Norton Sound Red King Crab Stock Assessment in Fall 2008

Jie Zheng[1], Hamachan Hamazaki[2] and Joyce K. Soong[3]
Alaska Department of Fish and Game
Commercial Fisheries Division
[1]P.O.Box 115526, Juneau, AK 99811-5526
Phone : 907-465-6102
Email : Jie.Zheng@alaska.gov
[2]333 Raspberry Rd., Anchorage, AK 99518-1565
Phone: 907-267-2158
Email: Hamachan.Hamazaki@alaska.gov
[3]P.O.Box 1148, Nome, AK 99762
Phone: 907-443-5167
Email: Joyce.Soong@alaska.gov

Executive Summary

Red king crab, *Paralithodes camtschaticus*, in Norton Sound, Alaska, support three main fisheries: summer commercial, winter commercial, and winter subsistence fisheries. Four types of surveys have been conducted periodically during the last three decades: summer trawl, summer pot, winter pot, and preseason summer pot, but none of these surveys were conducted every year. To improve abundance estimates, Zheng et al. (1998) developed a length-based stock synthesis model of male crab abundance that combines multiple sources of survey, catch, and mark-recovery data from 1976 to 1996. A maximum likelihood approach was used to estimate abundance, recruitment, and catchabilities of the commercial pot gear. We updated the model with the data from 1976 to 2008 and estimated population abundance in 2008. Estimated abundance and biomass in 2008 are:

Legal males: 1.4932 million crabs.

Mature male biomass: 5.240 million lbs.

Average of mature male biomasses during 1983-2008 was used as the B_{MSY} proxy and due to uncertainty of abundance estimates, γ=1 was used to derive the F_{MSY} proxy. Estimated B_{MSY} proxy, F_{MSY} proxy and retained catch limit in 2008 are:

B_{MSY} proxy = 3.567 million lbs,

F_{MSY} proxy = 0.18,

Retained catch limit: 0.2460 million crabs.

Summary of Major Changes in 2008

1. Historical trawl survey abundance estimates were revised. The original estimates were based on the core area with some survey stations outside of the core area not being used for abundance estimates. The new estimates were based on all sampled areas.
2. Historical harvest and size composition data were re-checked and revised as necessary.
3. Natural mortality was changed from 0.3 to 0.18.
4. Newshell and oldshell length compositions were combined to compute likelihood values.

Response to CPT Comments (from May 2008)

"The team requests that additional information be included in future assessment reports on asymptotic standard errors and selectivity parameters (to indicate which are fixed not estimated). The residual plots as shown are difficult to interpret and should be revised. The team discussed the rationale for using the M value of 0.18 and its basis on laboratory studies. Some team members did not agree with this estimate usage for this stock noting that model information could be used to inform the best estimate. The team recommends exploration of a broader range of models and sensitivity analyses for this stock in the future."

The previous report showed which parameters are estimated and which are fixed. The standard error of estimated parameters can be documented in the report in April 2009. Weights on various data and parameter sensitivities were investigated in Zheng et al (1998) and can be reexamined with alternative models in the future. Alternative M values can be examined in the report in April 2009. Residuals are standardized and re-graphed for improving presentation.

Response to SSC Comments specific to this assessment (from June 2008)

"A new model has been developed for this stock that includes a four-stage catch-survey analysis. There is need for further exploration of this model, in terms of which parameters can be estimated and sensitivity to model specifications. Nevertheless, the SSC agrees with the Plan Team and author that the model is appropriate for determining OFL. ***The SSC concurs with the placement of the stock in Tier 4 but encourages further investigation of whether this stock could be placed in Tier 3.*** *The SSC requests a presentation on this model at the October meeting.*

The SSC also accepts the choices for range of years, but requests that the rationale be elaborated more clearly. Similarly, a rationale for setting gamma equal to 1 needs to be provided."

Evaluation of parameters and Tier replacement will be carried out after fall 2008. The default gamma value of 1 is used in this report and evaluation of alternative gamma values will be carried out when evaluating Tier replacement after fall 2008. Changes to the May 2008 version of this report include:

1. Residuals by size were standardized and re-plotted in Figures 3 and 4 for a better presentation.

2. Objective function values by data components were added to Table 5.

Response to SSC Comments in General (from June 2008)

"General recommendations to all assessment authors for future assessments:

1. *To the extent possible, a consistent format should be used for the assessments; sections that are not relevant to a particular stock should be omitted.*
2. *Each assessment should provide a range of alternatives for the Plan Team and SSC to consider when setting OFLs, for example, alternative model configurations for Tier 1-3 stocks, alternative parameter values where these are highly uncertain and cannot be estimated, or alternative time periods used in Tier 4 and Tier 5 calculations.*
3. *Model-based stock assessments should clearly document all data sources, model equations, the number of parameters, a list of which parameters are estimated in the model, and a list of fixed parameters, and a justification for the selected parameter values.*
4. *The rationale for selecting a specific time period for establishing B_{MSY} proxies based on time series of recruitment (Tier 1-3) or biomass (Tier 4) or for establishing an OFL based on catch histories (Tier 5) should be clearly articulated. Unless compelling reasons exist to choose a different period, the default should be the full time series for which data are available. When alternative time periods are considered, the rationale and the resulting reference points should be presented for consideration by the Plan Team and SSC.*
5. *The crab OFL definitions are designed to provide a guide for defining the best available proxy for MSY when data are insufficient to directly estimate MSY. The guidelines allow gamma (γ) in the formula for computing F_{OFL} under Tier 4 to be set at a value higher or lower than 1. A gamma less than 1 might be justifiable if the available biomass measure includes a large portion of small crab that has not recruited to the fishery. A gamma greater than 1 might be justifiable if the directed fishery can be expected to harvest male crab with carapace widths well above the size at 50% maturity. The SSC agrees with the Plan Team recommendation that **future stock assessments should provide analyses to support the choice of gamma**. These analyses could include an exploration of fishery selectivity and a comparison of minimum size limits and size at 50% maturity for male crab. The SSC does not recommend the use of an $F_{35\%}/M$ ratio derived from one stock as a default for gamma on an unrelated stock unless there is a strong rationale for concluding that the fishery is likely to be prosecuted in an identical manner and knowledge of stock status is sufficient to justify the harvest rate.*
6. *To the extent possible, bycatch information should be provided for all stocks included in the SAFE so that stock OFLs can be moved from "retained catch OFL" to "total catch OFL".*
7. *For stocks with an assessment model, the SSC requests that the authors include a table summarizing the fit to data (including number of parameters, likelihood for each data component, etc.).*
8. *The ecosystem considerations sections could be expanded to include information on prey and predator composition in a consistent format (e.g., pie charts similar to the groundfish assessments). A discussion of seabird predation on crab would be a useful addition. We note that seabirds feed on larval through juvenile crab, particularly in shallow or nearshore areas, such as the Pribilof Islands. Plankton-feeding birds eat larval crab and juveniles are consumed by seaducks and seabirds, particularly during winter months.*
9. *Each assessment should include figures showing the available time series of catch and survey biomass, in addition to tables, to facilitate comparisons and the selection of appropriate time periods.*

10. *The presentation of recruitment time series should be standardized as to year (examples include year of recruitment to maturity for spawner/recruit data, or perhaps year of hatching; and year of recruitment to legal size for catch data) to clearly illustrate specific cohort strength.*
11. *Assessment authors should provide alternative options for setting OFLs to the Plan Team and the SSC, particularly where there are large uncertainties about correct model structure or parameter estimates."*

The schedule for this fishery is advanced by several months relative to most of the other Bering Sea crab fisheries, such that the SSC's review of the OFL and TAC occurred in June. Therefore, substantive changes to the assessment in response to these review comments will be addressed in the revised assessment in preparation for TAC setting for the summer fishery, to be presented at the May, 2009 crab plan team meeting.

Introduction

Norton Sound Red King Crab (*Paralithodes camtschaticus*) form one of the northernmost red king crab populations that can support a commercial fishery (Powell et al. 1983). It is distributed throughout Norton Sound with a westward limit of 167-168^{o} W. longitude with depths less than 30 m and bottom temperatures above 4 ^{o}C. One of the unique life-history traits of Norton Sound red king crab is that they spend their entire lives in shallow water since Norton Sound is generally less than 40 m in depth. Distribution and migration patterns of Norton Sound red king crab have not been well studied. Based on the 1976-2006 trawl surveys, red king crab in Norton Sound are found in areas with a mean depth range of 19 ± 6 (SD) m and bottom temperatures of 7.4 ± 2.5 (SD) ^{o}C during summer. The same surveys show that they are consistently abundant offshore of Nome. Red king crab generally show a migration pattern between deeper offshore waters during molting/feeding and inshore shallow waters during the mating period. Timing of the inshore mating migration is unknown. Scant data exists about mating location in the nearshore area. They are assumed to mate during March-June. Offshore migration is considered to begin in May-July. Trawl surveys during 1976-2006 show that crab distribution is dynamic. While crabs have always been abundant near shore in front of Nome, more recent surveys show high abundance on the southeast side of the Sound, offshore of Stebbins and Saint Michael. However, it is unknown whether this is due to a migratory shift because of oceanographic change or due to changes in stock composition. Thus far, no studies have been made on possible stock separation within the putative stock known as Norton Sound red king crab.

The Norton Sound red king crab management area consists of two units: Norton Sound Section (Q3) and Kotzebue Section (Q4) (Soong et al., *in prep*). The Norton Sound Section (Q3) consists of all waters in Registration Area Q north of the latitude of Cape Romanzof, east of the International Dateline, and south of 66°N latitude (Figure 1). The Kotzebue Section (Q4) lies immediately north of the Norton Sound Section and includes Kotzebue Sound. Commercial fisheries have not occurred regularly in the Kotzebue Section. Our report deals with the Norton Sound Section of the Norton Sound red king crab management area.

Fisheries

Norton Sound red king crab fisheries consist of commercial and subsistence fisheries. The commercial red king crab fishery started in 1977 and occurs in summer (July – August) and in winter (December – March) (Banducci et al. 2007).

Summer Commercial Fishery

A large-vessel summer commercial crab fishery existed in the Norton Sound Section from 1977 through 1990. No summer commercial fishery occurred in 1991 because there was no staff to manage the fishery. In 1992, the summer commercial fishery resumed. In March 1993, the Alaska Board of Fisheries (BOF) limited participation in the fishery to small boats. Then on June 27, 1994, a super-exclusive designation went into effect for the fishery. This designation stated that a vessel registered for the Norton Sound crab fishery may not be used to take king crabs in any other registration areas during that registration year. A vessel moratorium was put into place before the 1996 season. This was intended to precede a license limitation program. In 1998, Community Development Quota (CDQ) groups were allocated a portion of the summer harvest; however, no harvest occurred until the 2000 season. On January 1, 2000 the North Pacific License Limitation Program (LLP) went into effect for the Norton Sound crab fishery. The program dictates that a vessel which exceeds 32 feet in length overall must hold a valid crab license issued under the LLP by the National Marine Fisheries Service. Regulation changes and location of buyers resulted in harvest distribution moving eastward in Norton Sound in the mid 1990s. Commercial fisheries history and catch data are summarized in Table 1.

CDQ Fishery

The Norton Sound and Lower Yukon CDQ groups divide the CDQ allocation. Only fishers designated by the Norton Sound and Lower Yukon CDQ groups are allowed to participate in this portion of the king crab fishery. Fishers are required to have a CDQ fishing permit from the Commercial Fisheries Entry Commission (CFEC) and register their vessel with Alaska Department of Fish and Game (ADF&G) before they make their first delivery. Fishers operate under authority of the CDQ group and each CDQ group decides how their crab quota is to be harvested. During the March 2002 BOF meeting, new regulations were adopted that affect the CDQ crab fishery and relaxed closed-water boundaries in eastern Norton Sound and waters west of Sledge Island. At its March 2008 meeting, BOF changed the start date of the Norton Sound open-access portion of the fishery to be opened by emergency order and could occur as early as June 15. The CDQ fishery may open at any time, by emergency order.

Winter Commercial Fishery

The Norton Sound winter commercial fishery is a small fishery involving approximately 10 fishers harvesting 2,400 crabs on average annually during 1978-2007 (Soong 2007).

Subsistence Fishery

The Norton Sound subsistence crab fishery mainly occurs during winter using hand lines and pots through the nearshore ice. Average annual subsistence harvest is 5,300 crabs (1978-2007). Subsistence fishers need to obtain a permit before fishing and record their daily effort and catch. The subsistence fishery catch is influenced not only by crab abundance, but also by changes in distribution, changes in gear (e.g., more use of pots instead of hand lines since 1980s), and ice conditions (e.g., reduced catch due to unstable ice conditions: 1987-88, 1988-89, 1992-93, 2000-01, 2003-04, 2004-05, and 2006-07).

Harvest Strategy

Norton Sound red king crab have been conservatively managed since 1997 through varying harvest rates from 5% to 10% of estimated legal male abundance. The GHL for the summer fishery is set in three levels: (1) estimated legal biomass < 1.5 million lbs: legal harvest rate =

0%; (2) estimated legal biomass ranges from 1.5 to 2.5 million lbs: legal harvest rate ≤ 5%; and (3) estimated legal biomass >2.5 million lbs: legal harvest rate ≤ 10%.

Data

Available data are summarized in Table 2. National Marine Fisheries Service (NMFS) conducted trawl surveys every 3 years from 1976 to 1991 (Stevens and MacIntosh 1986), and ADF&G conducted four trawl surveys during 1996-2006 (Soong and Banducci 2006). Total population abundances and length and shell compositions for males >73 mm CL were estimated by "area-swept" methods from the trawl survey data (Alverson and Pereyra 1969). The compositions consisted of six 10-mm length groups. If multiple hauls were conducted for a single station (10X10 nmi) during a survey, then the average of abundances from all hauls within the station was used. Some trawl surveys occurred during September, the molting period for males. To make survey abundances comparable with premolt abundances, we adjusted trawl survey abundances by subtracting average growth increment of each length class (Table 3) from the length of each soft-shell crab (molting within the past 2 months).

Four summer pot surveys were conducted by ADF&G (Table 2), and total male crab abundances were estimated using Petersen mark-and-recapture methods (Brannian 1987). ADF&G also conducted 24 winter pot surveys during 1980-2008 and one preseason pot survey in the summer of 1995 (Table 2); total crab abundances were not estimated for these pot surveys because of unreliable catch per unit effort (CPUE) data due to change in environmental conditions over time and lack of tagging data. For all pot surveys, length and shell condition compositions were estimated.

Red king crab catches from the summer fishery were sampled by ADF&G from 1976 to 2007 to determine length and shell condition. Bycatch of sublegal males (observer data) from the summer fishery in 1987-90, 1992, and 1994 were also sampled by observers to determine length and shell condition. Total catch from all fisheries and effort (potlifts) from the summer fishery were obtained from the ADF&G office in Nome. Red king crabs were tagged and released during 1980-1991 (Powell et al. 1983; Brannian 1987); 222 tagged male crabs were recovered after spending at least one molting season at liberty. These tagging data were used to estimate a growth matrix and molting probabilities by premolt length.

Analytic Approach

Main Assumptions for the Model

A list of main assumptions for the model:

(1) Natural mortality is constant over time and length except for the last length group, which is 20% higher than natural mortality in the other five length groups, and was estimated with a maximum age of 25 and the 1% rule (Zheng 2005).

(2) Survey selectivities are a function of length and are constant over time and shell condition. Fisheries selectivities are constant over time except summer fishery selectivities that have two selectivity curves, one before 1993 and another after 1992 because of changes in fishing vessel compositions and pot limits.

(3) Growth is a function of length and does not change over time.

(4) Molting probabilities are an inverse logistic function of length for males.

(5) A summer fishing season for the directed fishery is short.

(6) Due to lack of data and the time of fishing mainly during summer and early fall, handling mortality is assumed to be zero.

(7) Annual retained catch is measured without error.

(8) Trawl survey catchability is set to be 1.0 for mature males.

(9) Male crabs are mature at sizes ≥94 mm CL.

(10) Length compositions have a multinomial error structure and abundance has a log-normal error structure.

Model Structure

Zheng et al. (1998) developed a length-based model for Norton Sound red king crab. The model is based on length structured model with model parameters estimated by the maximum likelihood method. The model estimates abundances of crabs with CL ≥74 mm and with 10-mm length intervals because few crabs with CL <74 mm were caught during surveys or fisheries and there were relatively small sample sizes for trawl and winter pot surveys.

The model was made for newshell and oldshell male crabs separately, but assumed they have the same molting probability and natural mortality. Summer crab abundances are the survivors of crabs from the previous winter:

$$N_{s,l,t+1} = (N_{w,l,t} - C_{w,t} P_{w,n,l,t} - C_{p,t} P_{p,n,l,t}) e^{-0.417 M_l},$$
$$O_{s,l,t+1} = (O_{w,l,t} - C_{w,t} P_{w,o,l,t} - C_{p,t} P_{p,o,l,t}) e^{-0.417 M_l}, \qquad (1)$$

where $N_{s,l,t}$ and $O_{s,l,t}$ are summer abundances of newshell and oldshell crabs in length class l in year t, $N_{w,l,t}$ and $O_{w,l,t}$ are winter abundances of newshell and oldshell crabs in length class l in year t, $C_{w,t}$ and $C_{p,t}$ are total winter and subsistence catches in year t, $P_{w,n,l,t}$ and $P_{p,n,l,t}$ are length compositions of winter and subsistence catches for newshell crabs in length class l in year t, $P_{w,o,l,t}$ and $P_{p,o,l,t}$ are length compositions of winter and subsistence catches for oldshell crabs in length class l in year t, and M_l is instantaneous natural mortality in length class l, which, for simplicity, we assumed constant (M) for all sizes and shell conditions except for the last length class where M_6 = 1.2 M. The time from Feb. 1 to July 1 is 5 months, or 0.417 year.

Winter abundance of newshell crabs is the combined result of growth, molting probability, mortality, and recruitment from the summer population:

$$N_{w,l,t} = \sum_{l'=1}^{l'=l} [G_{l',l}((N_{s,l',t} + O_{s,l',t}) e^{-y_t M_l} - C_{s,t}(P_{s,n,l',t} + P_{s,o,l',t})) m_{l'} e^{-(0.583-y_t) M_l}] + R_{l,t}, \qquad (2)$$

where $G_{l',l}$ is a growth matrix representing the expected proportion of crabs molting from length class l' to length class l, $C_{s,t}$ are total summer catch in year t, $P_{s,n,l,t}$ and $P_{s,o,l,t}$ are length compositions of summer catch for newshell and oldshell crabs in length class l in year t, m_l is molting probability in length class l, y_t is the time in year from July 1 to the mid-point of the summer fishery, and $R_{l,t}$ is recruitment into length class l in year t. The time from July 1 to Feb. 1 is 7 months, or 0.583 year. Winter abundance of oldshell crabs is the non-molting portion of survivors of crabs from summer:

$$O_{w,l,t} = [(N_{s,l,t} + O_{s,l,t}) e^{-y_t M_l} - C_{s,t}(P_{s,n,l,t} + P_{s,o,l,t})] (1 - m_l) e^{-(0.583-y_t) M_l}. \qquad (3)$$

Males >123 mm CL were grouped together to form the last length class. Sublegal males (<104 mm CL) are not legally retained in the commercial catch but are sorted, discarded, and subject to handling mortality. Due to complexity and lack of data, we did not model handling mortality.

Following Balsiger's (1974) findings, we used a reverse logistic function to fit molting probabilities as a function of length and time:

$$m_l = 1 - \frac{1}{1+e^{-\alpha(\iota-\beta)}}, \quad (4)$$

where α and β are parameters, and i is the mean length of length class l. The sample size for the mark-recapture data is too small to estimate annual molting probabilities.

We modeled recruitment, R_t, as a stochastic process about the mean, R_0:

$$R_t = R_0 e^{\tau_t}, \tau_t \sim N(0, \sigma_R^2). \quad (5)$$

R_t was assumed only to enter length classes 1 and 2; thus, $R_{l,t} = 0$ when $l \geq 3$. The recruits belonging to the first two length classes are:

$$R_{1,t} = r R_t, R_{2,t} = (1-r) R_t, \quad (6)$$

where r is a parameter with a value less than or equal to 1.

Estimated length/shell compositions of winter commercial catch were derived from the winter population, winter selectivity for pots, and proportion of legal crabs for each length class:

$$P_{w,n,l,t} = N_{w,l,t} S_{w,l} L_l / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l],$$
$$P_{w,o,l,t} = O_{w,l,t} S_{w,l} L_l / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l], \quad (7)$$

where L_l is proportion of legal crabs for length class l, estimated from the observer data, and $S_{w,l}$ is winter selectivity for pots for length class l. Based on winter pot survey data, winter selectivities for length classes 3-5 were assumed to be one, and $S_{w,1}$, $S_{w,2}$ and $S_{w,6}$ were estimated as parameters.

The subsistence fishery does not have a size limit, but crabs with size smaller than length class 3 are generally not retained. So, we estimated length compositions of subsistence catch as follow when $l > 2$:

$$P_{p,n,l,t} = N_{w,l,t} S_{w,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l}],$$
$$P_{p,o,l,t} = O_{w,l,t} S_{w,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l}]. \quad (8)$$

Estimated length compositions of winter pot survey for newshell and oldshell crabs, $P_{sw,n,l,t}$ and $P_{sw,o,l,t}$, were also based on equation (7) except that $l \geq 1$.

Estimated length/shell condition compositions of the summer commercial catch were based on summer population, selectivity, and legal abundance:

$$P_{s,n,l,t} = N_{s,l,t} S_{s,l} L_l / A_t,$$
$$P_{s,o,l,t} = O_{s,l,t} S_{s,l} L_l / A_t, \quad (9)$$

where $S_{s,l}$ is pot selectivity for the summer commercial fishery, and A_t is exploitable legal abundance in year t. $S_{s,l}$ was described by a logistic function with parameters ϕ and ω:

$$S_{s,l} = \frac{1}{1+e^{-\phi(l-\omega)}}. \quad (10)$$

$S_{s,l}$ was scaled such that $S_{s,5} = 1$ and $S_{s,6} \leq 1$. Two sets of parameters (ϕ_1, ω_1) and (ϕ_2, ω_2) were estimated for selectivities before 1993 and after 1992 to reflect the vessel changes and pot limits. To correct the bias of the residuals, $S_{s,6}$ was set to $0.6*S_{s,5}$ for the period after 1992. Exploitable abundance was estimated as:

$$A_t = \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l} L_l]. \quad (11)$$

Summer fishing effort (f_t) measured as the number of pot-lifts was estimated as total summer catch, C_t, divided by the product of catchability q and mean exploitable abundance:

$$f_t = C_t / [q(A_t - 0.5C_t)]. \quad (12)$$

Because of the change in the fishing fleet and pot limit in 1993, q was replaced by q_1 for fishing efforts before 1993 and by q_2 after 1992. Estimated length/shell compositions of bycatch were:

$$P_{b,n,l,t} = N_{s,l,t} S_{s,l}(1-L_l) / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l}(1-L_l)],$$
$$P_{b,o,l,t} = O_{s,l,t} S_{s,l}(1-L_l) / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l}(1-L_l)]. \quad (13)$$

The same selectivity for the summer commercial fishery was applied to the summer pre-season survey, resulting in estimated length compositions for both newshell and oldshell crabs as:

$$P_{sf,n,l,t} = N_{s,l,t} S_{s,l} / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l}],$$
$$P_{sf,o,l,t} = O_{s,l,t} S_{s,l} / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l}]. \quad (14)$$

Estimated length/shell condition compositions of summer pot survey abundance were:

$$P_{sp,n,l,t} = N_{s,l,t} S_{sp,l} / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{sp,l}],$$
$$P_{sp,o,l,t} = O_{s,l,t} S_{sp,l} / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{sp,l}] \quad (15)$$

where $S_{sp,l}$ = 1 when $l \geq 3$, and $S_{sp,1}$ and $S_{sp,2}$ were estimated as two parameters. Similarly, length/shell condition compositions of summer trawl survey abundance were estimated with selectivity $S_{st,l}$= 1 when $l \geq 3$, and $S_{st,1}$ and $S_{st,2}$ were two parameters. Because some trawl surveys occurred during the molting period, we combined the length compositions of newshell and oldshell crabs as one single shell condition, $P_{st,l,t}$.

Parameters Estimated Independently

The following parameters were estimated independently: natural mortality (M_1-M_5=0.18 and M_6=0.216), proportions of legal males by length group, and the growth matrix. Natural mortality is based on an assumed maximum age of 25 and the 1% rule (Zheng 2005). Tagging data were used to estimate mean growth increment per molt and standard deviation for each pre-molt length class (Table 3). The growth matrix was derived from normal distributions generated with estimated mean growth increments per molt and standard deviations (Table 3). Observed growth increments per molt are approximately normally distributed. Proportions of legal males by length group were estimated from the observer data (Table 4).

Parameters Estimated Conditionally

Estimated parameters are listed in Table 5. Selectivities and molting probabilities based on these estimated parameters are summarized in Table 4.

A likelihood approach was used to estimate parameters, which include fishing catchability, parameters for selectivities of survey and fishing gears and for molting probabilities, recruits each year except the first and the last, and total abundance in the first year (Table 5). Under assumptions that measurement errors of annual total survey abundances and summer commercial fishing efforts follow lognormal distributions and each type of length compositions has a multinomial error structure (Fournier and Archibald 1982; Methot 1989), the log-likelihood function is:

$$\sum_{i=1}^{i=6}\sum_{t=1}^{t=n_i}\{K_{i,t}\sum_{l=1}^{l=6}[\hat{P}_{i,l,t}\, ln(P_{i,l,t}+\kappa)]\} - \sum_{i=1}^{i=2}\{W_i\sum_{k=1}^{k=2}\sum_{t=1}^{t=n_i}[ln(\hat{B}_{i,k,t}+\kappa) - ln(B_{i,k,t}+\kappa)]^2\}$$
$$- W_f\sum_{t=1}^{t=32}[ln(\hat{f}_t+\kappa) - ln(f_t+\kappa)]^2 - W_R\sum_{t=1}^{t=32}\tau_t^2, \quad (16)$$

where i stands for a data set: 1 for summer trawl survey, 2 for summer pot survey, 3 for winter pot survey, 4 for summer pre-season survey, 5 for summer fishery, and 6 for observer data during the summer fishery; n_i is the number of years in which data set i is available; $k = 1$ stands for legal crabs and $k = 2$ for non-legal crabs; $K_{i,t}$ is the effective sample size of length compositions for data set i in year t; $\hat{p}_{i,l,t}$ and $P_{i,l,t}$ are observed and estimated length compositions for data set i, length class l, and year t; κ is a constant equal to 0.001; W_i is the weighting factor of annual total survey abundance for data set i; $\hat{B}_{i,k,t}$ and $B_{i,k,t}$ are observed and estimated annual total abundances for data set i and year t; W_f is the weighting factor of the summer fishing effort; $\hat{f}_t$ and f_t are observed and estimated summer fishing efforts; and W_R is the weighting factor of recruitment. It is generally believed that total annual commercial crab catches in Alaska are fairly accurately reported. Thus, no measurement error was imposed on total annual catch. Variances for total survey abundances and summer fishing effort were not estimated; rather, we used weighting factors to reflect these variances.

Crabs usually aggregate, and this increases the uncertainty in survey estimates of abundance. To reduce the effect of aggregation, annual total sample sizes for summer trawl and pot survey data sets were reduced to 50% and all other sample sizes were reduced to 10%. Also, annual effective sample sizes were capped at 400 to avoid overweighting the data with a large sample size (Fournier and Archibald 1982). Weighting factors represent prior assumptions about the accuracy or the variances of the observed data or random variables. W_i was set as 200 for all survey abundances, W_f was set to be 100, or 50% of W_i, and W_R was set to be 0.01. According to the fishery manager, the fishing effort in 1992 was not as reliable as in the other years (C. Lean, ADF&G, personal communication). Thus, we weighted the effort in 1992 half as much as in the other years. Sensitivity of estimated legal abundance to changes in W_i, W_f and maximum effective sample size was investigated.

We estimated parameters with AD Model Builder (Otter Research Ltd. 1994) using the quasi-Newton method to minimize negative likelihood values. To reduce the number of parameters, we assumed that length and shell compositions from the first year (1976) summer trawl survey data approximate true relative compositions. Abundances by length and shell condition in all other years were computed recursively from abundances by length and shell condition in the first year and by annual recruitment, catch, and model parameters. Initial parameter estimates were an educated guess based on observation and current knowledge.

Results

Abundance and Parameter Estimates

The model fit well to observed sublegal and legal male trawl abundances except in 1979 when the trawl survey greatly underestimated the crab abundance (Figure 2). Estimated fishing effort for the summer commercial fishery was very similar to, but smoother than, observed fishing effort in most years (Figure 2). This close fit between the observed effort and the model effort, which is calculated from catch and abundance data, indicates that the CPUE of the summer commercial fishery is closely associated with the estimated legal abundance.

The residuals of length compositions were generally large, except for the summer pot survey (Figures 3 and 4). The large residuals for the trawl survey are probably due to small sample sizes; all trawl surveys except in 1976 caught less than 200 legal crabs. The large residuals for the winter pot surveys and observer data also occurred in those years with a small sample size. The likelihood function placed less weight to those data with a small sample size. The sample sizes for the summer commercial fishery were large for most years; the large residuals may indicate a large sampling error. Residuals were generally uncorrelated among years and for length classes with two exceptions: (1) residuals of length classes for the winter pot surveys were generally negative for large length classes and positive for small length classes from 1981 to 1986, and (2) residuals of length class 6 for the summer trawl survey were mostly negative. These patterns could be modeled by increasing selectivity parameters. However, because the population abundance estimates are unaffected, we chose not to increase the number of model parameters to account for them.

Selectivities for both summer trawl and pot surveys were very close to each other; both were higher than for the summer commercial pot fishery (Table 4). The winter pot surveys caught a small number of crabs in the last length class. A small proportion of crabs belonged to legal crabs in length class 3, and almost all crabs in the last three length classes were legal crabs (Table 4). Here the proportion of legal crabs was only used to separate retained catch in the observer data. For the purpose of this study, legal crab abundance was the sum of abundances in the last three length classes.

Population abundances were very high in the late 1970s and low in the early 1980s and mid 1990s (Figure 5). Due to lack of commercial fishing, the abundance in the late 1970s was close to the pristine condition. Recruitment fluctuated greatly during the past 3 decades. Estimated recruitment was weak during the late 1970s and high during the early 1980s with a slightly downward trend from 1983 to 1993. Estimated recruitment was strong during the recent years (Figure 5; Table 5). High harvest rates (>25%) from the summer fishery occurred from 1979 to 1981, and since then estimated harvest rates have been below 20% (Figure 6). Estimated harvest rates during the last 10 years were below 15% (Figure 6).

Standard deviations of estimated parameters and abundances were artificially small except for those of recruitment estimates. Coefficients of variation for recruitment estimates were up to 71%, whereas coefficients of variation for other parameters and legal crab abundance estimates were below 11%. Such small standard deviations may partially be caused by the assumptions made in the model and a small number of survey abundances available to estimate catchabilities of the commercial fishing gear. AD Model Builder may also underestimate the standard deviations.

Zheng et al. (1998) examined sensitivity of weighting factors and concluded that estimates of parameters and legal crab abundance were not very sensitive to weighting factors for survey abundances and fishing effort, and maximum effective sample size. Zheng et al. (1998) assumed M = 0.3. With the low *M* value in this report, the model would not fit the shell condition data very well. We combined all shell condition data in this report. Increasing *M* from 0.18 to 0.22 would result in the best fit of the data (Figure 7). Estimates of legal male abundance and mature male biomass in 2008 decreased from $M = 0.18$ to $M = 0.22$, increased until $M = 0.26$ and then decreased again when *M* continued to increase (Figure 7).

Retrospective Analyses

Two kinds of retrospective analyses are presented in this report: (1) historical results and (2) the 2008 model results. The historical results are the trajectories of biomass and abundance from previous assessments that capture both new data and changes in methodology over time. Assuming the estimates in 2008 to be baseline values, we can also evaluate how well the model has done in the past. The 2008 model results are based on leaving one-year data out at a time to evaluate how well the current model performs with less data.

Several biologists conducted the stock assessments of Norton Sound red king crab using this model during the last 10 years. Complete historical results were not available. The estimated legal male abundances in terminal years from 1999 to present were available and were graphed to compare the results made in 2008 (Figure 8). The 2005 result was omitted in this report because it was most likely affected by a data input error. The historical results in 2001, 2002, 2003, and 2007 were very close to those made in 2008 and quite different in 1999, 2004 and 2006 (Figure 8). Note that large differences happened in years when the last trawl survey occurred two to four years prior. These errors were due to terminal years as well as lack of trawl surveys in the previous one to three years. The complete 2006 results were available and compared with those made in 2008 (Figure 8). Despite additional data and changes in the model fitting, estimated legal male abundance and mature male biomass were very close except during 2004-2006 (Figure 8).

Because no trawl survey was conducted prior to the abundance estimate before the summer fishery, the abundance estimate in a terminal year is like a one-year-ahead projection. Therefore, performance of the 2008 model includes leaving out data as well as one-year-ahead projection. The model performed very well except the estimates in the early 2000s and mid 2000s made with terminal years 2001, 2002, 2004, 2005 and 2006 (Figure 9). Like the historical results, the years with a large difference were without a trawl survey one year earlier. The average relative error from 2000 to 2007 was 25.7% for estimated legal male abundance and 28.0% for estimated mature male biomass.

The large projection errors were mainly due to data conflicts between the trawl survey and the winter pot survey. Based on modal progressions of length frequencies from the winter pot survey, strong year classes were observed to go through the population during 1996-1999 and 2002-2006 (Figure 10), yet legal abundance estimates from trawl surveys in 2002 and 2006 were unexpectedly low. In years without trawl survey data, winter pot survey data played an important role in projecting population abundances. Trawl survey data were weighted more heavily than winter pot survey data, and in years when trawl survey data were available, they influenced abundance estimates greatly. Because a trawl survey was conducted every three or four years, measurement errors from a single trawl survey could affect the model results greatly. It is hard to determine whether the large projection errors were due to sampling errors in winter pot surveys or measurement errors in summer trawl surveys.

Overfishing Limits for 2008

The Norton Sound red king crab stock is currently placed in Tier 4 (NPFMC 2007). For Tier 4 stocks, some abundance estimates are available, but complete population parameters are not available for computer simulation studies and spawning biomass per recruit analyses needed for Tier 3 stocks. Average of estimated biomasses for a given period is used to develop a B_{MSY}

proxy for Tier 4 stocks. We evaluated averages of mature male biomasses from three periods for the B_{MSY} proxy: 1976-2008, 1980-2008 and 1983-2008 (Figure 11).

Besides B_{MSY} proxy, a γ value is also needed to be determined. NPFMC (2007) sets the default γ for Tier 4 king crab stocks to be the ratio of $F_{35\%}$ to M based on the results of Bristol Bay Red king crab. This ratio is 1.844 (0.332/0.18) from the 2008 assessment results of Bristol Bay red king crab. Because Norton Sound red king crab occur at the edge of the distributional range for this species and historically the harvest rates were lower than those in Bristol Bay, we consider Norton Sound red king crab to sustain a lower exploitation rate than Bristol Bay red king crab. Therefore, we evaluated two γ values that are lower than the ratio of $F_{35\%}$ to M for setting overfishing limits for 2008: $\gamma = 1$ and $\gamma = 1.5$.

Estimated B_{MSY} proxy:

Based on average during 1976-2008: 4.328 million lbs,

Based on average during 1980-2008: 3.513 million lbs,

Based on average during 1983-2008: 3.567 million lbs.

Estimated F_{MSY} proxy:

$\gamma = 1$: 0.18,

$\gamma = 1.5$: 0.27.

Estimated mature male biomass in 2008 was 5.240 million lbs (Figure 12), above all three B_{MSY} proxies. Because the population was at a near pristine condition in the late 1970s, we should not use the mature biomasses during that period for B_{MSY} proxy. Year classes after the 1976/77 regime shift (Overland et al. 1999) were expected to reach the mature population after 1982, and thus the average of mature biomasses during 1983-2008 is appropriate for B_{MSY} proxy. Because a trawl survey was conducted only every three or four years, abundance estimates are very uncertain. Therefore, a conservative γ (=1) should be used to set the overfishing limits.

With B_{MSY} proxy = 3.567 million lbs, F_{MSY} proxy = 0.18 (γ=1), B = 5.240 million lbs in 2008, legal male abundance = 1.4932 million crabs or 4.1162 million lbs in 2008, the overfishing limits for retained catch in 2008 are 0.2460 million crabs or 0.6781 million lbs. The average weight for legal crabs is approximate and may need to be adjusted based on the actual mean weight of the catch.

Acknowledgments

We thank Doug Woodby, Shareef Siddeek, and James Menard of ADF&G for reviewing the earlier draft of this report. The study was funded, in part, by cooperative agreement from the National Oceanic and Atmospheric Administration (NOAA). The views expressed are those of the authors and do not necessarily reflect the views of NOAA or any of its sub-agencies.

References

Alverson, D.L., and W.T. Pereyra. 1969. Demersal fish in the Northeastern Pacific Ocean - an evaluation of exploratory fishing methods and analytical approaches to stock size and yield forecasts. J. Fish. Res. Board Can. 26:1985-2001.

Balsiger, J.W. 1974. A computer simulation model for the eastern Bering Sea king crab. Ph.D. thesis, Univ. Washington, Seattle, WA. 197 pp.

Banducci, A., T. Kohler, J. Soong, and J. Menard. 2007. 2005 Annual management report Norton Sound, Port Clarence, and Kotzebue. Alaska Department of Fish and Game, Divisions Sport Fish and Commercial Fisheries. Fishery Management Report No. 07-32. 194 pp.

Brannian, L.K. 1987. Population assessment survey for red king crab (*Paralithodes camtschatica*) in Norton Sound, Alaska, 1985. Alaska Dept. Fish and Game, Tech. Data Rep. 214. 51 pp.

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

Methot, R.D. 1989. Synthetic estimates of historical abundance and mortality for northern anchovy. Amer. Fish. Soc. Sym. 6:66-82.

North Pacific Fishery Management Coucil (NPFMC). 2007. Environmental assessment for proposed amendment 24 to the fishery management plan for Bering Sea and Aleutian Islands king and Tanner crabs to revise overfishing definitions. Public review draft.

Otter Research Ltd. 1994. An introduction to AD Model Builder: for use in nonlinear modeling and statistics. Otter Research Ltd., Nanaimo, B.C., Canada. 44 pp.

Overland, J.E., J.M. Adams, and N.A. Bond. 1999. Decadal variability of the Aleutian Low and its relation to high-latitude circulation. Journal of Climate 12:1542-1548.

Powell, G.C., R. Peterson, and L. Schwarz. 1983. The red king crab, *Paralithodes camtschatica* (Tilesius), in Norton Sound, Alaska: History of biological research and resource utilization through 1982. Alaska Dept. Fish and Game, Inf. Leafl. 222. 103 pp.

Soong, J. 2007. Norton Sound winter red king crab studies, 2007. Alaska Department of Fish and

Game, Fishery Data Series No. 07-53, Anchorage.

Soong, J., and A. O. Banducci. 2006. Analysis of red king crab data from the 2006 Alaska Department of Fish and Game trawl survey of Norton Sound. Alaska Department of Fish and Game, Fishery Data Series No. 06-55, Anchorage.

Soong, J., S.K. Kent, and J. Menard. *In prep.* 2006 Annual management report Norton Sound, Port Clarence, and Kotzebue. Alaska Department of Fish and Game, Divisions Sport Fish and Commercial Fisheries. Fishery Management Report No. 08-XX.

Stevens, B.G., and R.A. MacIntosh. 1986. Analysis of crab data from the 1985 NMFS survey of the northeast Bering Sea and Norton Sound. Northwest and Alaska Fisheries Science Center, Processed Rep. 86-16. National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, WA 98115, USA. 35 pp.

Zheng, J. 2005. A review of natural mortality estimation for crab stocks: data-limited for every stock? Pages 595-612 *in* G.H. Kruse, V.F. Gallucci, D.E. Hay, R.I. Perry, R.M. Peterman, T.C. Shirley, P.D. Spencer, B. Wilson, and D. Woodby (eds.). Fisheries Assessment and Management in Data-limite Situation. Alaska Sea Grant College Program, AK-SG-05-02, Fairbanks.

Zheng, J., G.H. Kruse, and L. Fair. 1998. Use of multiple data sets to assess red king crab, *Paralithodes camtschaticus*, in Norton Sound, Alaska: A length-based stock synthesis approach. Pages 591-612 *In* Fishery Stock Assessment Models, edited by F. Funk, T.J. Quinn II, J. Heifetz, J.N. Ianelli, J.E. Powers, J.F. Schweigert, P.J. Sullivan, and C.-I. Zhang, Alaska Sea Grant College Program Report No. AK-SG-98-01, University of Alaska Fairbanks.

Table 1. Historical summer commercial red king crab fishery economic performance, Norton Sound Section, eastern Bering Sea, 1977-2007.

Year	Guidline Harvest Level (lbs) [b]	Legal Male Population Est. No. crab (millions)	lbs [b]	Commercial Harvest (lbs) [a] Open Access	CDQ	Total Number (incl. CDQ) Vessels	Permits	Landings	Total Number of Registered	Pulls	Total Exvessel Price/lb	Total Fishery Value (millions $)	Season Length Days	Dates
1977	[c]	1.7	5.1	0.52		7	7	13	[c]	5,457	0.75	0.229	60	[c]
1978	3.00			2.09		8	8	54	[c]	10,817	0.95	1.897	60	6/07-
1979	3.00	0.8	2.4	2.93		34	34	76	[c]	34,773	0.75	1.878	16	7/15-
1980	1.00	1.9	5.7	1.19		9	9	50	[c]	11,199	0.75	0.890	16	7/15-
1981	2.50	1.2	3.6	1.38		36	36	108	[c]	33,745	0.85	1.172	38	7/15-
1982	0.50	0.9	2.7	0.23		11	11	33	[c]	11,230	2.00	0.405	23	8/09-
1983	0.30			0.37		23	23	26	3,583	11,195	1.50	0.537	3.8	8/01-
1984	0.40			0.39		8	8	21	1,245	9,706	1.02	0.395	13.6	8/01-
1985	0.45	1.1	3.3	0.43		6	6	72	1,116	13,209	1.00	0.427	21.7	8/01-
1986	0.42			0.48		3	3	[c]	578	4,284	1.25	0.600	13	8/01- [d]
1987	0.40			0.33		9	9	[c]	1,430	10,258	1.50	0.491	11	8/01-
1988	0.20	1.0	3.0	0.24		2	2	[c]	360	2,350	[c]	[c]	9.9	8/01-
1989	0.20			0.25		10	10	[c]	2,555	5,149	3.00	0.739	3	8/01-
1990	0.20			0.19		4	4	[c]	1,388	3,172	[c]	[c]	4	8/01-
1991	0.34	1.3	3.9			No Summer Fishery								
1992	0.34			0.07		27	27	[c]	2,635	5,746	1.75	0.130	2	8/01-
1993	0.34			0.33		14	20	208	560	7,063	1.28	0.430	52	7/01- [e]
1994	0.34			0.32		34	52	407	1,360	11,729	2.02	0.646	31	7/01-
1995	0.34			0.32		48	81	665	1,900	18,782	2.87	0.926	67	7/01-
1996	0.34	0.5	1.5	0.22		41	50	264	1,640	10,453	2.29	0.519	57	7/01- [f]
1997	0.08			0.09		13	15	100	520	2,982	1.98	0.184	44	7/01- [g]
1998	0.08			0.03	0.00	8	11	50	360	1,639	1.47	0.041	65	7/01- [h]
1999	0.08	1.6	4.8	0.02	0.00	10	9	53	360	1,630	3.08	0.073	66	7/01- [i]
2000	0.33	1.4	4.2	0.29	0.01	15	22	201	560	6,345	2.32	0.715	91	7/01- [j]
2001	0.30	1.3	3.8	0.28	0.00	30	37	319	1,200	11,918	2.34	0.674	97	7/01- [k]
2002	0.24	1.0	3.1	0.24	0.01	32	49	201	1,120	6,491	2.81	0.729	77	6/15- [l]
2003	0.25	1.0	3.1	0.25	0.01	25	43	236	960	8,494	3.09	0.823	68	6/15- [m]
2004	0.35	1.6	4.4	0.31	0.03	26	39	227	1,120	8,066	3.12	1.063	51	6/15- [n]
2005	0.37	1.7	4.8	0.37	0.03	31	42	255	1,320	8,867	3.14	1.264	73	6/15- [o]
2006	0.45	1.6	4.5	0.42	0.03	28	40	249	1,320	8,695	2.26	1.021	68	6/15- [n]

[a] Deadloss included

[b] Millions of pounds.

[c] Information not

[d] Fishing actually began 8/12.

[e] Fishing actually began 7/8.

[f] Fishing began 7/9 due to fishers'

[g] First delivery was made 7/10.

[h] First delivery was made

[i] The season was extended 24 hours

[j] Open access (OA) closed 8/29. CDQ

[k] OA closed 9/1. CDQ opened from

[l] OA opened 7/1 - 8/6. CDQ opened 6/15-6/28 and

[m] OA opened 7/1 - 8/13. CDQ opened 6/15-6/28 and

[n] CDQ opened 6/15-6/28. OA opened 7/1 to the end

[o] OA opened 7/1 - 8/15. CDQ opened 6/15-

Table 2. Summary of available data for Norton Sound male red king crab.

Data Set	Years	Data Types
Summer trawl survey	76,79,82,85,88,91,96, 99, 02,06	Abundance and prop. by length and shell condition
Summer pot survey	80-82,85	Abundance and prop. by length and shell condition
Winter pot survey	81-87, 89-91,93,95-00,02-08	Proportion by length and shell condition
Summer preseason survey	95	Proportion by length and shell condition
Summer commercial fishery	76-90,92-07	Catch, effort, and prop. by length and shell condition
Observer data	87-90,92,94	Proportion by length and shell condition
Winter commercial fishery	76-08	Catch
Subsistence fishery	76-08	Catch
Tagging data	80-91	Mean and standard deviation of growth increment

Table 3. Means and standard deviations (SD) of growth increments per molt and growth matrix (proportion of crabs molting from a given premolt carapace length range into postmolt length ranges) for Norton Sound male red king crab. Length is measured as mm CL. Results are derived from mark-recapture data from 1980 to 1991.

Pre-molt	Growth Increment (mm)		Post-molt Length Class					
Length Class	Mean	STDEV	74-83	84-93	94-103	104-113	114-123	124+
74-83	14.50	3.344	0.01	0.54	0.45	0	0	0
84-93	14.50	3.344	0	0.01	0.54	0.45	0	0
94-103	14.09	2.685	0	0	0.01	0.58	0.41	0
104-113	13.35	2.795	0	0	0	0.01	0.65	0.35
114-123	11.35	2.192	0	0	0	0	0.03	0.97
124+	11.35	2.192	0	0	0	0	0	1.00

Table 4. Estimated selectivities, molting probabilities, and proportions of legal crabs by length (mm CL) class for Norton Sound male red king crab.

			Selectivities					Molt. Prob.
Length Class	Length Range	Proportion of Legals	Summer Trawl	Summer Pot Surv	Winter Pot Surv	Summer Fishery 77-92	93-07	All Years
1	74 - 83	0.00	0.90	0.80	0.80	0.30	0.20	1.00
2	84 - 93	0.00	1.00	0.80	1.00	0.47	0.33	0.87
3	94 - 103	0.15	1.00	1.00	1.00	0.67	0.52	0.67
4	104 - 113	0.92	1.00	1.00	1.00	0.86	0.75	0.43
5	114 - 123	1.00	1.00	1.00	1.00	1.00	1.00	0.23
6	>123	1.00	1.00	1.00	0.31	1.00	0.60	0.10

Table 5. Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab. Recruits R and N_{76} are in million crabs. Total number of free parameters: 49.

Parameter	Value	Parameter	Value	Data Component	Neg.Likelihood Value
N_{76}	5.5809	q_1	1.6031E-05	Trawl immat. indices	67.080
R_{76}	NA	q_2	1.5464E-05	Trawl mat. indices	342.684
R_{77}	0.0002	r	0.6098	Pot immat. indices	40.071
R_{78}	0.0002	α	0.0891	Pot mat. indices	122.201
R_{79}	0.2302	β	103.6272	Total effort	434.185
R_{80}	1.0515	$S_{st,1}$	0.9000	Trawl length compos.	2258.730
R_{81}	0.4078	$S_{st,2}$	1.0000	Pot length compos.	2569.830
R_{82}	0.7891	$S_{sp,1}$	0.8000	Winter length compos.	3819.950
R_{83}	0.9727	$S_{sp,2}$	0.8000	Summer length compos	7059.130
R_{84}	0.5390	$S_{w,1}$	0.8000	Pre-fishery length com.	310.742
R_{85}	0.2422	$S_{w,2}$	1.0000	Observed length comp.	553.780
R_{86}	0.5243	$S_{w,6}$	0.3078	Recruitment deviation	1.398
R_{87}	0.5319	ϕ_1	0.0670	Total	17579.781
R_{88}	0.4257	ω_1	95.6887		
R_{89}	0.2806	ϕ_2	0.0571		
R_{90}	0.1877	ω_2	114.8584		
R_{91}	0.1616				
R_{92}	0.1105				
R_{93}	0.1540				
R_{94}	0.5161				
R_{95}	0.4221				
R_{96}	0.4208				
R_{97}	1.0182				
R_{98}	0.0488				
R_{99}	0.0865				
R_{00}	0.9034				
R_{01}	0.4955				
R_{02}	0.7407				
R_{03}	0.1574				
R_{04}	0.4004				
R_{05}	1.6180				
R_{06}	0.8356				
R_{07}	0.9548				

Table 6. Annual abundance estimates (million crabs) and mature male biomass (MMB, million lbs) for Norton Sound red king crab estimated by length-based analysis from 1976-2008.

Year	Total (>73 mm)	Matures (>93 mm)	Legals (>103 mm)	MMB
1976	5.5950	4.8633	3.6343	11.1457
1977	4.7563	4.5394	3.9143	11.6665
1978	3.7666	3.7233	3.4686	10.4654
1979	2.5652	2.5602	2.4744	7.6627
1980	1.5171	1.3030	1.2784	4.0644
1981	1.9494	0.9051	0.8164	2.7715
1982	1.6774	0.9771	0.5529	2.3229
1983	2.0616	1.1714	0.7871	2.7925
1984	2.4954	1.3396	0.8962	3.1743
1985	2.4505	1.6313	1.0678	3.8162
1986	2.1310	1.7093	1.2405	4.1490
1987	2.1131	1.5324	1.2423	3.9522
1988	2.1582	1.4976	1.1951	3.9342
1989	2.1156	1.5430	1.2063	4.0540
1990	1.9338	1.5263	1.2154	4.0564
1991	1.7163	1.4419	1.2002	3.9386
1992	1.5521	1.3349	1.1640	3.7867
1993	1.3608	1.2025	1.0716	3.5094
1994	1.1585	0.9762	0.8798	2.9122
1995	1.3308	0.8015	0.7060	2.3931
1996	1.4001	0.8486	0.6197	2.2927
1997	1.4867	0.9522	0.6767	2.4408
1998	2.1417	1.0552	0.7756	2.6931
1999	1.8071	1.4417	0.9492	3.4912
2000	1.5652	1.4343	1.1562	3.7195
2001	2.0398	1.1703	1.0437	3.2667
2002	2.0635	1.3304	0.9632	3.4547
2003	2.3162	1.4502	1.0671	3.7056
2004	1.9891	1.6018	1.1632	4.0449
2005	1.9151	1.4695	1.1994	3.8891
2006	2.9711	1.3422	1.0972	3.6225
2007	3.1046	1.8316	1.1431	4.4005
2008	3.3649	2.1733	1.4932	5.2397

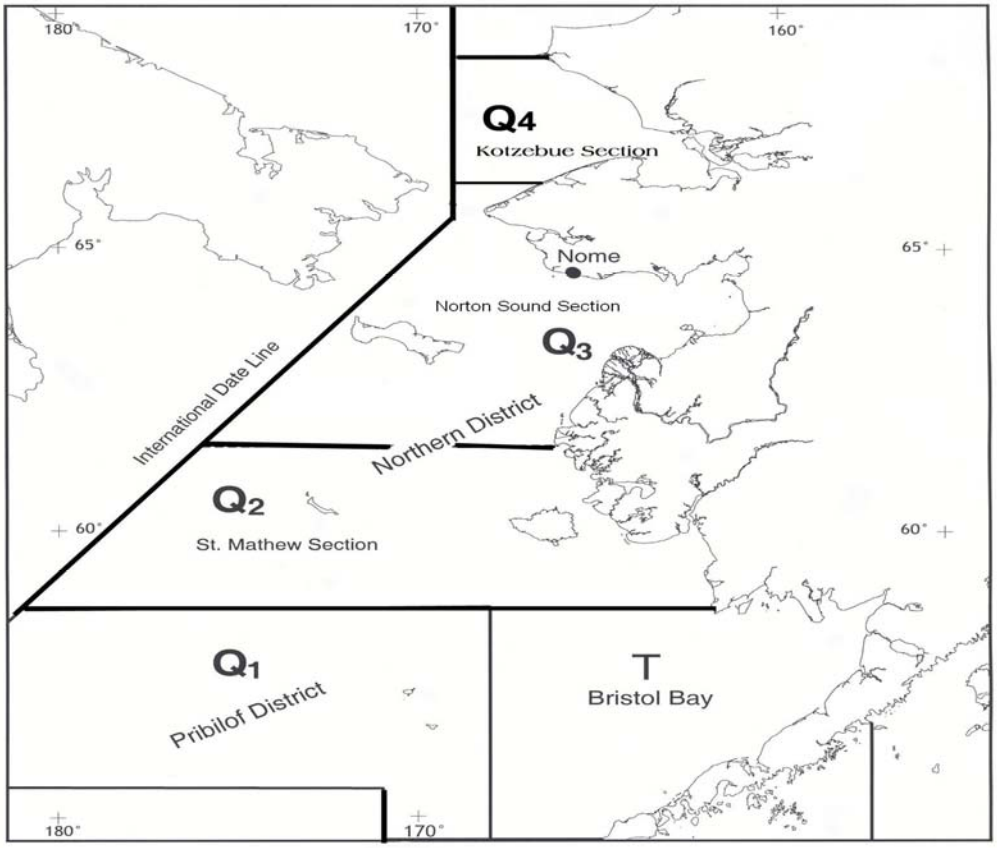


Figure 1. King crab fishing districts and sections of Statistical Area Q.

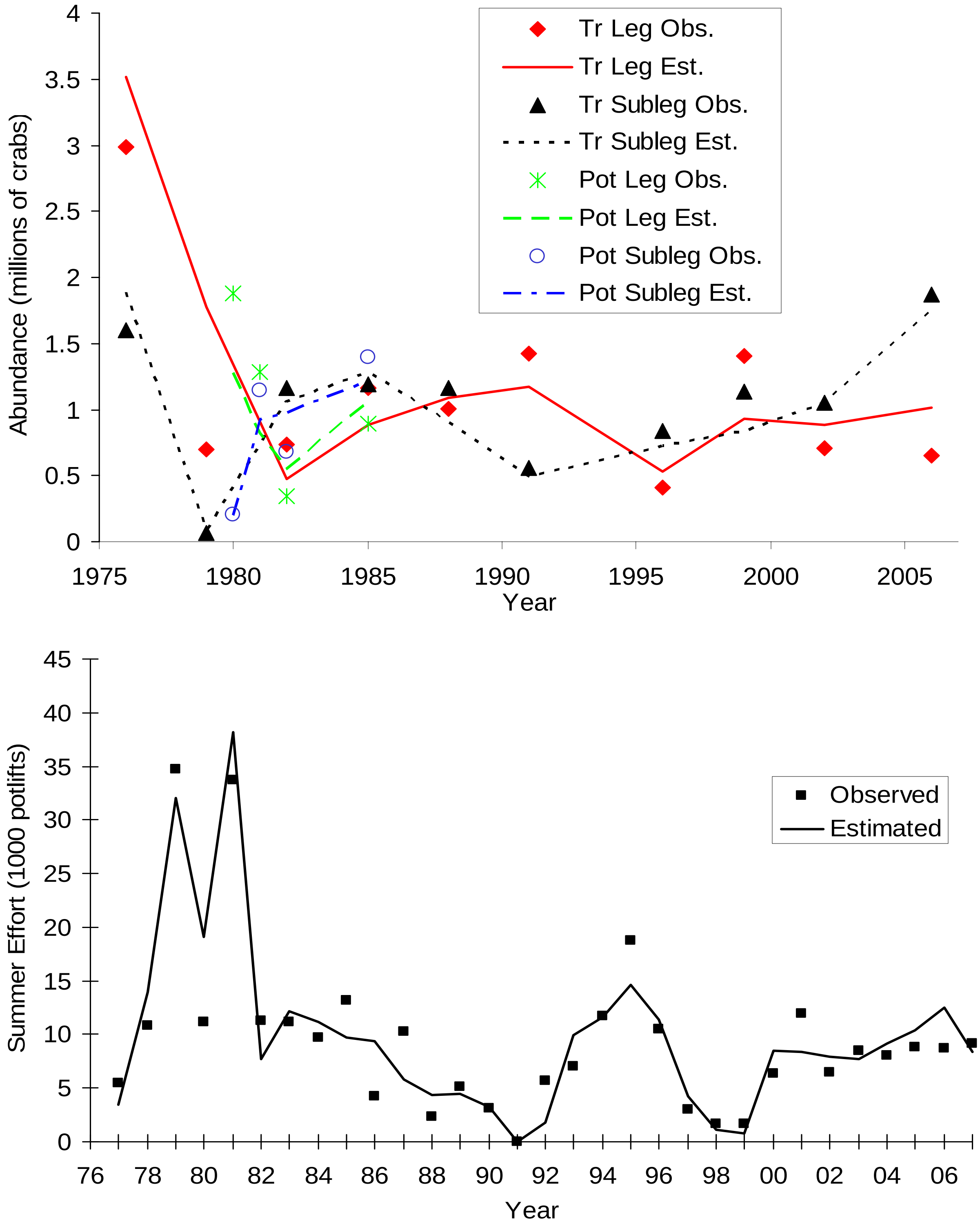


Figure 2. Comparison of observed and estimated Norton Sound red king crab abundances (legal and sublegal males) by summer trawl and pot surveys (upper plot) and observed and estimated summer fishing efforts (lower plot). "Tr" is trawl, "Leg" is legal, "Obs." is observed or survey catchable abundance, and "Est." is estimated catchable abundance. Catchable abundance is equal to population abundance times survey selectivities.

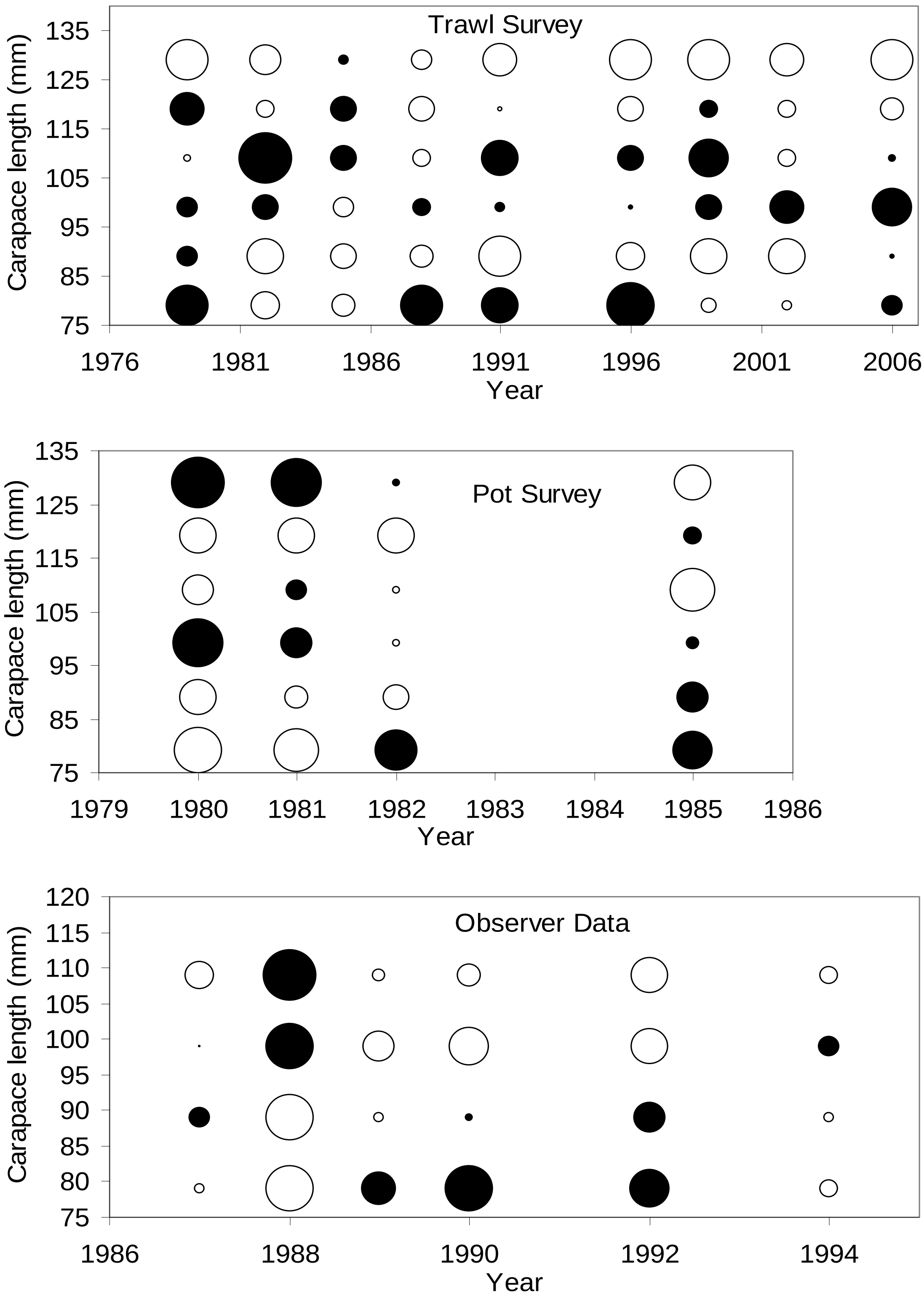


Figure 3. Residuals of length compositions by year for summer trawl and pot surveys and observer data for Norton Sound red king crab. Solid circles are positive residuals, and open circles are negative residuals.

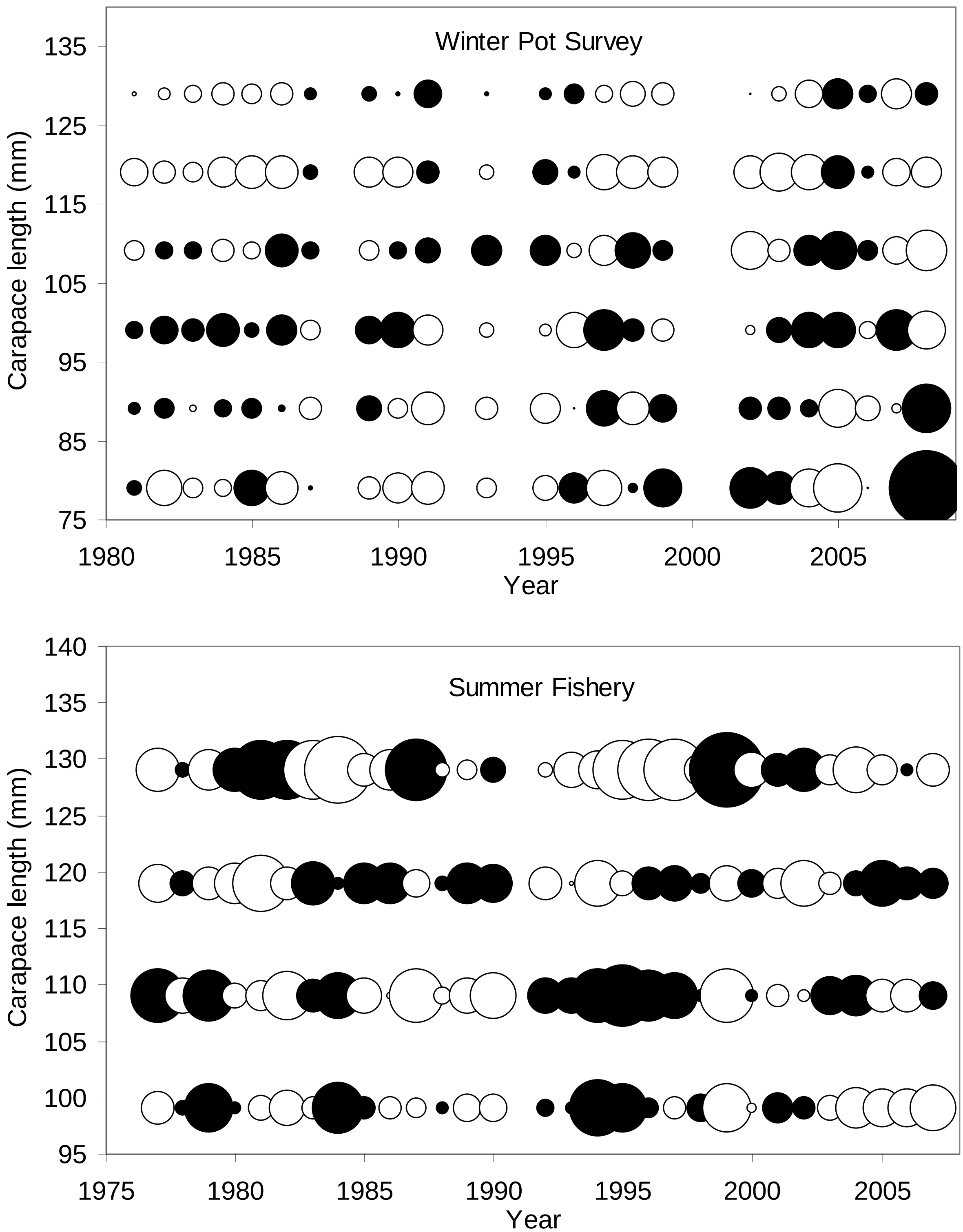


Figure 4. Residuals of length compositions by year for winter pot surveys and summer fishery for Norton Sound red king crab. Solid circles are positive residuals, and open circles are negative residuals.

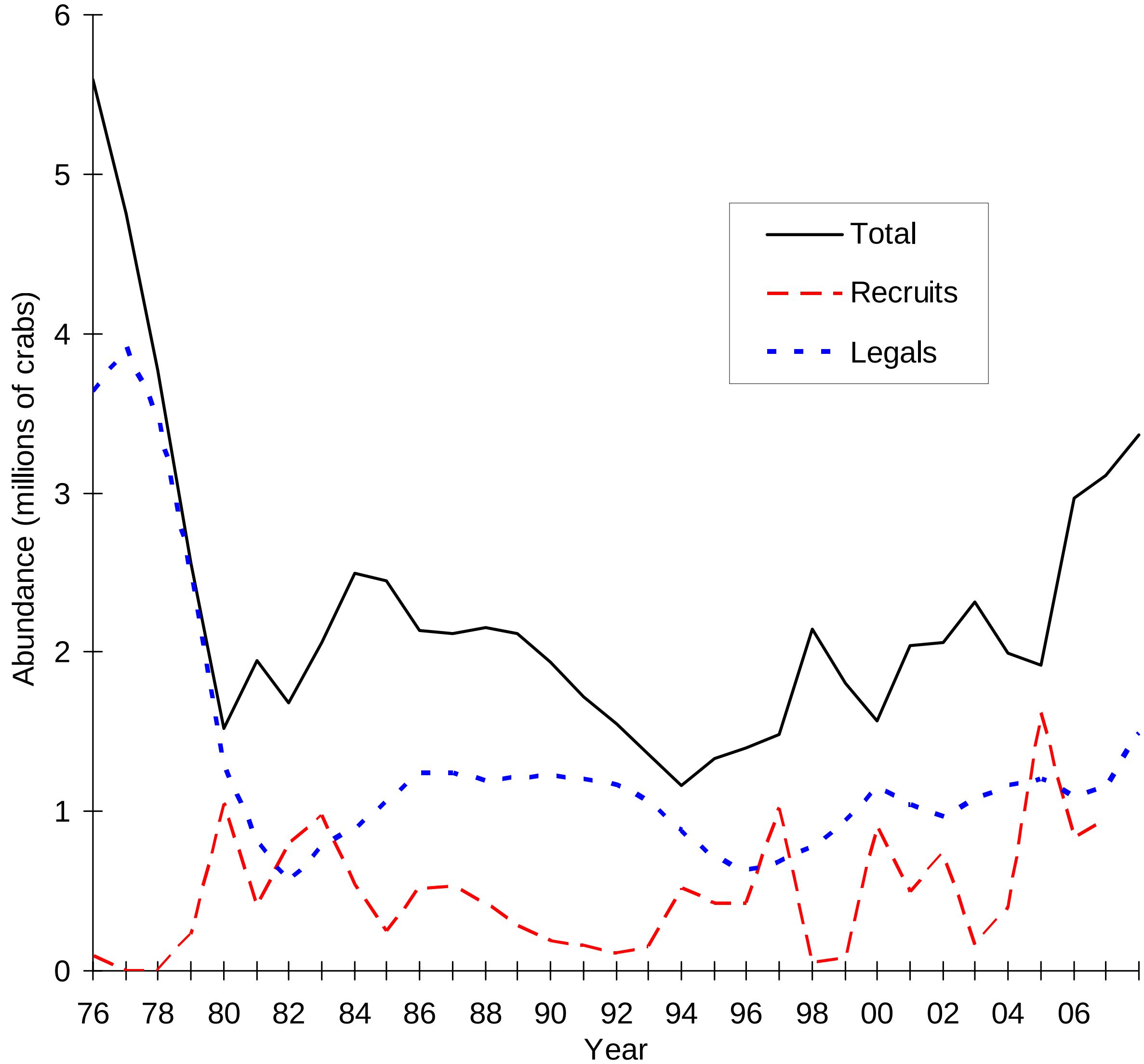
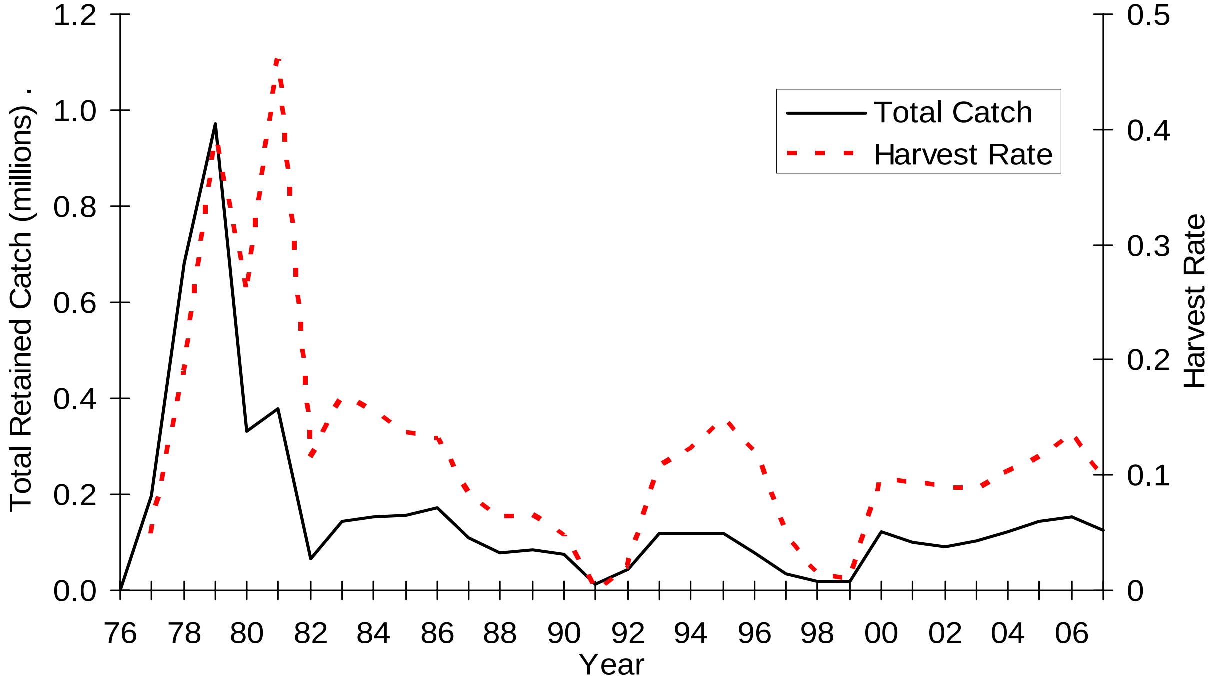


Figure 5. Estimated total (crabs>73 mm CL) and legal male abundances and recruits from 1976 to 2008.



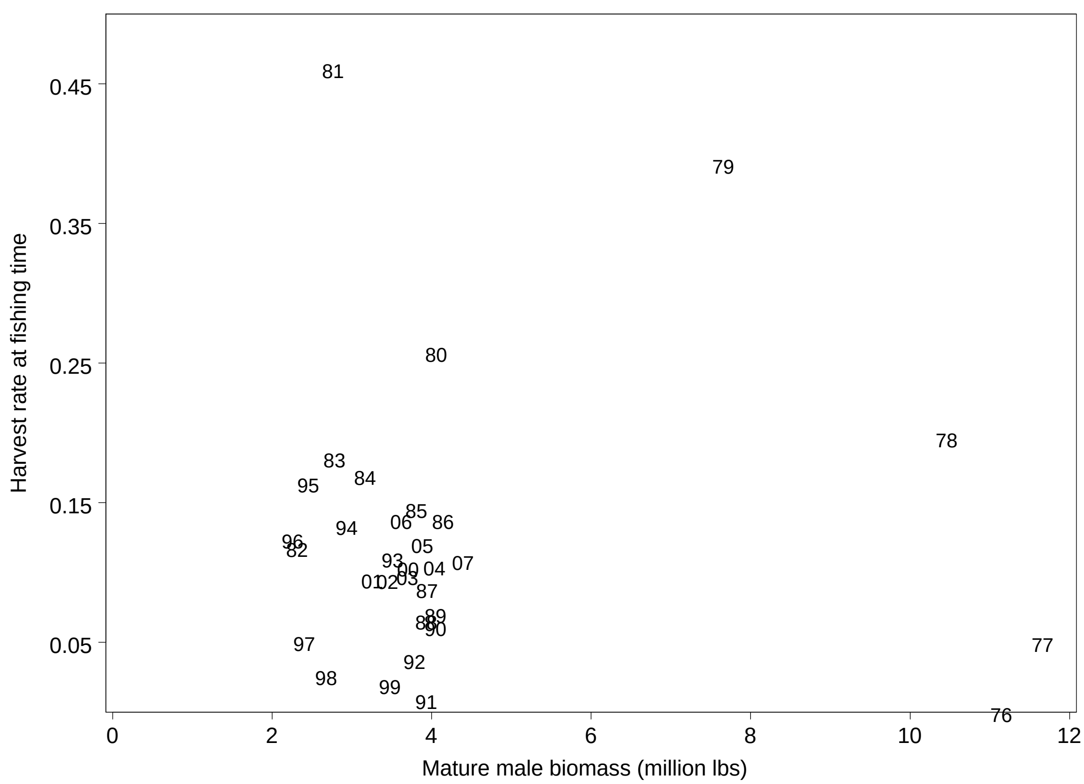


Figure 6. Total retained catches and harvest rates (upper plot) and relationship between harvest rates and mature male biomass (lower plot) of Norton Sound red king crab from July 1, 1976 to June 30, 2008.

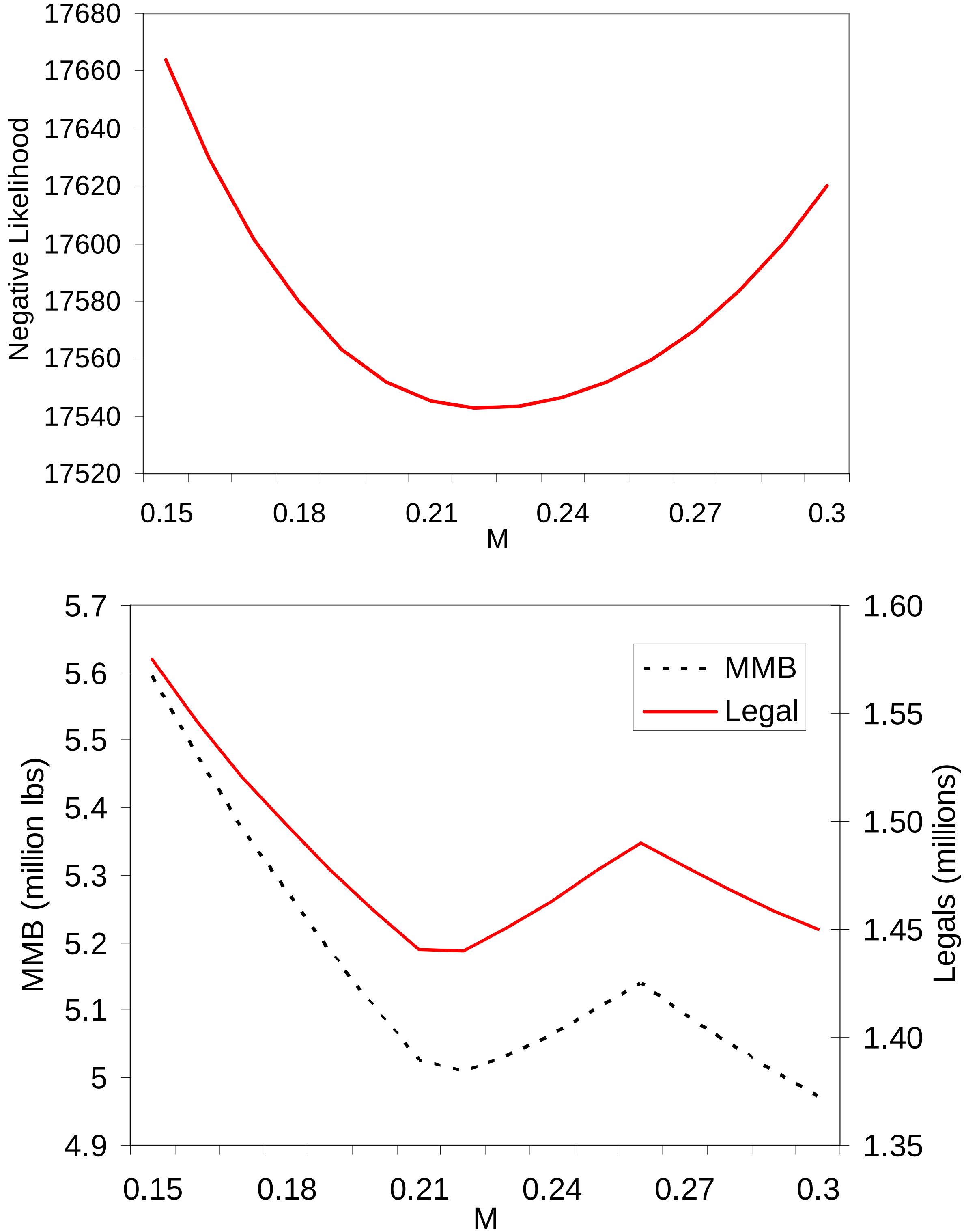


Figure 7. Likelihood profile for natural mortality and estimated legal abundance and mature male biomass in 2008 under different natural mortality values.

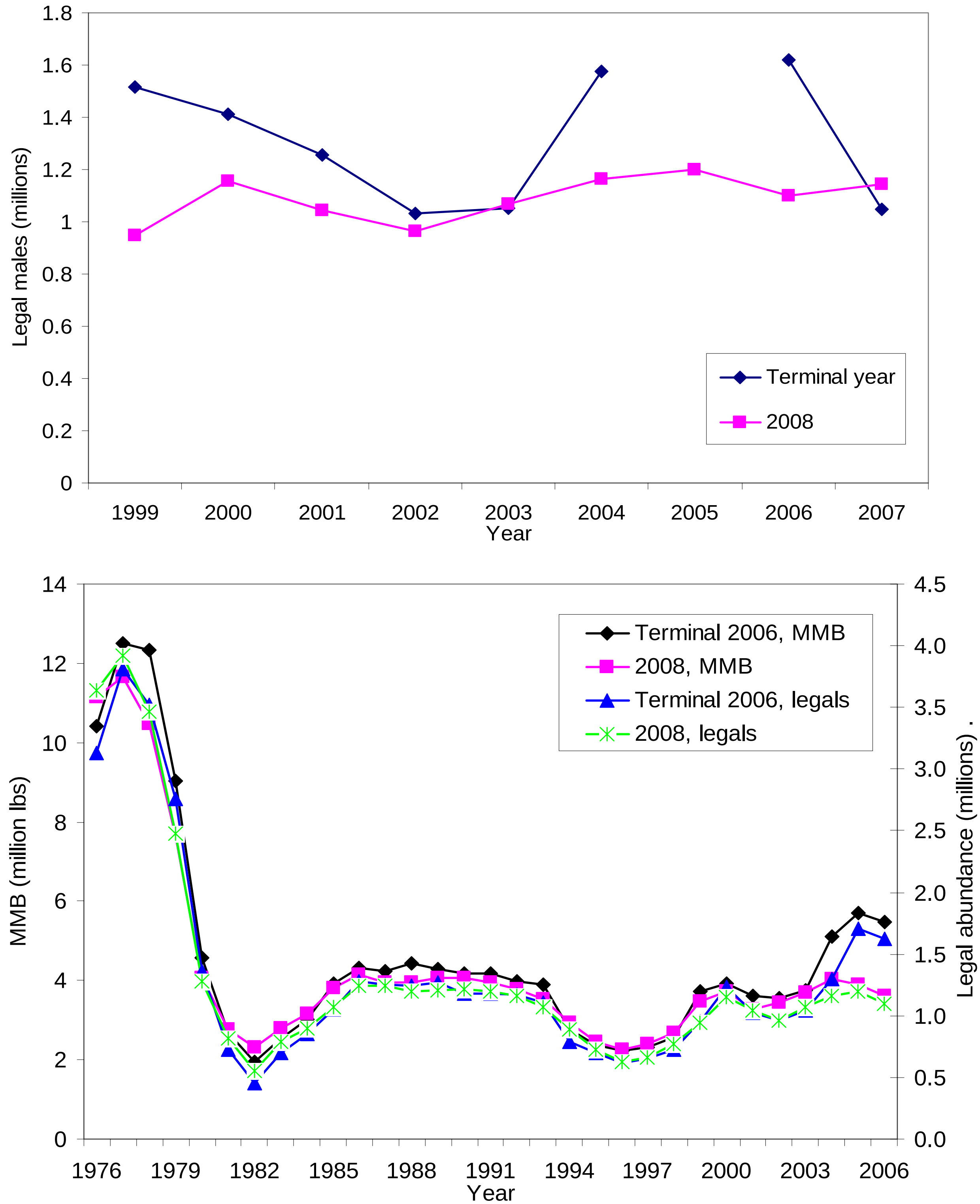


Figure 8. Comparison of estimates of legal male abundance (upper plot) of Norton Sound red king crab with terminal years 1999-2008 and legal abundance and mature male biomass (lower plot) with terminal years of 2006 and 2008. These are results of historical assessments. Legend shows the year in which the assessment was conducted.

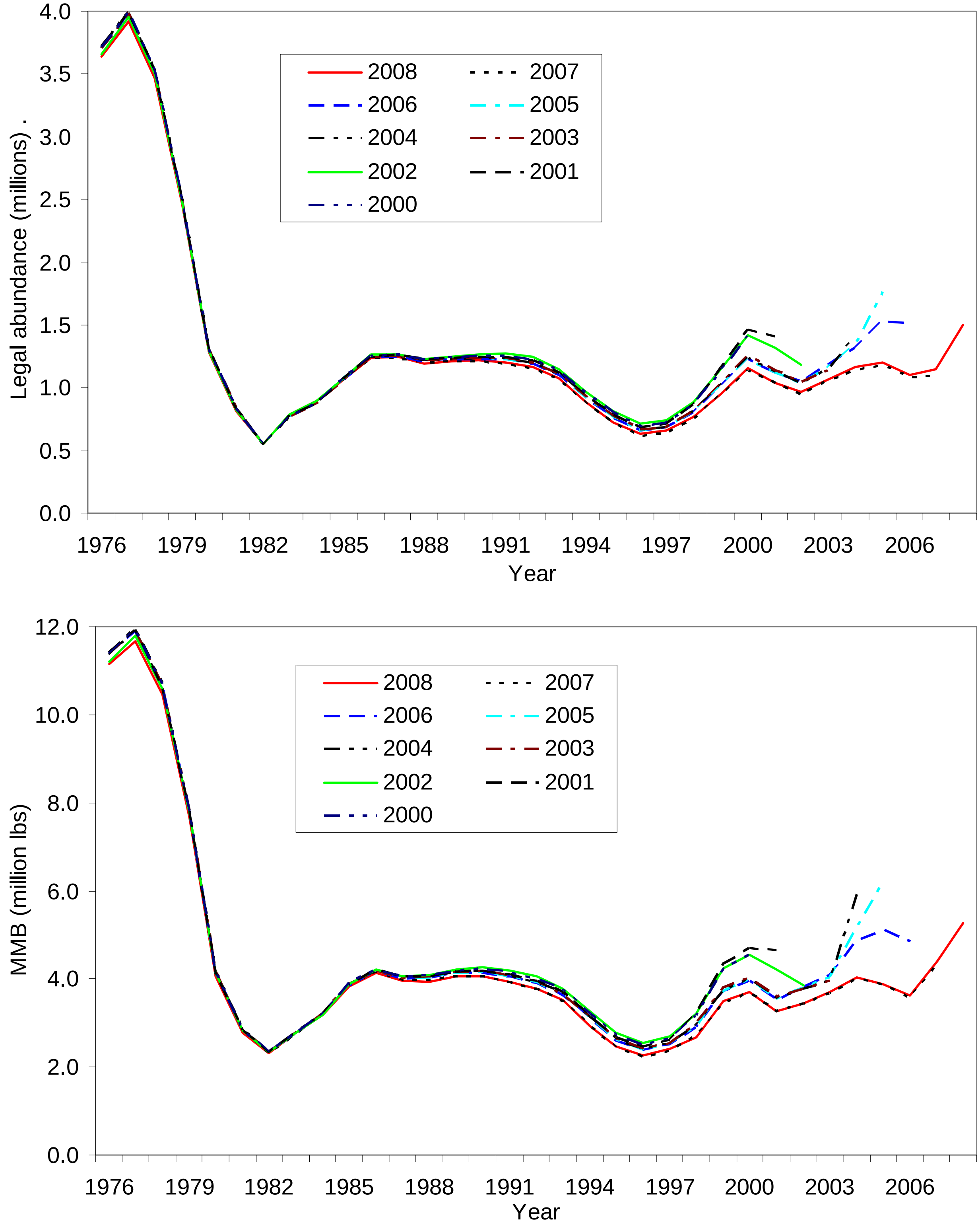


Figure 9. Comparison of estimates of legal male abundance (upper plot) and mature male biomass (lower plot) of Norton Sound red king crab from 1976 to 2008 made with terminal years 2000-2008. These are results of the 2008 model. Legend shows the year in which the assessment was conducted.

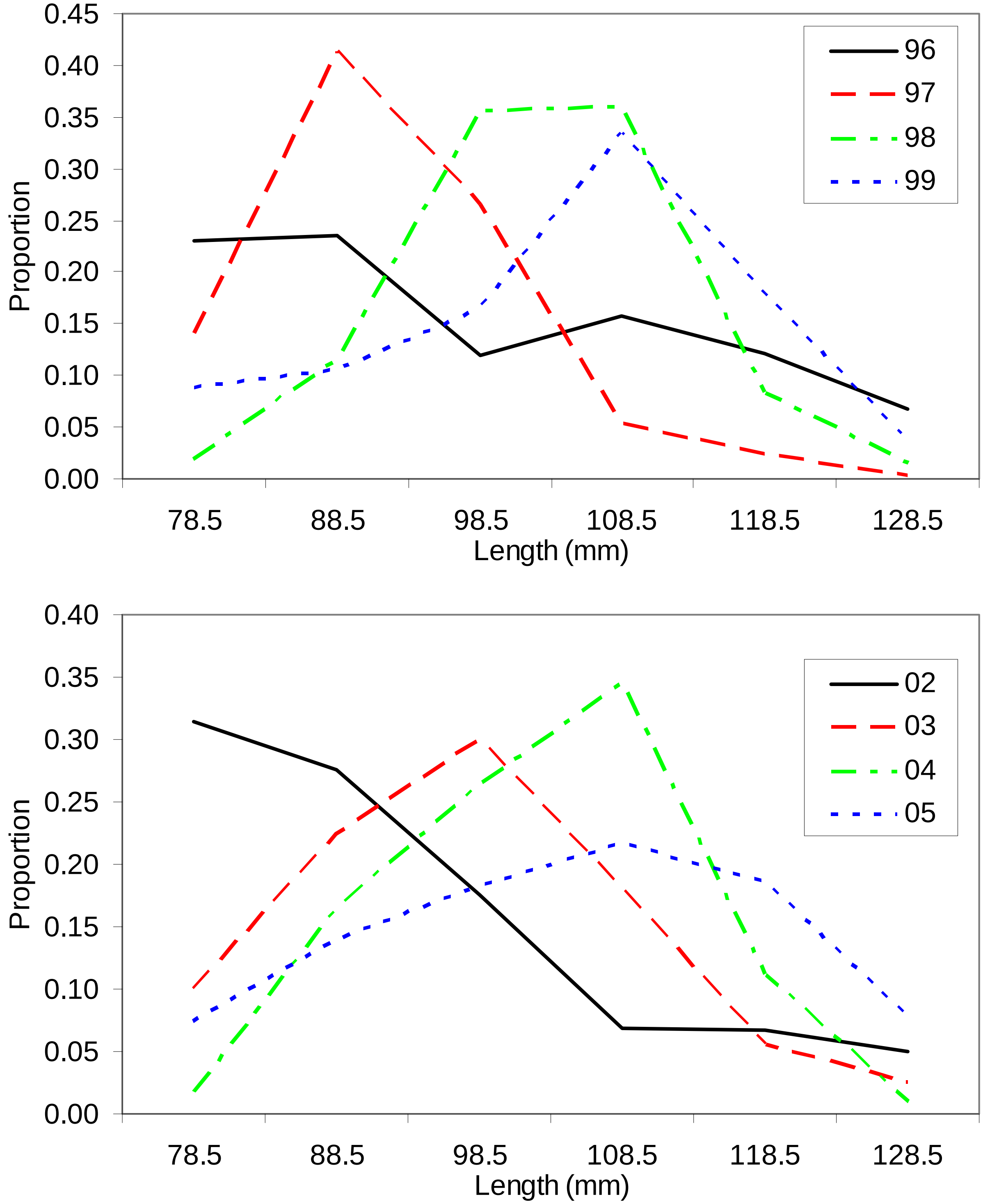


Figure 10. Length frequency of newshell crabs from the winter survey during two periods: 1996-1999 and 2002-2005.

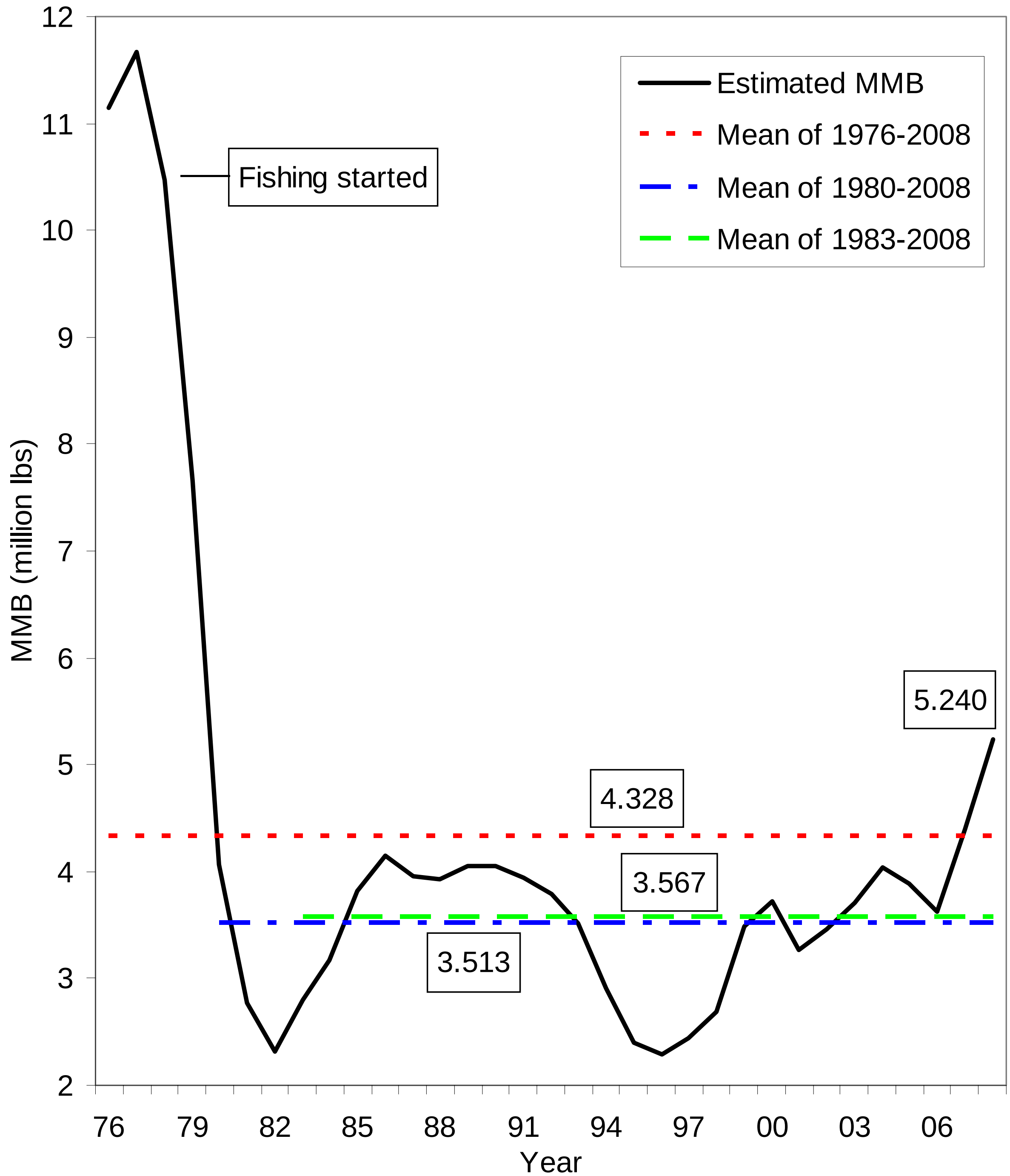


Figure 11. Comparison of estimated mean mature male biomasses during different periods of Norton Sound red king crab.

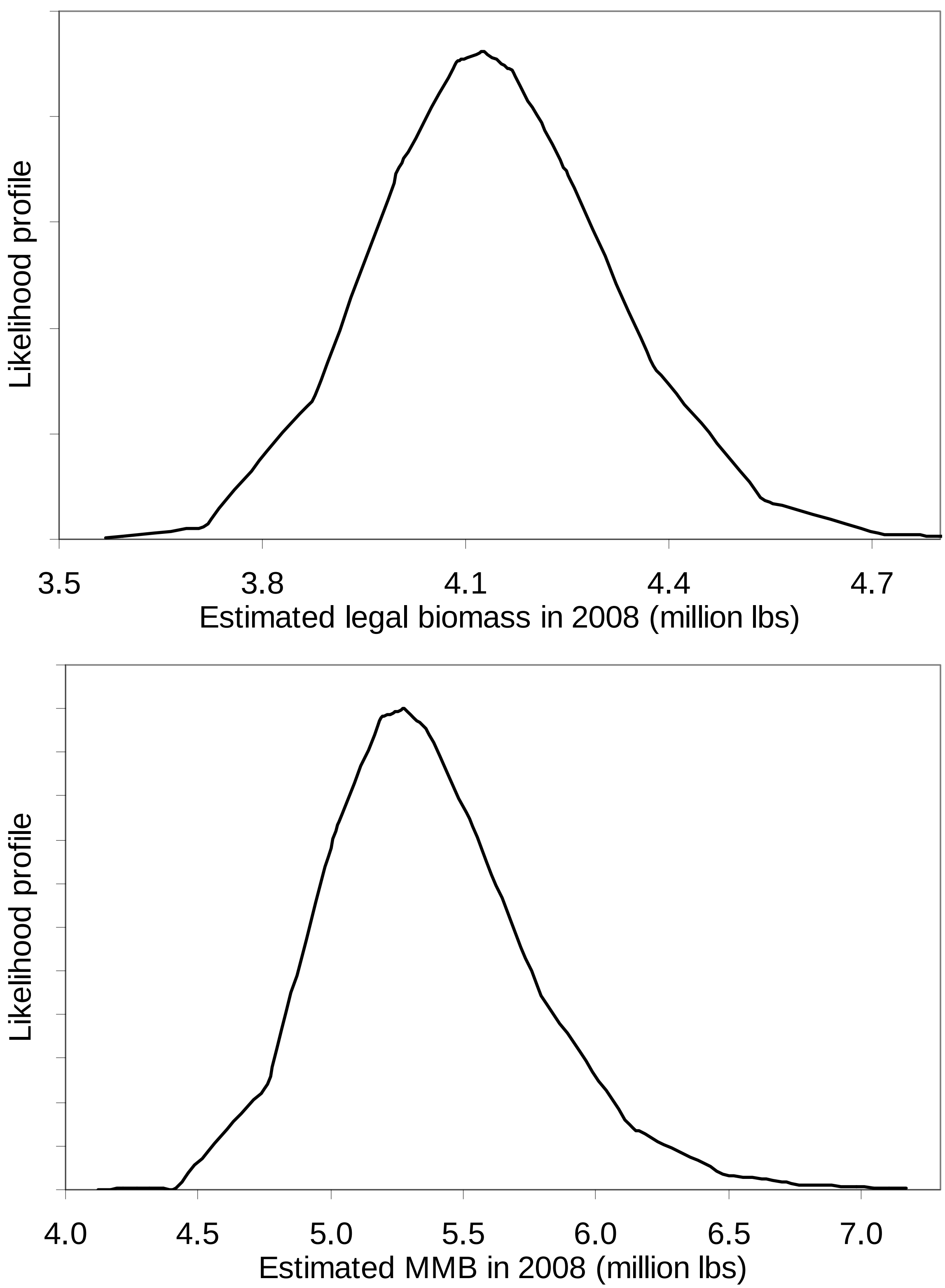


Figure 12. Likelihood profiles for estimated legal male biomass and mature male biomass in 2008.