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

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Preamble

This document provides a model based assessment of the Aleutian Islands east of 174°W longitude (EAG) and west of 174°W (WAG) golden king crab stock segments. An extended pot fishery (1985/86 to 2010/11), triennial pot survey (1997-2006), and groundfish fishery bycatch (1995/96 to 2010/11) data were used to derive OFL and ABC by a Tier 4 approach.

Executive Summary

1. Stock: Golden king crab, *Lithodes aequispinus* / east of 174°W longitude (EAG) and west of 174°W longitude (WAG)

2. Catches:

Aleutian Islands golden king crab 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 has been steady since 1996/97 following 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 an Alaska Board of Fisheries decision. These levels are below the limit TACs determined under Tier 5 criteria (considering 1991-1995 mean catch as the limit catch) under the new crab management plan. The fishery has harvested close to the TAC levels since 1996/97.

3. Stock biomass:

Estimated mature male biomass has decreased from initial years and then increased for both EAG and WAG. The low biomasses for EAG were realized in 1998-99 and the highest in 2002, the low for WAG were realized in 1994-96 and the highest in 1985. Stock trends are similar to fishery CPUE trends in both regions.

4. Recruitment:

The number of recruits to the model size group showed fluctuating trends for both EAG and WAG. For EAG, model recruitment was highest in 1997, lowest in 2001 with a fluctuating trend throughout the years. For WAG, model recruitment was high in different years, e.g., 1987, 2000, 2006, 2007, and lowest in 2008.

5. Management performance:

See Executive summary under Tier 5 analysis in the September 2011 SAFE report. The model has not yet been used for making any management decision.

6. Basis for the OFL:

The length-based model developed for Tier 4 analysis estimates mature male biomass (MMB) each year from 1986 Feb 15 to 2011 Feb 15 and also project to 2012 Feb 15 for OFL and ABC determination. This model proposes the following OFL and ABC based on the 1986-2011 mean MMB as Bref and a projected 2012 Feb 15 MMB. The OFL and ABC estimates are provided for Scenario 1 (nominal observer CPUE data with 5th and

95th percentile cut-off points, denoted by 1)) and Scenario 2 (standardized observer CPUE data with 5th and 95th percentile cut-off points, denoted by 2)):

EAG:

Biomass in million pounds

Year	Tier	B_{ref}	Current MMB	MMB/MMB_{ref}	F_{OFL}	Years to define B_{ref}	M	OFL	ABC (P*=0.49)
1) 2012/13	4a	29.49	36.64	1.24	0.18	1986-11	0.18	3.955	3.949
2) 2012/13	4a	26.57	35.07	1.32	0.18	1986-11	0.18	3.893	3.887

Biomass in 1000 t

Year	Tier	B_{ref}	Current MMB	MMB/MMB_{ref}	F_{OFL}	Years to define B_{ref}	M	OFL	ABC (P*=0.49)
1)2012/13	4a	13.38	16.62	1.24	0.18	1986-11	0.18	1.794	1.791
2)2012/13	4a	12.05	15.91	1.32	0.18	1986-11	0.18	1.766	1.763

WAG:

Biomass in million pounds

Year	Tier	B_{ref}	Current MMB	MMB/MMB_{ref}	F_{OFL}	Years to define B_{ref}	M	OFL	ABC (P*=0.49)
1)2012/13	4a	9.28	12.80	1.38	0.18	1986-11	0.18	1.927	1.919
2)2012/13	4a	10.85	13.08	1.21	0.18	1986-11	0.18	1.930	1.922

Biomass in 1000 t

Year	Tier	B_{ref}	Current MMB	MMB/MMB_{ref}	F_{OFL}	Years to define B_{ref}	M	OFL	ABC (P*=0.49)
1)2012/13	4a	4.21	5.80	1.38	0.18	1986-11	0.18	0.874	0.870
2)2012/13	4a	4.92	5.93	1.21	0.18	1986-11	0.18	0.875	0.872

7. Probability density functions of OFL:

Assuming a lognormal distribution of total OFL, we determined the cumulative distributions of OFL and selected the median as the OFL.

8. The basis for the ABC recommendation:

   See the ABC section

9. A summary of results of any rebuilding analysis:

   Not applicable.

A. Summary of Major Changes

1. Changes (if any) to the management of the fishery: None.
2. Changes to the input data:
   (a) Data update: The 2010/11 commercial fishery retained and discarded catch, CPUE by size, and groundfish discarded catch by size are added.
   (b) New data: (a) Retained catch by size data for 1985 to 1989 are added to the existing time series (1990/91 to 2010/11). (b) Groundfish male catch by size for 1995/96 to 2010/11 are included.
   (c) Observer pot retained and discarded CPUE are standardized for soak-time (see the Data section for details).
3. Changes to the assessment methodology: None. The same model has been improved.
4. Changes to the assessment results: Not applicable because the model has not been used previously.

B. Response to SSC and CPT comments

September 2011 CPT comments:

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1. The author reviewed responses to CPT and SSC comments. One aspect of note was the author's implementation of asymptotic selectivity. **The CPT wishes to clarify that dome-shaped selectivity should also be examined for the May 2012 model draft**. …

Response: Dome shaped selectivity is incorporated as scenario 5.

2. When asked about inconsistencies in the time series of observed retained data, Pengilly clarified that observed retained represents dockside samples whereas observed discarded represent at sea observations (a shorter time series). In addition, at-sea observers don't always sample slightly undersized crab that may be subsequently delivered. An observer effect may also be indicated in bubble plots of residuals. **Punt suggested using two retained selectivity functions to represent CPUE**: **(1) at-sea observer samples (knife-edged selectivity); and (2) dockside samples.**

Response: We updated the observer data for this assessment. Only the 1998/99 onward observer CPUE data were used in the model fit because prior to this fishing year, the data were not reliable (personal communication Observer Database Team, Kodiak). So, different retained selectivity functions were not needed.

3. Fishery retained and discarded CPUE were standardized by separating CPUE into two time periods and discarding soak times longer than the 95th percentile (≥456-hr for 1985–2004 and ≥936 hr for 2005–2010). The public expressed concern about long soak times skewing the assessment owing to reduced catch from bio-twine degradation. Given the need for the bait to be effective, it was further noted that survey data was limited to soak times of 30–140 hrs. **The authors could examine model sensitivity to further restrictions on long soak times.**

   Response: We used the CPUE vs. soak-time model to standardize the EAG observer data for 6-day soak-time and WAG observer data for 12-day soak-time. Scenario 2 considers this set of CPUE data.

4. The author discussed optimization scenarios and weighting factors for the EAG and WAG. **The CPT recommends the listing of sigmas instead of absolute values as being more informative for factors such as L_{50} and β**. Three scenarios were examined, differing by weighting applied to pot survey CPUE, mean CPUE ratio, molt L_{50}, and β components in the negative log likelihood functions.

Response: We explained the justification for some weights and the corresponding sigmas in the text.

5. The CPT engaged a lively discussion about some of the model likelihood components. **In particular, there may be an excessive number of penalty functions for aspects that might not be justified.** An example is the mean CPUE penalty ratio (Eq. 37) for the pot fishery; because pot fishery CPUE is already incorporated into the model (Eq. 12), the CPUE penalty ratio represents additional inclusion of the same data. There was also substantial discussion about the QQ parameter. Many lambdas are listed in formulas, but likelihoods are not

presented in tables. The authors should be fitting the model to the data and not using lambdas to simply improve model fit. For example, Eq. 18 estimates catch, but another likelihood function treats catch data as being without error. In examining parameter estimates, the CPT noted many estimates appear to be constrained, or nearly so, by bounds, particularly for the EAG (Table 4 and negative Hessian gradients in Table 7); the author noted that many bounds had been expanded. **The CPT suggested expanding bounds or reducing weighting factors.**

Response: In this run we used an independent estimate of catchability ratio using the Leslie method instead of mean CPUE ratio. New tables (Tables 3 and 10) are created to explain different scenarios and associated weights. Scenarios 3 and 4 relaxed the penalty functions for nominal and standardized input CPUE data, respectively.

The CPT also noted:

1. large confidence intervals in early time series discarded CPUE data (Fig. 4b, perhaps due to small number of pot lifts);

Response: Yes, large confidence intervals were due to small number of pot lifts in initial years. We considered only the CPUE data series for 1998/99-2010/11 for model fit.

2. poor fit to fishery CPUE trend in post-rational years (Figs. 4a and 26);

Response: Appears good in the current analysis.

3. poor fit to pot survey CPUE (Fig. 4c);

Response: Appears good in the current analysis.

4. extremely good fit to retained catch length frequencies (Fig. 5);and

   poor fit to groundfish discards for small crab sizes (Fig. 7).

Response: We used small weights to groundfish data because small length samples were reported.

The CPT requested the model be updated and brought to the January 2012 workshop, with a preliminary distribution to Andre and Steve.

Response: Will do.

September 2011 SSC comments:

A detailed review of this assessment is planned for a crab modeling workshop in January 2012 and the SSC looks forward to receiving a revised assessment in the future. In preparation for this workshop, the SSC offers the following recommendations:

- Include models that evaluate and contrast alternative selectivity curves.

Response: Please see the response to CPT item 1.

- Observer and retained data should be treated as in the Tanner assessment to illuminate the effects of observer assigned animals as discarded when they are actually landed.

Response: Please see the response to CPT item 2.

- Investigate retained and bycatch CPUE time series in relation to soak times and time period and provide rationale for standardization. Cite any relevant published studies on soak time effects.

Response: We have provided rationale for standardization in this document.

- Document and justify all penalty functions, constraints and weighting. The mean CPUE ratio penalty should not force the fit to be equal to the observed data. This issue needs more attention at the workshop.

Response: Please see the response to CPT item 5.

- Properly document sample sizes and confidence intervals for CPUE time series.

Response: Sample sizes and standard errors are documented in Tables 2a, 2b, and 9b.

- The extent and causes of legal discards should be more fully explained.

Response: We have provided some justifications in the Appendix.

- Attempt to resolve fundamental issues among survey catches, fishery CPUE, and discard length data, particularly during the post-rationalization period. Divergent abundance trends inferred by CPUE from the pot survey and fishery are disconcerting. If trends in fishery CPUE data are largely due to fisher behavior, then model results based on them may not be useful. One approach to partially address these concerns is to try fitting the model without fishery CPUE data and other versions leaving out other data (e.g., length frequencies or survey data). This could also inform uncertainties about how informative the length frequency data may be. A second approach is to consider whether the rapid increase in biomass inferred from fishery CPUE is biologically possible, knowing what is known about golden king crab demographics. Finally, reconsider the length-frequency data. Is it possible that fishers are targeting depth zones with crabs of particular sizes?

Response: We have standardized the observer CPUE data to address this problem.

- Carefully evaluate residuals for evidence of systematic patterns indicating model misspecification. For instance, residual plots seem to imply that the retention curve should be steeper in the discard length data to show a drop off in legal size.

Response: We have updated the observer CPUE data and considered only the 1998/99-2010/11 time series for the model when the reporting by categories (sublegal, retained legal, and non-retained legal) was reliable (personal communication, observer database group, Kodiak).

C. Introduction

1. Scientific name: Golden king crab, *Lithodes aequispinus.*
2. Distribution: The golden king crab are distributed in the Aleutian Islands, Bering Sea (Pribilof Islands), and south east Alaska.
3. Evidence of stock structure: There is no direct evidence of separate stock structure in the Aleutian Islands.
4. Life history characteristics relevant to management: 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). Inter-molt period is also protracted creating difficulties in determining annual molt probability (Watson et al., 2002). Limited stock information and lack of annual survey data prevent developing the standard length-based assessment model.
5. Brief summary of management history: 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 EAG and the west of 174°W longitude stock segment is referred to as WAG. 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 EAG and 2.7 million pounds for the WAG). In 2008, however, the total allowable catch was increased to 3.15 and 2.835 million pounds for EAG and WAG, respectively, following the Alaska Board of Fisheries decision (approximately 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 (Figures 1 - 3). 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.

D. Data

1. Summary of new information: Data update: The 2010/11 commercial fishery retained and discarded catch and observer CPUE by size are added to the time series.

   New data: (a) Retained catch by size data for 1985 to 1989 are added to the existing time series (1990/91 to 2010/11). (b) Groundfish bycatch by size for 1995/96 to 2010/11 are included. We considered only the male removals by the groundfish pot and trawl gear because the model is male-only. We considered groundfish bycatch from the Federal fishing area 541 for EAG and 542 & 543 for WAG.

2. a.-c. Available time series of data: A time series of retained and discarded pot catch and groundfish discarded catch by length, observer retained and discarded CPUE data by length, triennial pot survey CPUE data by length, and tagging data for growth increment and harvest rate estimation. The length aggregated annual retained catch, pot fishery discard, groundfish fishery discard, plus retained and discarded CPUE are listed in Tables 2 and 9 for the EAG and WAG, respectively. Information on length compositions are provided in various plots (Figures 11-16 for EAG and 34-36 for WAG).

   d. Survey biomass estimates are not available for the area because no systematic surveys, covering the entire fishing area, have occurred.

e. Triennial pot survey (1997, 2000, 2003, and 2006) catch at length and CPUE are used in the model fit. Length aggregated pot survey CPUE are listed in Table 2. Information on length composition is provided in Figure 16.

f. Other time series data: None.

3. a. Growth-per-molt: Using Watson et al.'s (2002) 12-15 months tag-recovery data, we fitted a linear growth increment model, $\Delta l = a + b * l$ (a = 18.173, b = -0.029, size range 102-155 mm carapace length CL).

   b. Weight-at-length: $W = al^b$ where a= $2.988*10^{-4}$, b = 3.135.

4. Information on any data source available, but were excluded from the assessment: None.

Catch and CPUE data

The commercial catch and length frequency distribution were estimated from Alaska Department of Fish and Game (ADF&G) landing records and dockside sampling. The length frequency data were used to distribute the catch into different (5-mm) size intervals. The discarded catch by size was estimated using the observer discarded CPUE data which was first distributed into size intervals from observer length frequency information, then multiplied by the total effort (number of pot lifts) and a 20% handling mortality to obtain the discarded (dead) catch by size (Siddeek et al., 2005). The retained and discarded CPUE (total number of crabs / total number of pot lifts) data were obtained from onboard observer sampling. Observer data have been collected since 1988 (Gaeuman, 2011), but initial years' data are not comprehensive, so a shorter time series of data for the period 1990-2010 was selected for this analysis. Onboard observers count and measure entire sampled pot content of crabs and categorize it into number of females, sublegal males, retained legal males, and non-retained legal males. For male-only fisheries modeling purpose, sublegal and non-retained legal males were lumped together as discarded crabs. Annual mean CPUE and standard error of retained and discarded crabs were estimated considering the whole season's records of sampled pots (Tables 2b and 9b). The observer sample

length frequency data by sublegal, retained legal, and non-retained legal males were used to distribute the CPUE into different size intervals by categories and broadly grouped into retained and discarded crabs by size intervals. For model fitting purpose, the CPUE time series was further restricted to 1998-2010 because the reliability of categorization of crabs by observers was better after 1998. Length-specific CPUE data collected by observers provide information on a wider size range of the stock than does the commercial catch length frequency data obtained from mostly legal-sized landed males. The pot survey CPUE by length was estimated with the same method used for the observer data, except that the entire set of pot haul' catches were measured and CPUE was estimated as the catch divided by the effort. The pot survey catches also cover a wider size range than the commercial size frequency. Furthermore, the four sets 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 and soak-time, which may reflect the actual in situ population abundance. The majority of the commercial fishery takes place in this area.

CPUE Standardization:

I. The four sets (1997, 2000, 2003, and 2006) of pot survey CPUE data were standardized to soak-time by considering only those pot hauls with soak-time in the range of 1.25-5.83 days. Box plot provided a 5th and 95th percentile values at these points. Very few fell above 5.83 days soak-time.

II. The pot fishery soak-time dramatically increased after crab rationalization (Figures 5 and 6). However, there was no significant change in depth of fishing during pre- and post- rationalization period (Figure 5). We standardized the observer retained and discarded CPUE by soak- time by considering first the 5th to 95th percentile soak-time range (this data set was considered as Scenario 1 nominal data) and then fitting the Zhou-Shirley (1997) CPUE vs. soak-time model separately for retained and discard categories for three different periods, 1990-1997, 1998-2004, and 2005-2010 to obtain standardized CPUE at 6-day and 12-day soak-time

for EAG and WAG, respectively. These two soak-times have reasonably high overlap among the three periods' soak-time distributions (Figure 6). The fitted curves are depicted in Figure 7. There appears a significant escapement of sublegal crabs during the post-rationalization period in both regions (Figures 7 and 8). There were significant changes in fishing practice due to changes in management regulation (e.g., since 1996/97 constant TAC and since 2005/06 crab rationalization), pot configuration (since 1999 increase in escape web on the pot door to 9"), and improvement in observer recording (since 1998). These changes prompted us to consider three different fishing periods for standardization and consider three sets of catchability and selectivity parameters. The CPUE vs. soak-time model specification and fitted parameters are given in Table 1. This model was also used for various Bering Sea crab stock by van Tamelan (2001).

E. Analytic Approach

1. *History of modeling approaches for this stock*

The model is under development, and yet to be accepted for OFL and ABC setting.

2. *Model Description*

a. The underlying population dynamics model is male-only and length-based (Appendix A). This model combines commercial retained and discarded catch, groundfish fishery discarded catch, observer retained and discarded catch-per-unit-effort (CPUE), fishery retained and discards size composition, groundfish discard size composition, triennial pot survey CPUE, and pot survey size composition to estimate stock assessment parameters.

The data series used in the current assessment for the EAG ranges from 1985/86 to 2010/11 for retained catch biomass and size composition; 1998/99 to 2010/11 for nominal (Scenario 1, Table 3) and standardized (Scenario 2, Table 3) pot retained and discarded CPUE, 1990/91-2010/11 for pot bycatch biomass, and 1998/99-2010/11 for pot bycatch length composition; 1997-2006 for triennial pot

survey standardized CPUE and size composition; and 1995/96 to 2010/11 for groundfish fishery male bycatch biomass and size composition.

The data series used for the WAG ranges from 1985/86 to 2010/11 for retained catch biomass and size composition; 1998/99 to 2010/11 for nominal (Scenario 1, Table 10) and standardized (Scenario 2, Table 10) pot retained and discarded CPUE, 1990/91-2010/11 for pot bycatch biomass, and 1998/99-2010/11 for pot bycatch length composition; and 1995/96 to 2010/11 for groundfish fishery male bycatch biomass and size composition.

b. Software: AD model builder.

c.-f. Details are given in Appendix A.

g. Critical assumptions and consequences of assumption failures: We kept M constant at 0.18. We assumed different q's and logistic selectivity patterns for different periods for the pot fishery, < 2004 and >= 2005. Because of the lack of annual stock survey we relied heavily on CPUE and catch information to determine the stock abundance trends in both regions. There were some tagging experiments done in the EAG area and harvest rates reported based on tagging analysis by Watson (2005) and Watson and Gish (2002). We calculated harvest rates for 1997, 2000, 2003, and 2006 to determine the exploited legal male biomasses from the observed total catches for the respective years and compared them with the model estimated exploited legal male biomasses using penalty functions (Appendix A). We used the tagging estimated molt probability L_{50} value (Watson et al. 2002) and growth function shape parameter β in penalty functions for both regions. We also used the mean ratio of Leslie method estimated catchability for the periods 1998-2004 and 2005-2010 in a penalty function separately for each region to hypothesize that the relative catchability during the two periods for the respective region was the same (Appendix A).

We considered six scenarios for EAG (Table 3) and five scenarios for WAG (Table 10) and presented OFL and ABC results for scenarios 1 and 2. Summary of various Scenarios are:

Scenario 1: nominal observer CPUE data, Scenario 2: standardized observer CPUE data, Scenario 3: nominal observer CPUE data and omit penalty functions, Scenario 4: standardized observer CPUE data and omit penalty functions, Scenario 5: standardized observer CPUE data and dome shape selectivity, Scenario 6: standardized observer CPUE data and estimate *M* in the model.

h. Changes to any of the above since the previous assessment: Does not apply for this assessment since the model has not yet been used.

i. Model code has been checked by the co-authors and validated. The code is available from the author.

3. Model Selection and Evaluation

a. Description of alternative model configurations: No change, entire time period 1985/86-2010/11, was used to define B_{MSY}/B_{ref}.
b. Progression of results: Model was not previously used, so, not applicable.
c. Evidence of search for balance between realistic and simpler models: The six/five scenarios considered including and dropping penalty functions. The results are provided in tables.
d. Convergence status and criteria: ADMB default convergence criteria.
e. Table of the sample sizes assumed for the size compositional data: Although in the previous model runs we used annually varying sample sizes based on actual number of crabs measured, standardized to a maximum of 400, we used fixed constant effective sample sizes for this run for the two regions (see Tables 3 and 10).
f. Do parameter estimates make sense: Number of parameter estimates appears to be reasonable for a fixed *M* of 0.18.
g. Model selection criteria: We used a number of criteria to select the base models (Scenarios 1 and 2) over the other Scenarios: different components and total sums of the negative log likelihood values (Tables 4 and 11 for EAG and WAG,

respectively); retrospective fits; CPUE fits; and length composition fits. Tables and figures are provided in the Results section for various Scenarios.

h. Residual analysis: We illustrate residual fits by various figures in the Results section.

i. Model evaluation: Only one model is presented and the evaluations are presented in the Results section below.

4. *Results*

1. List of effective sample sizes and weighting factors:

We used fixed constant effective sample sizes for the two regions – The sample sizes for various scenarios are listed in Tables 3 and 10 for EAG and WAG, respectively. These weights adequately fitted the length compositions and no further changes were examined.

Weighting factors for CPUE; catch biomass; recruitment deviation; pot fishery F; groundfish fishery F; mean q ratio; 1997, 2000, 2003, and 2006 exploited legal biomass (for EAG only); molt probability L_{50}; and growth function β for various scenarios are also provided in Tables 3 and 10 for EAG and WAG, respectively.

2. Tables of estimates:
   a. We provide the parameter estimates with one standard deviation for the base models, Scenario 1 in Tables 5a and Scenario 2 in Table 5b for EAG; and Scenario 1 in Tables 12a and Scenario 2 in Table 12b for WAG.
   b. We provide the mature male and legal male abundance time series in Tables 6a and 6b for EAG, and 13a and 13b for WAG, respectively for Scenarios 1 and 2.
   c. We list the recruitment estimates in Tables 6a and 6b for EAG, and 13a and 13b for WAG, respectively for Scenarios 1 and 2
   d. We provide the time series of catch divided by mature male abundance in Tables 7 and 14 for EAG and WAG, respectively. The harvest rate in

EAG appears to be lower than that of WAG probably due to high abundance in this region.

3. Graphs of estimates:
   a. We provide the fishery total and retained, groundfish bycatch, and pot survey selectivity in Figures 17 and 37 for EAG and WAG, respectively. Dome shape selectivity (Scenario 5) is also provided for comparison. The pot survey and groundfish bycatch selectivity appear flat indicating all size groups were vulnerable to the gear. This is also shown in the size compositions of pot survey for EAG and groundfish bycatch for EAG and WAG (Figures 15, 16, and 36).

      We provide the molt probability curve for EAG in Figure 18 and that for WAG in Figure 38.

      We provide the legal and mature male biomass time series for Scenarios 1 and 2 in Figure 26 for EAG and in Figure 45 for WAG. Both legal and mature male biomass trends tracked the CPUE trends well. We determined the mature male biomass values on 15 February and considered the entire time series for B_{ref} calculation.
   b. We show the full selection F over time for Scenarios 1 and 2 for EAG in Figure 27 and for WAG in Figure 46. The F value peaked in 1989 and systematically declined in the recent years.
   c. F vs. MMB: We did not provide this figure because the model has not yet been approved.
   d. Stock-Recruitment relationship: None.

      We provide the temporal changes in total number of recruits to the modeled population for Scenarios 1 and 2 in Figure 24 for EAG and in Figure 43 for WAG. We also provide the recruitment distribution to the model size group (101-185 mm CL) in Figures 25 and 44 for EAG and WAG, respectively for the two Scenarios.
4. Evaluation of the fit to the data:

a. Fits to catches: We present graphs of observed vs. model fitted retained, pot discards, and groundfish discarded catches (t) for Scenarios 1 and 2 in Figures 28 for EAG and in Figures 47 for WAG. We also provide graphs of observed vs. model fitted retained and pot discarded CPUE in Figures 9 and 10 for EAG and in Figures 32 and 33 for WAG for Scenarios 1 and 2, respectively. The fittings appear good. Although the CPUE increased during the post-rationalization period, observed recruitment trends showed decline in recent years (Figure 4).
b. Survey data plot: We provide observed vs. predicted plot of EAG pot survey CPUE in Figure 9(c). The predicted line tracked the CPUE trend.
c. Fit to catch size compositions: We provide retained, pot discard, and groundfish discard length compositions in Figures 11-15 for EAG and in Figures 34-36 for WAG. To save space we provide retained and discard catch composition fits for Scenarios 1 and 2 only for EAG. The retained and pot discard size composition fits appear satisfactory. We illustrate the standardized residual plots as bubble plots of size composition over time for retained (Figures 19 and 39 for EAG and WAG, respectively), for pot discards (Figures 20 and 40 for EAG and WAG, respectively) and for groundfish discard (Figures 21 and 41 for EAG and WAG, respectively). We also provide a bubble plot for pot survey CPUE (Figure 22). To save space, we provide bubble plots for all six scenarios for EAG, but only for first two scenarios for WAG.
d. Fit to pot survey size composition: We provide pot survey length compositions in Figure 16 for EAG. The fits appear good.
e. Marginal distributions for the fits to the composition data: We did not provide this plot in this report.
f. Plots of implied versus input effective sample sizes and time series of implied effective sample sizes: We did not provide these plots in this report.
g. Tables of RMSEs for the indices: We did not provide this table in this report.

h. Quantile-quantile plot: We did not provide this plot in this report.

5. Retrospective and historical analysis: We provide the retrospective fits of mature male biomass under Scenarios 1 and 2 with terminal years 2006/07 to 2010/11 in Figure 23 for EAG and in Figure 42 for WAG. For EAG, the model adequately fit the time series for most of the years under Scenario 1, but slightly diverges after 2006/07 for terminal years 2005/06 and 2007/08 under Scenario 2. For WAG, slight divergence after 2006/07 occurs for the same terminal years for both scenarios.
6. Uncertainty and sensitivity analysis:

a. We investigated the sensitivity of the model to varying weights on critical likelihood components by considering the likelihoods of various scenarios in some cases dropping the penalty functions (Tables 4 and 11 for EAG and WAG, respectively).
b. We provide the likelihood profile for mature male biomass in Figures 29 and 48, total OFL in Figures 31 and 49 for EAG and WAG, respectively, to describe the uncertainty of those statistics from current assessment. We present the profile curves for Scenarios 1 and 2. We also explored the likelihood profile of *M* estimate (0.3653) under Scenario 6 for EAG. We rescaled the profile to probability. The distribution is symmetric around the mean estimate and satisfactory.

   The CVs of 2012/13 total OFL for EAG are 0.06 and 0.06, and for WAG are 0.18 and 0.16, for Scenarios 1 and 2, respectively. The CVs of mature male biomass for EAG are 0.08 and 0.07, and for WAG are 15 and 0.16, for Scenarios 1 and 2, respectively.

F. Calculation of the OFL

1. Specification of the Tier level:

   The Aleutian Islands golden king crab stocks are currently managed under Tier 5 (average catch OFL) control rule. Our analysis tries to upgrade this stock to the Tier 4 level.
2. List of parameters and stock size required by the control rule:

An average mature male biomass (*MMB*) for a specified period, MMB_{ref}, current *MMB*, an *M* value, and a γ value.

3. Specification of the total catch OFL:

(a) If $MMB_t \geq MMB_{ref}$, $F_{OFL} = \gamma M$,

(b) If $MMB_t < MMB_{ref}$ and $MMB_t > 0.25 MMB_{ref}$,

$$F_{OFL} = \gamma M \frac{\left(\frac{MMB_t}{MMB_{ref}} - \alpha\right)}{(1-\alpha)}$$

(c) If $MMB_t \leq 0.25 MMB_{ref}$, $F_{OFL} = 0$,

where *MMB* is mature male biomass, MMB_{ref} is average mature male biomass, and γ is a multiplying factor of *M*.
The *OFL* is estimated by an iterative procedure accounting for intervening total removals (see Appendix A for the formulas).

For the selection of MMB_{ref}, we chose the period between 1986 Feb 15 to 2011 Feb 15. This resulted in a MMB_{ref} of 13,376t and 12,053t for EAG and 4,209t and 4,922t for WAG for Scenarios 1 and 2, respectively. The current MMB_{2011} were 16,618t and15,907t for EAG and 5,804 and 5,934t for WAG for the respective Scenarios, resulting in an F_{OFL} of 0.18 for both regions. The total OFL for EAG were 1,794t and 1,766t and that for WAG were 874t and 875t for the respective Scenarios. The γ value was set to 1 and an *M* value of 0.18 was used for *OFL* calculation.

We estimated the total and retained catch OFL under various Scenarios for EAG (Table 8) and WAG (Tables 15). The estimates are similar for different Scenarios indicating stability of the overall model structure.

4. Specification of the retained catch portion of the total catch OFL:

We applied the F_{OFL} with retained selectivity to calculate the retained catch portion of the total catch OFL. The retained catch OFL for EAG were 1,674t and 1,636t and that for WAG were 830t and 825t for Scenarios 1 and 2, respectively.

5. Recommendation for F_{OFL}, OFL total catch, and the retained catch portion of the OFL for coming year:
   We recommend the estimates of OFLs given in sections 3 and 4 for the 2012/13 fishing season.

G. Calculation of the ABC

1. Specification of the probability distribution of the total catch OFL:
   We estimated the cumulative probability distribution of OFL assuming a log normal distribution of OFL (Figures 31 and 49 for EAG and WAG, respectively). We calculated the OFL at the 0.5 probability and the ABC at the 0.49 probability. Our recommended ABC estimates for EAG are 1,791t and 1,763t and that for WAG are 870t and 872t under Scenarios 1 and 2, respectively.

H. Rebuilding Analysis

Not applicable.

I. Data Gaps and research Priorities

1. The recruit abundances were estimated from commercial catch sampling data. The implicit assumption in the analysis was that the estimated recruits come solely from the same exploited stock through growth and mortality. While it possible that additional recruitment occurs through immigration from neighboring areas and possibly separate sub-stocks, the current analysis did not consider this possibility. Extensive tagging experiments are needed to investigate stock distributions.

2. An independent estimate of *M* is needed for this stock. Tagging is one possibility.

3. An extensive tagging study will also provide independent estimates of molting probability and growth.

4. 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.

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Table 1. Zhou and Shirley (1997) CPUE vs. soak-time model fitted parameters with standard deviation (in parentheses) for sublegal and legal males for different time periods in EAG and WAG.

Model: $CPUE_t = ab + a \times (t - b) \times e^{-c \times t}$ (a, b, and c are parameters and t is soak-time in number of days).

Parameter (period)	EAG: Sublegal Male	EAG: Legal Male	WAG: Sublegal Male	WAG: Legal Male
a (1990/91-97/98)	0.9635 (8.914)	2.4831(13.702)	2.464(0.5833)	1.7659(0.6042)
b	12.205(114.89)	0.2171(57.498)	4.64E-07(0.0036)	8.41E-07(0.0074)
c	0.4241(0.789)	0.1080(0.5494)	0.0918(0.0235)	0.0840(0.0332)
a (1998/99-04/05)	2.6814(14.906)	4.3026(1.8558)	2.7043(0.6861)	1.1035(0.3127)
b	4.8574(30.892)	0.00012(0.2388)	3.57E-07(0.0026)	0.0003(2.3741)
c	0.4008(1.2079)	0.1072(0.0742)	0.1002(0.0247)	0.0322(0.0262)
a (2005/06-10/11)	2.8759(0.5396)	4.7394(1.0182)	3.571(1.3287)	1.3396(6.0812)
b	0.0001(0.0002)	0.0001(0.0109)	0.8828(0.7365)	13.741(175.98)
c	0.1065(0.0115)	0.057296(0.0127)	0.1112(0.0404)	0.0317(0.0912)

Table 2(a). Time series of annual retained catch (number of crabs), groundfish fishery discard mortality (handling mortality rate of 50% for pot and 80% for trawl gear applied, only male portion), pot survey CPUE, and survey sample size for the EAG golden king crab stock. The data are for the size range 101-185 mm CL. The CPUE are determined from 5th to 95th percentile soak-time pot lifts with standard errors given in parentheses. 1985 refers to the 1985/86 fishery.

Year	Retained Catch	Groundfish Discard Mortality	Pot Survey CPUE	Sample Size (no.pot lifts)
1985	1,400,577			
1986	1,307,032			
1987	1,029,424			
1988	1,169,427			
1989	1,317,833			
1990	950,008			
1991	1,093,983			
1992	1,118,955			
1993	832,194			
1994	1,128,013			
1995	1,046,780	339		
1996	731,909	133		
1997		25	21.2386	703
	780,610		(1.064)	
1998	740,011	364		
1999	709,332	648		
2000		349	17.3572	728
	704,702		(1.030)	
2001	730,030	132		
2002	643,886	7.620		
2003		4,277	8.0404	893
	643,074		(0.451)	
2004	637,536	100		
2005	623,971	114		
2006		3,063	8.6643	729
	650,587		(0.571)	
2007	633,253	19,942		
2008	666,946	4,858		
2009	679,886	1,079		
2010	670,983	12,735		

Table 2(b). Time series of annual observer retained catch-per-unit-effort (CPUE, number of crabs per pot lift) and discard CPUE, pot fishery discard mortality (20% handling mortality applied), and CPUE sample size for the EAG golden king crab stock. Standard errors are given in parentheses. The data are for the size range 101-185 mm CL. The observer CPUE are determined by two ways: (a) 5th to 95th percentile soak-time range of pot lifts (nominal) and (b) 5th to 95th percentile soak-time range of pot lifts standardized at 6-day soak-time (standardized). NO = no sampling information. 1985 refers to the 1985/86 fishery.

Year	(a)Obs. Retained CPUE	(a)Obs. Discard CPUE	(a)Pot Discard Mortality	(b)Obs. Retained CPUE	(b)Obs. Discard CPUE	(b)Pot Discard Mortality	Sample Size (no.pot lifts)
1990	7.156	27.112	581,854	9.160	30.655	657,898	
	(1.075)	(7.471)		(1.430)	(8.235)		90
1991	6.026	11.271	300,770	7.536	12.416	331,318	
	(0.496)	(2.864)		(0.639)	(3.021)		206
1992	7.412	22.510	602,266	8.969	25.774	689,592	
	(0.512)	(5.223)		(0.640)	(6.172)		137
1993	6.899*	NO	172,518*	8.348*	NO	189,182*	NO
1994	5.221*	NO	309,003*	6.318*	NO	338,852*	NO
1995	6.273	8.070	286,921	7.464	8.849	314,636	
	(0.195)	(0.452)		(0.238)	(0.491)		1547
1996	5.816	7.980	181,087	6.694	8.5870	194,855	
	(0.102)	(0.246)		(0.116)	(0.267)		4943
1997	7.362	9.790	208,345	8.569	10.830	230,460	
	(0.126)	(0.290)		(0.148)	(0.328)		3906
1998	9.207	14.733	245,681	11.480	16.148	269,276	
	(0.187)	(0.530)		(0.235)	(0.581)		2822
1999	8.979	10.244	162,115	11.072	11.206	177,342	
	(0.171)	(0.346)		(0.199)	(0.381)		3379
2000	9.791	14.233	203,672	11.771	15.404	220,433	
	(0.151)	(0.340)		(0.179)	(0.369)		4450
2001	11.723	10.731	134,431	14.001	11.705	146,644	
	(0.181)	(0.294)		(0.213)	(0.327)		4052
2002	12.559	10.273	106,925	15.520	11.201	116,581	
	(0.205)	(0.267)		(0.251)	(0.290)		3540
2003	10.993	8.016	94,399	14.004	8.849	104,205	
	(0.171)	(0.210)		(0.220)	(0.235)		3765
2004	18.411	10.670	74,367	23.636	11.755	81,926	
	(0.374)	(0.373)		(0.483)	(0.411)		2012
2005	28.459	9.017	44,307	21.139	9.145	44,938	
	(0.718)	(0.430)		(0.529)	(0.442)		915
2006			43,590		7.996	41,892	
	24.426	8.320		18.125	(0.420)		
	(0.540)	(0.434)		(0.396)			1034
2007	30.058	9.971	45,175	20.739	10.579	47,927	
	(0.590)	(0.531)		(0.404)	(0.546)		931
2008	28.745	9.506	46,512	20.069	9.697	47,448	
	(0.843)	(0.535)		(0.586)	(0.593)		565
2009	25.623	10.025	52,728	17.896	11.021	57,966	
	(0.851)	(0.673)		(0.588)	(0.727)		387
2010	25.216	10.946	56,595	17.961	11.322	58,535	
	(0.944)	(0.790)		(0.674)	(0.808)		379

*Missing observation filled by averaging 1992 and 1995 values.

Table 3. Optimization scenarios and weighting factors considered for the stock assessment model for the eastern Aleutian Islands golden king crab (EAG) . Catchability ratio and its variance were estimated by Leslie depletion method and the legal male biomass (LMB) harvest rate variances were estimated from tagging data.

Scenario	Remarks	Weights for Likelihoods & Effective Sample Sizes
1	Nominal observer CPUE for 1998-2010, commercial retained catch for 1985-2010, discard catch for 1998-2010, and groundfish bycatch for 1995-2010; M = 0.18, pot fishery handling mortality = 0.2, and ground fish bycatch handling mortality for trawl = 0.8 and for pot = 0.5. Penalty functions: molt L50, growth beta, catchability ratio for the 1998-2004 and 2005-2010 periods; 1997, 2000, 2003, and 2006 LMB estimates; recruitment deviation, pot fishing mortality deviation, groundfish bycatch fishing mortality deviation, and legal discard in certain years deviation.	Catch biomasses: retained=600, pot discard=300, groundfish bycatch=25. Effective sample sizes: retained =350, pot discard=75, groundfish discard=25, pot survey=350. CPUE: pre-rationalization retained = 10, post-rationalization retained = 20, pot discard = 10, pot survey = 50. Penalties: molt L50= 0.25, growth beta = 0.25, catchability ratio = 0.69, 1997LMB= 397, 2000LMB = 268, 2003LMB=132, 2006LMB=114 , recruit dev.=1., pot fishing mortality dev.=0.0001, groundfish bycatch mortality=2. Legal discard dev. = 0.5.
2	Scenario 1 using standardized observer CPUE.	Changes to Scenario 1: Effective sample sizes: groundfish discard=50. CPUE: pre-rationalization retained = 5, post-rationalization retained = 35, pot discard = 15. Penalties: recruit dev.=2.
3	Scenario 1 omitting penalties for molt L50, growth beta, catchability ratio, and LMB.	Changes to Scenario 1: Effective sample sizes: retained =300, pot discard=100, groundfish discard=80, pot survey=300. CPUE: pre-rationalization retained = 5, post-rationalization retained = 10, pot discard = 5, pot survey = 25.

Table 3 continued.

Scenario	Remarks	Weights for Likelihoods & Effective Sample Sizes
4	Scenario 3 using standardized observer CPUE.	Changes to Scenario 1: Effective sample sizes: groundfish discard=50. CPUE: pre-rationalization retained = 4.5, post-rationalization retained = 10, pot discard = 5.5, pot survey = 25. Penalties: recruit dev.=5.
5	Scenario 1 using standardized observer CPUE and dome shape selectivity.	Changes to Scenario 1: CPUE: pre-rationalization retained = 5, post-rationalization retained = 35, pot discard = 15. Penalties: recruit dev.=2.
6	Scenario 1 using standardized observer CPUE and estimating M in the model.	Changes to Scenario 1: Effective sample sizes: groundfish discard=50. CPUE: pre-rationalization retained = 5, post-rationalization retained = 35, pot discard = 15. Penalties: M = 61.73

Table 4. Negative log likelihood component values for the six scenarios for the golden king crab stock in EAG.

Negative Log Likelihood Component	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
like_retlencomp	-1546.0400	-1563.9100	-1532.5600	-1555.5700	-1532.9400	-1548.7900
like_discdlencomp	-1024.7400	-1011.8200	-1069.0800	-1029.6600	-1013.4800	-1004.5700
like_gdiscdlencomp	-457.0240	-459.8080	-463.4590	-481.6510	-458.1050	-475.3260
like_survcpuelen	-187.8250	-195.3600	-206.9820	-212.9510	-200.8060	-182.6160
like_retcpue	-110.2820	-165.1700	-62.9362	-52.1141	-155.2910	-40.2781
like_discdcpue	-150.4420	-184.6510	-60.8575	-20.7570	-192.6870	-216.0650
like_survcpue	1.8576	41.5706	10.6087	16.8752	12.9838	-194.7260
like_retdcatchB	7.2520	28.7401	3.3746	5.6631	30.8029	31.3811
like_discdcatchB	10.0014	54.9336	6.4545	10.2497	56.5766	50.7675
like_gdiscdcatchB	7.5612	7.3648	7.7261	7.6434	7.4604	8.0122
like_rec_dev	14.3503	17.8357	18.6864	15.6183	21.6533	18.7169
like_F	0.0011	0.0011	0.0016	0.0009	0.0011	0.0010
like_gF	92.8273	90.5411	95.1471	94.1530	91.6098	98.3444
like_qq	1.1133	5.3517	2.2120	1.9783	4.5815	3.1751
like_Legal97	13.8332	17.5550	0	0	17.5466	7.9434
like_Legal00	25.8048	24.8688	0	0	26.7083	49.3410
like_Legal03	0.9182	0.2396	0	0	0.2015	0.5688
like_Legal06	7.4786	10.1744	0	0	13.9660	25.2513
like_molt50	49.8940	36.8802	0	0	35.9378	21.9890
like_beta	6.0108	4.5022	0	0	5.7111	4.6406
like_meanqratio	0.0029	0.1887	0	0	0.1460	0.0152
like_Mpenalty						8.5838
Total negative log likelihood	-3237.44	-3239.97	-3251.66	-3200.52	-3227.42	-3333.64

Table 5(a). Parameter estimates and standard deviations with the 2011 (February 15) MMB for the Scenario 1 model (with nominal CPUE data) for the golden king crab data from the EAG, 1985/86-2010/11. Parameter bounds are given in parentheses. A total of 118 parameters were estimated, but recruitment, fishing mortality, and legal discard (certain years) deviations, and initial size frequency determination parameters were omitted from this list.

Parameter	Estimate	Std Dev	Parameter	Estimate	Std Dev
a	0.0778(0.01-0.75)	0.0036	log_newsh1	2.3561(0.01-10)	0.0597
log_b	4.8273(3.98-5.5)	0.0097	log_mean_rec	1.1164(0.01-3)	0.0698
log_beta	1.7014(-3.6-2)	0.1771	log_mean_Fpot	-1.1929(-15- -0.35)	0.0286
c	0.0100(0.01-0.5)	0.0000	log_mean_Fground	-9.5517(-15- -1.6)	0.0818
log_d	3.5000(3.5-5.5)	0.0001	mean_qq	3.4798(unbounded)	0.2441
c2	0.0410(0.01-0.8)	0.0050	ret_var	0.0190(0.01-1.25)	0.0022
log_d2	5.0061(3.98-5.5)	0.0541	discd_var	0.01(0.01-1.25	0.0000
c3	0.1503(0.01-0.8)	0.0098	surv_var	0.0566(0.01-1.25	0.0062
log_d3	4.9125(3.98-5.5)	0.0070	2011 MMB	16,618	1,294.00
aa2	0.4788(0.01-1.5)	0.0171			
log_bb2	4.9147(4.85-4.98)	0.0011			
aa3	0.4432(0.01-3)	0.0301			
log_bb3	4.9206(4.25-4.98)	0.0013			
aa4	0.9170(0.01-1.5)	502.5500			
log_bb4	4.3862(3.98-5.5)	174.5200			
log_betar	-0.2253(-4.6-3.2)	0.1346			
logq	-14.086(-25 - -0.01)	0.0756			
logq2	-12.6500(-25 - -.01)	0.0316			
logq3	-12.0570(-25 - -.01)	0.0628			

Table 5(b). Parameter estimates and standard deviations with the 2011 (February 15) MMB for the Scenario 2 model (with standardized CPUE data) for the golden king crab data from the EAG, 1985/86-2010/11. Parameter bounds are given in parentheses. A total of 118 parameters were estimated, but recruitment, fishing mortality, and legal discard (certain years) deviations, and initial size frequency determination parameters were omitted from this list.

Parameter	Estimate	Std Dev	Parameter	Estimate	Std Dev
a	0.0779(0.01-0.75)	0.0038	log_newsh1	2.4028(0.01-10)	0.1282
log_b	4.8143(3.98-5.5)	0.0940	log_mean_rec	1.0973(0.01-3)	0.0614
log_beta	1.5731(-3.6-2)	0.2158	log_mean_Fpot	-1.1793(-15 - -0.35)	0.0289
c	0.0100(0.01-0.5)	0.0000	log_mean_Fground	-9.4526(-15 - -1.6)	0.0768
log_d	3.5000(3.5-5.5)	0.0002	mean_qq	2.7236(unbounded)	0.1390
c2	0.0610(0.01-0.8)	0.0056	ret_var	0.0171(0.01-1.25)	0.0024
log_d2	4.9239(3.98-4.98)	0.0232	discd_var	0.01(0.01-1.25	0.0000
c3	0.1122(0.01-0.8)	0.0081	surv_var	0.0857(0.01-1.25	0.0132
log_d3	4.9055(3.98-5.5)	0.0099	2011 MMB	15,907.00	1,135.00
aa2	0.4822(0.01-1.5)	0.0182			
log_bb2	4.9131(4.85-4.98)	0.0011			
aa3	0.5223(0.01-3)	0.0425			
log_bb3	4.9217(4.25-4.98)	0.0014			
aa4	0.8940(0.01-1.5)	486.690			
log_bb4	4.3734(3.98-5.1)	177.850			
log_betar	-0.2712(-4.6-3.2)	0.1305			
logq	-13.9940(-25- -0.01)	0.0715			
logq2	-12.4340(-25 - -0.01)	0.0361			
Logq3	-12.300(-25 - -0.01)	0.0564			

Table 6 (a). Annual abundance estimates of model recruits (millions of crabs), legal male biomass with standard deviation (t), and mature male biomass with standard deviation (t) for the Scenario 1 model (with nominal CPUE data) for golden king crab in the EAG. 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. 1985 refers to the 1985/86 fishery.

Year	Recruits to the Model (≥ 101 mm CL)	Mature Male Biomass (≥ 121 mm CL)	Standard Deviation	Legal Male Biomass (≥ 136 mm CL)	Standard Deviation
1985	NA	15,057	675.47	16,924	809.53
1986	1.89	10,602	544.87	12,990	493.57
1987	1.50	8,341	468.83	9,385	379.75
1988	7.64	6,778	499.49	7,310	338.43
1989	5.37	7,106	666.99	5,720	352.43
1990	2.74	8,580	724.22	5,225	396.79
1991	4.57	9,148	790.73	6,050	440.97
1992	4.98	9,781	842.83	6,584	486.25
1993	2.97	10,812	883.49	7,133	514.84
1994	3.49	10,862	894.84	7,964	535.41
1995	2.63	10,789	898.63	8,134	546.85
1996	2.52	10,876	915.57	8,188	562.67
1997	13.35	12,272	1,081.60	8,446	592.85
1998	0.77	15,456	1,306.90	9,841	709.84
1999	1.50	16,265	1,364.60	11,596	817.59
2000	9.42	16,808	1,386.60	12,526	879.12
2001	0.64	18,184	1,424.00	13,596	938.96
2002	3.54	18,249	1,394.30	14,434	968.69
2003	1.05	17,683	1,307.30	14,860	972.43
2004	5.19	17,052	1,242.50	14,613	945.39
2005	2.11	16,835	1,205.90	14,441	925.81
2006	1.88	16,110	1,152.20	14,090	897.06
2007	6.09	15,727	1,143.30	13,483	868.06
2008	1.79	15,980	1,187.60	13,286	867.40
2009	4.13	15,807	1,217.40	13,154	878.68
2010	8.29	16,618	1,294.00	13,049	900.86
2011	3.05			13,703	956.21

Table 6 (b). Annual abundance estimates of model recruits (millions of crabs), legal male biomass with standard deviation (t), and mature male biomass with standard deviation (t) for the Scenario 2 model (with standardized CPUE data) for golden king crab in the EAG. 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. 1985 refers to the 1985/86 fishery.

Year	Recruits to the Model (≥ 101 mm CL)	Mature Male Biomass (≥ 121 mm CL)	Standard Deviation	Legal Male Biomass (≥ 136 mm CL)	Standard Deviation
1985	NA	12,989	971.75	15,242	748.50
1986	2.39	9,588	503.50	11,450	582.15
1987	1.84	8,318	459.65	8,475	381.77
1988	3.87	6,763	475.24	7,113	309.70
1989	5.55	6,181	534.23	5,583	323.61
1990	2.97	7,392	592.96	4,811	340.50
1991	3.98	7,968	662.46	5,512	384.33
1992	3.45	8,380	656.34	5,991	433.60
1993	3.14	9,039	676.32	6,341	415.48
1994	3.19	9,034	675.18	6,972	410.10
1995	2.21	8,967	661.01	7,036	410.05
1996	2.60	9,081	676.29	7,026	413.36
1997	11.00	10,241	817.44	7,281	437.26
1998	1.31	13,047	1,009.80	8,488	536.48
1999	1.28	13,860	1,074.10	10,115	630.03
2000	9.02	14,372	1,127.60	10,994	696.09
2001	1.15	16,006	1,183.10	12,028	769.07
2002	3.94	16,506	1,183.80	13,033	808.96
2003	1.36	16,476	1,130.20	13,752	827.60
2004	4.78	16,163	1,090.90	13,867	816.11
2005	1.25	16,133	1,068.00	13,932	811.95
2006	2.30	15,383	1,024.20	13,787	798.12
2007	5.26	15,022	1,009.70	13,284	778.86
2008	2.05	15,289	1,043.90	13,098	777.35
2009	4.23	15,267	1,074.80	13,028	785.64
2010	5.73	15,907	1,135.20	13,040	805.62
2011	3.00			13,534	844.54

Table 7. Time series of catch divided by mature male abundance for Scenarios 1 (nominal CPUE) and 2 (standardized CPUE) for golden king crab in the EAG. We provide only the 1995/96 to 2010/11 time series because reliable estimates of total removals from all sources (pot fishery and groundfish fishery) are only available from 1995/96 to 2010/11.

Year	Scenario 1: Total Removal/Mature Male Abundance	Scenario 2: Total Removal/Mature Male Abundance
1995/96	0.21	0.25
1996/97	0.15	0.18
1997/98	0.14	0.17
1998/99	0.11	0.13
1999/00	0.09	0.11
2000/01	0.09	0.11
2001/02	0.09	0.10
2002/03	0.08	0.08
2003/04	0.08	0.09
2004/05	0.08	0.08
2005/06	0.08	0.08
2006/07	0.09	0.09
2007/08	0.09	0.09
2008/09	0.09	0.10
2009/10	0.10	0.10
2010/11	0.09	0.09

Table 8. Total and retained catch OFL, F_{OFL}, and MMB/MMBref ratio for various scenarios for golden king crab in the EAG.

Scenario	Total Catch OFL (t)	Total Catch OFL (mlbs)	Retained Catch OFL (t)	Retained Catch OFL (mlbs)	F_{OFL}	MMB/MMB_{ref}
1	1794.23	3.96	1674.36	3.69	0.18	1.24
2	1765.36	3.89	1636.33	3.61	0.18	1.32
3	1942.70	4.28	1822.23	4.02	0.18	1.24
4	1695.27	3.74	1580.08	3.48	0.18	1.22
5	1707.89	3.77	1533.66	3.38	0.18	1.31
6	2614.18	5.76	2427.29	5.35	0.37	1.17

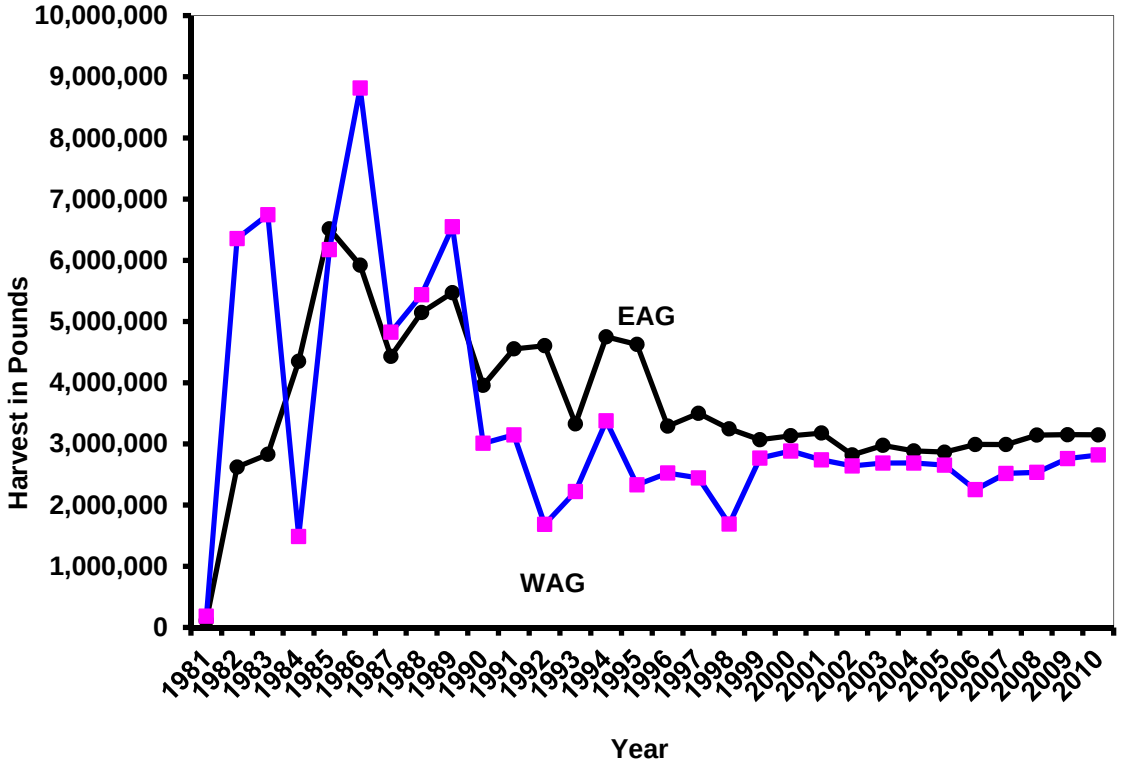


Figure 1. Historical commercial harvest (from fish ticket and in pounds) of golden king crab in the EAG and WAG, 1981-2010 (note: 1981 refers to the 1981/82 fishery).

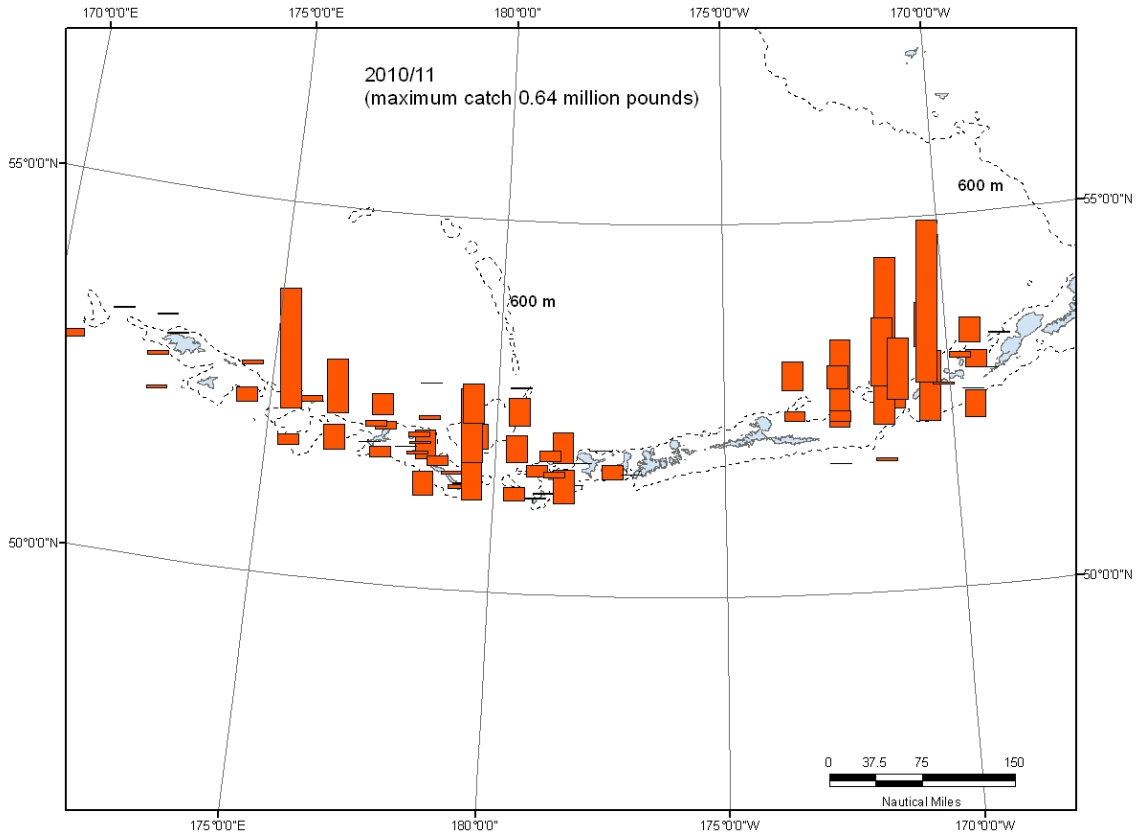


Figure 2. Aleutian Islands golden king crab harvest by ADF&G statistical areas for 2010/11.

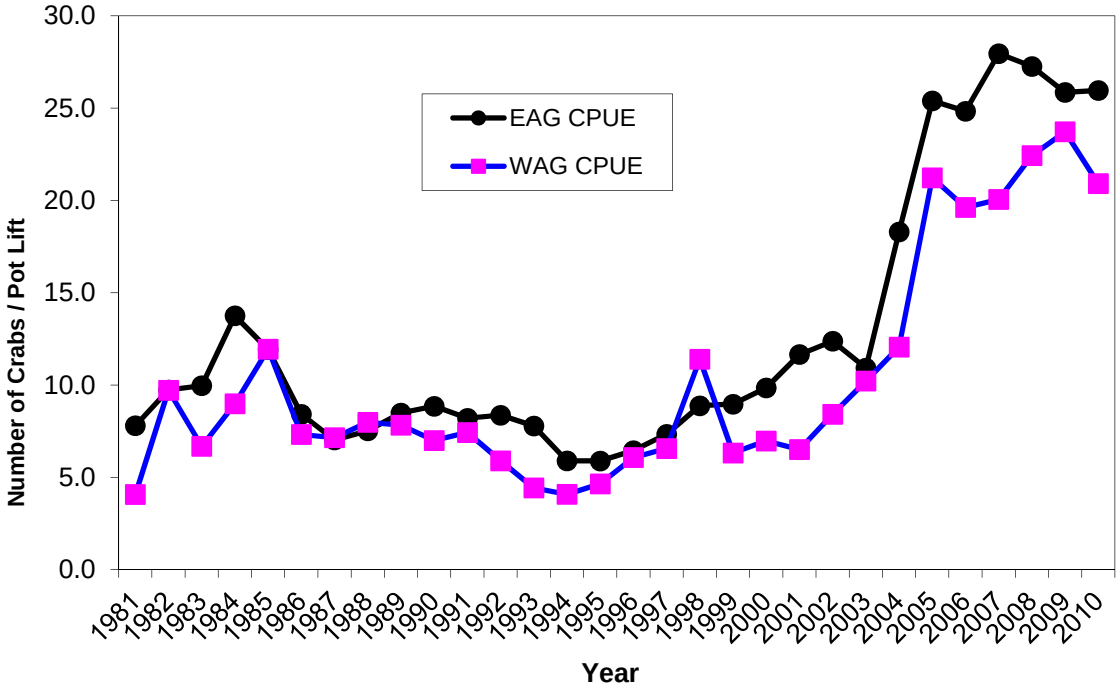


Figure 3. Historical catch-per-unit-effort CPUE (number of crabs per pot lift) in the commercial fishery (from fish ticket) for golden king crab in the EAG and the WAG, 1981-2010 (note: 1981 refers to the1981/82 fishery).

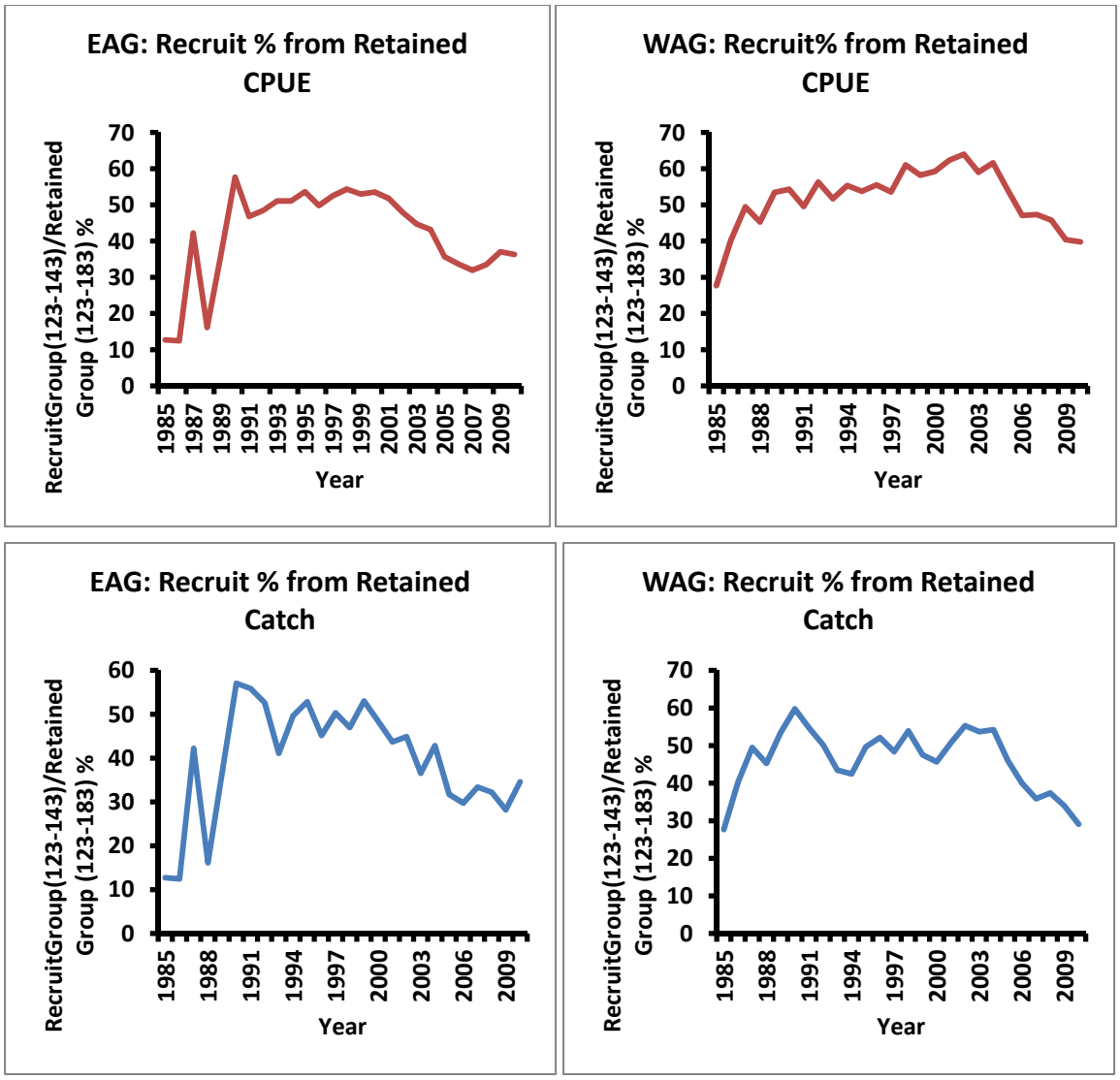


Figure 4. Recruitment trends in the observed CPUE and commercial golden king crab catch in the EAG and WAG. Recruit size group is arbitrarily selected as the 123-143 mm CL mid-point size range and the total retained size group is the entire mid-point size range, 123-183 mm CL.

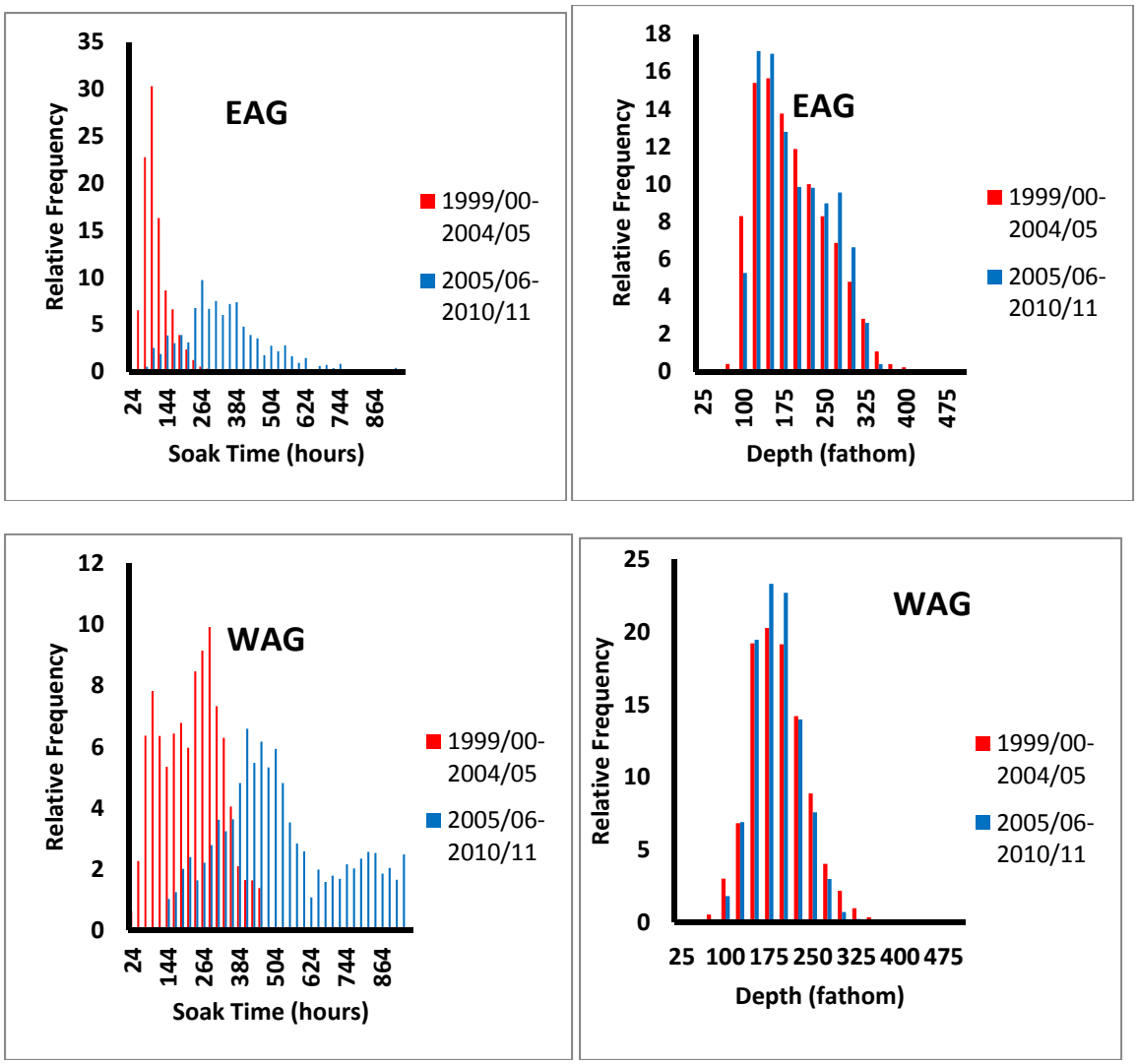


Figure 5. Soak time and depth relative frequency distributions of golden king crab pots during pre (1999/00-2004/05)- and post (2005/06-2010/11)- rationalization periods.

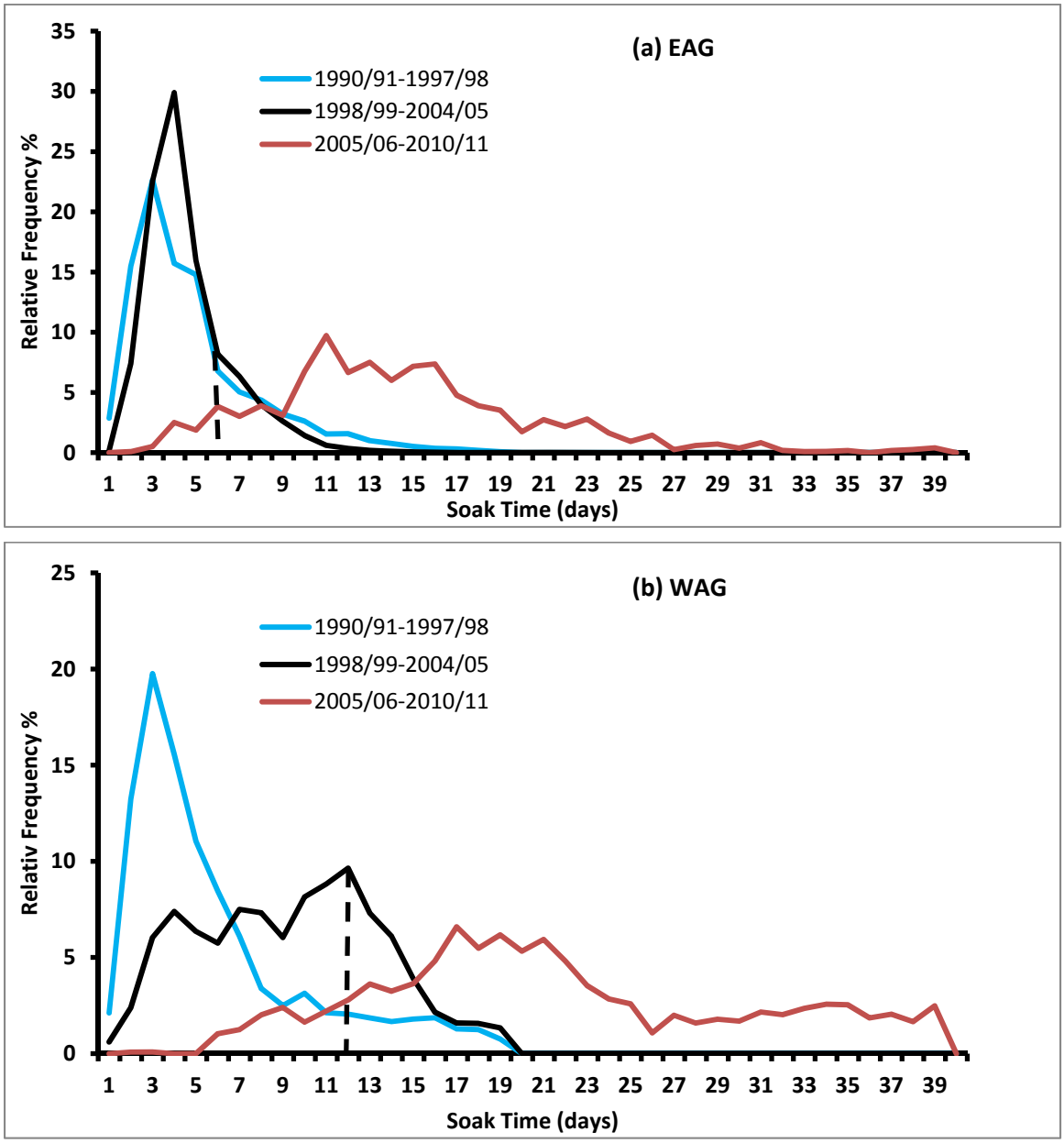


Figure 6. Relative frequency of soak time (days) in (a) EAG and (b) WAG. Different color solid lines are for different time periods when different catchability and selectivity parameters were used. The dash vertical lines mark the 6-day and 12-day soak times respectively for EAG and WAG, which meet the three lines at reasonably high frequency points. The observer CPUE were standardized to respective soak time using the fitted Zhou and Shirley (1997) model.

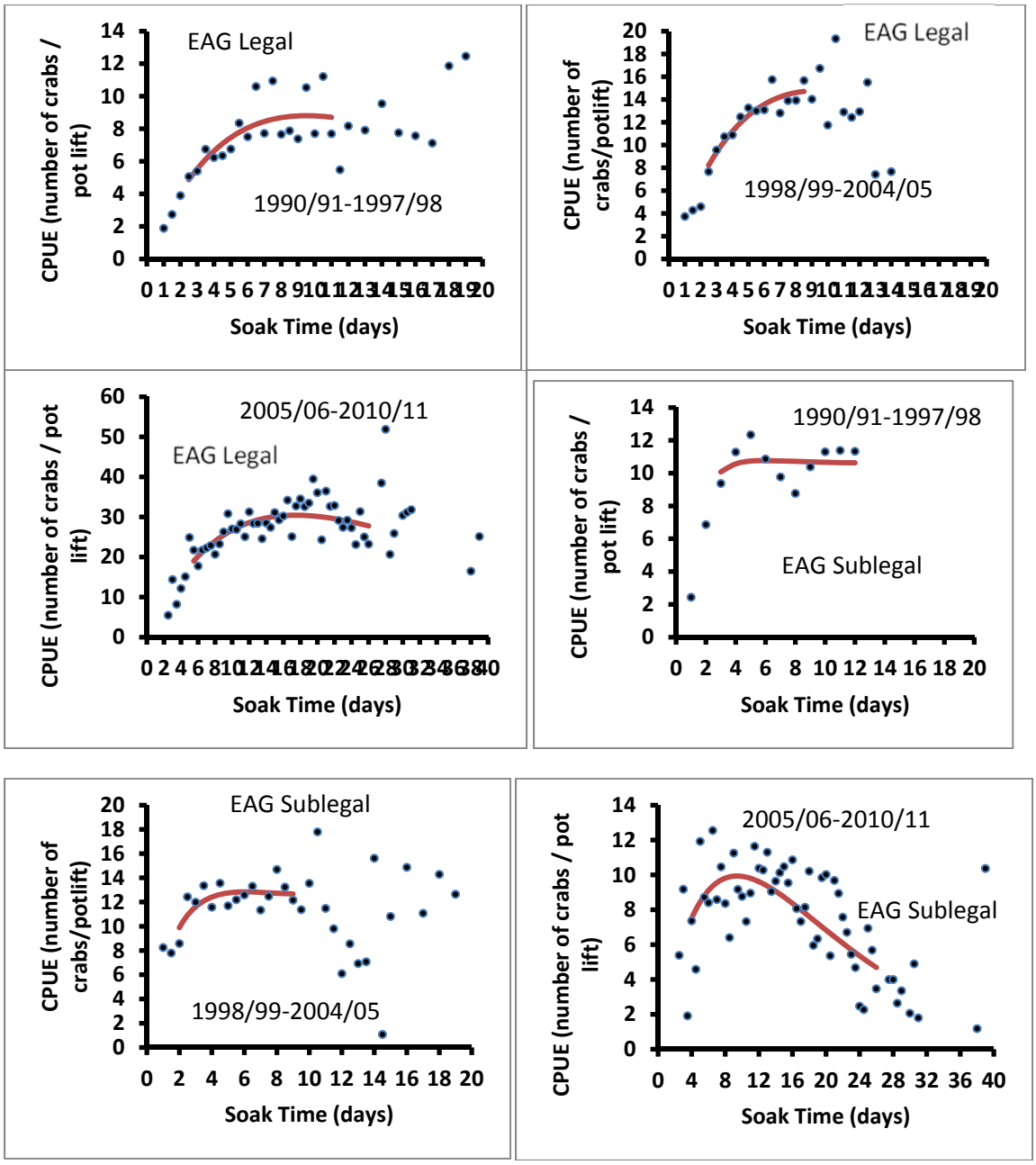


Figure 7. Zhou and Shirley (1997) model fit to observer legal and sublegal male CPUE vs. soak time for EAG for different time periods. 5th- to 95th - percentile soak time are the cut off marks for consideration.

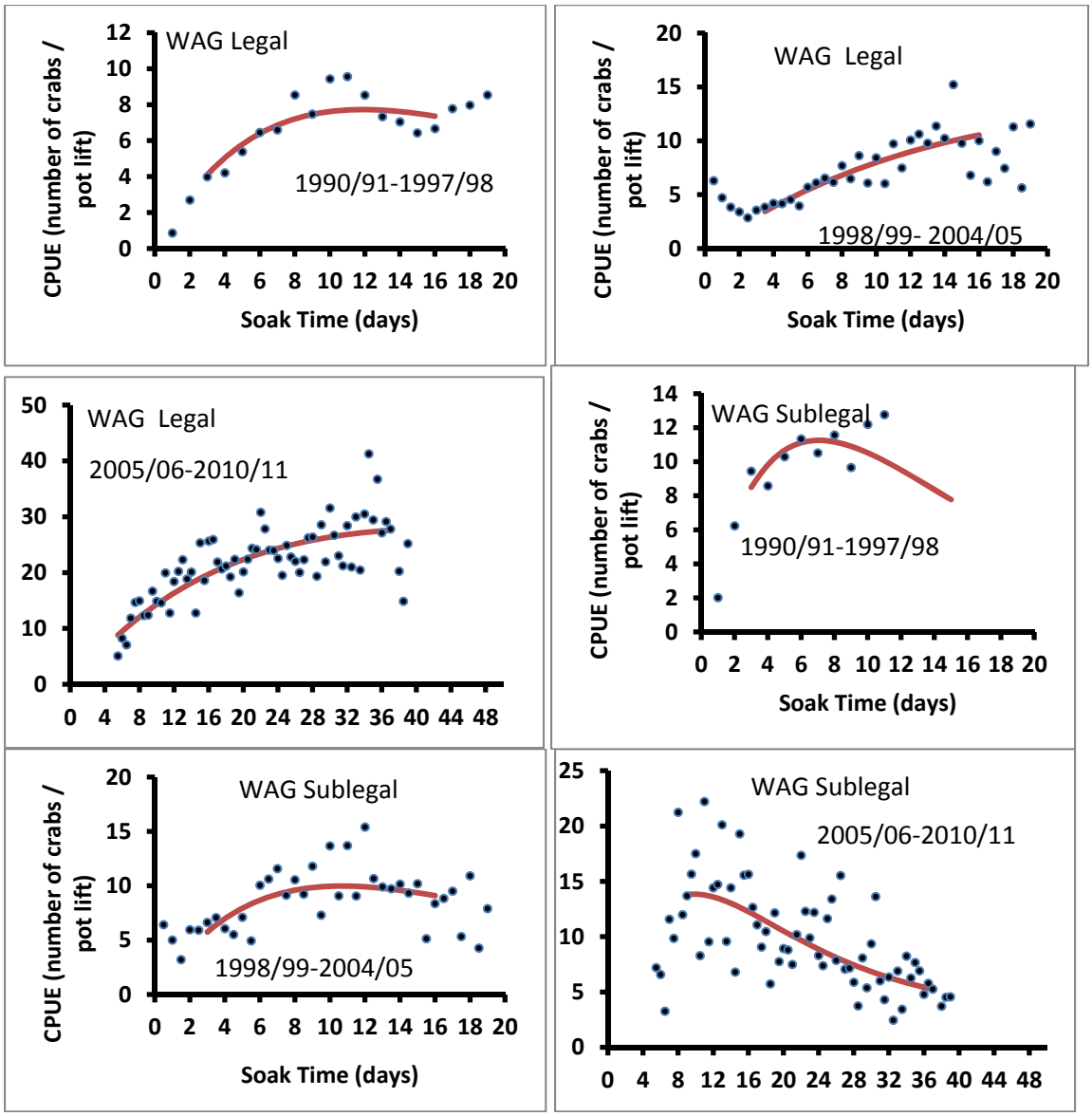


Figure 8. Zhou and Shirley (1997) model fit to observer legal and sublegal male CPUE vs. soak time for WAG for different time periods. 5th- to 95th - percentile soak time are the cut off marks for consideration.

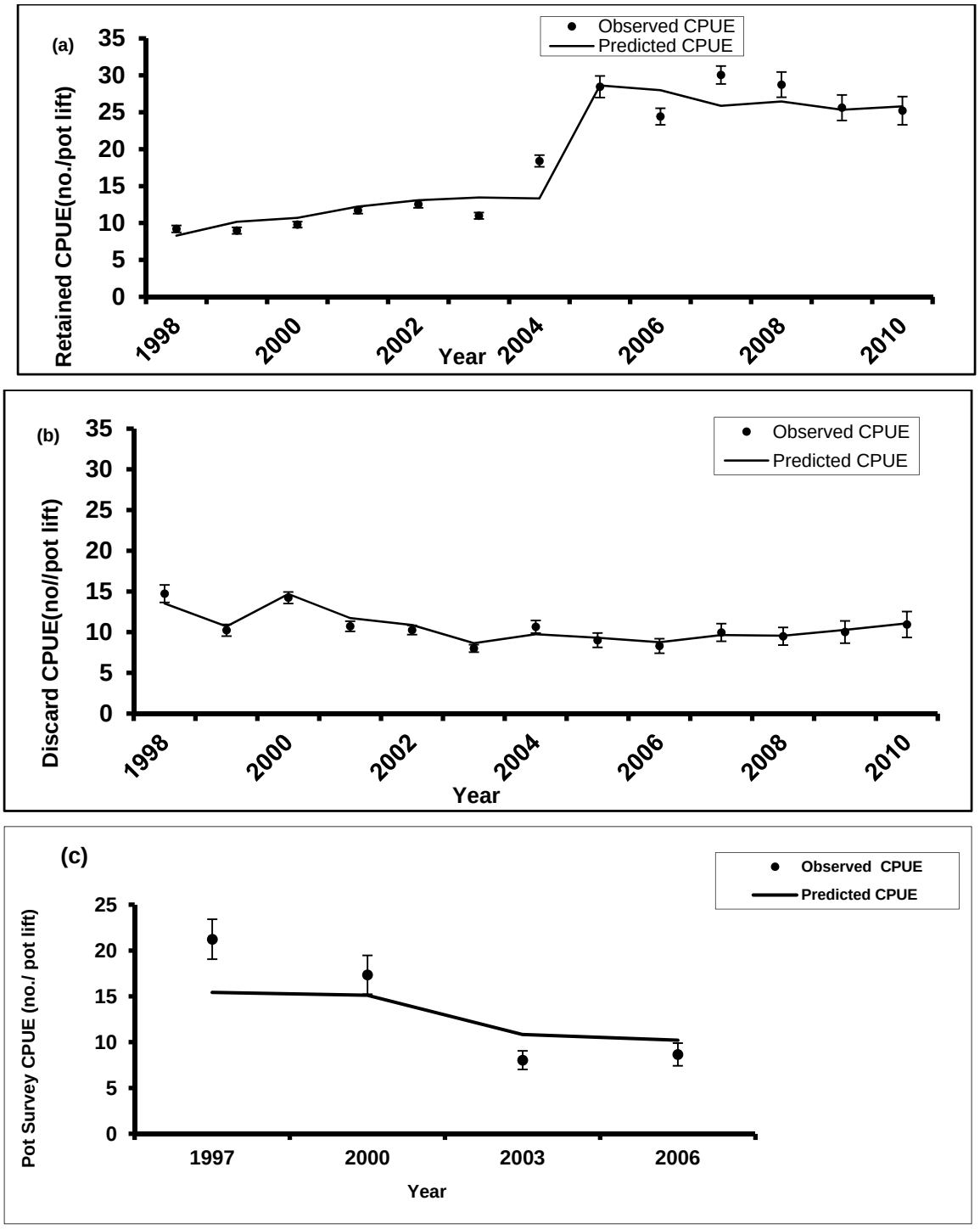


Figure 9. Predicted (line) vs. observed (filled circle) (a) retained catch-per-unit-effort (CPUE), (b) discard CPUE, and (c) pot survey CPUE for golden king crab in the EAG. Two-standard deviation confidence bars are attached to observed points. The fishery retained and discard CPUE values are nominal data (Scenario 1) from observer samples for 1998-2010 (note: 1998 refers to the 1998/99 fishery). The pot survey CPUE values are for 1997, 2000, 2003, and 2006.

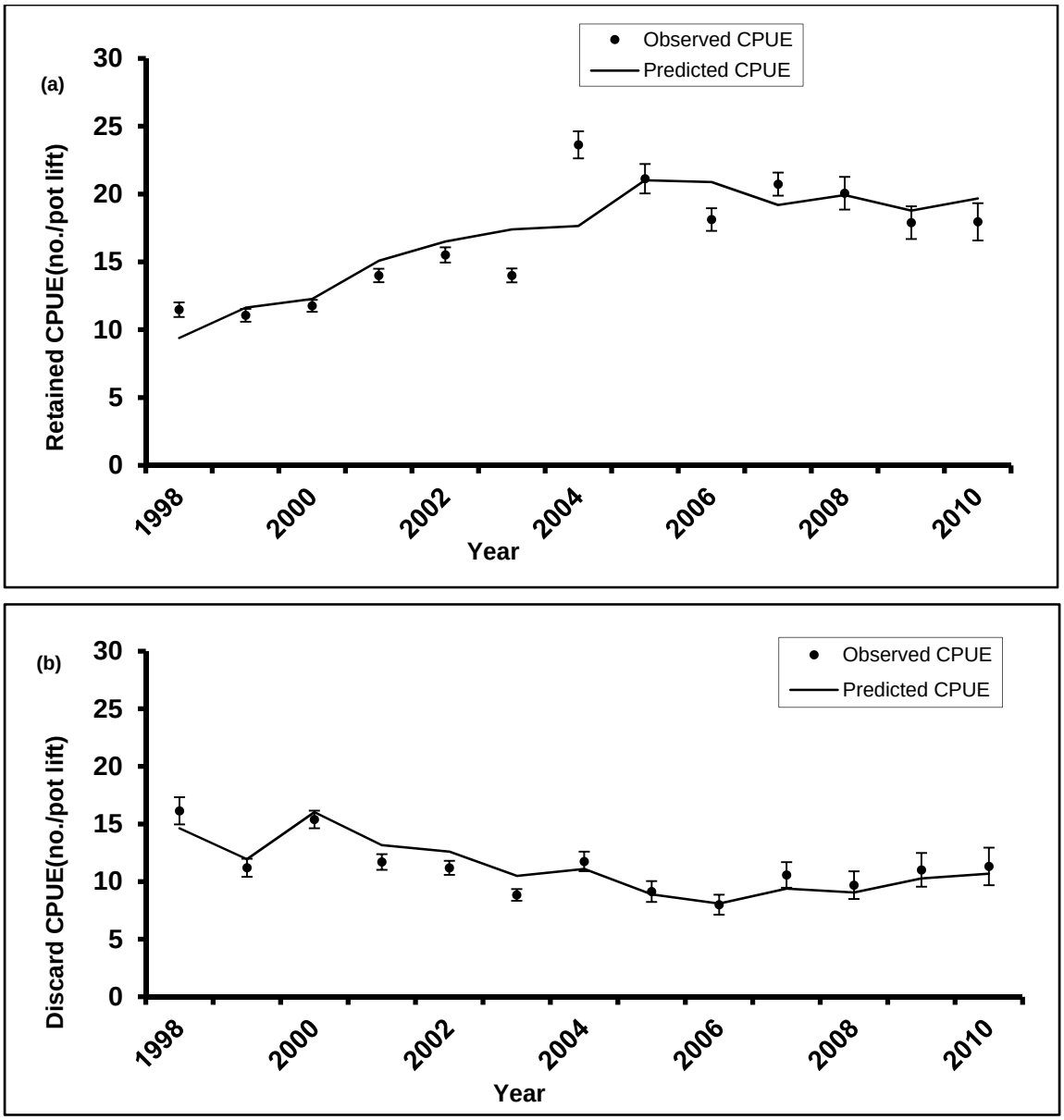


Figure 10. Predicted (line) vs. observed (filled circle) (a) retained catch-per-unit-effort (CPUE) and (b) discard CPUE for golden king crab in the EAG. Two-standard deviation confidence bars are attached to observed points. The fishery retained and discard CPUE values are standardized data (Scenario 2) from observer samples for 1998-2010 (note: 1998 refers to the 1998/99 fishery).

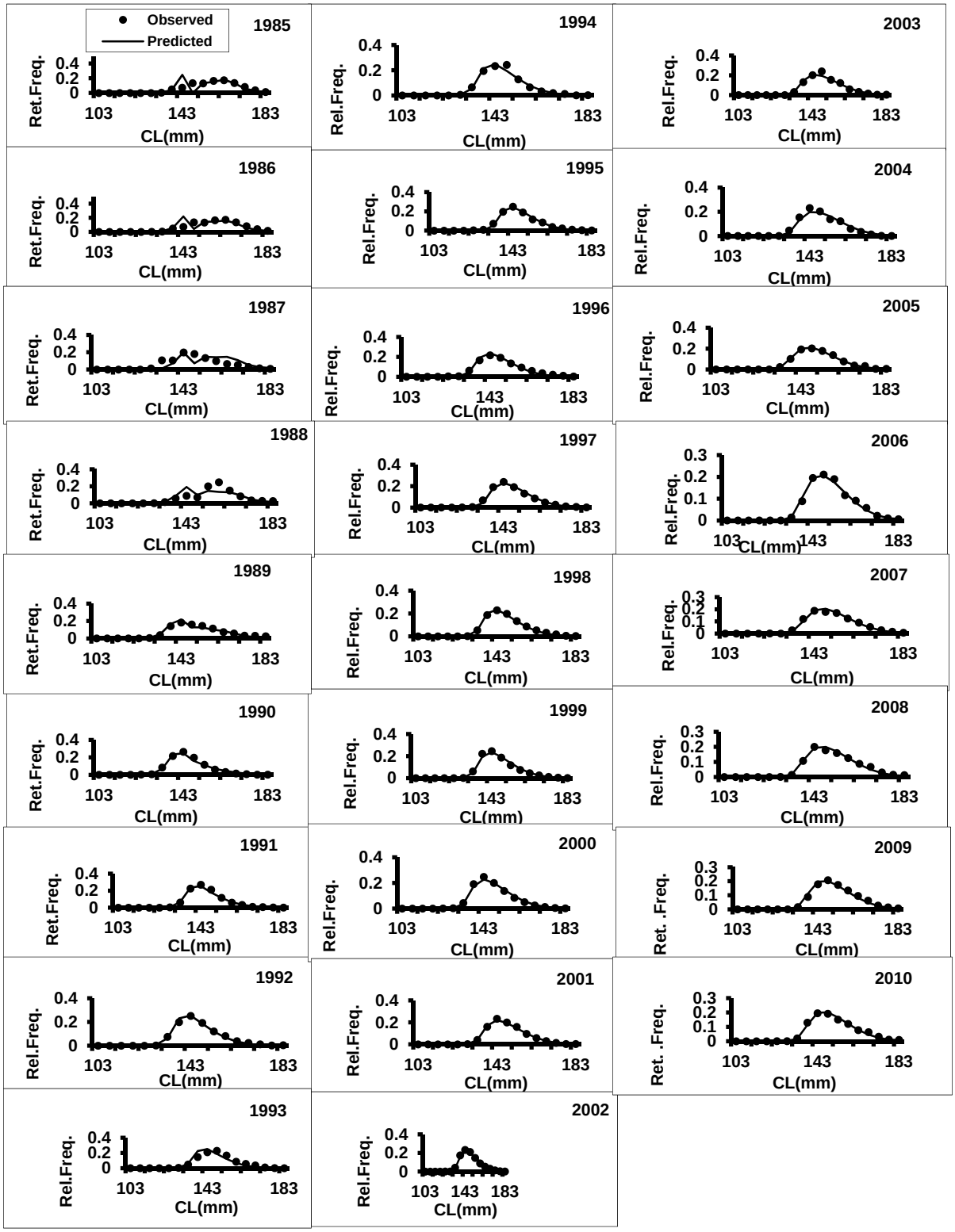


Figure 11. Predicted (line) vs. observed (filled circle) retained catch relative length frequency distributions for Scenario 1 data of golden king crab in the EAG, 1985 to 2010 (note: 1985 refers to the 1985/86 fishery).

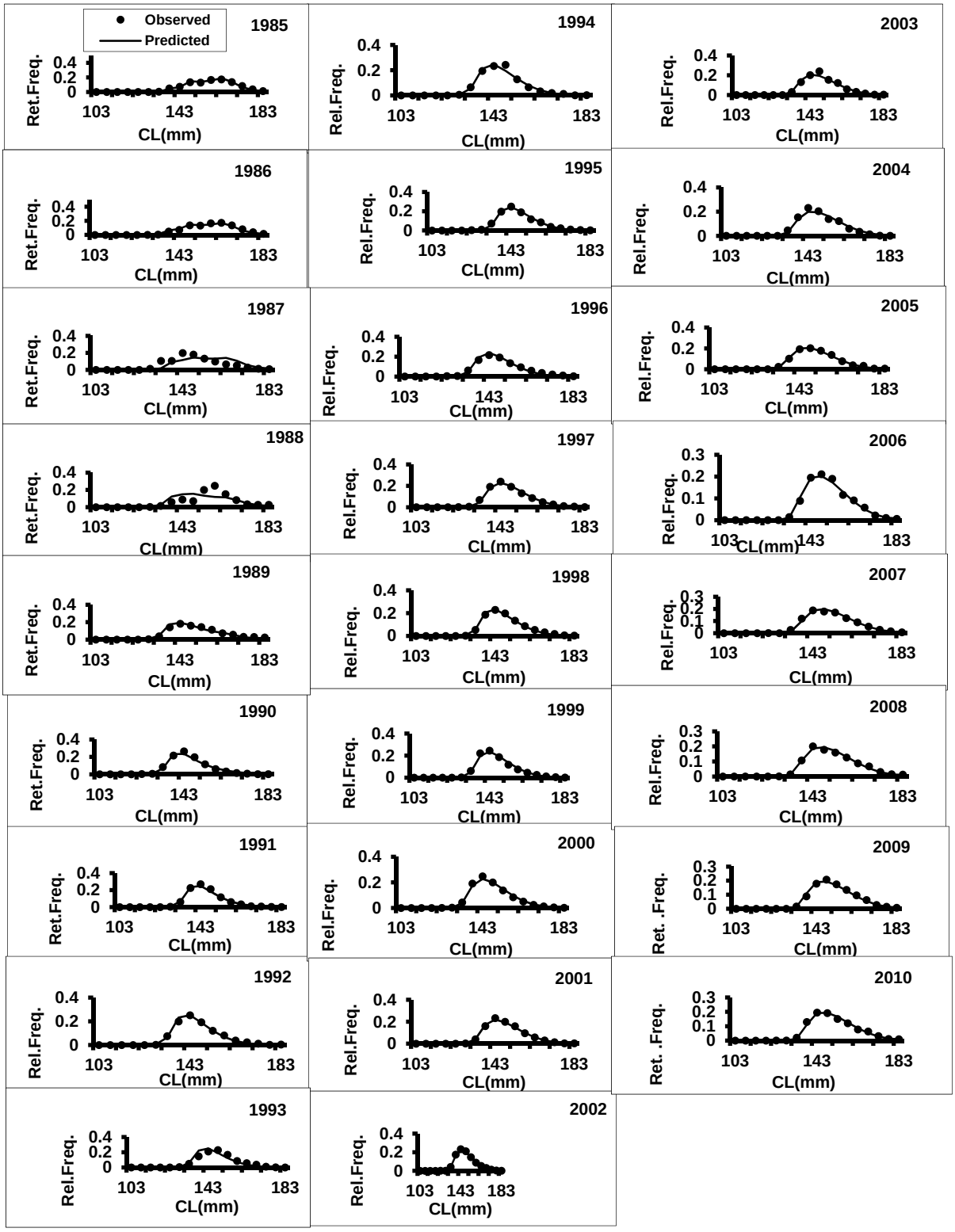


Figure 12. Predicted (line) vs. observed (filled circle) retained catch relative length frequency distributions for Scenario 2 data of golden king crab in the EAG, 1985 to 2010 (note: 1985 refers to the 1985/86 fishery).

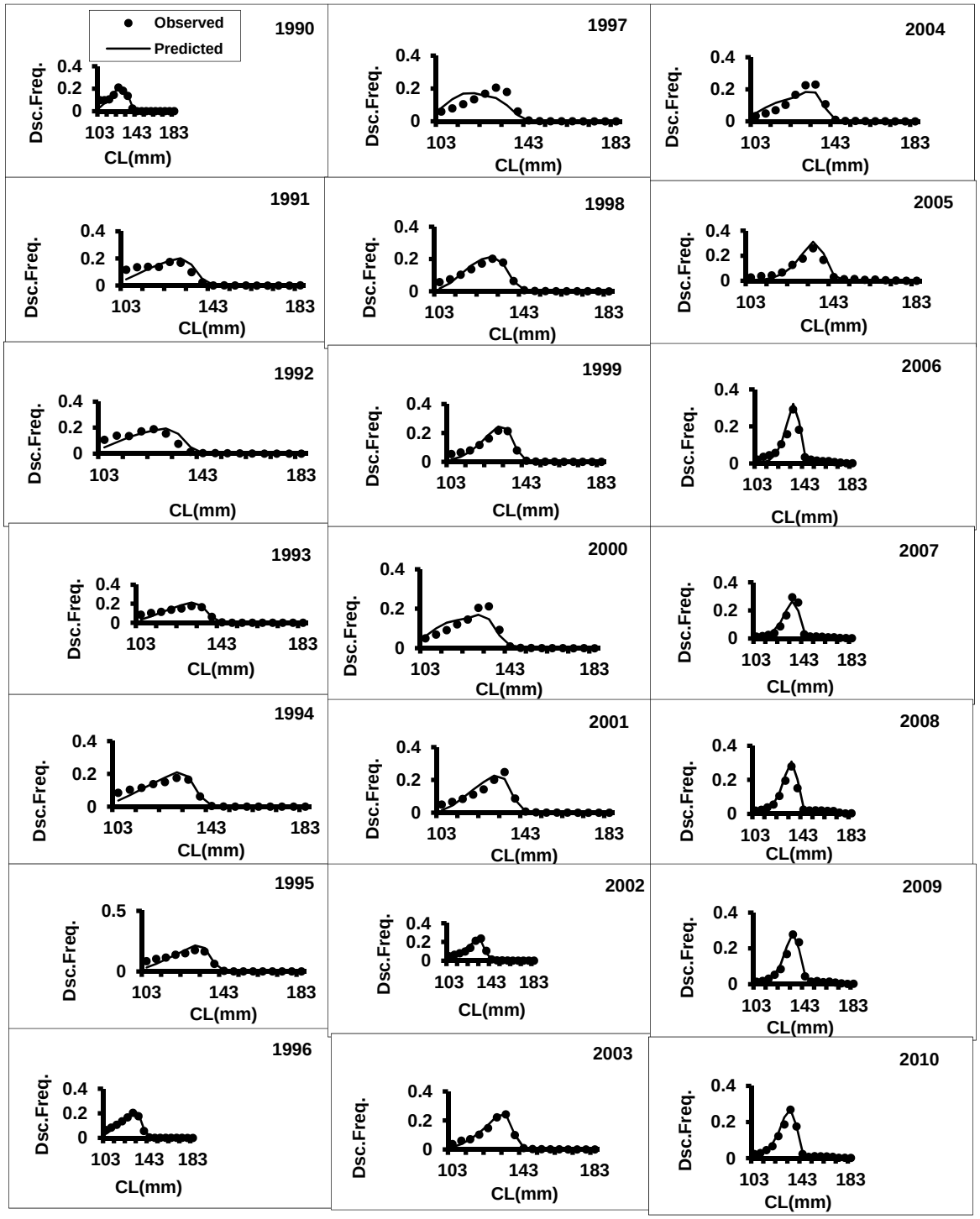


Figure 13. Predicted (line) vs. observed (filled circle) pot discarded catch relative length frequency distributions for Scenario 1 data of golden king crab in the EAG, 1990 to 2010 (note: 1990 refers to the 1990/91 fishery).

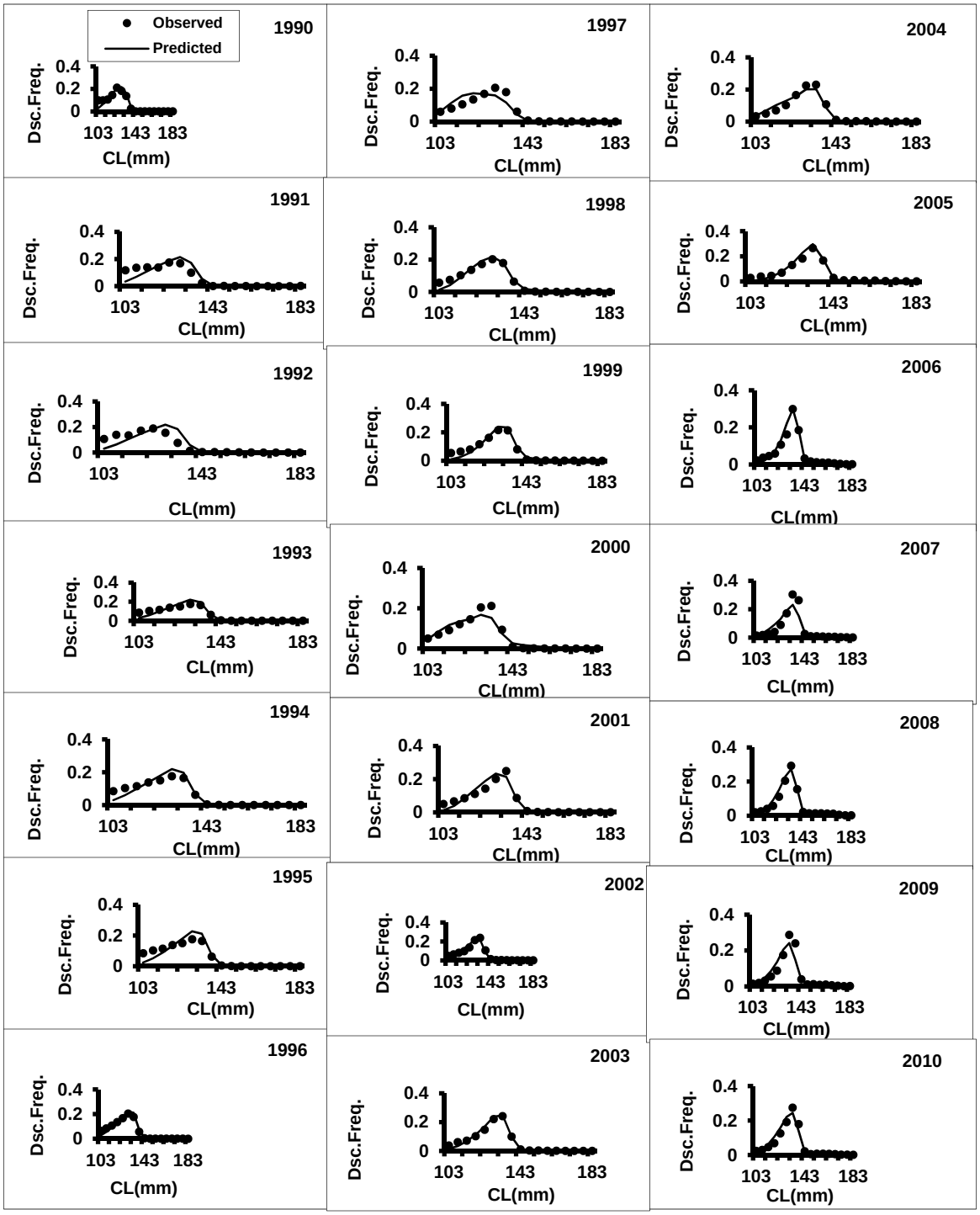


Figure 14. Predicted (line) vs. observed (filled circle) pot discarded catch relative length frequency distributions for Scenario 2 data of golden king crab in the EAG, 1990 to 2010 (note: 1990 refers to the 1990/91 fishery).

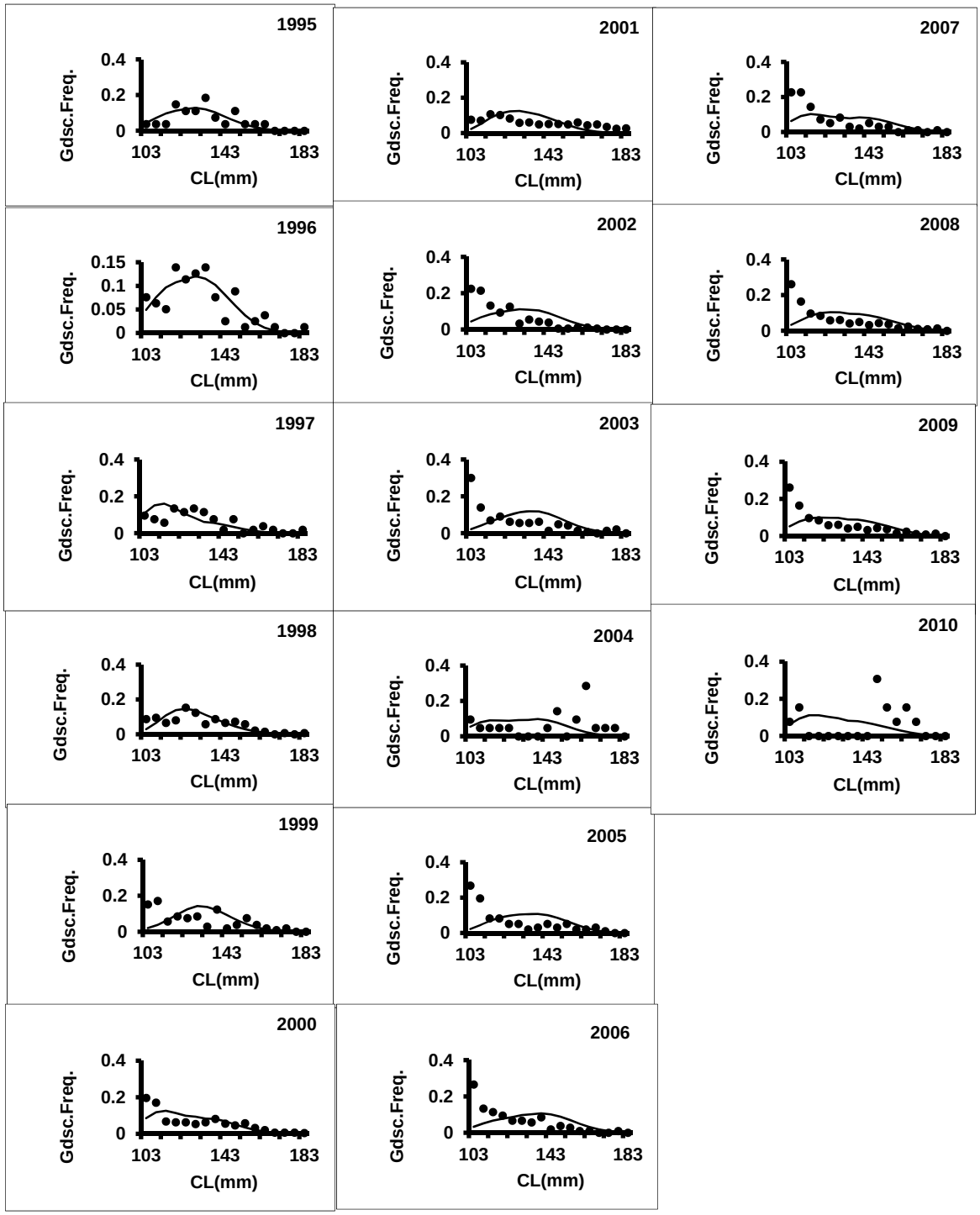


Figure 15. Predicted (line) vs. observed (filled circle) groundfish discarded catch relative length frequency distributions for Scenario 2 data of golden king crab in the EAG, 1995 to 2010 (note: 1995 refers to the 1995/96 fishery).

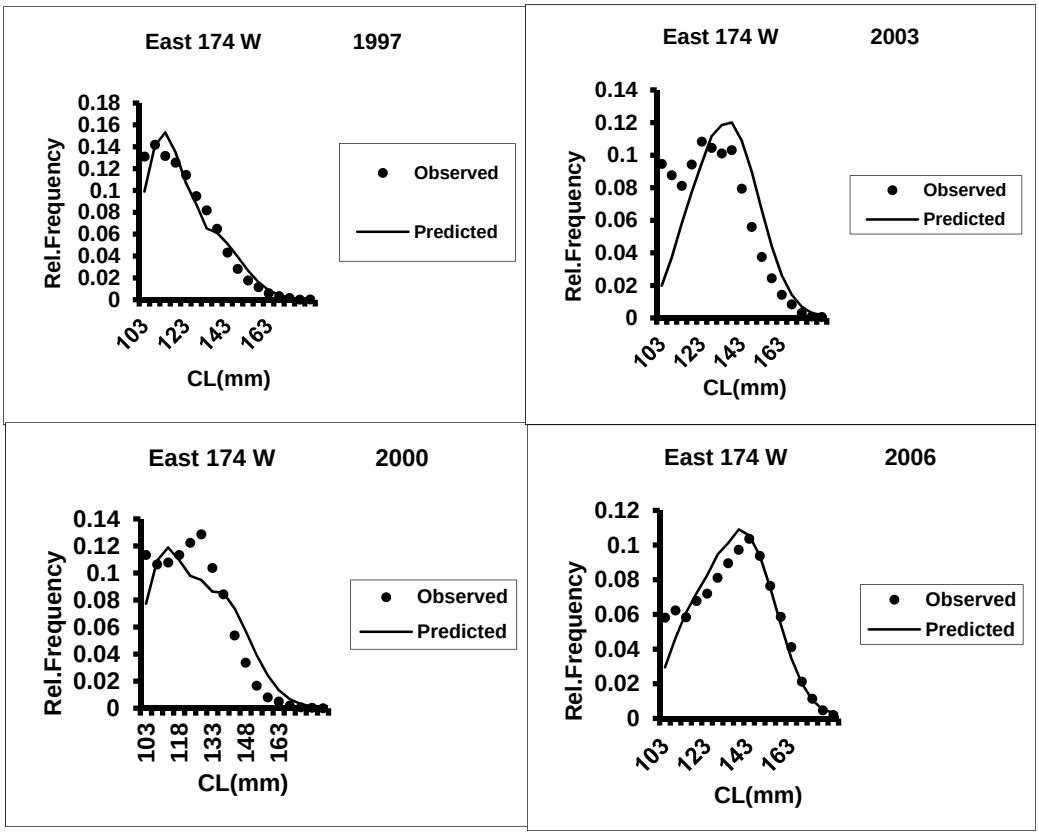


Figure 16. Predicted (line) vs. observed (filled circle) CPUE relative length frequency distributions for Scenario 2 data of golden king crab in the triennial pot surveys in a restricted area in the EAG, 1997 to 2006.

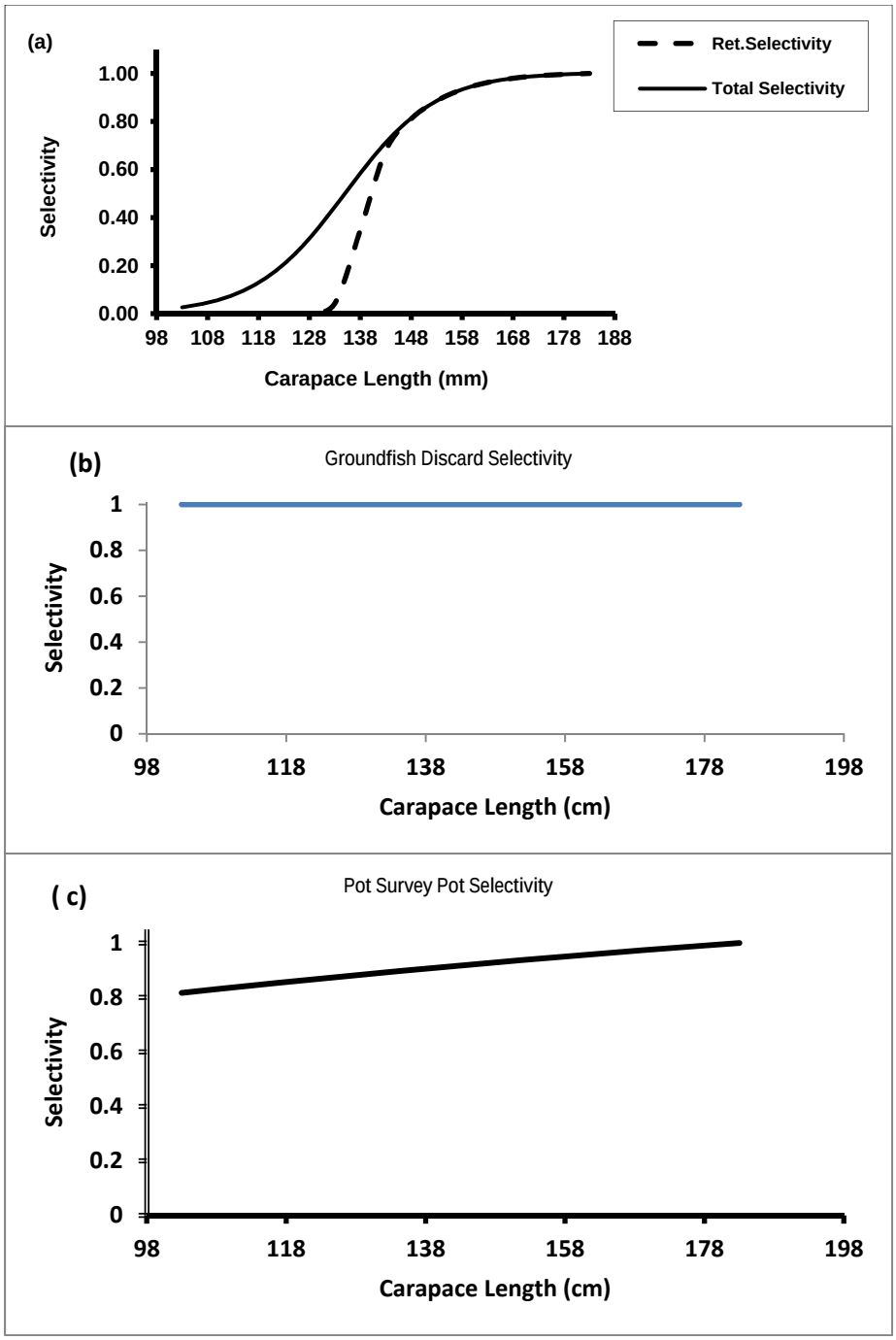


Figure 17. Estimated (a) total selectivity (solid line) and effective retained catch selectivity (total selectivity*retained selectivity; dashed line) during 2005- present (post-rationalization period); (b) groundfish discard selectivity; and (c) pot survey selectivity for Scenario 2 data for EAG golden king crab fishery.

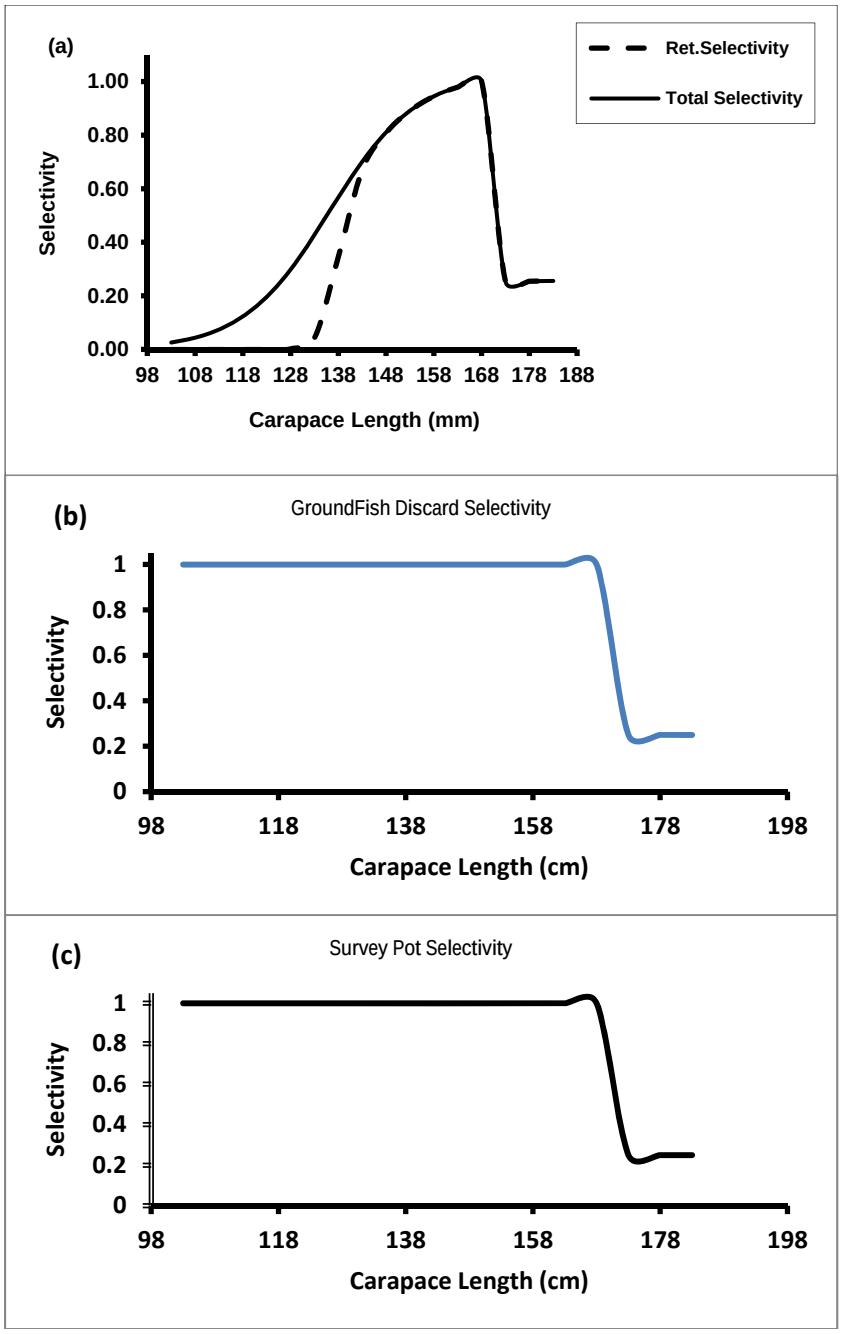
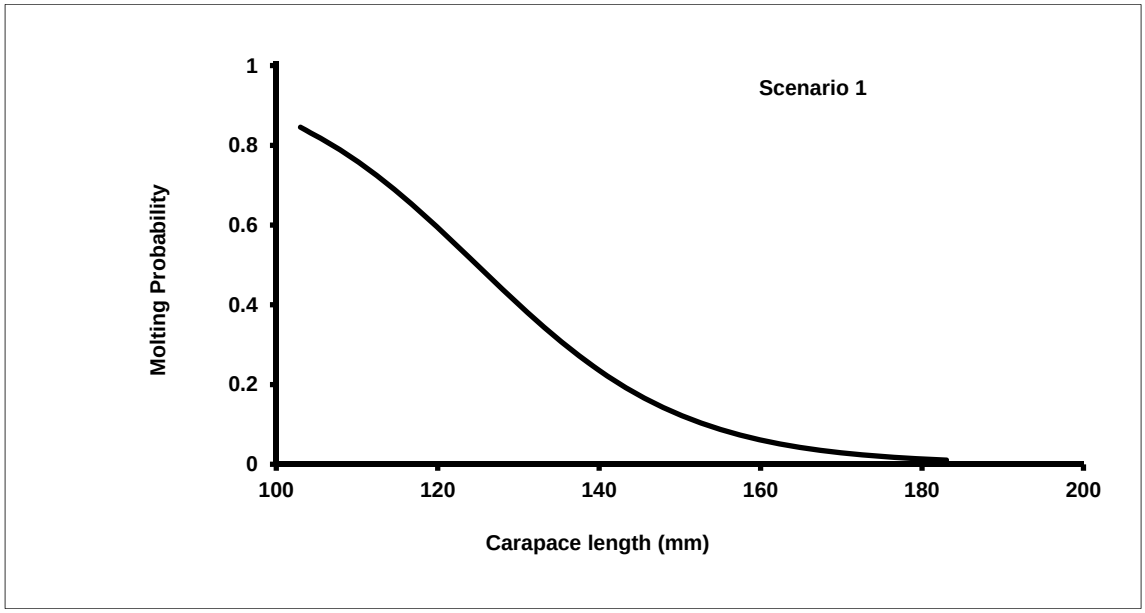


Figure 17 continued. Estimated (a) total selectivity (solid line) and effective retained catch selectivity (total selectivity*retained selectivity; dashed line) during 2005- present (post-rationalization period); (b) groundfish discard selectivity; and (c) pot survey selectivity for Scenario 5 (dome shape selectivity) for EAG golden king crab fishery.



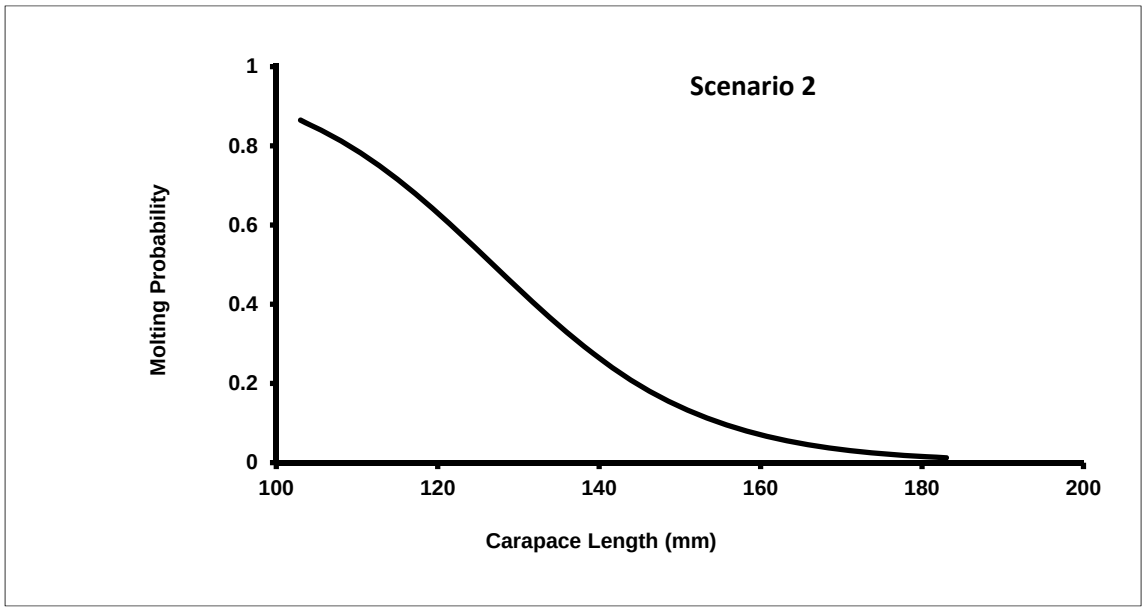
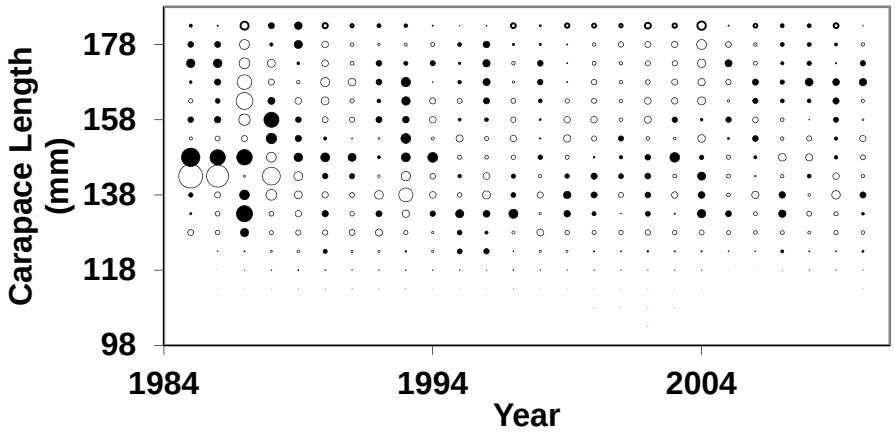
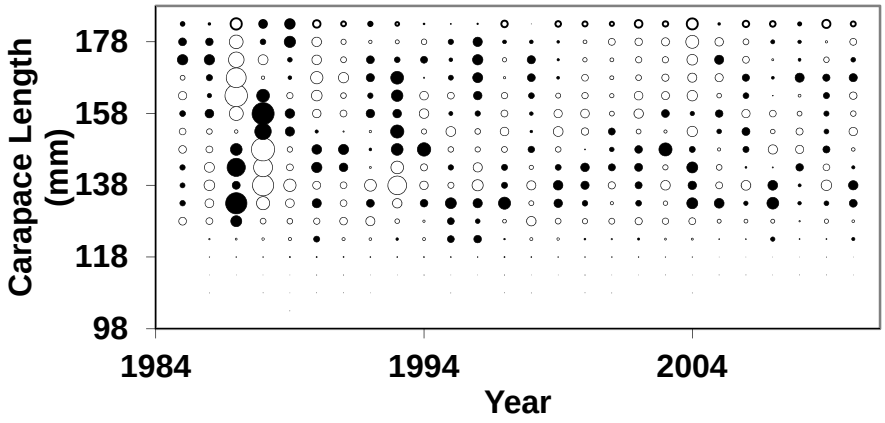


Figure 18. Estimated molt probability for Scenarios 1 and 2 data of EAG golden king crab.

(1)



(2)



(3)

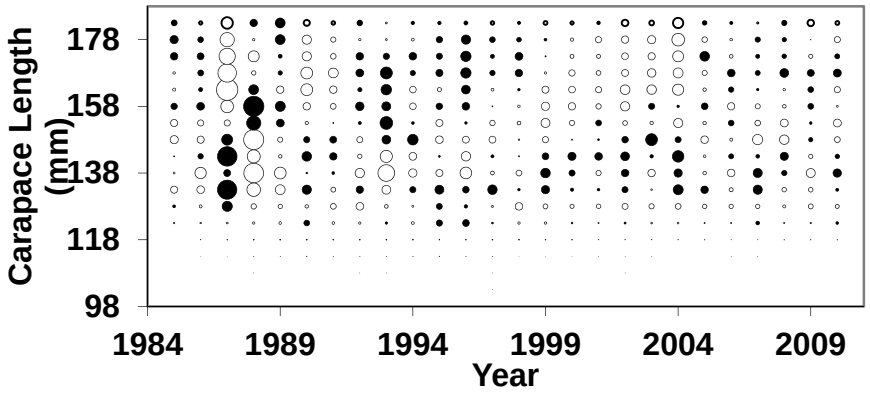
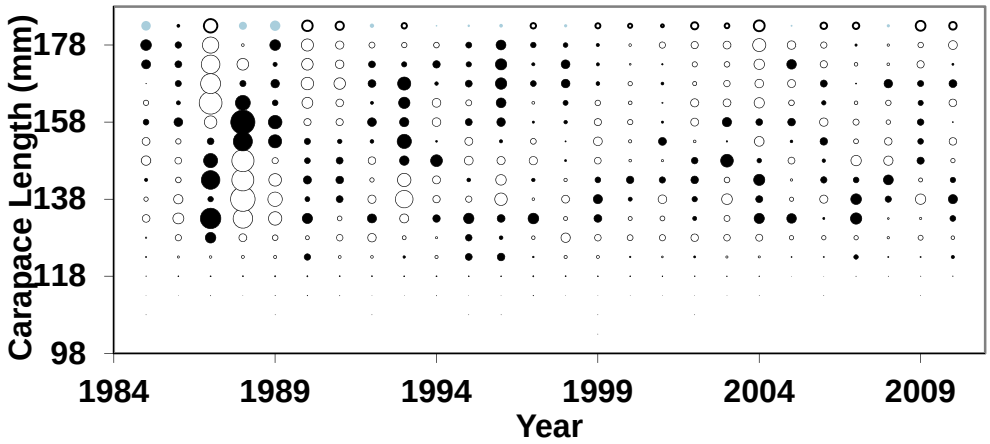
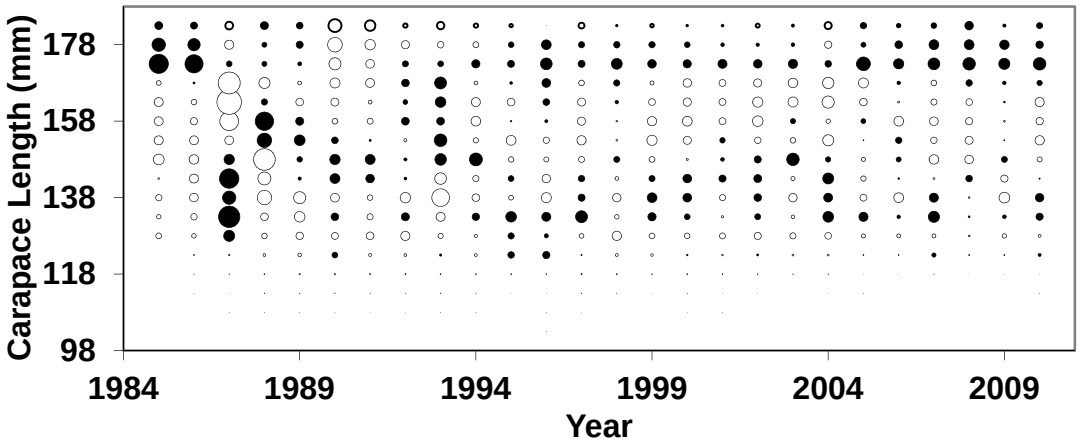


Figure 19. Bubble plot of standardized residuals of retained length composition for Scenarios 1, 2 and 3 for EAG golden king crab, 1985-2010 (note: 1985 refers to the 1985/86 fishery).

(4)



(5)



(6)

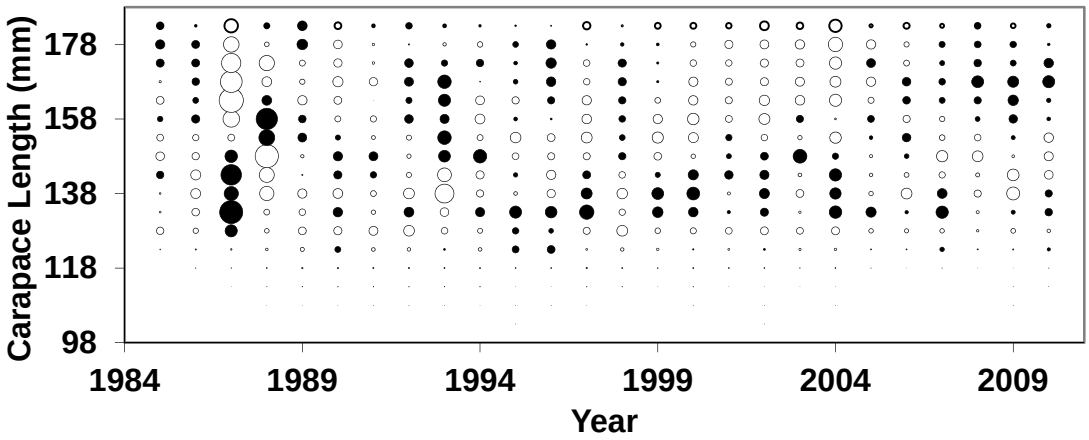
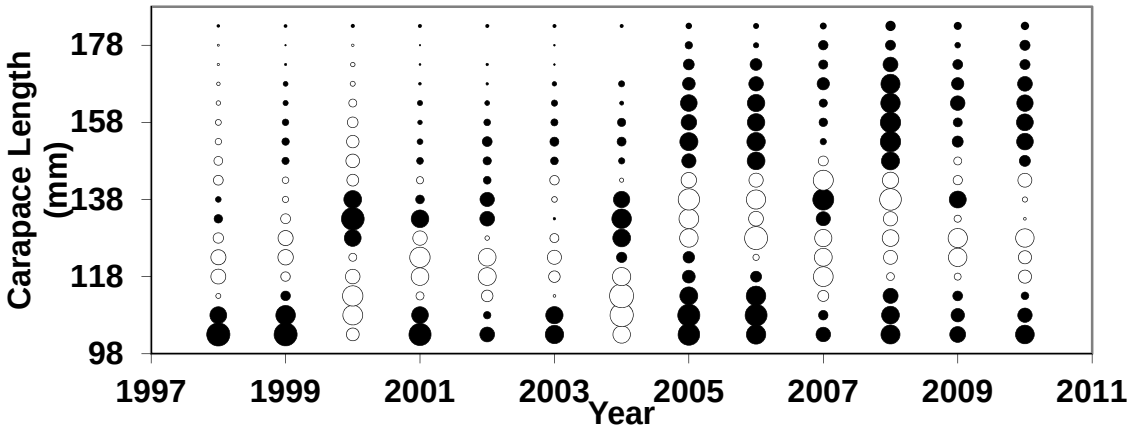
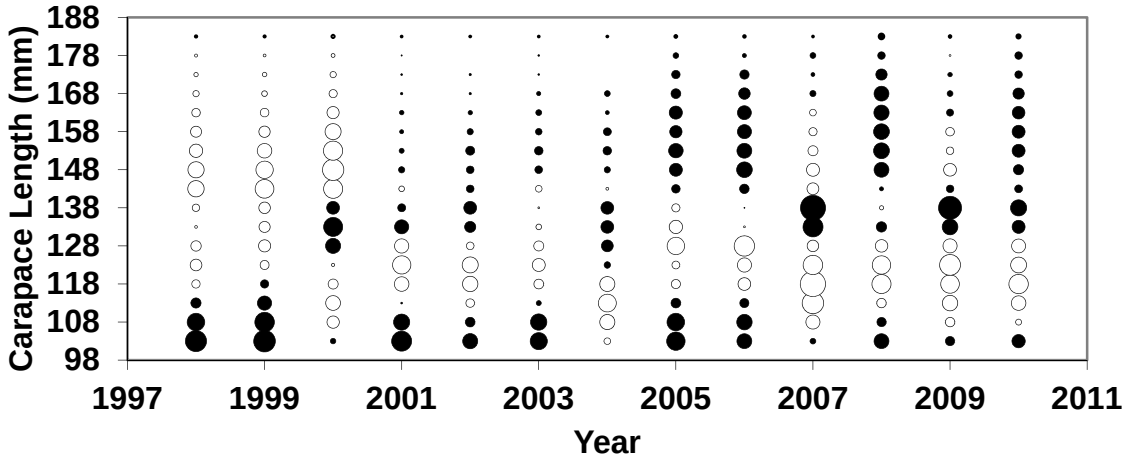


Figure 19 continued. Bubble plot of standardized residuals of retained length composition for Scenarios 4, 5 and 6 for EAG golden king crab, 1985-2010 (note: 1985 refers to the 1985/86 fishery).

(1)



(2)



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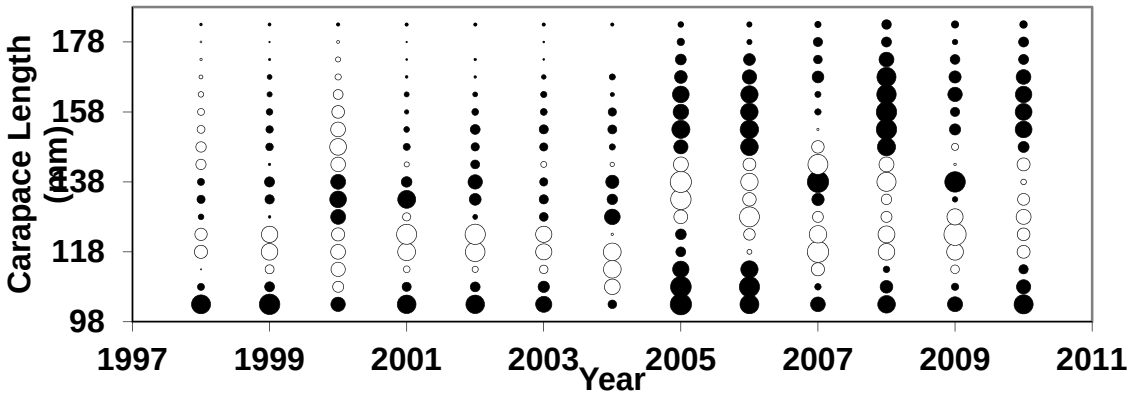
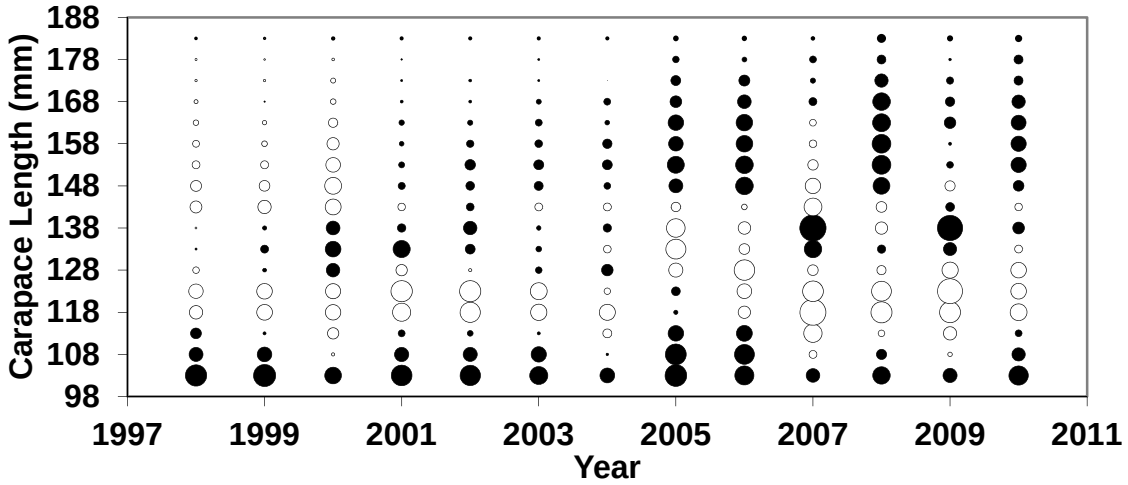
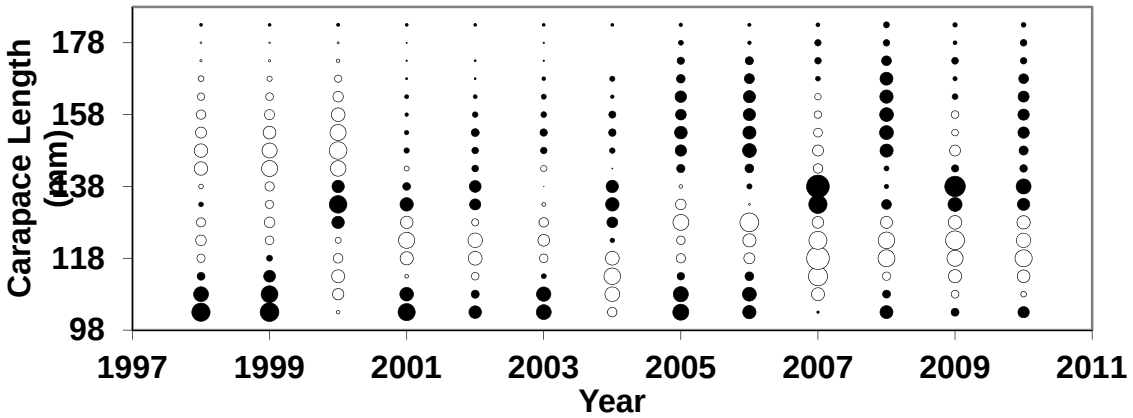


Figure 20. Bubble plot of standardized residuals of pot discarded length composition for Scenarios 1, 2 and 3 for EAG golden king crab, 1998-2010 (note: 1998 refers to the 1998/99 fishery).

(4)



(5)



(6)

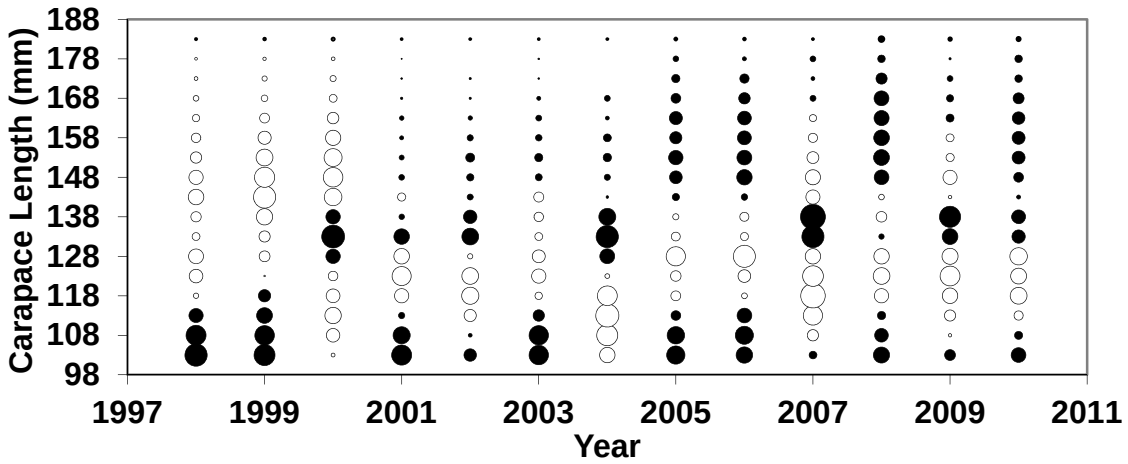
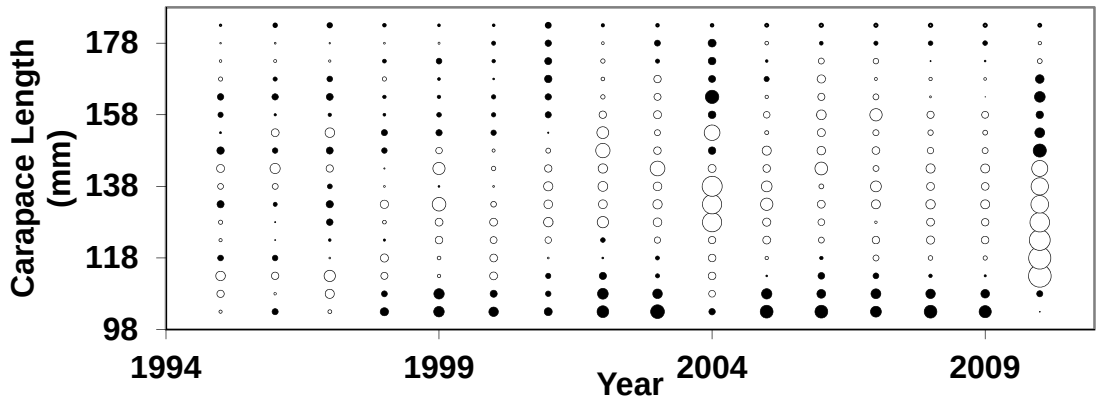
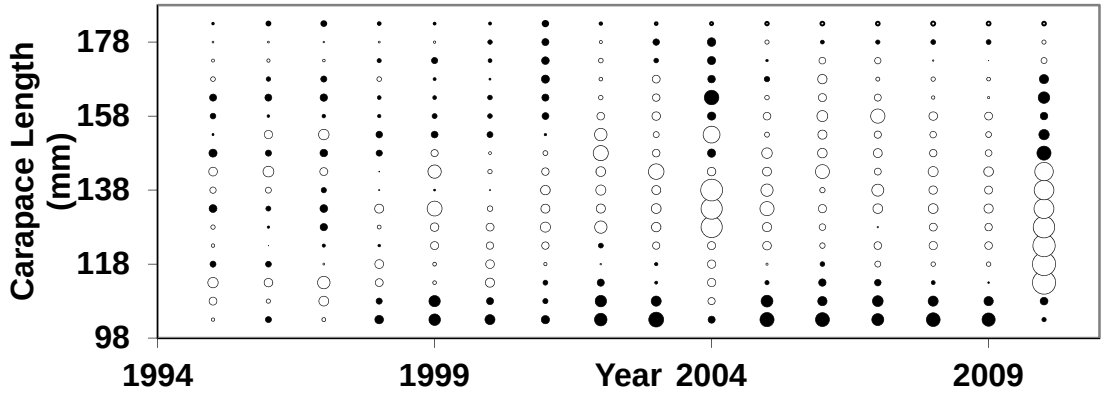


Figure 20 continued. Bubble plot of standardized residuals of pot discarded length composition for Scenarios 4, 5 and 6 for EAG golden king crab, 1998-2010 (note: 1998 refers to the 1998/99 fishery).

(1)



(2)



(3)

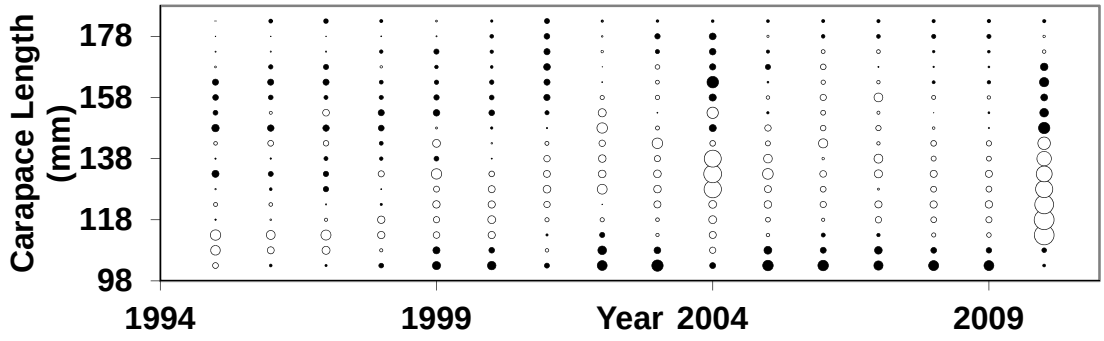
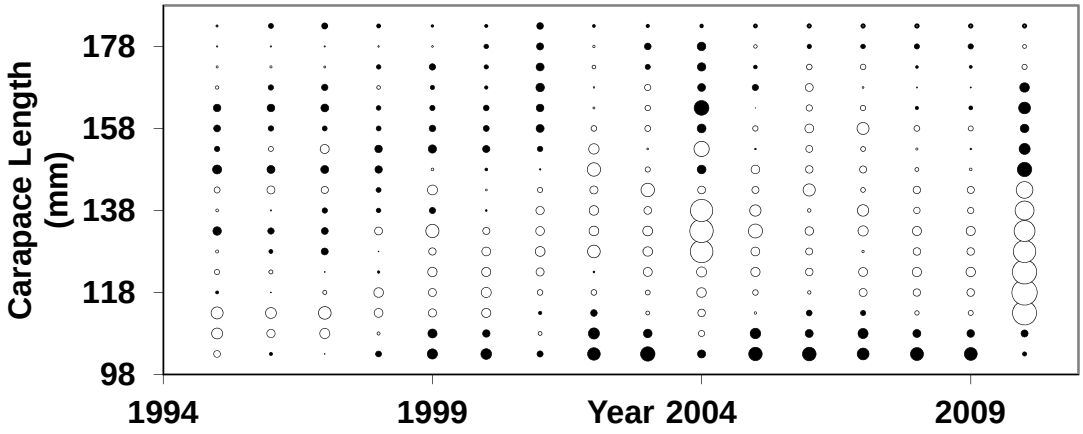
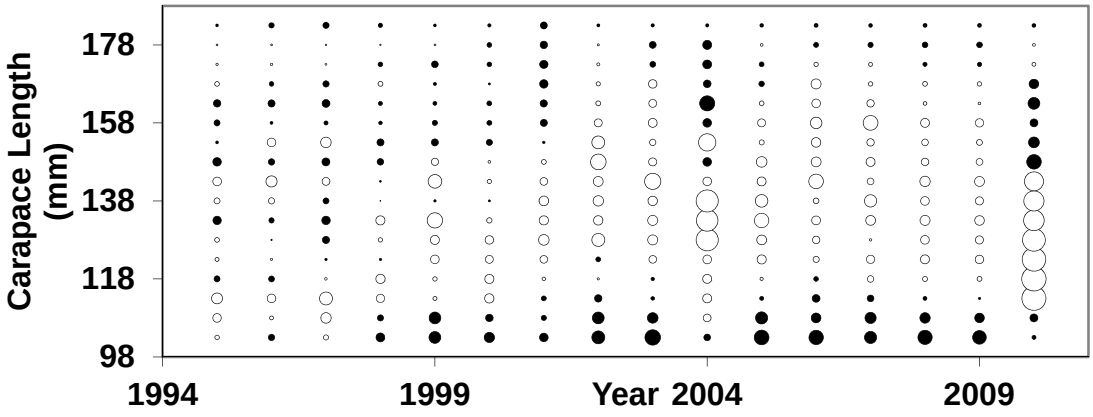


Figure 21. Bubble plot of standardized residuals of groundfish discarded length composition for Scenarios 1, 2, and 3 for EAG golden king crab, 1985-2010 (note: 1985 refers to the 1985/86 fishery).

(4)



(5)



(6)

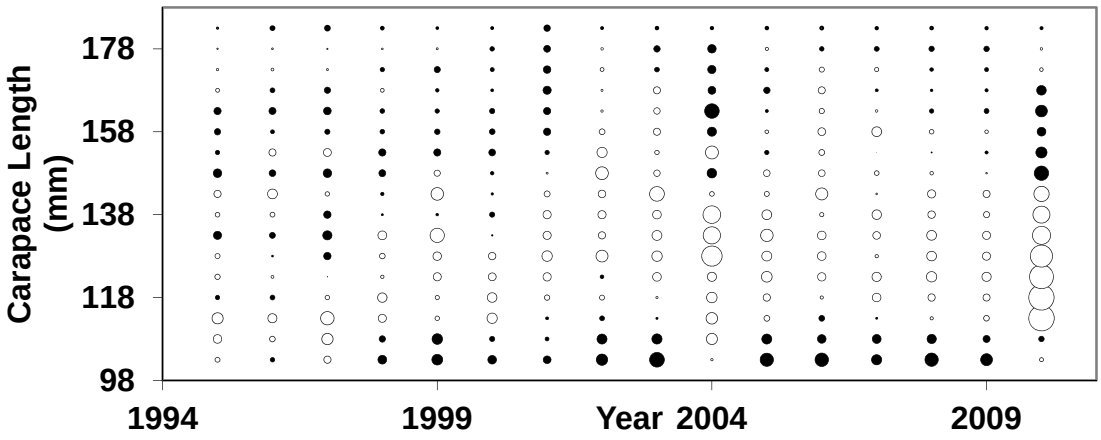
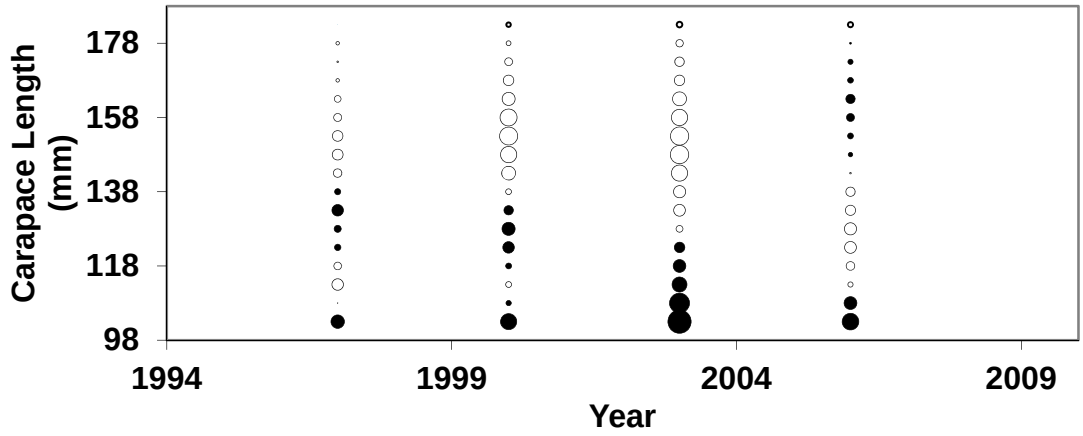
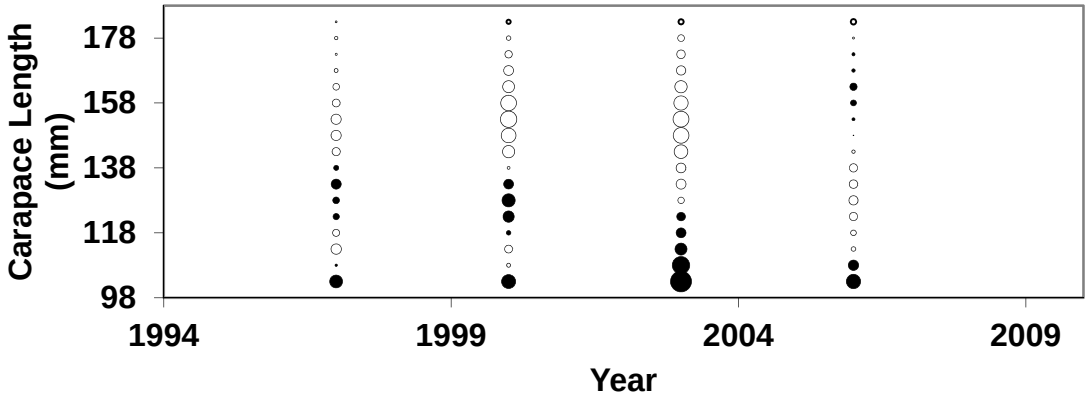


Figure 21 continued. Bubble plot of standardized residuals of groundfish discarded length composition for Scenarios 4, 5, and 6 for EAG golden king crab, 1985-2010 (note: 1985 refers to the 1985/86 fishery).

(1)



(2)



(3)

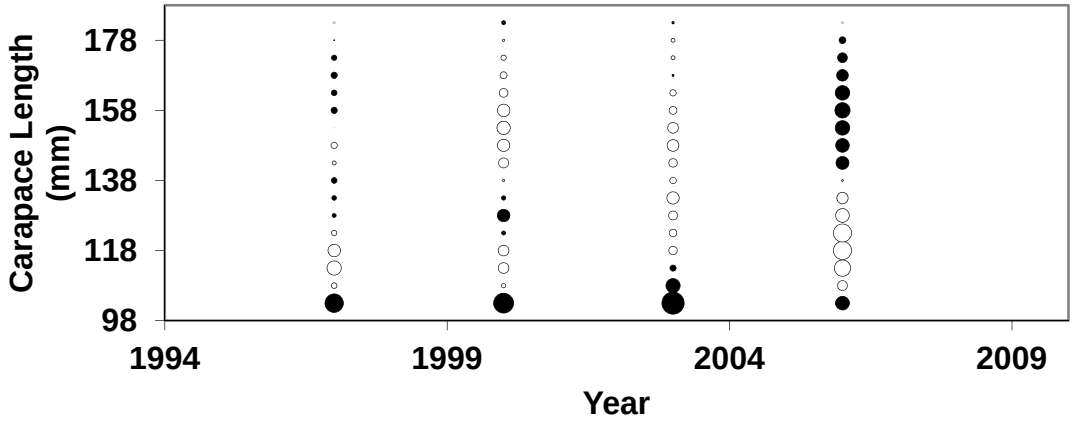
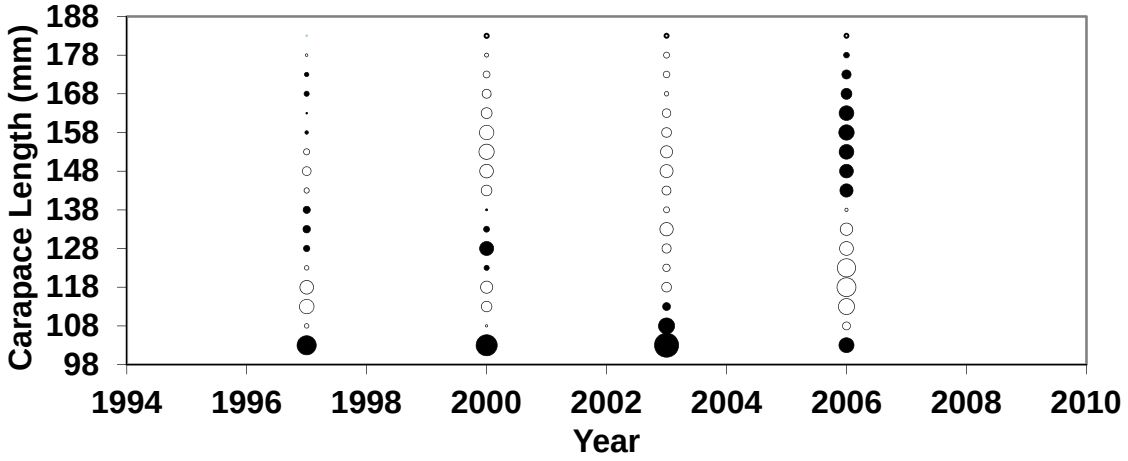
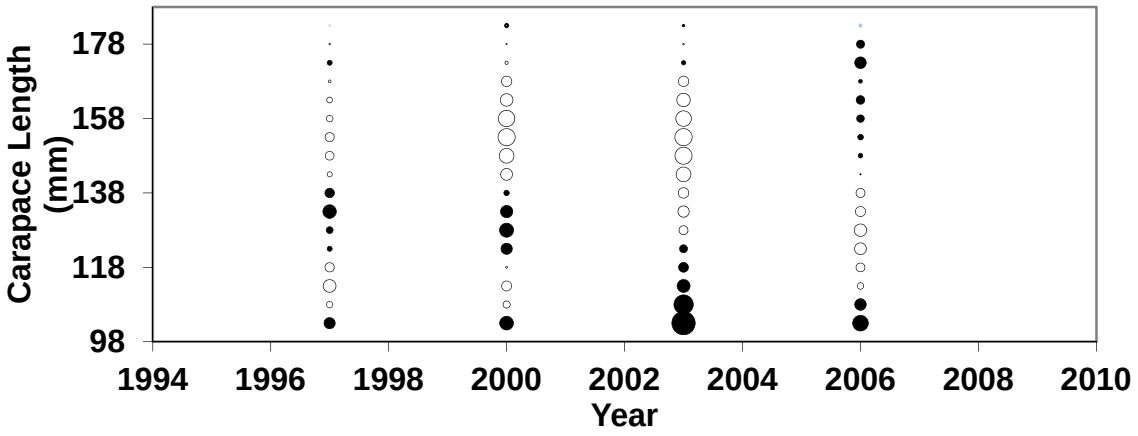


Figure 22. Bubble plot of standardized residuals of pot survey CPUE length composition for Scenarios 1, 2, and 3 for EAG golden king crab (1997, 2000, 2003, and 2006).

(4)



(5)



(6)

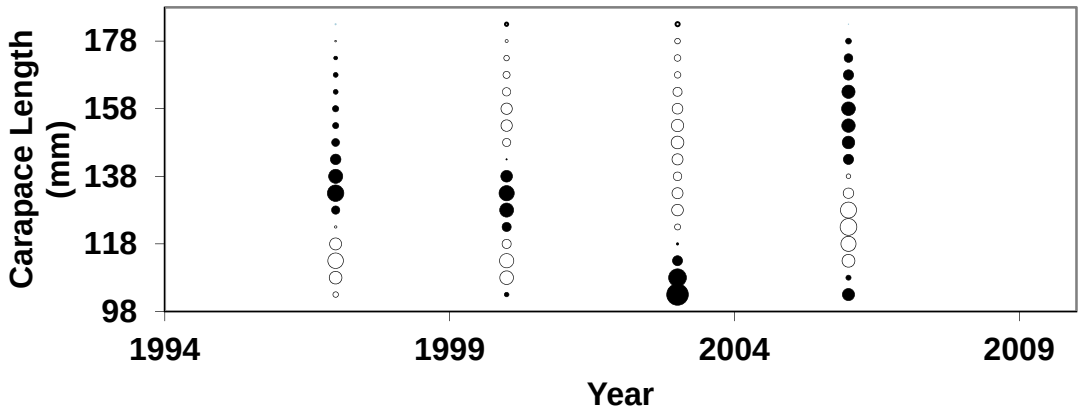
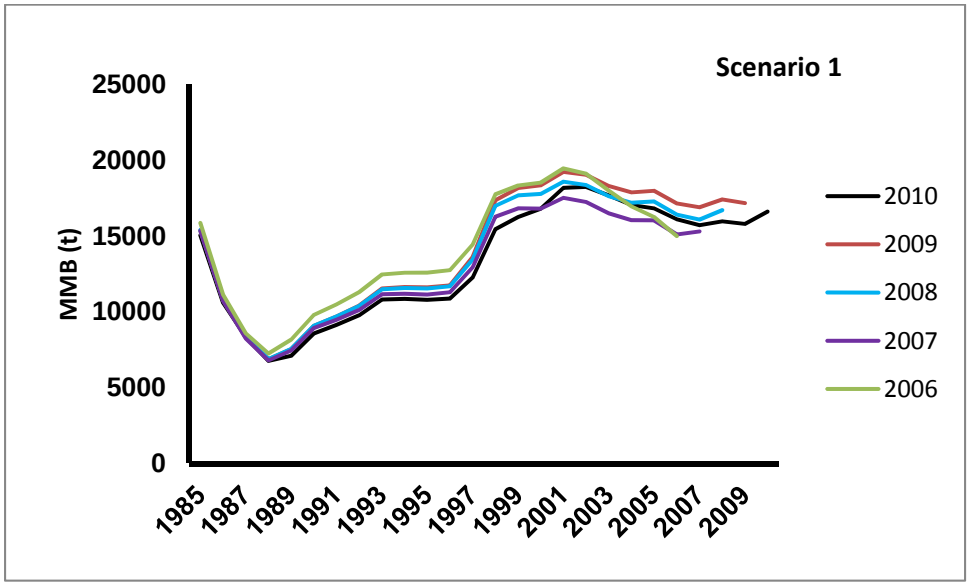


Figure 22 continued. Bubble plot of standardized residuals of pot survey CPUE length composition for Scenarios 4, 5, and 6 for EAG golden king crab (1997, 2000, 2003, and 2006).



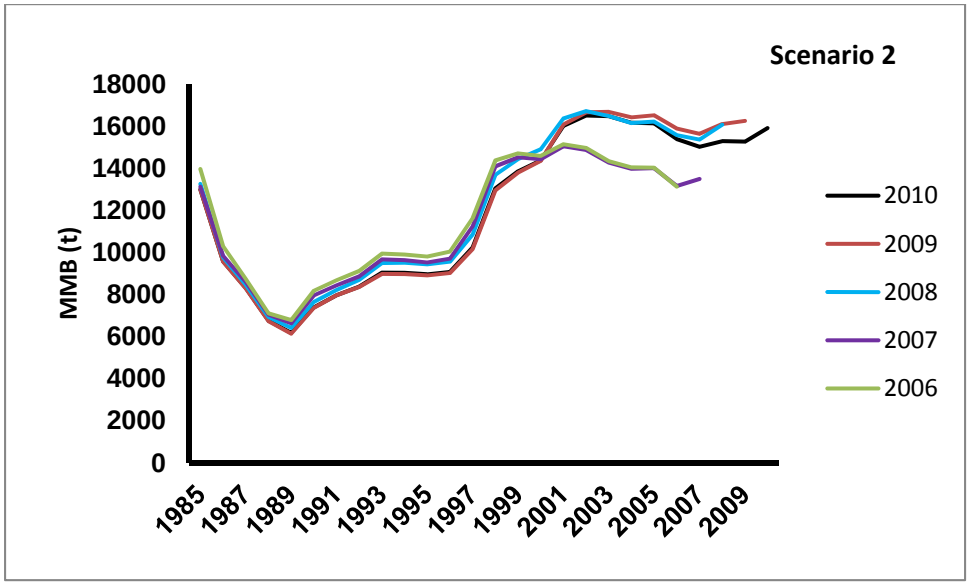
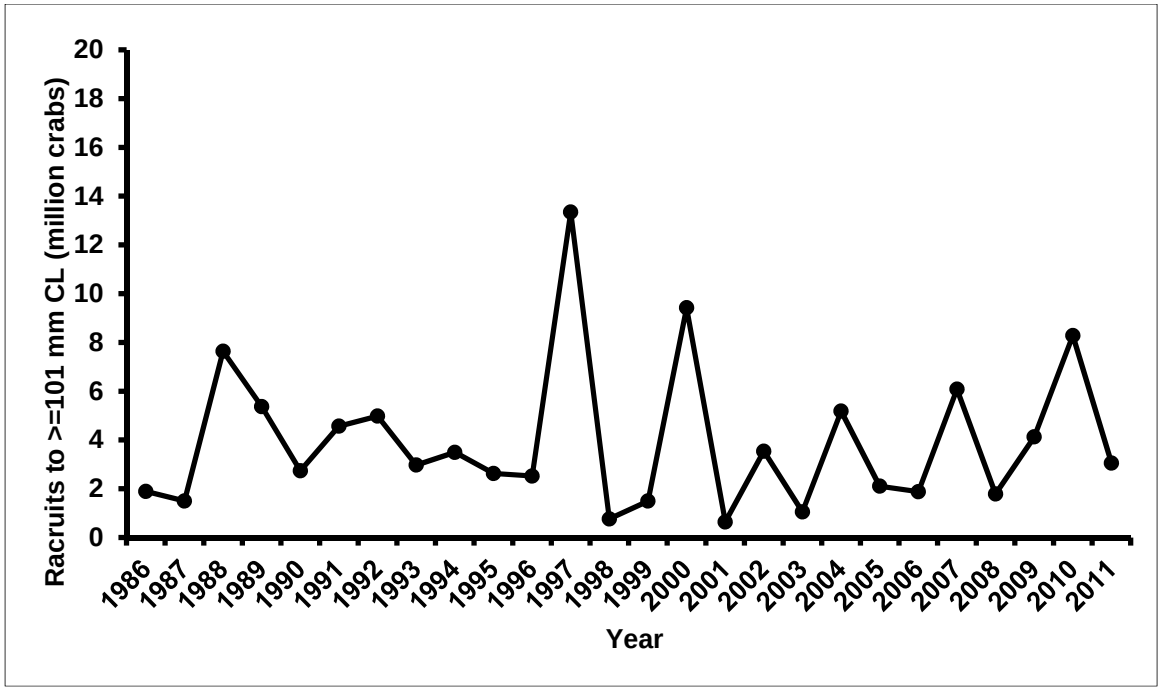


Figure 23. Retrospective fits of mature male biomass with terminal years 2006 to 2010 using the 2011 model for Scenarios 1 and 2 for EAG (note: 1985 refers to the 1985/86 fishery).

(1)



(2)

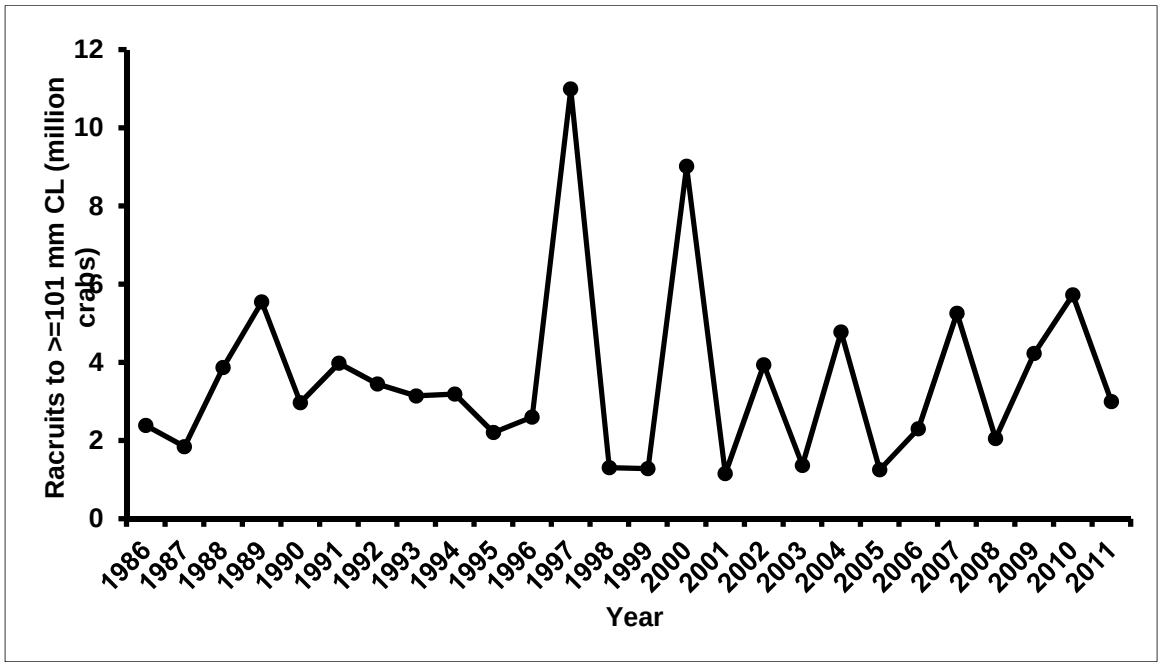
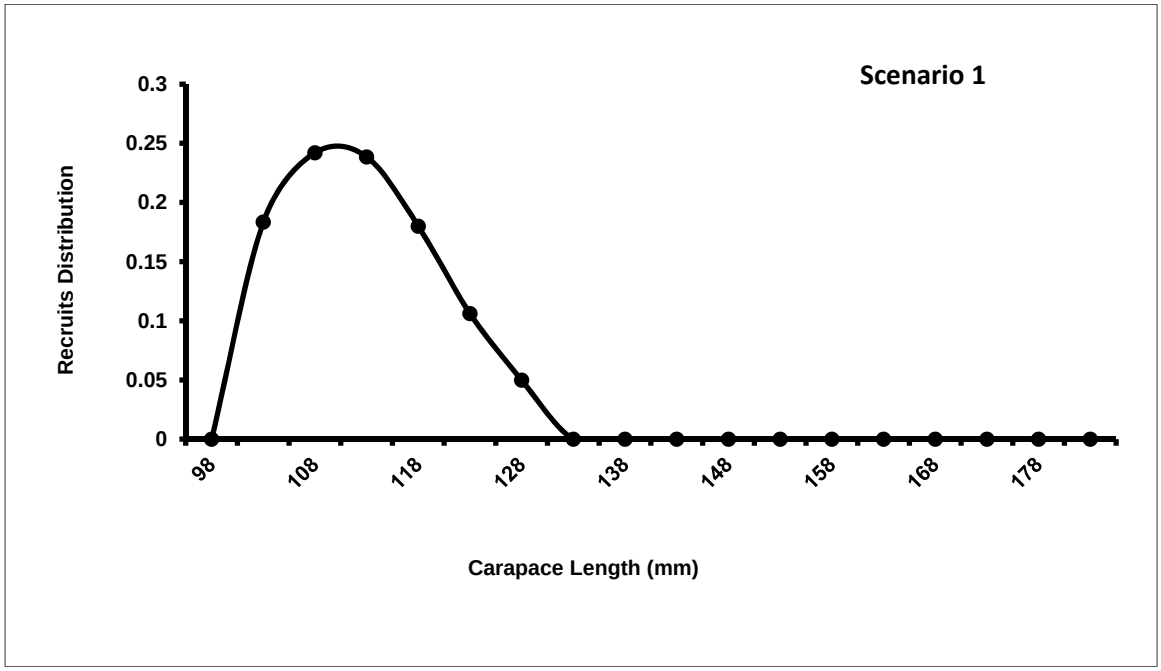


Figure 24. Estimated number of male recruits (millions of crabs ≥ 101 mm CL) to the golden king crab assessment model for Scenarios 1 and 2 in EAG, 1986-2011.



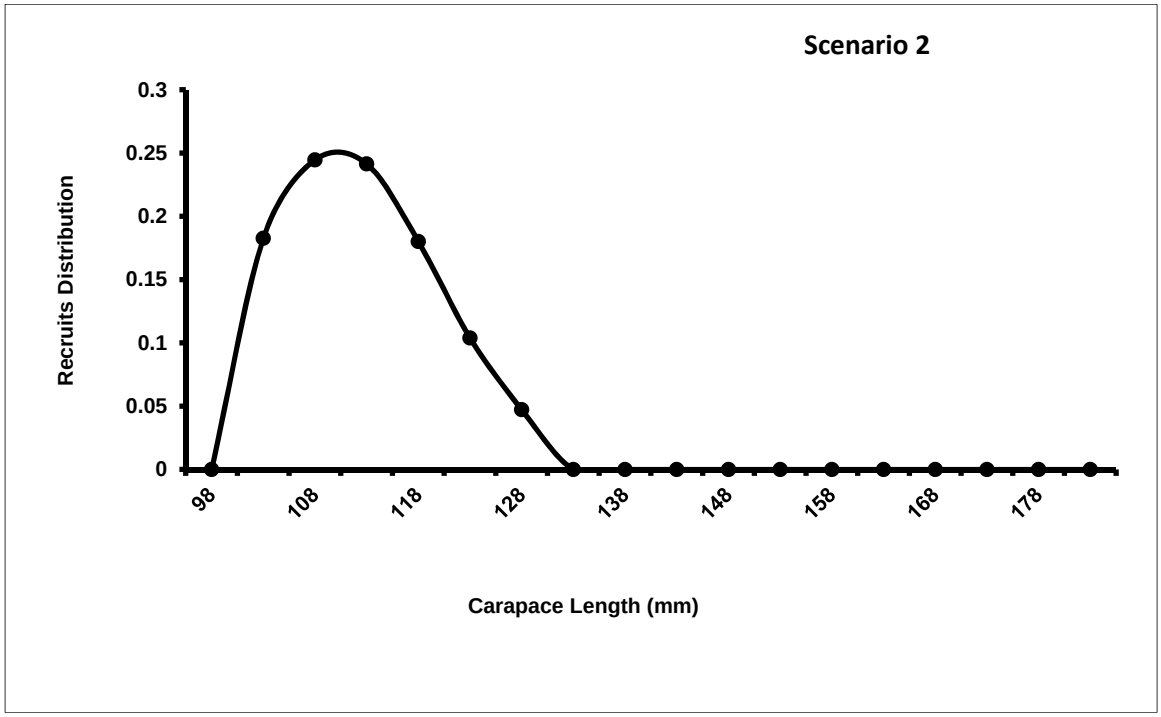


Figure 25. Recruit distribution to the golden king crab assessment model size group for Scenarios 1 and 2 in EAG.

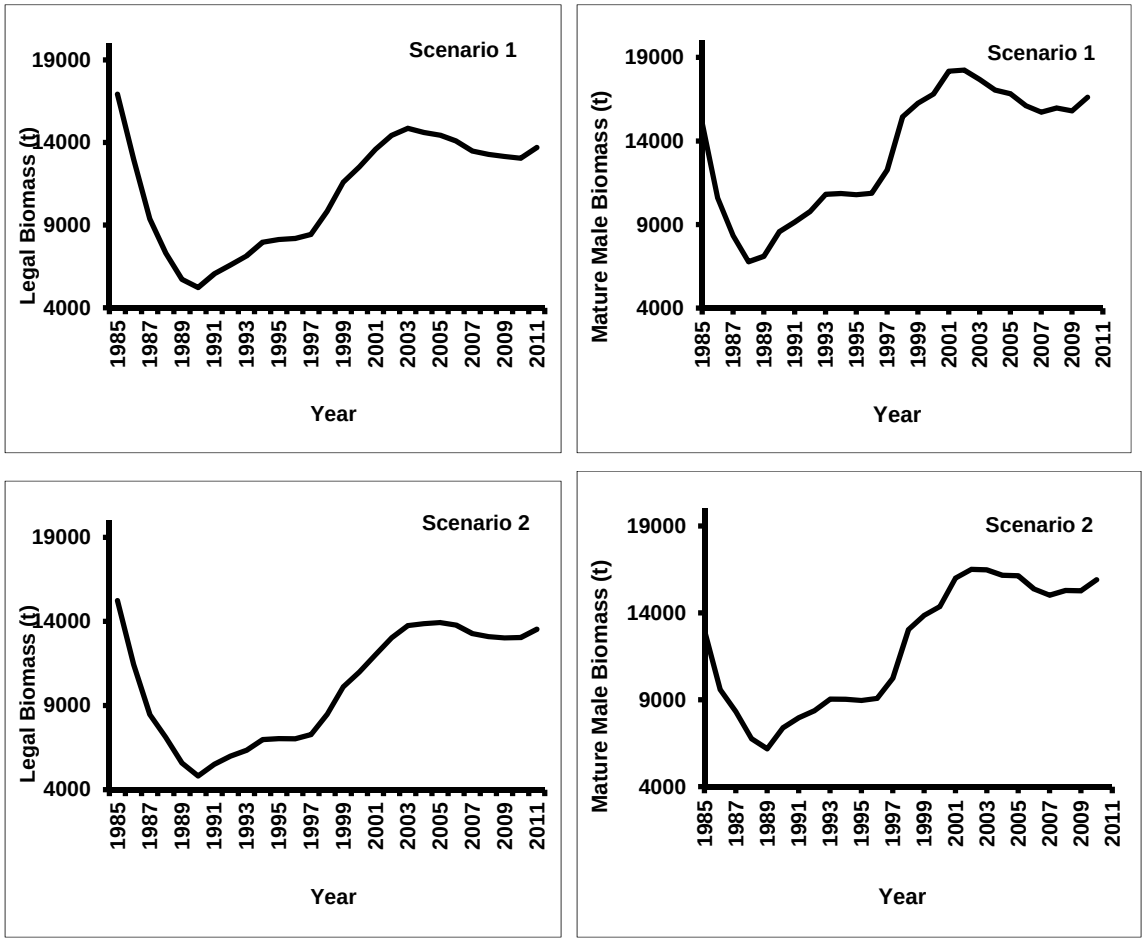


Figure 26. Trends in golden king crab legal male biomass (t) and mature male biomass for Scenarios 1 and 2 in the EAG, 1985-2010/11. Legal male crabs are ≥ 136 mm CL and mature male crabs are ≥ 121 mm CL.

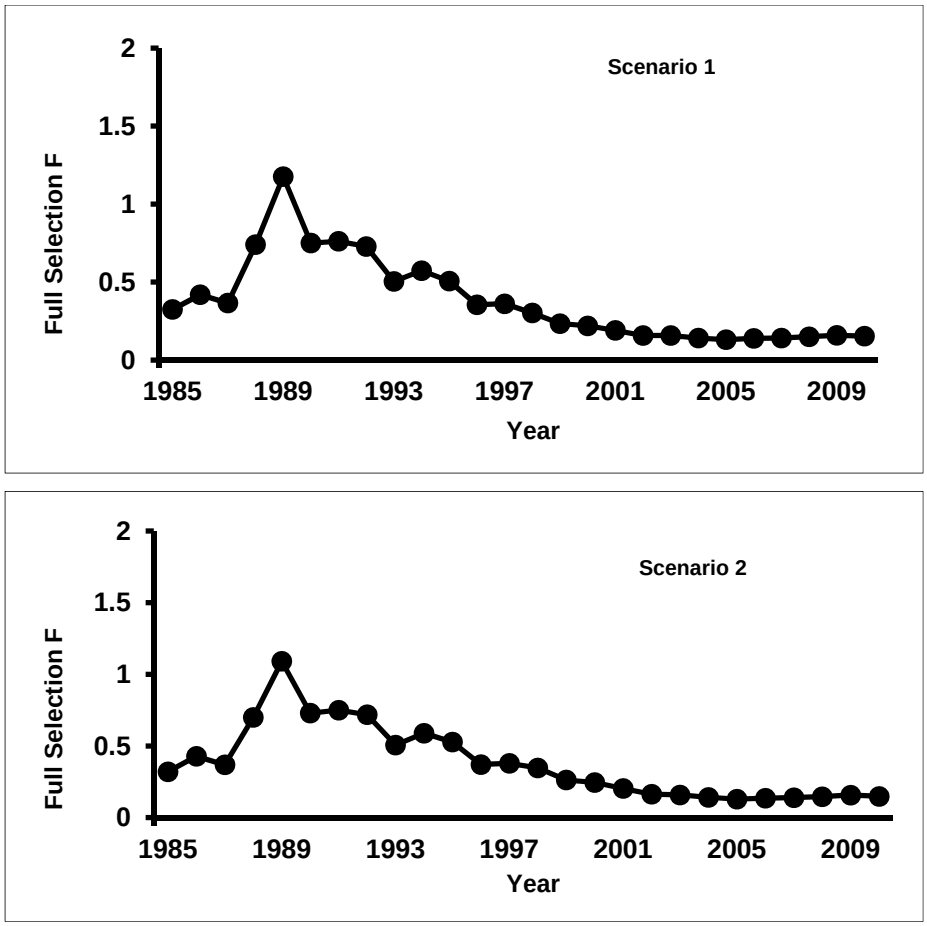


Figure 27. Trends in full selection fishing mortality of golden king crab for Scenarios 1 and 2 in the EAG, 1985-2010 (note: 1985 refers to the1985/86 fishery).

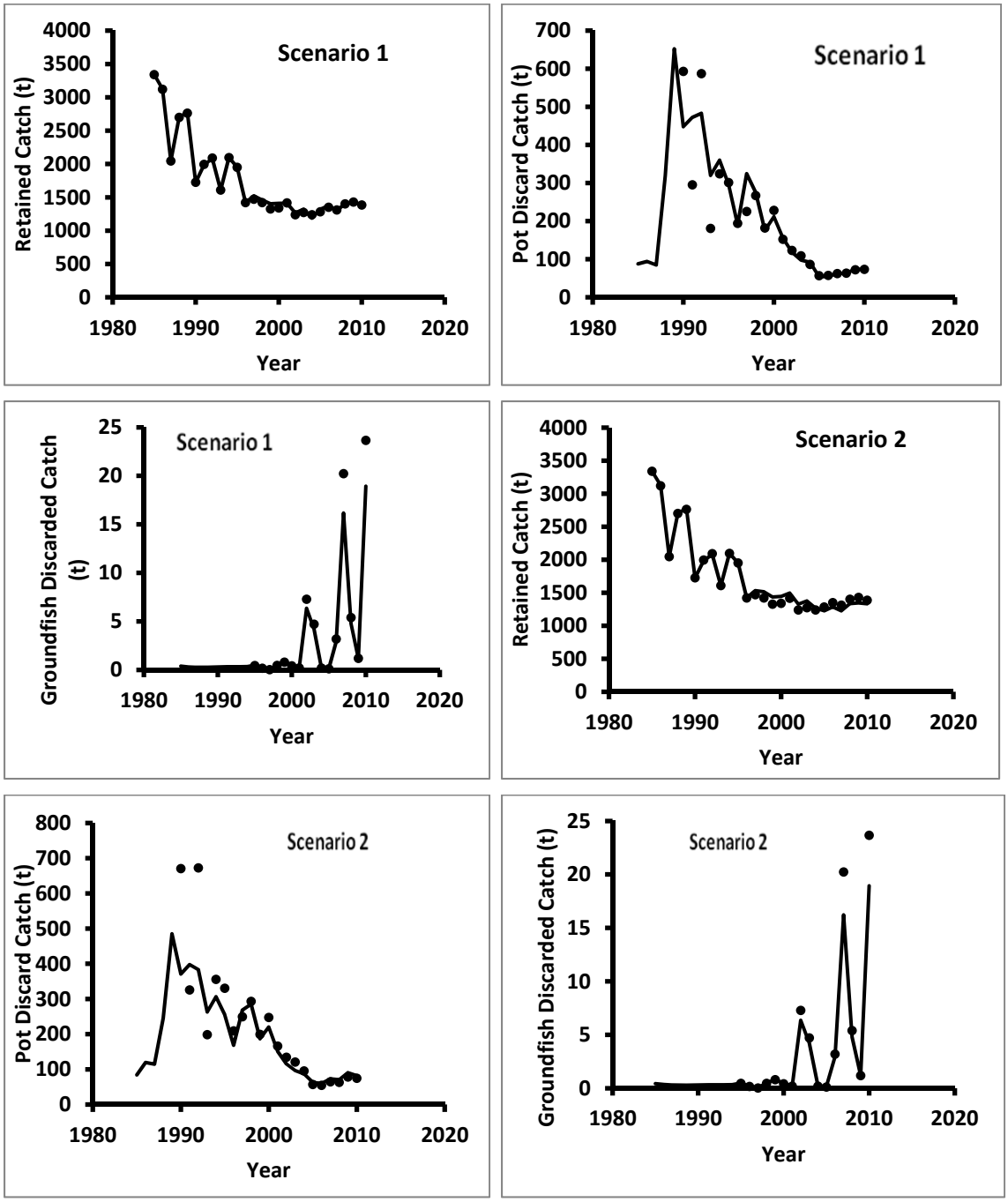


Figure 28. Observed (filled circle) vs. predicted (solid line) retained, pot discard, and groundfish discard catches of golden king crab for Scenarios 1 and 2 in the EAG, 1985-2010 (note: 1985 refers to the 1985/86 fishery). A handling mortality rate of 20% was applied for pot discard and an average handling mortality rate of 65% (average of 80% and 50%) was applied for groundfish discard.

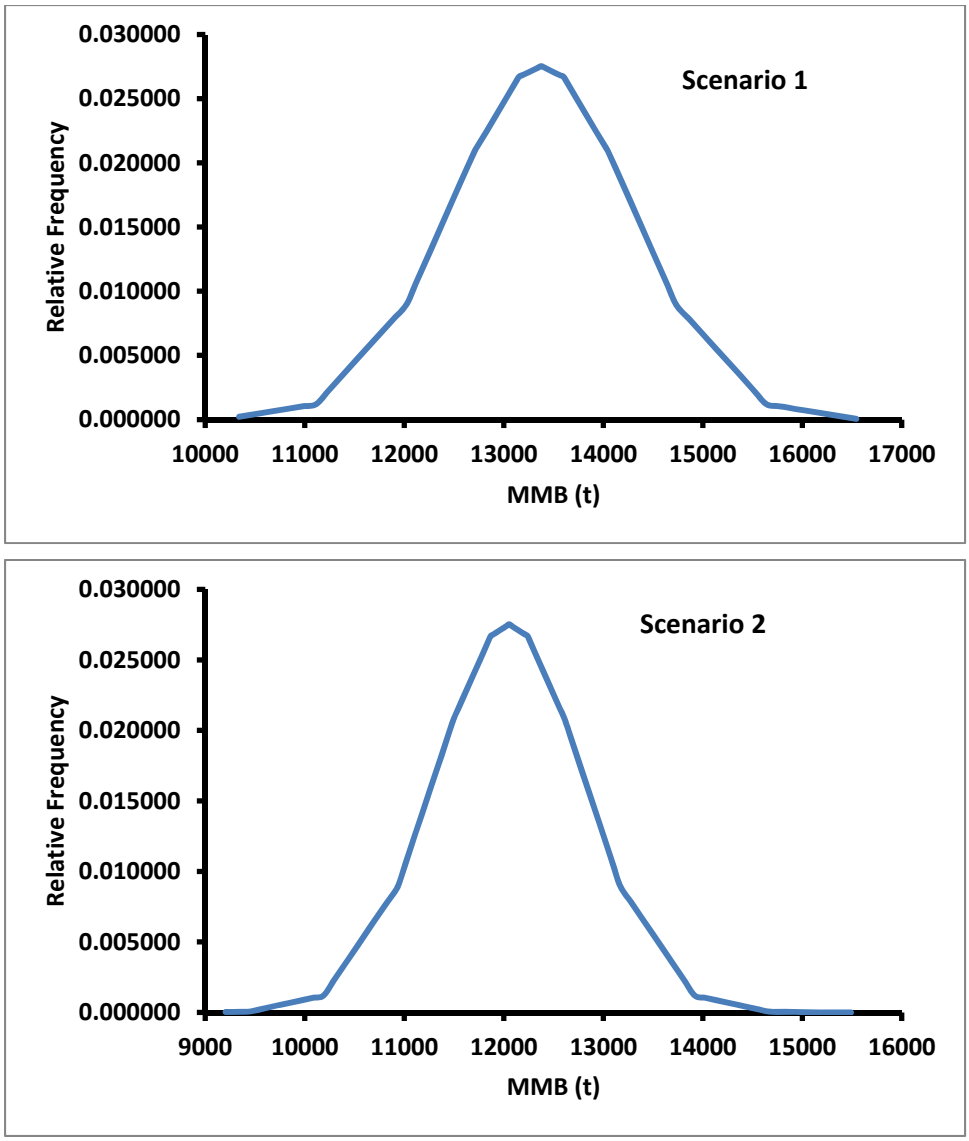


Figure 29. Profile likelihood distributions of mature male biomass (MMB) based on 1985-2010 data of golden king crab for Scenarios 1 and 2 in the EAG. Relative frequency was created based on the profile likelihood.

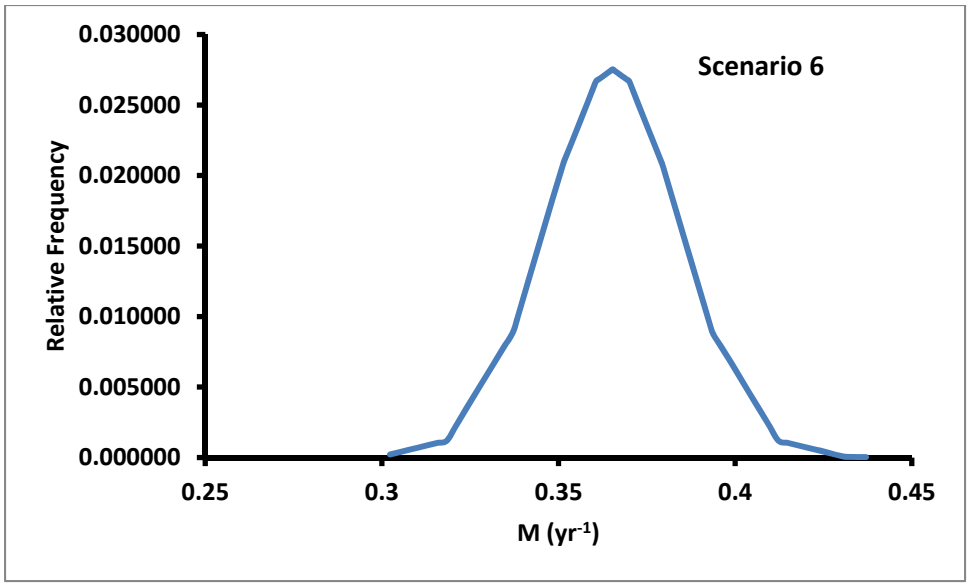


Figure 30. Profile likelihood distribution of natural mortality (*M*) estimate based on 1985-2010 data of golden king crab for Scenario 6 in the EAG. Relative frequency was created based on the profile likelihood.

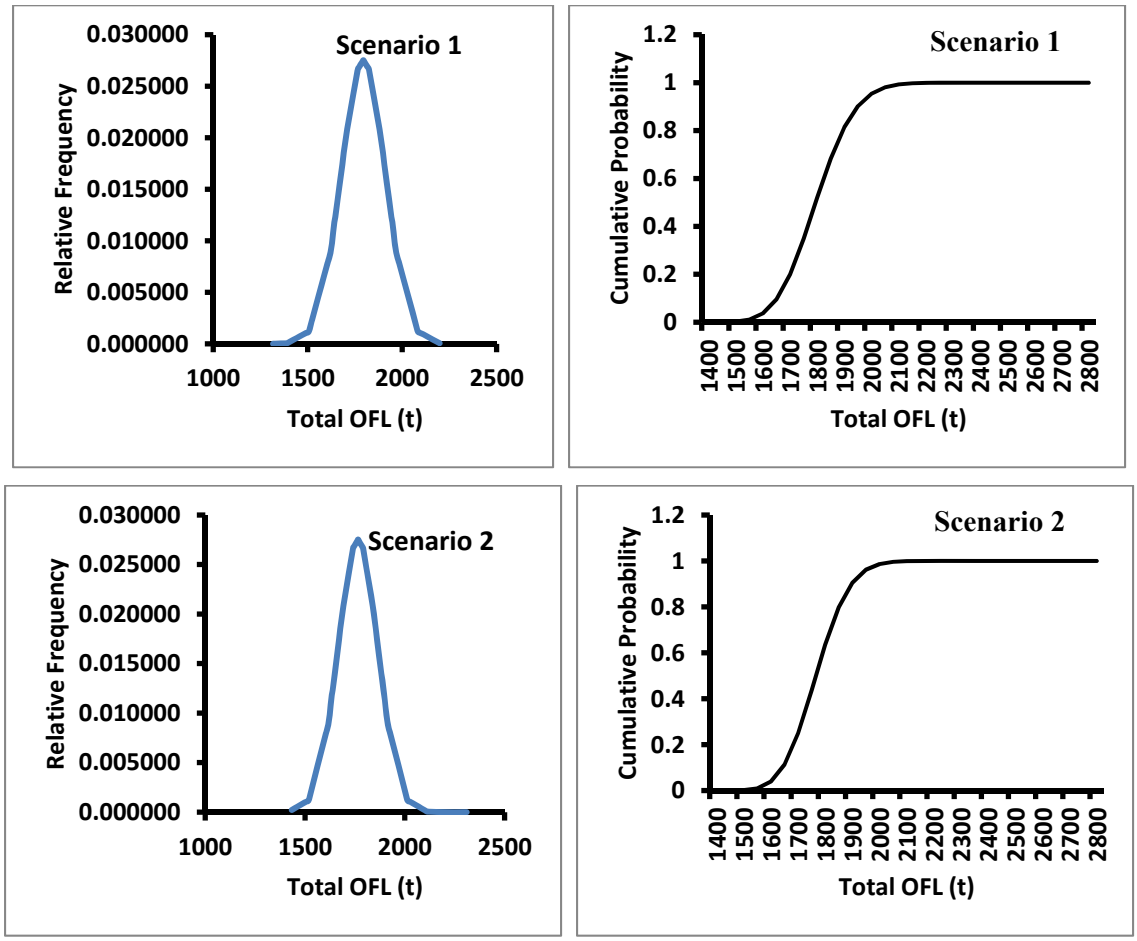


Figure 31. Probability of total OFL based on 1985-2010 data for Scenarios 1 and 2 for EAG golden king crab. Profile likelihood was used to create the probability distribution (left) and the cumulative distribution (right) was established assuming lognormal distribution of OFL.

Table 9(a). Time series of annual retained catch (number of crabs) and groundfish fishery discard mortality (handling mortality rate of 50% for pot and 80% for trawl gear applied, only male portion) for the WAG golden king crab stock. The data are for the size range 101-185 mm CL. Note: 1985 refers to the1985/86 fishery.

Year	Retained Catch	Groundfish Discard Mortality
1985	1,401,322	
1986	2,033,595	
1987	1,145,152	
1988	1,310,033	
1989	1,585,080	
1990	757,610	
1991	753,415	
1992	409,373	
1993	565,336	
1994	796,258	
1995	535,553	331
1996	602,968	398
1997	569,550	136
1998	409,531	479
1999	676,558	330
2000	705,613	230
2001	686,738	184
2002	664,823	593
2003	676,633	3,087
2004	685,465	559
2005	639,368	2,145
2006	523,701	1,488
2007	600,604	3,794
2008	587,661	8,953
2009	628,332	2,738
2010	626,246	1,112

Table 9(b). Time series of annual observer retained catch-per-unit-effort (CPUE, number of crabs per pot lift) and discard CPUE, pot fishery discard mortality (20% handling mortality applied), and CPUE sample size for the WAG golden king crab stock. The data are for the size range 101-185 mm CL. The observer CPUE are determined two ways: (a) 5th to 95th percentile soak-time range of pot lifts (nominal) and (b) 5th to 95th percentile soak-time range of pot lifts standardized at 12-day soak-time (standardized). 1985 refers to the 1985/86 fishery. The CPUE standard errors are given in parentheses.

Year	(a)Observer Retained CPUE	(a)Observer Discard CPUE	(a)Pot Discard Mortality	(b)Observer Retained CPUE	(b)Observer Discard CPUE	(b)Pot Discard Mortality	Sample Size (no.pot lifts)
1990	7.116	13.375	289,616	8.792		359,846	
	(0.552)	(2.263)		(0.695)	16.618		380
1991	6.809	9.286	188,377	8.767		230,428	
	(0.373)	(0.873)		(0.486)	11.359		637
1992		10.222	141,969			183,942	
	5.407	(1.043)		7.170			
	(0.288)			(0.359)	13.244		550
1993	4.278	10.291	262,957	5.526		321,393	
	(0.513)	(1.761)		(0.611)	12.578		260
1994	3.945	10.601	413,736	5.096		539,336	
	(0.273)	(0.790)		(0.339)	13.819		986
1995	4.929	8.488		6.950		279,770	
	(0.099)	(0.275)	195,644	(0.136)	12.138		5355
1996	5.610	8.478		7.194		214,736	
	(0.106)	(0.257)	168,313	(0.132)	10.816		4741
1997	6.460	7.732		7.947		162,894	
	(0.148)	(0.339)	134, 241	(0.169)	9.382		3219
1998	11.059	15.483		14.488		116,456	
	(0.286)	(0.770)	111,232	(0.371)	16.210		1185
1999	6.248	8.110		8.862		196,375	
	(0.136)	(0.279)	173,613	(0.191)	9.173		3410
2000	6.065	10.140		8.681		230,894	
	(0.134)	(0.372)	205,307	(0.200)	11.403		3729
2001	5.531	8.206		7.351		184,366	
	(0.118)	(0.304)	173,172	(0.158)	8.737		3489
2002	7.218	9.857		8.765		160,928	
	(0.189)	(0.449)	155,703	(0.234)	10.188		2085
2003	9.372	8.994		10.326		122,459	
	(0.193)	(0.329)	119,141	(0.215)	9.244		2695
2004	10.807	11.393		11.953		133,789	
	(0.254)	(0.490)	129,533	(0.281)	11.768		2397
2005	23.762	13.202		19.036		95,382	
	(0.699)	(0.830)	79,520	(0.572)	15.836		1030
2006	23.144	9.915		17.772		72,791	
	(0.682)	(0.482)	52,927	(0.511)	13.636		952
2007	20.649	12.203		15.629		96,509	
	(0.608)	(0.728)	73,096	(0.434)	16.112		948
2008	24.627	14.367		18.121		102,419	
	(0.661)	(0.774)	75,282	(0.489)	19.546		875
2009	26.161	8.186		18.123		63,534	
	(0.827)	(0.561)	43,368	(0.563)	11.992		764
2010	7.078	7.958		9.143		62,704	
	(0.678)	(0.472)	47,660	(0.472)	10.470		380

Table 10. Optimization scenarios and weighting factors considered for the stock assessment model for the western Aleutian Islands golden king crab (WAG). Catchability ratio and its variance were estimated by Leslie depletion method.

Scenario	Remarks	Weights for Likelihoods & Effective Sample Sizes
1	Nominal observer CPUE for 1998-2010, commercial retained catch for 1985-2010, discard catch for 1998-2010, and groundfish bycatch for 1995-2010; M = 0.18, pot fishery handling mortality = 0.2, and ground fish bycatch handling mortality for trawl = 0.8 and for pot = 0.5. Penalty functions: molt L50, growth beta, catchability ratio for the 1998-2004 and 2005-2010 periods; recruitment deviation, pot fishing mortality deviation, groundfish bycatch fishing mortality deviation, and legal discard in certain years deviation.	Catch biomasses: retained=600, pot discard=300, groundfish bycatch=25. Effective sample sizes: retained =250, pot discard=10, groundfish discard=10. CPUE: pre-rationalization retained = 2, post-rationalization retained = 2, pot discard = 2. Penalties: molt L50= 0.25, growth beta = 0.25, catchability ratio = 0.69, recruit dev.=3., pot fishing mortality dev.=0.01, groundfish bycatch mortality=2. Legal discard dev. = 0.5.
2	Scenario 1 using standardized observer CPUE.	Changes to Scenario 1: Effective sample sizes: retained =200, pot discard=125, groundfish discard=200. CPUE: pre-rationalization retained = 1, post-rationalization retained = 3, pot discard = 2.5. Penalties: pot fishing mortality dev.=0.0001.
3	Scenario 1 omitting penalties for molt L50, growth beta, and catchability ratio.	Changes to Scenario 1: Effective sample sizes: retained =350, pot discard=10, groundfish discard=20. CPUE: pre-rationalization retained = 1, post-rationalization retained = 1, pot discard = 1. Penalties: recruit dev.=5, pot fishing mortality dev.=0.0001.

Table 10 continued.

Scenario	Remarks	Weights for Likelihoods & Effective Sample Sizes
4	Scenario 3 using standardized observer CPUE.	Changes to Scenario 1: Effective sample sizes: retained =200, pot discard=150, groundfish discard=175. CPUE: pre-rationalization retained = 1, post-rationalization retained = 3, pot discard = 2.5. Penalties: recruit dev.=5, pot fishing mortality dev.=0.0001.
5	Same as Scenario 2 with dome shape selectivity.	Changes to Scenario 1: Same as Scenario 2.

Table 11. Negative log likelihood component values for the five scenarios for the golden king crab stock in WAG.

Negative Log Likelihood Component	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
like_retlencomp	-1577.5300	-1518.2600	-1632.4400	-1515.8200	-1504.5200
like_discdlencomp	-739.8230	-1129.4100	-740.2700	-1152.3300	-1130.5900
like_gdiscdlencomp	-409.5900	-522.8280	-456.1910	-522.7940	-517.7340
like_retcpue	-3.1389	-5.4888	-0.7643	-5.3756	-5.9712
like_discdcpue	-1.9980	-1.3952	-0.9567	-1.2852	-1.2078
like_retdcatchB	3.7111	4.3560	3.2462	4.4507	4.2915
like_discdcatchB	7.1213	8.7408	7.3417	8.8437	8.5206
like_gdiscdcatchB	1.9518	2.5266	1.9176	2.5202	2.5652
like_rec_dev	6.8574	4.7657	8.5984	6.7619	4.8485
like_F	0.0691	0.0006	0.0008	0.0007	0.0006
like_gF	24.2335	31.3793	23.8359	31.2928	31.8647
like_qq	0.0017	0.2105	0.0043	0.2064	0.1803
like_molt50	1.4518	0.0002	0	0	0.0317
like_beta	0.0567	0.0177	0	0	0.0135
like_meanqratio	0.0824	0.0956	0	0	0.0763
Total negative log likelihood	-2686.55	-3125.29	-2785.68	-3143.53	-3107.63

Table 12(a). Parameter estimates and standard deviations with the 2011 (February 15) MMB for the Scenario 1 model (with nominal CPUE data) for the golden king crab data from the WAG, 1985/86-2010/11. Parameter bounds are given in parentheses. A total of 112 parameters were estimated, but recruitment, fishing mortality, and legal discard (certain years) deviations, and initial size frequency determination parameters were omitted from this list.

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Parameter	Estimate	Std Dev	Parameter	Estimate	Std Dev
a	0.0745(0.01-0.75)	0.0101	log_mean_rec	0.5197(0.01-3)	0.0486
log_b	4.9517(3.98-5.5)	0.0091	log_mean_Fpot	-0.4896(-15- -0.35)	0.1131
log_beta	0.0527(-0.7-2.)	0.3825	log_mean_Fground	-7.6349(-15 - - 1.6)	0.1293
c2	0.1056(0.01-0.8)	0.0198	mean_qq	3.1466(unbdd)	1.9588
log_d2	4.8428(3.98-4.98)	0.0242	ret_var	0.0453(0.01-1.25)	0.0141
c3	0.1931(0.01-0.8)	0.0400	discd_var	0.0481(0.01-1.25)	0.0151
log_d3	4.8520(3.98-5.5)	0.0130	2011 MMB	5,804.40	1,036.9
aa2	0.5045(0.01-1.5)	0.0261			
log_bb2	4.9122(4.85-4.98)	0.0016			
aa3	0.4745(0.01-3)	0.0447			
log_bb3	4.9192(4.25-4.98)	0.0021			
aa4	0.2095(0.01-1.5)	0.0597			
log_bb4	4.8217 (3.98-5.1)	0.0209			
log_betar	-1.6593(-4.6 – 3.2)	0.3524			
logq2	-11.8090(-25- -0.01)	0.1434			
logq3	-11.4970(-25- -0.01)	0.1474			
log_newsh1	2.4382(0.01-10)	0.0554			

Table 12(b). Parameter estimates and standard deviations with the 2011 (February 15) MMB for the Scenario 2 model (with standardized CPUE data) for the golden king crab data from the WAG, 1985/86-2010/11. Parameter bounds are given in parentheses. A total of 115 parameters were estimated, but recruitment, fishing mortality, and legal discard (certain years) deviations, and initial size frequency determination parameters were omitted from this list.

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Parameter	Estimate	Std Dev	Parameter	Estimate	Std Dev
a	0.0813(0.01-0.75)	0.0058	log_mean_rec	0.5501(0.01-3)	0.0513
log_b	4.9347(3.98-5.5)	0.0086	log_mean_Fpot	-0.6696(-15- -0.35)	0.0904
log_beta	-1.1640(-1.2-2)	0.3526	log_mean_Fground	-8.1604(-15 - - 1.6)	0.0921
c2	0.0785(0.01-0.8)	0.0088	mean_qq	3.4048(unbdd)	0.3386
log_d2	4.7935(3.98-4.98)	0.0199	ret_var	0.0383(0.0001-1.25)	0.0131
c3	0.1759(0.01-0.8)	0.0177	discd_var	0.0518(0.0001-1.25)	0.0153
log_d3	4.817(3.98-5.5)	0.0066	2011 MMB	5,933.6	969.39
aa2	0.4902(0.01-1.5)	0.0198			
log_bb2	4.9141(4.85-4.98)	0.0010			
aa3	0.5278(0.01-3)	0.0439			
log_bb3	4.9258(4.25-4.98)	0.0013			
aa4	2.0892(0.01-3)	1465.5			
log_bb4	4.5265(3.98-5.1)	122.81			
log_betar	-0.0680(-4.6 – 3.2)	0.1894			
logq2	-12.055(-25- -0.01)	0.1187			
logq3	-11.7700(-25- -0.01)	0.1190			
log_newsh1	2.4485(0.01-10)	0.0689			

Table 13(a). Annual abundance estimates of model recruits (millions of crabs), legal male biomass with standard deviation (t), and mature male biomass with standard deviation (t) for the Scenario 1 model (with nominal CPUE data) for golden king crab in the WAG. 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. 1985 refers to the 1985/86 fishery.

Year	Recruits to the Model (≥ 101 mm CL)	Mature Male Biomass (≥ 121 mm CL)	Standard Deviation	Legal Male Biomass (≥ 136 mm CL)	Standard Deviation
1985	NA	7,589	792.90	8,613	477.15
1986	1.73	5,929	408.02	7,721	419.40
1987	2.75	5,379	365.33	5,749	314.74
1988	1.82	4,616	294.31	5,330	275.54
1989	1.92	2,999	270.95	4,490	222.31
1990	1.47	3,071	255.08	2,888	207.52
1991	1.26	2,851	238.45	2,976	202.78
1992	1.22	3,135	217.51	2,776	194.48
1993	1.47	2,982	200.87	3,098	176.22
1994	1.32	2,394	195.01	2,957	158.44
1995	1.39	2,401	197.25	2,333	151.25
1996	1.52	2,320	199.63	2,351	154.14
1997	1.70	2,359	217.25	2,270	155.62
1998	1.63	2,902	234.19	2,308	171.09
1999	2.00	2,877	249.26	2,844	188.68
2000	1.91	2,980	279.46	2,827	199.53
2001	2.29	3,266	330.63	2,904	230.79
2002	1.88	3,851	392.77	3,207	276.90
2003	2.62	4,311	456.59	3,762	342.49
2004	1.82	5,053	556.98	4,278	405.56
2005	1.25	5,469	605.59	4,957	506.58
2006	2.82	5,594	648.09	5,393	570.11
2007	2.18	6,262	756.16	5,640	615.50
2008	0.65	6,774	880.31	6,185	711.31
2009	1.56	6,257	927.41	6,642	840.26
2010	1.66	5,804	1,036.90	6,275	908.79
2011	1.68			5,791	1,008.70

Table 13(b). Annual abundance estimates of model recruits (millions of crabs), legal male biomass with standard deviation (t), and mature male biomass with standard deviation (t) for the Scenario 1 model (with standardized CPUE data) for golden king crab in the WAG. 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. 1985 refers to the 1985/86 fishery.

Year	Recruits to the Model (≥ 101 mm CL)	Mature Male Biomass (≥ 121 mm CL)	Standard Deviation	Legal Male Biomass (≥ 136 mm CL)	Standard Deviation
1985	NA	8,877	592.24	9,539	540.80
1986	1.82	6,790	522.37	8,528	467.15
1987	2.68	6,135	357.14	6,437	406.77
1988	1.71	5,101	282.41	5,926	298.16
1989	1.85	3,333	242.86	4,886	229.98
1990	1.51	3,245	229.71	3,142	198.96
1991	1.42	2,964	225.08	3,083	188.63
1992	1.46	3,309	224.89	2,821	188.62
1993	1.54	3,290	225.20	3,185	187.48
1994	1.58	2,764	228.71	3,163	187.73
1995	1.67	2,911	236.79	2,625	191.63
1996	1.67	3,012	248.21	2,772	194.71
1997	1.68	3,182	273.32	2,867	200.03
1998	1.85	3,766	300.99	3,035	220.31
1999	1.98	3,832	328.62	3,621	243.01
2000	2.76	4,067	375.98	3,672	268.87
2001	1.61	4,645	446.89	3,888	309.53
2002	2.77	5,117	501.01	4,435	368.69
2003	1.87	5,805	566.17	4,941	424.58
2004	1.99	6,158	612.64	5,603	483.91
2005	1.76	6,406	658.68	5,978	535.93
2006	1.90	6,728	709.96	6,236	587.41
2007	2.39	6,887	775.32	6,564	641.91
2008	1.03	7,065	866.25	6,708	709.78
2009	1.10	6,659	923.48	6,865	801.02
2010	1.11	5,934	969.39	6,518	872.55
2011	1.73			5,816	927.75

Table 14. Time series of catch divided by mature male abundance for Scenarios 1 (nominal CPUE) and 2 (standardized CPUE) for golden king crab in the WAG. We provide only the 1995/96 to 2010/11 time series because reliable estimates of total removals from all sources (pot fishery and groundfish fishery) are only available from 1995/96 to 2010/11.

Year	Scenario 1: Total Removal/Mature Male Abundance	Scenario 2: Total Removal/Mature Male Abundance
1995/96	0.51	0.45
1996/97	0.57	0.45
1997/98	0.53	0.40
1998/99	0.30	0.24
1999/00	0.51	0.39
2000/01	0.53	0.40
2001/02	0.45	0.32
2002/03	0.36	0.27
2003/04	0.32	0.24
2004/05	0.28	0.23
2005/06	0.24	0.21
2006/07	0.20	0.17
2007/08	0.21	0.20
2008/09	0.19	0.19
2009/10	0.22	0.21
2010/11	0.25	0.24

Table 15. Total and retained catch OFL, F_{OFL}, and MMB/Bref ratio for various scenarios for golden king crab in the WAG.

Scenario	**Total Catch OFL (t)**	**Total Catch OFL (mlbs)**	**Retained Catch OFL (t)**	**Retained Catch OFL (mlbs)**	**F_{OFL}**	**MMB/B_{ref}**
1	873.94	1.93	830.01	1.83	0.18	1.38
2	875.09	1.93	824.68	1.82	0.18	1.21
3	861.61	1.90	827.11	1.82	0.18	1.72
4	901.15	1.99	848.53	1.87	0.18	1.23
5	806.75	1.78	759.03	1.67	0.18	1.17

Table 16. Estimated catchability by Leslie depletion method using the commercial retained catch (crab numbers) and effort (pot lifts) data.
Leslie depletion formula: $CPUE_t = qN_1 - q \times \sum_1^{t-1} C_k$ where C is catch, q is catchability, and N_1 is initial abundance.
Mean q_2 (of significant regression fit) for 1999/00 – 2004/05 = 0.00000639
Mean q_3 (of significant regression fit) for 2005/06 – 2010/11 = 0.00001233
q_3/q_2 = 1.928795. This ratio was used in the penalty function.

	EAG			WAG		
Year	q	AdjR^2 (P-value)	n	q	AdjR^2 (P-value)	n
1999/00		0.82 (0.19)	3	0.00000519	0.34 (0.03)	11
2000/01		Cannot determine	2	0.00000759	0.43 (0.03)	11
2001/02		Cannot determine	2	0.00000585	0.26 (0.09)	9
2002/03		Cannot determine	2	0.00000491	0.34 (0.08)	8
2003/04		Cannot determine	2		-0.16 (0.71)	7
2004/05		Cannot determine	2		-0.24 (0.84)	6
2005/06		-0.03 (0.40)	7	0.00002349	0.42 (0.07)	7
2006/07		0.34 (0.13)	6		-0.13 (0.77)	9
2007/08		-0.19 (0.86)	7	0.00001174	0.61 (0.01)	9
2008/09		-0.50 (0.94)	4	0.00001297	0.51 (0.02)	9
2009/10	0.00001001	0.46 (0.08)	6	0.00001451	0.48 (0.02)	9
2010/11		0.08 (0.33)	5	0.00001008	0.73 (0.01)	7

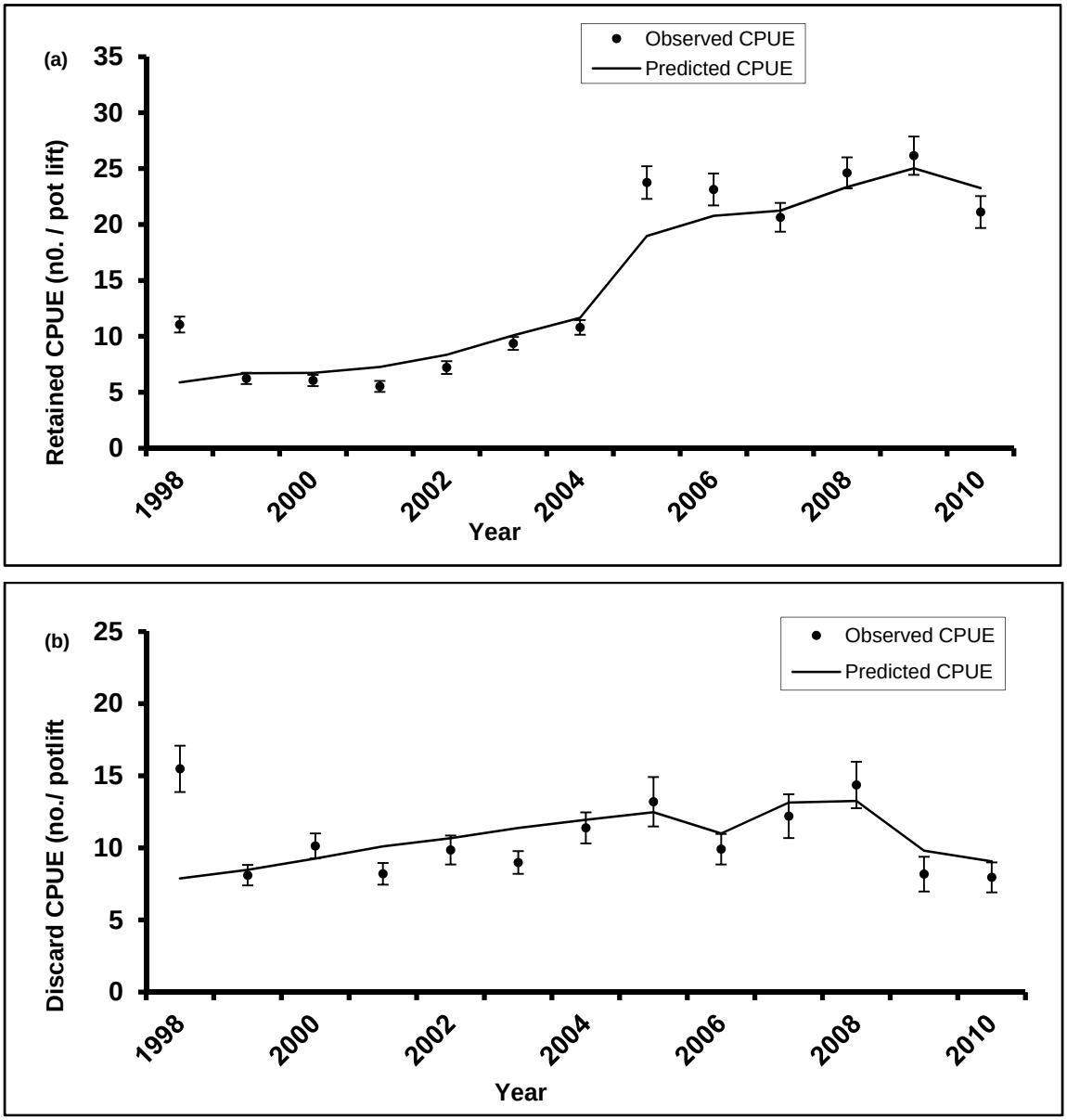


Figure 32. Predicted (line) vs. observed (filled circle) (a) retained catch-per-unit-effort (CPUE) and (b) discard CPUE for golden king crab in the WAG. Two-standard deviation confidence bars are attached to observed points. The fishery retained and discard CPUE values are nominal data (Scenario 1) from observer samples for 1998-2010 (note: 1998 refers to the 1998/99 fishery).

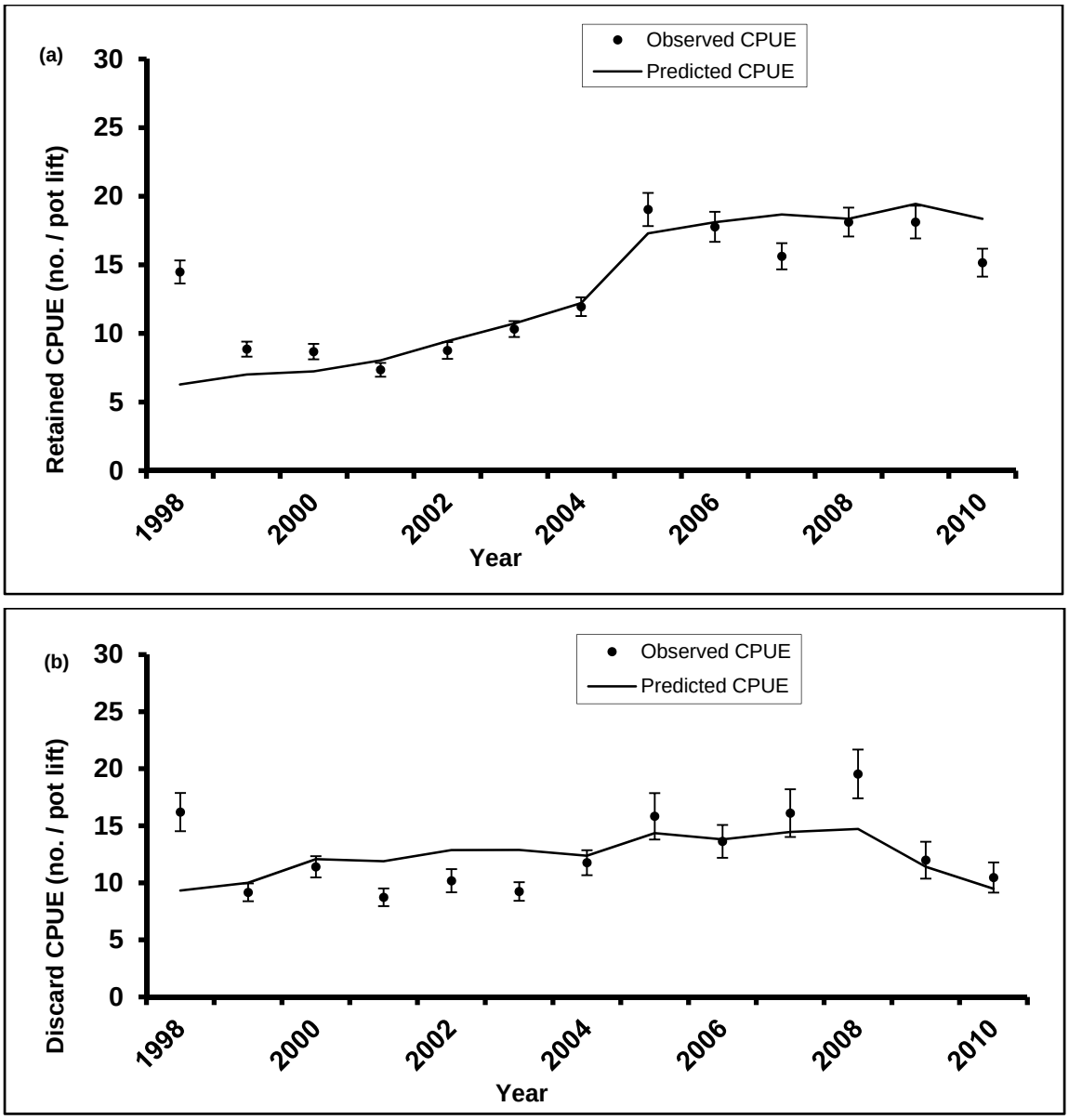


Figure 33. Predicted (line) vs. observed (filled circle) (a) retained catch-per-unit-effort (CPUE) and (b) discard CPUE for golden king crab in the WAG. Two-standard deviation confidence bars are attached to observed points. The fishery retained and discard CPUE values are standardized data (Scenario 2) from observer samples for 1998-2010 (note: 1998 refers to the 1998/99 fishery).

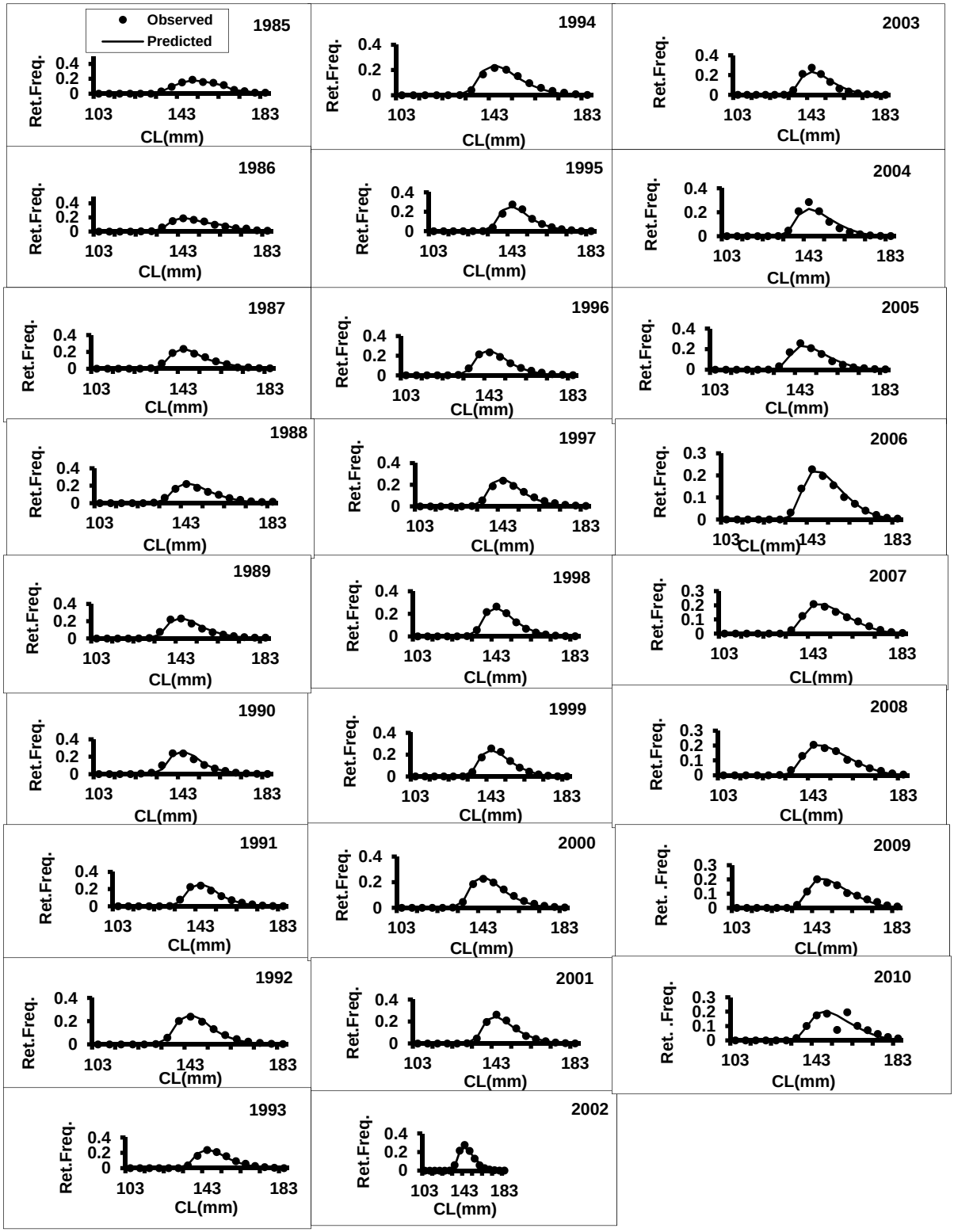


Figure 34. Predicted (line) vs. observed (filled circle) retained catch relative length frequency distributions of golden king crab for Scenario 2 in the WAG, 1985 to 2010 (note: 1985 refers to the 1985/86 fishery).

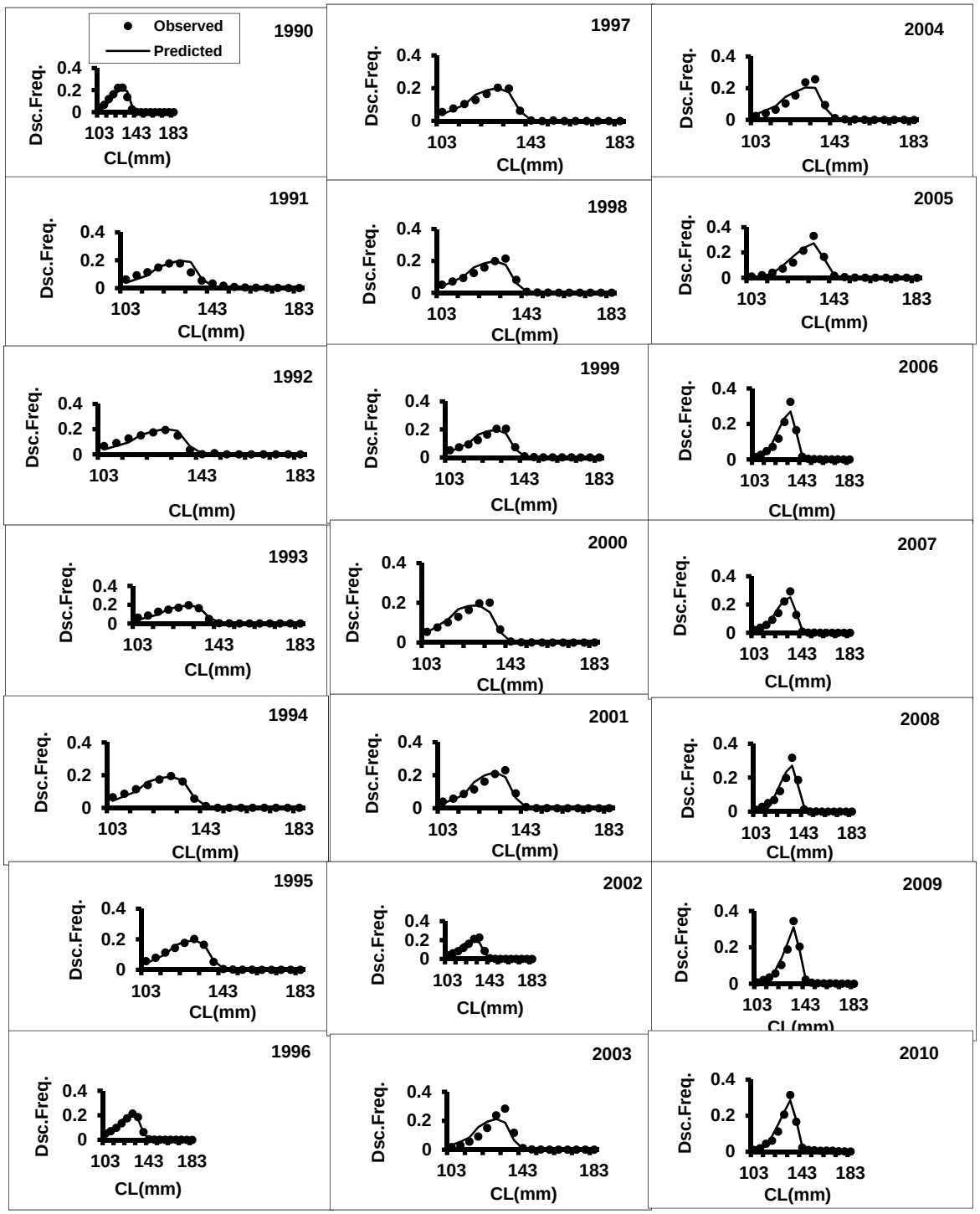


Figure 35. Predicted (line) vs. observed (filled circle) pot discarded catch relative length frequency distributions of golden king crab for Scenario 2 in the WAG, 1990 to 2010 (note: 1990 refers to the 1990/91 fishery).

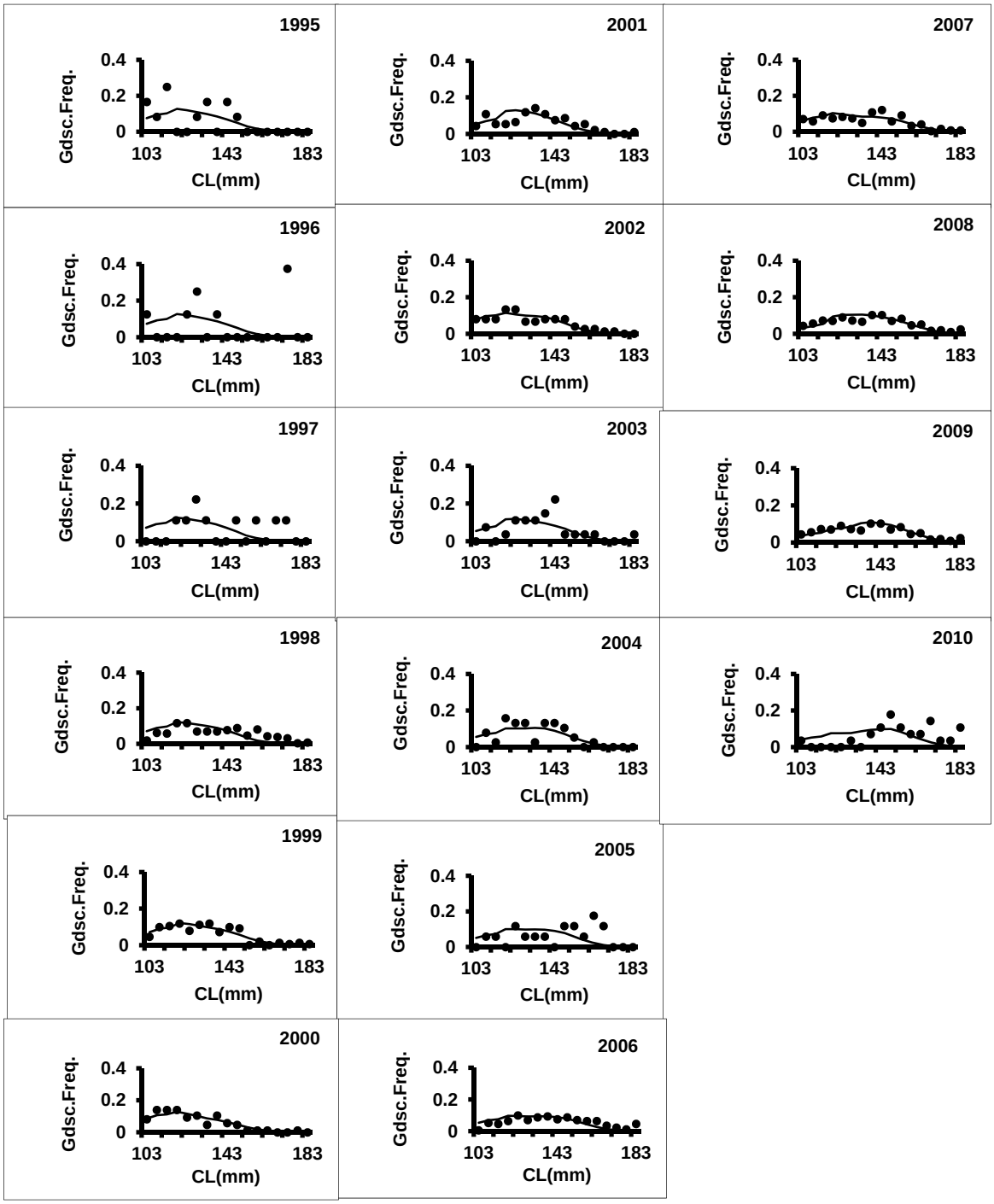


Figure 36. Predicted (line) vs. observed (filled circle) groundfish discarded catch relative length frequency distributions of golden king crab for Scenario 2 in the WAG, 1995 to 2010 (note: 1995 refers to the 1995/96 fishery).

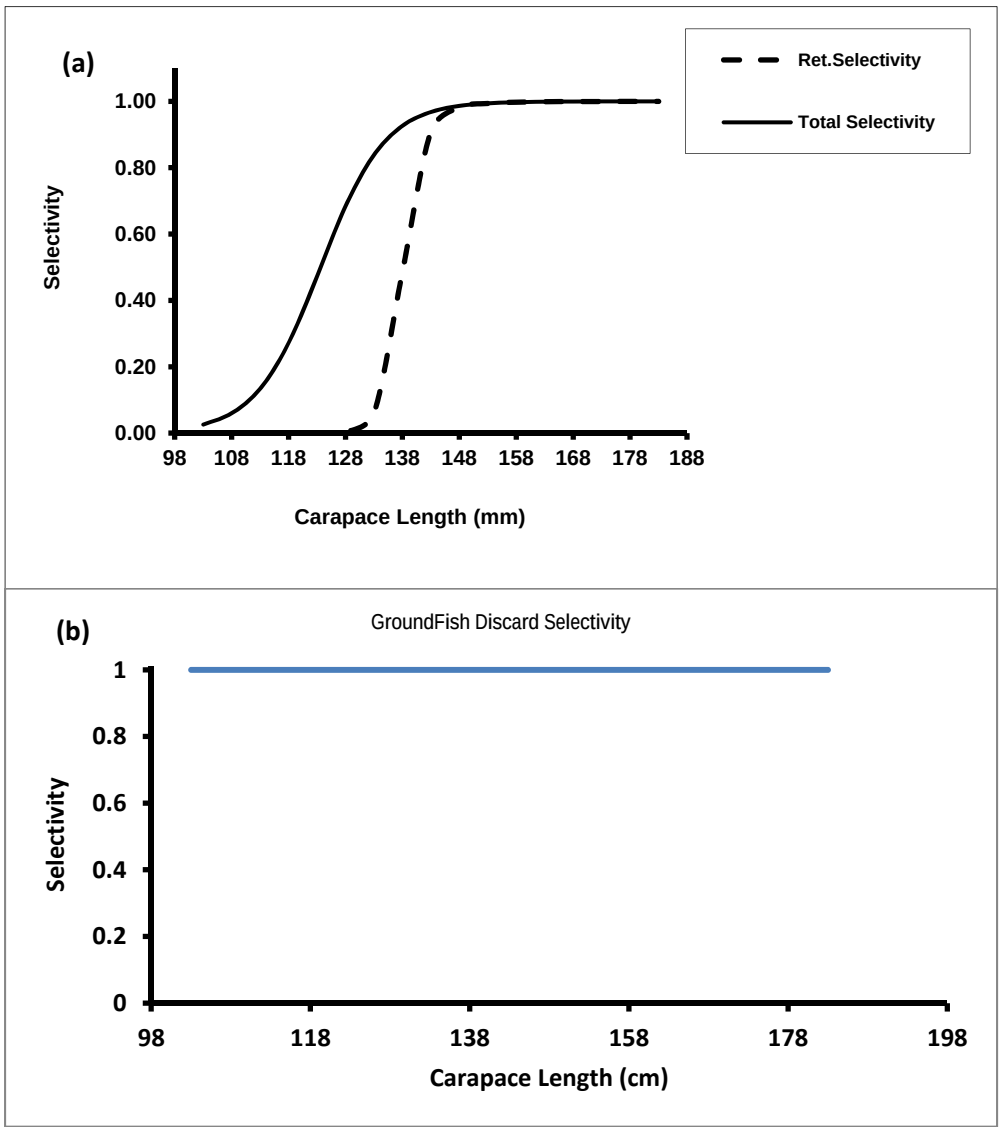


Figure 37. Estimated (a) total selectivity (solid line) and effective retained catch selectivity (total selectivity*retained selectivity; dashed line) during 2005- present (post-rationalization period); and (b) groundfish discard selectivity for Scenario 2 data for WAG golden king crab fishery.

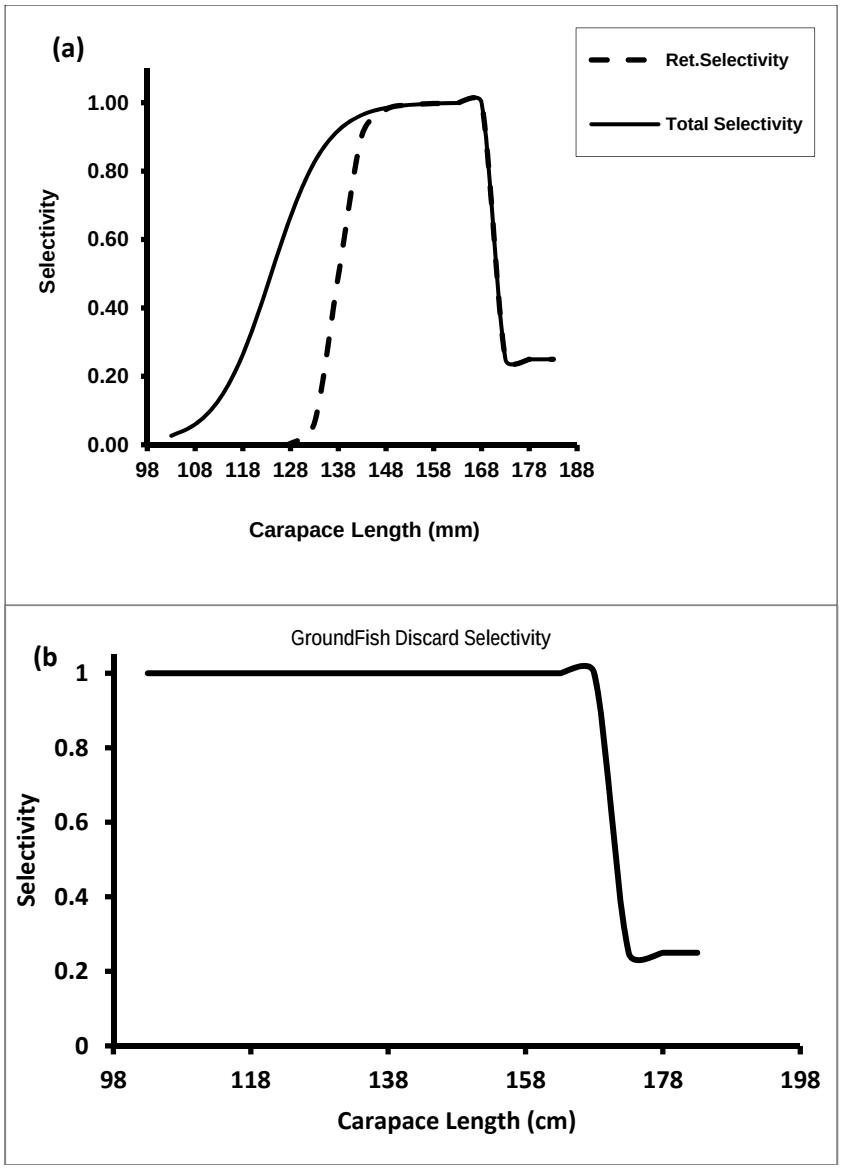


Figure 37continued. Estimated (a) total selectivity (solid line) and effective retained catch selectivity (total selectivity*retained selectivity; dashed line) during 2005- present (post-rationalization period); and (b) groundfish discard selectivity for Scenario 5 (dome shape selectivity) for WAG golden king crab fishery.

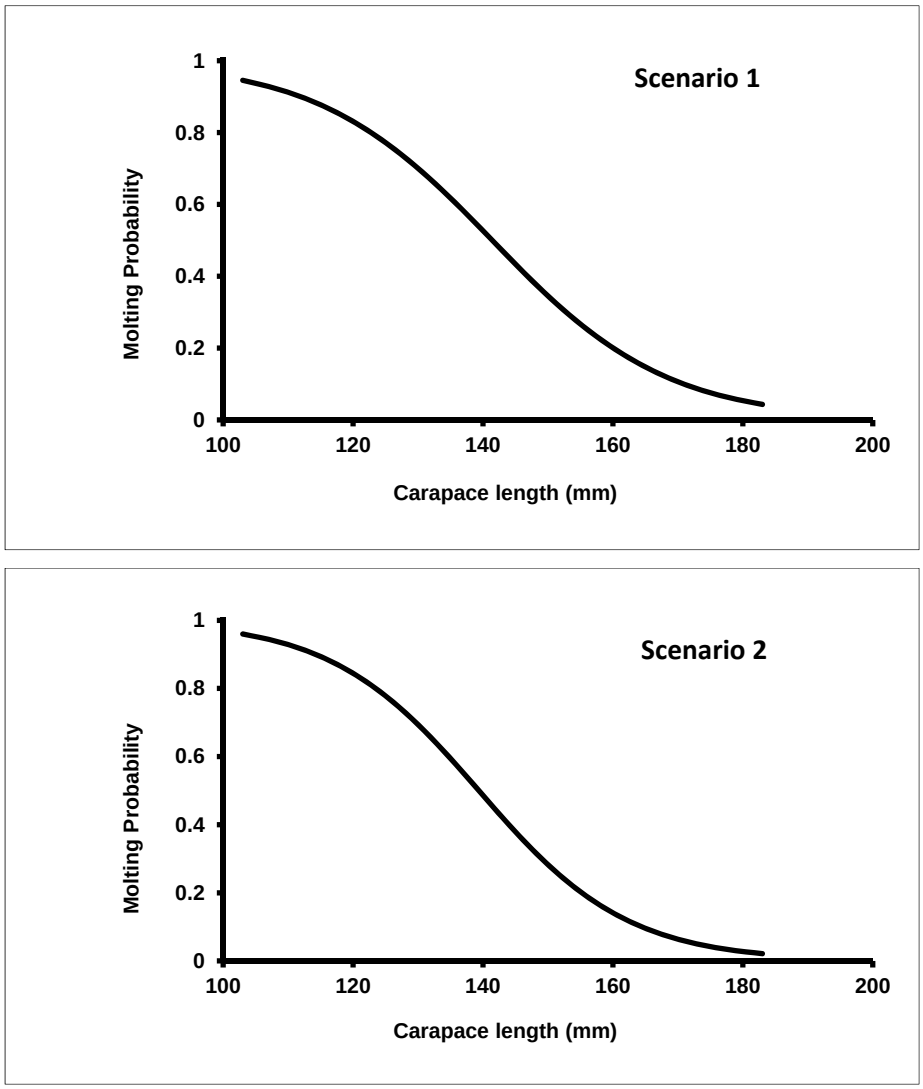
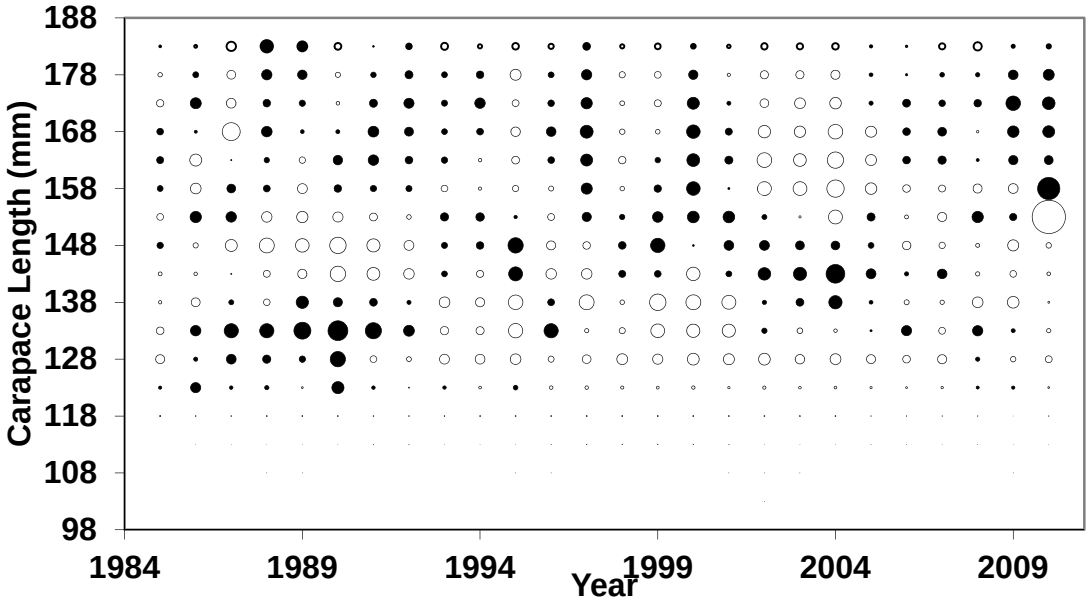


Figure 38. Estimated molt probability of WAG golden king crab for Scenarios 1 and 2.

(1)



(2)

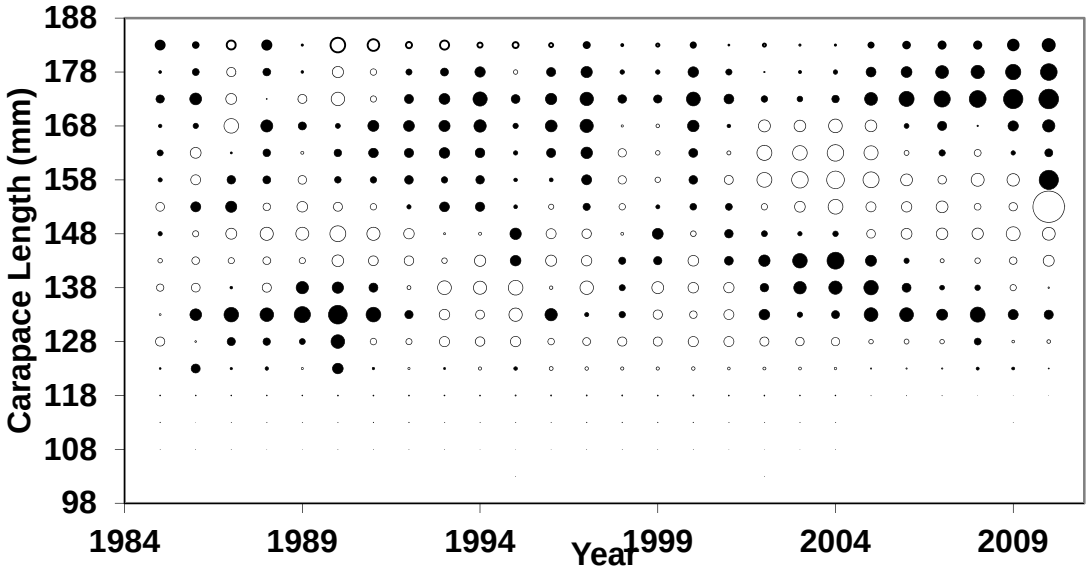
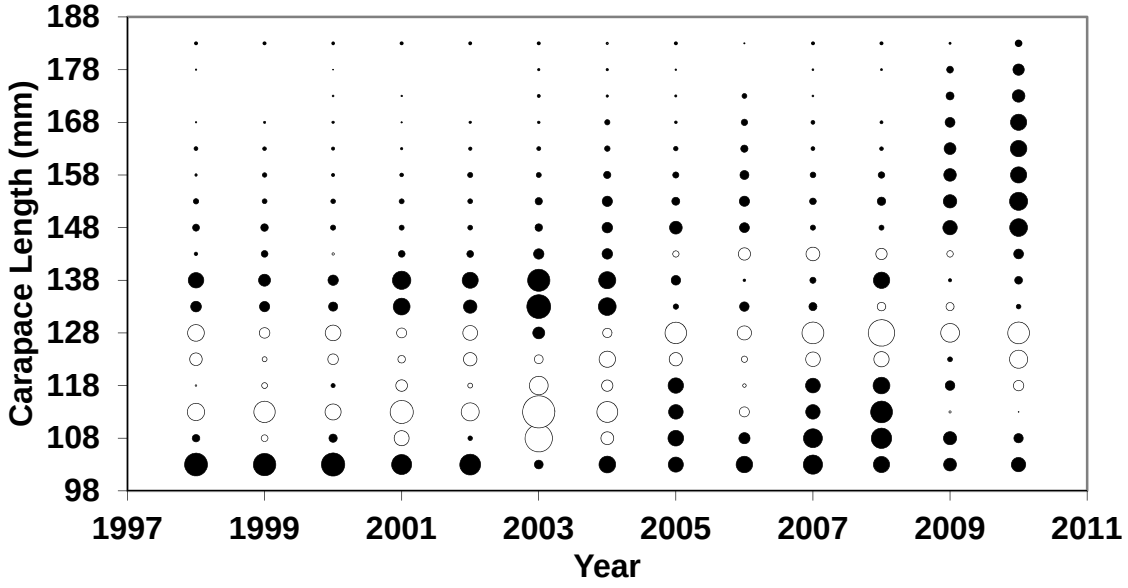


Figure 39. Bubble plot of standardized residuals of retained length composition for Scenarios 1 and 2 for WAG golden king crab, 1985-2010 (note: 1985 refers to the 1985/86 fishery).

(1)



(2)

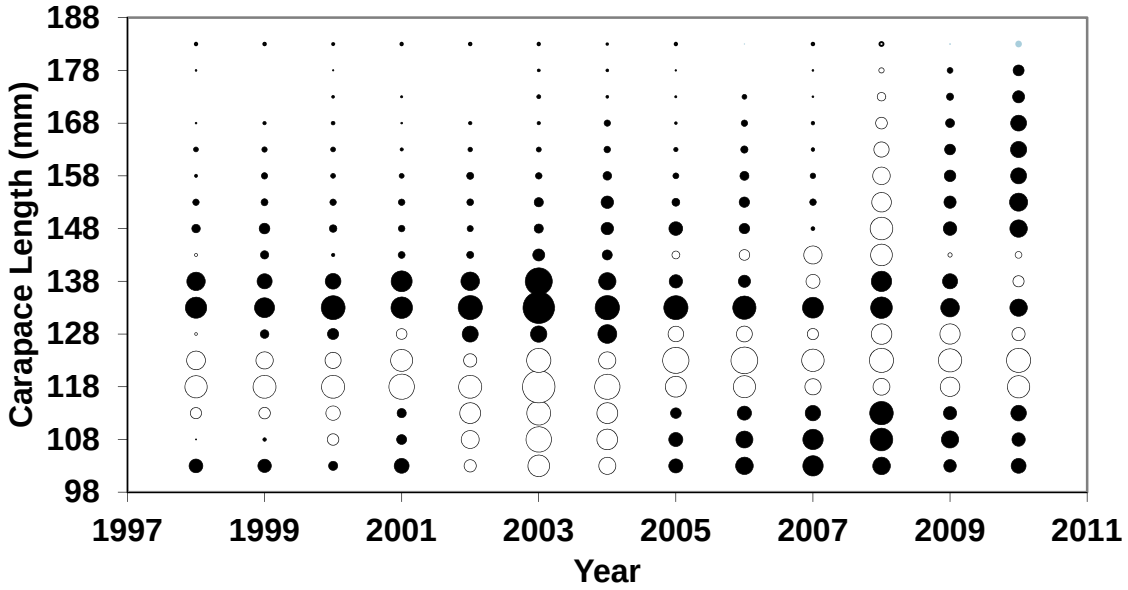
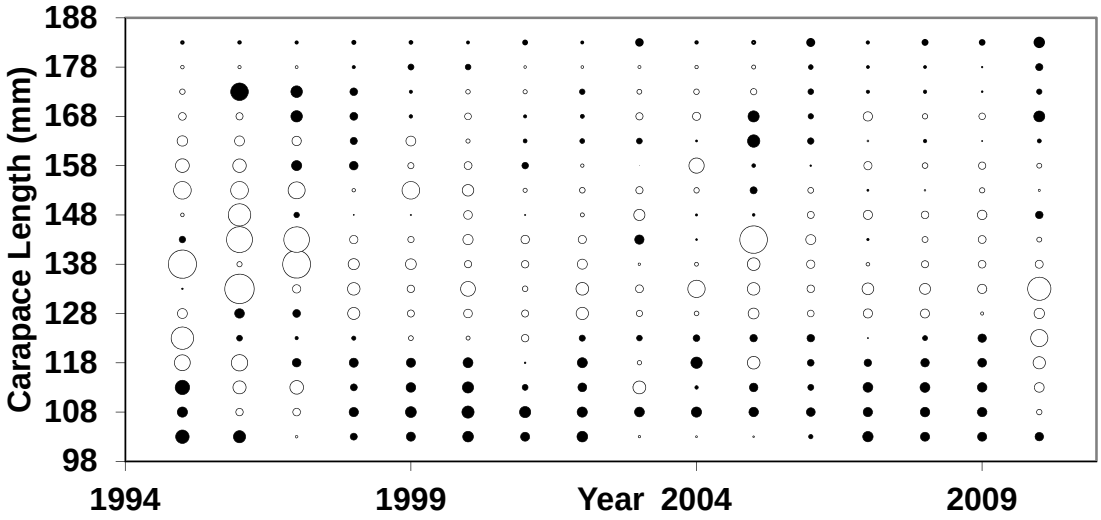


Figure 40. Bubble plot of standardized residuals of pot discard length composition for Scenarios 1 and 2 for WAG golden king crab, 1998-2010 (note: 1998 refers to the 1998/99 fishery).

(1)



(2)

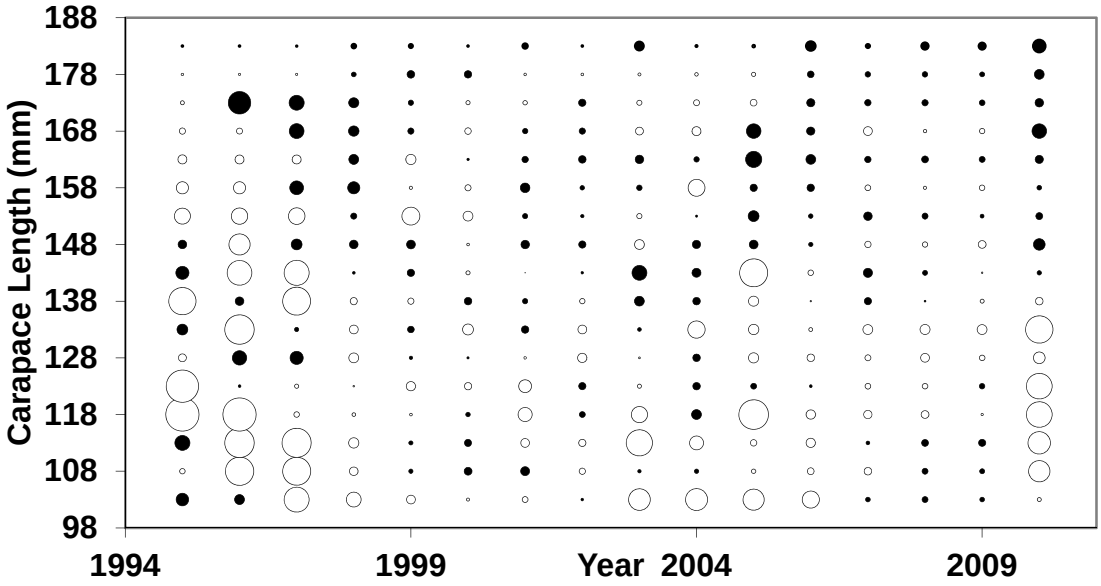


Figure 41. Bubble plot of standardized residuals of groundfish discarded length composition for Scenarios 1 and 2 for WAG golden king crab, 1995-2010 (note: 199 refers to the1995/96 fishery).

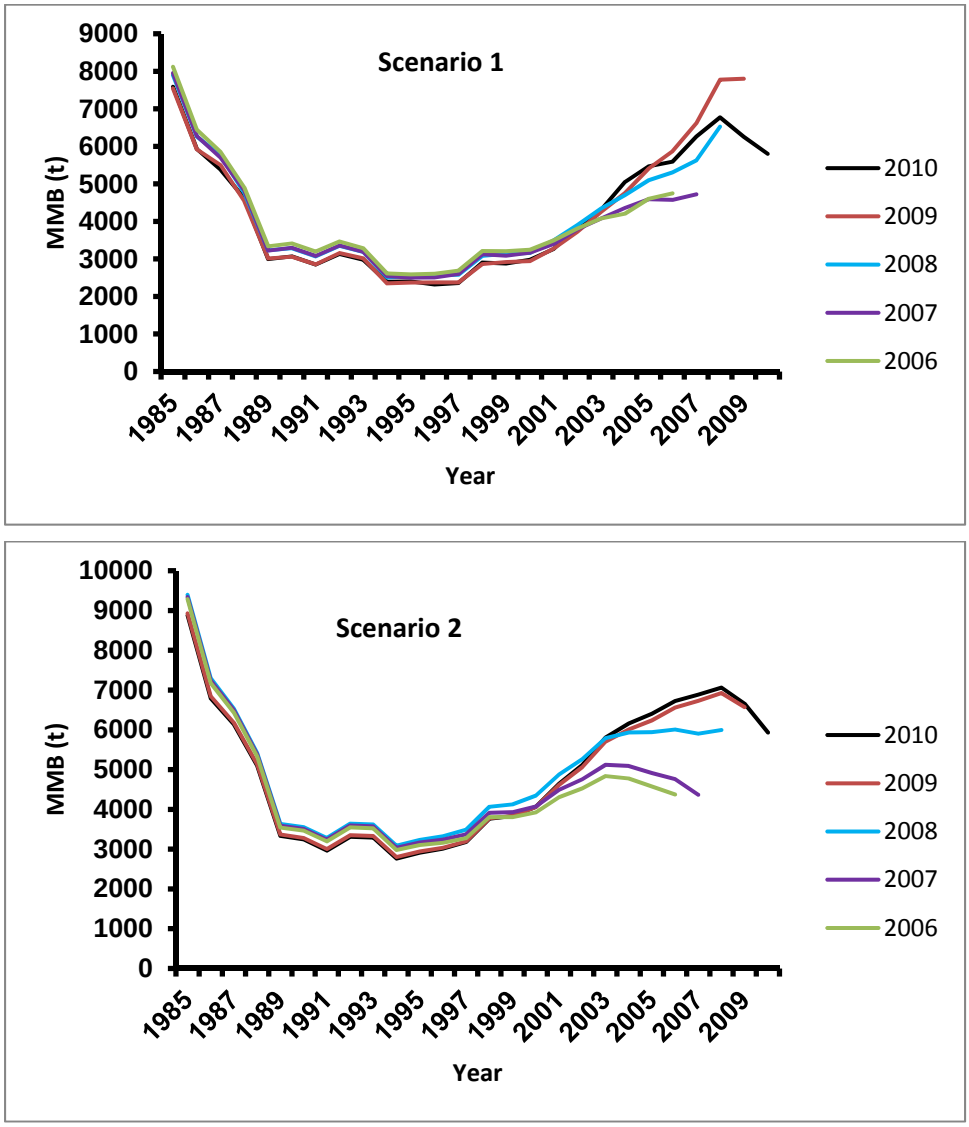


Figure 42. Retrospective fits of mature male biomass with terminal years 2006 to 2010 using the 2011 model for Scenarios 1 and 2 for WAG (note: 1985 refers to the1985/86 fishery).

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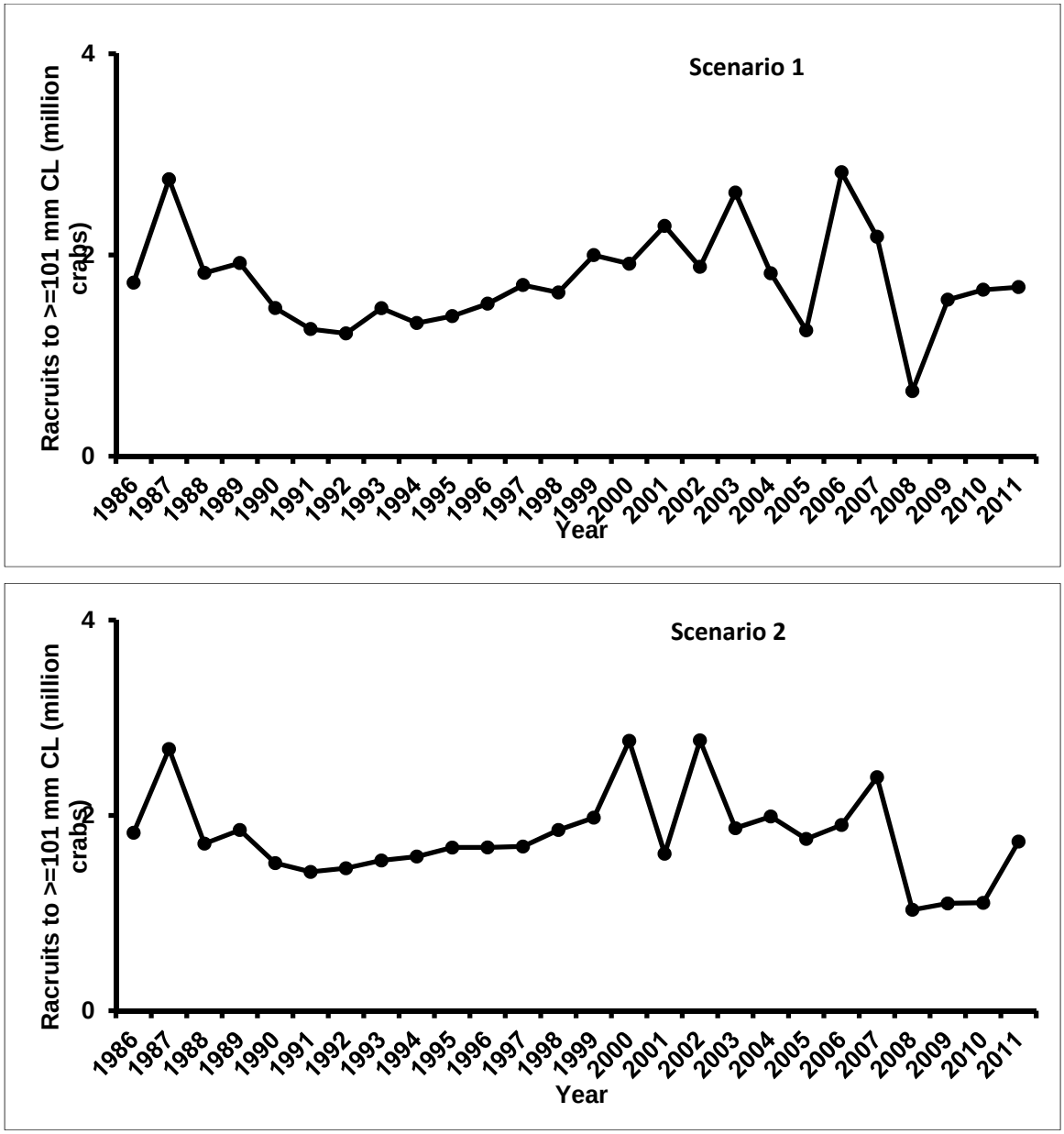
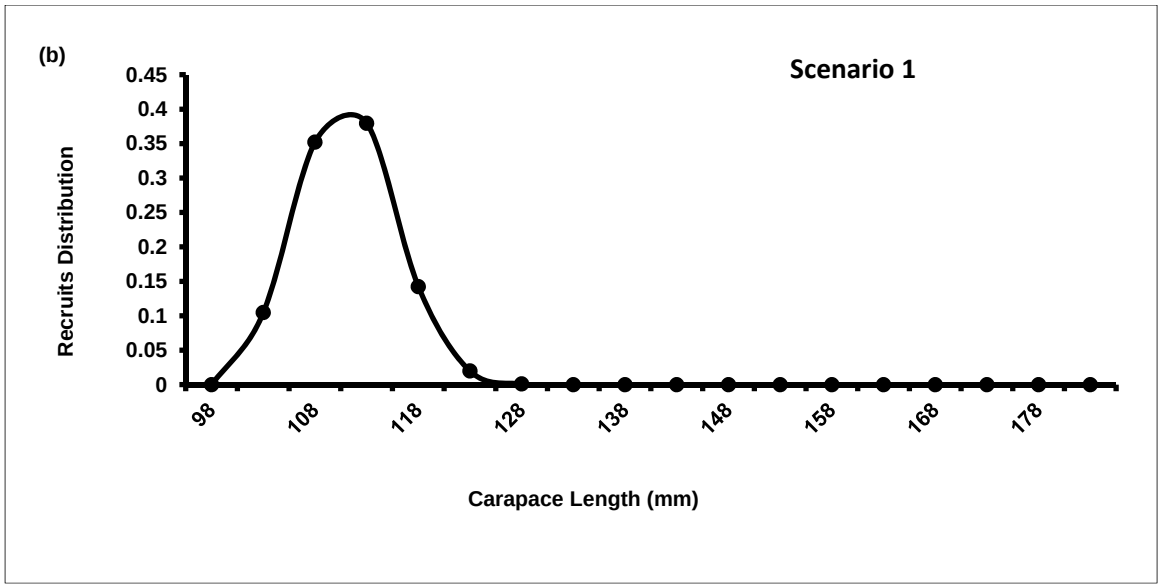


Figure 43. Estimated number of male recruits (millions of crabs ≥ 101 mm CL) to the golden king crab assessment model size group for Scenarios 1 and 2 in WAG, 1986-2011.



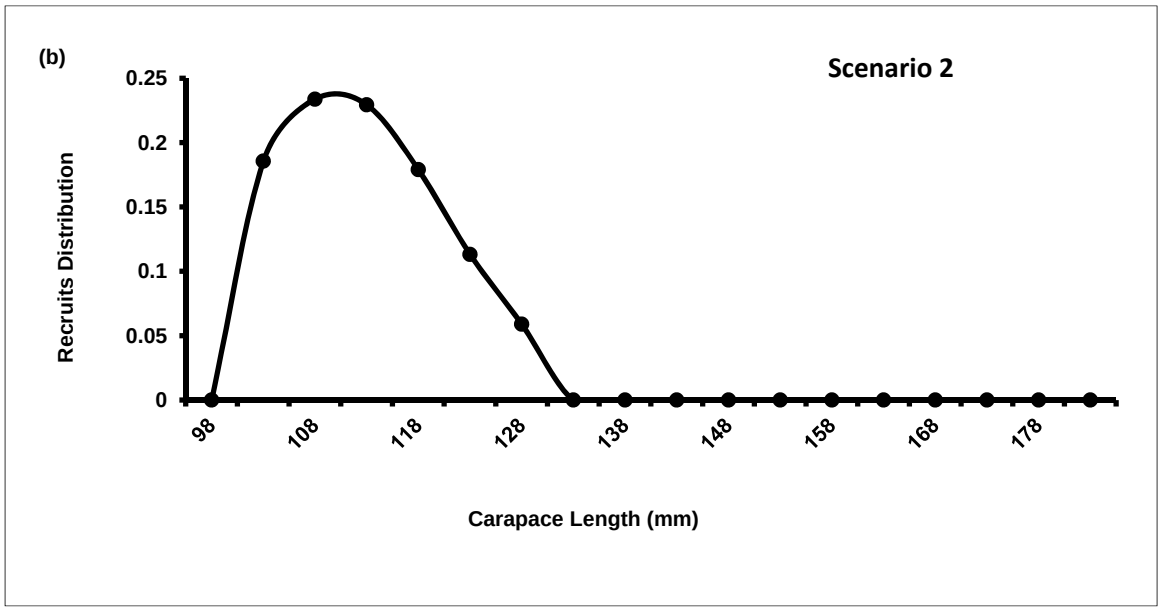


Figure 44. Recruit distribution to the golden king crab assessment model size group for Scenarios 1 and 2 in WAG.

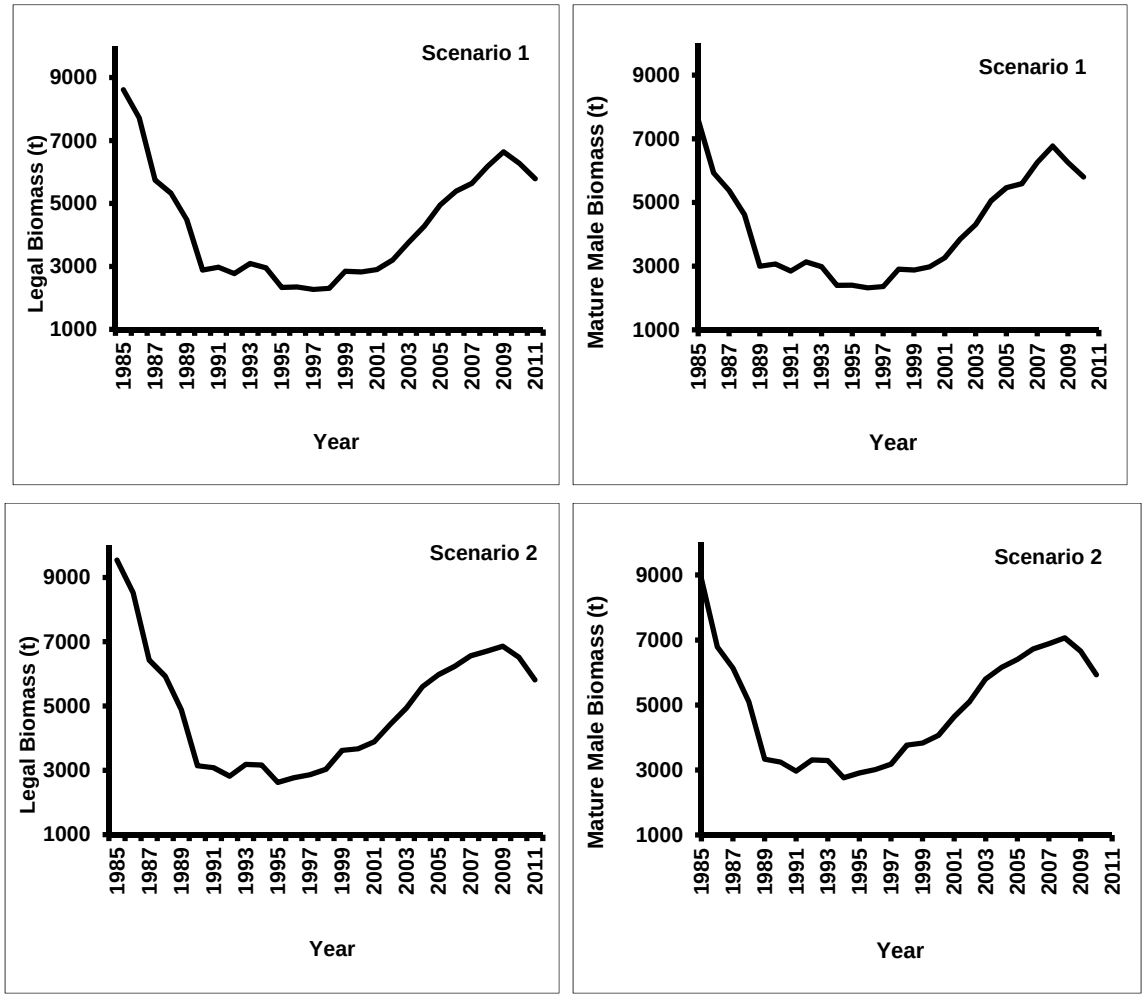


Figure 45. Trends in golden king crab legal male (left) and mature male (right) biomass (t) for Scenarios 1 and 2 in the WAG, 1985-2010/11. Legal male crabs are ≥ 136 mm CL and mature male crabs are ≥ 121 mm CL.

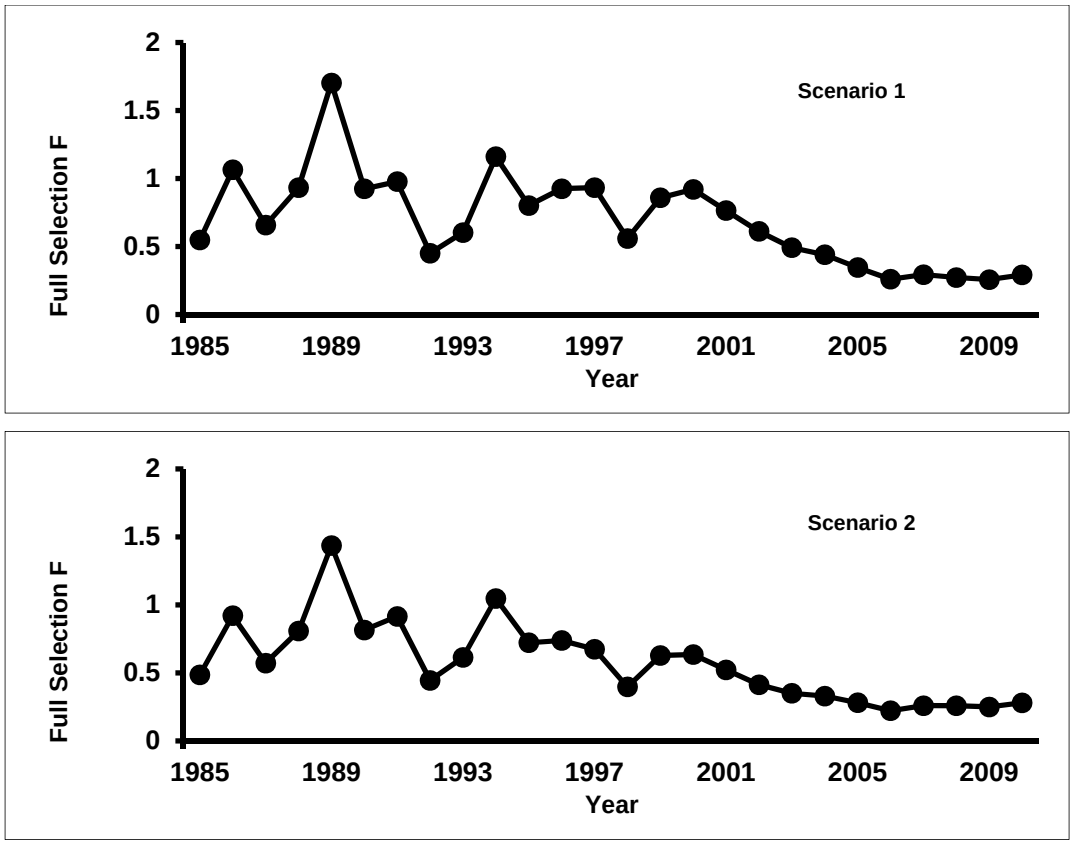


Figure 46. Trends in full selection fishing mortality of golden king crab for Scenarios 1 and 2 in the WAG, 1985-2010 (note: 1985 refers to the 1985/86 fishery).

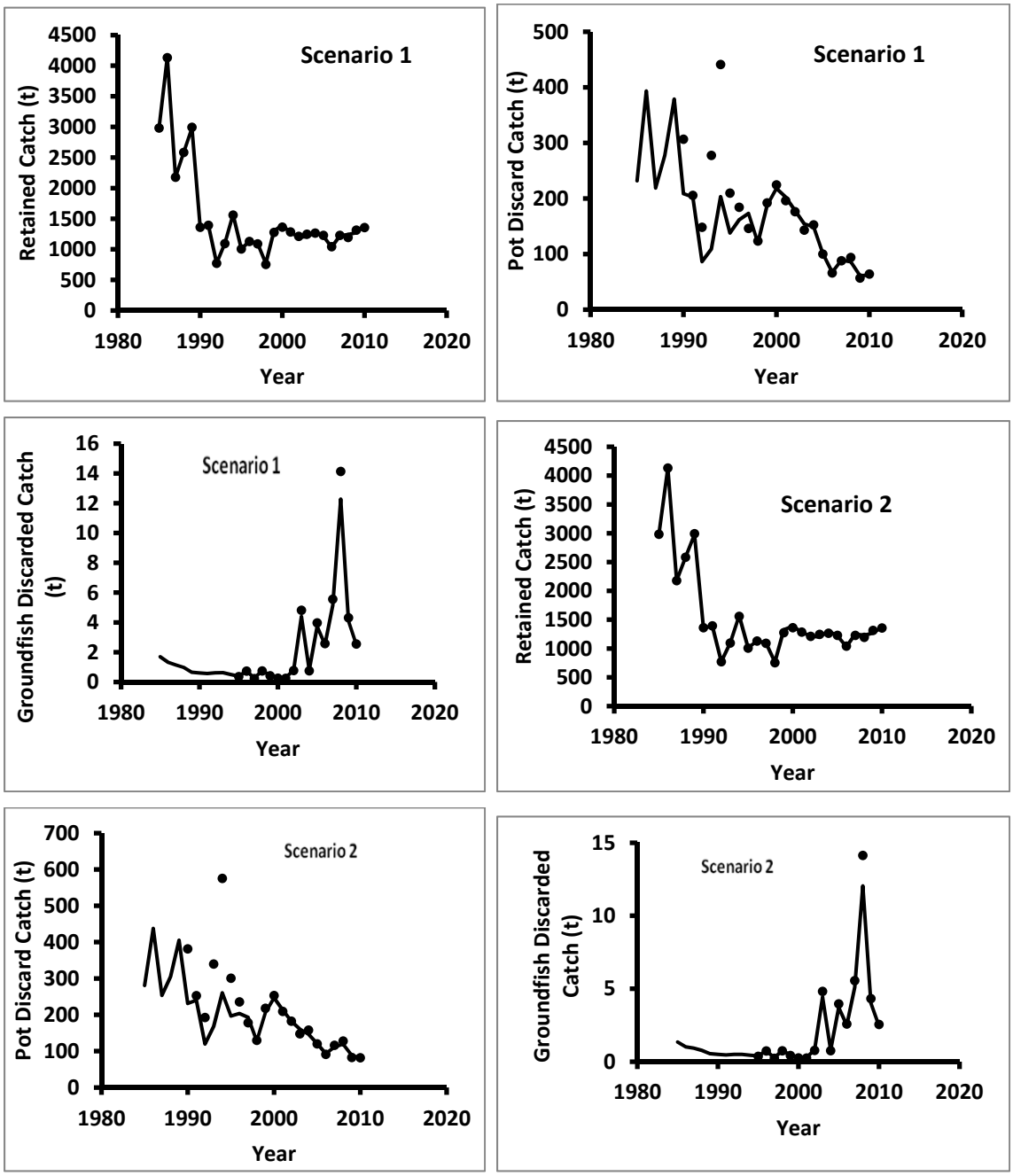


Figure 47. Observed (filled circle) vs. predicted (solid line) retained, pot discard, and groundfish discard catches of golden king crab for Scenarios 1 and 2 in the WAG, 1985-2010 (note: 1985 refers to the 1985/86 fishery). A handling mortality rate of 20% was applied for pot discard and an average handling mortality rate of 65% (average of 80% and 50%) was applied for groundfish discard.

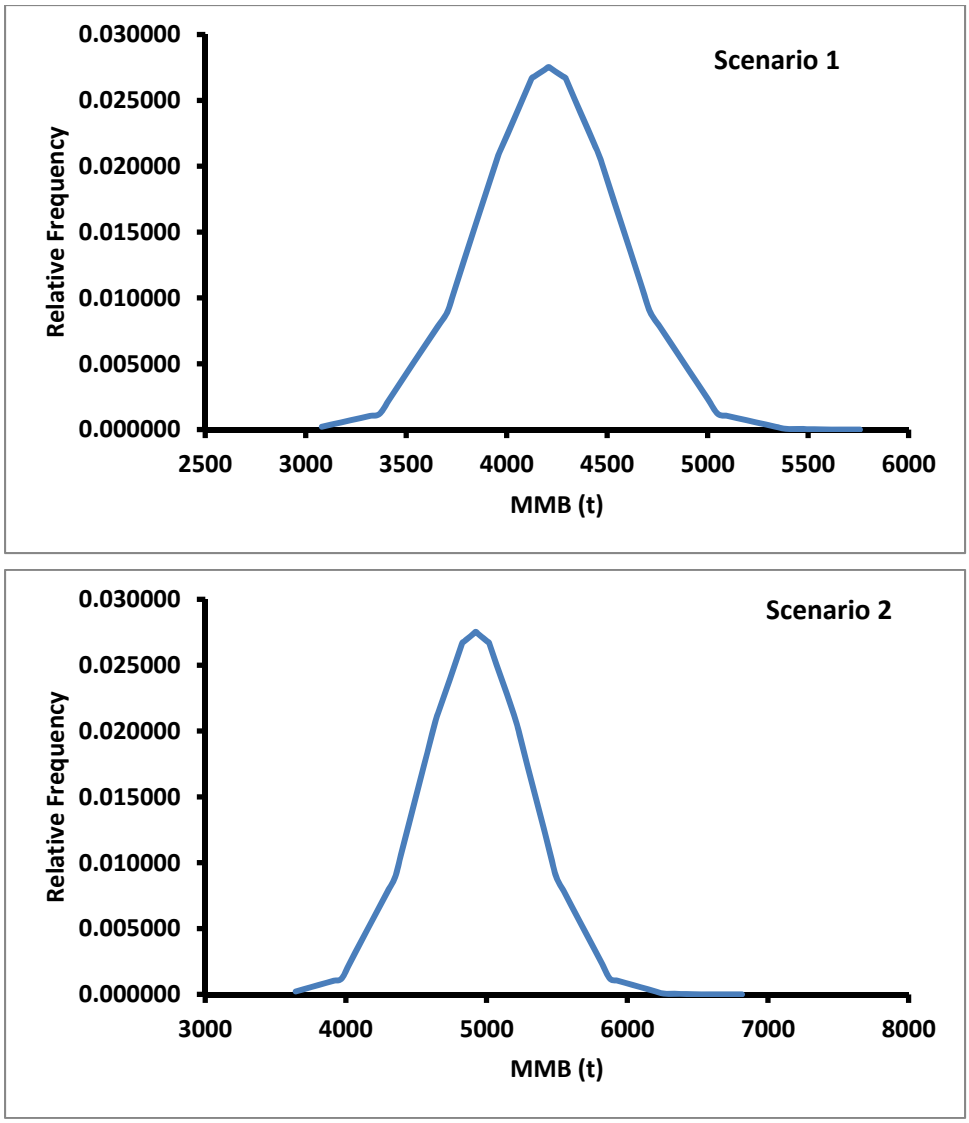


Figure 48. Profile likelihood distributions of mature male biomass (MMB) based on 1985-2010 data of golden king crab for Scenarios 1 and 2 in the WAG. Relative frequency was created based on the profile likelihood.

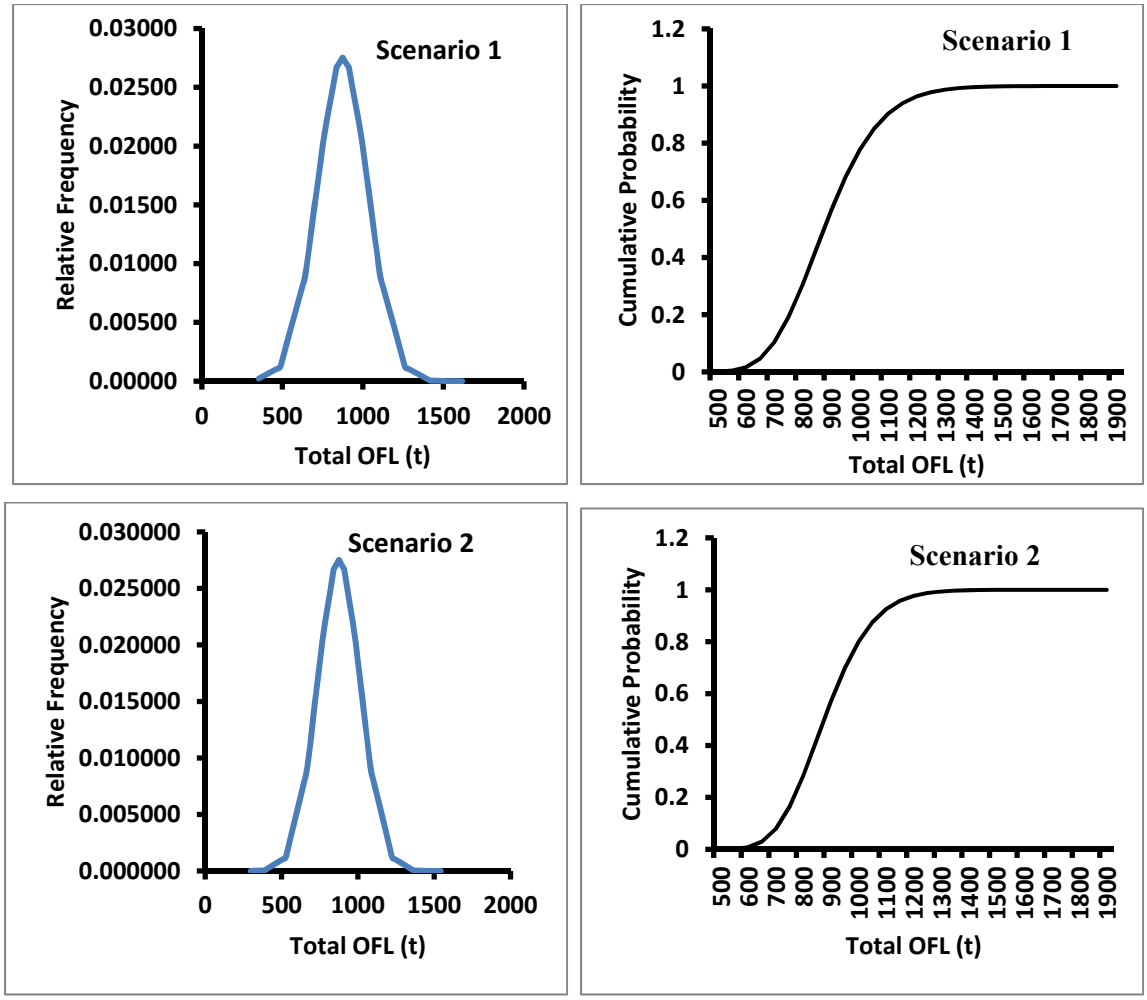


Figure 49. Probability of total OFL based on 1985-2010 data for Scenarios 1 and 2 for WAG golden king crab. Profile likelihood was used to create the probability distribution (left) and the cumulative distribution (right) was established assuming lognormal distribution of OFL.

Appendix A: Integrated model

Aleutian Islands Golden King Crab (*Lithodes aequispinus*) Stock Assessment Model Development- East of 174°W (EAG) and west of 174°W (WAG) Aleutian Island stocks

Parameters estimated conditionally

a and b: for the molt probability model;
S_i^T : total selectivity;
S_i^{surv} : survey selectivity for the EAG only;
S_i^r : retained selectivity;
S_i^{Tr} : groundfish bycatch selectivity;

For Scenario 5 (dome shape selectivity), the total, groundfish bycatch, and survey selectivity (logistic model) are set to a constant multiple of the 14th bin selectivity for adequate fits of the length compositions. The constant SP1 is estimated as a parameter in the model.

R_t: total number of male recruits for each year, except the first year, R_{86} to R_{11};
q: pot survey catchability;
q_1: pot fishery catchability for the period 1985-1997;
q_2: pot fishery catchability for the period 1998-2004;
q_3: pot fishery catchability for the period 2005 onward;
F_t : Instantaneous full selection fishing mortality for each year, F_{85} to F_{10};
β: shape parameter of the gamma growth function;
α_r, β_r : recruitment parameters for the Gamma function;
N_{ini}: initial total number of (new-shell) crabs, N_{85}; and
pn_i : relative length frequency proportion for new–shell (17 parameters each for 17 bins) for start year, 1985 (Effective for EAG and WAG).

Parameters fixed

Natural mortality is fixed at $0.18yr^{-1}$.
Linear growth increment model is estimated externally using tagging data.
Effective sample sizes are fixed at 50 for retained, pot discard, and pot survey length composition log likelihoods, and at 10 for groundfish discard length composition log likelihood.

Model

Molting probability

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

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

where a and b are parameters.

Growth increment probability

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 (in mm CL), 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.

Recruit distribution

Similar Gamma function as above with α_r, and β_r parameters.

Selectivity

Fishery selectivity and survey selectivity (only for the EAG*)*

The total fishery (S_i^T) selectivity, pot survey selectivity (S_i^{surv}), retained selectivity (S_i^r), and groundfish bycatch selectivity (S_i^{Tr}) are modeled as logistic functions.

$$S_i = \frac{1}{1+e^{-a_k(i-b_k)}} \tag{4}$$

Three sets of selectivity (a_k, b_k) and catchability (q_k) parameters for the periods 1985-1997, 1998-2004, and 2005 – onward are considered for fishery (total and retained) selectivity. One set of selectivity (a', b') is considered for groundfish fishery bycatch. One set of selectivity (a, b) and catchability parameter, q, are considered for pot survey.

Population dynamics

Initial year (1985 for the EAG and WAG) stock abundance is modeled as

$$N_{i,1} = N_1 pn_i \tag{5}$$

where N_1 is total new-shell initial abundance parameter and pn_i is relative size frequency parameter in size class *i*. These proportions are treated as separate parameters (for 17 bins) to be estimated from model fit. Sum of these proportions are set to one in the following formulation:

Let α_i are any real numbers (we used a bound -5 to 5 for convergence purpose). pn_i are determined using the following formulas such that all pn_i add up to 1:

$$pn_i = \frac{e^{\alpha_i}}{\sum_j e^{\alpha_j}} \tag{6}$$

The annual abundances by size and shell condition for other years are modeled considering growth, mortality, and recruitment:

$$N_{t+1,j} = \sum_i^j [(N_{t,i} + O_{t,i})e^{-M} - (\hat{C}_{t,i} + \hat{D}_{t,i} + \hat{T}_{t,i})e^{(y_t-1)M}]m_i P_{i,j} + R_{t+1,j} \tag{7}$$

$$O_{t+1,j} = [(N_{t,j} + O_{t,j})e^{-M} - (\hat{C}_{t,j} + \hat{D}_{t,j} + \hat{T}_{t,i})e^{(y_t-1)M}](1 - m_j) \tag{8}$$

where $N_{t,i}$ and $O_{t,i}$ are respective abundances of new-shell and old-shell crabs in length class *I* on 1 July (start of biological year coincided with mid survey time) in year *t*; $\hat{C}_{t,i}$, $\hat{D}_{t,i}$, and $\hat{T}_{t,i}$ are predicted fishery retained, pot fishery discard dead, and groundfish fishery discard dead catches determined by equations (15), (16), and (17) in length class *i* 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.

Predicted fishery CPUE

Total catch-per-unit-effort by length and year is estimated as

$$C\hat{P}UE^T_{t,j} = q_k[s^T_j(N_{t,j} + O_{t,j} - 0.5(\hat{C}_{t,j} + \hat{D}_{t,j} + \hat{T}_{t,j}))e^{-y_t M}] \tag{9}$$

Retained catch-per-unit-effort by length and year is estimated as

$$C\hat{P}UE^r_{t,j} = q_k[s^T_j QQ(t)s^r_j(N_{t,j} + O_{t,j} - 0.5(\hat{C}_{t,j} + \hat{D}_{t,j} + \hat{T}_{t,j}))e^{-y_t M}] \tag{10}$$

Pot discarded catch-per-unit-effort by length and year is estimated as

$$C\hat{P}UE^d_{t,j} = q_k[s^T_j(1 - s^r_j)(N_{t,j} + O_{t,j} - 0.5(\hat{C}_{t,j} + \hat{D}_{t,j} + \hat{T}_{t,j}))e^{-y_t M}] \tag{11}$$

where ^ sign refers to predicted value. QQ(t) is defined in the paragraph after equation (17).

Assuming that CPUE have log normally distributed measurement errors, the negative log likelihoods for the retained and discard catch-per-unit-effort data are

$$LL_r^{CPUE} = \lambda_{rCPUE}\{\ 0.5\sum_t\ ln[\,2\Pi(\sigma^2{}_{r,t} + \sigma^2{}_e)] + \sum_t\ \frac{\sum_j\{log(C\hat{P}UE^r_{t,j} + c) - log(CPUE^r_{t,j} + c)\}^2}{2(\sigma^2_{r,t} + \sigma^2{}_e)}\ \}$$

(12)

$$LL_D^{CPUE} = \lambda_{DCPUE}\{\ 0.5\sum_t\ ln[\,2\Pi(\sigma^2{}_{D,t} + \sigma^2{}_f)] + \sum_t\ \frac{\sum_j\{log(C\hat{P}UE^D_{t,j} + c) - log(CPUE^D_{t,j} + c)\}^2}{2(\sigma^2_{D,t} + \sigma^2{}_f)}\ \}$$

(13)

where c is a small constant (0.001), $\sigma^2{}_e$ and $\sigma^2{}_f$ are additional variance parameters to be estimated by the fit, λs are weights, and $\sigma^2_{r,t}$ and $\sigma^2_{D,t}$ are the annual variances of log(CPUE), estimated from observed variances.

Predicted retained and discarded dead catches

The predicted pot fishery total catch, retained catch, and pot discard and groundfish fishery discard mortality are estimated as follows:

Total catch,

$$\hat{C}^T{}_{t,j} = (N_{t,j} + O_{t,j})e^{-y_t M}(1 - e^{-F_t s_j^T - F_t^{Tr} s_j^{Tr}}) * \frac{F_t\ s_l^T}{F_t\ s_l^T + F_t^{Tr} s_l^{Tr}} \quad (14)$$

Retained catch,

$$\hat{C}_{t,j} = (N_{t,j} + O_{t,j})e^{-y_t M}(1 - e^{-F_t s_j^T - F_t^{Tr} s_j^{Tr}}) * \frac{F_t\ s_l^T QQ(t)\, s_l^r}{F_t\ s_l^T + F_t^{Tr} s_l^{Tr}} \quad (15)$$

Pot fishery discarded dead catch,

$$\hat{D}_{t,j} = 0.2 * (\hat{C}^T{}_{t,j} - \hat{C}_{t,j}) \quad (16)$$

Groundfish discarded dead catch,

$$\hat{T}_{t,j} = 0.8(N_{t,j} + O_{t,j})e^{-y_t M}(1 - e^{-F_t s_j^T - F_t^{Tr} s_j^{Tr}}) * \frac{F_t^{Tr} s_l^{Tr}}{F_t\ s_l^T + F_t^{Tr} s_l^{Tr}} \quad (17)$$

There is an additional time varying discard catchability QQ (t) on legal size crab in equations (10) and (15). QQ(t) is set to 1.0 for all years except 1998, 2000, 2007, and 2009 in EAG and 1991 and 1994 in WAG. The years were selected based on the observed legal size discard/legal size retained catch ratio. The ratios were higher during those fishing seasons than the other years.

QQ(t) is defined by a logistic function

$$QQ(t) = \frac{e^{\overline{QQ}+QQ_Dev(t)*\sigma}}{1+e^{\overline{QQ}+QQ_Dev(t)*\sigma}} \quad (18)$$

where $\overline{QQ}$ is the mean and QQ_Dev(t) is the time varying deviation vector with $\sum QQ_Dev(t) = 0$. The σ is set to 0.25.

Assuming catch biomasses have log normally distributed measurement errors, the negative log likelihoods for the retained and discard catch biomass data are

$$LL_r^{catch} = \lambda_r \sum_t \{log(\sum_j \hat{C}_{t,j} w_j + c) - log(\sum_j C_{t,j} w_j + c)\}^2 \quad (19)$$

$$LL_D^{catch} = \lambda_D \sum_t \{log(\sum_j \hat{C}^D{}_{t,j} w_j + c) - log(\sum_j C^D{}_{t,j} w_j + c)\}^2 \quad (20)$$

$$LL_{GD}^{catch} = \lambda_{GD} \sum_t \{log(\sum_j \hat{T}_{t,j} w_j + c) - log(\sum_j T_{t,j} w_j + c)\}^2 \quad (21)$$

where λ_r, λ_D and λ_{GD} are retained, pot discard and groundfish discard catch weights for the likelihoods.

Predicted pot survey CPUE(only for the EAG)

Pot survey $CPUE_t^s$ by length and year was estimated as

$$C\hat{P}UE_{t,j}^s = q_k s_j^{surv} (N_{t,j} + O_{t,j}) \quad (22)$$

Assuming that CPUE have log normally distributed measurement errors, the negative log likelihood for the pot survey catch-per-unit-effort data is

$$LL_S^{CPUE} = \lambda_{SCPUE} \{ 0.5 \sum_t ln[2\Pi(\sigma^2{}_{S,t} + \sigma^2{}_g)] + \sum_t \frac{\sum_j \{log(C\hat{P}UE_{t,j}^S + c) - log(CPUE_{t,j}^S + c)\}^2}{2(\sigma_{S,t}^2 + \sigma^2{}_g)} \}$$

(23)

where c is a small constant (0.001), λ_{sCPUE} is the weight, and $\sigma_{s,t}^2$ is the annual variance of log(CPUE)), estimated from observed variances.

Length composition

Predicted retained length composition $\hat{L}^r_{t,j}$ in year t is computed as

$$\hat{L}^r_{t,j} = \frac{\hat{C}_{t,j}}{\sum_j^n \hat{C}_{t,j}} \tag{24}$$

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

$$LL_r^{LF} = 0.5 \sum_t \sum_j log(2\pi\sigma^2_{t,j}) - \sum_t \sum_j log\left[e^{-\frac{(L^r_{j,t} - \hat{L}^r_{t,j})^2}{2\sigma^2_{t,j}}} + 0.01 \right] \tag{25}$$

Where

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

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

Predicted pot discard catch length composition $\hat{L}^D_{t,j}$ in year *t* is computed as

$$\hat{L}^D_{t,j} = \frac{\hat{C}^D_{t,j}}{\sum_j^n \hat{C}^D_{t,j}} \tag{26}$$

Negative log likelihood, LL_D^{LF}, for discard length composition is similar to equation (25) with discard catch effective sample size and length composition replacing the corresponding retained values.

Predicted groundfish discard catch length composition $\hat{L}^{GD}_{t,j}$ in year *t* is computed as

$$\hat{L}^{GD}_{t,j} = \frac{\hat{T}_{t,j}}{\sum_j^n \hat{T}_{t,j}} \tag{27}$$

Negative log likelihood, LL_{GD}^{LF}, for groundfish discard length composition is similar to equation (25) with groundfish discard catch effective sample size and length composition replacing the corresponding retained values.

Predicted pot survey (only for the East) length composition $\hat{L}^s_{t,j}$ in year t is computed as

$$\hat{L}^S_{t,j} = \frac{\hat{C}^S_{t,j}}{\sum_j^n \hat{C}^S_{t,j}} \tag{28}$$

Negative log likelihood, LL_s^{LF}, for pot survey length composition is similar to equation (25) with pot survey sample size and length composition replacing the corresponding retained values.

Pot fishery fishing mortality penalty
Assuming lognormal distribution of annual *F*, the weighted negative log likelihood is

$$LL_F = \lambda_F \sum_t \{\log(F_t) - \log(\overline{F})\}^2 \tag{29}$$

where $\overline{F}$ is the mean fishing mortality parameter and λ_F is the fishing mortality weight.

Groundfish fishery bycatch fishing mortality penalty

Assuming lognormal distribution of annual groundfish bycatch *GF*, the weighted negative log likelihood is

$$LL_{GF} = \lambda_{GF} \sum_t \{log(GF_t) - log(G\overline{F})\}^2 \tag{30}$$

where $G\overline{F}$ is the mean groundfish bycatch fishing mortality parameter and λ_{GF} is the groundfish bycatch fishing mortality weight.

Recruitment penalty

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

$$LL_R = \lambda_R \sum_t \{\log(R_t) - \log(\overline{R})\}^2 \tag{31}$$

where $\overline{R}$ is the mean recruitment parameter and λ_R is the weight for the recruitment likelihood.

Legal discard in certain years penalty

$$LL_{QQ} = \lambda_{QQ} \sum_t \{log(QQ_t) - log(Q\overline{Q})\}^2 \tag{32}$$

where $Q\overline{Q}$ is the mean QQ parameter and λ_{QQ} is the weight for the QQ likelihood.

Legal biomass penalty (for the EAG stock)

Assuming lognormal distribution of estimated legal male biomass (LMB),

(a) The weighted negative log likelihood for 1997 LMB is

$$LL_{1997\,LMB} = \lambda_{1997\,LMB} \{log(LMB_{1997} + c) - log(LM\hat{B}_{1997} + c)\}^2 \tag{33}$$

where $LM\hat{B}_{1997}$ is the independently estimated exploited legal male biomass based on retained catch and tagging data estimated harvest rate (0.254, CV=0.0355) and $\lambda_{1997\,LMB}$ is the weight (397) for the exploited legal male biomass likelihood, which is estimated for the corresponding CV.

(b) The weighted negative log likelihood for 2000 LMB is

$$LL_{2000\,LMB} = \lambda_{2000\,LMB}\{log(LMB_{2000} + c) - log(\hat{LMB}_{2000} + c)\}^2 \quad (34)$$

where $\hat{LMB}_{2000}$ is the independently estimated exploited legal male biomass based on retained catch and tagging estimated harvest rate (0.2550, CV=0.0432) and $\lambda_{2000\,LMB}$ is the weight (268) for the exploited legal male biomass likelihood, which is estimated for the corresponding CV.
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(c) The weighted negative log likelihood for 2003 LMB is

$$LL_{2003\,LMB} = \lambda_{2003\,LMB}\{log(LMB_{2003} + c) - log(\hat{LMB}_{2003} + c)\}^2 \quad (35)$$

where $\hat{LMB}_{2003}$ is the independently estimated exploited legal male biomass based on retained catch and tagging estimated harvest rate (0.1327, CV=0.0617) and $\lambda_{2003\,LMB}$ is the weight (132) for the exploited legal male biomass likelihood, which is estimated for the corresponding CV.

(d) The weighted negative log likelihood for 2006 LMB is

$$LL_{2006\,LMB} = \lambda_{2006\,LMB}\{log(LMB_{2006} + c) - log(\hat{LMB}_{2006} + c)\}^2 \quad (36)$$

where $\hat{LMB}_{2006}$ is the independently estimated exploited legal male biomass based on retained catch and tagging estimated harvest rate (0.0946, CV=0.0664) and $\lambda_{2003\,LMB}$ is the weight (114) for the exploited legal male biomass likelihood, which is estimated for the corresponding CV.

The CV of the harvest rate is estimated by the delta method as follows:

$$E = 1 - e^{-F}$$

$$\sigma(E) = e^{-F}\sigma(F)$$

$$CV = \frac{\sigma(E)}{E}$$

Molt probability L_{50} penalty

Assuming normal distribution of estimated molt probability L_{50}, the weighted negative likelihood is

$$LL_{L50} = \lambda_{L50}\{L_{50} - 139.0\}^2 \quad (37)$$

where 139.0 mm CL is independently estimated molt probability L_{50} parameter based on tagging data (Watson et al., 2002) and λ_{L50} is the L_{50} likelihood weight.

Growth increment probability β penalty

Assuming normal distribution of estimated β, the weighted negative likelihood is

$$LL_{\beta} = \lambda_{\beta}\{\beta - 0.578\}^2 \quad (38)$$

where 0.578 is independently estimated β parameter based on tagging data (Watson et al., 2002) and λ_β is the β likelihood weight.

Mean catchability ratio penalty
Assuming log normal distribution of pot fishery catchability during the two periods,1998-2004 and 2005-2009, and hypothesizing that the mean catchability values are equal during the two periods, the following weighted negative log likelihood is formulated

$$LL_{CPUERATIO} = \lambda_{CPUERATIO} \{log(q3/q2) - log(1.9292045)\}^2$$

for EAG, and WAG

(39)

where 1.9292045 is the ratio of the mean catchabilty estimated by the Leslie depletion method (Table 16) for the two periods for WAG; and $\lambda_{CPUERATIO}$ is the catchability ratio likelihood weight estimated to be 0.69 (=0.5/estimated variance). We could not get significant Leslie model fits for EAG. Hence we used the WAG estimate in the penalty function. Variance of the loq(q) ratio was estimated using the ratio method.

Thus, the objective function for minimization is

$$f = LL_r^{LF} + LL_D^{LF} + LL_{GD}^{LF} + LL_s^{LF} + LL_r^{CPUE} + LL_D^{CPUE} + LL_s^{CPUE} + LL_r^{catch} + LL_D^{catch} + LL_{GD}^{catch} + LL_R$$
$$+ LL_F + LL_{GF} + LL_{QQ} + LL_{1997LMB} + LL_{2000LMB} + LL_{2003LMB} + LL_{L50} + LL_\beta + LL_{CPUERATIO}$$
. (40)

Following quantities are computed from the estimated parameters:

Harvest rate

Total pot fishery harvest rate:

$$E_t = \frac{\hat{C}_t + \hat{D}_t}{\sum_j^n (N_{j,t} + O_{j,t})} \quad (41)$$

where $\hat{C}$, and $\hat{D}$ are predicted legal-sized retained and pot discarded catches.

Exploited legal male biomass at the survey time in year *t*:

$$LMB_t = \sum_{j=legal\ size}^{n} s_j^T s_j^r (N_{j,t} + O_{j,t})\, w_j \quad (42)$$

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

$$MMB_t = \sum_{j=mature\ size}^{n} \{(N_{j,t} + O_{j,t})e^{-y'M} - (\hat{C}_{j,t} + \hat{D}_{j,t} + \hat{T}_{j,t})e^{-(y_t - y')M}\} w_j \tag{43}$$

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 is applied to compute F' :

(a) If $MMB_t \geq M\overline{MB}$, $F' = \gamma M$,

(b) If $MMB_t < M\overline{MB}$ and $MMB_t > 0.25 M\overline{MB}$,

$$F' = \gamma M \frac{(\frac{MMB_t}{M\overline{MB}} - \alpha)}{(1-\alpha)} \tag{44}$$

(c) If $MMB_t \leq 0.25 M\overline{MB}$, $F' = 0$

where γ is a constant multiplier of M, α is a parameter, and $M\overline{MB}$ 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 MMB_t is depended on the intervening retained and discard catch (i.e., MMB_t is estimated after the fishery), an iterative procedure is used using equations (43) and (44) with retained and discard catch predicted from equations (15), (16), and (17). The next year limit harvest catch is estimated using equations (15), (16), and (17) with the estimated F' value.