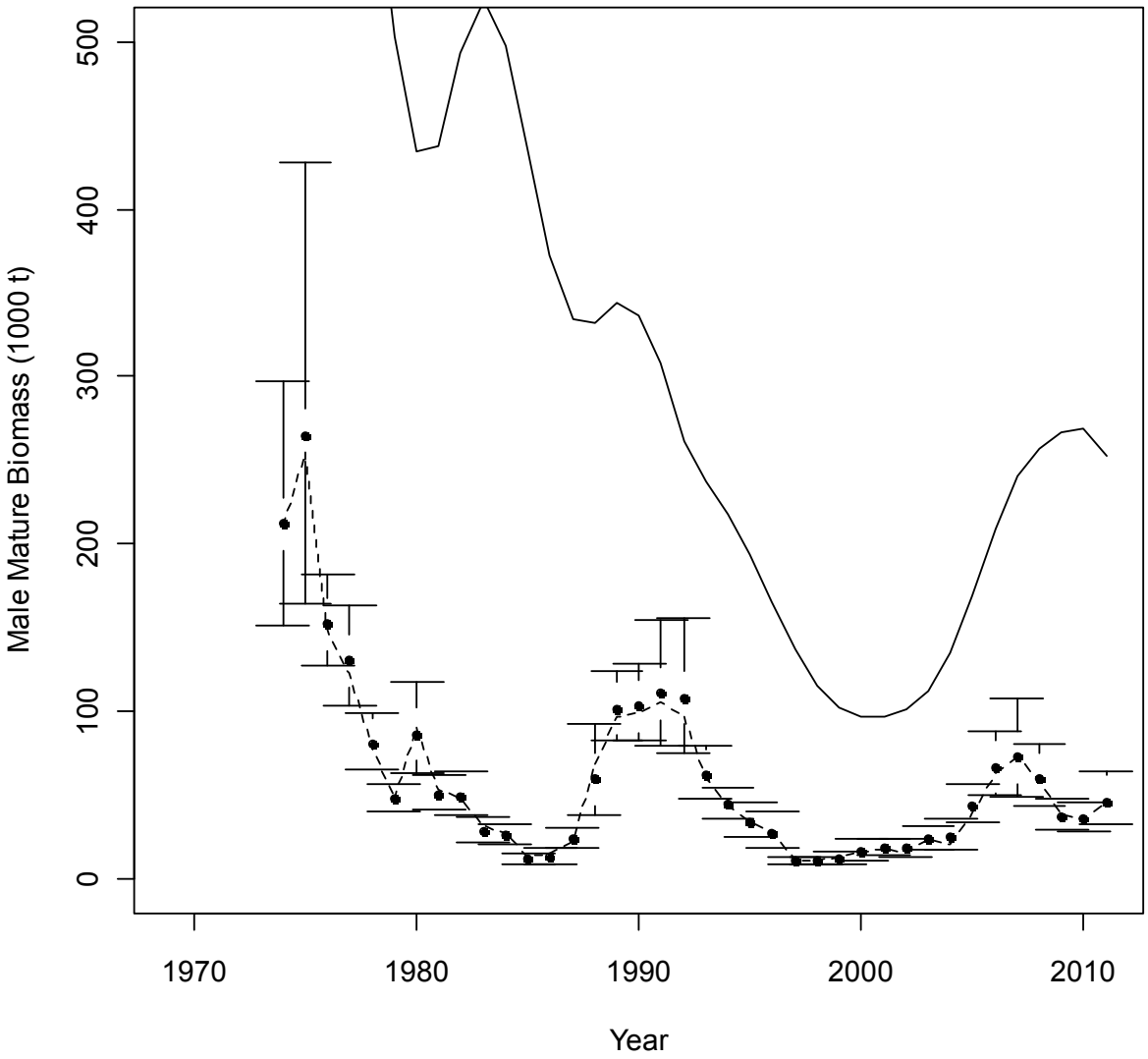


Figure 57. *Model (2)* population mature male biomass (1000 t, solid line) at the time of the survey, model estimate of survey mature biomass (dotted line) and observed survey mature male biomass with approximate lognormal 95% confidence intervals.

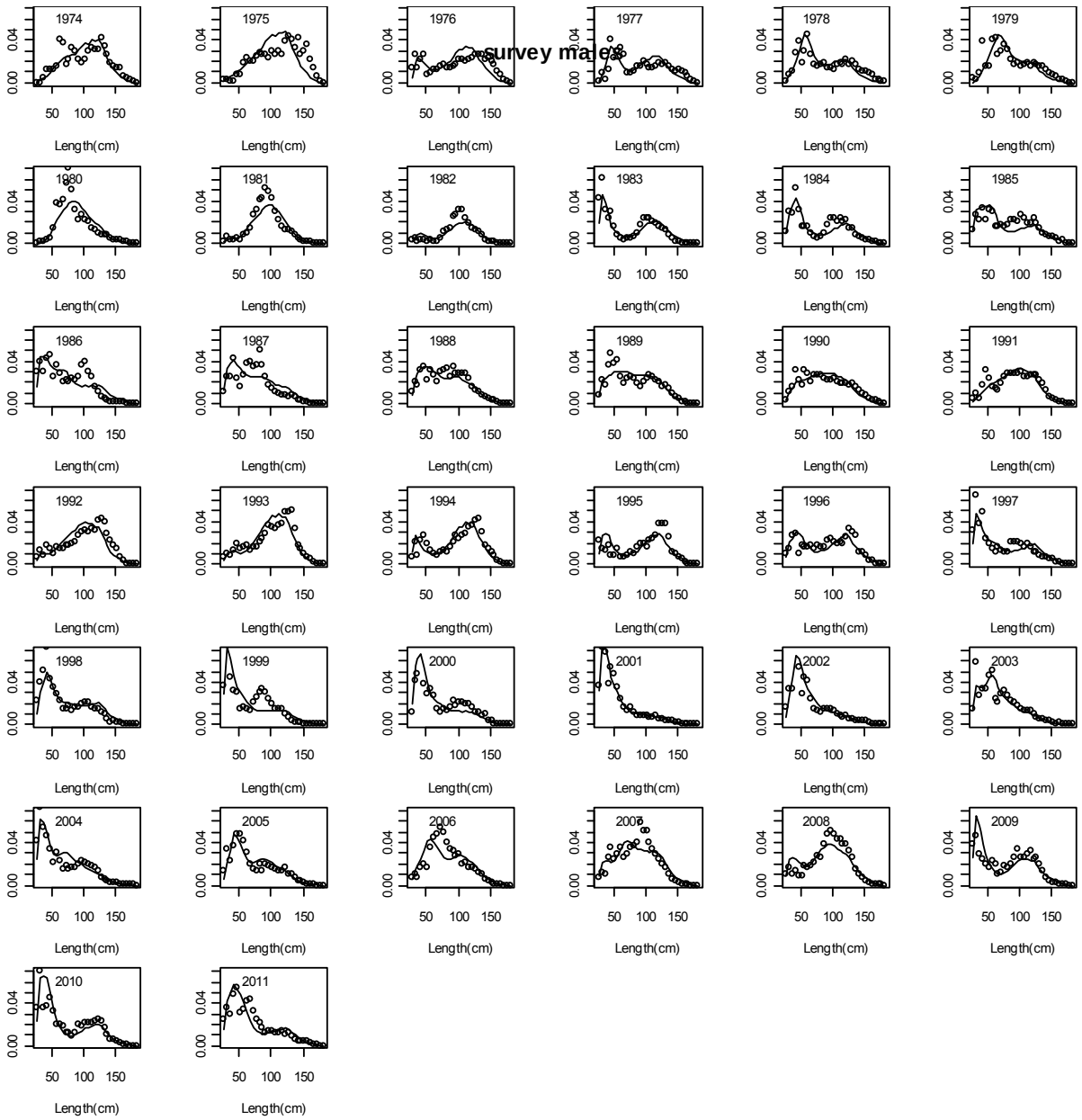


Figure 58. *Model (2)* fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

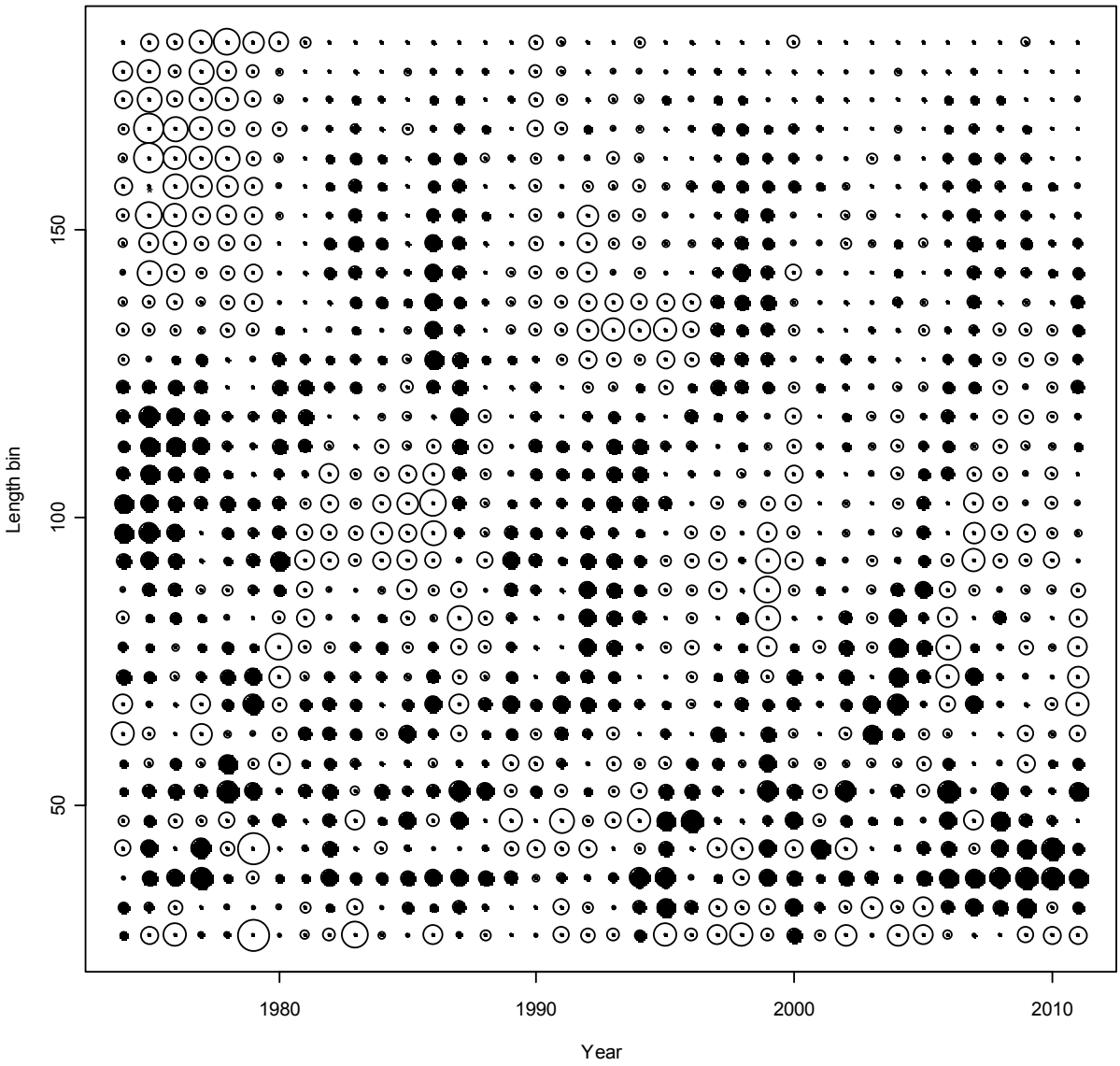


Figure 59. *Model (2)* residuals of the model fit to the survey male size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

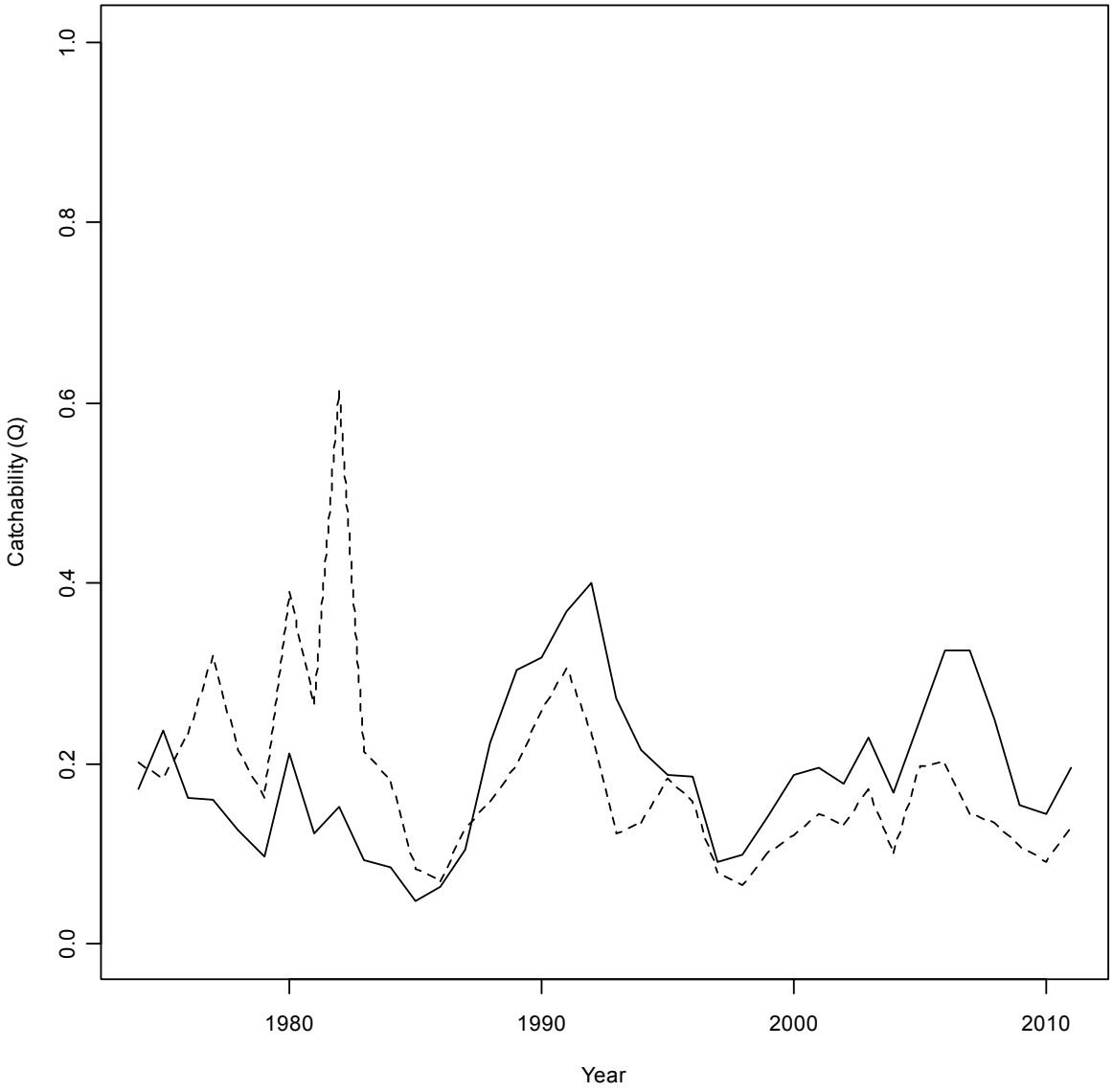


Figure 60 *Model (2)* estimates annual survey selectivity (Q) for male (solid) and female (dashed) Tanner crab in the NMFS bottom trawl survey, 1974-2011.

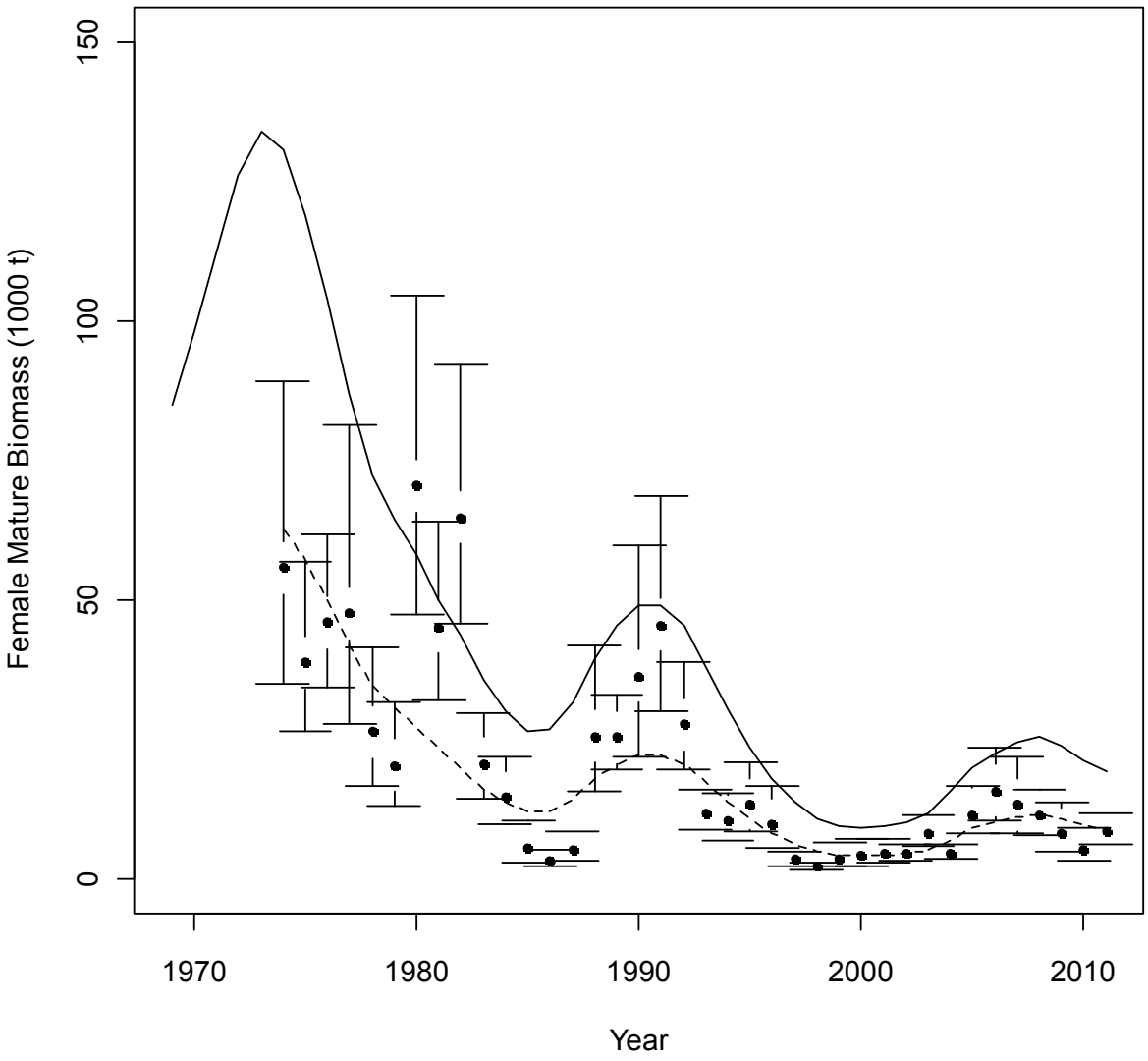


Figure 61. *Model (3)* population female mature biomass (1000 t, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

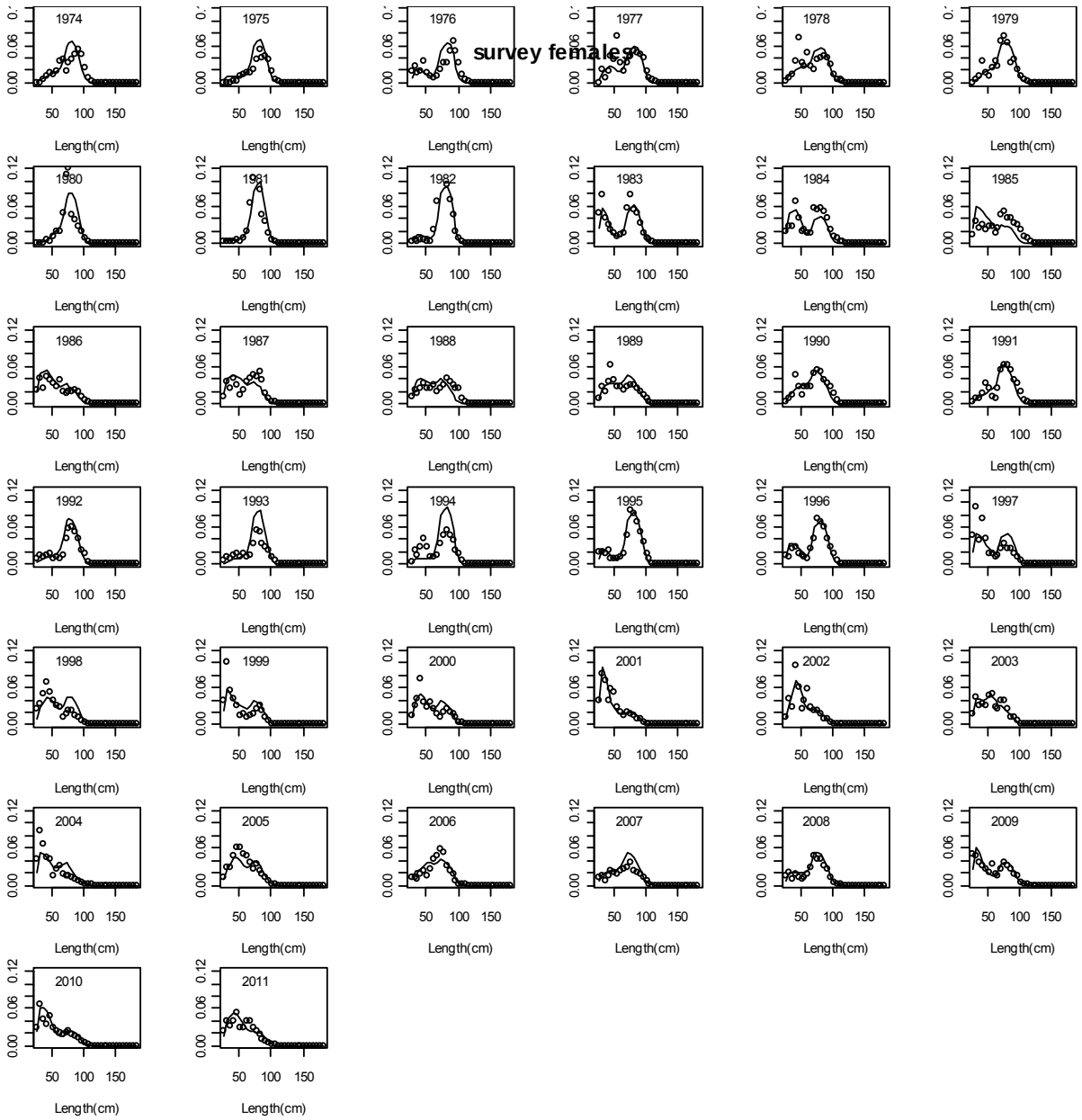


Figure 62. *Model (3)* fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

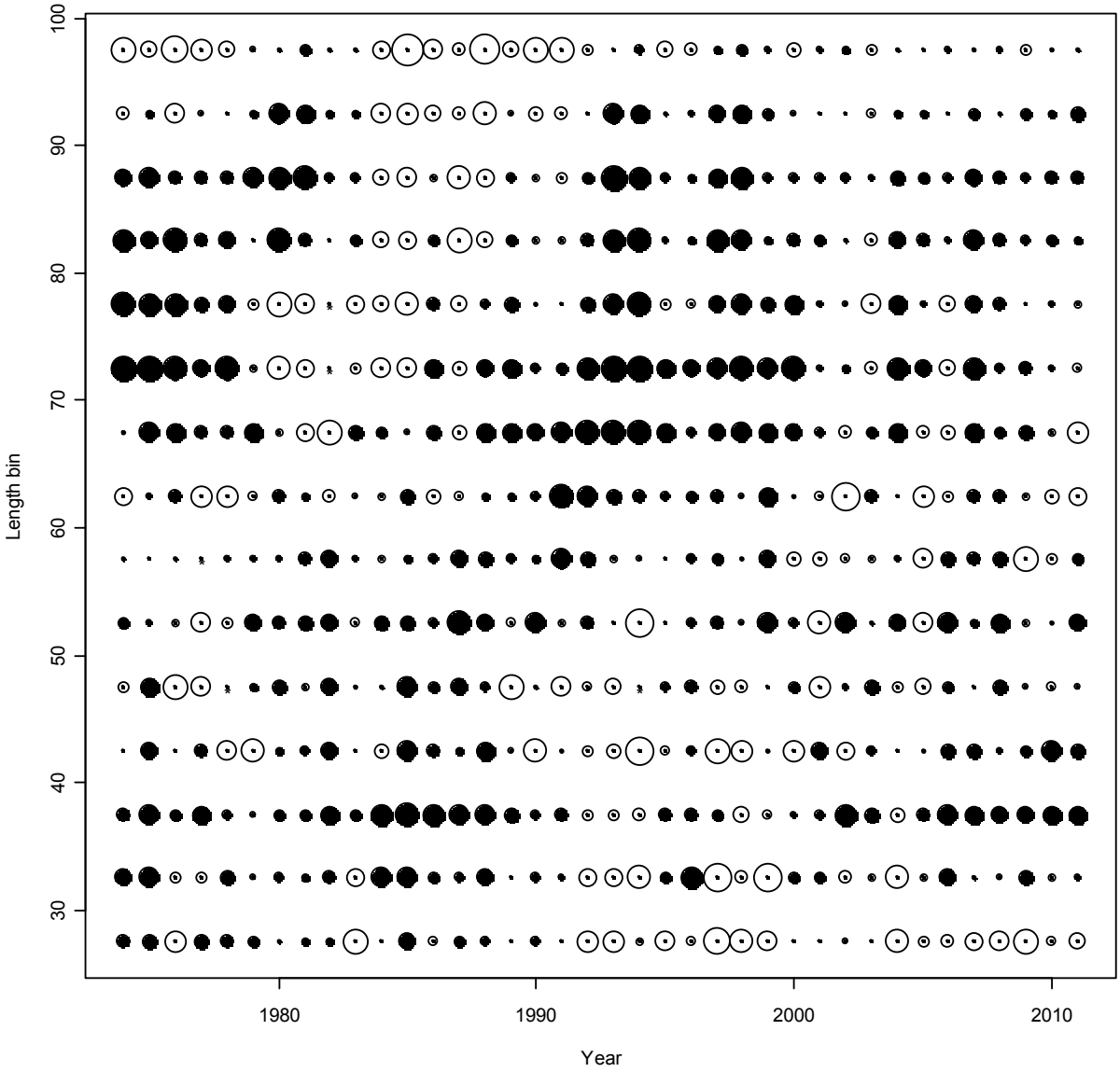


Figure 63. *Model (3)* residuals of the model fit to the survey female size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

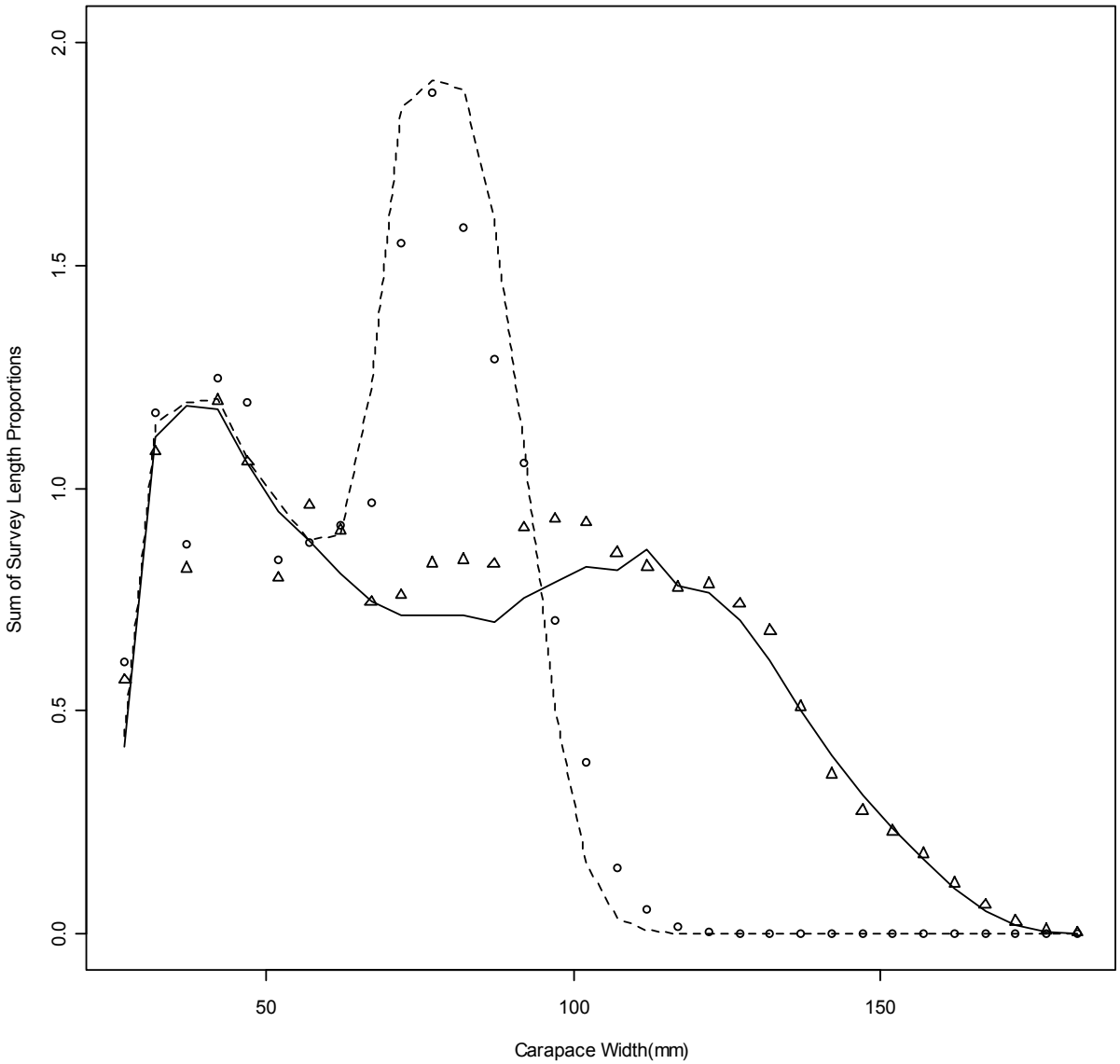


Figure 64. *Model (3)* summary fit to the survey male (solid line) and female (dotted line) size frequency data, all shell conditions combined. Symbols are observed data.

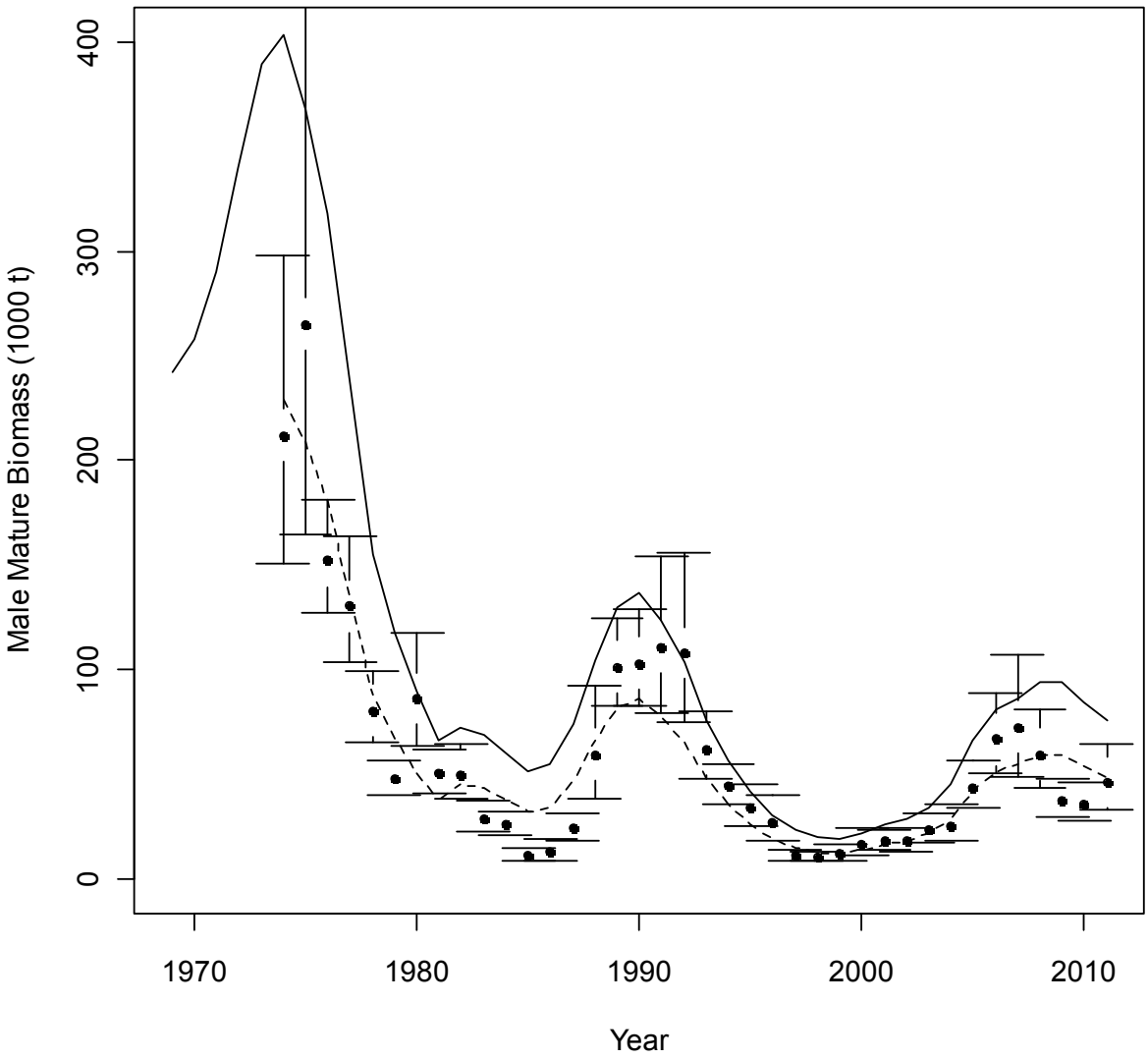


Figure 65. *Model (3)* population mature male biomass (1000 t, solid line) at the time of the survey, model estimate of survey mature biomass (dotted line) and observed survey mature male biomass with approximate lognormal 95% confidence intervals.

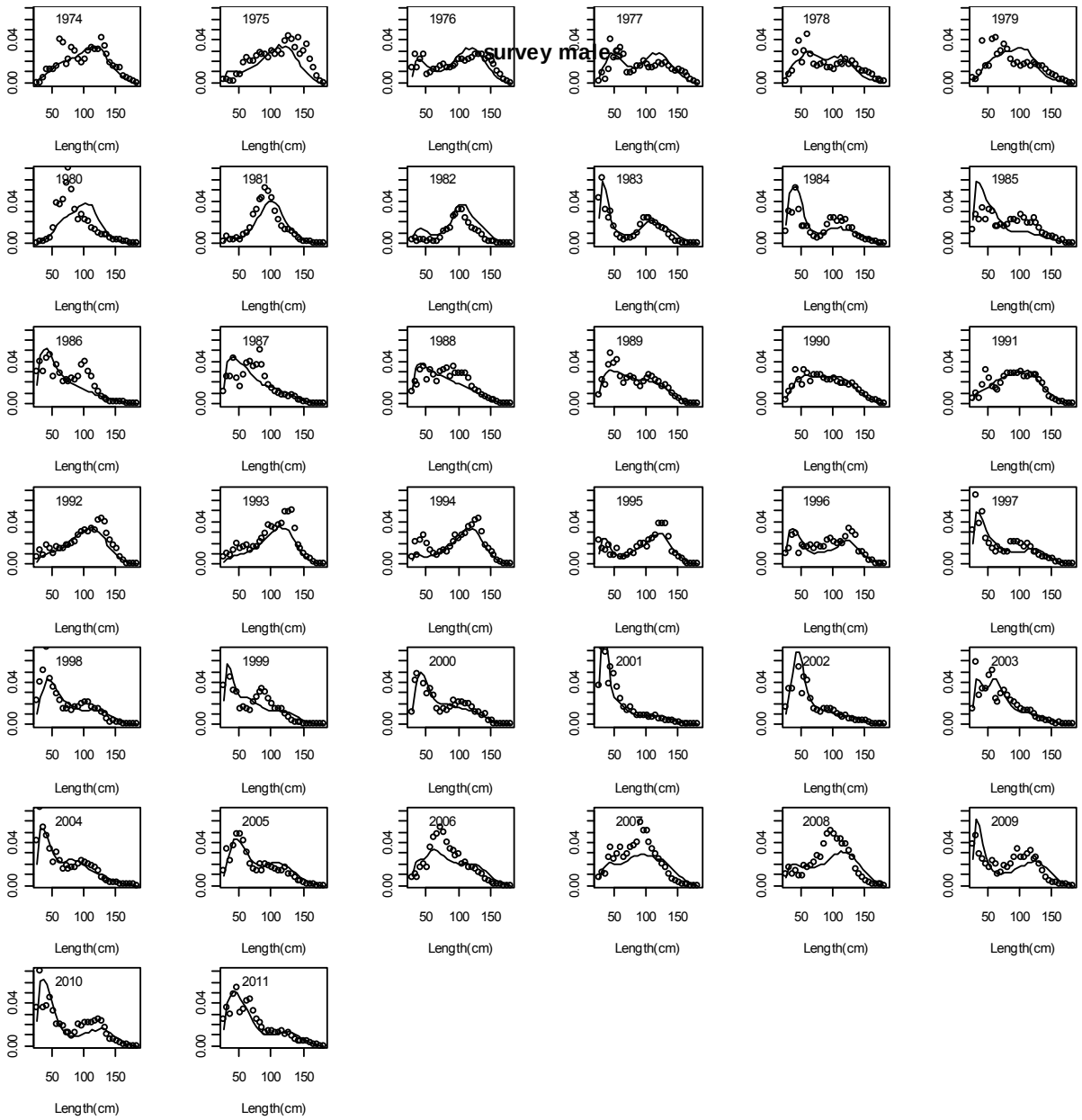


Figure 66. *Model (3)* fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

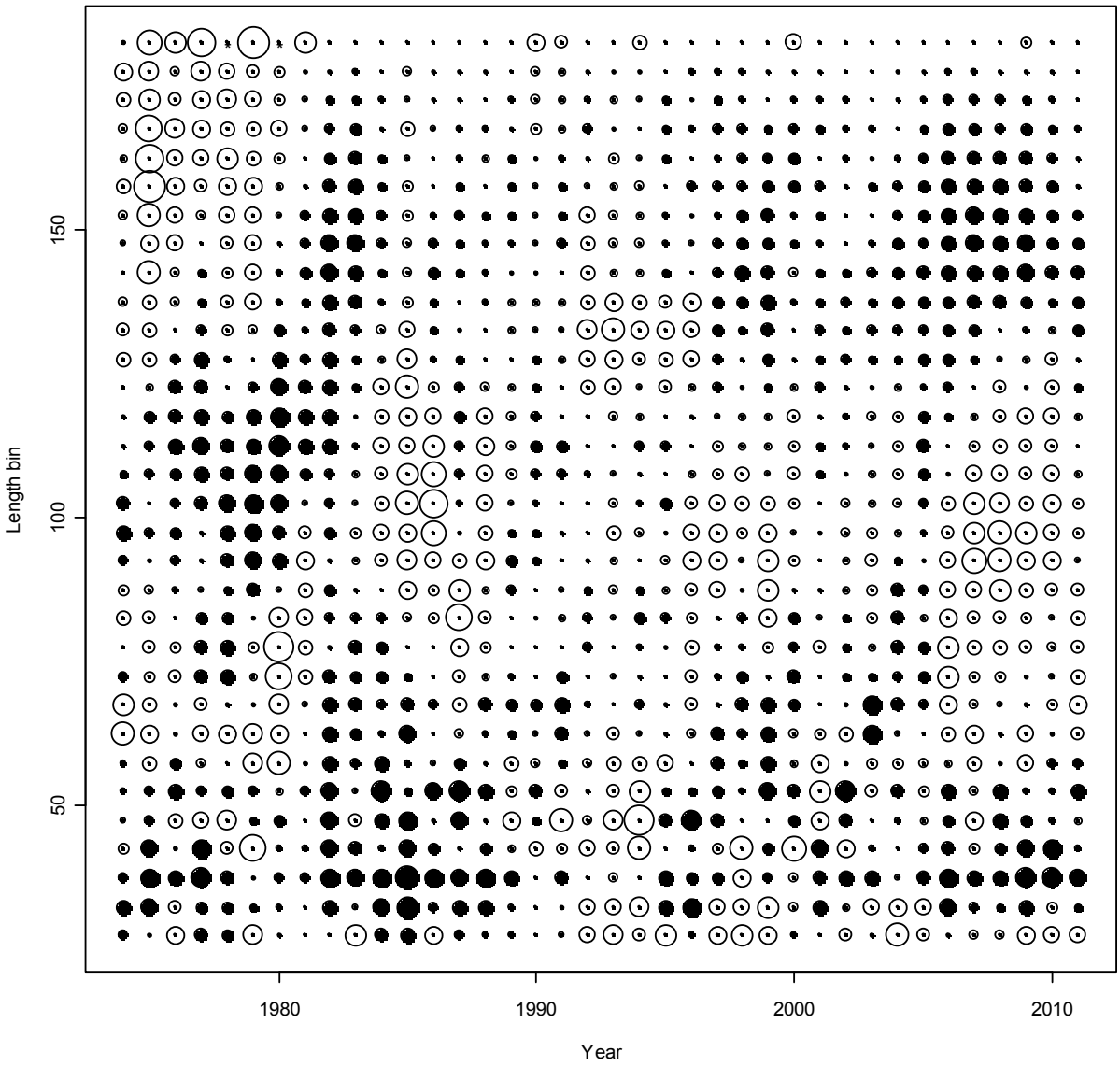


Figure 67. *Model (3)* residuals of the model fit to the survey male size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

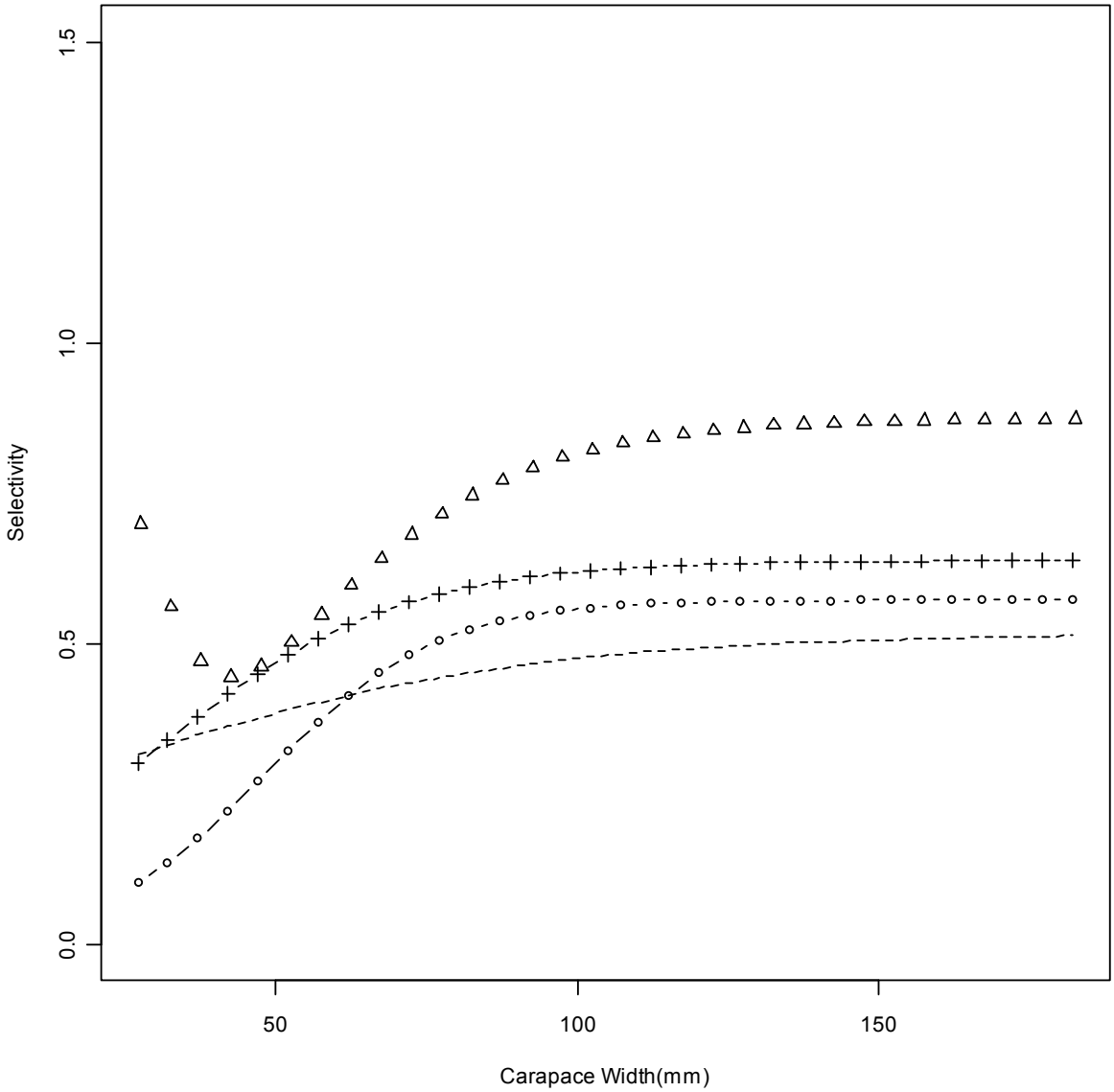


Figure 68. *Model (3)* survey selectivity curves for male Tanner crab estimated for 1974-1981 (dashed line with circles), and 1982-2011 (dashed line with pluses). Survey selectivity estimated by Somerton and Otto (1998) are triangle symbols, and female selectivity for 1982-2011 is dashed line for reference.

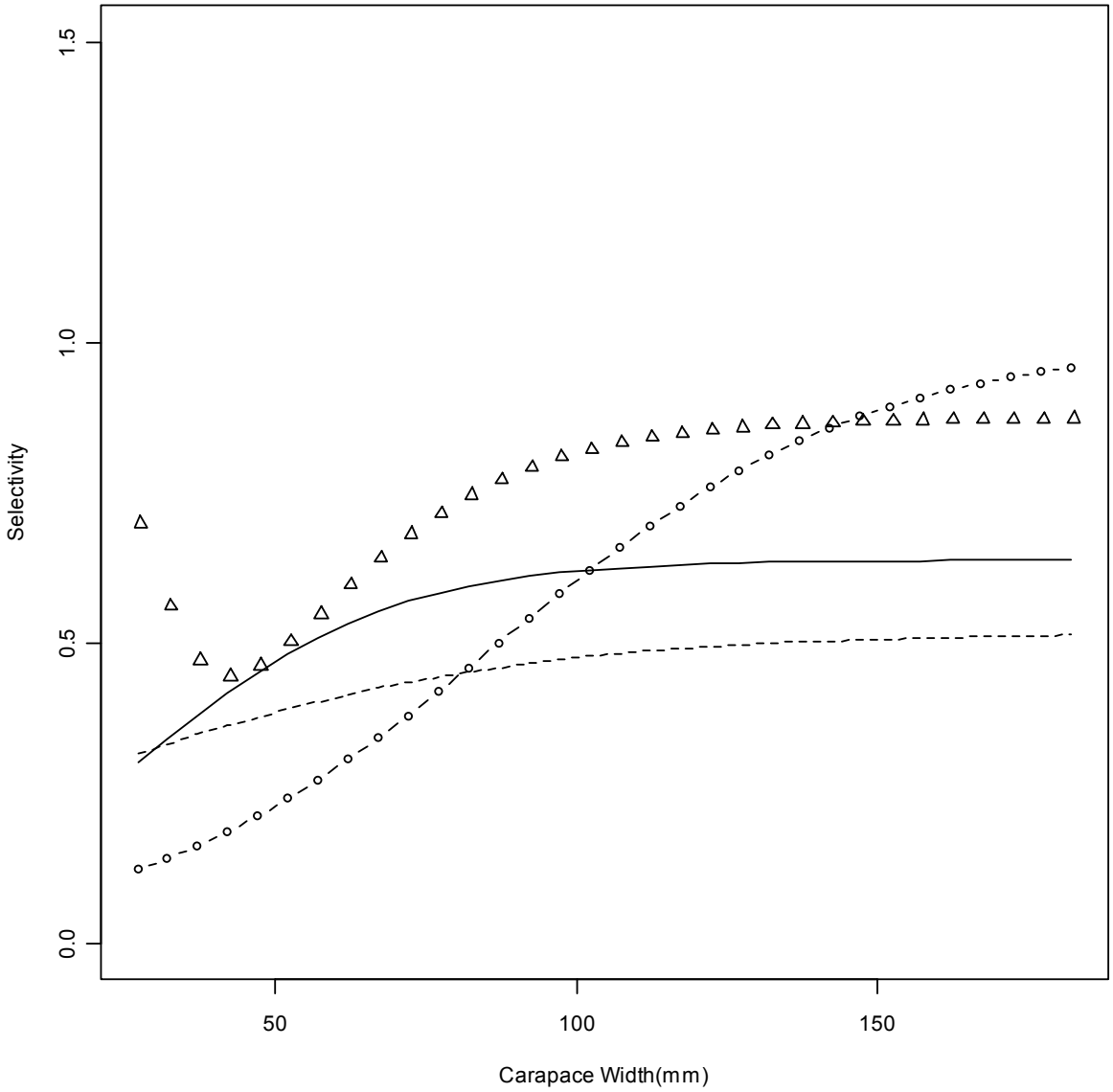


Figure 69. *Model (3)* survey selectivity curves for female Tanner crab estimated for 1974-1981 (dashed line with circles) and 1982-2011 (dashed line). Survey selectivity estimated by Somerton and Otto (1998) are triangle symbols, and male selectivity for 1982-2011 is solid line for reference.

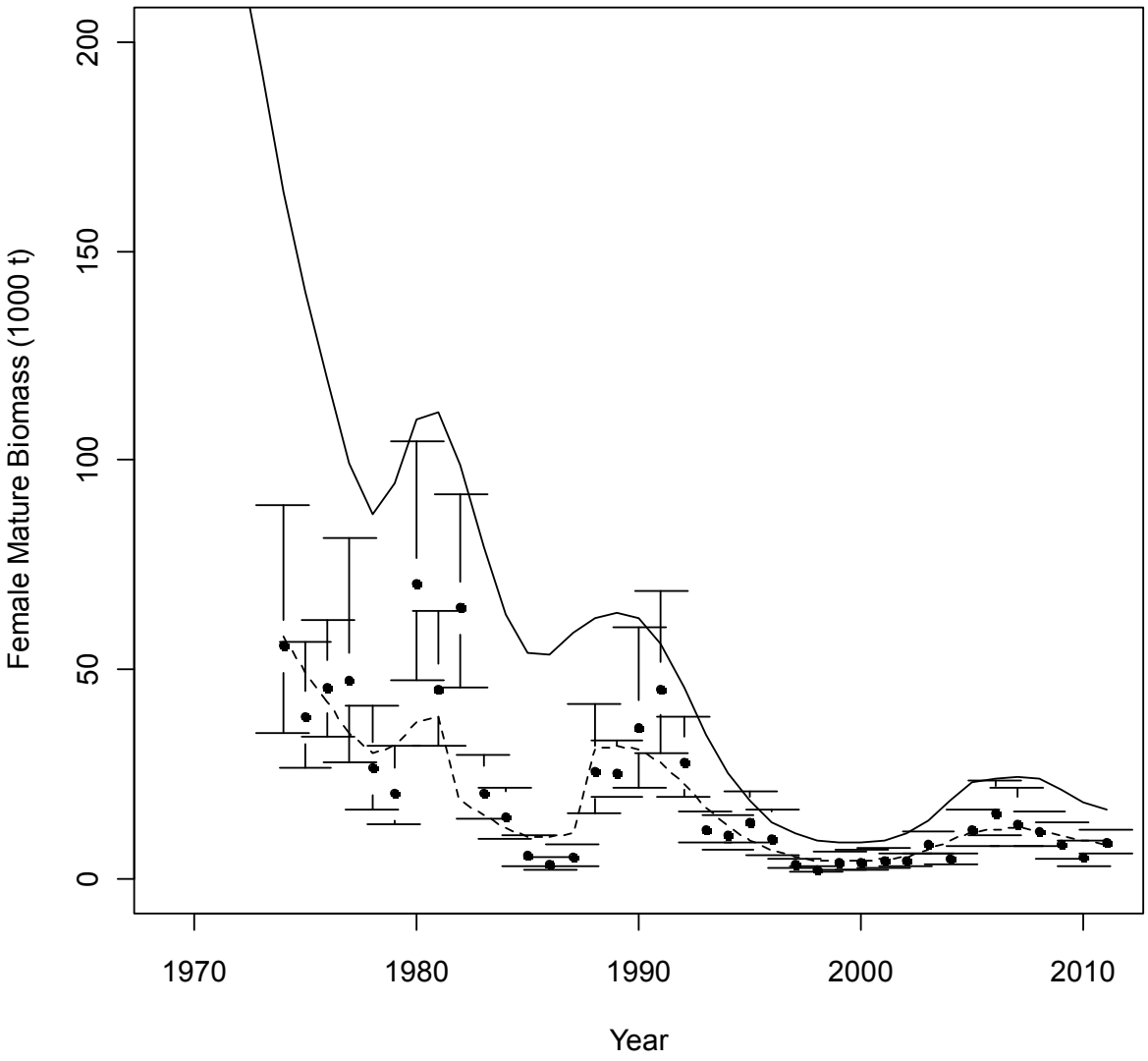


Figure 70. *Model (4)* population female mature biomass (1000 t, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

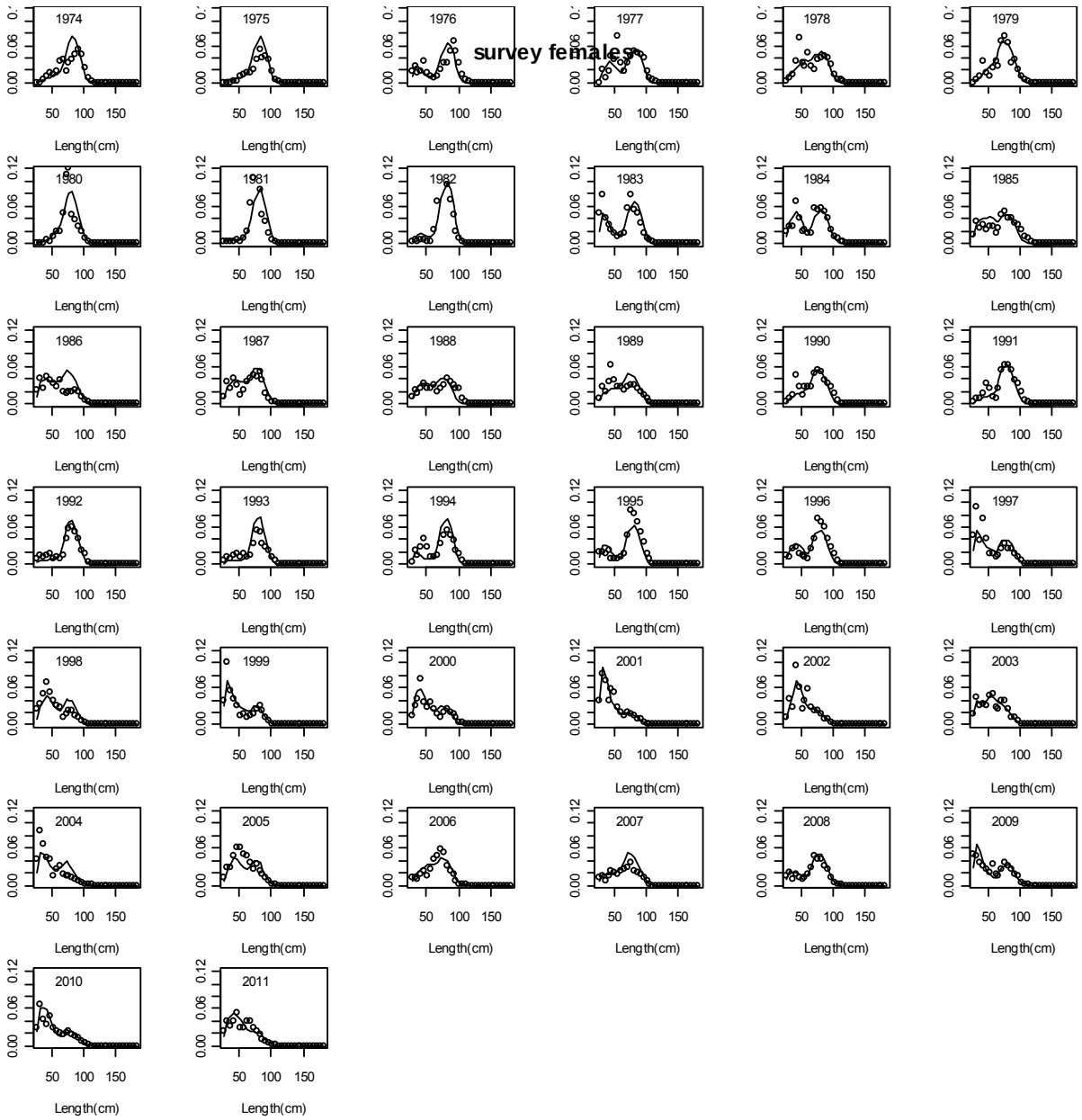


Figure 71. *Model (4)* fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

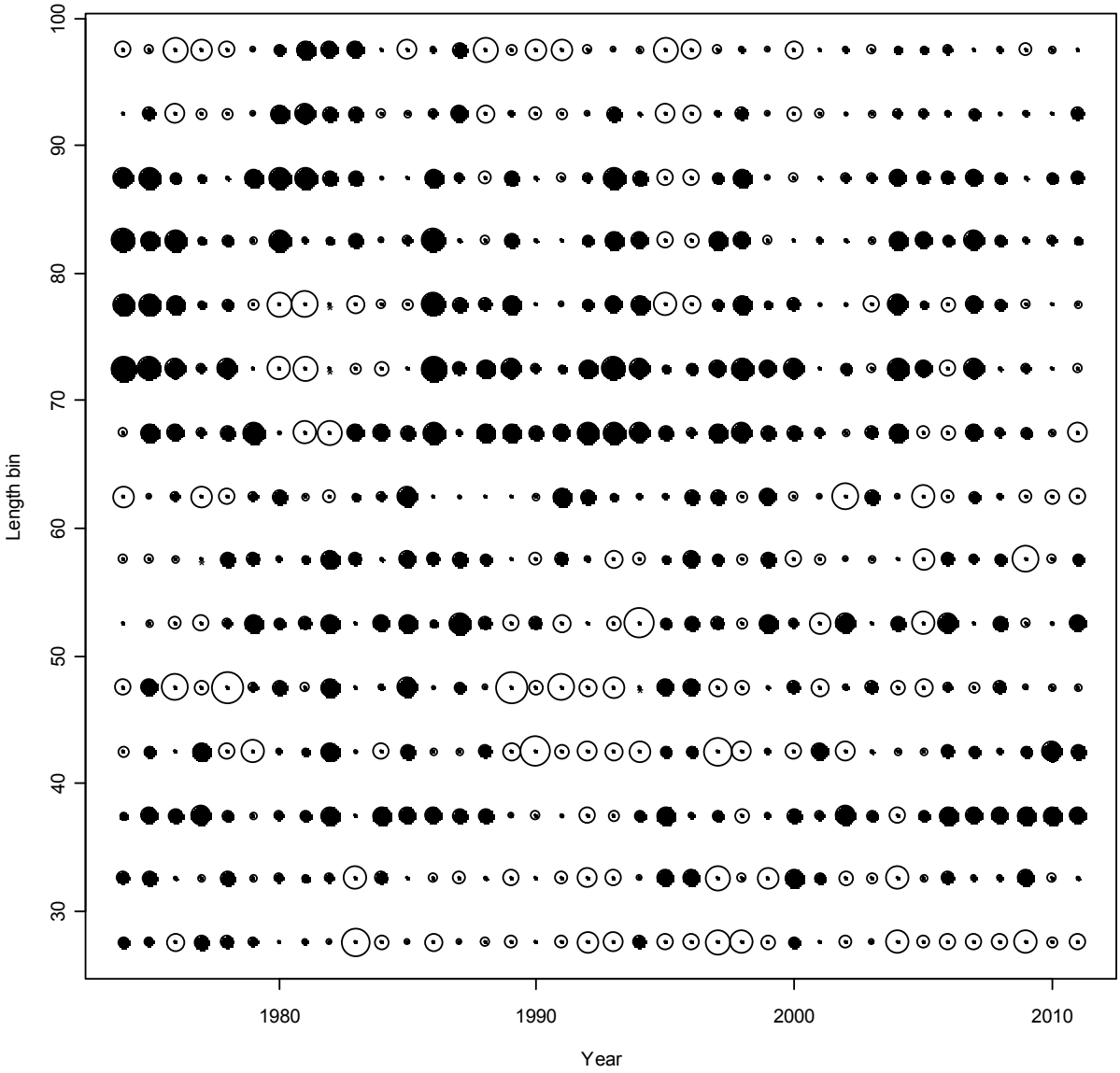


Figure 72. *Model (4)* residuals of the model fit to the survey female size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

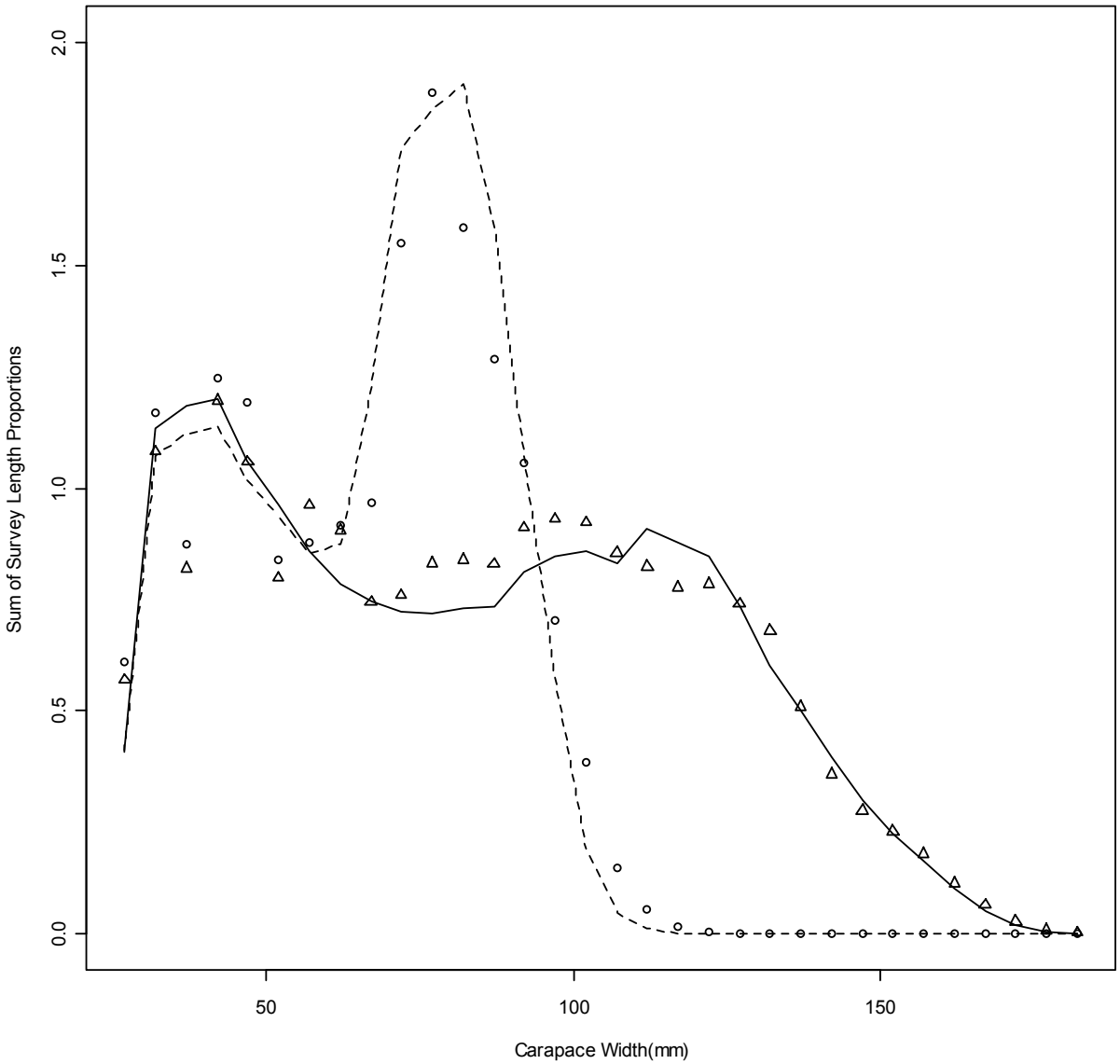


Figure 73. *Model (4)* summary fit to the survey male (solid line) and female (dotted line) size frequency data, all shell conditions combined. Symbols are observed data.

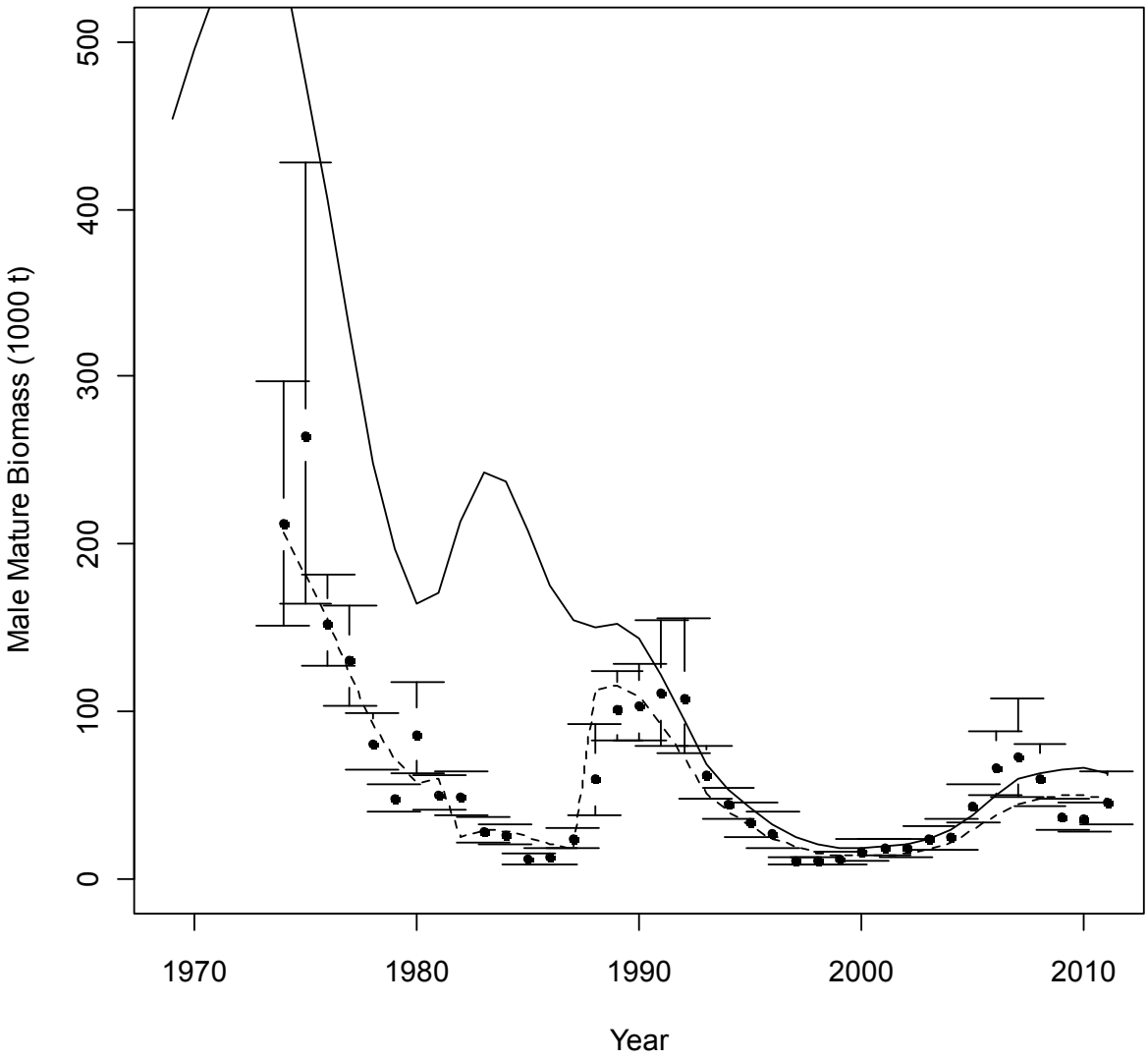


Figure 74. *Model (4)* population mature male biomass (1000 t, solid line) at the time of the survey, model estimate of survey mature biomass (dotted line) and observed survey mature male biomass with approximate lognormal 95% confidence intervals.

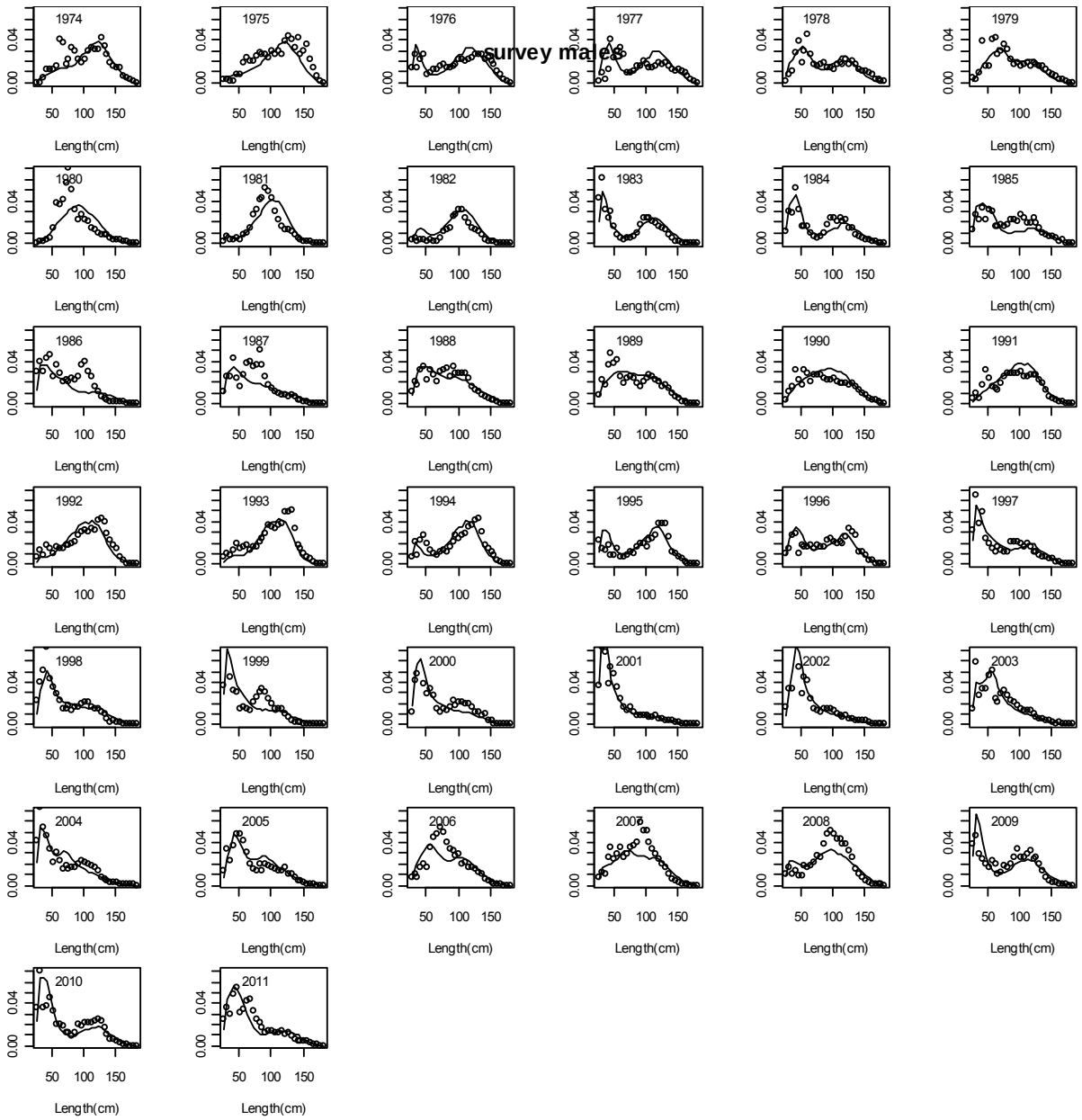


Figure 75. *Model (4)* fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

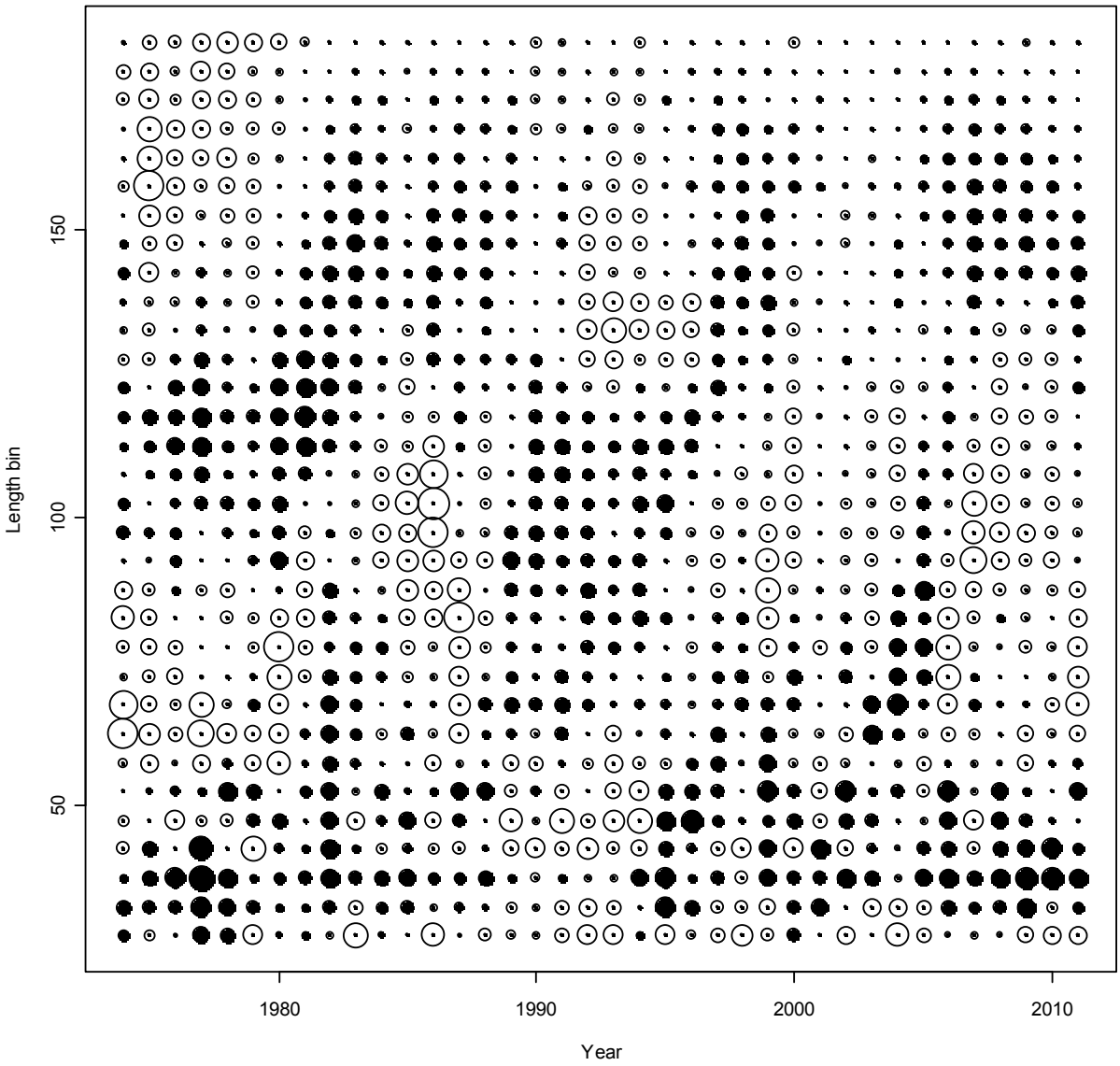


Figure 76. *Model (4)* residuals of the model fit to the survey male size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

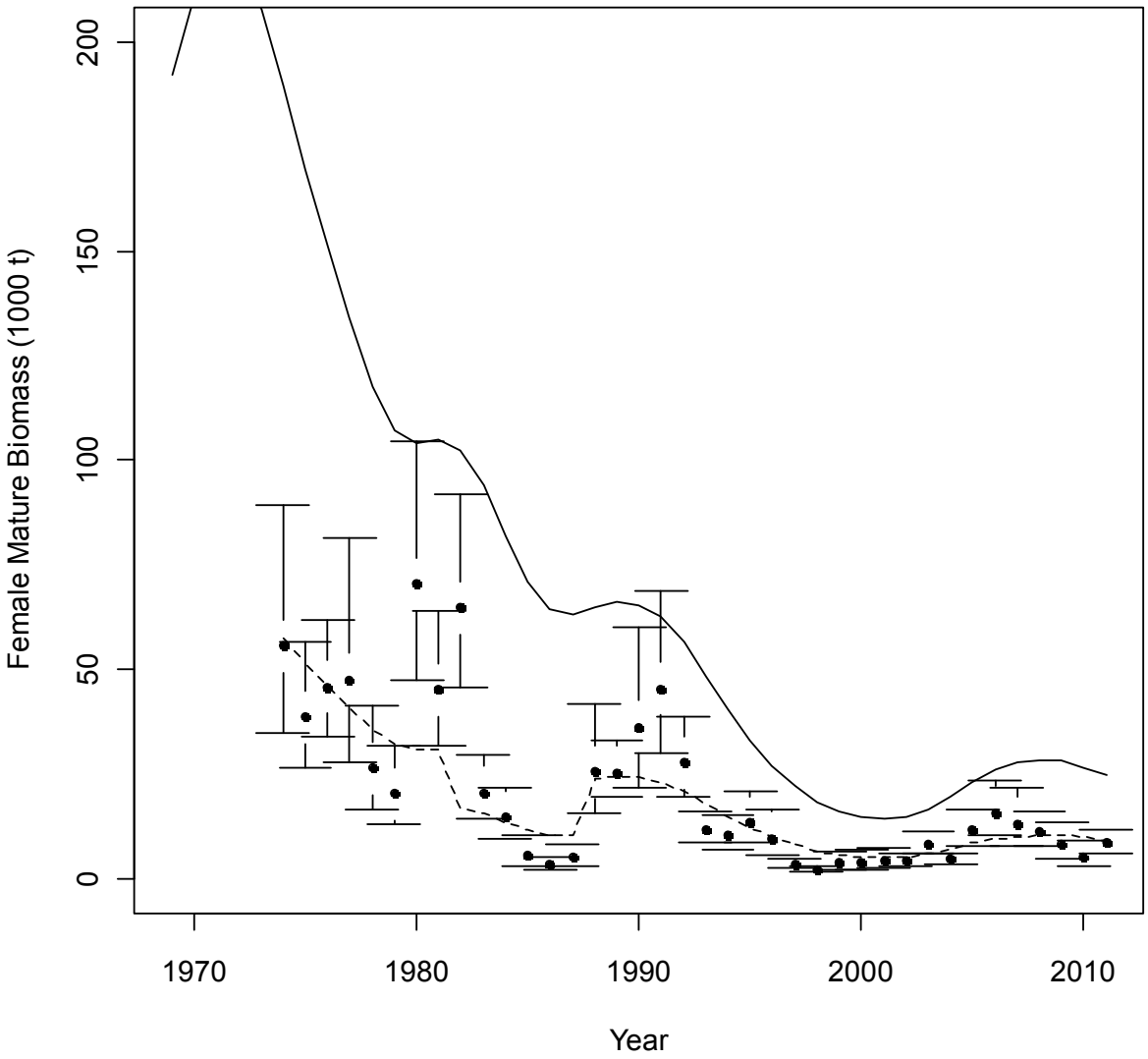


Figure 77. *Model (5)* population female mature biomass (1000 t, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

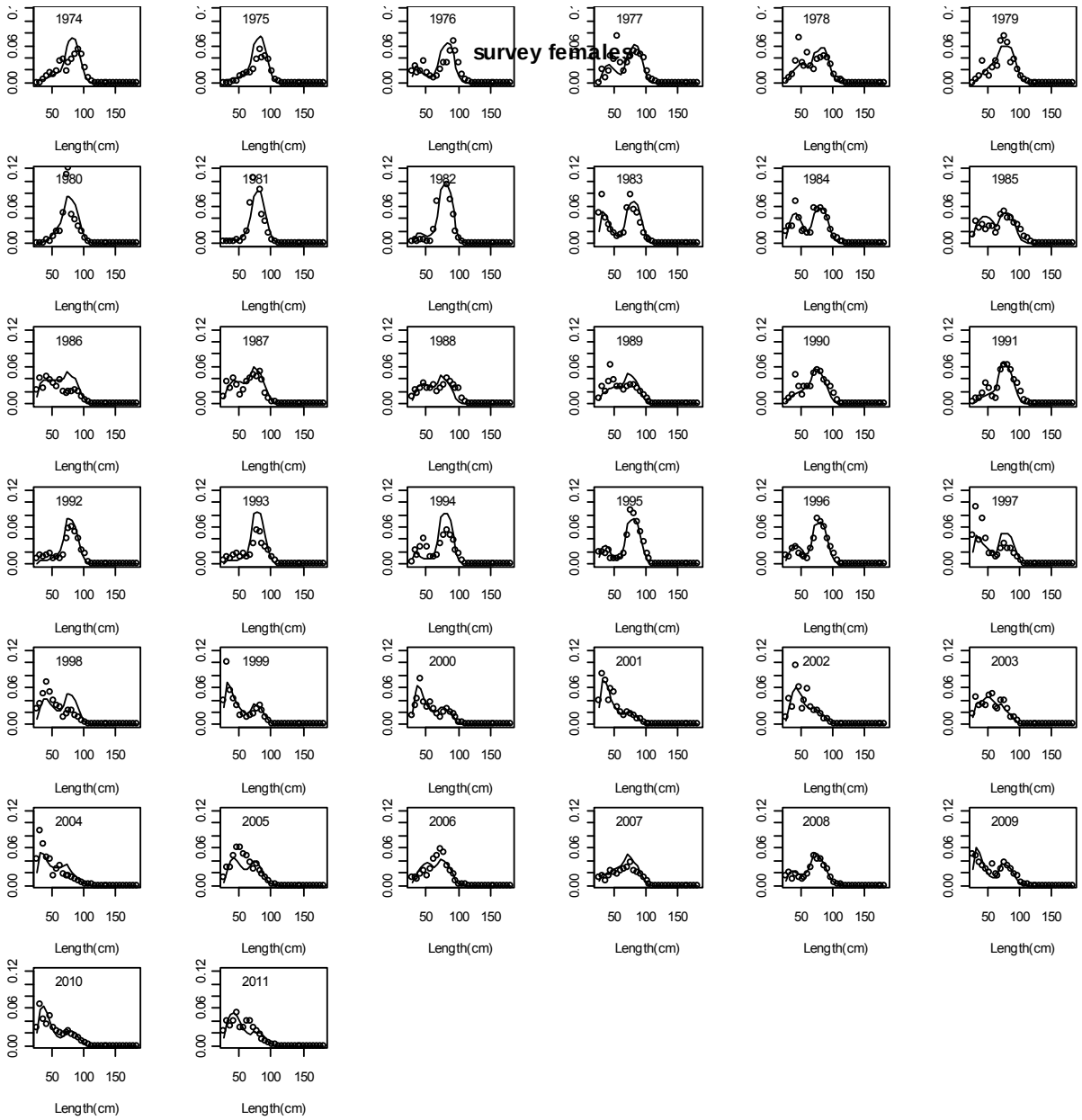


Figure 78. *Model (5)* fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

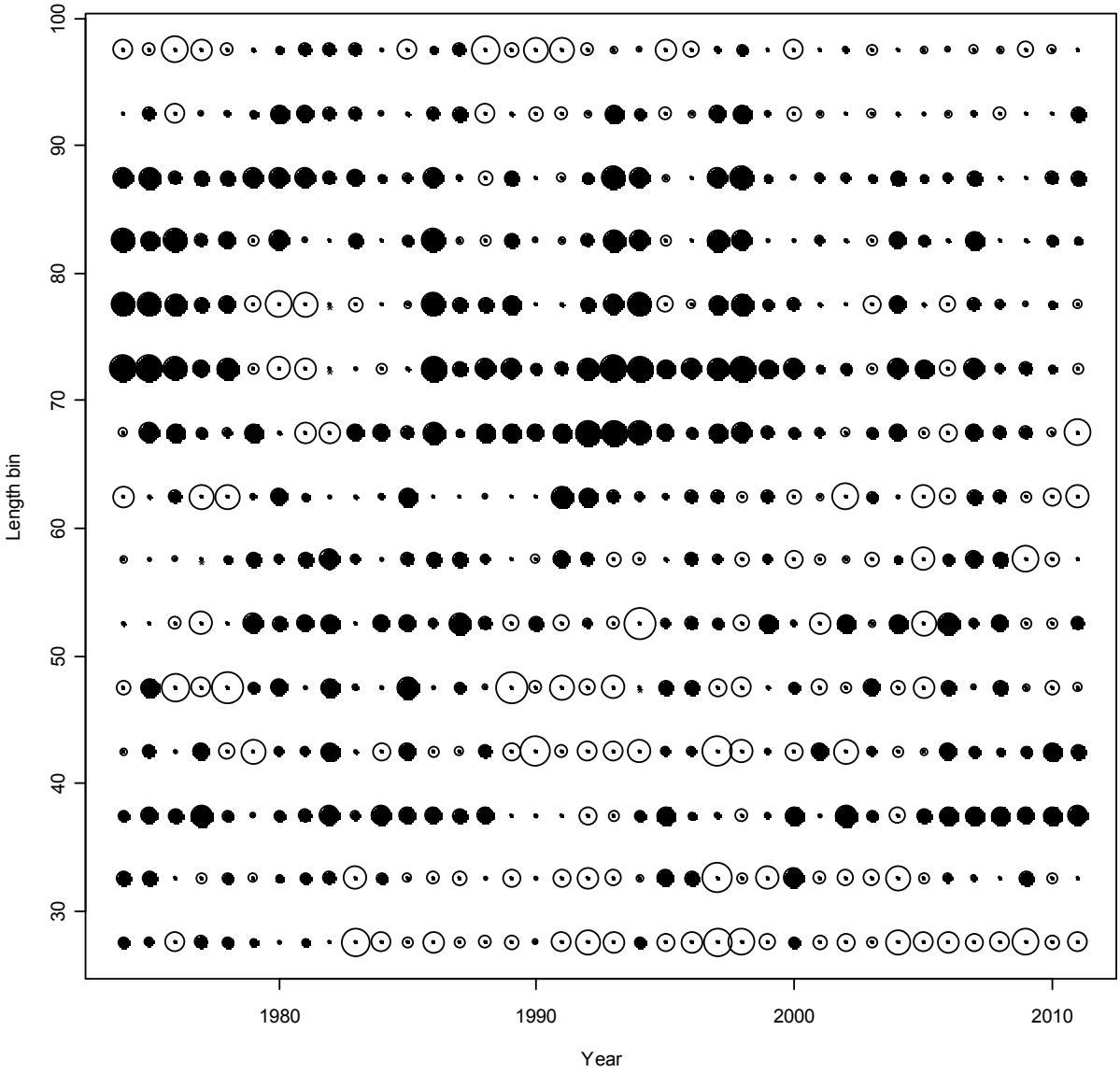


Figure 79. *Model (5)* residuals of the model fit to the survey female size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

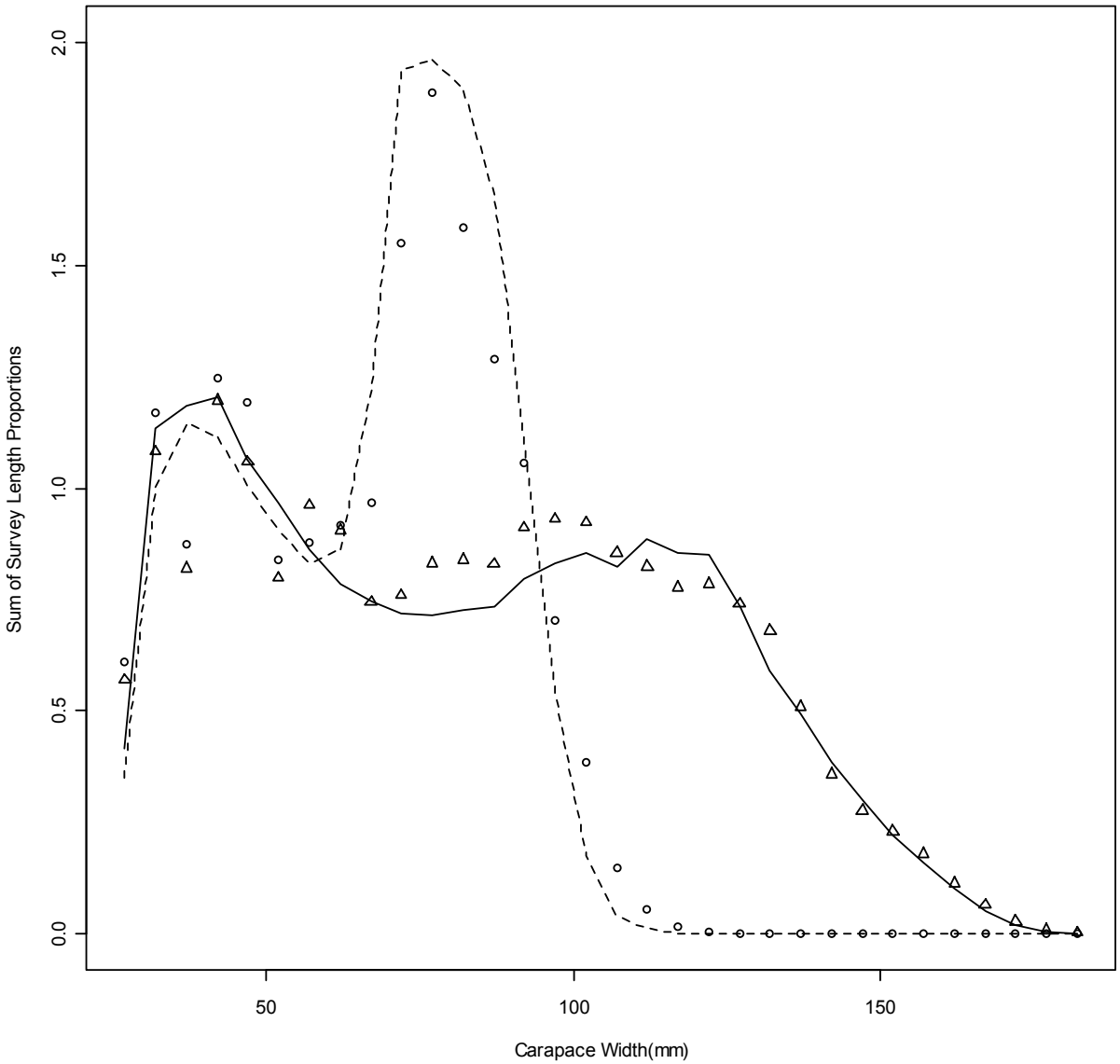


Figure 80. *Model (5)* summary fit to the survey male (solid line) and female (dotted line) size frequency data, all shell conditions combined. Symbols are observed data.

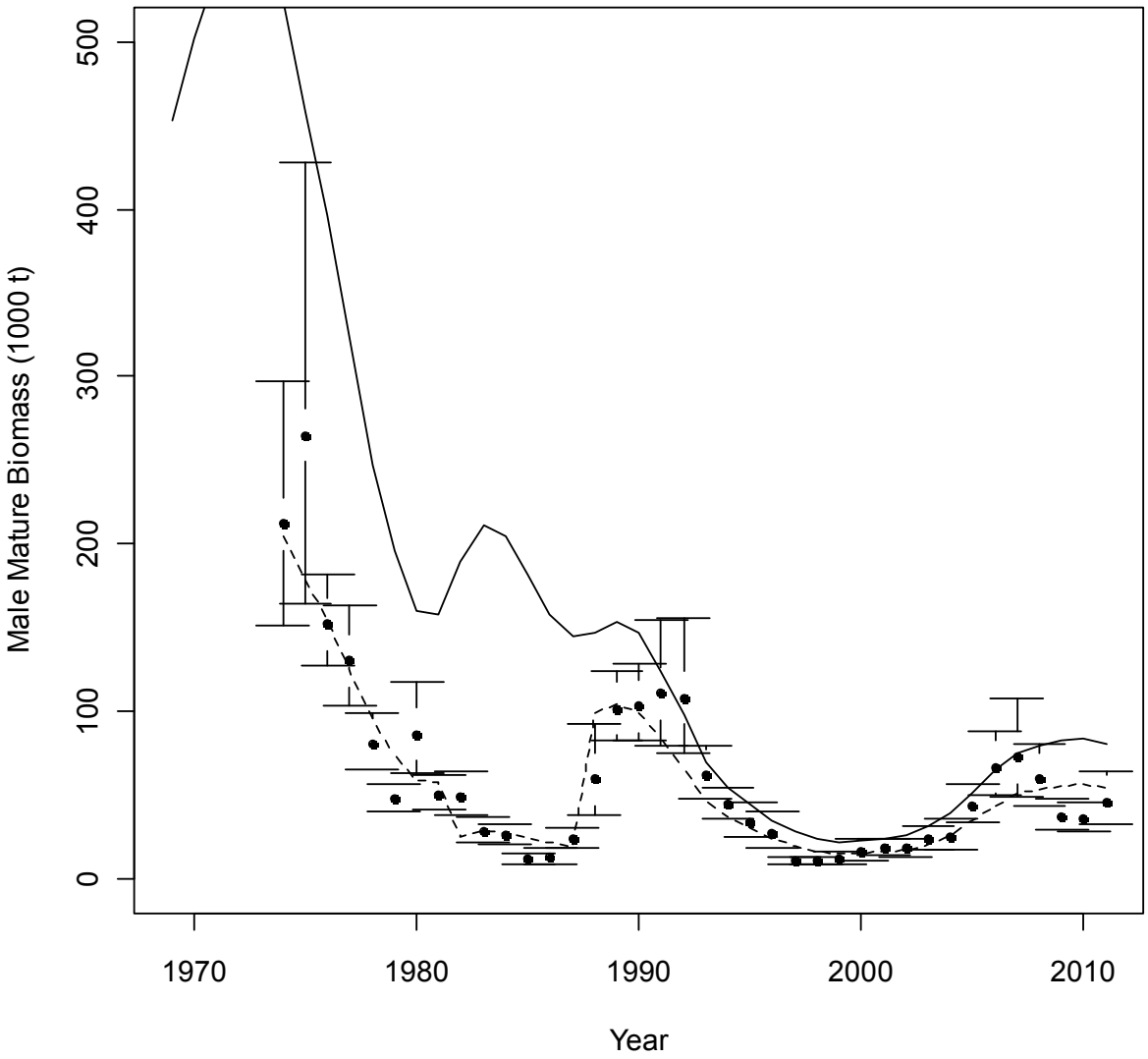


Figure 81. *Model (5)* population mature male biomass (1000 t, solid line) at the time of the survey, model estimate of survey mature biomass (dotted line) and observed survey mature male biomass with approximate lognormal 95% confidence intervals.

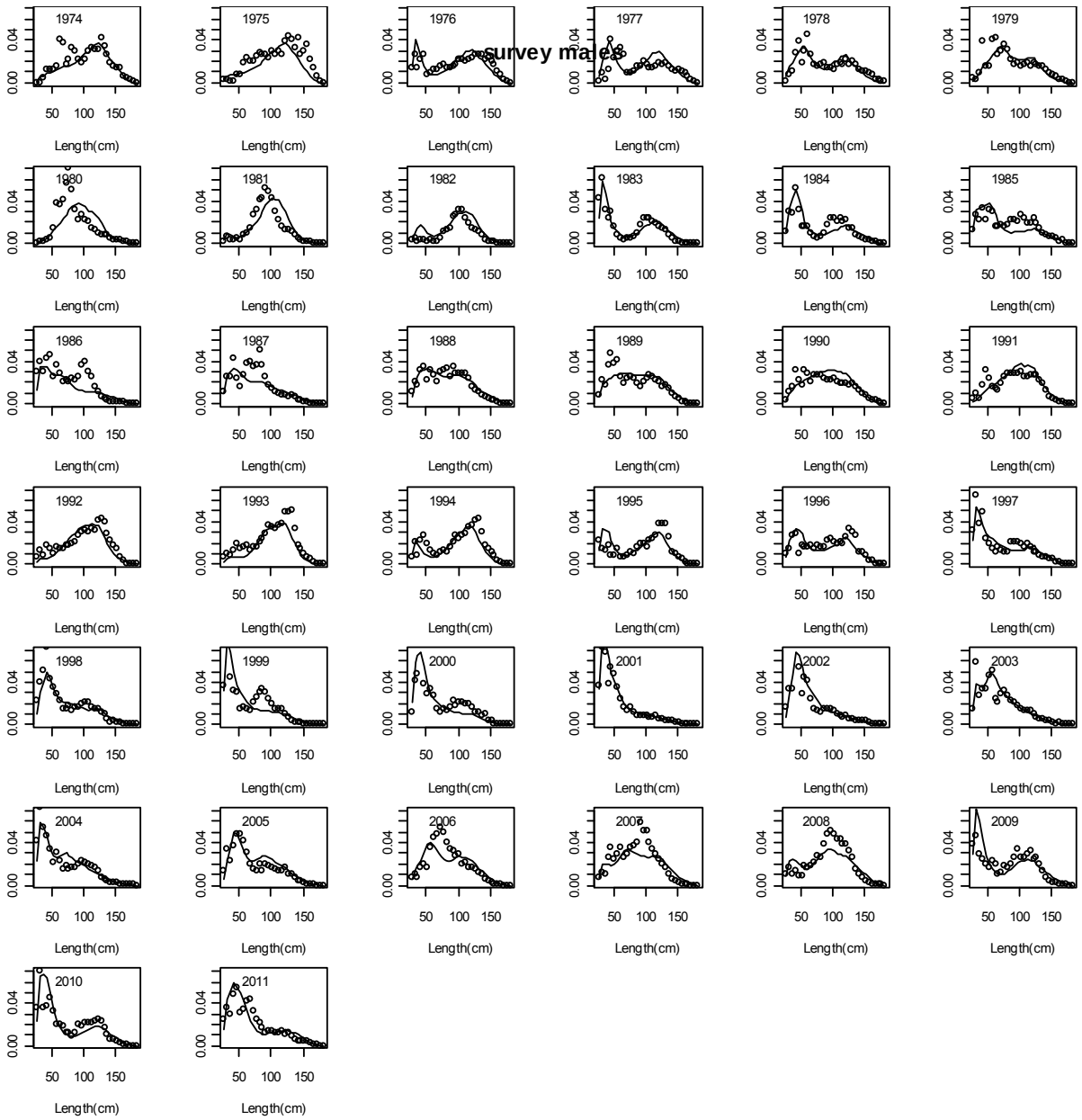


Figure 82. *Model (5)* fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

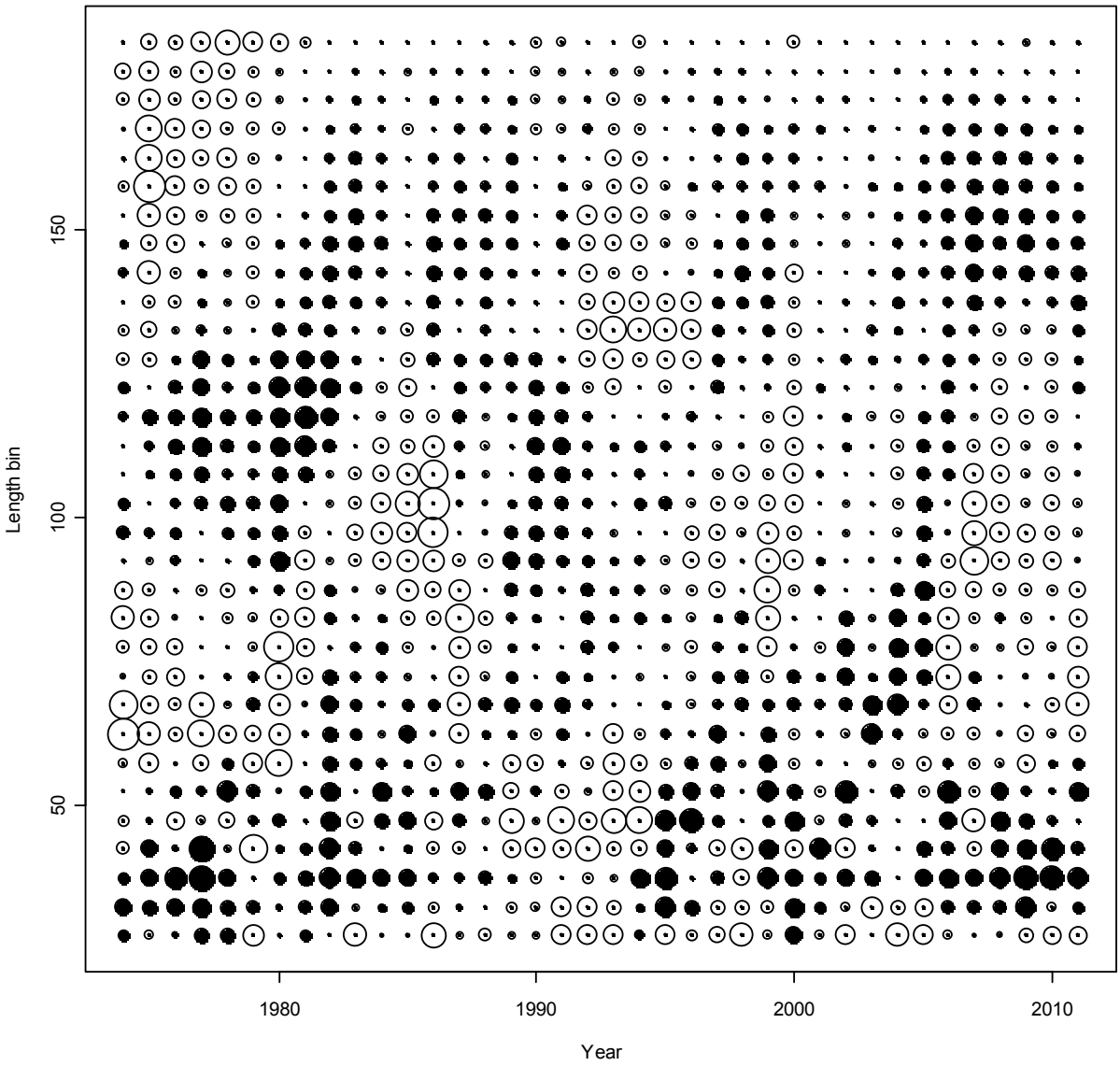


Figure 83. *Model (5)* residuals of the model fit to the survey male size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

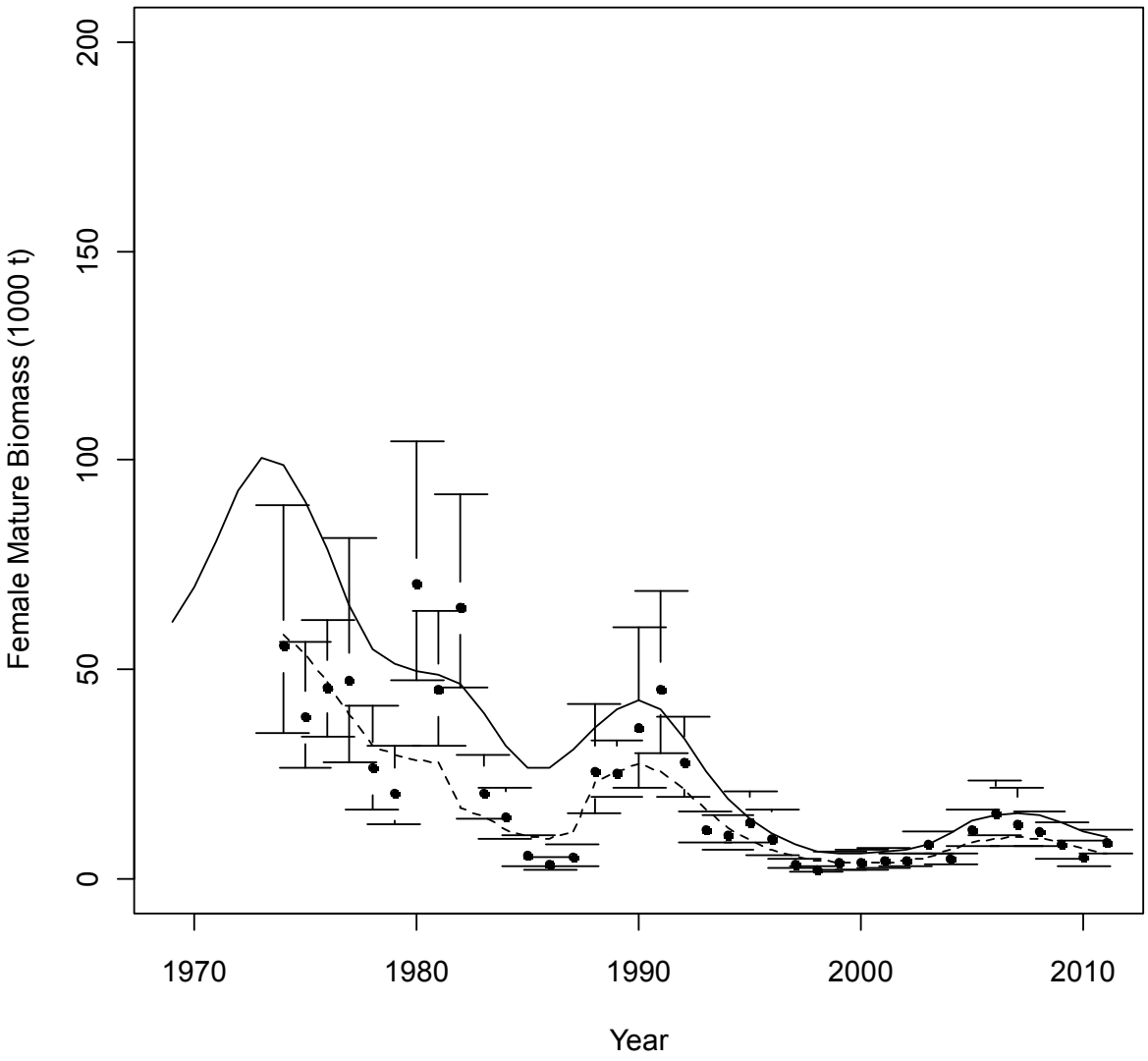


Figure 84. *Model (6)* population female mature biomass (1000 t, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

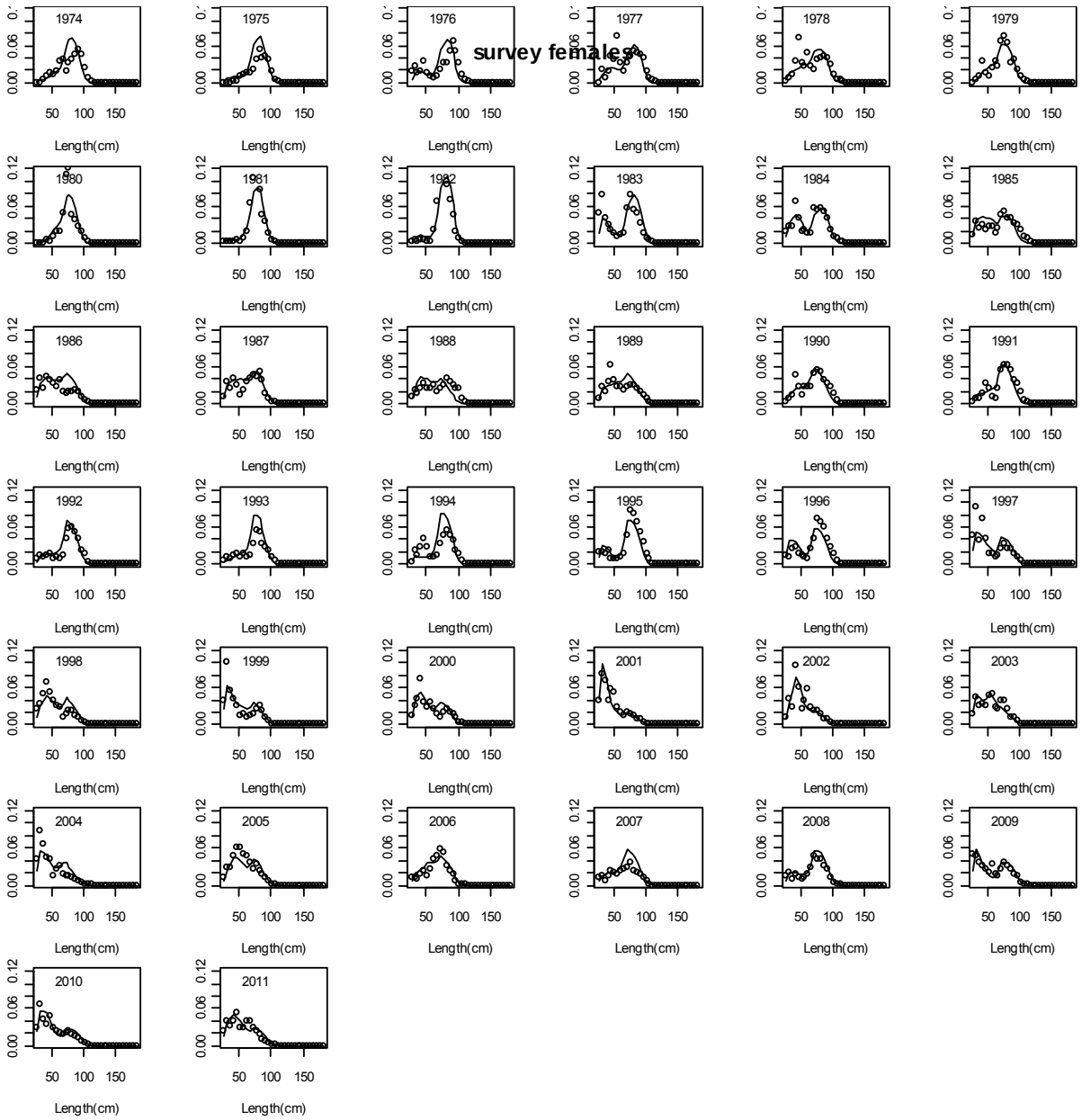


Figure 85. *Model (6)* fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

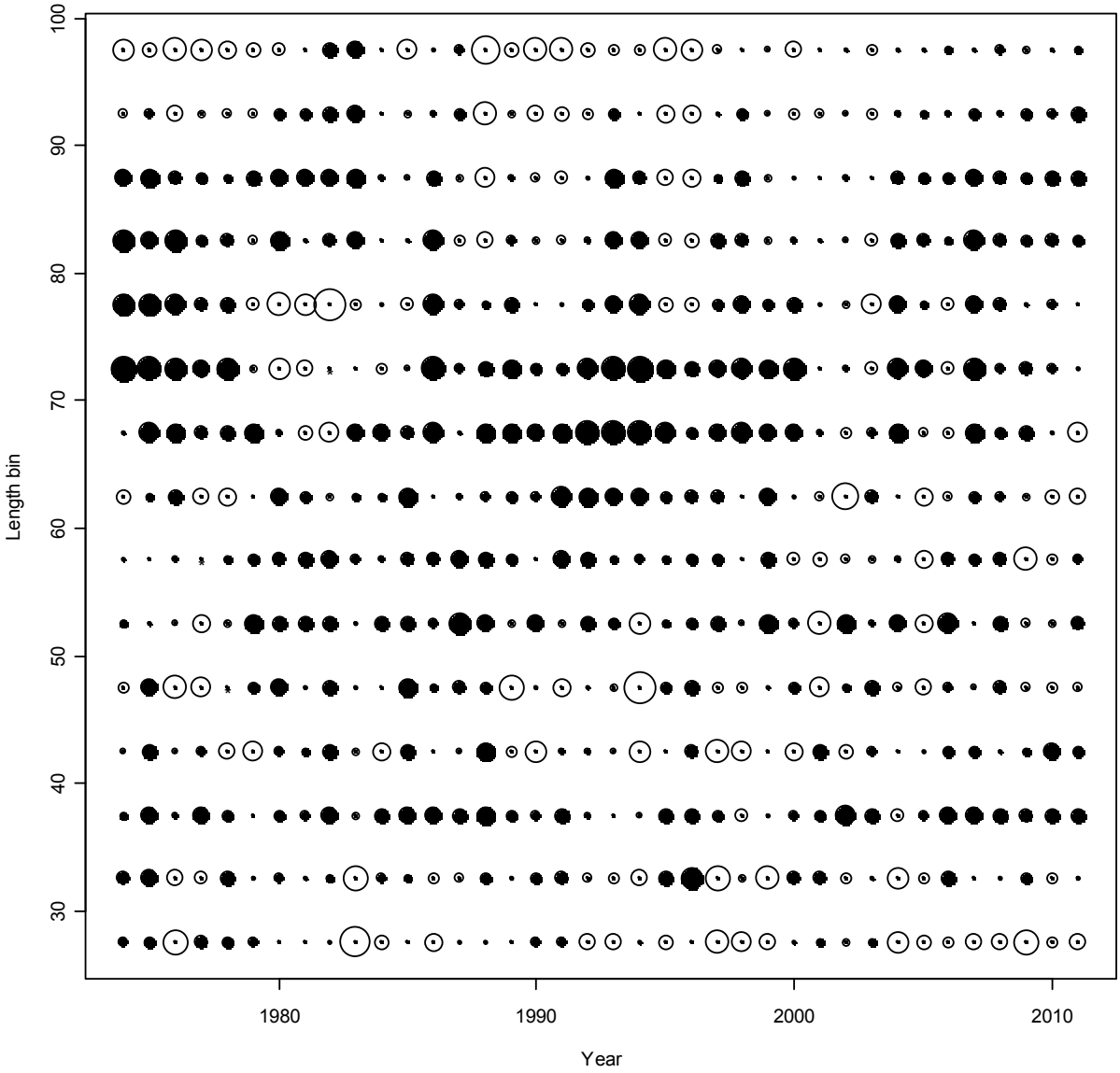


Figure 86. *Model (6)* residuals of the model fit to the survey female size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

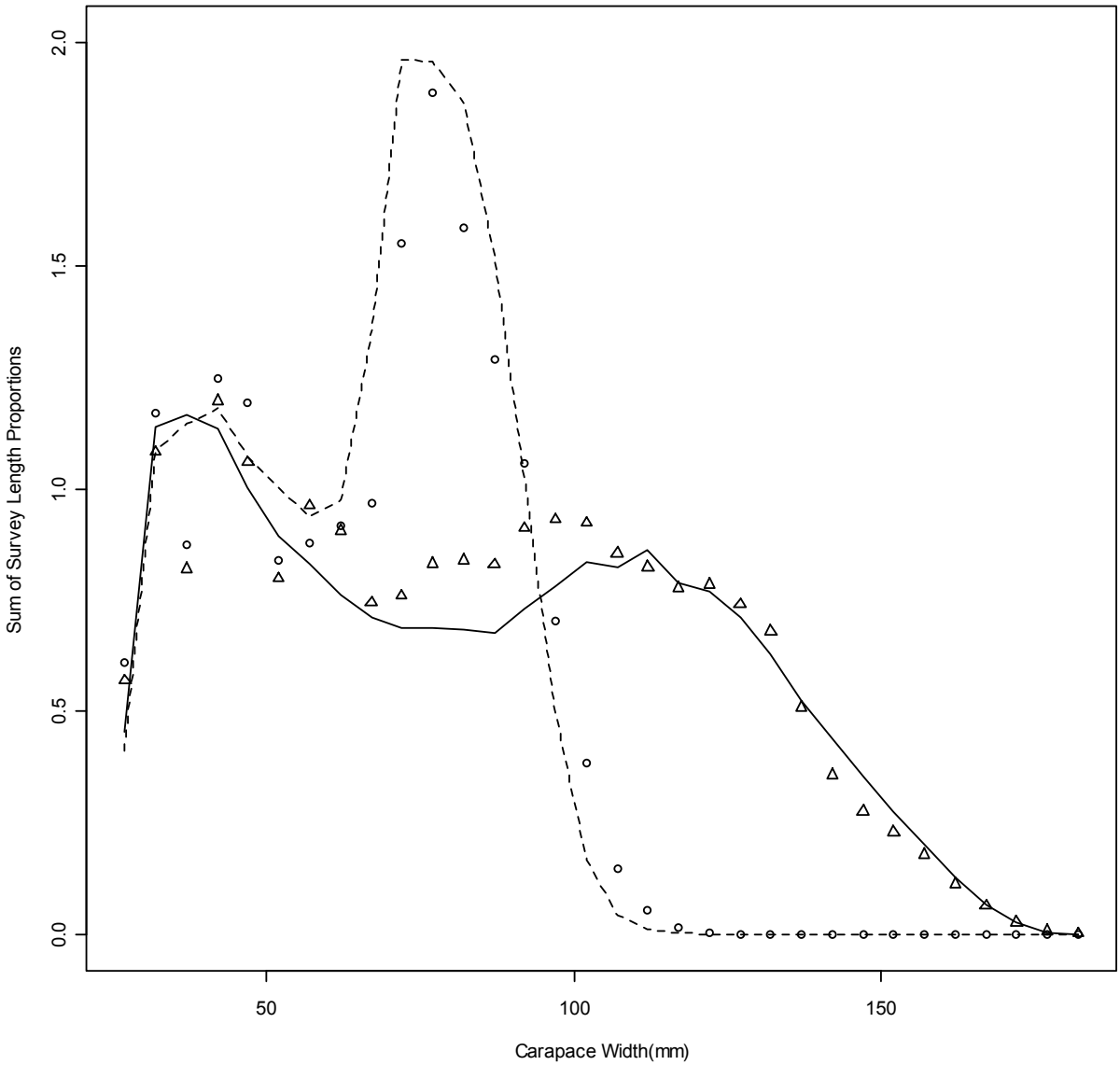


Figure 87. *Model (6)* summary fit to the survey male (solid line) and female (dotted line) size frequency data, all shell conditions combined. Symbols are observed data.

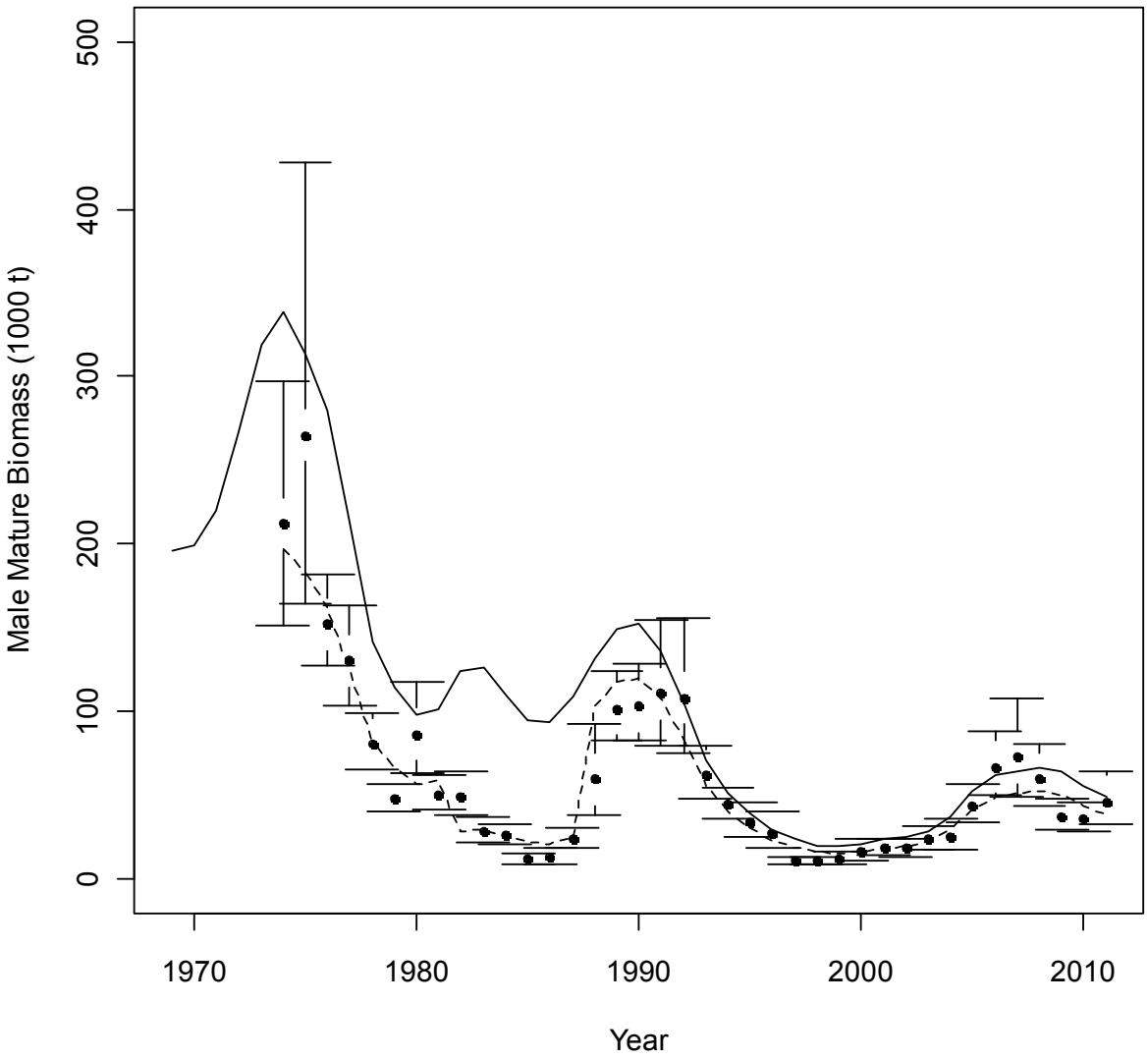


Figure 88. *Model (6)* population mature male biomass (1000 t, solid line) at the time of the survey, model estimate of survey mature biomass (dotted line) and observed survey mature male biomass with approximate lognormal 95% confidence intervals.

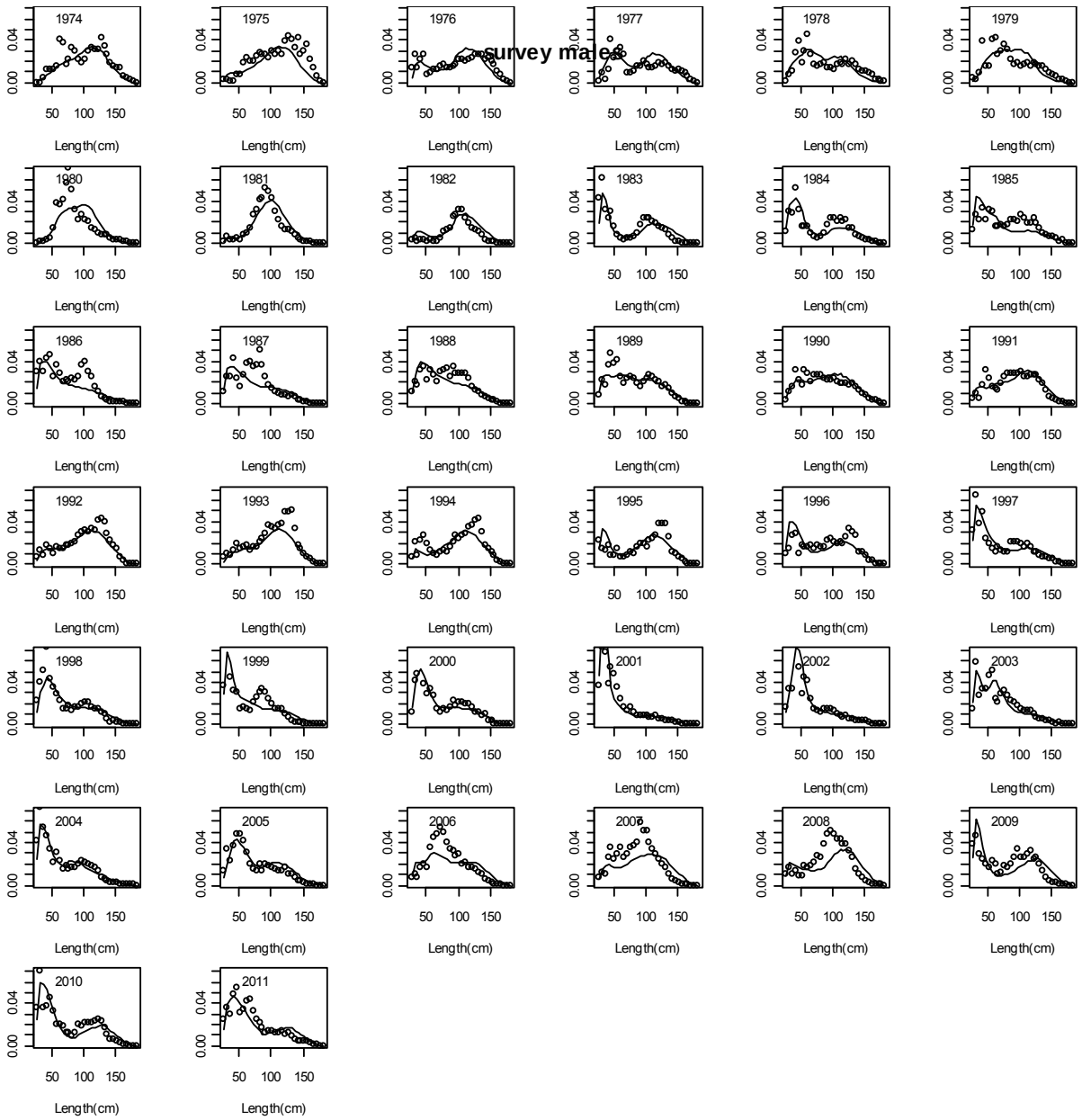


Figure 89. *Model (6)* fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

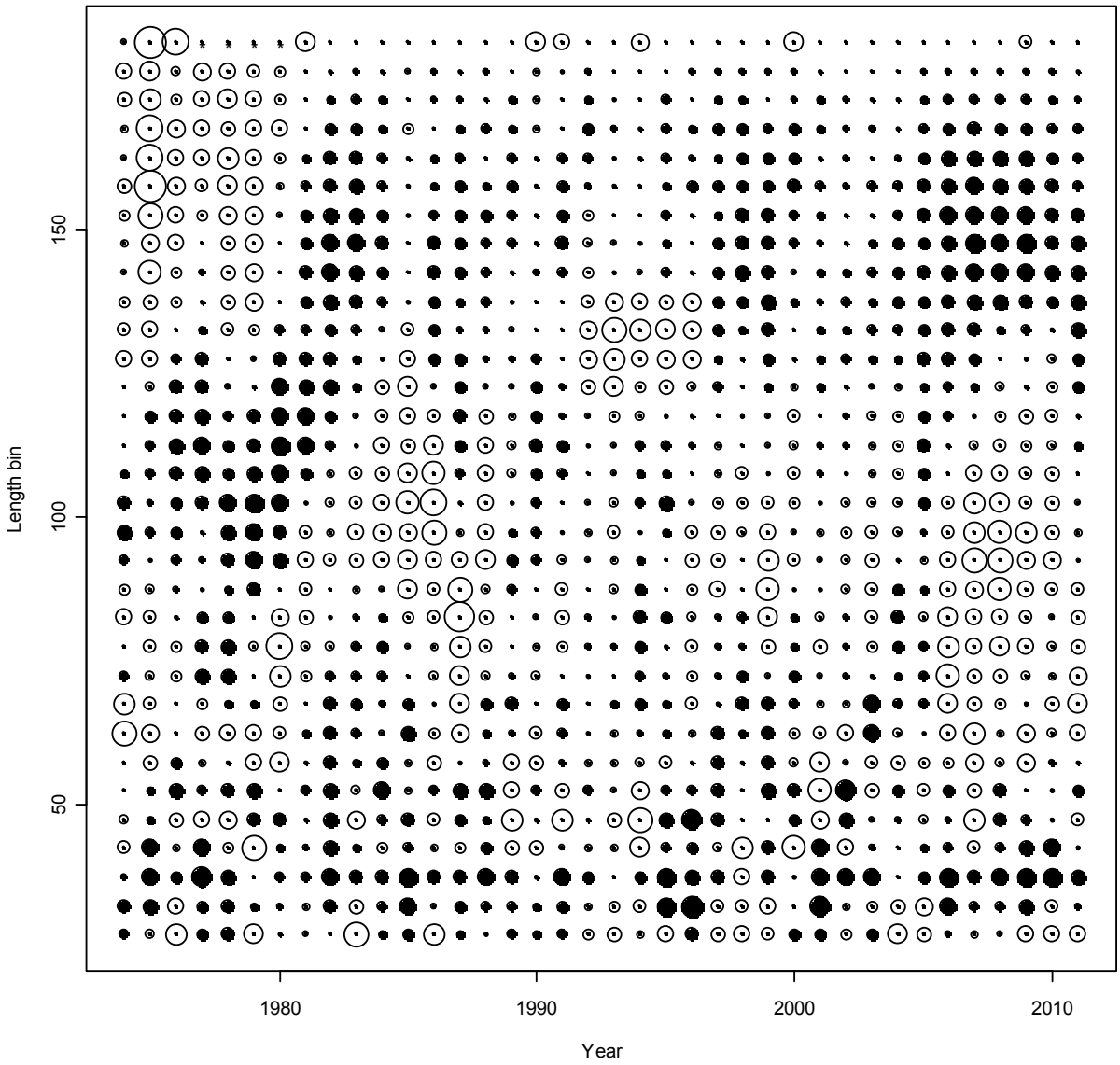


Figure 90. *Model (6)* residuals of the model fit to the survey male size frequency data. Solid circles= overestimate and open circles=underestimate. Diameter of circle proportional to extent of lack of fit.

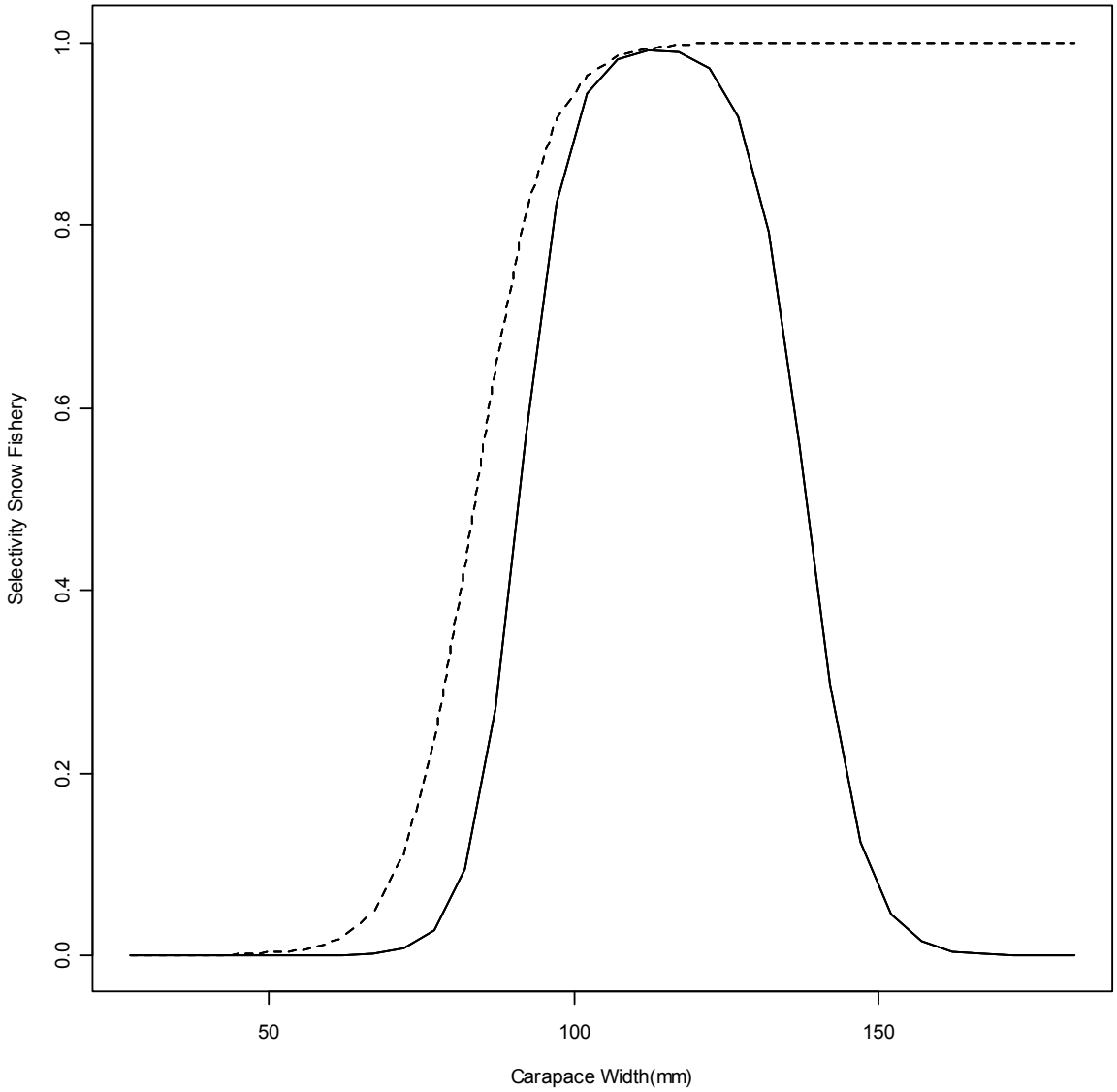


Figure 91. *Model (6)* selectivity curve estimated in the model for bycatch of Tanner crab in the snow crab fishery for females (dashed) and males (solid), 1989-2011.

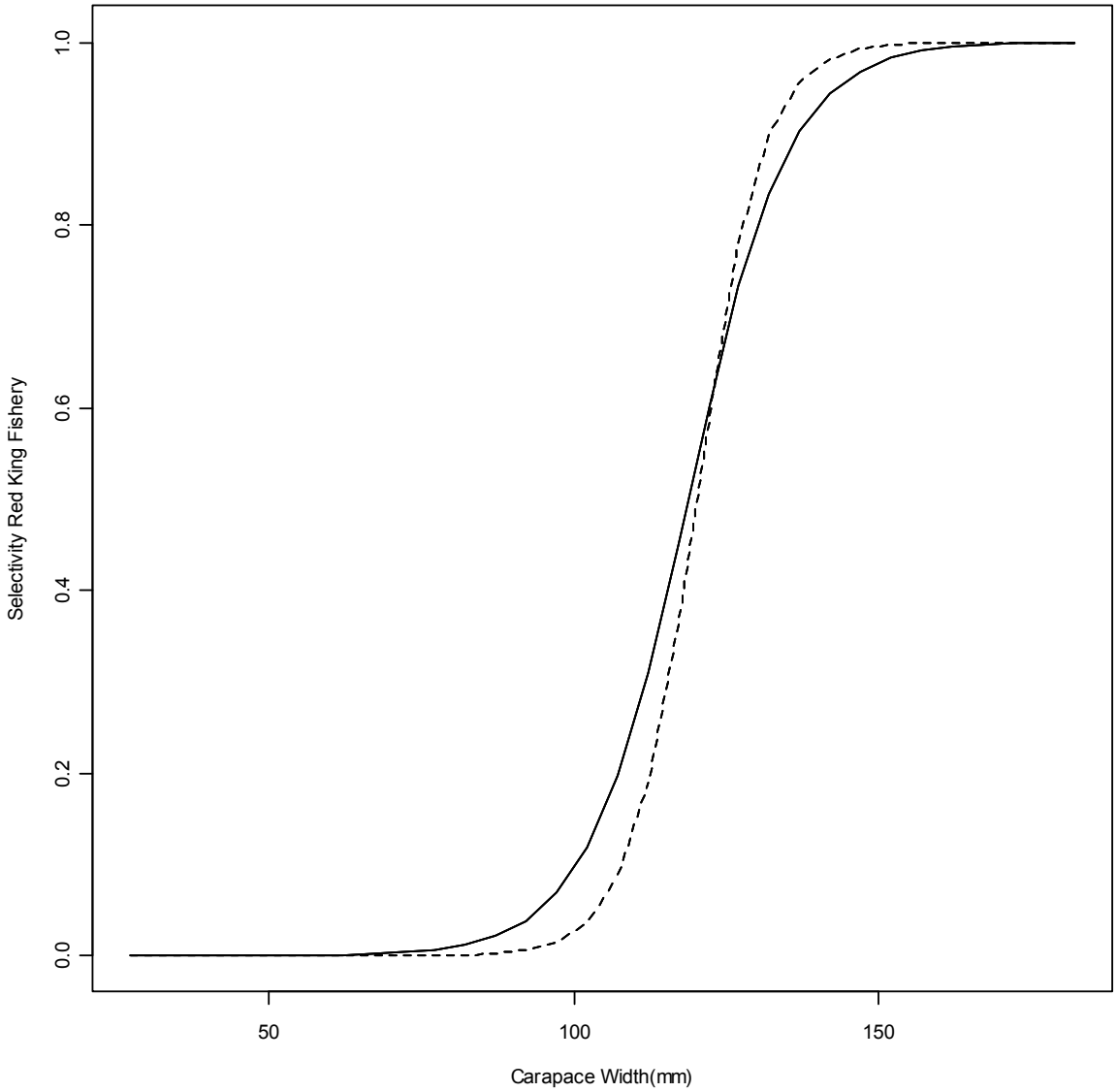


Figure 92. *Model (6)* selectivity curve estimated by the model for bycatch of Tanner crab in the Bristol Bay red king crab fishery for females (dashed) and males (solid), 1989-2011.

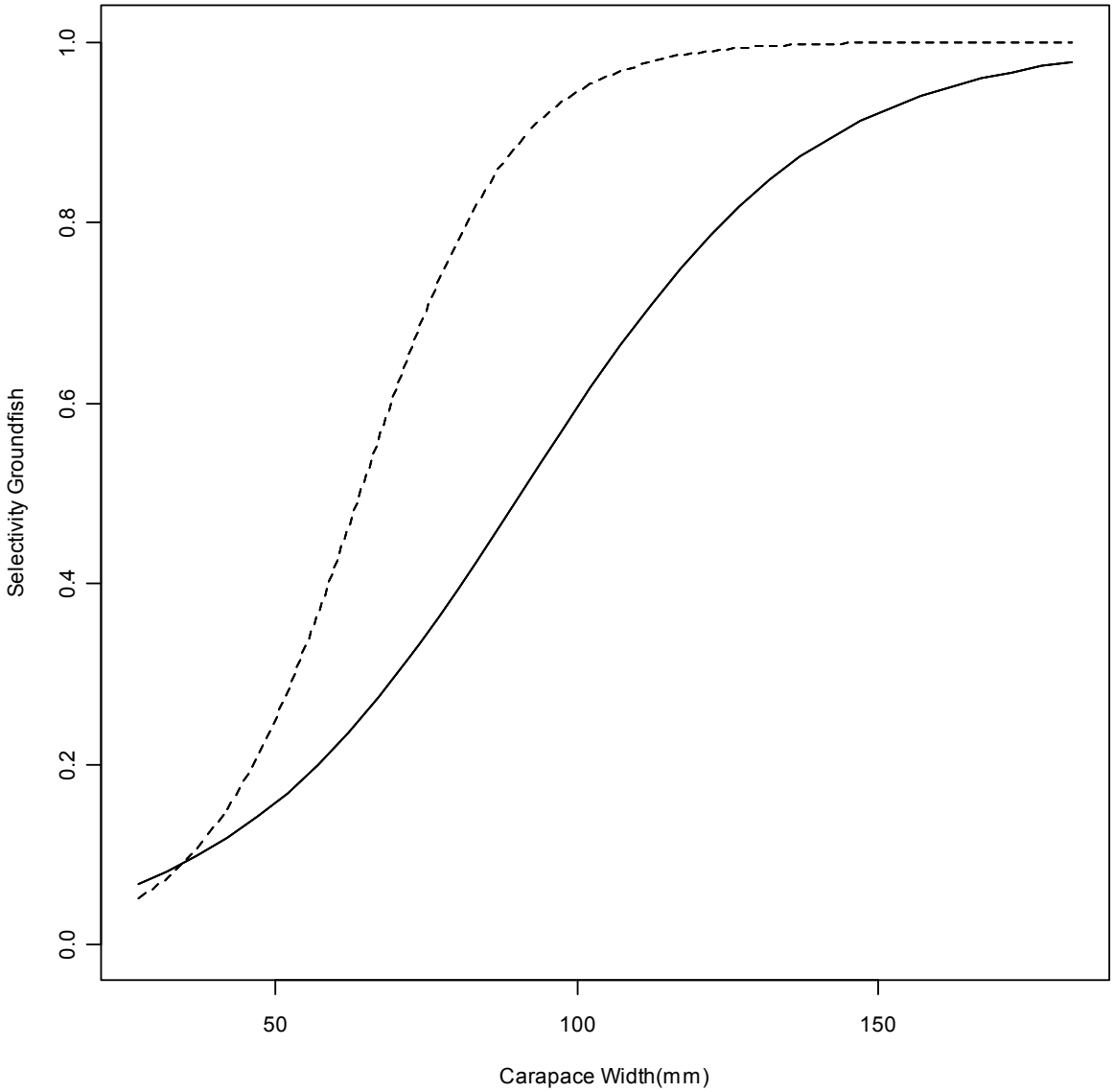


Figure 93. *Model (6)* selectivity curve estimated by the model for bycatch of Tanner crab in the groundfish fishery for males (dashed) and females (solid), 1973-2010.

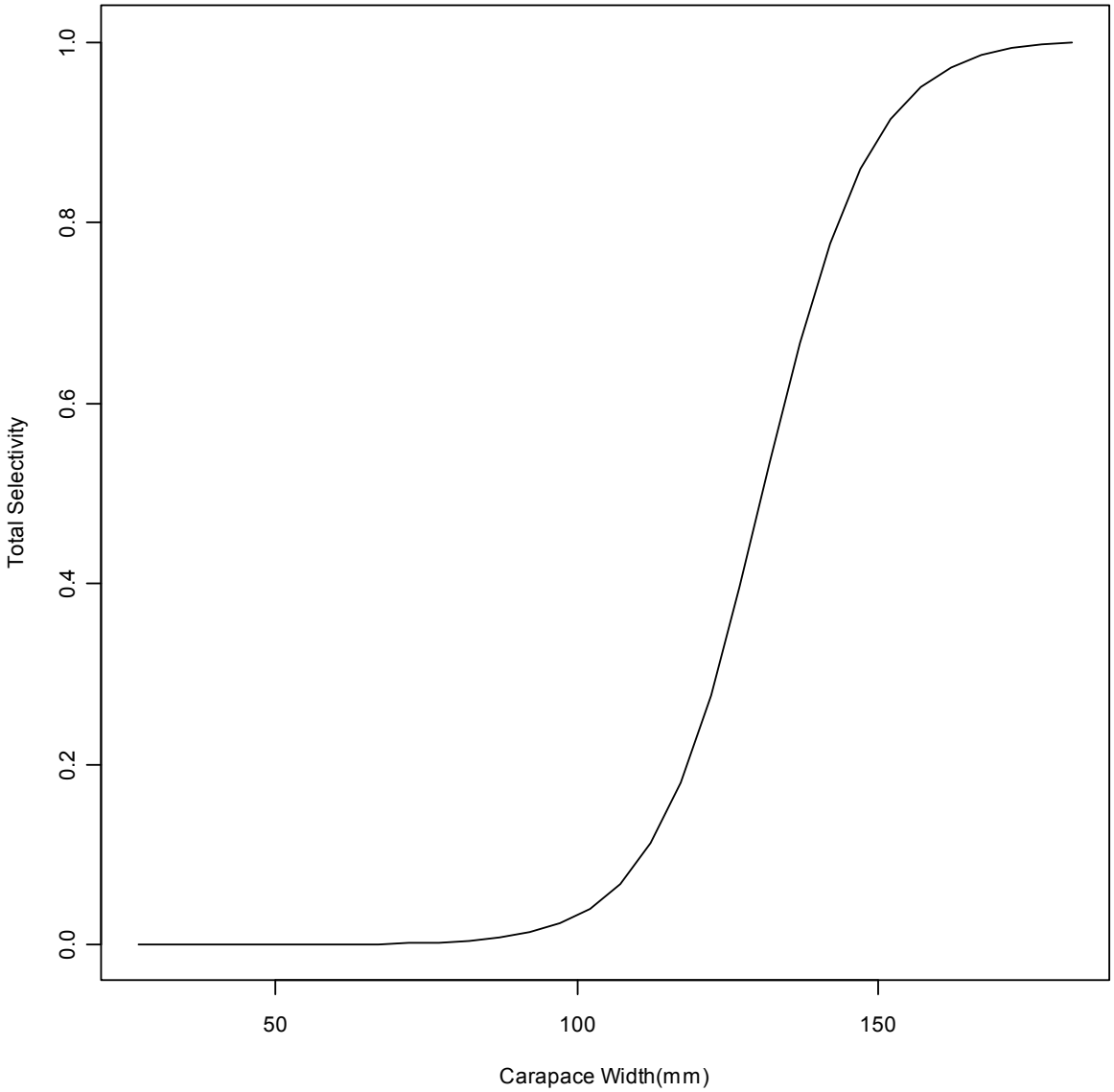


Figure 94. *Model (6)* estimated total selectivity for combined shell condition male Tanner crab in the directed fishery 1981-2010.

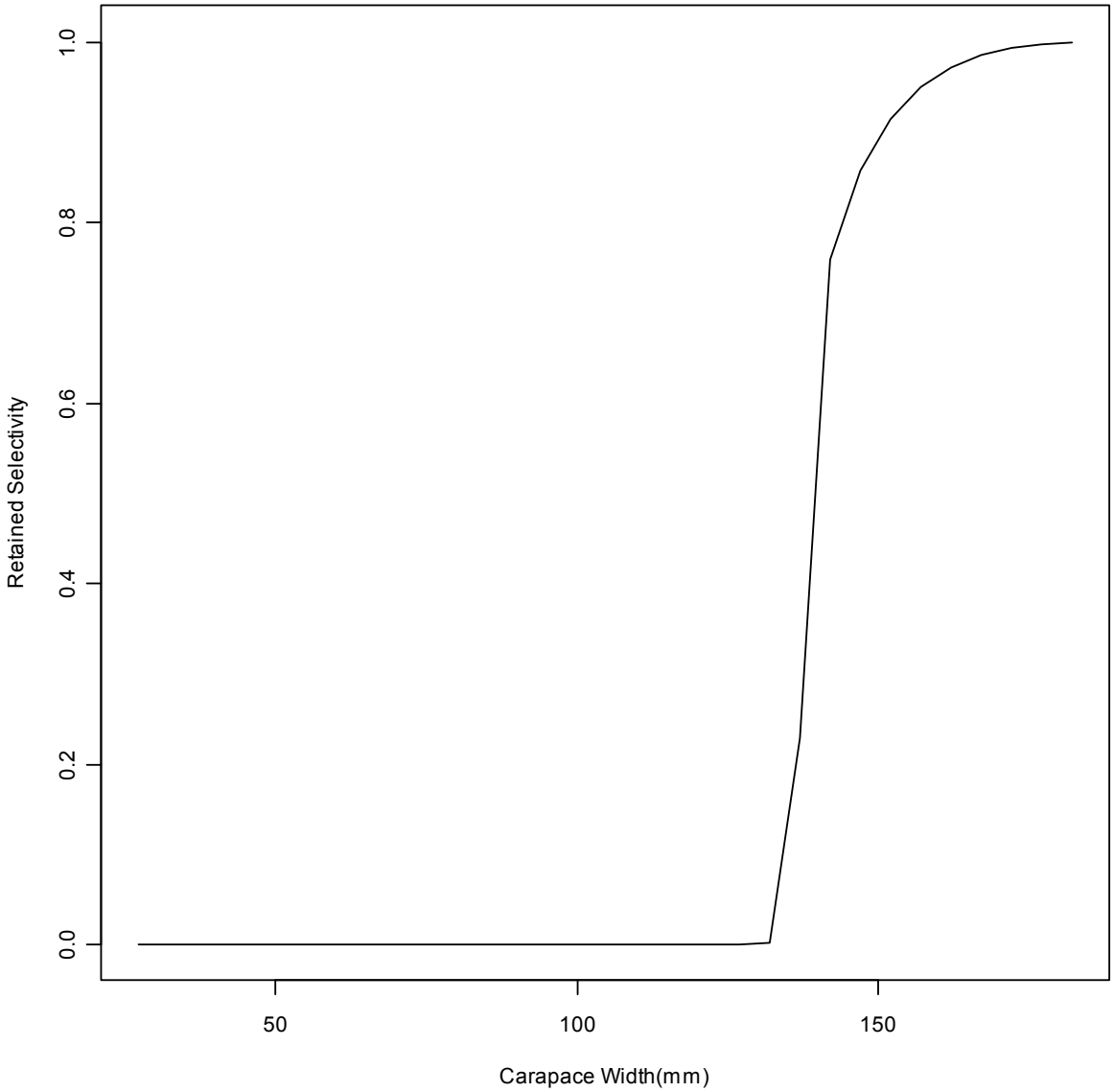


Figure 95. *Model (6)* estimated fraction of total male catch retained by size in the directed fishery, all shell condition classes combined, 1981-2010.

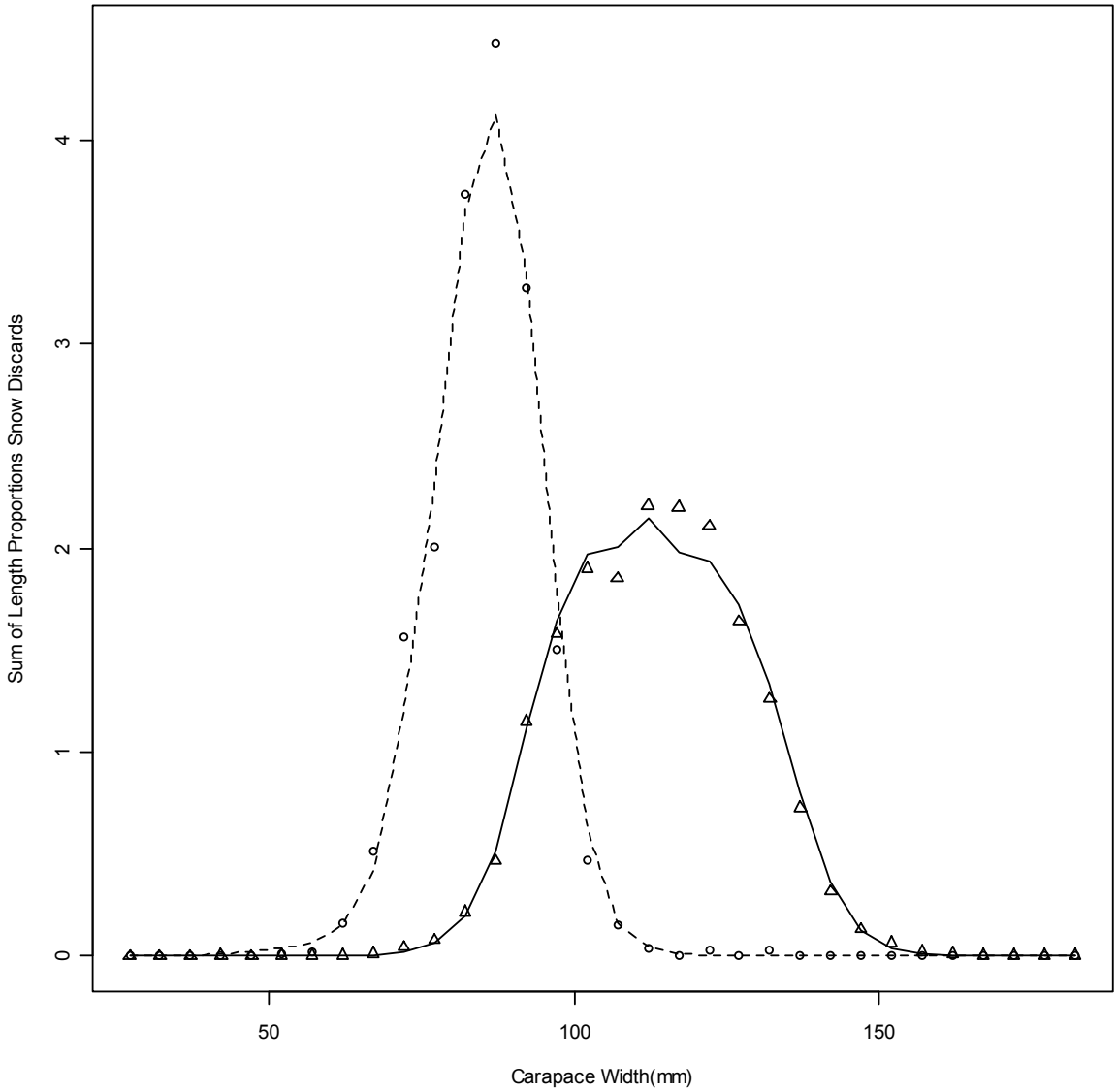


Figure 96. *Model (6)* summary fit to the discards in the snow crab fishery for males (solid line) and females (dotted line) size frequency data. Symbols are observed data.

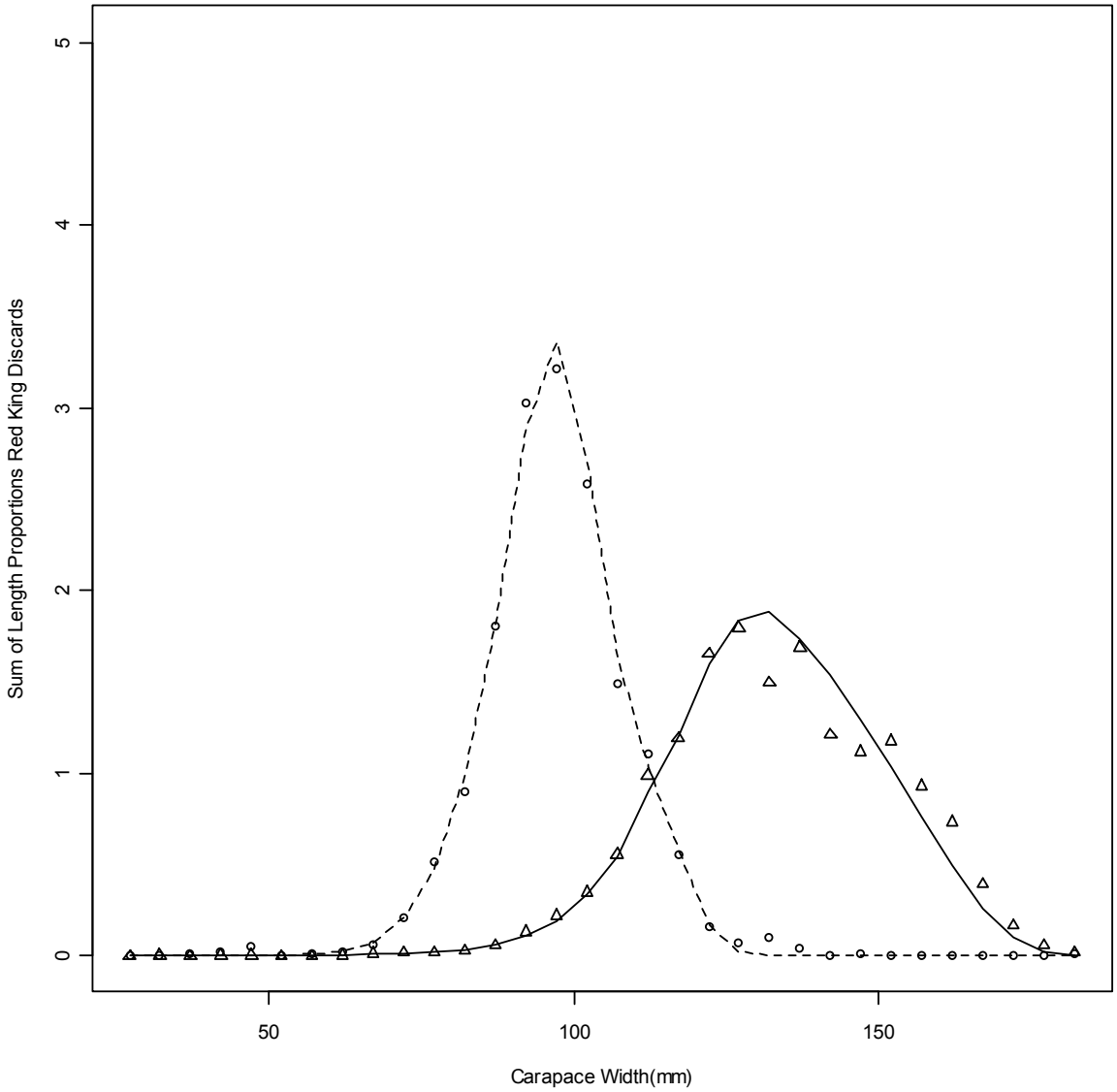


Figure 97. *Model (6)* summary fit to the discards in the Bristol Bay red king crab fishery for males (solid line) and females (dotted line) size frequency data. Symbols are observed data.

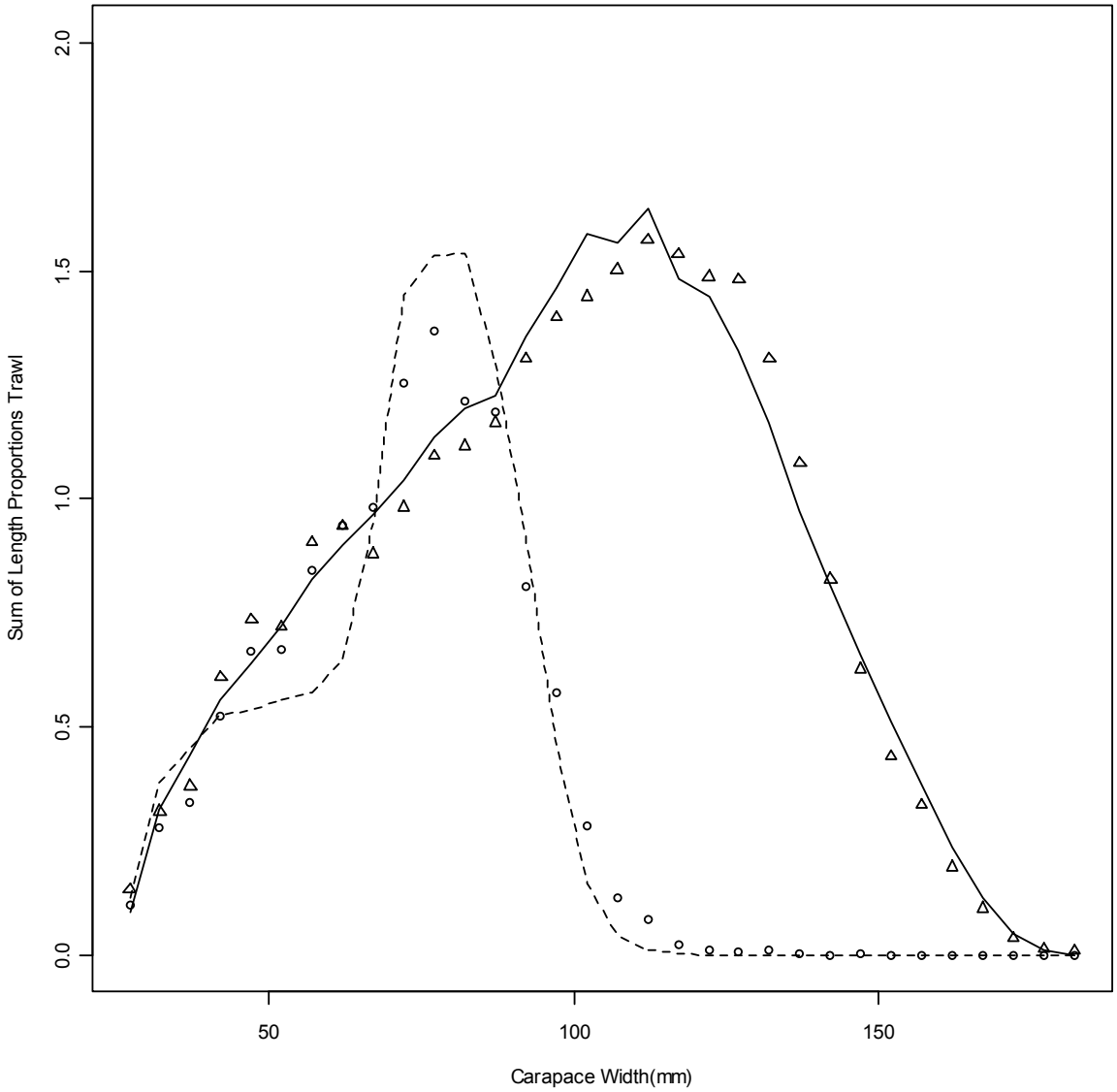


Figure 98. *Model (6)* summary fit to the discards in the eastern Bering Sea groundfish fisheries for males (solid line) and females (dotted line) size frequency data. Symbols are observed data.

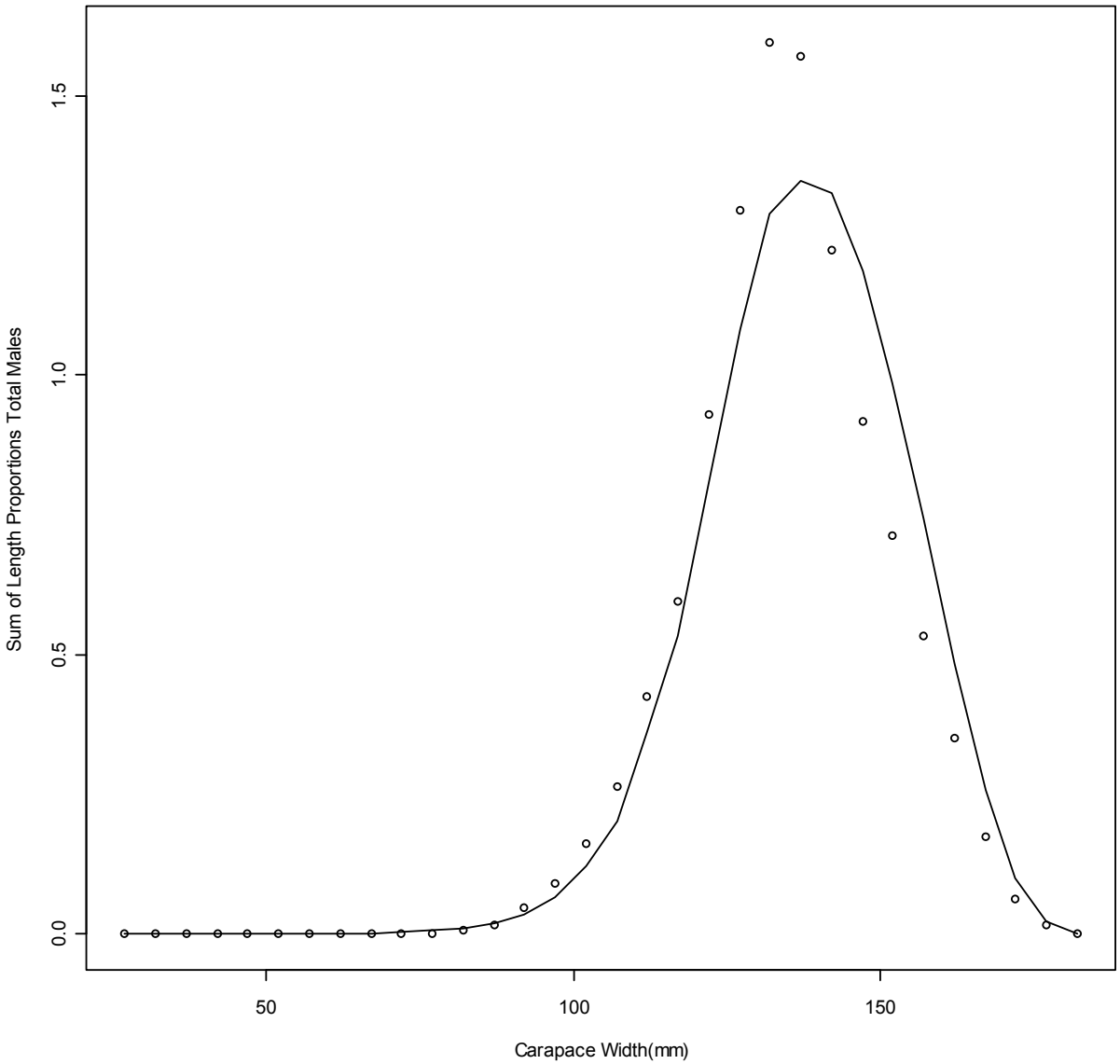


Figure 99. *Model (6)* summary fit to the total (discard plus retained) male size frequency data, shell condition classes combined. Solid line is the model fit. Circles are observed data.

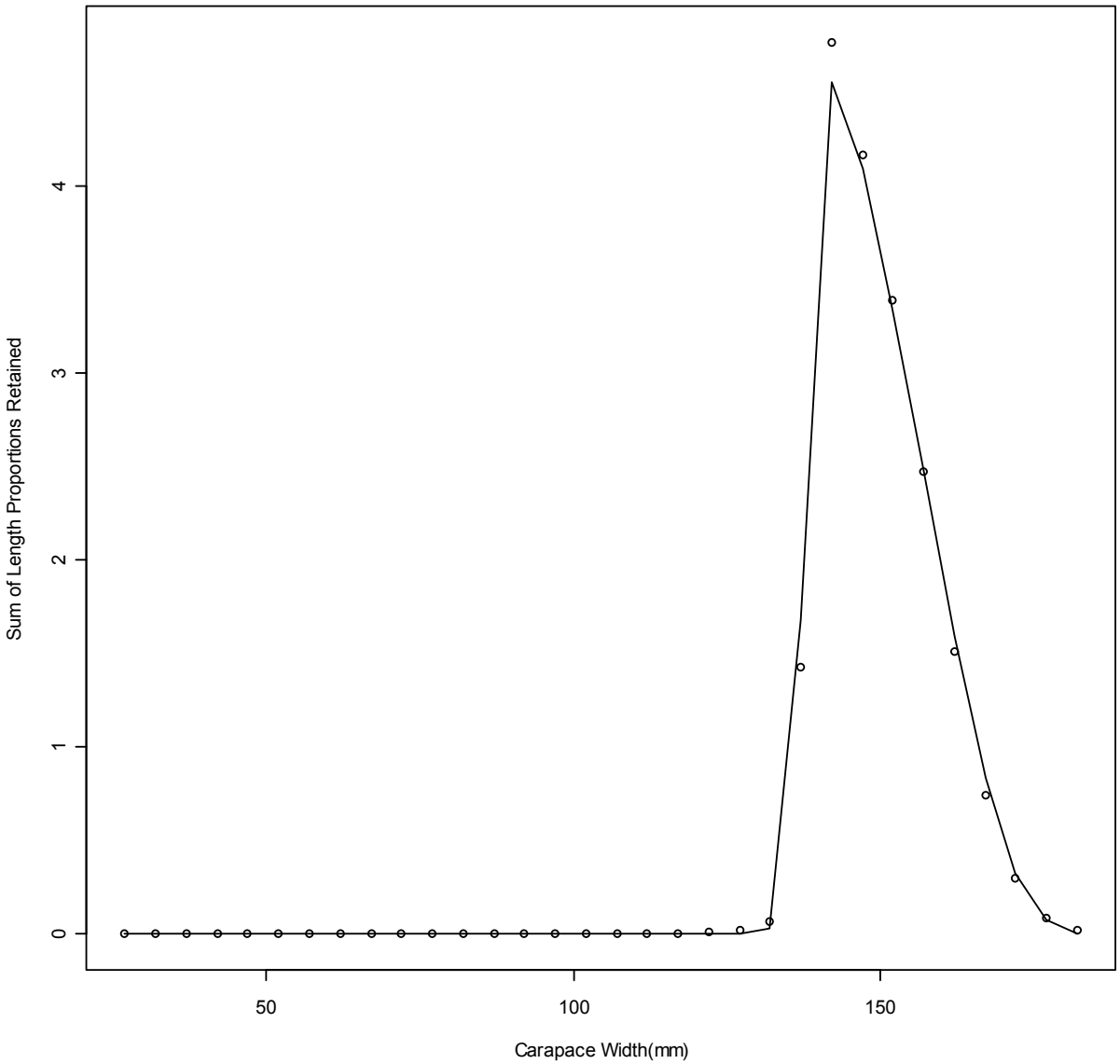


Figure 100. *Model (6)* summary fit to the retained male size frequency data, shell condition classes combined. Solid line is the model fit. Circles are observed data.

Appendix A. Projections and Rebuilding Analysis

Introduction

In this appendix, we report on results of a rebuilding analysis using results of *Base Model (0)* in a projection model to perform stock simulations in order to evaluate the consequences of harvest strategies on stock rebuilding and fishery performance. The specification of the projection model is shown in G.9 (Projection Model Structure). The OFL in this analysis is based on the Tier-3 control rule where the proxy F_{MSY} is taken to be $F_{35\%}$ and the proxy B_{MSY} to be B_{35} (NPFMC, 2008). The OFL is a total-catch OFL computed as the sum of catches from five sources: (i) retained legal males in directed fishery, (ii) discards in the directed fishery, (iii) bycatch in the snow crab fishery, (iv) bycatch in the Bristol Bay red king crab fishery, and (v) bycatch in the groundfish fisheries.

For the *Base Model (0)*, we estimated $B_{35\%}$=162.31 thousand t and $F_{35\%}$=0.574. The model estimate of 2010/11 MMB at mating (53.45 thousand t) represents $0.33B_{35\%}$. Thus, simulations begin with the stock in an overfished condition. Simulations are performed under three scenarios: (1) fishing at the full F_{OFL}; (2) fishing at $0.75F_{OFL}$; and fishing at F_{OFL}=0 with only groundfish fishery discard mortality included.

The calculation of the total catch OFL is based on the assumption that F_{OFL} is the fishing mortality rate from the directed fishery for total males, plus the full-selection F for males in the snow crab, Bristol Bay red king crab and groundfish fisheries. The future full-selection retained fishing mortality rate for males in the directed fishery is given by the directed fishery component of the F_{OFL} multiplied by the fishery selectivity for retained males estimated in the assessment model. The future fishing mortality rate on Tanner crab in the snow crab, Bristol Bay red king crab and groundfish trawl fisheries equals the average value over the last five years with their applied fishery selectivity curves estimated in the model. Thus, changes to F_{OFL} directly impact the predicted catches of retained males in the directed fishery as well as the predicted discard of males and females in the directed fishery, while the fishing mortality rates leading to bycatch in the snow, red king crab and groundfish fisheries are constant and independent of $F_{OFL.}$

Directed fishery selectivity used for projections was based on a minimum legal size limit >=138mm for the area east of 166^0 W longitude (Figure A-1). The new legal minimum size limit in effect for the 2010/11 fisheries to the east of 166^0 W longitude is 122 mm, however, retention will uncertain until several fishery seasons have been prosecuted under this new size limit. The average of the previous three years for both total selectivity and retained selectivity was used for projections in the eastern area. The new size limit in effect for the area west of 166^0 W longitude was changed to 112 mm, however, an preferred minimum size limit of >127 mm may be imposed by the industry. For this analysis, the selectivity curve for the eastern area was shifted by 10 mm to approximate a possible industry-imposed limit of 127mm for the western area.

Results

Projections using the *Base Model (0)* were run fishing at $1.0F_{OFL}$, at $0.75F_{OFL}$, and at F_{OFL}=0 except for groundfish bycatch (Tables A-1,A-2 and A-3). $B_{35\%}$ (162,308 t) was estimated using average recruitment to the model from 1966-1972, or 1961-1967 fertilization year, which resulted in MMB estimated in 1974-1980 (Figure 30). The total catch OFL estimated for the 2011/12 fisheries was 4,500 t. Tables A-1, A-2 and A-3 contain the splits of directed fishery total male catch and retained catch in the eastern and western areas based on the observed 2011/12 survey abundance by length in each area. Fishing at $1.0F_{OFL}$, a probability of MMB at mating exceeding $B_{35\%}$ of 0.5 is achieved in 2022/23 (Table A-1). Fishing at F_{OFL}=0 except for groundfish bycatch, a probability of 0.50 of MMB exceeding $B_{35\%}$ is reached in 2018/19 (Table A-2), and that fishing at $0.75F_{OFL}$ in 2021/22 (Table A-3). If fishery selectivity is different than those used here, $F_{35\%}$ and $B_{35\%}$ will be different and rebuilding trajectories will change.

Table A-1. *Base Model (0)* fishing at $1.0F_{35\%}$ control rule (OFL). $B_{35\%} = 162.31$, $F_{35\%}=0.574$. East and west of 166^0 W longitude total catch splits do not include bycatch from the snow crab, the red king crab or the groundfish fisheries.

Year	ABC_{TOT}	C_{DIR}	$\%MMB/B_{35\%}$	$P[MMB > B_{35\%}]$	Full-Select F	Directed Fishery Catch (1000 t)			
						East		West	
	(1000 t)					Total	Retain	Total	Retain
2011/12	4.5(3.7,5.2)	2.2(1.7,2.6)	28.8(26.6,30.8)	0	0.11	1.4	1.0	1.7	1.1
2012/13	3.1(2.0,5.1)	1.3(0.6,2.6)	24.9(22.9,26.8)	0	0.08	0.9	0.6	1.1	0.7
2013/14	2.9(1.8,4.8)	1.0(0.4,2.2)	23.6(21.5,25.6)	0	0.07	0.7	0.5	1	0.6
2014/15	3.8(2.3,6.3)	1.2(0.5,2.6)	26.2(23.6,28.5)	0	0.08	0.9	0.5	1.3	0.7
2015/16	5.9(3.5,10.5)	2.1(0.9,4.2)	31.9(27.8,37.5)	0	0.12	1.5	0.9	2.3	1.2
2016/17	9.6(4.9,27.4)	3.6(1.6,8.6)	40.2(31.7,61.5)	0.003	0.17	2.6	1.6	4.2	2.1
2017/18	17.5(6.7,68.5)	6.7(2.4,22.0)	53.0(35.1,105.9)	0.060	0.26	4.9	2.8	8.7	4.0
2018/19	29.5(8.3,107)	12.1(3.2,41.5)	68.6(38.3,154.3)	0.198	0.35	8.8	4.9	15.6	7.4
2019/20	38.9(9.1,124.4)	17.1(3.9,54.9)	80.1(40.9,189.8)	0.333	0.40	12.2	7.2	20.4	10.3
2020/21	43.4(9.9,135.8)	19.8(4.2,59.3)	84.8(41.4,198.5)	0.399	0.42	13.6	8.3	23.1	11.5
2021/22	45.9(10.8,130.1)	20.5(4.5,57.7)	86.4(40.8,205.7)	0.450	0.44	14.6	8.6	24.6	12.1
2022/23	44.1(9.2,129.1)	20.7(4.0,60.1)	86.0(40.2,211.5)	0.500	0.43	14.6	8.5	23.5	12.0
2023/24	42.3(8.0,131.7)	19.4(3.3,60.2)	83.0(40.9,195.7)	0.535	0.43	13.9	8.2	22.4	11.7
2024/25	38.3(9.4,133.1)	17.2(3.6,60.3)	81.3(40.9,202.7)	0.565	0.42	12.4	7.3	20.2	10.2

Table A-2. *Base Model (0)* fishing at $0.75F_{35\%}$ control rule (OFL). $B_{35\%} = 162.31$, $F_{35\%}=0.574$. East and west of 166^0 W longitude total catch splits do not include bycatch from the snow crab, the red king crab or the groundfish fisheries.

Year	ABC_{TOT}	C_{DIR}	$\%MMB/B_{35\%}$	$P[MMB > B_{35\%}]$	Full-Select F	Directed Fishery Catch			
						East		West	
	(1000 t)					Total	Retain	Total	Retain
2011/12	3.7(3.1,4.3)	1.6(1.3,2.0)	29.2(27.0,31.4)	0	0.08	1.1	0.8	1.3	0.8
2012/13	2.7(1.8,4.3)	1.0(0.4,2.1)	25.5(23.5,27.5)	0	0.06	0.7	0.5	0.8	0.5
2013/14	2.6(1.7,4.2)	0.8(0.3,1.8)	24.3(22.3,26.2)	0	0.05	0.6	0.4	0.7	0.4
2014/15	3.3(2.2,5.4)	1.0(0.4,2.2)	27.0(24.5,29.2)	0	0.06	0.7	0.4	1.0	0.5
2015/16	5.1(3.1,9.0)	1.7(0.7,3.5)	33.0(29.1,38.5)	0	0.09	1.2	0.7	1.8	1.0
2016/17	8.3(4.3,23.6)	3.0(1.3,7.3)	41.7(33.5,64.1)	0.005	0.13	2.1	1.3	3.4	1.7
2017/18	15.2(5.9,56.7)	5.7(2.0,18.6)	55.9(36.7,112.1)	0.079	0.2	4.1	2.3	7.1	3.3
2018/19	25.9(7.4,90.6)	10.6(2.7,34.8)	72.7(40.7,164.5)	0.242	0.27	7.5	4.3	13.2	6.3
2019/20	35(8.1,106.4)	15.3(3.3,47.7)	86.4(43.6,211.4)	0.388	0.32	11.0	6.4	17.9	9.1
2020/21	39.8(8.9,118.6)	18.3(3.7,52.3)	93.4(44.4,228.7)	0.468	0.34	12.7	7.9	20.5	10.6
2021/22	43.9(9.8,114.6)	19.9(4.0,53.8)	95.7(43.8,237.2)	0.524	0.34	14.0	8.4	22.8	11.7
2022/23	42.9(8.6,113.8)	20.0(3.6,55.9)	97.5(44.0,245.6)	0.562	0.35	14.2	8.6	22.4	11.6
2023/24	40.8(7.6,118)	19.5(3.1,55.7)	94.1(44.6,237)	0.609	0.36	13.7	8.4	21.4	11.4
2024/25	3.7(3.1,4.3)	1.6(1.3,2.0)	29.2(27.0,31.4)	0	0.08	1.1	0.8	1.3	0.8

Table A-3. *Base Model (0)* fishing at F=0 with bycatch from the groundfish fisheries only. $B_{35\%}$ = 162.31, $F_{35\%}$=0.574.

Year	ABC_{TOT}	C_{DIR}	%MMB/$B_{35\%}$	P[MMB >$B_{35\%}$]	Full-Select F	Directed Fishery Catch			
						East		West	
	(1000 t)					Total	Retain	Total	Retain
2011/12	0.1(0.1,0.1)	0	31.2(28.6,33.7)	0	0	0	0	0	0
2012/13	0.1(0.1,0.1)	0	28.6(26.3,30.9)	0	0	0	0	0	0
2013/14	0.2(0.2,0.2)	0	28.1(25.8,30.4)	0	0	0	0	0	0
2014/15	0.3(0.2,0.4)	0	31.8(29.2,34.6)	0	0	0	0	0	0
2015/16	0.4(0.3,0.9)	0	40.1(36.1,48.6)	0	0	0	0	0	0
2016/17	0.7(0.3,1.8)	0	54.3(43.1,91.3)	0.036	0	0	0	0	0
2017/18	1.0(0.4,3.0)	0	80.5(50.1,185.8)	0.314	0	0	0	0	0
2018/19	1.3(0.4,3.9)	0	118.5(59.0,312.2)	0.627	0	0	0	0	0
2019/20	1.3(0.4,4.1)	0	156.5(67.0,424.3)	0.775	0	0	0	0	0
2020/21	1.3(0.4,4.0)	0	181.7(72.8,510.1)	0.857	0	0	0	0	0
2021/22	1.3(0.4,4.0)	0	204.0(76.9,550.3)	0.887	0	0	0	0	0
2022/23	1.2(0.3,3.7)	0	224.0(81.5,582.7)	0.910	0	0	0	0	0
2023/24	1.1(0.3,3.9)	0	233.6(85.4,614.8)	0.934	0	0	0	0	0
2024/25	1.2(0.4,4.1)	0	236.7(87.7,636.2)	0.950	0	0	0	0	0

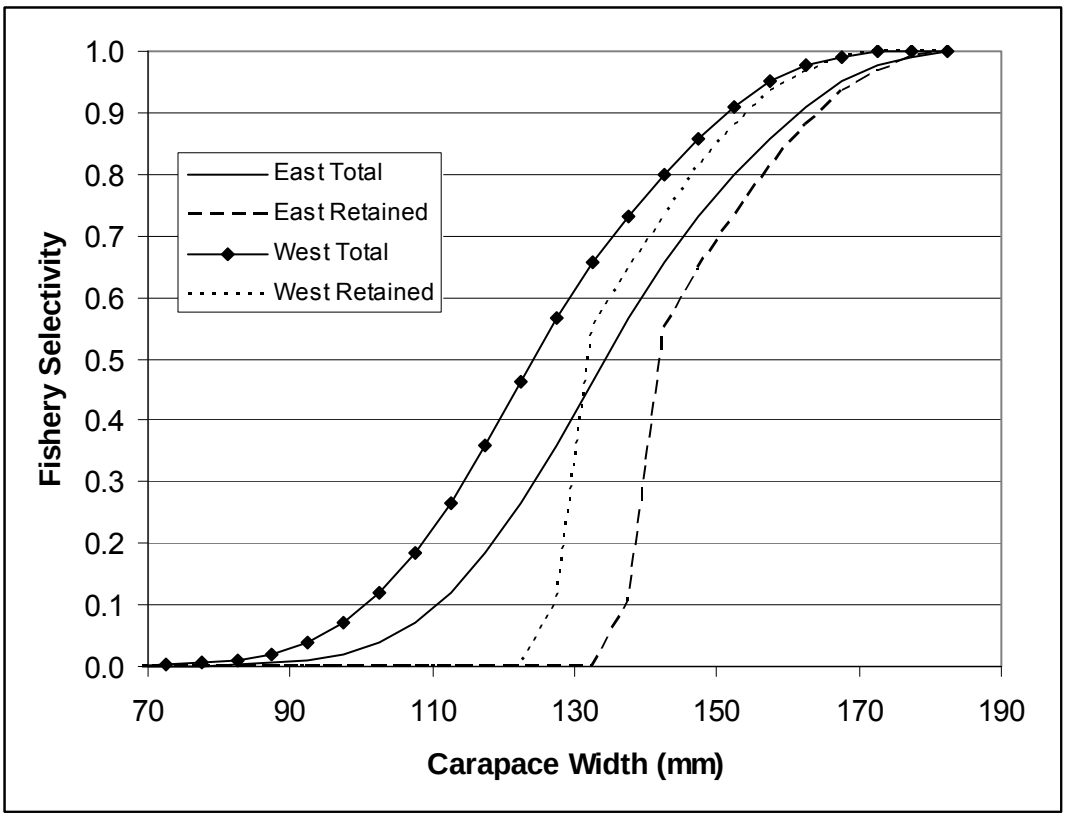


Figure A-1. Fishery selectivity curves for the areas east and west of 166^0 W longitude. The east area selectivity is estimated from the *Base Model (0)* with a minimum legal size limit >=138mm. the west area selectivity is shifted 10mm to approximate an industry preferred size limit >=128 mm.