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Aleutian Islands Golden King Crab (*Lithodes aequispinus*) Stock Assessment Model Development

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Executive Summary

This document describes an assessment of the Aleutian Islands golden king crab (*Lithodes aequispinus*) stock in management areas both east and west of 174°W longitude based on an integrated model.

The Aleutian Islands golden king crab stock contributes to a commercially important male-only fishery. The commercial fishery developed in the early 1980s, the harvest peaked in 1986/87 (5.9 and 8.8 million pounds for east and west of 174°W longitude, respectively), and became steady since 1996/97 because of implementation of fixed guideline harvest levels (total allowable catch, TAC) of 3 and 2.7 million pounds for east and west of 174°W longitude, respectively. The TACs were increased to 3.15 and 2.835 million pounds for the two respective regions for the 2008/09 fishery following the Alaska Board of Fisheries decision, which were below the limit TACs determined under Tier 5 criteria (considering 1991-1995 mean catch as the limit catch) under the new crab management plan.

Despite its economic importance, the stock has not been surveyed annually, biological data are limited, and assessment models are lacking. An integrated analysis method was developed, which combined commercial retained and discarded catch, and triennial pot survey catch-per-unit-effort (CPUE). The data series used in the current assessment for the area east of 174°W longitude ranges from 1990/91 to 2007/08 for catch and catch length frequency, 1997-2006 for triennial pot survey standardized CPUE. Data series considered for the area west of 174°W longitude ranges from 1989/90 to 2007/08 for catch and catch length and frequency. A maximum likelihood method was used to estimate stock assessment parameters and the time series of abundance of male recruits (≥101 mm carapace length, CL) as well as biomasses of legal males (≥136 mm CL), and mature males ((≥121 mm CL).

Assessment based on the eastern data indicated that male recruit abundance fluctuated during initial years, peaked in 2003, declined until 2007, and slightly increased in 2008. The legal and mature male biomasses systematically increased from 1990 to 1998 and declined thereafter. The estimated retained harvest rate fluctuated with a declining trend during 1990 to 1996, remained steady at lower level during 1996 to 2004 and systematically increased since 2004.

Assessment based on the western data showed that male recruit abundance fluctuated until 1999, declined until 2005, and increased during 2006 to 2008. The legal and mature male biomasses systematically declined until 2004, sharply increased in 2005 and slightly declined thereafter. The estimated retained harvest rate has declined from 1989 to 1992, fluctuated during 1993 to 1998, steadily increased to a peak in 2004 and sharply declined thereafter.

The model was used to determine the limit harvest level for both the eastern and western regions under Tier 4, assuming an estimated average *M* of 0.13 as the limit *F* for the two regions. Two options for limit harvest levels are provided below:

East of 174°W longitude:

Mean Mature Biomass Calculation Period	Retained Limit Catch (t)	Discard Limit Catch (t)	Total Limit Catch (t)	Total Limit Catch (million pounds)
1990-2007	2139.7	237.7	2377.4	5.24
1996-2007	2049.0	227.7	2276.7	5.02

West of 174°W longitude:

Mean Mature Biomass Calculation Period	Retained Limit Catch (t)	Discard Limit Catch (t)	Total Limit Catch (t)	Total Limit Catch (million pounds)
1989-2007	1747.2	183.6	1930.8	4.26
1996-2007	1964.3	206.4	2170.7	4.79

Because the 2008/09 fishery is still in progress (closes May 15, with observer and catch data lagged from that date), the selected limit harvest level from the above two options can be provisionally considered for the 2009/10 fishing season.

Limited data are available on the groundfish bycatch of golden king crab. The groundfish fishery bycatch of golden king crab for 2007/08 and 2008/09 (not fully completed year) from the region were 122.2 t (0.269 million pounds) and 12.0 t (0.026 million pounds), respectively.

Lack of reliable estimates of important life history parameters, such as *M*, annual biomass, and changes in fishing practices introduce greater uncertainty to biomass estimates and hence the yields. The poor quality of data also restricts investigation of different model scenarios. Following are some research recommendations for future improvement in assessment:

(a) Continue tagging to estimate mortality, growth, movement, and determination of proportion of biomass available for the commercial fishery.
(b) Continue the triennial pot survey to increase the fishery independent data series.
(c) Increase the observer coverage frequency to get estimates of CPUE and biological characteristics based on larger samples.
(d) Investigate appropriate methods to standardize CPUE considering space and time of the fishery.
(e) Investigate the handling mortality.
(f) Investigate the selectivity pattern in the fishery.

Summary of Major Changes from the September 2008 version (Siddeek et al. 2008)

1. Commercial fishery CPUE data and tagging data were not used in the parameter estimation.
2. Pot survey CPUE data, after standardization, were incorporated in the integrated model.
3. The natural mortality penalty function was not included in the likelihood function because of its insignificant effect.
4. A fishing mortality likelihood component is added for parameter estimation.
5. Annual total number of recruits was assumed to fall into the first two size groups only.

CPT comments (September 2008)

The CPT raised the following technical comments (in Italic) on the assessment:
1. Use of CPUE data. Standardization of the data prior to their incorporation is desirable. Sensitivity should be examined to ignoring these data owing to concerns regarding the use of catch-rate as an index of relative abundance in stock assessments.

Response: Only pot survey CPUE data, standardized for soak-time (considered only 40 to 140 hours soak-time), were used in the model fitting. To explore the predictability of the commercial fishery total CPUE, the commercial CPUE were standardized in terms of standardized pot survey CPUE (see the text section).

2. Tag loss. The model ignores systematic tag loss, which could be important as the tagging data likely have an important impact of the outcome of the assessment and systematic tag loss could be confounded with fishing mortality. Sensitivity should be conducted to various plausible levels of systematic tag loss.

Response: As per SSC suggestion (see in the next section), tagging data were not considered in this assessment.

3. Parameters hitting bounds. Many of the estimated fishing mortality rates are on the bounds assumed for these parameters. This is undesirable and should be explored further.

Response: Fishing mortality was considered as a separate component of the likelihood model to address this problem.

4. Realism of the population trajectory for the western area. The MMB for the western stock drops in 1998. Fishing industry previously indicated that the mesh size on pot gear changed in this period. The team noted the predicted trajectory of population size seems contrary to the data.

Response: Entire modeling approach has been changed and the trends are different. The population size dropped and increased during the last few years for the west of 174°W longitude region.

SSC comments (October 2008)

The SSC made the following additions to CPT advice:

1. Standardization of the CPUE data prior to their incorporation into the model is desirable. The SSC recommends that effort be standardized for soak time, area, vessel, and season. The SSC also suggests that a "core" fleet approach be investigated as an aid to understanding changes in fishery performance.

Response: Addressed this problem to a certain extent. The pot survey CPUE were standardized to soak-time to incorporate them into the maximum likelihood function and the commercial CPUE data were not used in the parameter estimation (please see response to item 1 of CPT). A core fleet approach will be investigated for the next assessment.

2. The SSC agrees that temporal partitions in fishery selectivity should be incorporated into the model to account for changes in the mesh size used in crab pots since 1999, provided that there is evidence that changes in mesh size were adopted by all or nearly all of the fleet.

Response: Temporal partition of selectivity is maintained as before because of fishing gear and fishing strategy modifications during different periods, which have been verified to be correct.

3. The SSC notes that the inclusion of the tagging data did not make marked improvements to the model.

Response: In this assessment, tagging data were not considered.

4. The SSC recommends that the weights applied to different components of the model (e.g. retained CPUE, discard CPUE, pot survey CPUE, catch biomass, recruitment deviations and natural mortality penalties) be explored in a systematic manner. The selection of "arbitrary" weights is not recommended.

Response: In this revision, the number of maximum likelihood components was reduced. Only retained catch length composition, discard catch length composition, pot survey CPUE, catch biomass, fishing mortality, and recruitment deviation were used in the likelihoods. The natural mortality penalty was not included because different runs with and without this penalty did not make much difference. The biomass and recruitment deviation likelihood functions were given arbitrary weights based on best fit criteria. There will be a workshop addressing this problem, and their recommendations will be considered to address this problem in a future assessment.

Introduction

The golden king crab (*Lithodes aequispinus*) stocks in the Aleutian Islands have produced steady catches and steadily increasing catch-per-unit-effort (CPUE, defined as number of crabs per pot lift) in recent years (Figures 1 and 2). They are not surveyed by trawl gear because of the deep water and rocky habitats they live in. Therefore, annual stock-abundance estimates are not provided for this species from National Marine Fisheries Service (NMFS) surveys.

Data limitations combined with life history characteristics of golden king crab pose problems to development of appropriate stock assessment models. Golden king crab larvae are lecithotrophic and not known to rise to the upper water layer to feed, suggesting that the spring bloom is an unlikely cue for spawning and the spawning period is protracted (Shirley and Zhou 1997, Otto and Cummiskey 1985). Limited stock information and lack of annual survey data prevent developing the standard length-based assessment model as used in snow crab (*Chionoecetes opilio*) and red king crab (*Paralithodes camtschaticus*) stock assessments (Turnock and Rugolo 2007, Zheng 2007). To overcome these problems, we developed an integrated analysis method, which combines commercial catch, catch size frequency composition, and triennial pot survey CPUE (restricted to east of 174°W longitude stock). The 1990/91-2007/08 data series from the area east of 174°W longitude and the 1989/90-2007/08 data series from the area west of 174°W longitude were used in the analysis. The model estimates of historical stock and recruit male abundances, harvest rate, and a number of stock assessment parameters are provided in this report.

Fishery

The Aleutian Islands golden king crab fishery developed in early 1980s and became a lucrative fishery after the collapse of a number of commercial crab stocks in the Bering Sea and Aleutian Islands (BSAI). Because of deep water habitat, the fishery is conducted using sets of pots in a long-line fashion. Since 1996, the Alaska Department of Fish and Game (ADF&G) has divided the Aleutian Islands golden king crab fishery into eastern and western districts at 174°W longitude (ADF&G 2002). Hereafter the stock segment east of 174°W longitude is referred to as ES and the stock segment west of 174°W longitude is referred to as WS. The stocks in the two areas are managed with a constant annual guideline harvest level or total allowable catch (3.0 million pounds for the ES and 2.7 million pounds for the WS). In 2008, however, the total allowable catch was increased to 3.15 and 2.835 million pounds for ES and WS, respectively, following the Alaska Board of Fisheries decision (approximately a 5% increase in TAC). Because of a lack of information on total removal of crabs, the total allowable catch was determined to be the retained catch. Additional management measures include a male-only fishery and a minimum legal size limit (152.4-mm carapace width or approximately 136 mm CL), which is at least one annual molt increment larger than the 50% maturity length of 120.8 mm CL for males (Otto and Cummiskey 1985). Daily catch and CPUE are determined for in-season monitoring of fishery performance. Beginning in 2000/01, and with the introduction of crab rationalization in 2005/06, the CPUE increased. This is likely due to gear modification (starting from 1999, door web size was increased to 9.5 inches; crab fisher, Jeff Davis, personal communication, July 1, 2008), increased soak time, and decreased competition from the reduction in the number of vessels fishing. Decreased competition allows crab vessels to target only the most productive areas.

Data

A time series of commercial retained and discarded catch by length, observer CPUE data by length, triennial pot survey CPUE data by length (restricted to the ES), and the mean annual growth increment per molt (Watson et al. 2002) are the primary data and parameter values considered for model fitting and evaluation. The annual CPUE, retained, and discard catch are listed in Table 1 for the ES and in Table 5 for the WS.

The Aleutian Islands golden king crab fishery observer coverage declined from 100% of vessels and 100% of their catch prior to the 2004/05 season to 100% of vessels and 65-70% of their catch during the 2005/06 to 2007/08 seasons. Observers randomly selected a pre-determined number of pots daily and examined the entire pot contents for catch composition, including measuring carapace lengths and scoring shell conditions. The number of pots sampled accounts for 4-8% of the total pot lifts (Moore et al. 2000, Barnard et al. 2001, Neufeld and Barnard 2003, Barnard and Burt 2004). Observer data have been collected since 1988, but initial years' data from the collection are not comprehensive, so shorter time series of data for the period 1990-2007 for the ES and for the period 1989-2007 for the WS were selected for analysis along with other data sets.

Length-specific CPUE data collected by at-sea observers provide information on a wider size range of the stock than does the commercial catch length frequency data obtained from dockside samples. Monthly mean length frequency data were constructed from observer samples. The mean CPUE for retained and discarded male crabs were estimated for each month. The size range was restricted to 101 mm CL to 185 mm CL to allow use of an externally estimated mean growth increment (Watson et al., 2002) as input when fitting the population dynamics model. The total male CPUE for each month was estimated by adding each male CPUE category (retained legal, discarded legal, and sublegal). The observer sample monthly length frequency was used to split the total monthly CPUE into monthly length-specific CPUE. If the fishing season exceeded one month, a weighted average (weighted by the effort) of the monthly length-specific CPUE was determined for the fishing season. The length-specific CPUEs were summed by length to obtain the total CPUE for the season. The length specific discard CPUE for the season was estimated similarly, but using only the sum of discarded legal and sublegal CPUE categories.

The commercial fishery annual total CPUE (i.e., observer CPUE) was standardized in terms of pot survey (soak-time standardized) CPUE as follows:

$$P_t = \frac{CPUE_t}{CPUE_{s,t}} \tag{1}$$

$$E_t^s = P_t \; E_t \tag{2}$$

$$CPUE_t^s = \frac{C_t}{E_t^s} \tag{3}$$

where

P_t = fishing power of the commercial fleet relative to survey vessel in year t,

$CPUE_t$ = catch-per-unit-effort (number of crabs / pot lift) of commercial vessels in year t,

$CPUE_{s,t}$ = catch-per-unit-effort of pot survey vessel in year t,

E_t^s = standardized total fishing effort in year t,

E_t = nominal total fishing effort (number of pot lifts) in year t,

$CPUE_t^s$ = standardized catch-per-unit-effort in year t, and

C_t = total catch (number of crabs) in year t.

The monthly commercial catch and length frequency data were estimated from ADF&G landing records (fish tickets) and dockside length measurements. The monthly length frequency data were used to distribute the monthly total catch into different size intervals and summed by month to obtain the annual retained catch by size. The annual discard (dead) catch by size was estimated using the annual observer discard CPUE by size data multiplied by the annual effort (pot lifts) and a 20% handling mortality. Note that the observer CPUE by length data were used only for estimating discard catch by size to input into the population dynamic model, but not included in the parameter estimation.

The pot survey CPUE by length was estimated with the same method used for the observer data, except that the entire set of pot catches were measured and CPUE was estimated as the catch divided by the effort (pot lifts) (Watson 2007). The CPUE were standardized to soak-time by considering only those pot hauls with soak-time in the range of 30-140 hours for CPUE estimation as described above. A Box plot provided a 95th percentile value of 140-hour soak-time. Very few fell above 140 hours soak-time. The pot survey catches also cover a wider size range than the commercial size frequency. Furthermore, the four sets (1997, 2000, 2003, and 2006) of CPUE data came from a standard survey grid in a restricted area (between 52°15' and 53°00' N latitude and 170°00' and 171°30' W longitude), using a standard pot configuration, which may reflect the actual in situ population abundance. The majority of the ES commercial fishery takes place in this area; however, the soak time between the commercial and research pots may vary.

The model input parameters also include elapsed time from a biological start year to the mid-fishing period. The biological start of the year was arbitrarily set to July 1 (mid-survey time). The elapsed time from July 1 to the mid-date of fishing season y_t (as a fraction of a year) was estimated for each year (Table 2 for the ES and Table 6 for the WS fisheries).

Analytical Approach

Model Structure
The underlying population dynamics models are length-based. Overall negative likelihood is the sum of the negative log likelihoods of the robust normal distribution of length composition (Fournier et al., 1990), lognormal pot survey standardized CPUE, lognormal catch biomass, lognormal fishing mortality, and log normal recruit deviation (see Appendix A for detailed model structure). AD Model Builder, ver. 8.0.2 (Otter Research Ltd., 2007), was used to estimate the model parameters and to derive statistics, such as biomass and limit yield.

Parameters estimated independently
The analysis of tagging data indicated that the linear relationship between annual growth increment and pre-molt length was not significant ($p > 0.05$). Thus, a mean annual growth increment 14.4 mm CL was computed from the original tagging data to be applicable to the entire length range considered in the analysis (Watson et al. 2002, Siddeek et al. 2005).

Scant information is available on the level of handling mortality as a result of capture and release of unmarketable crabs although a large number of sublegal males and females are captured and released in the fishery (Neufeld and Barnard 2003, Blau et al. 1996). Lacking such information for golden king crab, we used an arbitrary 20% handling mortality rate on discarded males, which was obtained from the red king crab literature (Siddeek 2002, Kruse et al. 2000).

A length-weight model ($W = a1 * CL^{b1}$) for males was determined using 276 measurements taken during April – July 1997. The estimated parameters were: $a1 = 2.988*10^{-4}$ and $b1 = 3.135$ ($R_{adj}^2 = 0.93$).

Parameters estimated conditionally

The following stock parameters were estimated by minimizing the overall negative log likelihood function:
a and *b*: for the molt probability model;
c_1 and d_1: for the total and pot survey selectivity model;
c_2 and d_2: for the retention selectivity model for the period 1990-1998;
c_3 and d_3: for the retention selectivity model for the period 1999-2004;
c_4 and d_4: for the retention selectivity model for the period 2005 onward;
r: proportion of recruits falling into the first length interval (recruits were assumed to fall into the first two length intervals);
R_{90} to R_{08},: total number of male recruits for each year, except the first year;
q_1: pot survey catchability;
q_2: pot fishery catchability for the period 1990-1998;
q_3: pot fishery catchability for the period 1999-2004;
q_4: pot fishery catchability for the period 2005 onward;
F_{89} to F_{07}: full selection fishing mortality for 1989 to 2007;
β: shape parameter of the gamma growth function;
M: natural mortality;
N_{89}, N_{90}: available initial total number of new-shell crabs; and
O_{89}, O_{90}: available initial total number of old-shell crabs.

Different fishery retention selectivities and catchabilities were considered for the time period before 1998/99, between 1999/00 and 2004/05, and 2005/06 onwards. In 1985/86, the size limit was lowered from 6.5 to 6.0 inches and long-lined pots began to be used at this time as well (Forrest Bowers, personal communication). In 1999/00-2000/01, the industry changed the pot webbing to large mesh size (9.5") (Jeff Davis, Crab fisher, personal communication, July 1, 2008). Since 2005/06, crab rationalization was in place, which has led to longer soak times and hence more self-sorting on the bottom.

Model evaluation
Predicted vs. observed value plots were the major criteria for model evaluation. The stock availability parameter (ν) was fixed at 3% and 1% for the ES and WS segments of the stock, respectively. We tried to estimate this parameter from the model fit, but it hit the lowest bound and hence needed to be fixed at the lowest bounds to get feasible estimates of other parameters.

The following weights were attached to negative log likelihood components of catch biomass, recruitment deviation, and fishing mortality:

- For ES: catch biomass (λ_B =0.5), recruit deviation (λ_R = 3.5), and fishing mortality (λ_F = 200).
- For WS: catch biomass (λ_B =1.0), recruit deviation (λ_R = 2.0), and fishing mortality (λ_F = 800)

The weights were chosen arbitrarily to obtain better fits to observed data. Larger weights for *F* likelihood were chosen with the assumption that variances in *F* were low to obtain a closer fit to *F* parameter estimates with independent estimates of *F* within the model (based on predicted catch and abundance).

Time varying effective sample sizes (K_t) were used for robust normal length composition log likelihoods (Fournier and Archibold 1980, Pribac and Punt 2005). They were estimated using the formula $K_t = \frac{400 \times n_t}{\max n_t}$ where n_t is the number of length measurements in year t and 400 is the maximum cap placed on effective sample size (Fournier and Archibold 1980). They were calculated separately for retained and discarded catch (Table 9).

Results

Model evaluation

ES:
The time series of predicted versus observed fishery (total) and pot survey CPUEs are shown in Figure 3a-b. The fit to pot survey standardized CPUE were reasonable. However, the standardized total CPUEs did not track the fitted values after 2005/06 (after crab rationalization). This was perhaps due to a different fishing strategy under taken by fishers after crab rationalization and the pot survey CPUE values as the standard may not be applicable to latter years' fishery CPUEs. Nevertheless, this appears not to affect the parameter estimates because the commercial fishery CPUEs were not used in the likelihood. The time series of predicted vs. observed retained catch relative length frequency (Figure 4) and discard catch relative length frequency (Figure 5) depicted reasonably good fits for the ES. The profile likelihood of model estimated constant M indicated a peak near the 0.123 value (Figure 6).

Negative log likelihood components

Retained length composition	374.843
Discard length composition	379.449
Pot survey CPUE	0.185
Retained catch biomass	24.820
Recruitment deviation	0.163
Fishing mortality	4.039
Total	783.499

WS:
The time series of predicted versus observed total CPUEs (standardized in terms of 2003 pot survey CPUE) tracked the observed CPUE for WS, but was not a very good fit for the reasons mentioned previously (Figure 7). The trend in the predicted CPUE for WS was similar to that for ES, which was perhaps the result of similar dramatic increases in CPUE after rationalization in both areas (see Figure 2). The time series of predicted vs. observed retained catch relative length frequency (Figure 8) and discard catch relative length frequency (Figure 9) depicted reasonably good fits for most years, except for the last three years of discard relative frequencies for the WS. The profile likelihood of model estimated constant M indicated a peak near the 0.145 value (Figure 10).

Negative log likelihood components

Retained length composition	274.944
Discard length composition	341.344
Retained catch biomass	41.604
Recruitment deviation	0.111
Fishing mortality	13.514

Total	671.517

Parameters estimated conditionally

ES:
Table 3 lists the parameter values estimated from the base model fit.
The molting probability systematically decreased as the crab size increased with the 50% probability near 91.7 mm CL (Figure 11a). The fishery retention selectivity curves for the three periods (1990/91-1998/99, 1999/00-2004/05, and 2005/06-) systematically increased and 50% selectivity was achieved at 153.3, 173.8, and 188.0 mm CL, respectively (Figure 11b). The unusually high 50% selectivity during the last two periods appears to be an artifact of fitted values, nevertheless it emphasizes that the mean size of retained crab has increased in the recent period (see Pengilly's Aleutian Islands golden king crab stock assessment report, 2009). The catchability in the survey pot gear and the fishery pot gear for the three periods ranged from $1.12*10^{-7}$ to $8.30*10^{-7}$. Fishery catchability has dramatically increased during the last period after crab rationalization, perhaps due to an increase in fishing efficiency and fishing practices.

Estimated time series of number of recruits to the size group considered in the model (101-185 mm CL), legal male biomass (≥ 136 mm CL) and mature male biomass (≥ 121 mm CL) are provided in Table 4. The estimated male recruit abundance to the model fluctuated during initial years, peaked in 2003, declined until 2007, and slightly increased in 2008 (Figure 12). All recruits entered the model population in the first length group (estimated proportion (r) of 0.99), 101-105 mm CL. The legal and mature biomasses systematically increased until 1998, then declined (Figure 13 a-b). The estimated retained harvest rate has declined until 1996/97, remained steady at a lower level from 1996/97 to 2004/05, and systematically increased since 2005/06. The corresponding *F* behaved similarly (Figure 14 a-b).

WS:
Table 7 lists the parameter values estimated from the base model fit.
The molting probability systematically decreased as the crab size increased with the 50% probability near 69.5 mm CL (Figure 15a). The fishery retention selectivity curves for the three periods (1989/90-1998/99, 1999/00-2004/05, and 2005/06-) systematically increased and 50% selectivity was achieved at 151.2, 156.8, and 139.0 mm CL, respectively (Figure 15b). The 50% selectivity for the last period is somewhat low considering the increase in mean weight of retained crab during the last period as reported by Pengilly (2009). This can be an artifact of estimated value as mentioned before. The catchability ranged from $1.05*10^{-7}$ to $7.48*10^{-7}$ for the fishery pot gear for different periods. Different fishery catchabilities were considered for the time period before 1998, between 1999 and 2004, and 2005 onwards. Fishery catchability has increased during the last period, perhaps due to an increase in fishing efficiency.

Estimated time series of number of recruits to the size group considered in the model (101-185 mm CL), legal male biomass (≥ 136 mm CL) and mature male biomass (≥ 121 mm CL) are provided in Table 8. The estimated male recruit abundance to the model fluctuated until 1999, declined until 2005, and slightly increased thereafter (Figure 16). The recruits entered the model population in two length groups, 101-105 and 106-110 mm CL, with estimated proportions of 0.598 and 0.402, respectively. The legal and mature biomasses systematically decreased until 2004, then increased to a peak in 2005 and then declined (Figure 17 a-b). The estimated retained harvest rate has declined until 1992, fluctuated at a low level during 1992 to 1998, increased to a peak in 2004 and declined thereafter (Figure 18a). The corresponding *F* behaved similarly (Figure 18b).

Harvest alternatives

ES:
The limit harvest levels for the ES under Tier 4, assuming an average model estimated *M* value of 0.13 (i.e., assuming a λ value of 1 with this *M* estimate) for the two regions, were estimated by an iterative procedure because the mature biomass, which was used in determining the *F* level, had to be estimated after the fishery was completed. Two options for limit harvest level are provided below. The first option uses the entire time series of data used to estimate parameters whereas the second option uses the time series corresponding to the period after implementation of the guide line harvest level / total allowable catch.

Mean Mature Biomass Calculation Period	Retained Limit Catch (t)	Discard Limit Catch (t)	Total Limit Catch (t)	Total Limit Catch (million pounds)
1990-2007	2139.7	237.7	2377.4	5.24
1996-2007	2049.0	227.7	2276.7	5.02

If an *M* of 0.18 (a default value for all king crab stocks, NPFMC 2007) is used, higher values of limit estimates are obtained for the two options as follows. This *M* value corresponds to a λ value of 1.38 with the model estimated *M* value.

Mean Mature Biomass Calculation Period	Retained Limit Catch (t)	Discard Limit Catch (t)	Total Limit Catch (t)	Total Limit Catch (million pounds)
1990-2007	2783.8	309.3	3093.1	6.82
1996-2007	2665.1	296.1	2961.2	6.53

WS:
The limit harvest levels for the WS under Tier 4, assuming an average model estimated *M* value of 0.13 for the two regions, were estimated. Two options for limit harvest level are provided below:

Mean Mature Biomass Calculation Period	Retained Limit Catch (t)	Discard Limit Catch (t)	Total Limit Catch (t)	Total Limit Catch (million pounds)
1989-2007	1747.2	183.6	1930.8	4.26
1996-2007	1964.3	206.4	2170.7	4.79

If an *M* of 0.18 is used, higher values of limit estimates are obtained for the two options as follows:

Mean Mature Biomass Calculation Period	Retained Limit Catch (t)	Discard Limit Catch (t)	Total Limit Catch (t)	Total Limit Catch (million pounds)
1989-2007	2277.3	239.3	2516.6	5.55
1996-2007	2604.8	273.7	2878.5	6.35

One of the two options of limit harvest levels for the lower *M* value is suggested for the 2009/10 fishing season for both ES and WS.

Data gaps and research priorities

The recruit abundances were estimated from commercial catch sampling data. The implicit assumption in the analysis was that the estimated recruits came from the same exploited stock through reproduction, growth, and mortality. However, there is a possibility that additional recruitment can occur as a result of immigration from neighboring areas and possibly separate sub-stocks; however, the current analysis did not consider this possibility. Extensive tagging experiments are needed to investigate stock distributions.

Standardization of commercial CPUE data with respect to soak-time and depth were not pursued in this assessment; instead the pot survey data were standardized to soak-time. Pot survey soak-time ranged from approximately 30 to over 300 hours, but a Box plot of the four pot survey data indicated that the 95th percentile soak-time was 140 hours. Nominal CPUE (catch / pot lift) of selected pots with 30-140 hours soak-time were considered as standard CPUE to input into to the likelihood function. Commercial CPUE data were not considered to estimate model parameters, but used, after standardization, for comparing the outputs from model estimates.

The natural mortality was estimated by the model fit, which appears to be slightly low (~ 0.12 to 0.15). An independent estimate of *M* is needed for this stock. Tagging is one possibility. An extensive tagging study will also provide independent estimates of molting probability and growth increment.

An arbitrary 20% handling mortality rate on discarded males was used, which was obtained from the red king crab literature (Siddeek 2002, Kruse et al. 2000). An experiment-based independent estimate of handling mortality is needed for golden king crab.

Summary

Aleutian Islands golden king crab stocks were assessed in an attempt to upgrade them from Tier 5 to Tier 4 level as defined in the proposed new crab fishery management plan (NPFMC 2007). The following table provides the essential parameters and derived statistics obtained from the ES and WS data analysis for Tier 4 upgrade:

Parameters/Tier	**Parameter values/Tier level**	
	ES	WS
M	0.12	0.15
Mature male biomass on 15 Feb 2008	19997 t	15899 t
a. Proxy MSY mature male biomass (1990-07 mean (ES),1989-07 mean (WS))	28649 t	16494 t
b. Proxy MSY mature male biomass (1996-07 mean)	29716 t	14629 t
Tier allocation	4(b)	4(b) under a., 4(a) under b.
Proxy F_{OFL} (1990-07 / 1989-07option)	0.08	0.12
Proxy F_{OFL} (1996-07 option)	0.08	0.13
Limit total catch (1990-07/ 1989-07option)	5.24 mill.pounds	4.26 mill.pounds

Limit total catch (1996-2007 option)	5.02 mill. pounds	4.78 mill.pounds

The groundfish fishery bycatch of golden king crab for 2007/08 and 2008/09 (not fully completed year) from the region were 122.2 t (0.269 million pounds) and 12.0 t (0.026 million pounds), respectively.

Acknowledgments

We thank Doug Woodby and Jie Zheng of the ADF&G, Juneau, and Doug Pengilly of the ADF&G, Kodiak for initial review of this draft report.

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Table 1. Time series of annual retained catch (number of crabs), discarded and dead catch (assuming a handling mortality of 20%), observer retained catch-per-unit-effort (CPUE, number of crabs per pot lift), observer discard CPUE, and pot survey CPUE for the ES golden king crab stock. The data are for the size range 101-185 mm CL. NO = no sampling information, and + = low value not considered in the fit.

Year	Retained Catch	Discarded and Dead Catch	Observer Retained CPUE	Observer Discard CPUE	Pot Survey CPUE
1990/91	950,008	458,060	6.5071	21.3435	
1991/92	1,093,983	289,390	5.3043	10.8444	
1992/93	1,118,955	572,451	11.3052	21.4618	
1993/94	832,194	149,178	NO	NO	
1994/95	1,128,013	536,467	NO	NO	
1995/96	1,046,780	248,104	5.2710	6.9781	
1996/97	731,909	167,578	5.6212	7.3849	
1997/98	780,610	201,238	7.1164	9.4564	24.3435
1998/99	740,011	250,371	8.7964	15.0142	
1999/00	709,332	170,431	9.0003	10.7692	
2000/01	704,702	205,392	9.8166	14.3528	19.0676
2001/02	730,030	625	10.9693	0.0499+	
2002/03	643,886	107,952	11.8289	10.3717	
2003/04	643,074	97,249	10.9252	8.2578	7.9807
2004/05	637,536	74,610	18.7475	10.7051	
2005/06	623,971	42,997	26.7399	8.7502	
2006/07	650,587	45,746	24.0939	8.7319	8.4636
2007/08	633,253	43,963	29.7912	9.7037	

Table 2. Elapsed time (in years) between July 1 (an arbitrarily set mid-survey time) and mid-date of the golden king crab fishery, y_t, in the ES, 1990/91-2007/08. Data are from ADF&G (2008).

Fishing Season	y_t
1990/91	0.2630
1991/92	0.2712
1992/93	0.2740
1993/94	0.4603
1994/95	0.2479
1995/96	0.2219
1996/97	0.3274
1997/98	0.2849
1998/99	0.2630
1999/00	0.2452
2000/01	0.1781
2001/02	0.1589
2002/03	0.1548
2003/04	0.1562
2004/05	0.1425
2005/06	0.4973
2006/07	0.4973
2007/08	0.4973

Table 3. Estimates of parameters by the base model for the golden king crab data from the ES, 1990/91-2007/08.

Parameter	Estimate
a	0.060
b	91.734
c_1	0.01
d_1	188.0
c_2	0.178
d_2	153.308
c_3	0.042
d_3	173.767
c_4	0.030
d_4	188.0
r	0.99
R_{91} to $R_{08,}$ (million crabs)	6.32, 6.54, 6.94, 7.59, 8.66, 10.89, 9.92, 7.54, 6.93, 6.39, 6.08, 5.74, 5.52, 5.44, 5.34, 5.49, 5.62, 6.08
q_1	$1.52*10^{-7}$
q_2	$1.12*10^{-7}$
q_3	$1.12*10^{-7}$
q_4	$8.30*10^{-7}$
F_{90} to F_{07}	0.69, 0.47, 0.50, 0.31, 0.68, 0.31, 0.19, 0.20, 0.18, 0.20, 0.20, 0.21, 0.19, 0.20, 0.21, 0.25, 0.28, 0.29
β	0.245
M	0.122
N_{90} (million crabs)	5049.816
O_{90} (million crabs)	0.497

Table 4. Annual abundance estimates of recruits to the model (millions of crabs), available legal male biomass (t), and available mature biomass (t) for golden king crab in the ES. Legal male biomass was estimated at the survey time and mature male biomass for year y was estimated on February 15, year y+1 after the year y fishery total catch removal. NA = not available.

Year	Recruits to the model (≥ 101 mm CL)	Mature male Biomass (≥ 121 mm CL)	Legal male Biomass (≥ 136 mm CL)
1990	NA	17,176	16,858
1991	8.5025	22,585	21,687
1992	5.8185	26,498	25,993
1993	7.5260	26,902	31,766
1994	7.5019	30,777	29,993
1995	6.5148	35,137	35,660
1996	6.5431	33,990	34,789
1997	7.6120	37,365	40,398
1998	6.6797	38,297	40,525
1999	5.7310	35,642	32,804
2000	6.7699	31,314	30,211
2001	6.9486	30,929	29,445
2002	7.3186	30,518	28,550
2003	7.7875	28,109	27,565
2004	6.9587	26,721	23,520
2005	6.4160	22,502	24,165
2006	6.3714	21,214	21,126
2007	6.3616	19,997	20,105
2008	6.4447	NA	19,113

Table 5. Time series of annual retained catch (number of crabs), discarded and dead catch (assuming a handling mortality of 20%), observer retained catch-per-unit-effort (CPUE, number of crabs per pot lift), observer discard CPUE, and pot survey CPUE for the WS golden king crab stock. The data are for the size range 101-185 mm CL.

Year	Retained Catch	Discarded and Dead Catch	Observer Retained CPUE	Observer Discard CPUE
1989/90	1,585,080	465,045	8.8093	11.4803
1990/91	757,610	212,733	4.9755	9.8241
1991/92	753,415	190,614	7.6125	9.3964
1992/93	409,373	137,176	5.6989	9.8769
1993/94	565,336	255,809	6.7760	10.0110
1994/95	796,258	399,059	6.3274	10.2250
1995/96	535,553	200,387	4.7003	8.6937
1996/97	605,137	160,413	5.7014	8.0557
1997/98	569,550	127,647	6.5811	7.3520
1998/99	409,531	107,749	10.9770	14.9985
1999/00	676,558	165,544	6.0588	7.7328
2000/01	705,613	190,119	6.6000	9.3896
2001/02	686,738	172,061	6.3609	8.1536
2002/03	665,045	176,065	7.7090	9.2056
2003/04	676,633	112,150	9.2891	8.4659
2004/05	685,465	127,386	10.8300	11.2045
2005/06	639,368	73,526	21.0381	12.2071
2006/07	523,701	52,351	21.1843	9.8073
2007/08	600,604	68,473	20.3124	11.4312

Table 6. Elapsed time (in years) between July 1 (an arbitrarily set mid-survey time) and mid-date of the golden king crab fishery, y_t, in the WS, 1989/90-2007/08. Data are from ADF&G (2008).

Fishing Season	y_t
1989/90	0.7315
1990/91	0.7315
1991/92	0.7315
1992/93	0.7329
1993/94	0.7315
1994/95	0.7315
1995/96	0.7315
1996/97	0.7329
1997/98	0.6699
1998/99	0.6699
1999/00	0.6699
2000/01	0.6466
2001/02	0.5151
2002/03	0.4342
2003/04	0.4041
2004/05	0.3630
2005/06	0.3164
2006/07	0.4973
2007/08	0.4973

Table 7. Estimates of parameters by the base model for the golden king crab data from the WS, 1989-2007.

Parameter	Estimate
a	0.051
b	69.467
c_1	0.01
d_1	188.0
c_2	0.181
d_2	151.233
c_3	0.083
d_3	156.764
c_4	0.367
d_4	139.0
r	0.598
R_{90} to $R_{08,}$ (million crabs)	6.96, 6.98, 6.97, 7.05, 7.10, 7.23, 7.44, 7.64, 7.79, 7.62, 7.69, 7.81, 7.84, 7.95, 7.72, 7.43, 7.30, 7.16, 6.87
q_2	$1.05*10^{-7}$
q_3	$1.05*10^{-7}$
q_4	$7.48*10^{-7}$
F_{89} to F_{07}	0.80, 0.34, 0.34, 0.18, 0.26, 0.39, 0.26, 0.31, 0.30, 0.22, 0.42, 0.46, 0.47, 0.49, 0.53, 0.58, 0.23, 0.20, 0.25
β	0.711
M	0.145
N_{89} (million crabs)	11775.263
O_{89} (million crabs)	0.497

Table 8. Annual abundance estimates of recruits to the model (millions of crabs), available legal male biomass (t), and available mature biomass (t) for golden king crab in the WS. Legal male biomass was estimated at the survey time and mature male biomass for year y was estimated on February 15, year y+1 after the year y fishery total catch removal. NA = not available.

Year	Recruits to the model (≥ 101 mm CL)	Mature male Biomass (≥ 121 mm CL)	Legal male Biomass (≥ 136 mm CL)
1989	NA	20,935	21,308
1990	7.2983	18,960	19,483
1991	8.3268	20,206	23,855
1992	7.3656	19,914	20,660
1993	6.4211	18,861	18,684
1994	7.5030	23,076	22,956
1995	8.6003	15,886	16,802
1996	7.6609	17,107	16,048
1997	7.7670	17,400	19,562
1998	7.5780	15,505	16,459
1999	8.1632	12,820	13,204
2000	8.0468	14,697	14,262
2001	7.6379	13741	13,459
2002	7.3052	11,052	10,896
2003	6.8467	11,127	11,078
2004	6.9055	10,366	10,404
2005	6.7301	18,620	19,965
2006	6.8298	17,200	18,470
2007	7.0584	15,899	17,098
2008	7.2521	NA	15,843

Table 9. Effective sample sizes, K_t , for fitting relative retained and discarded catch compositions of golden king crab east and west of 174°W longitude. NC = not considered.

Year	East of 174°W longitude		West of 174°W longitude	
	Retained Catch	Discard Catch	Retained Catch	Discard Catch
1989/90	NC	NC	400	74
1990/91	300	14	109	16
1991/92	400	16	133	35
1992/93	328	24	72	21
1993/94	28	152*	30	12
1994/95	49	152*	47	56
1995/96	105	150	6	400
1996/97	87	400	78	175
1997/98	119	357	83	118
1998/99	128	391	57	77
1999/00	98	339	68	138
2000/01	71	132	48	159
2001/02	73	162	55	139
2002/03	70	110	49	91
2003/04	33	101	37	83
2004/05	51	86	36	75
2005/06	33	54	34	51
2006/07	26	41	35	57
2007/08	46	54	82	57

* = Mean for the entire time series of discarded catch K_t values was substituted for missing observer samples for discarded crab.

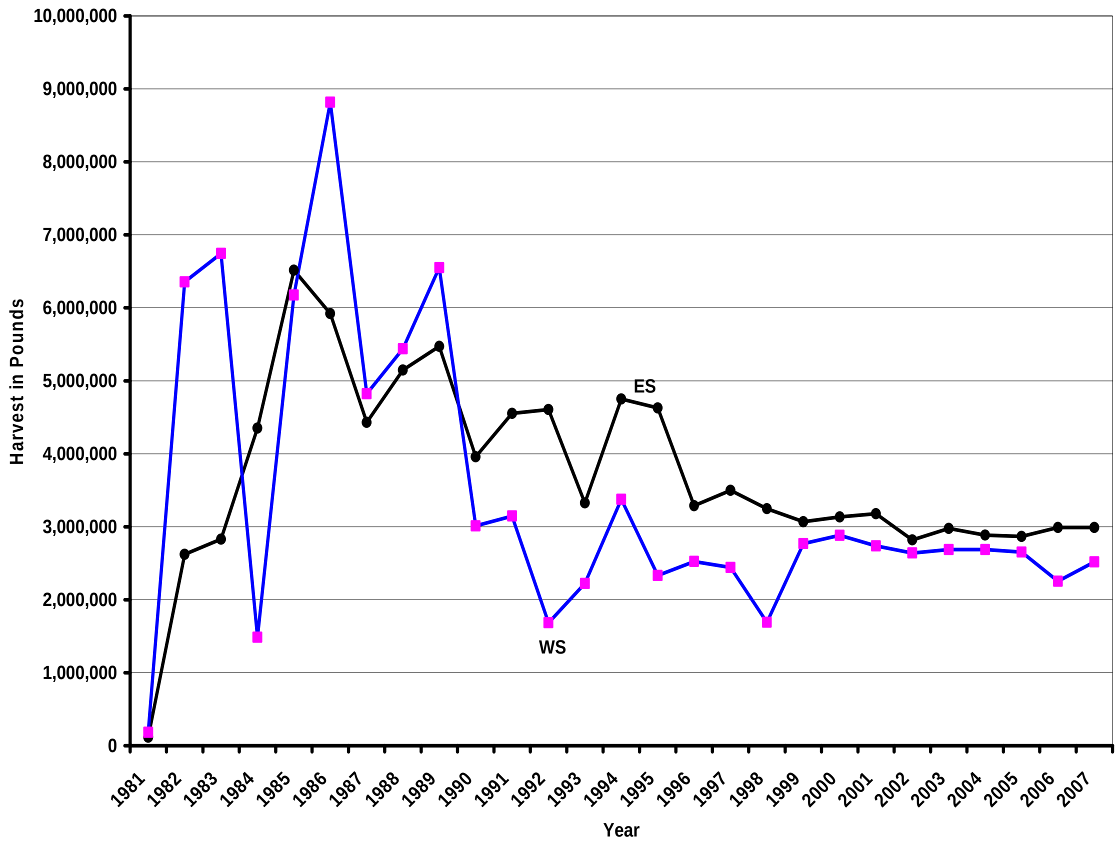


Figure 1. Historical commercial harvest (in pounds) of golden king crab east of 174°W longitude (ES, Eastern Segment) and west of 174°W longitude (WS, Western Segment), 1981/82-2007/08. Note: 1) The years on the X-axis refer to fishing seasons, e.g., 1981 refers to the 1981/82 fishery. 2) The catch data were derived from fish tickets.

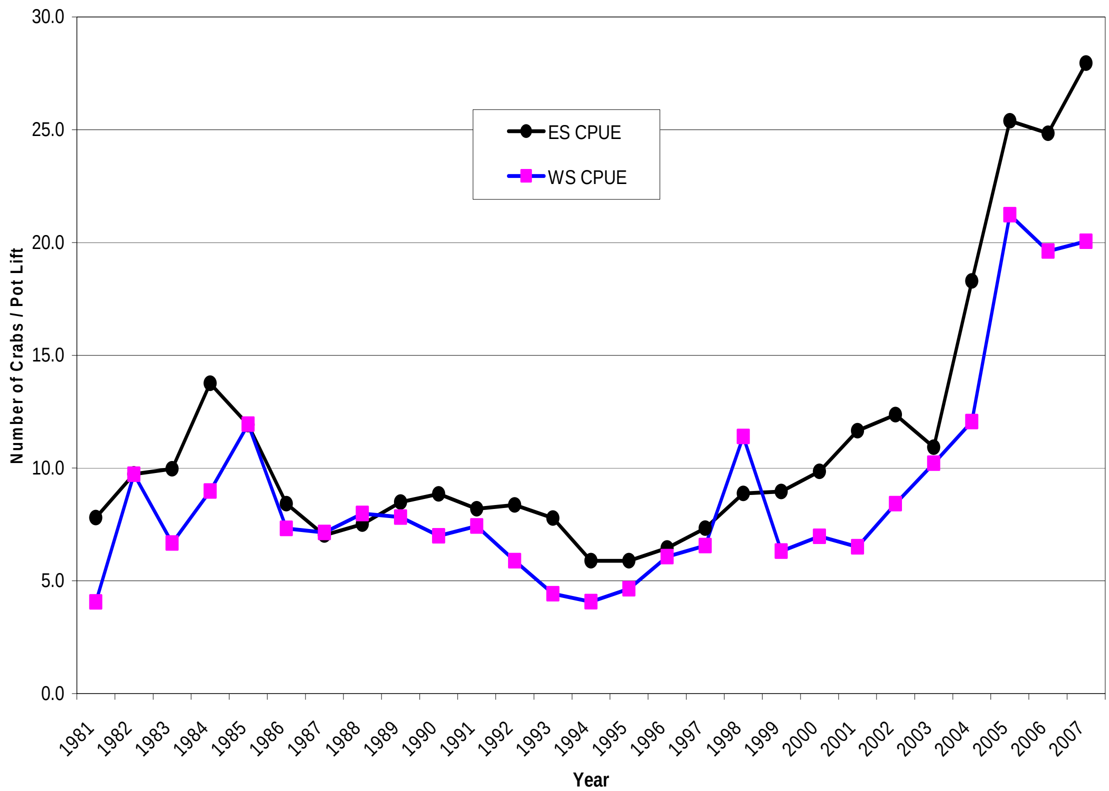


Figure 2. Historical catch-per-unit-effort CPUE (number of crabs per pot lift) in the commercial fishery for golden king crab in the ES and the WS, 1981/82-2007/08. Note: 1) The years on the X-axis refer to fishing seasons, e.g., 1981 refers to the 1981/82 fishery. 2) The CPUE data were derived from fish tickets.

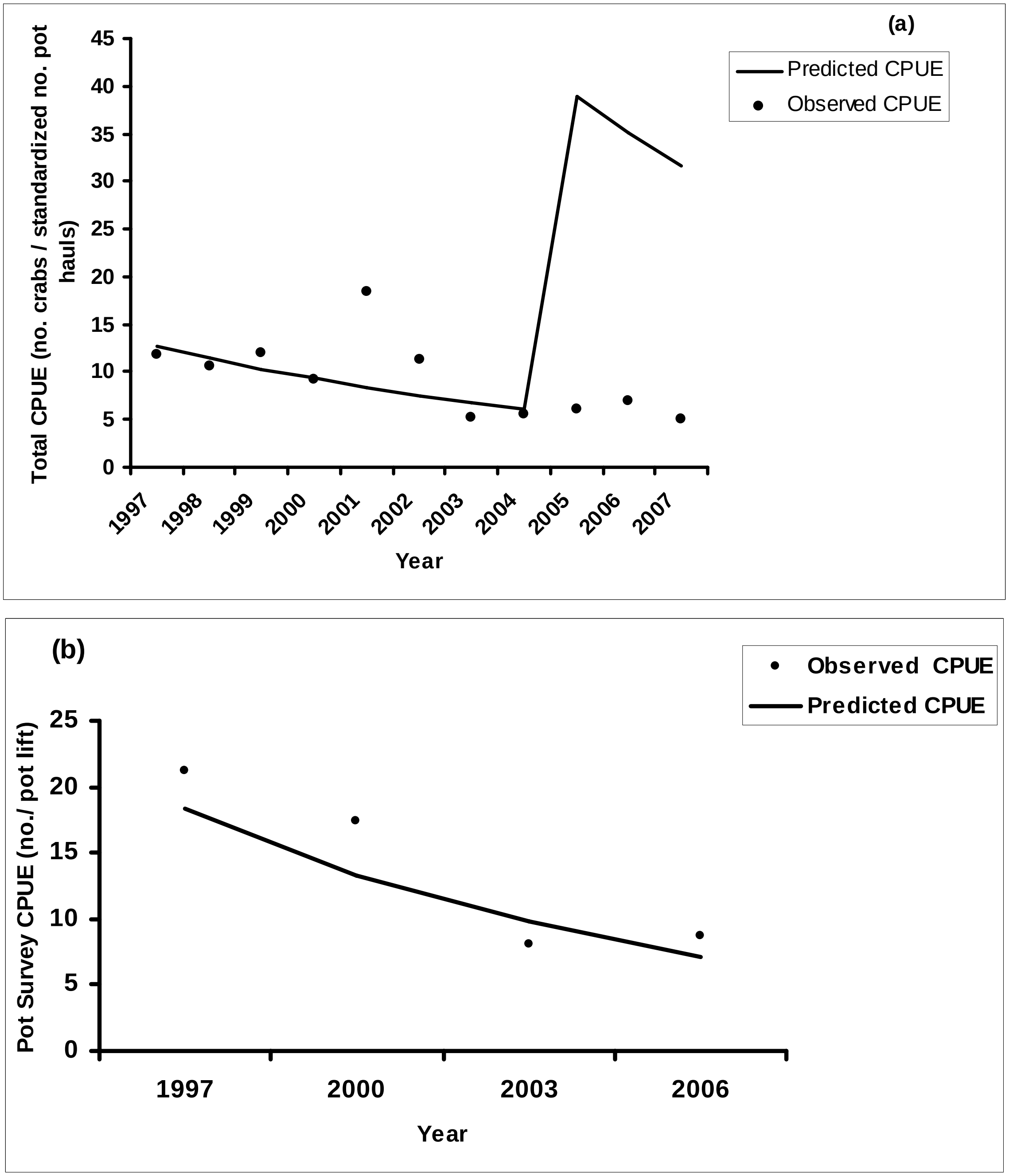


Figure 3. Predicted (line) versus observed (filled circle) (a) standardized total catch-per-unit-effort (CPUE) and (b) pot survey standardized CPUE for golden king crab in the ES. Note: The years on the X-axis in Figure (a) refer to fishing seasons, e.g., 1997 refers to the 1997/98 fishery.

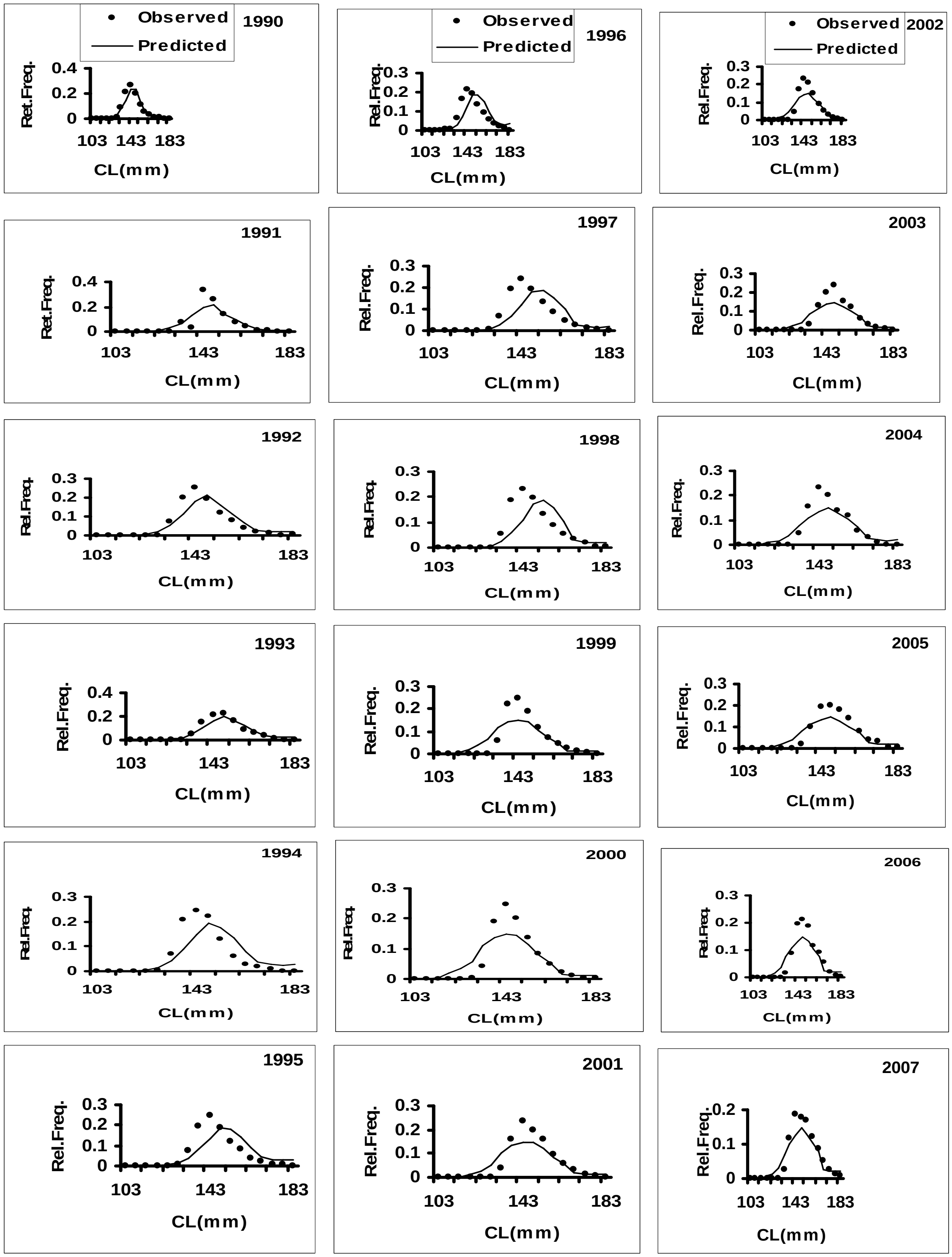


Figure 4. Predicted (line) vs. observed (filled circle) retained catch relative length frequency distributions of golden king crab in the ES, 1990/91 – 2007/08. The years refer to fishing seasons, e.g., 1990 refers to the 1990/91 fishery.

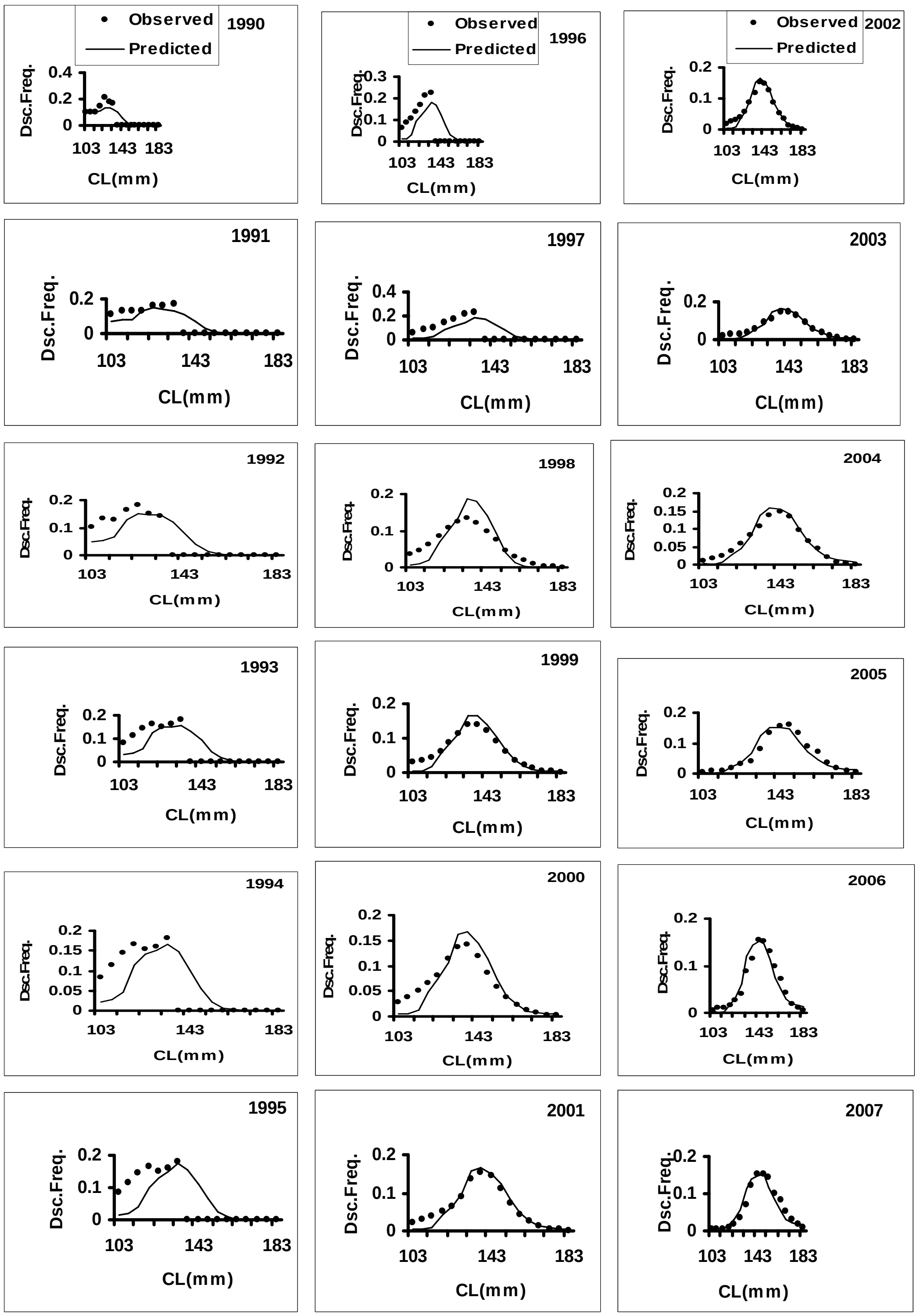


Figure 5. Predicted (line) vs. observed (filled circle) discarded catch relative length frequency distributions of golden king crab in the ES, 1990/91 – 2007/08. The years refer to fishing seasons, e.g., 1990 refers to the 1990/91 fishery.

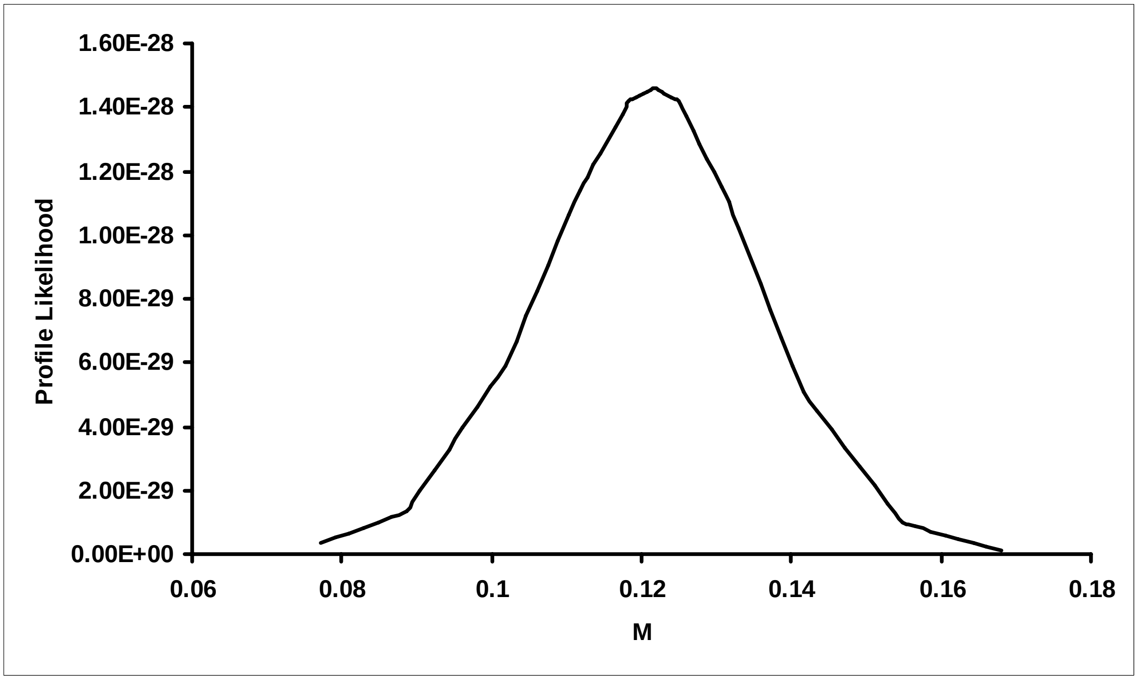


Figure 6. Profile likelihood of estimated natural mortality (*M*) based on 1990/91-2007/08 data for ES golden king crab.

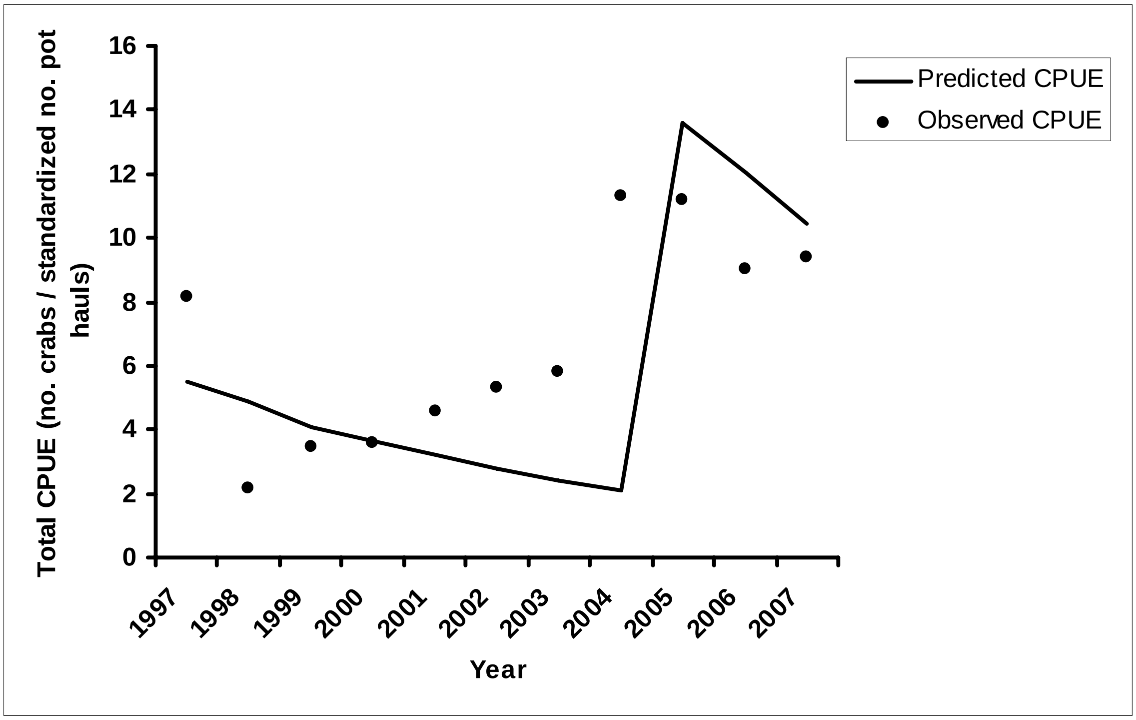


Figure 7. Predicted (line) versus observed (filled circle) (a) standardized total catch-per-unit-effort (CPUE) for golden king crab in the WS. Commercial fishery total CPUEs were standardized in terms of the 2003 pot survey CPUE. Note: The years on the X-axis refer to fishing seasons, e.g., 1997 refers to the 1997/98 fishery.

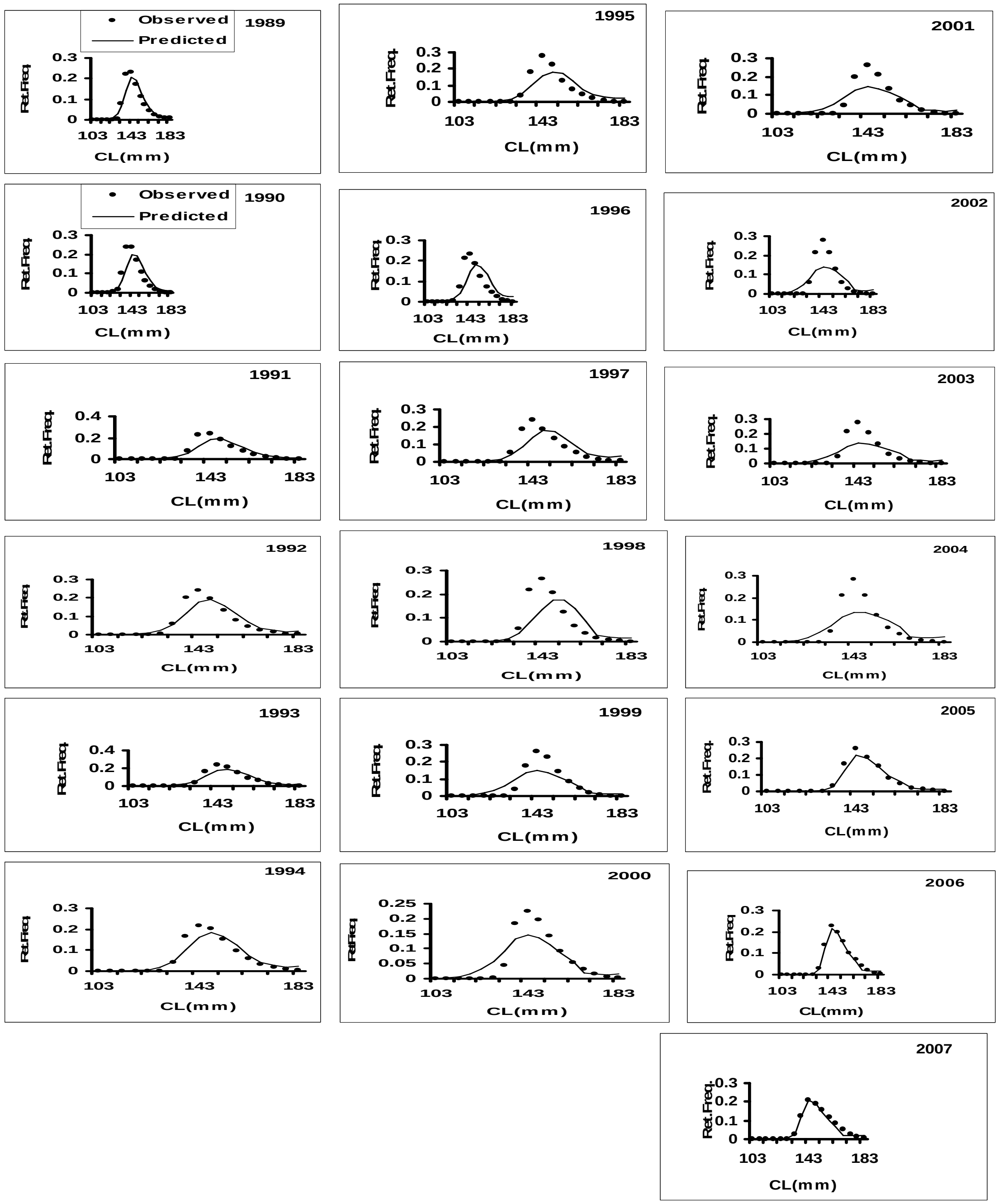


Figure 8. Predicted (line) vs. observed (filled circle) retained catch relative length frequency distributions of golden king crab in the WS, 1989/90 – 2007/08. The years refer to fishing seasons, e.g., 1989 refers to the 1989/90 fishery.

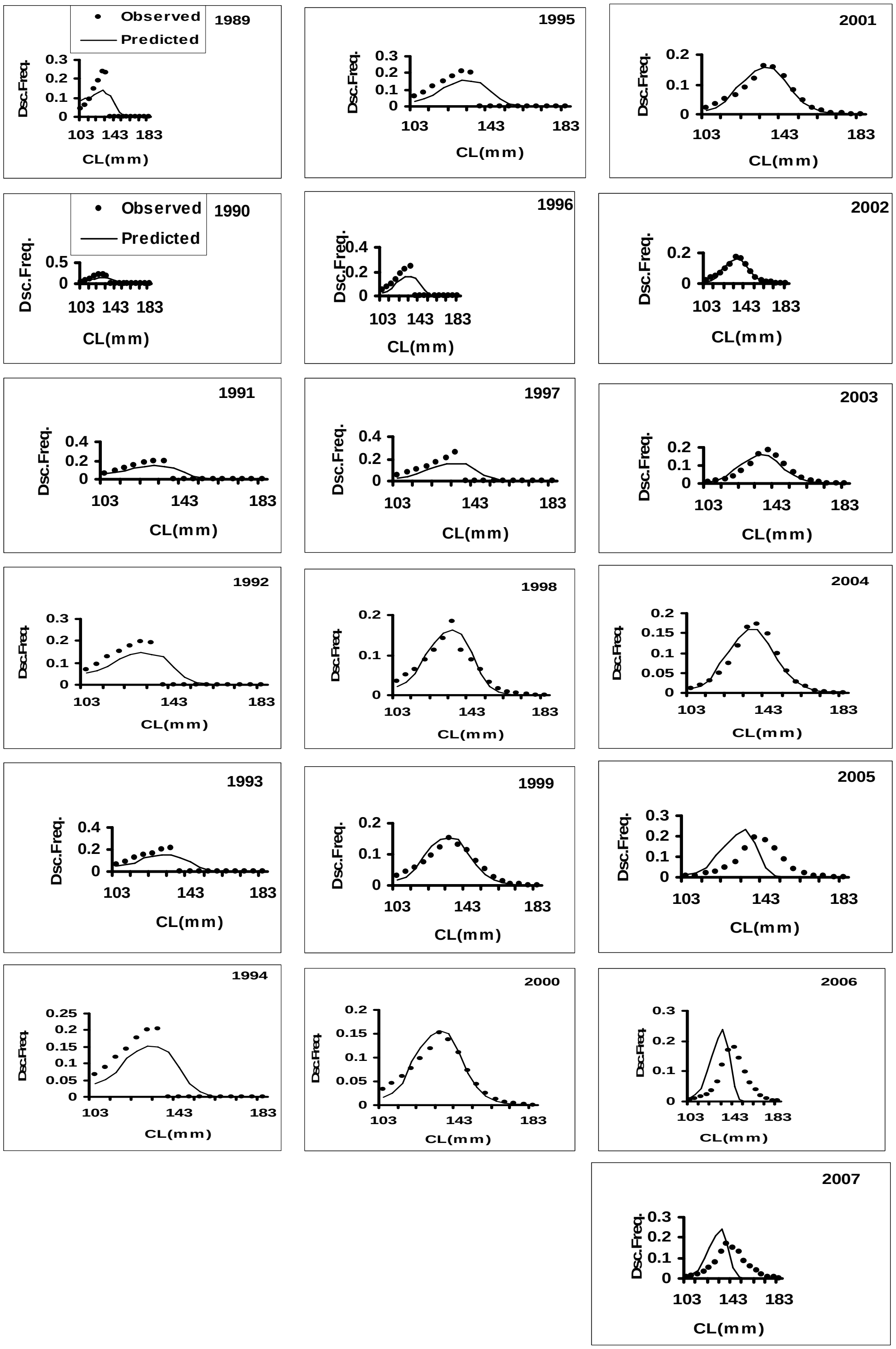


Figure 9. Predicted (line) vs. observed (filled circle) discarded catch relative length frequency distributions of golden king crab in the WS, 1989/90 to 2007/08. The years refer to fishing seasons, e.g., 1989 refers to the 1989/90 fishery.

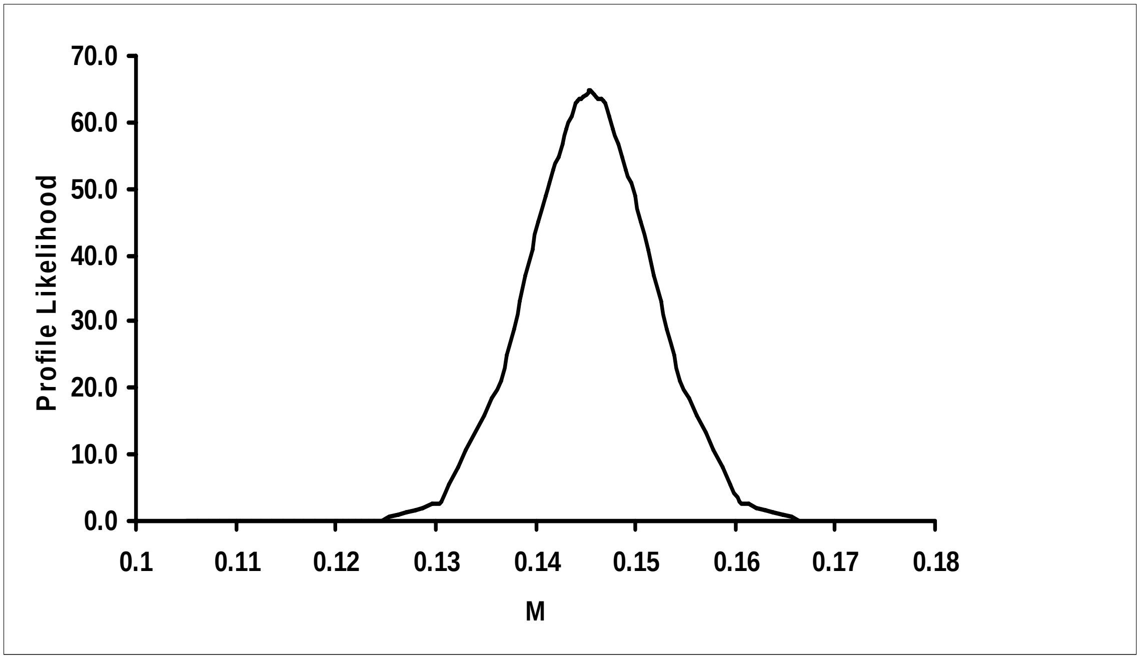
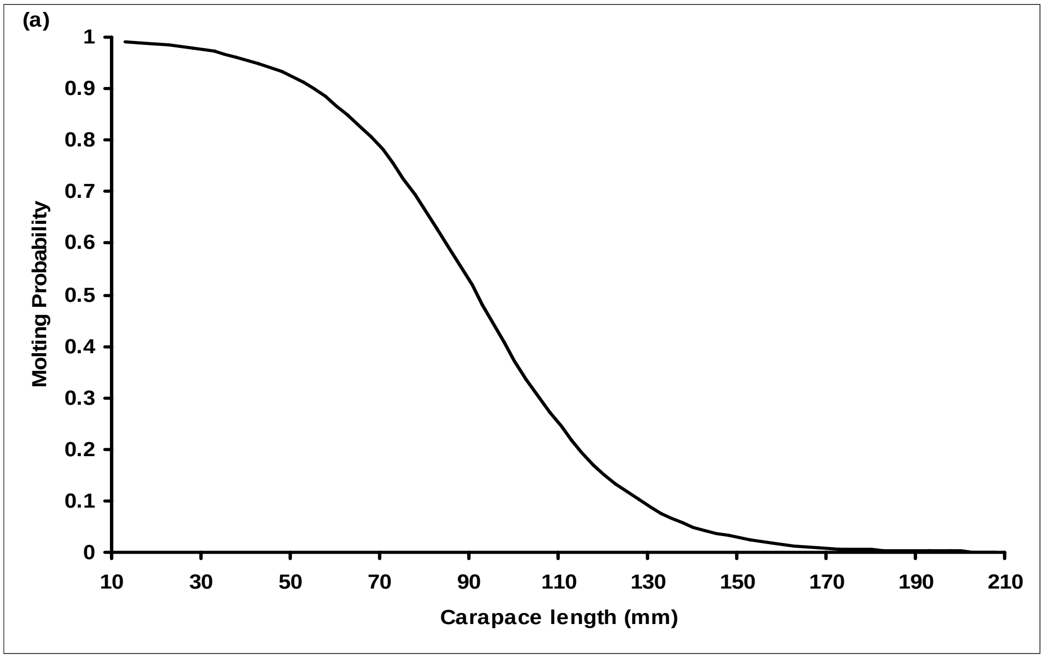


Figure 10. Profile likelihood of estimated natural mortality (*M*) based on 1989/90-2007/08 data for WS golden king crab.



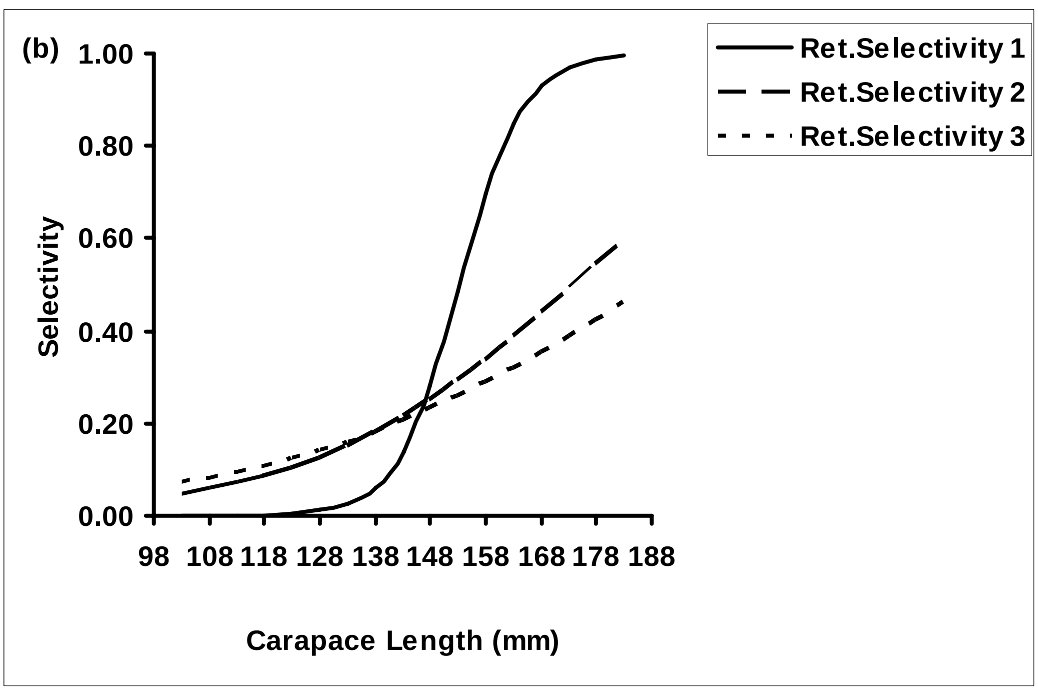


Figure 11. Estimated (a) molt probability and (b) retained selectivities for ES golden king crab. Ret. Selectivity 1 (solid line): retained selectivity curve for the 1990/91-1998/99 period; Ret. Selectivity 2 (dashed line): retained selectivity curve for the 1999/00-2004/05 period; and Ret. Selectivity 3 (dotted line): retained selectivity curve since 2005/06.

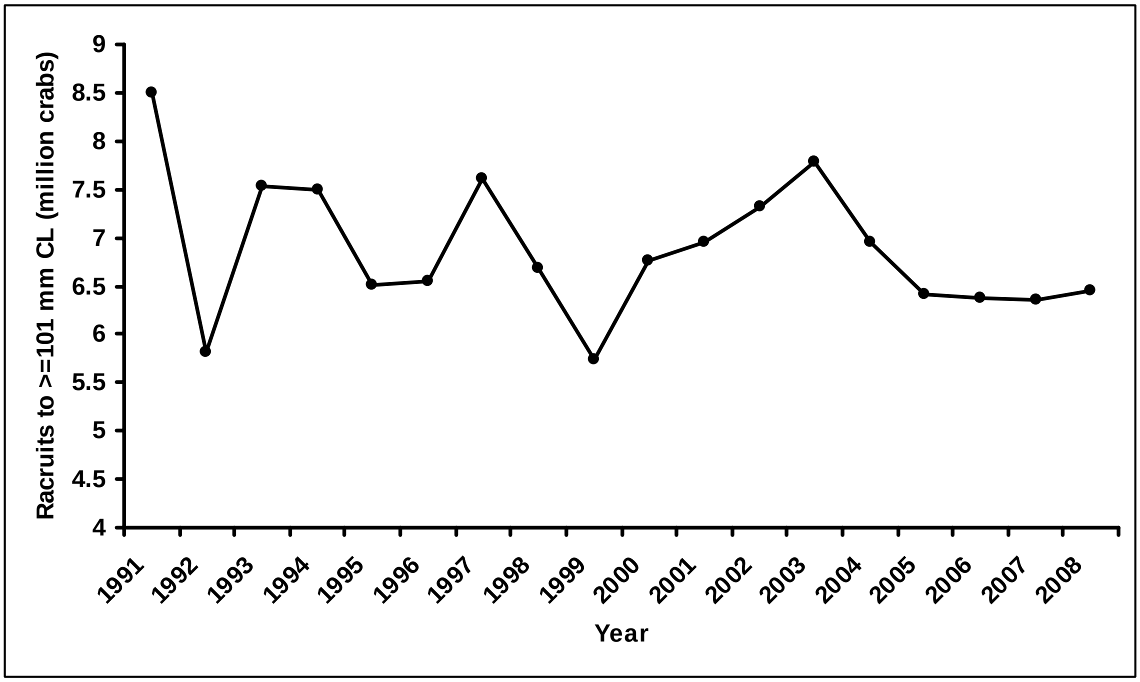
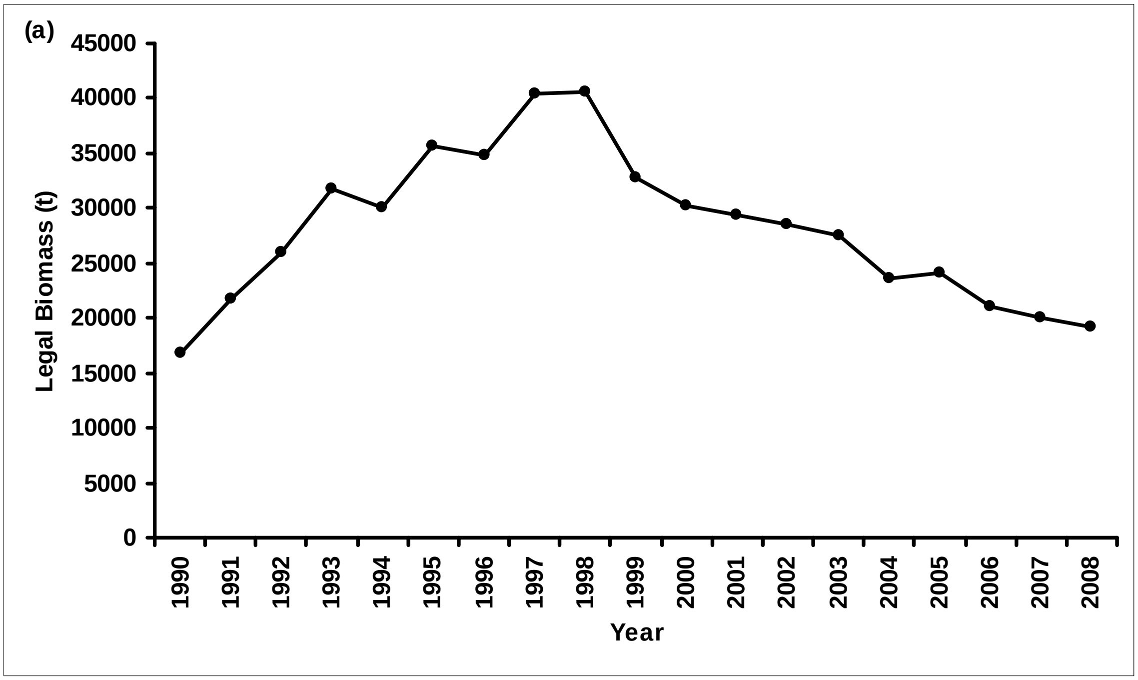


Figure 12. Estimated number of male recruits (millions of crabs ≥ 101 mm CL) to the golden king crab fishery east of 174°W longitude, 1991-2008.



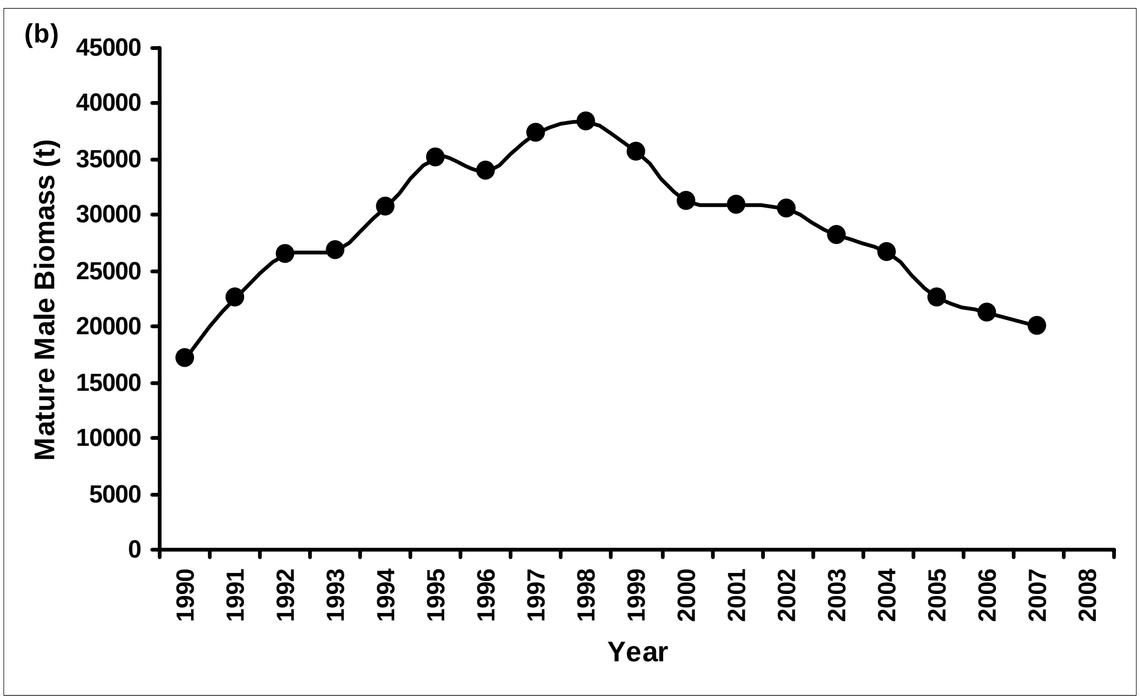


Figure 13. (a) Trends in available golden king crab (a) legal male biomass (t) and (b) mature biomass in the ES, 1990-2008. Legal male crabs are ≥ 136 mm CL and mature male crabs are ≥ 121 mm CL.

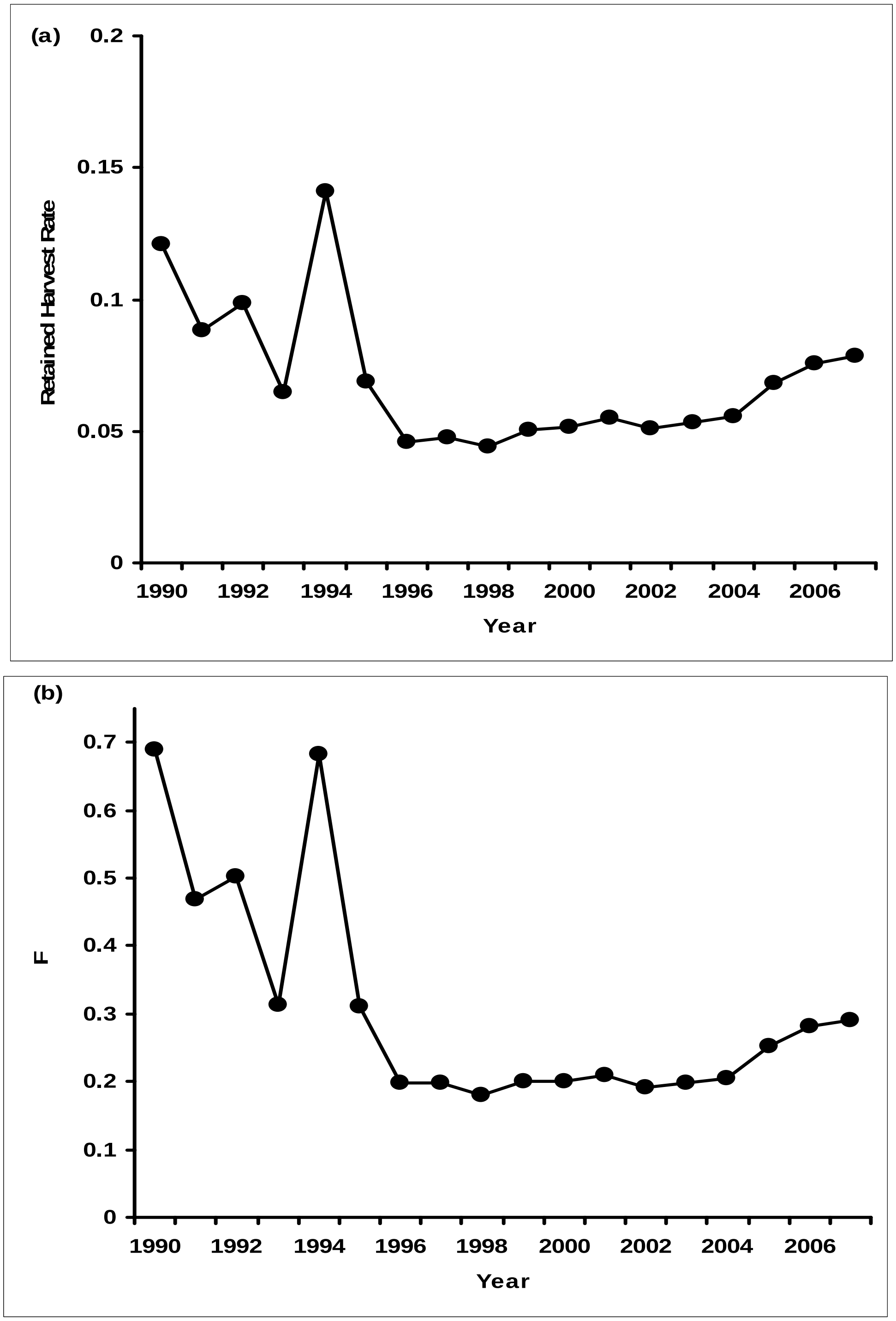


Figure 14. Trends in (a) retained harvest rate and (b) full selection fishing mortality of golden king crab in the ES, 1990/91-2007/08. The years on the X-axis refer to fishing seasons, e.g., 1990 refers to the 1990/91 fishery.

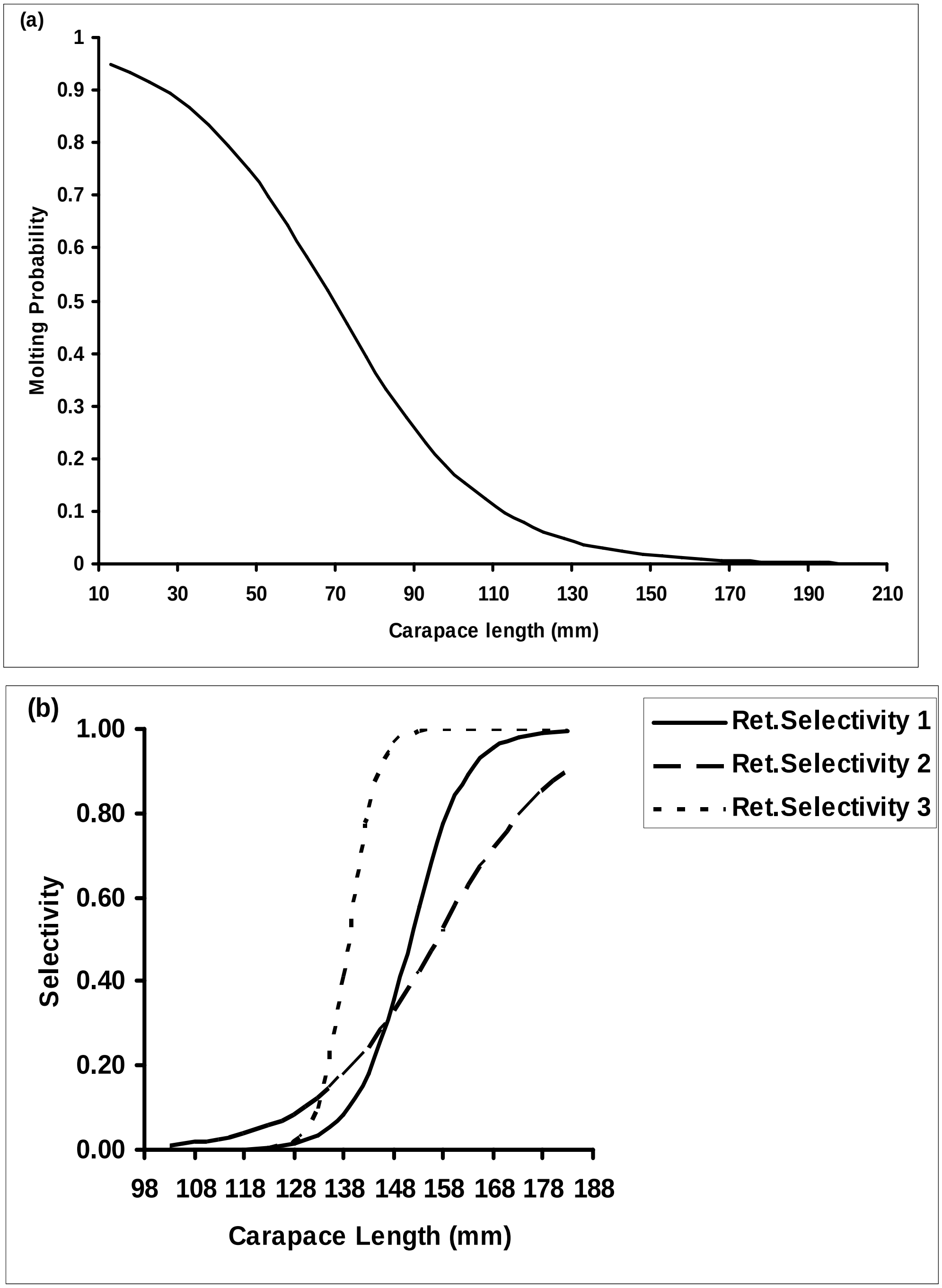


Figure 15. Estimated (a) molt probability and (b) retained selectivities for WS golden king crab. Ret. Selectivity 1 (solid line): retained selectivity curve for the 1989/90-1998/99 period; Ret. Selectivity 2 (dashed line): retained selectivity curve for the 1999/00-2004/05 period; and Ret. Selectivity 3 (dotted line): retained selectivity curve since 2005/06.

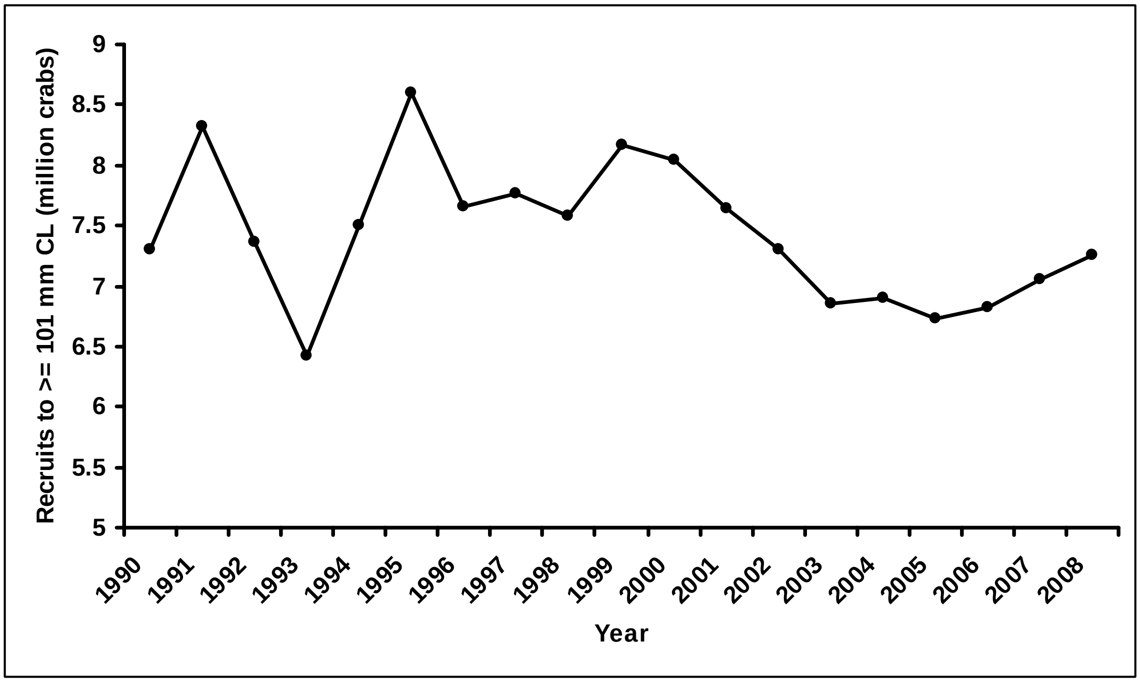


Figure 16. Estimated number of male recruits (millions of crabs ≥101 mm CL) to the golden king crab fishery in the WS, 1990-2008.

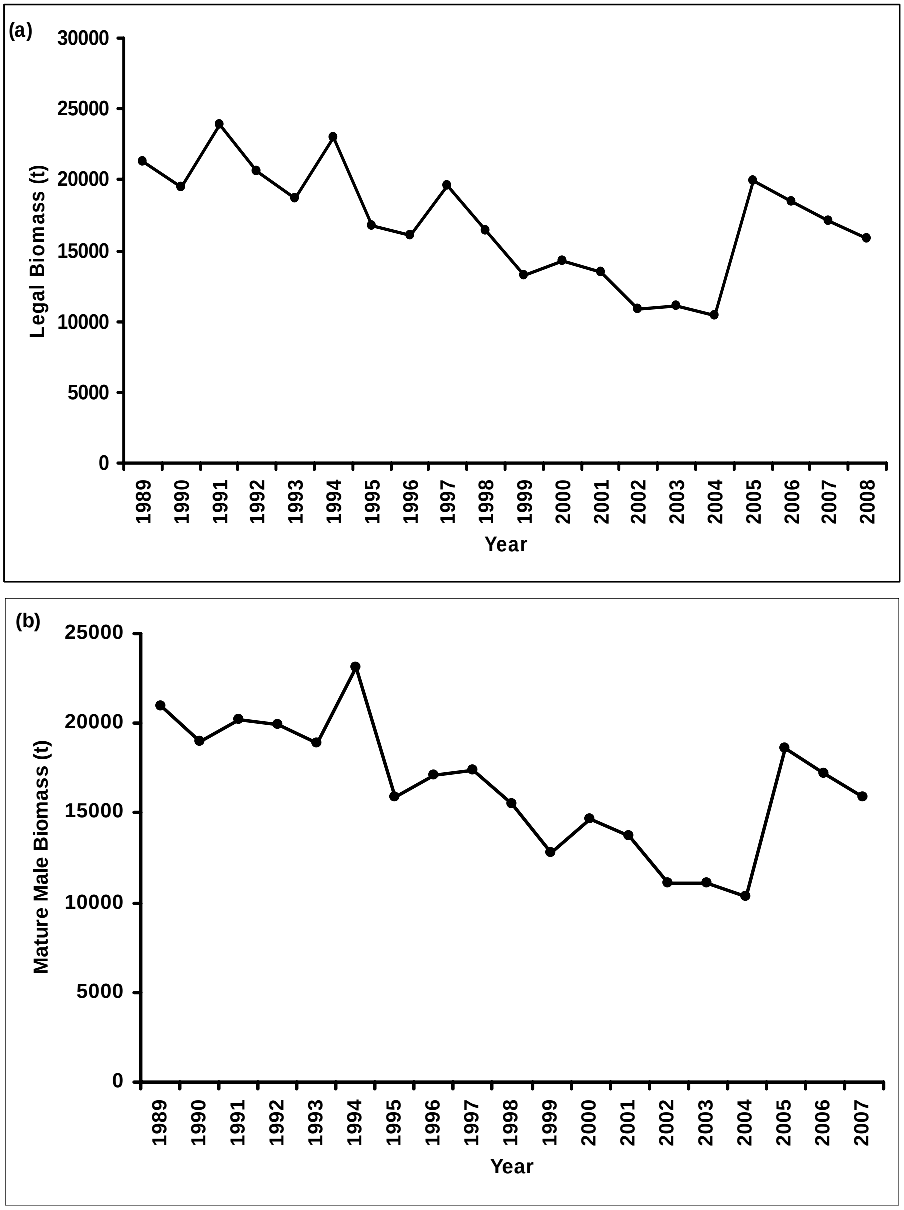


Figure 17. Trends in available golden king crab (a) legal male biomass (t) and (b) mature biomass in the WS, 1989-2008. Legal male crabs are ≥ 136 mm CL and mature male crabs are ≥ 121 mm CL.

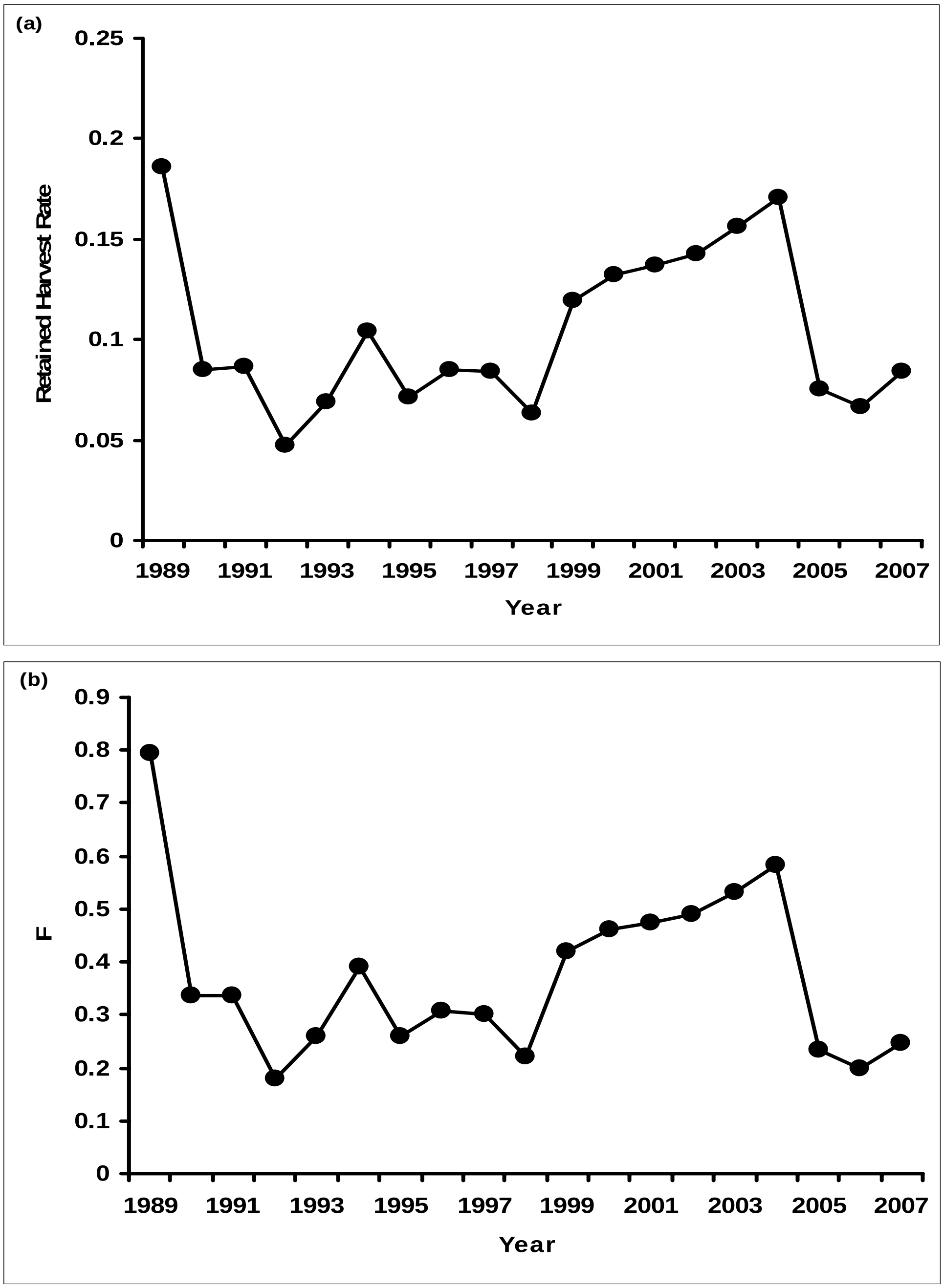


Figure 18. Trends in (a) retained harvest rate and (b) corresponding full selection F of golden king crab in the WS, 1989/90-2007/08. : The years on the X-axis refer to fishing seasons, e.g., 1989 refers to the 1989/90 fishery.

Appendix A: Integrated model

The molting probability (m_i) for a length class i is

$$m_i = 1 - \frac{1}{1 + e^{-a(i-b)}} \tag{1}$$

where a and b are parameters.

A gamma distribution was selected to describe the variation in growth increment per molt:

$$gamma(x / \alpha_i, \beta) = \frac{x^{\alpha_i - 1} e^{-\frac{x}{\beta}}}{\beta^{\alpha_i} \Gamma(\alpha_i)} \tag{2}$$

where x is the growth increment, α_i and β are parameters, and α_i = mean growth increment $/\beta$.

The expected proportion of molting crabs ($P_{i,j}$) growing from length class i to length class j during a year was estimated by

$$P_{i,j} = \frac{\int_{j_1-\tau_i}^{j_2-\tau_i} gamma(x / \alpha_i, \beta) dx}{\sum_{j=1}^{n} \int_{j_1-\tau_i}^{j_2-\tau_i} gamma(x / \alpha_i, \beta) dx} \tag{3}$$

where j_1 and j_2 are lower and upper limits of the receiving length interval j, τ_i is the mid-point of the contributing length interval i, and n is the total number of receiving length intervals. The summation in the denominator is a normalizing factor for the discrete gamma function.

The total number of annual recruits (R_t) was assumed to fall into the first two size groups (101-105 and 106-110 mm CL) only:

$$R_{1,t} = rR_t, \text{ and} \tag{4}$$

$$R_{2,t} = (1-r)R_t \tag{5}$$

where r is a parameter.

Because it is assumed that only a portion of the stock is available for exploitation, a proportionality factor, ν, was used in the population abundance to estimate catch and CPUEs. The total fishery and survey selectivity (s_i^T) were modeled by a logistic function:

$$s_i^T = \frac{1}{1 + e^{-c_k(i-d_k)}} \tag{6}$$

where c_k and d_k are parameters with k = 1 and i is the crab size.

Commercial pot fishery retention selectivity (s_i^r) was also modeled as a logistic function:

$$s_i^r = \frac{1}{1 + e^{-c_k(i-d_k)}} \tag{7}$$

where c_k and d_k are parameters and i is the crab size. Three selectivity with three catchability (q_k) parameters (k = 2, 3, 4) were used to describe the fishery removal during 1990-1998, 1999-2004, and 2005-2006 periods. A separate q_k (k = 1) was considered for the standard pot gear used in the survey.

Initial year (1989 for WS and 1990 for ES) stock abundance was modeled as

$$N_{i,1} = N_1 p_i^N \tag{8}$$

$$O_{i,1} = O_1 p_i^O \tag{9}$$

where N_1 and O_1 are respective total new-shell and old-shell initial abundance parameters and p_i^N and O_i^O are respective relative size frequencies in size class i. The annual abundances by size and shell condition for other years were modeled considering growth, mortality, and recruitment:

$$N_{j,t+1} = \sum_{i}^{j}[(N_{i,t} + O_{i,t})e^{-M} - (C_{i,t} + D_{i,t})e^{(y_t-1)M}]m_i P_{i,j} + R_{j,t+1} \tag{10}$$

$$O_{j,t+1} = [(N_{j,t} + O_{j,t})e^{-M} - (C_{j,t} + D_{j,t})e^{(y_t-1)M}](1 - m_j) \tag{11}$$

where $N_{j,t}$ and $O_{j,t}$ are respective abundances of new-shell and old-shell crabs in length class j on 1 July (start of biological year coincided with mid survey time) in year t; $C_{j,t}$ and $D_{j,t}$ are fishery retained and discard dead total catches (20% discard death rate was used) in length class j and year t; y_t is elapsed time period from 1 July to the mid –point of fishing period in year t; and M is instantaneous natural mortality.

Total catch-per-unit-effort in year t was estimated as

$$C\hat{P}UE_t^T = q_k[\sum_{j}^{n}\{s_j^T \nu\, (N_{j,t} + O_{j,t})e^{-y_t M} - 0.5(\hat{C}_{j,t} + \hat{D}_{j,t})\}] \tag{12}$$

where n is the number of length classes and the ^ sign refers to predicted value.

The predicted retained and discarded dead catches were estimated as

$$\hat{C}_{j,t} = \nu\, (N_{j,t} + O_{j,t})e^{-y_t M}(1 - e^{-F_t s_j^T s_j^r}) \tag{13}$$

$$\hat{D}_{j,t} = 0.2\, \nu\, (N_{j,t} + O_{j,t})e^{-y_t M}(1 - e^{-F_t s_j^T (1 - s_j^r)}) \tag{14}$$

Pot survey $CPUE_t^s$ in year t was estimated as

$$C\hat{P}UE_t^s = q_k \sum_{j}^{n} s_j^T \nu\, (N_{j,t} + O_{j,t}) \tag{15}$$

Assuming that $CPUE_t^s$ have log normally distributed measurement errors, the weighted negative log likelihood for the retained catch-per-unit-effort data is

$$LL_s = 0.5\frac{\sum_t \{\log(C\hat{P}UE^s + c) - \log(CPUE_t^s + c)\}^2}{\sigma_{s,t}^2} \tag{16}$$

where c is a small constant (0.001), $\sigma_{s,t}^2$ is the annual variances of pot survey catch-per-unit-effort.

Retained length composition $L_{j,t}^r$ in year t was computed as

$$\hat{L}^r_{j,t} = \frac{s^T_j s^r_j (N_{j,t} + O_{j,t})}{\sum_j^n s^T_j s^r_j (N_{j,t} + O_{j,t})} \tag{17}$$

Retained length composition is assumed to follow a robust normal distribution and the negative log likelihood is

$$LL_{rL} = 0.5 \sum_t \sum_j \log(\sigma^2_{j,t}) - \sum_t \sum_j \log\left[e^{-\frac{(L^r_{j,t} - \hat{L}^r_{j,t})^2}{2\sigma^2_{j,t}}} + 0.01 \right] \tag{18}$$

Where

$$\sigma^2_{j,t} = \left[(1 - \hat{L}^r_{j,t}) \hat{L}^r_{j,t} + \frac{0.1}{n} \right] / S_t$$

n= number of size classes, and S_t = effective sample size for year t.

Discard catch length composition $L^d_{j,t}$ in year *t* was computed as

$$\hat{L}^d_{j,t} = \frac{s^T_j (1 - s^r_j)(N_{j,t} + O_{j,t})}{\sum_j^n s^T_j (1 - s^r_j)(N_{j,t} + O_{j,t})} \tag{19}$$

Negative log likelihood, LL_{dL}, for discard length composition is similar to equation (18) with discard effective sample size and length composition replacing the corresponding retained values.

Catch biomass in year *t* was estimated assuming pulse fishery

$$\hat{Y}_t = \sum_j^n \nu\, (N_{j,t} + O_{j,t}) e^{-y_t M} (1 - e^{-F s^T_j s^r_j}) w_j \tag{20}$$

where w_j is the mean weight for class *j* crabs.

Assuming that Y_t have log normally distributed measurement errors, the weighted negative log likelihood for the catch biomass data is

$$LL_B = \lambda_B \sum_t \{\log(\hat{Y}_t + c) - \log(Y_t + c)\}^2 \tag{21}$$

where λ_B is the weight.

Harvest rate is estimated as follows:

$$E_t = \frac{C}{\sum_j^n \{ s^T_j s^r_j \nu\, (N_{j,t} + O_{j,t}) e^{-y_t M} - 0.5(C_{j,t} + D_{j,t})}} \tag{22}$$

Mean selectivity is estimated as

$$\bar{s}_t = \frac{\sum_{j=1}^{n} s_j^T s_j^r (N_{j,t} + O_{j,t})}{\sum_{j=legal\ size}^{n} s_j^T (N_{j,t} + O_{j,t})} \tag{23}$$

Mean selectivity is used to estimate *F'* from internally estimated harvest rate as follows:

$$F_t'' = -\log(1.0 - E_t) / \bar{s}_t \tag{24}$$

Assuming lognormal distribution of F, the weighted negative log likelihood is

$$LL_F = \lambda_F \sum_t \{\log(F''_t + c) - \log(F_t + c)\}^2 \tag{25}$$

Assuming lognormal distribution of annual recruitment, the weighted negative log likelihood is

$$LL_R = \lambda_R \sum_t \{\log(R_t) - \log(\bar{R})\}^2 \tag{26}$$

where $\bar{R}$ is the mean recruitment parameter and λ_R is the recruitment weight.

Thus, the total negative log likelihood for minimization is

$$f = LL_s + LL_{rL} + LL_{dL} + LL_B + LL_F + LL_R\,. \tag{27}$$

Following quantities were computed from the estimated parameters:

Vulnerable legal male biomass at the survey time in year *t* is

$$LM_t = \sum_{j=legal\ size}^{n} s_j^T s_j^r \nu\, (N_{j,t} + O_{j,t})\, w_j \tag{28}$$

Mature male biomass on 15 February spawning time (NPFMC 2007) in the following year is

$$MM_t = \sum_{j=mature\ size}^{n} s_j^T s_j^r \nu\, \{(N_{j,t} + O_{j,t}) e^{-y'M} - (C_{j,t} + D_{j,t}) e^{-(y_t - y')M}\}\, w_j \tag{29}$$

where y' is the elapsed time from 1 July to 15 February in the following year.

For estimating next year's limit harvest level from the current year's stock abundance, a limit F' value is needed. The current crab management plan specifies five different Tier formulas for different stocks depending on the strength of information available for a stock, for computing F' (NPFMC 2007). For the golden king crab, the following Tier 4 formula was applied to compute F':

(a) If $MM_t \geq M\bar{M}$, $F' = \gamma M$

(b) If $MM_t < M\bar{M}$ and $MM_t > 0.25M\bar{M}$,

$$F' = \gamma M \frac{(\frac{MM_t}{M\bar{M}} - \alpha)}{(1-\alpha)} \tag{30}$$

(c) If $MM_t \leq 0.25M\bar{M}$, $F' = 0$

where γ is a constant multiplier of M, α is a parameter, and $M\overline{M}$ is the mean mature biomass for a selected time period, which is a proxy for maximum sustainable yield (*MSY*) producing mature biomass under Tier 4.

Because projected MM_t is depended on the intervening retained and discard catch (i.e., MM_t is estimated after the fishery), an iterative procedure was used using equations (29) and (30) with retained and discard catch predicted from equations (13) and (14). The next year limit harvest catch was estimated using equations (13) and (14) with the estimated F' value.