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Aleutian Islands golden king crab (*Lithodes aequispinus*) stock assessment

M.S.M. Siddeek[1], Leslie J. Watson[2], David R. Barnard[2], and Robert K. Gish[2]

Alaska Department of Fish and Game

1. Division of Commercial Fisheries
P.O. Box 115526
Juneau, Alaska 99811

2. Division of Commercial Fisheries
211 Mission Road
Kodiak, Alaska 99615

Executive Summary

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

The Aleutian Islands golden king crab stocks contribute 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 catch, triennial pot survey catch-per-unit-effort (CPUE), observer CPUE, and tagging data. The data series used in the current assessment for the area east of 174°W longitude ranges from 1990 to 2007 for catch and catch length frequency, 1990 to 2007 for observer CPUE and length frequency, and 1997-2006 for triennial pot survey CPUE and tag release-recaptures. Data series considered for the area west of 174°W longitude ranges from 1989 to 2007 for catch, catch length frequency, and observer CPUE and length 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 of the eastern stock indicated that male recruit abundance to the fishery peaked in 1996, declined to the lowest level in 2005, and slightly increased thereafter. The trends in legal and mature male biomasses were high during 1990-1998 and declined thereafter. The estimated retained harvest rate has systematically increased since 1996.

Assessment of the western stock showed that male recruit abundance to the fishery peaked in 2003 and slightly declined thereafter. The trends in legal and mature male biomasses were high during 1990-1998 and declined thereafter. The estimated retained harvest rate has systematically increased since 1998.

The integrated model procedure was used to determine the limit harvest level for both the eastern and western stocks under Tier 4, assuming an *M* value of 0.18 (a default value for all king crab stocks, NPFMC 2007). Two options for limit harvest levels are provided below:

East of 174°W longitude stock:

Mean Mature Biomass Calculation Period	Retained Limit Catch (t)	Discard Limit Catch (t)	Total Limit Catch (t)	Total Limit Catch (million pounds)
1990-2007	1996.0	111.9	2107.9	4.65
1996-2007	2434.5	136.5	2571.0	5.67

West of 174°W longitude stock:

Mean Mature Biomass Calculation Period	Retained Limit Catch (t)	Discard Limit Catch (t)	Total Limit Catch (t)	Total Limit Catch (million pounds)
1990-2007	1733.7	113.0	1846.7	4.07
1996-2007	2347.8	153.0	2500.8	5.51

Because the 2008/09 fishery is in progress, the selected limit harvest level from the above two options can be provisionally considered for the 2009/10 fishing season with the intention of updating the values in May 2009 once the 2008/09 fishery is completed.

Limited data are available on the groundfish bycatch of golden king crab. The 2007/2008 groundfish bycatch from the region was 122.2 t (0.269 million pounds).

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. The model development is ongoing. Following are some research recommendations:

(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.

Some of the above investigation may be under taken in collaboration with the fishing industry.

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 occupy. 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, triennial pot survey CPUE (restricted to east of 174°W longitude stock), observer CPUE, and tagging data (restricted to east of 174°W longitude stock). The 1990-2007 data series from the area east of 174°W longitude and the 1989-2007 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 east of 174°W longitude stock segment is referred to as ES and the west of 174°W longitude stock segment 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. 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, and with the introduction of crab rationalization in 2005, the CPUE increased. This is likely due to gear modification (crab fishers, 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 male CPUE by length, commercial retained and discarded catch by length, triennial pot survey CPUE by length (restricted to the ES), tagged male release-recaptures associated with the four surveys (1997, 2000, 2003, and 2006), and the mean annual growth increment per molt (Watson et al. 2002) are the primary input data and parameter values for the integrated model. The annual CPUE, retained, and discard catch are listed in Table1 for the ES and in Table 6 for the WS; and the tag release-recapture data are provided in Table 2.

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 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 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 season. The annual length-specific CPUEs were summed by length to obtain the total CPUE to use in the maximum likelihood function. The annual length specific discard CPUE was estimated similarly, but using only the sum of discarded legal and sublegal CPUE categories.

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.

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 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.

Four mark-recapture experiments conducted during the surveys in the ES were considered in the analysis to determine a constant natural mortality, *M*, value. Only male release-recapture data were considered (Table 2). The total recovery rate ranged from 11.8% to 22% except for recoveries from the 2006 release, which was 6.4% and for which additional recoveries are expected in the next several years.

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 3 for east the ES and Table 7 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 multinomial length composition, lognormal CPUE, multinomial tag-recaptures (for the ES), lognormal catch biomass, log normal recruit deviation, and a normal natural mortality penalty (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^2_{adj} = 0.93).

Parameters estimated conditionally

The following stock parameters were estimated by minimizing the optimizing function:

a and b: for the molt probability model;

v, 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;

α_r and β_r: for the recruitment distribution model;

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;

F^*_{97}, F^*_{2000}, F^*_{2003}, F^*_{2006}: tagged crab release year additional fishing mortality (to offset non mixing effect);

β: shape parameter of the gamma growth function;

M: natural mortality;

ϕ : tagged population initial survival and a constant reporting rate product;

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, between 1999 and 2004, and 2005 onwards. In 1985, 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 1999-2000, the industry changed the pot webbing to large mesh size (9.5”) (Jeff Davis, Crab fisher, personal communication, July 1, 2008). Since 2005, crab rationalization was in place, which has led to long soak time and hence more self-sorting on the bottom.

Model evaluation

Predicted vs. observed value plots were the major criteria for model evaluation.

The weights attached to negative log likelihood components for the base optimization were:

- For ES: retained CPUE (λ_r = 20), discard CPUE (λ_d =4), pot survey CPUE (λ_s =1), catch biomass (λ_B =1), recruit deviation (λ_R =3), and natural mortality penalty (λ_M =8).
- For WS: retained CPUE (λ_r = 6), discard CPUE (λ_d =1), catch biomass (λ_B =1), recruit deviation (λ_R =4), and natural mortality penalty (λ_M =8).

The weights were chosen arbitrarily to obtain better fits to observed data. However, values of these weights were reduced by 50% and increased by 50% for sensitivity analysis.

Time varying effective sample sizes (K_t) were used for multinomial 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 10).

Results

Model evaluation

ES:

The time series of predicted versus observed retained, discard, and pot survey CPUEs showed reasonably good fits for the ES (Figure 3a-c). The predicted versus observed tag recaptures also depicted a reasonable fit (Figure 4a). Estimated full selection fishing mortality (*F*) based on only tagging and natural mortality penalty negative log likelihoods, the complete negative log likelihood, and the complete negative log likelihood without the tagging component, showed reasonable agreement for the years during which tagged populations were at large (Figure 4b). The time series of predicted vs. observed retained catch relative length frequency (Figure 5) and discard catch relative length frequency (Figure 6) depicted reasonably good fits for the ES. The profile likelihood of model estimated constant *M* indicated a peak near the 0.144 value (Figure 7).

Negative log likelihood components

M penalty	2.52988
Retained length composition	283.862
Discard length composition	404.172
Retained CPUE	75.745
Discard CPUE	27.9289
Pot survey CPUE	0.128852
Tagging	4586.25

Retained catch biomass	88.3763
Recruitment deviation	2.21801
Total	5471.211

WS:

The time series of predicted versus observed retained and discard CPUEs showed reasonably good fits for the WS (Figure 12a-b). The time series of predicted vs. observed retained catch relative length frequency (Figure 13) and discard catch relative length frequency (Figure 14) depicted reasonably good fits for the WS. The profile likelihood of model estimated constant *M* indicated a peak near the 0.14 value (Figure 15).

Negative log likelihood components

M penalty	2.30274
Retained length composition	249.54
Discard length composition	159.123
Retained CPUE	51.8478
Discard CPUE	7.1678
Retained catch biomass	94.4822
Recruitment deviation	0.16573
Total	564.62927

Parameters estimated conditionally

ES:

Table 4 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 83.1 mm CL (Figure 8a). The fishery retention selectivity curves for the three periods (1990-1998, 1999-2004, and 2005-) systematically increased and 50%

selectivity were achieved at 136.2, 141.7, and 96.6 mm CL, respectively (Figure 8b). The catchability in the survey pot gear and the fishery pot gear for the three periods ranged from $4.26*10^{-7}$ to $2.26*10^{-6}$. Fishery catchability has dramatically increased during the latter two periods, perhaps due to increases 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 5. The estimated male recruit abundance to the model peaked in 1996, declined to the lowest level in 2005, and slightly increased thereafter. The recruits entered the model population in the length range 101-110 mm CL (Figure 9a-b). The trends in legal and mature biomasses were high during 1990-1998 and systematically declined thereafter (Figure 10a-b). The estimated retained harvest rate has systematically increased since 1996 (Figure 11).

WS:

Table 8 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 79.5 mm CL (Figure 16a). The fishery retention selectivity curves for the three periods (1990-1998, 1999-2004, and 2005-) systematically increased and 50% selectivity were achieved at 135.5, 140.8, and 137.2 mm CL, respectively (Figure 16b). The catchability ranged from $3.15*10^{-7}$ to $2.08*10^{-6}$ 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 latter two periods, perhaps due to increases 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 9. The estimated male recruit abundance to the model did not show high variation, peaked in 2003, and declined thereafter (Figure 17a). The recruits entered the model population in the length range 121-171 mm CL (Figure 17b). The trends in legal and mature biomasses were high during 1990-1998 and systematically declined thereafter (Figure 18). The estimated retained harvest rate has systematically increased since 1998 (Figure 19).

Harvest alternatives

ES:

The limit harvest level for the ES under Tier 4, assuming an M value of 0.18 (a default value for all king crab stocks, NPFMC 2007), which is equivalent to a γ value of 1.25 with the model estimated M, 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:

Mean Mature Biomass Calculation Period	Retained Limit Catch (t)	Discard Limit Catch (t)	Total Limit Catch (t)	Total Limit Catch (million pounds)
1990-2007	1996.0	111.9	2107.9	4.65
1996-2007	2434.5	136.5	2571.0	5.67

WS:

The limit harvest level for the WS under Tier 4, assuming an *M* value of 0.18, which is equivalent to a γ value of 1.23 with the model estimated *M*, 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)
1990-2007	1733.7	113.0	1846.7	4.07
1996-2007	2347.8	153.0	2500.8	5.51

Because the 2008/09 fishery is in progress, the above limit total harvest levels can be provisionally considered for the 2009/10 fishing season with the intention of updating the values in May 2009 once the 2008/09 fishery is completed.

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 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.

Tag-recapture data in ES indicated the possibility of misclassification of shell condition by onboard observers (Doug Pengilly and Leslie Watson, personal communication, ADF&G, Kodiak). The effect of the possible misclassification of shell condition on the rest of the parameter estimates was minimized by considering the total CPUE (old- and new-shell CPUEs lumped together) from the pot survey and observer samples in the likelihood function.

We used the simple weighted average (weighted by effort) of nominal monthly CPUE (catch in observer samples / number of pot hauls in observer samples) to obtain the annual CPUE. The CPUE can be further standardized for area and time effect to reflect the true stock abundance variation (Starr, 2007).

We formulated the tag-recapture multinomial model incorporating an initial survival parameter to account for initial loss of tagged crabs and a constant under-reporting parameter due to less observer coverage in recent years. These two parameters cannot be separated unless independent experiments are conducted to estimate one of the two or both. Thus, our optimization estimated the product of the two parameters.

The natural mortality was estimated by the model fit, which appears to be slightly low (~ 0.145). 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.

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). 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 stocks analysis for Tier 4 upgrade:

Parameters/Tier	**Parameter values/Tier level**	
	ES	WS
M	0.1442	0.1459
γ	1.25	1.23
Mature male biomass on 15 Feb 2008	23018 t	22848 t
a. Proxy MSY mature male biomass (1990-2007 mean)	38018 t	42848 t
b. Proxy MSY mature male biomass (1996-2007 mean)	32203 t	33384 t
Tier allocation	4(b)	4(b)
Proxy F_{OFL} (1990-2007 option)	0.09	0.08
Proxy F_{OFL} (1996-2007 option)	0.11	0.11
Limit total catch (1990-2007 option)	4.65 million pounds	4.07 million pounds
Limit total catch (1996-2007 option)	5.67 million pounds	5.51 million pounds

Limited data are available on the groundfish bycatch of golden king crab. The 2007/2008 groundfish bycatch from the region was 122.2 t (0.269 million pounds) (Gretchen Harrington, NMFS, personal communication).

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

Table 2. Tagged male golden king crab releases (sublegal and legal crabs ≥ 85 mm CL) and recaptures east of 174°W longitude.

Release Year	Number of Crabs Released	Percent Total Recovery	Number Recaptured										
			1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1997	7,660	22.0	834	495	243	88	17	2	1	0	1		
2000	7,779	14.9				727	227	128	52	19	4	2	
2003	6,174	11.8							318	210	100	82	19
2006	5,235	6.4										228	107

Table 3. 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, 1990-2007. Data are from ADF&G (2008).

Fishing Season	y_t
1990/01	0.2630
1991/02	0.2712
1992/03	0.2740
1993/04	0.4603
1994/05	0.2479
1995/06	0.2219
1996/07	0.3274
1997/08	0.2849
1998/09	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 4. Estimates of parameters by the base model for the golden king crab data from the ES, 1990-2007.

Parameter	Estimate
a	0.0437
b	83.1442
ν	0.0135
c_1	0.3988
d_1	58.0439
c_2	0.3732
d_2	136.2326
c_3	0.0690
d_3	141.7292
c_4	0.0210
d_4	96.6480
α_r	2.8334
β_r	0.2496
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	$4.29*10^{-7}$
q_2	$4.26*10^{-7}$
q_3	$9.84*10^{-7}$
q_4	$2.26*10^{-6}$
F_{90} to F_{07}	0.75, 0.68, 0.15, 0.15, 0.15, 0.75, 0.75, 0.48, 0.55, 0.75, 0.64, 0.26, 0.20, 0.15, 0.17, 0.15, 0.15, 0.15
F^*_{97}, F^*_{2000}, F^*_{2003}, F^*_{2006}	0.08, -0.15, 0.09, 0.05
β	0.4741
M	0.1442
ϕ	0.2568
N_{90} (million crabs)	16.2841
O_{90} (million crabs)	0.0065

Table 5. 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	48,117	49,062
1991	6.3236	49,449	50,539
1992	6.5389	50,297	51,599
1993	6.9415	50,552	52,092
1994	7.5857	50,184	51,993
1995	8.6627	49,292	51,312
1996	10.8879	47,953	50,162
1997	9.9167	46,264	48,625
1998	7.5359	44,324	46,794
1999	6.9326	33,233	32,639
2000	6.3861	31,456	31,340
2001	6.0795	29,723	29,987
2002	5.7374	28,059	28,618
2003	5.5214	26,481	27,265
2004	5.4383	25,000	25,948
2005	5.3417	26,338	26,270
2006	5.4857	24,587	24,794
2007	5.6226	23,018	23,428
2008	6.0783	NA	22,174

Table 6. 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	1,585,080	465,045	8.8093	11.4803
1990	757,610	212,733	4.9755	9.8241
1991	753,415	190,614	7.6125	9.3964
1992	409,373	137,176	5.6989	9.8769
1993	565,336	255,809	6.7760	10.0110
1994	796,258	399,059	6.3274	10.2250
1995	535,553	200,387	4.7003	8.6937
1996	605,137	160,413	5.7014	8.0557
1997	569,550	127,647	6.5811	7.3520
1998	409,531	107,749	10.9770	14.9985
1999	676,558	165,544	6.0588	7.7328
2000	705,613	190,119	6.6000	9.3896
2001	686,738	172,061	6.3609	8.1536
2002	665,045	176,065	7.7090	9.2056
2003	676,633	112,150	9.2891	8.4659
2004	685,465	127,386	10.8300	11.2045
2005	639,368	73,526	21.0381	12.2071
2006	523,701	52,351	21.1843	9.8073
2007	600,604	68,473	20.3124	11.4312

Table 7. 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, 1989-2007. Data are from ADF&G (2008).

Fishing Season	y_t
1989/90	
1990/01	0.7315
1991/02	0.7315
1992/03	0.7329
1993/04	0.7315
1994/05	0.7315
1995/06	0.7315
1996/07	0.7329
1997/08	0.6699
1998/09	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 8. Estimates of parameters by the base model for the golden king crab data from the WS, 1989-2007.

Parameter	Estimate
A	0.0475
B	79.5397
ν	0.0143
c_1	0.4173
d_1	58.0033
c_2	0.5000
d_2	135.5080
c_3	0.1006
d_3	140.7948
c_4	0.0695
d_4	137.1664
α_r	40.0979
β_r	1.2092
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	$3.15*10^{-7}$
q_3	$6.89*10^{-7}$
q_4	$2.08*10^{-6}$
F_{89} to F_{07}	0.72, 0.44, 0.15, 0.15, 0.15, 0.15, 0.66, 0.37, 0.15, 0.15, 0.75, 0.64, 0.62, 0.15, 0.15, 0.15, 0.15, 0.15, 0.15
F^*_{97}, F^*_{2000}, F^*_{2003}, F^*_{2006}	0.07, -0.15, 0.09, 0.05
β	0.9744
M	0.1459
N_{89} (million crabs)	18.3239
O_{89} (million crabs)	0.0070

Table 9. 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	64,198	67,033
1990	6.9611	62,797	65,485
1991	6.9837	61,266	63,904
1992	6.9673	59,518	62,144
1993	7.0454	57,520	60,177
1994	7.1027	55,297	57,994
1995	7.2262	52,913	55,634
1996	7.4379	50,417	53,159
1997	7.6444	47,868	50,616
1998	7.7854	45,324	48,057
1999	7.6233	35,378	35,457
2000	7.6934	33,368	33,765
2001	7.8125	31,481	32,133
2002	7.8446	29,722	30,578
2003	7.9473	28,094	29,108
2004	7.7174	26,591	27,726
2005	7.4281	25,443	26,100
2006	7.2957	24,079	24,879
2007	7.1592	22,848	23,760
2008	6.8698	NA	22,735

Table 10. 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	NC	NC	400	74
1990	300	14	109	16
1991	400	16	133	35
1992	328	24	72	21
1993	28	152*	30	12
1994	49	152*	47	56
1995	105	150	6	400
1996	87	400	78	175
1997	119	357	83	118
1998	128	391	57	77
1999	98	339	68	138
2000	71	132	48	159
2001	73	162	55	139
2002	70	110	49	91
2003	33	101	37	83
2004	51	86	36	75
2005	33	54	34	51
2006	26	41	35	57
2007	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.

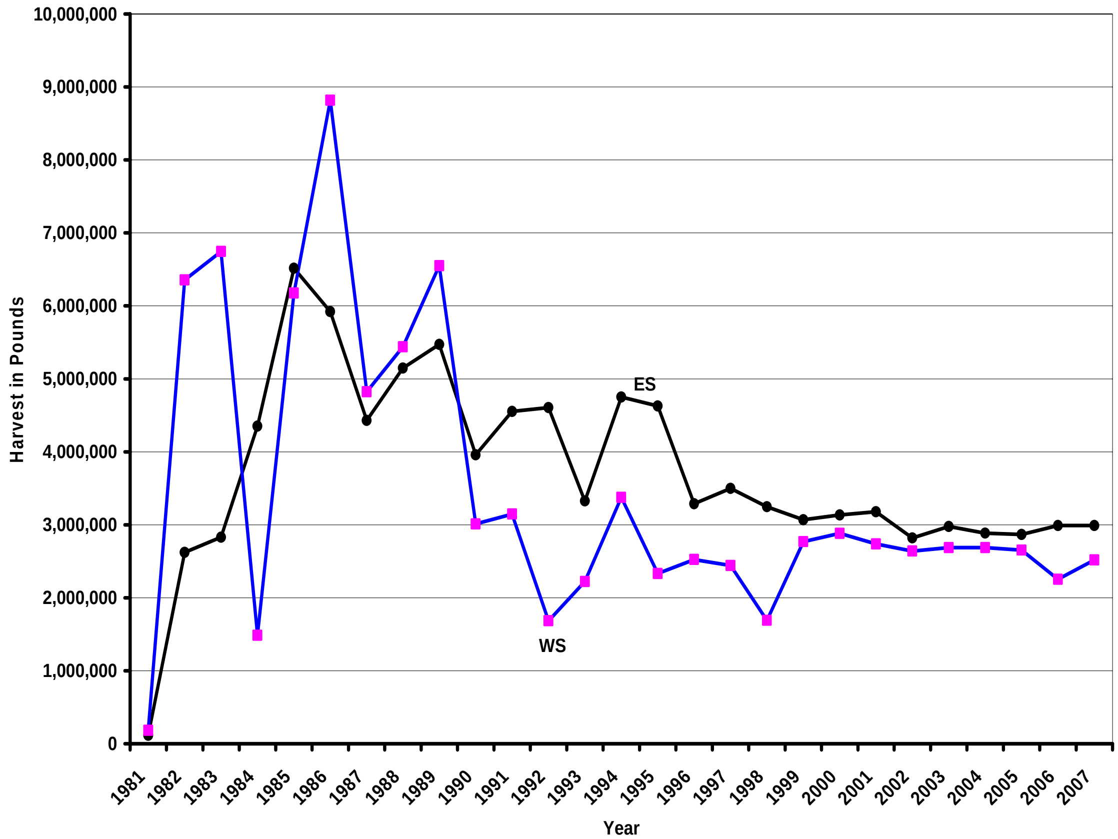


Figure 1. Historical commercial harvest (in pounds) of golden king crab east of 174°W longitude (ES, Eastern Segment) and west of 174°W longitude (WS, Western Segment), 1981-2007.

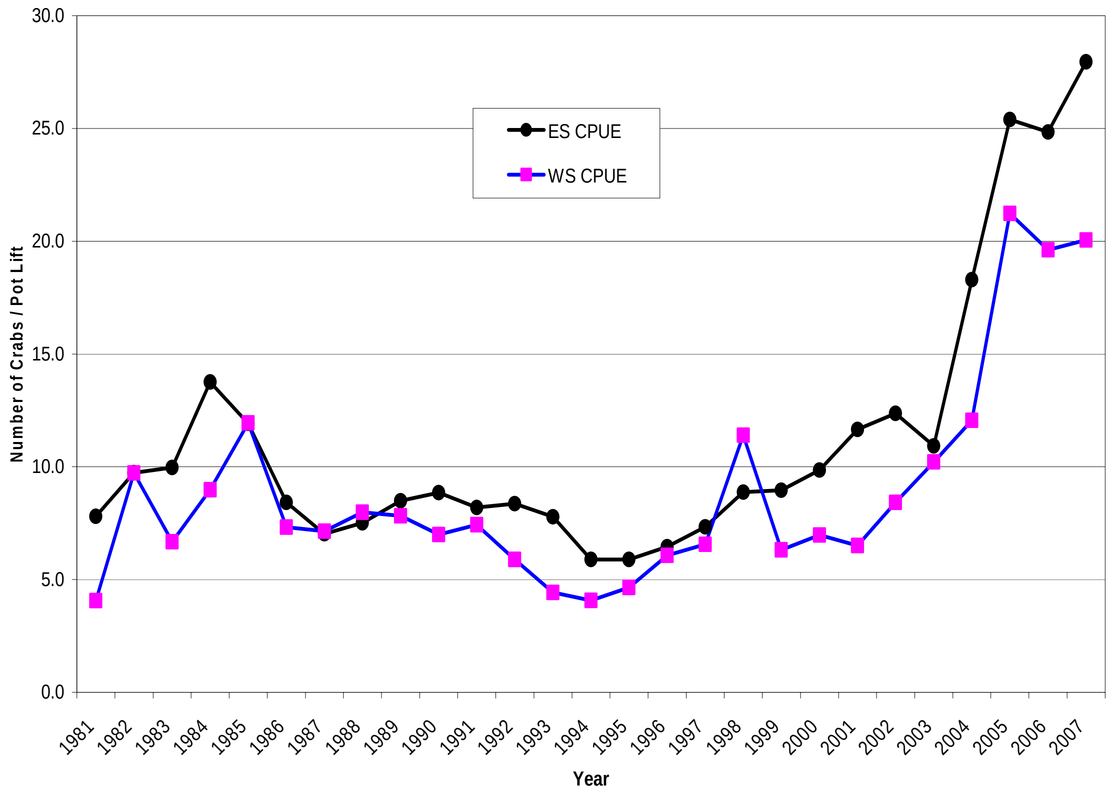


Figure 2. Historical catch-per-unit-effort CPUE (number of crabs per pot lift) in the commercial fishery for golden king crab in the ES and the WS, 1981-2007.

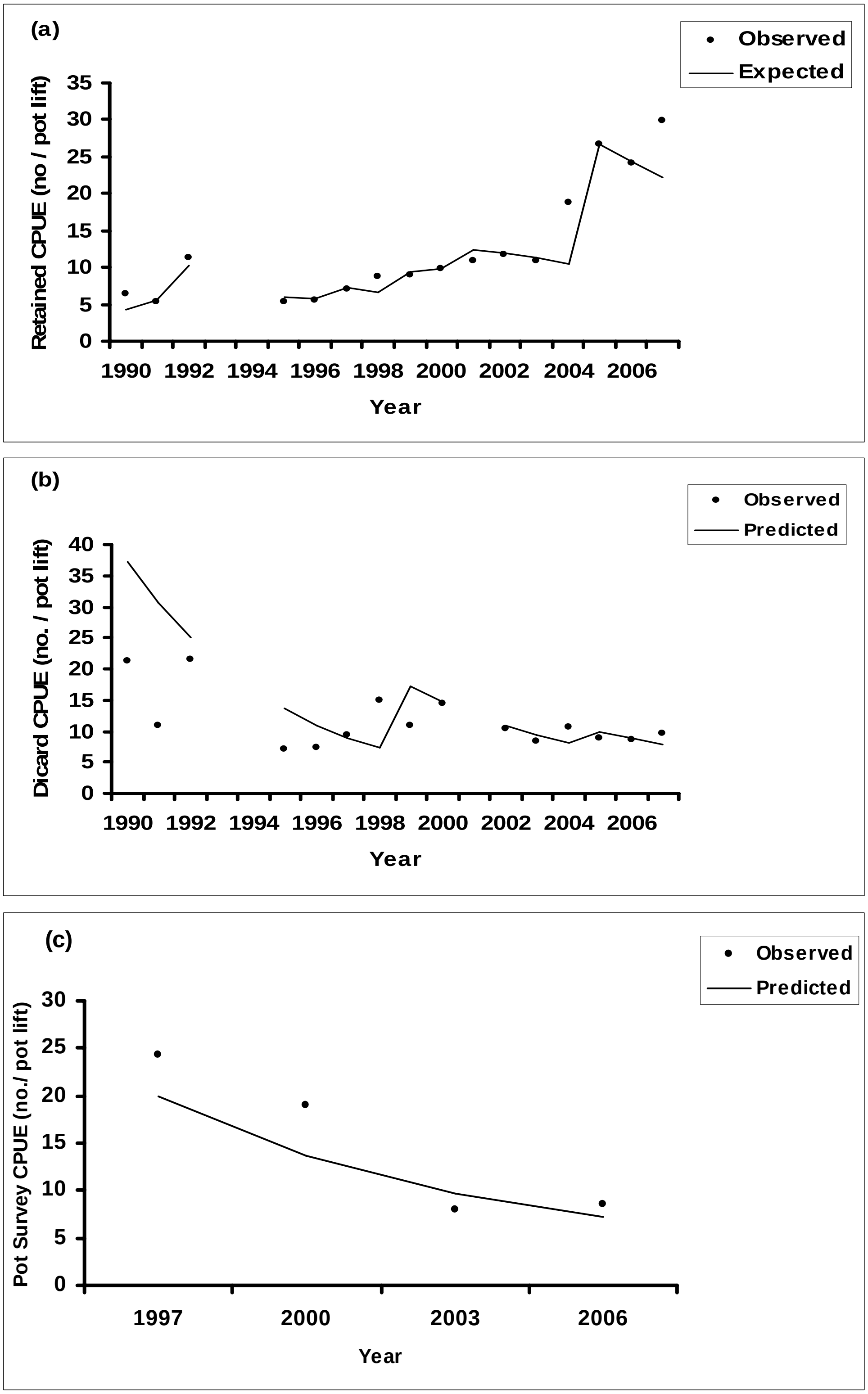


Figure 3. Predicted (line) versus observed (filled circle) (a) retained catch-per-unit-effort (CPUE), (b) discard CPUE, and (c) pot survey CPUE for golden king crab in the ES.

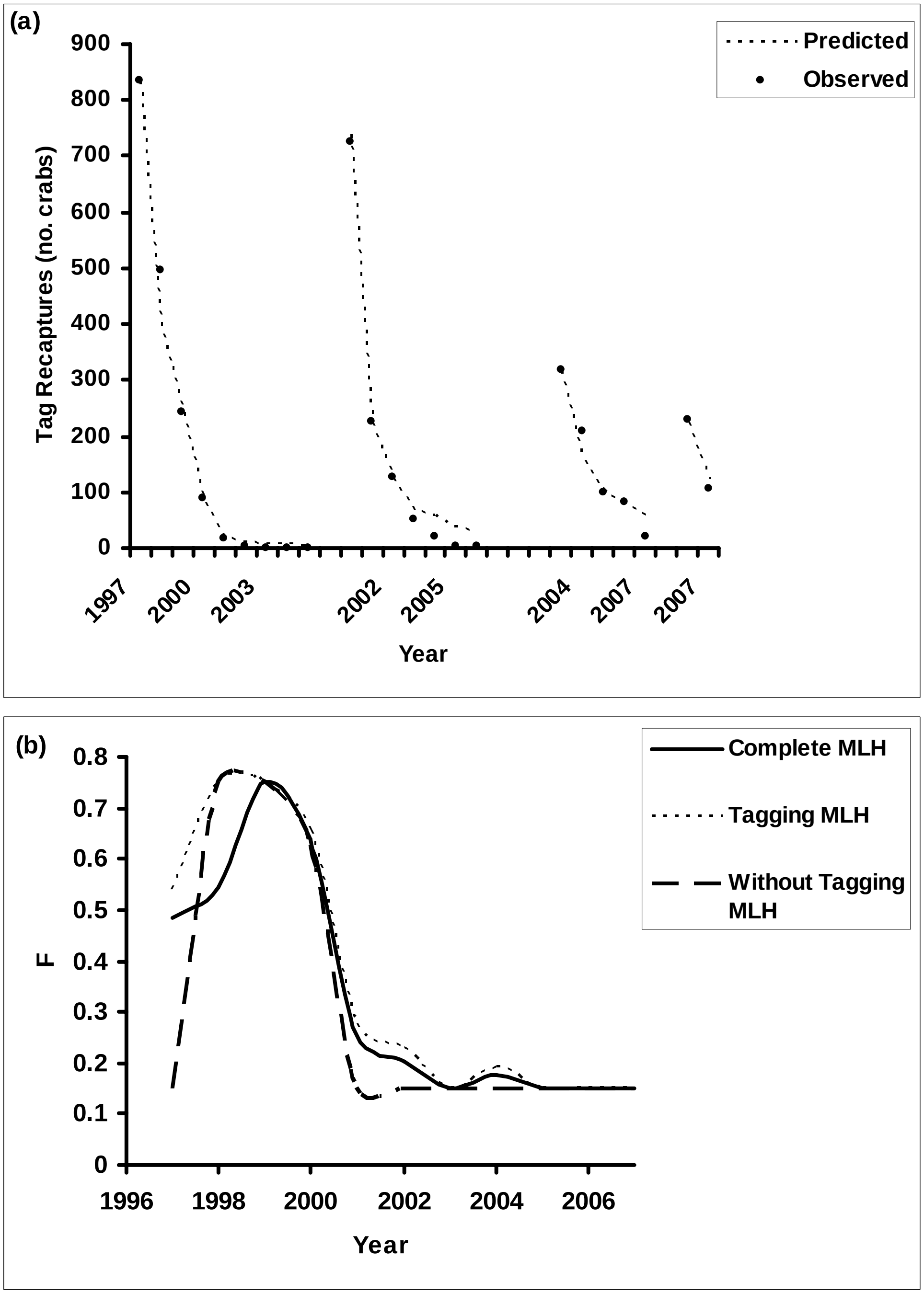
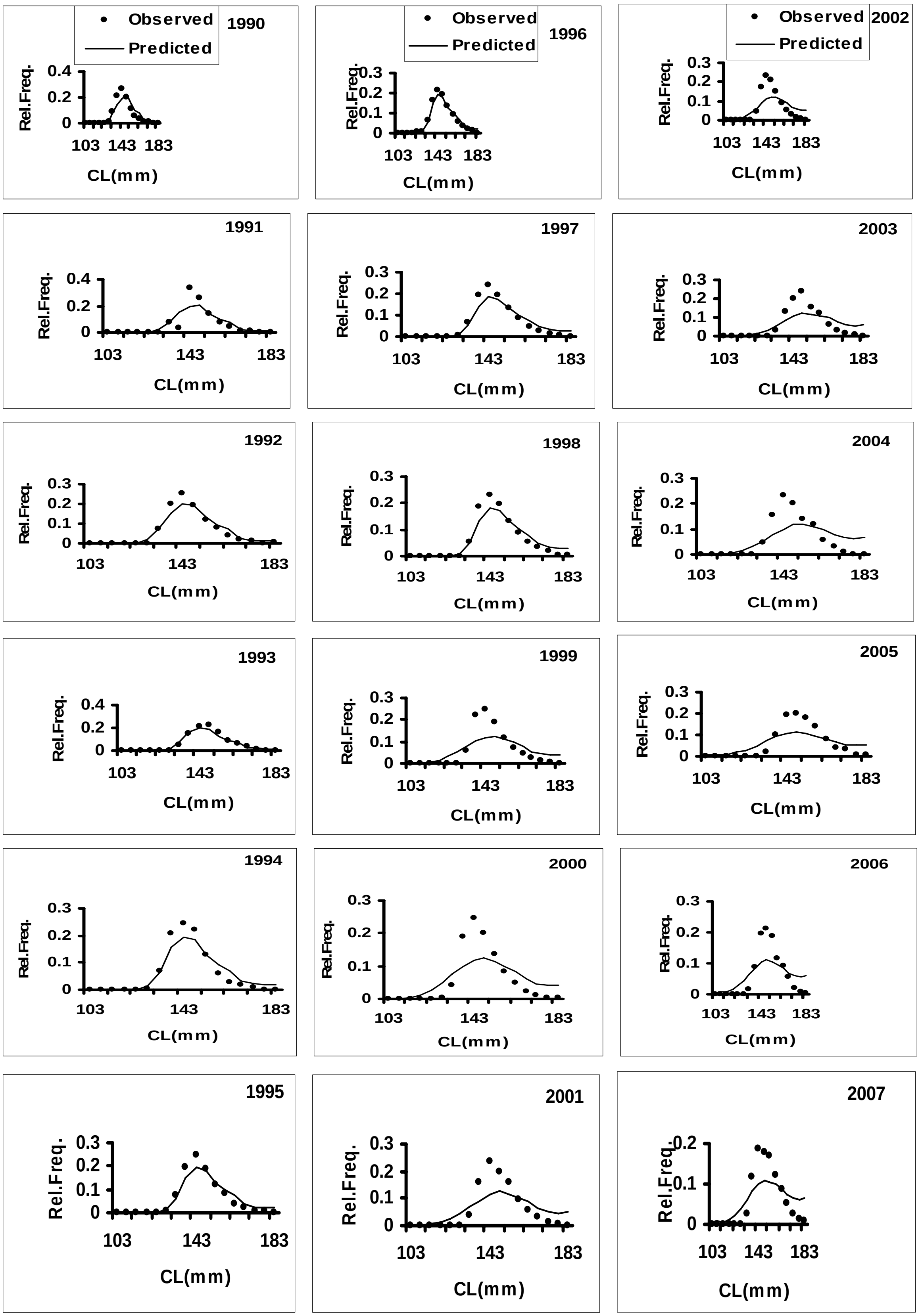


Figure 4. (a) Predicted (line) versus observed (filled circle) annual recaptures of tagged male golden king crab in the ES for the four triennial pot survey releases, 1997-2006. (b) Estimated full selection fishing mortality considering the complete negative log likelihood (line), only natural mortality and tag negative log likelihoods (dotted line), and the full negative log likelihood without tag negative log likelihood (broken line) for the same period.



Observed
Predicted
1990
1996
2002
1991
1997
2003
1992
1998
2004
1993
1999
2005
1994
2000
2006
1995
2001
2007
Rel.Freq.
CL(mm)
103 143 183

Figure 5. Predicted (line) vs. observed (filled circle) retained catch relative length frequency distributions of golden king crab in the ES, 1990 to 2007.

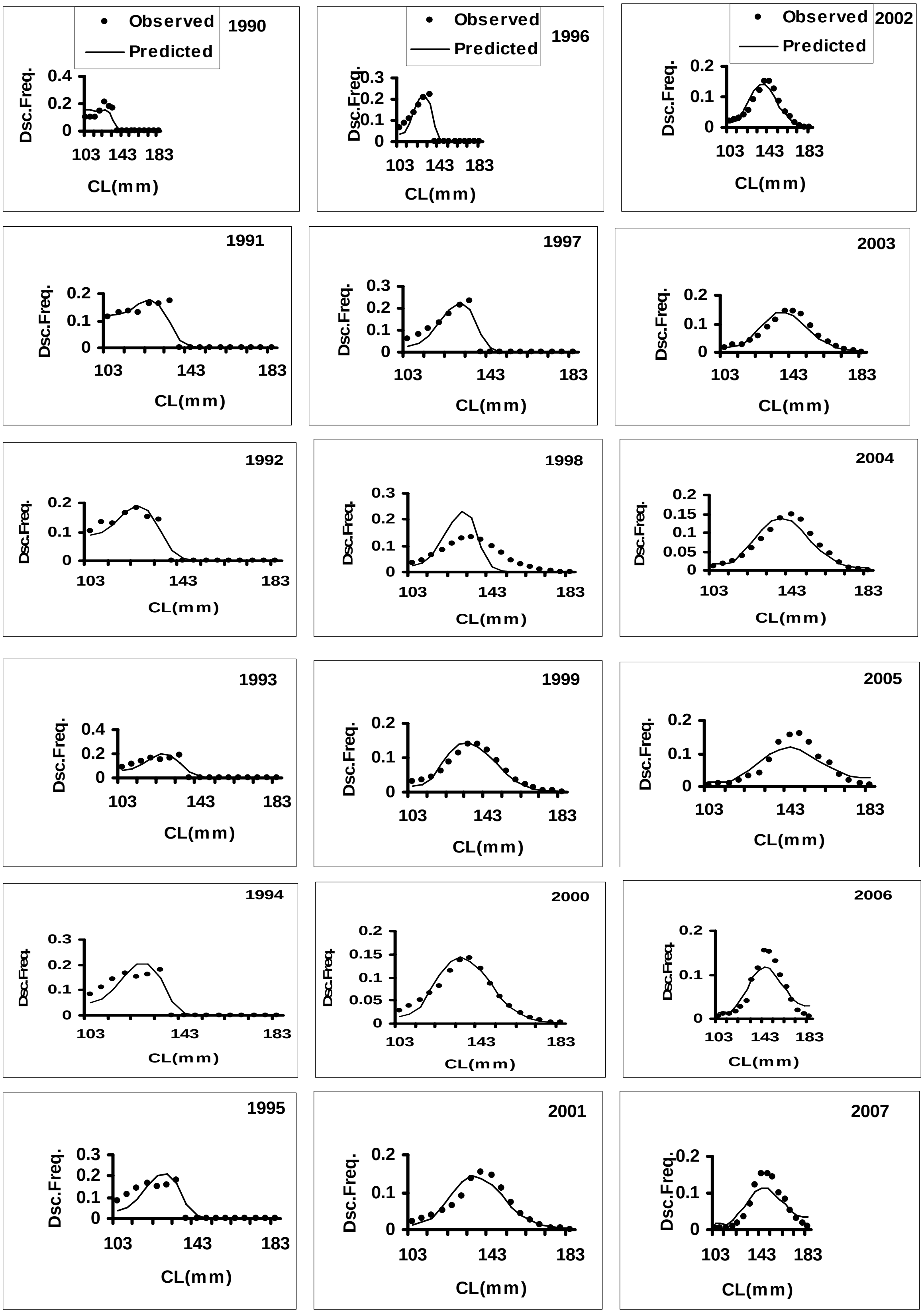

Observed
Predicted
1990
1996
2002
1991
1997
2003
1992
1998
2004
1993
1999
2005
1994
2000
2006
1995
2001
2007
Dsc.Freq.
CL(mm)
103
143
183

Figure 6. Predicted (line) vs. observed (filled circle) discarded catch relative length frequency distributions of golden king crab in the ES, 1990 to 2007.

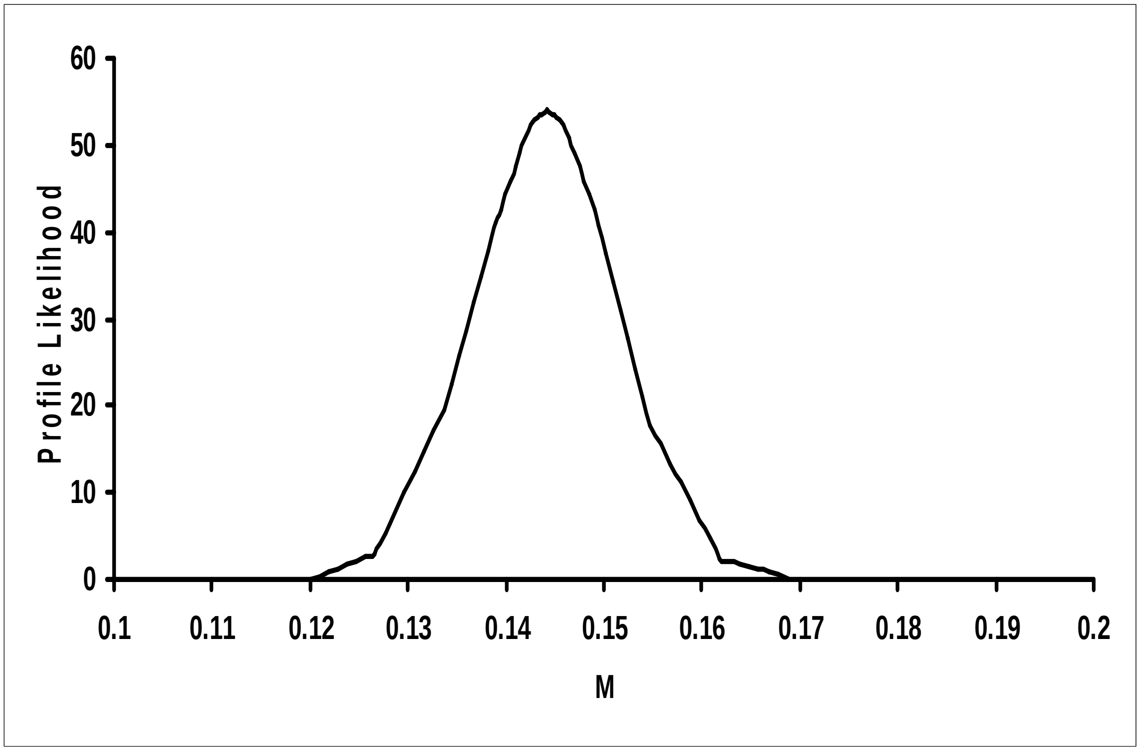


Figure 7. Profile likelihood of estimated natural mortality (*M*) based on 1990-2007 data for ES golden king crab.

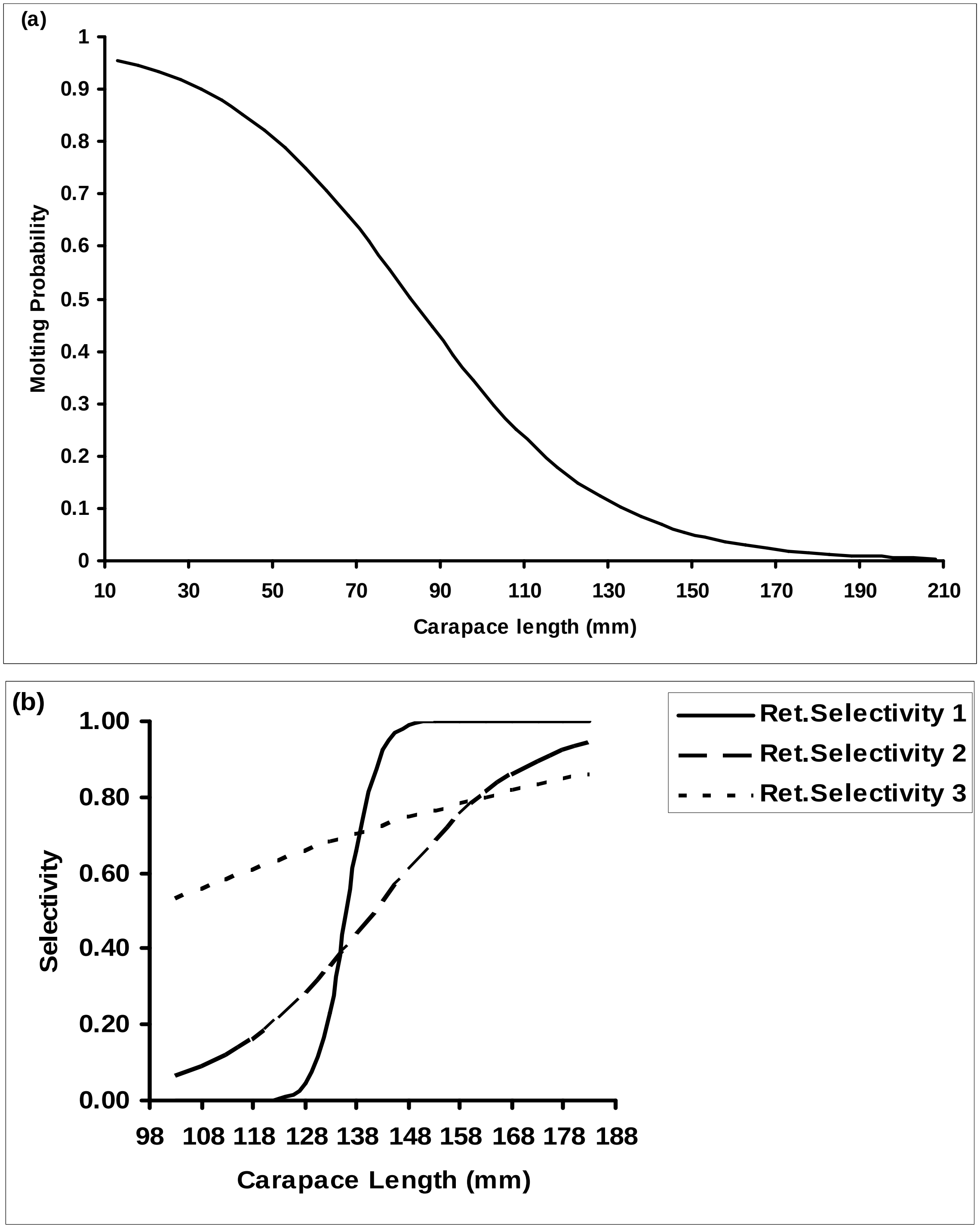


Figure 8. Estimated (a) molt probability and (b) retained selectivities for ES golden king crab. Ret. Selectivity 1 (solid line): retained selectivity curve for the 1990-1998 period; Ret. Selectivity 2 (broken line): retained selectivity curve for the 1999-2004 period; and; Ret. Selectivity 3 (dotted line): retained selectivity curve since 2005.

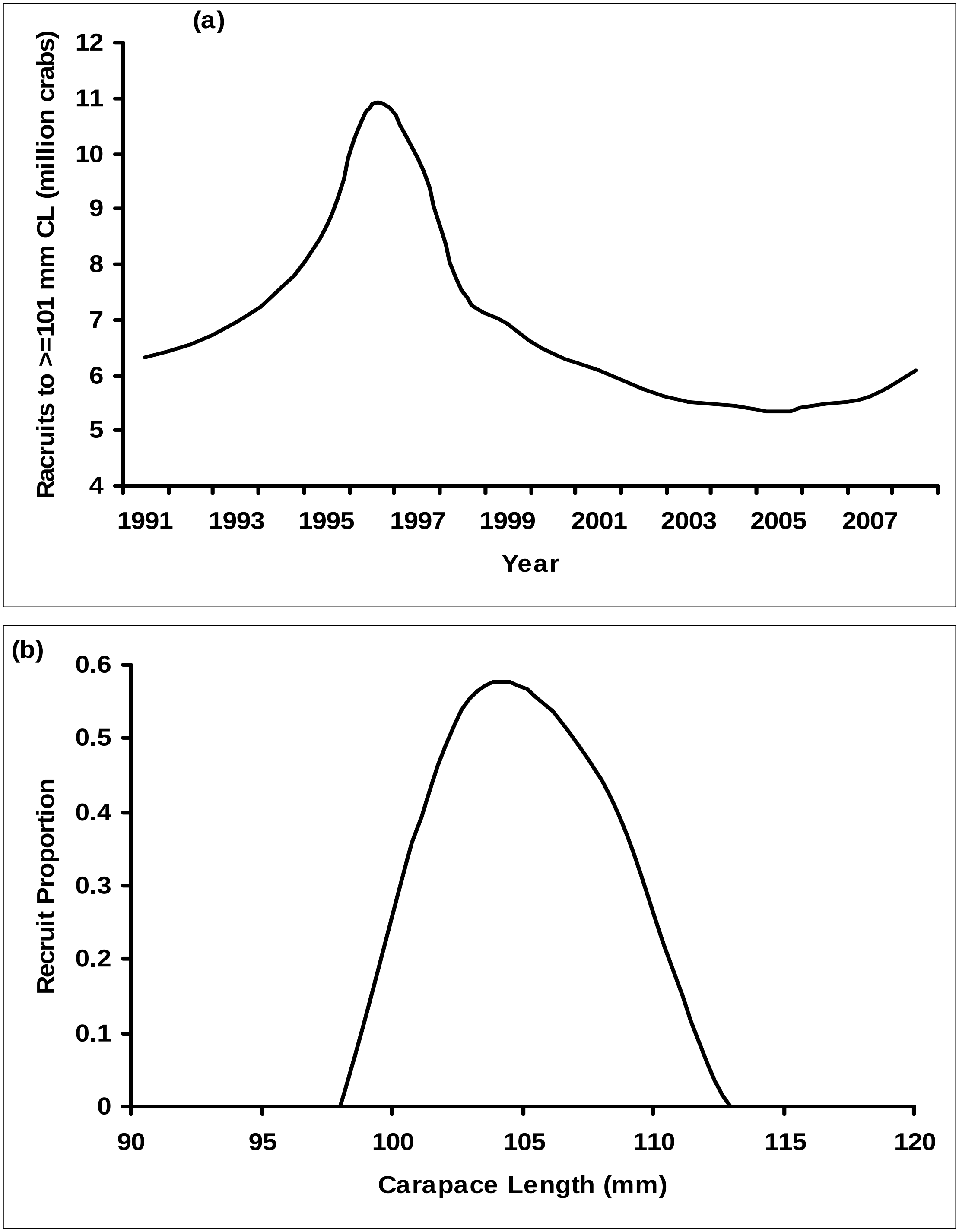
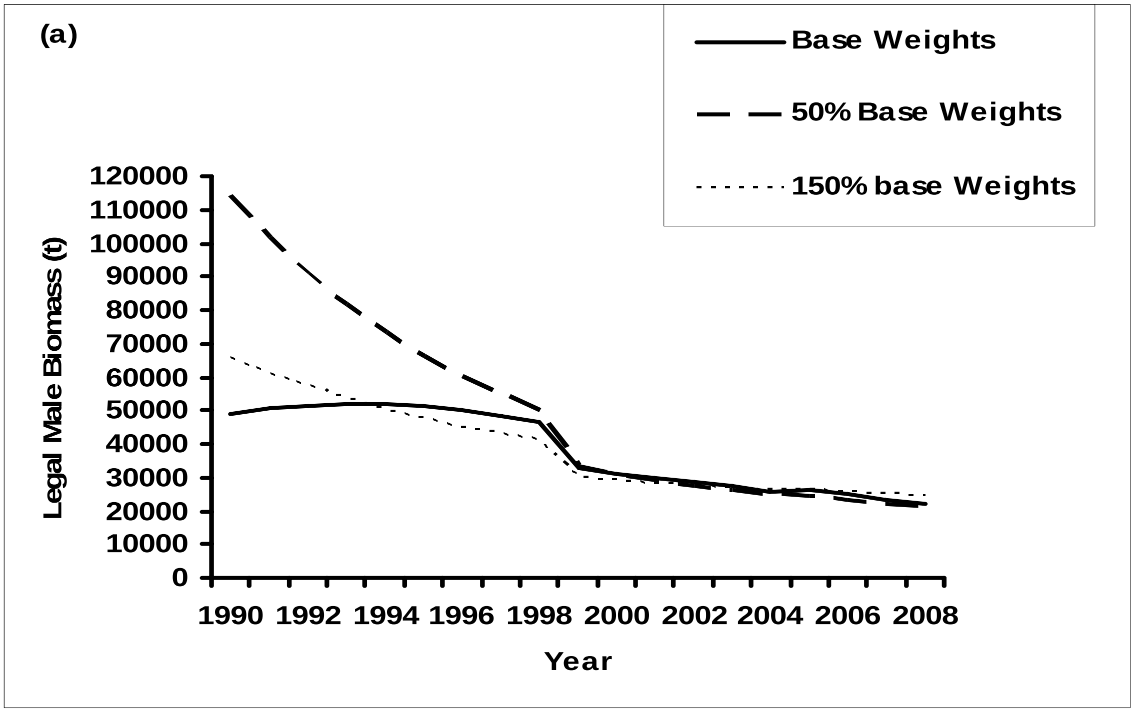


Figure 9. (a) Estimated number of male recruits (millions of crabs ≥ 101 mm CL) to the golden king crab fishery east of 174°W longitude, 1991-2008; and (b) recruit distribution to different length intervals.



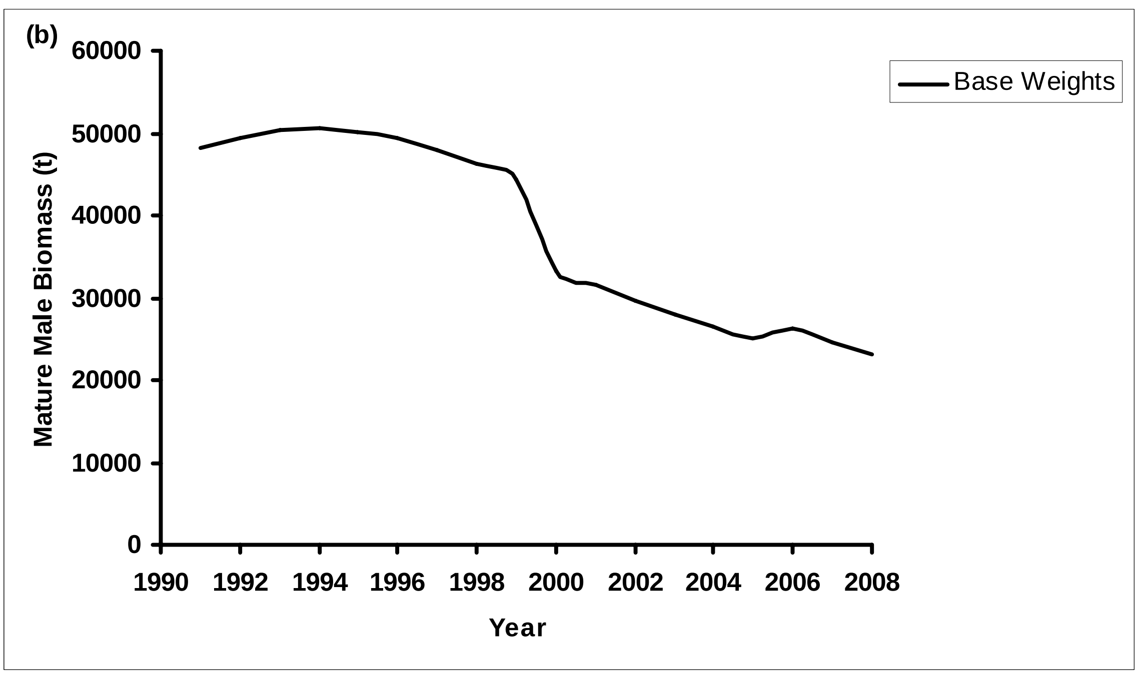


Figure 10. (a) Trends in available golden king crab legal male biomass (t) in the ES, 1990-2008 for different combinations of weights applied to the negative log likelihood components. Trend for the base weights is in solid line; trend for the 50% of the base weights is in broken line; and trend for the 150% of the base weights is in dotted line. (b) Trend in available golden king crab mature male biomass (t) in the ES, 1991-2008 for the

base weights applied to the negative log likelihood components. Legal male crabs are ≥ 136 mm CL and mature male crabs are ≥ 121 mm CL.

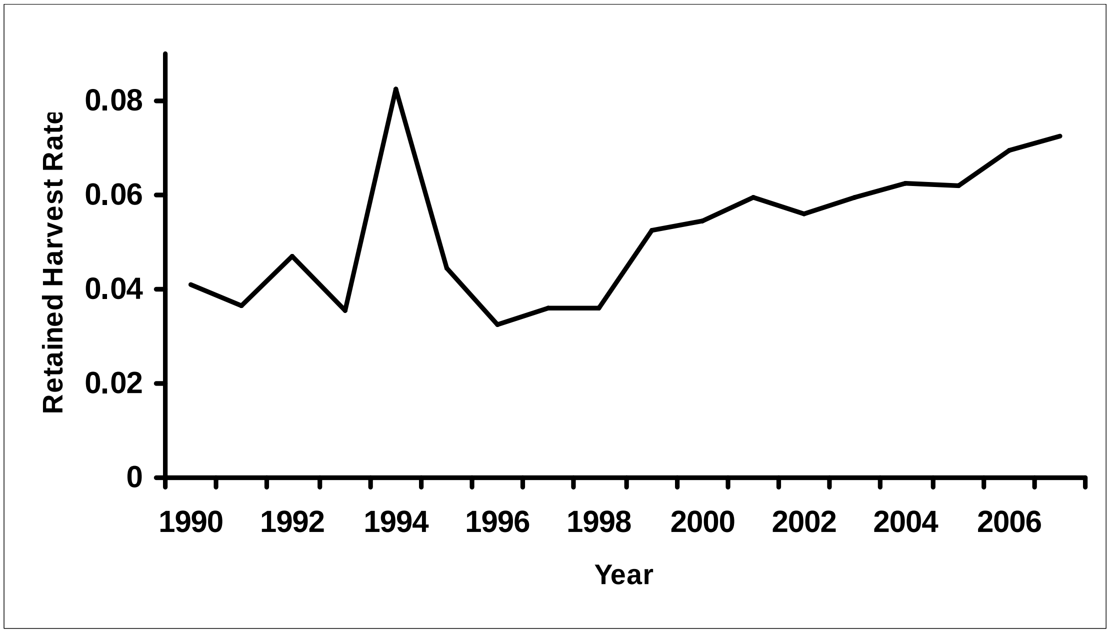


Figure 11. Trend in retained harvest rate of golden king crab in the ES, 1990-2007.

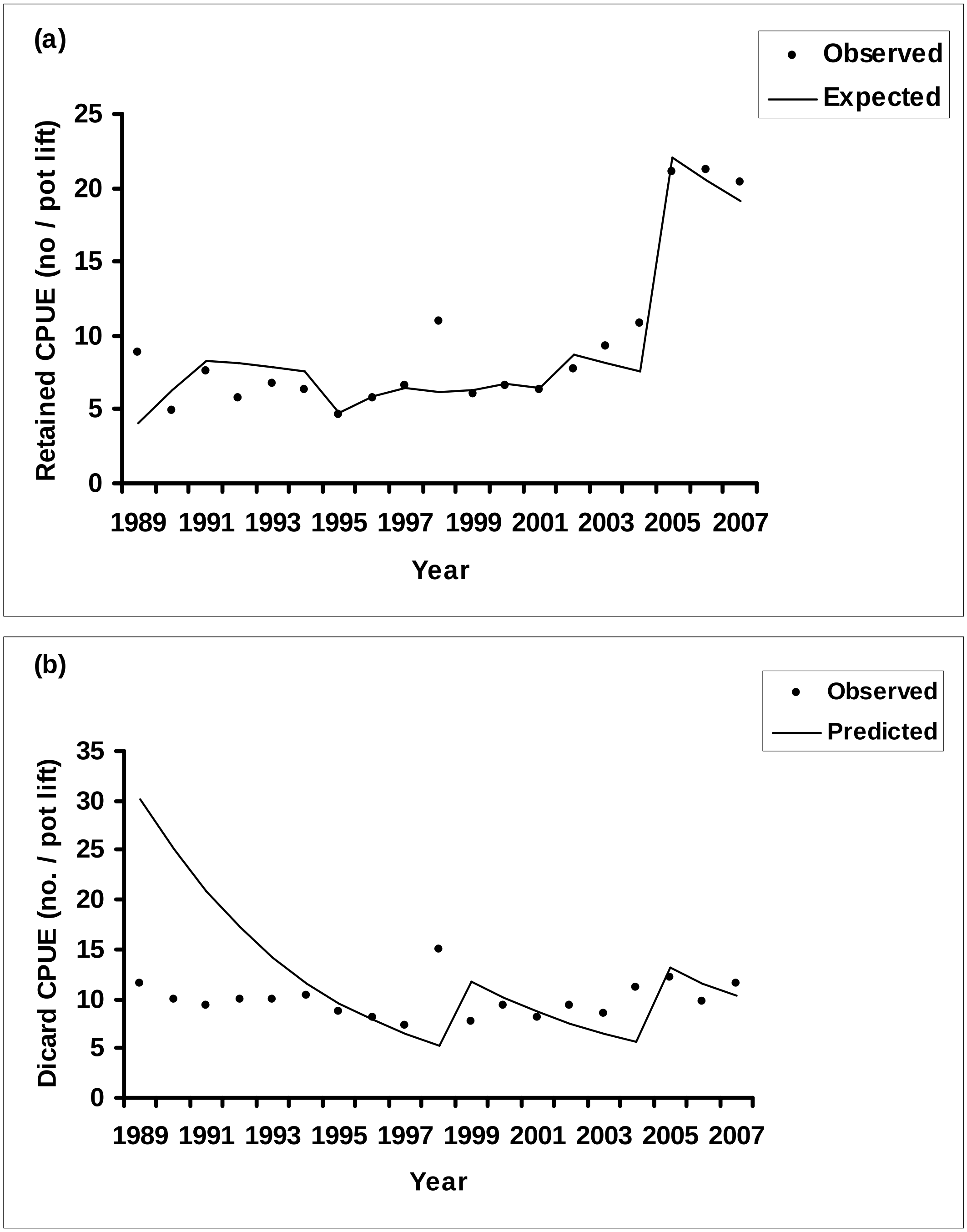
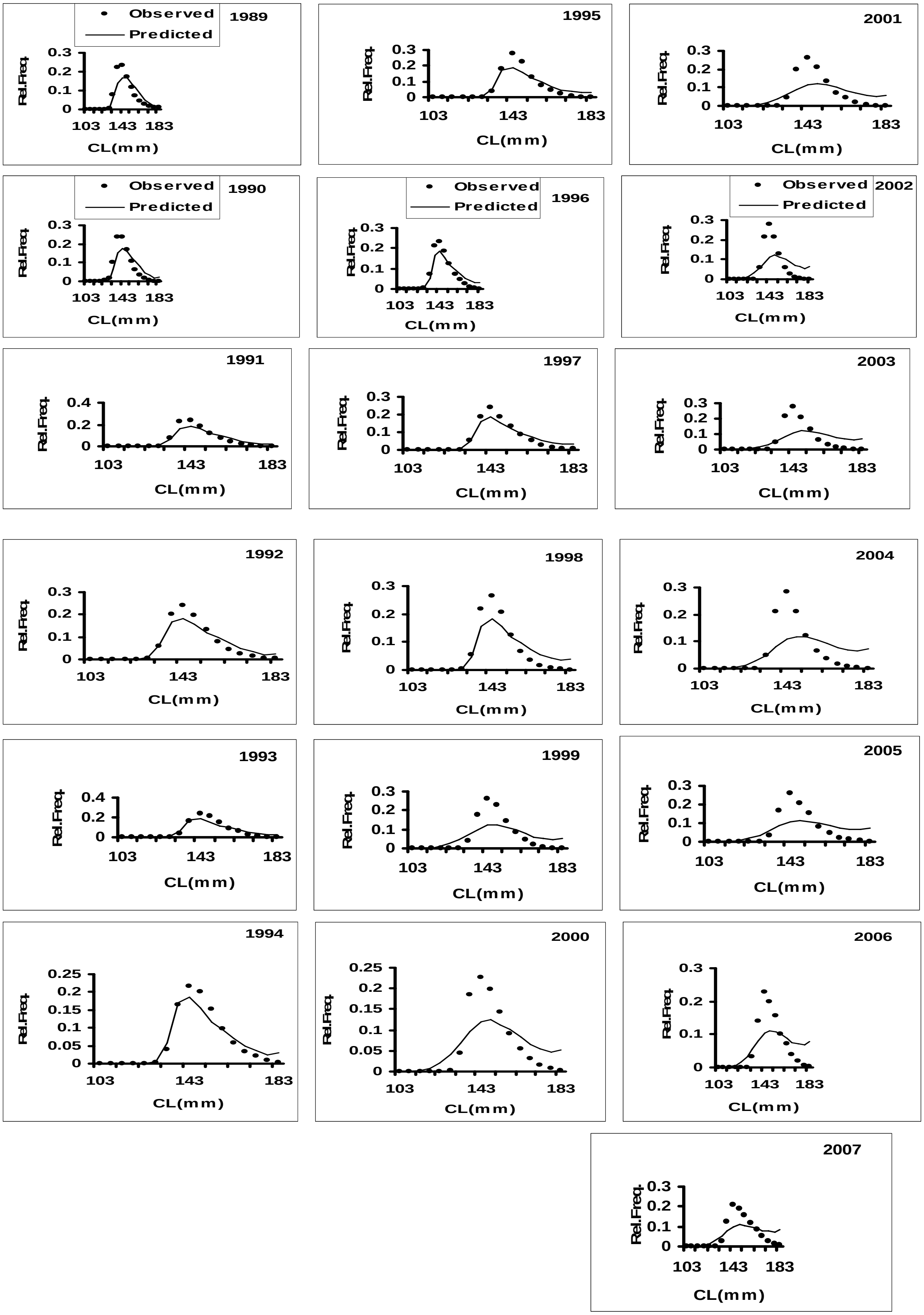


Figure 12. Predicted (line) versus observed (filled circle) (a) retained catch-per-unit-effort (CPUE) and (b) discard CPUE for golden king crab in the WS.


Observed
Predicted
1989
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
1995
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
2001
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
Observed
Predicted
1990
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
Observed
Predicted
1996
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
Observed
Predicted
2002
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
1991
Rel.Freq.
0.4
0.2
0
103 143 183
CL(mm)
1997
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
2003
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
1992
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
1998
Rel.Freq.
0.3
0.2
0.1
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103 143 183
CL(mm)
2004
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
1993
Rel.Freq.
0.4
0.2
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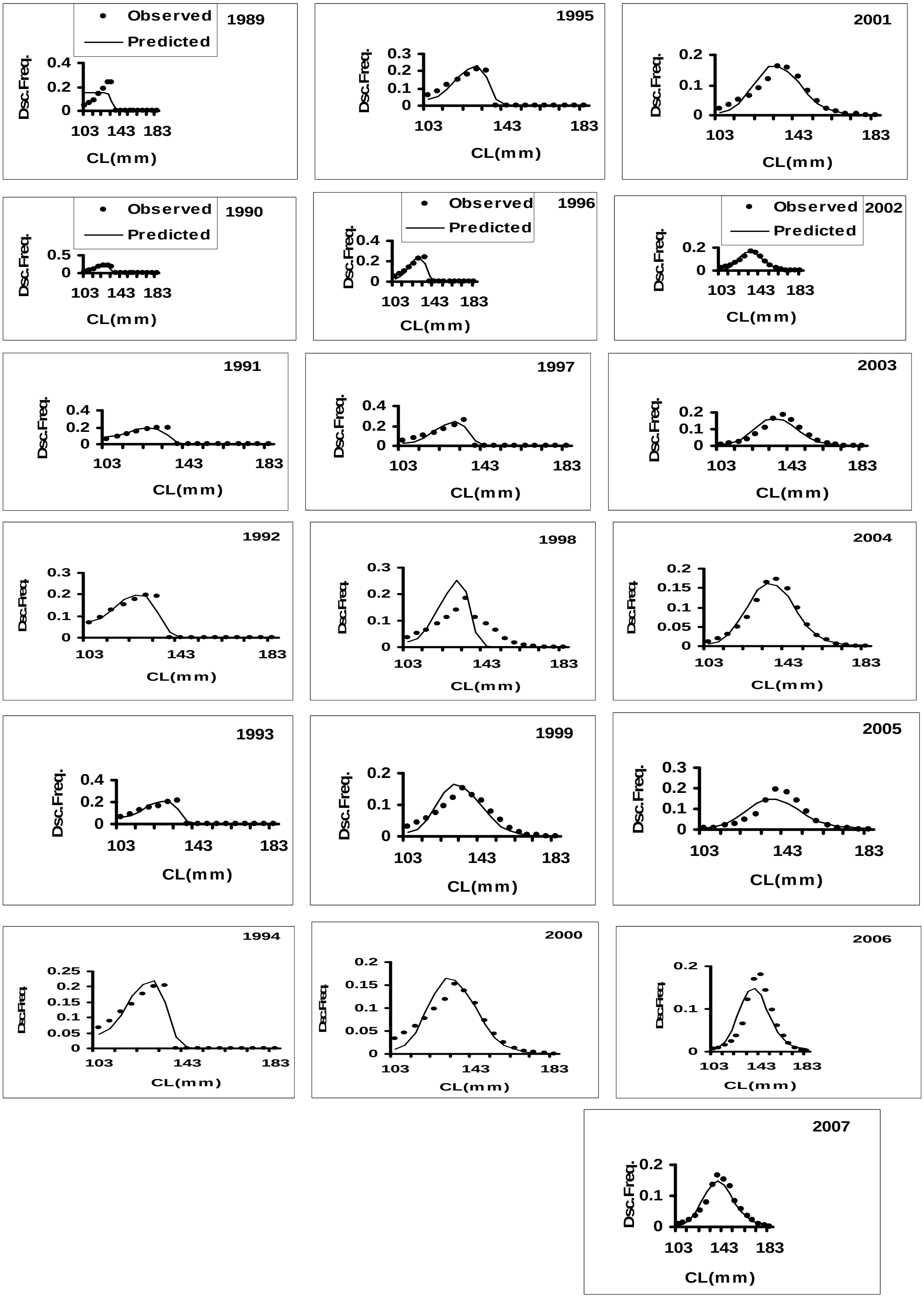
103 143 183
CL(mm)
1999
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
2005
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
1994
Rel.Freq.
0.25
0.2
0.15
0.1
0.05
0
103 143 183
CL(mm)
2000
Rel.Freq.
0.25
0.2
0.15
0.1
0.05
0
103 143 183
CL(mm)
2006
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)
2007
Rel.Freq.
0.3
0.2
0.1
0
103 143 183
CL(mm)

Figure 13. Predicted (line) vs. observed (filled circle) retained catch relative length frequency distributions of golden king crab in the WS,1989 to 2007.



Observed
Predicted
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Dsc.Freq.
CL(mm)
103
143
183

Figure 14. Predicted (line) vs. observed (filled circle) discarded catch relative length frequency distributions of golden king crab in the WS,1989 to 2007.

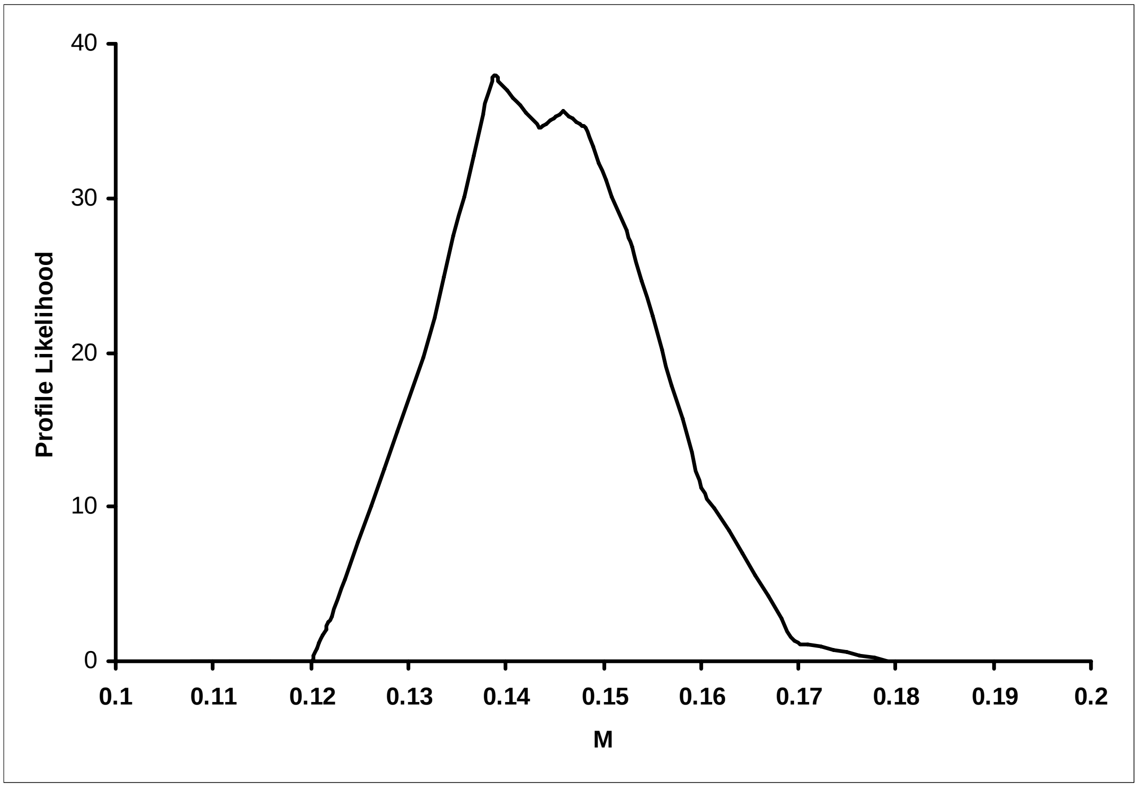


Figure 15. Profile likelihood of estimated natural mortality (*M*) based on 1989-2007 data for WS golden king crab.

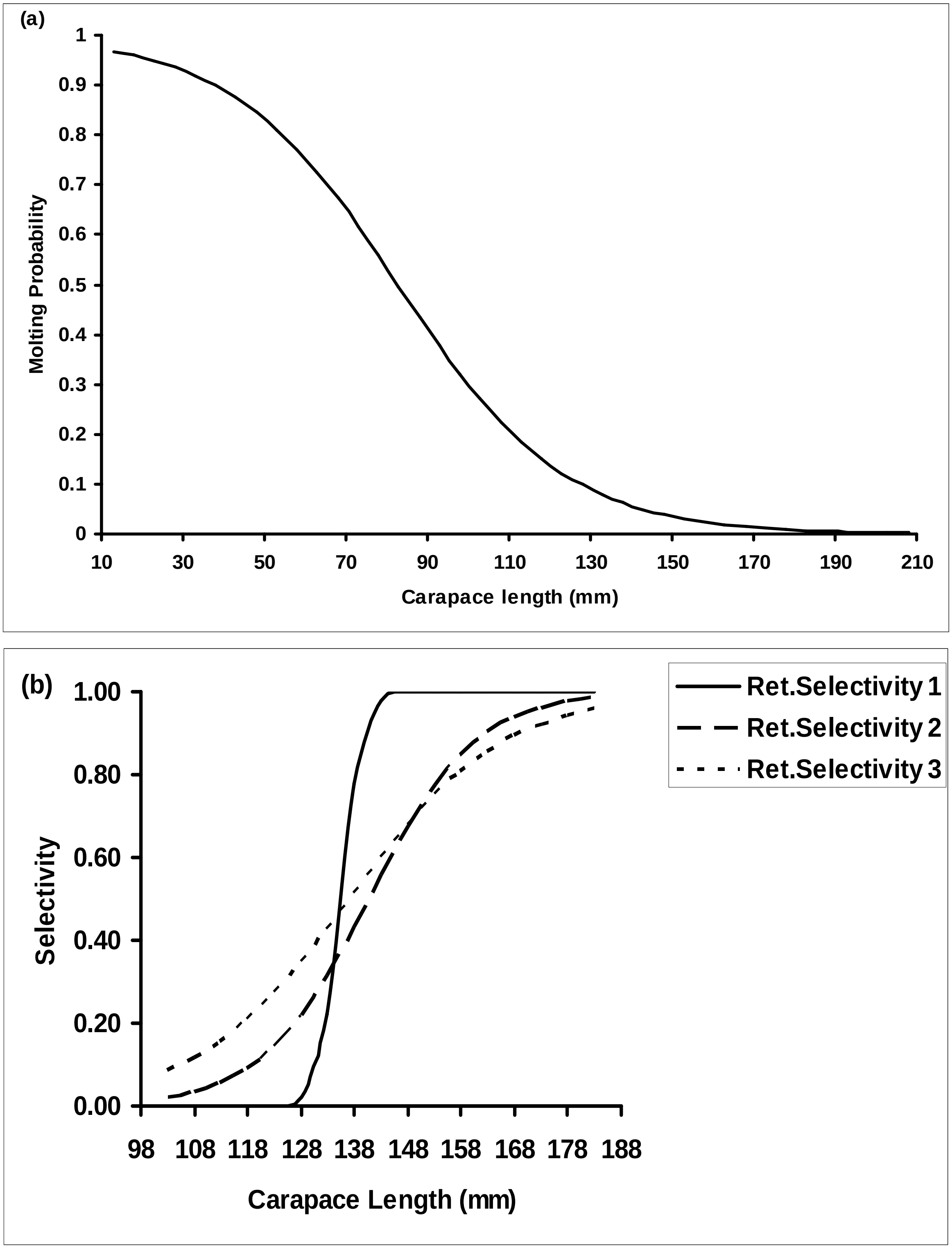


Figure 16. Estimated (a) molt probability and (b) retained selectivities for WS golden king crab. Ret. Selectivity 1 (solid line): retained selectivity curve for the 1990-1998 period; Ret. Selectivity 2 (broken line): retained selectivity curve for the 1999-2004 period; and; Ret. Selectivity 3 (dotted line): retained selectivity curve since 2005.

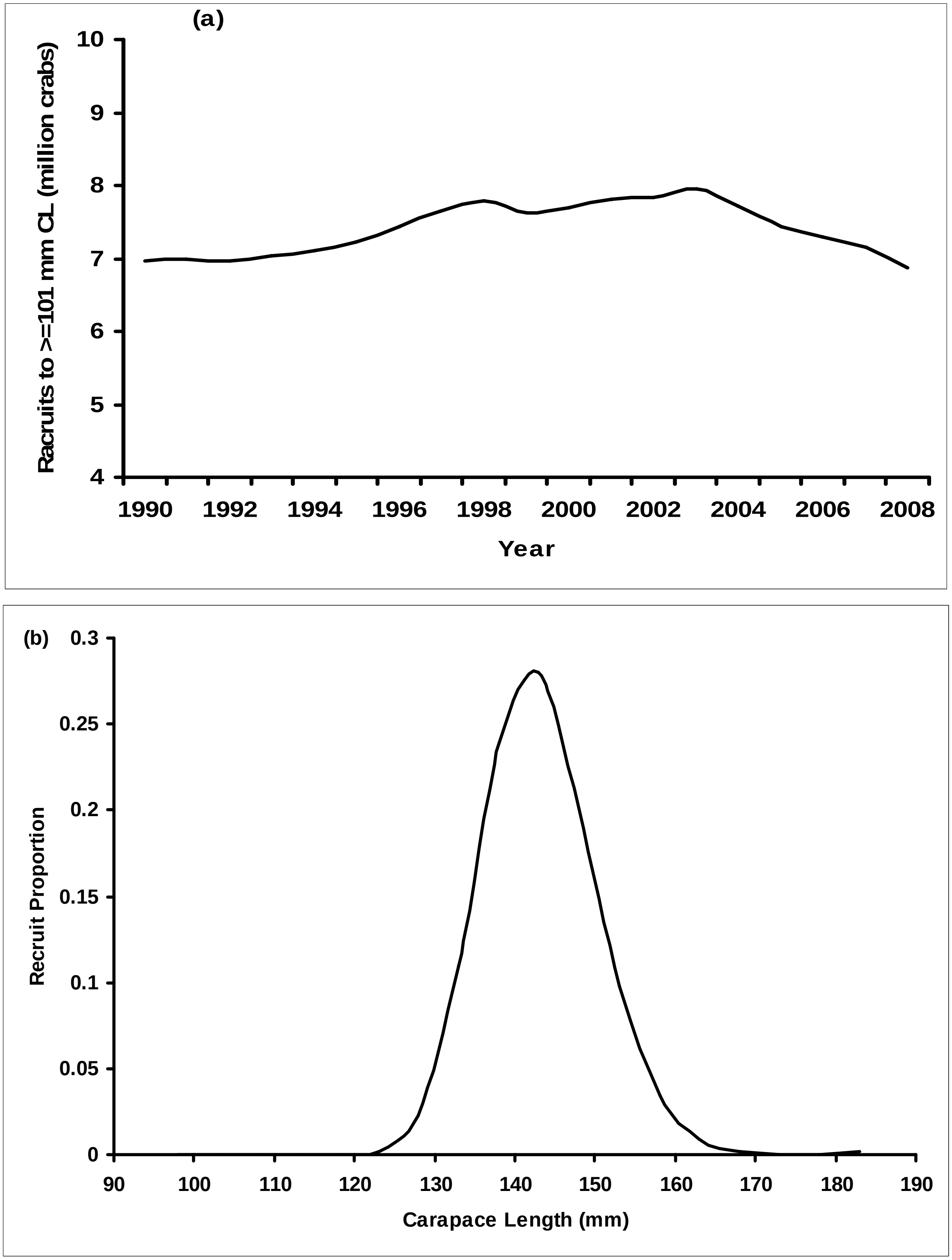


Figure 17. (a) Estimated number of male recruits (millions of crabs ≥101 mm CL) to the golden king crab fishery west of 174°W longitude, 1990-2008; and (b) recruit distribution to different length intervals.

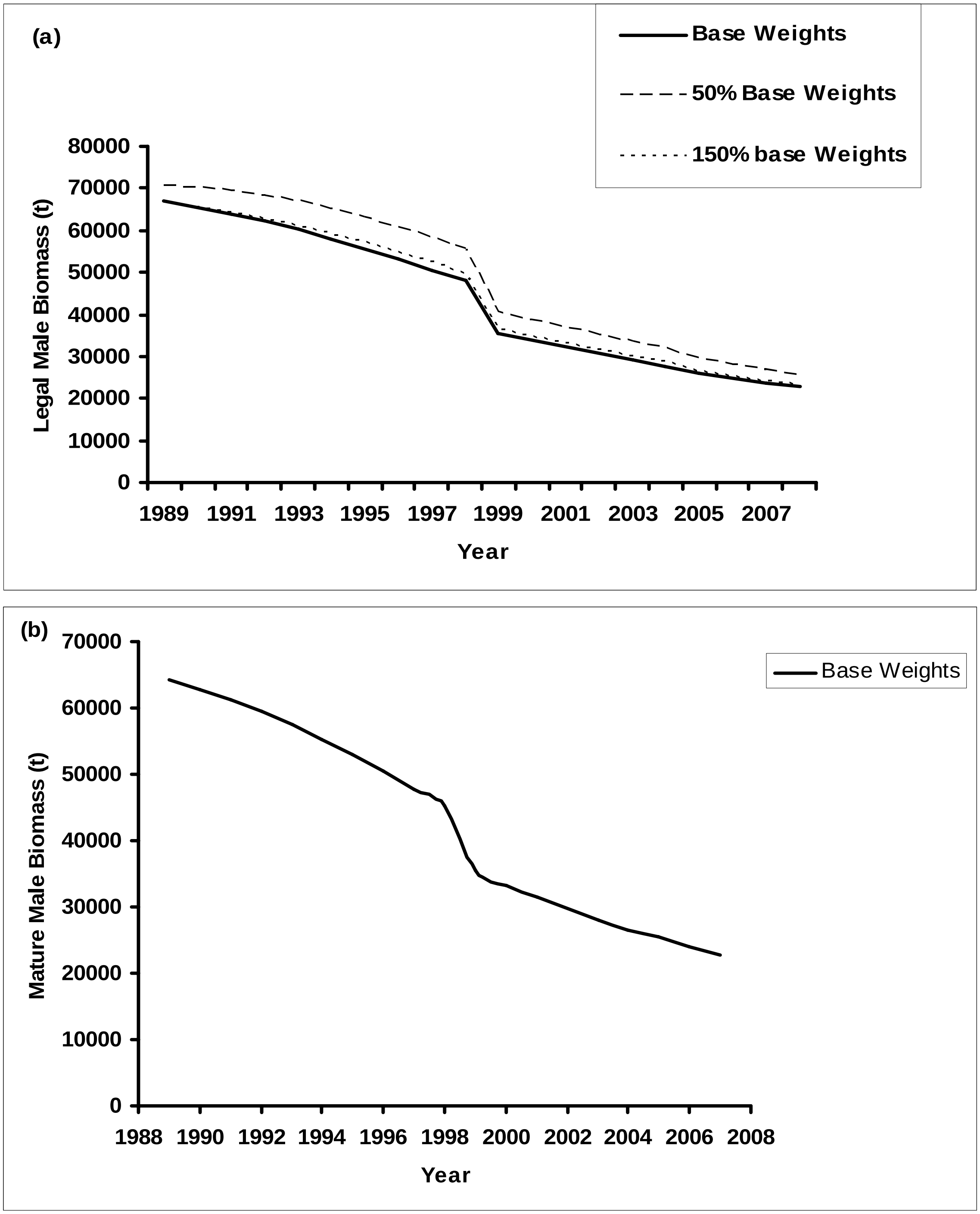


Figure 18. (a) Trends in available golden king crab legal male biomass (t) in the WS, 1989-2008 for different combinations of weights applied to the negative log likelihood components. Trend for the base weights is in solid line; trend for the 50% of the base weights is in broken line; and trend for the 150% of the base weights is in dotted line. (b) Trend in available golden king crab mature male biomass (t) in the WS, 1990-2008 for the base weights applied to the negative log likelihood components. Legal male crabs are ≥ 136 mm CL and mature male crabs are ≥ 121 mm CL.

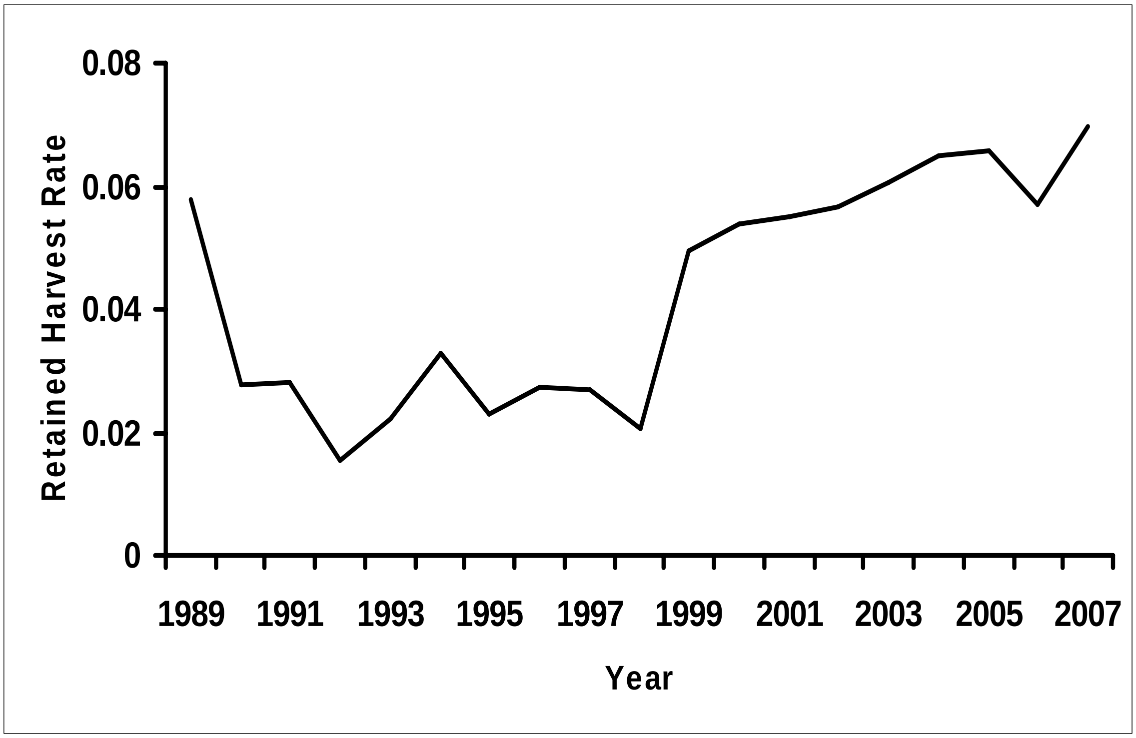


Figure 19. Trend in retained harvest rate of golden king crab in the WS, 1989-2007.

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 /β.

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 (parameter R_t) to the size range 101–185 mm CL was distributed to different length intervals (i) by a fixed proportion (P''_i):

$$R_{i,t} = R_t P''_i \tag{4}$$

where ,

$$P_i'' = \frac{\int_{i_1}^{i_2} gamma(x/\alpha_r, \beta_r)dx}{\sum_{i=1}^{n}\int_{i_1}^{i_2} gamma(x/\alpha_r, \beta_r)dx} \tag{5}$$

where x is the length, α_r and β_r are parameters, i_1 and i_2 are lower and upper limits of the receiving length interval i, and n is the total number of receiving length intervals.

Because only a portion of the stock is available for exploitation, the total fishery and survey selectivity (s_i^T) were modeled by a logistic function with an additional availability parameter, v:

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

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

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

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

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

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

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

Retained catch-per-unit-effort in year *t* was estimated as

$$C\hat{P}UE_t^r = q_k[\sum_j^n \{s_j^T s_j^r (N_{j,t} + O_{j,t})e^{-y_t M} - 0.5(\hat{C}_{j,t} + \hat{D}_{j,t})\}] \tag{15}$$

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

$$LL_r = \lambda_r \times 0.5 \frac{\sum_t \{\log(C\hat{P}UE_t^r + c) - \log(CPUE_t^r + c)\}^2}{\sigma_r^2} \tag{16}$$

where λ_r is the weight, c is a small constant (0.001), σ_r^2 is the variance of retained catch-per-unit-effort.

Discard catch-per-unit-effort, $CPUE_t^d$, in year t was the difference between the total and retained catch-per-unit effort. The weighted negative log likelihood for discard catch-per-unit-effort data, LL_d, is similar to equation (16) with discard weight (λ_d), catch-per-unit-effort, and variance replacing the corresponding retained values.

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

$$C\hat{P}UE_t^s = q_k \sum_j^n s_j^T (N_{j,t} + O_{j,t}) \tag{17}$$

The weighted negative log likelihood for pot survey catch-per-unit-effort data, LL_s, is similar to equation (16) with survey weight (λ_s), catch-per-unit-effort, and variance replacing the corresponding retained values.

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

$$\hat{L}_{j,t}^r = \frac{s_j^T s_j^r (N_{j,t} + O_{j,t})}{\sum_j^n s_j^T s_j^r (N_{j,t} + O_{j,t})} \tag{18}$$

Retained length composition is assumed to be multinomial and the negative log likelihood is

$$LL_{rL} = -\sum_{t}\sum_{j=1}^{n} K_t L^r_{j,t}\{\log(\hat{L}^r_{j,t} + c) - \log(L^r_{j,t} + c)\} \tag{19}$$

where K_t is the effective sample size.

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

$$\hat{L}^d_{j,t} = \frac{s^T_j(1 - s^r_j)(N_{j,t} + O_{j,t})}{\sum_{j}^{n} s^T_j(1 - s^r_j)(N_{j,t} + O_{j,t})} \tag{20}$$

Negative log likelihood, LL_{dL}, for discard length composition is similar to equation (19) with discard effective sample size and length composition replacing the corresponding retained values.

Catch biomass in year t was estimated assuming pulse fishery

$$\hat{Y}_t = \sum_{j}^{n}(N_{j,t} + O_{j,t})e^{-y_t M}(1 - e^{-Fs^T_j s^r_j})w_j \tag{21}$$

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

$$LL_B = \lambda_B \sum_{t}\{\log(\hat{Y}_t + c) - \log(Y_t + c)\}^2 \tag{22}$$

where λ_B is the weight.

Number of tag returns TR^k_t in year t from release k was predicted as

$$T\hat{R}^k_t = \phi N_k e^{-\sum_{tt}^{t-1} Z_{tt} - T_k M}(1 - e^{-F_t \bar{s}_t}) \tag{23}$$

where ϕ is the tagged population initial reduction parameter (initial survival*a constant reporting rate), N_k is the number of tagged crabs released in k th experiment, $Z_{tt} = F_{tt} + M$ in year tt, F_t is instantaneous fishing mortality in year t, and $\bar{s}_t$ is mean selectivity in year t. An additional fishing mortality (F_t^*) is included for the year of release to account for non-mixing of tagged crabs with untagged crabs. Mean selectivity was estimated as

$$\bar{s}_t = \frac{\sum_{j=1}^{n} s_j^T s_j^r (N_{j,t} + O_{j,t})}{\sum_{j=legal\ size}^{n} s_j^T (N_{j,t} + O_{j,t})} \tag{24}$$

Assuming multinomial recapture probability, the negative log likelihood function for tag recaptures is

$$LL_{TR} = -\log[\prod_k \frac{(\phi N_k)!}{(\prod_{t=1}^{T} TR_t^k!)\,(\phi N_k - \sum_{t=1}^{T} TR_t^k)!}(1 - \frac{\sum_{t=1}^{T} T\hat{R}_t^k}{\phi N_k})^{(\phi N_k - \sum_{t=1}^{T} TR_t^k)} \prod_{t=1}^{T} (\frac{T\hat{R}_t^k}{\phi N_k})^{TR_t^k}\ ] \tag{25}$$

where T is the last tag returns year.

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.

A penalty function for M was added to the overall likelihood. Assuming a normal distribution with a 25% coefficient of variation about a mean ($\bar{M}$), assumed to be 0.18 (NPFMC 2007), the weighted negative log likelihood is

$$LL_M = \lambda_M \times 0.5 \frac{(M - \bar{M})^2}{\sigma_M^2} \tag{27}$$

where $\sigma_M^2 = \bar{M}^2 CV^2$.

Thus, the total negative log likelihood for minimization is

$$f = LL_r + LL_d + LL_s + LL_{rL} + LL_{dL} + LL_B + LL_{TR} + LL_R + LL_M \quad . \tag{28}$$

Following quantities were computed from the estimated parameters:

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

$$LM_t = \sum_{j=legal\ size}^{n} s_j^T s_j^r (N_{j,t} + O_{j,t})\, w_j \tag{29}$$

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

$$MM_t = \sum_{j=mature\ size}^{n} s_j^T s_j^r \{(N_{j,t} + O_{j,t}) e^{-y'M} - (C_{j,t} + D_{j,t}) e^{-(y_t - y')M}\}\, w_j \tag{30}$$

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

For estimating next year limit harvest level from current year stock abundance, a limit F' value is needed. 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 $MM_t \geq \overline{MM}$, $F' = \gamma M$

(b) If $MM_t < \overline{MM}$ and $MM_t > 0.25\overline{MM}$,

$$F' = \gamma M \frac{(\frac{MM_t}{\overline{MM}} - \alpha)}{(1 - \alpha)} \tag{31}$$

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

where γ is a constant multiplier of M, α is a parameter, and $\overline{MM}$ 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 (30) and (31) 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.