DRAFT

Aleutian Islands Golden King Crab (*Lithodes aequispinus*) Model Based Stock Assessment in Fall 2011

M.S.M. Siddeek[1], D. Pengilly[2], and J. Zheng[1]
Alaska Department of Fish and Game

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

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

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 became steady since 1996/97 because of implementation of fixed guideline harvest levels (total allowable catch, TAC) of 3 and 2.7 million pounds for east and west of 174°W longitude, respectively. The TACs were increased to 3.15 and

2.835 million pounds for the two respective regions for the 2008/09 fishery following the Alaska Board of Fisheries decision. Those levels were below the limit TACs determined under Tier 5 criteria (considering 1991-1995 mean catch as the limit catch) under the new crab management plan. The fishery has harvested close to the TAC levels since 1996/97 (Figure 1).

3. Stock biomass:

Estimated mature male biomass systematically decreased from initial years and then increased for both stock segments (EAG and WAG). The lowest biomass for EAG was realized in 1990 and the highest in 2011, the lowest for WAG was realized in 1993 and the highest in 2010 (Figures 20 and 39). The stock trends are similar to the fishery CPUE trends in both regions.

4. Recruitment:

The number of recruits to the model size group showed fluctuating trends for both stock segments (EAG and WAG). For EAG, the highest number of recruits to the model size group occurred in 2000, lowest in 1993, and the 2010 and 2011 recruitment trend was lower. For WAG, the high number of recruits to the model size group occurred in 2006-2007, lowest in 1990, and the 2008 - 2011 recruitment trend was lower (Figures 18 and 37).

5. Management performance:

See Pengilly's Executive summary under Tier 5 analysis in the 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. This model proposes the following OFL and ABC based on the entire time series of MMB:

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)**
2012/13	4a	23.33	39.13	1.68	0.18	1986-2011	0.18	4.726	4.714

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)**
2012/13	4a	10.58	17.75	1.68	0.18	1986-2011	0.18	2.144	2.138

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)**
2012/13	4a	10.73	17.71	1.65	0.18	1986-2011	0.18	2.465	2.452

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)**
2012/13	4a	4.87	8.03	1.65	0.18	1986-2011	0.18	1.118	1.112

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 (Figures 25 and 44).

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 discard 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 catch by size for 1995/96 to 2010/11 are included.
   (c) Observer pot retained and pot discarded CPUE are standardized for soak-time.
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

May 2010 CPT Comments:

Aleutian Islands golden king crab:

Tier 4 discussion:

Check whether the residual variance is compatible with the pre-specified CVs (check the residual patterns to the model fit). Increase the CV inputs (or estimate the extent of overdispersion) if needed

Response: We added an extra variance parameter term in the log CPUE likelihood component (see Appendix A) and estimated by model fitting.

Include CIs on annual CPUE graphs of model fits.

Response: We included CIs in the fitted annual CPUE graph.

Include bubble plots.

Response: We included standardized residuals bubble plots for carapace length vs. year in this report.

Run the model with M fixed at $0.18yr^{-1}$.

Response: Our mode runs are only for M = 0.18.

Selectivity for the eastern stock: why are the large crabs not available? The shape of the dome is not realistic. Explore standard models in which selectivity is asymptotic for at least one of the periods. Look for empirical evidence such as the size distribution of crab at depth to examine the plausibility of dome-shaped selectivity. Is the need for dome-shaped selectivity a consequence of the model assuming a growth transition matrix that implies higher growth than is actually the case?

Response: A model coding error affecting recruitment was corrected and the dome-shaped selectivity no longer applies.

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There are tagging data to estimate growth for golden king crab. The CPT recommends including growth data from tagging in the assessment to estimate growth within the model. Andre Punt has a paper in ICES journal on how to do this and will distribute to assessment author.

Response: For this assessment we externally estimated the linear growth increment model using tagging data.

Do not apply the selectivity curve when calculating MMB.

Response: In this assessment we did not apply the selectivity curve when calculating MMB.

Using λ as a correction factor makes it hard to see what the productivity of the stock actually is, it's biologically confusing.

Response: We did not consider this correction factor in this assessment.

Model framework looks correct, but secondary fixes need to be worked on.CPT would like to see the model again before Tier 4 adoption.

Response: None.

Calculate F_{35} for evaluation whether the stock could be moved to Tier 3.

Response: We did not address this topic in this report. We are trying to get the Tier 4 model acceptable first.

It appears from Table 3 that some parameters are hitting bounds; this needs to be checked and if parameters hit bounds reported.

Response: We avoided many parameters hitting bounds.

Molting probability is quite different between east and west. However, there are no data on growth in west. The CPT recommends using the tagging data from the east to estimate molting probabilities and use the same molting probability east and west.

Response: We considered a penalty function for molt probability with externally estimated molt L_{50} value of 139.0 mm CL for both regions. We also considered another penalty function with externally estimated growth shape parameter β value of 0.578 for both regions. Thus we hypothesized that the growth parameters for both regions were same.

There was some discussion on various gamma values (1, 0.5 and 0.25). Clear justification for gamma alternatives should be included in future assessments.

Response: In this assessment we only considered a gamma value of 1.

While the model is much improved, the CPT would like to see the alternative model scenarios recommended above (concerning molting probabilities, fishery selectivity, M, growth) before adoption of the model.

Response: The model fit improved dramatically once the coding error was corrected. There is now a base scenario for which alternative scenarios can be developed. This report includes three scenarios with different weights on likelihood components.

June 2010 SSC comments:

The SSC appreciates the opportunity to examine the stock assessment model, which is still undergoing development. The SSC suggests that Table 2 (page8-24) would be easier to use and interpret if the values in the footnotes (a-h) were incorporated into the body of

the table. The SSC compliments the CPT on their excellent comments to the authors on the assessment model and endorses those recommendations. The SSC anticipates reviewing an assessment model for potential adoption in 2011.

Response: SSC endorsed the CPT comments in their entirety; so no further comments are needed.

May 2011 CPT comments:

(a) Fix the selectivity to be asymptotic.

Response: In this run we only considered the asymptotic selectivity model.

(b) Modify weights on the likelihoods (run scenarios with modified weighting of data components: e.g., emphasize the fit to the length frequency in retained catch, in pot survey, CPUE, etc) and evaluate a range of model scenarios. Scenarios should start with a simple model and only free up parameters as necessary.

Response: With the current improvement of the model, length composition fits no longer pose problems; hence, modification of weights was not warranted. However, for exploratory analysis we considered three scenarios with different weights on critical likelihood components (Tables 2 and 8).

(c) The authors should also look at shell ages to see if there is some sort of accumulation effect of old shells.

Response: With the current improvement of the model this problem no longer exists.

(d) The CPT would like to see this model again for review in September to continue to move the model forward for May review.

Response: The revised version is ready for evaluation

June 2011 SSC comments:

Although the SSC did not receive a presentation of the model during its June meeting, the team's comments seem reasonable. Their comments included considerations of apparent data conflicts, dome-shaped selectivity, and the desire to simplify the model. The Crab Plan Team is scheduled to review the next version of the model at its September 2011 meeting. The SSC requests a presentation on the assessment model at its October meeting. **Given the**

importance Aleutian Islands golden king crab fishery, the development of an accepted stock assessment model is high priority.

Response: We cleaned up the data (especially the observer CPUE data) to resolve data conflicts as much as possible. We considered a scenario where the conflicting pot survey CPUE data set was given a zero weight. We no longer consider dome-shaped selectivity.

The revised model is ready for September CPT evaluation.

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 providing 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 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 pot discarded and groundfish discarded catch by length, observer CPUE data by length, triennial pot survey CPUE data by length and tagging data on growth increment. The length aggregated annual retained catch, pot fishery

discard, groundfish fishery discard, plus retained and discarded CPUE are listed in Tables 1 and 7 for the EAG and WAG, respectively. Information on length compositions are provided in various plots (Figures 5-8 for EAG and 27-29 for WAG).

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

e. Triennial pot survey (1997, 2000, 2003, and 2006) catch at length and CPUE are used in the model fit. The length aggregated pot survey CPUE are listed in Table 1. Information on length composition is provided in Figure 8.

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.

E. Analytic Approach

1. *History of modeling approaches for this stock*

The model is under development, 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 discard catch, groundfish fishery discard catch, observer retained and discard catch-per-unit-effort (CPUE), fishery retained and discard 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; 1985/86 to 2010/11

for standardized retained CPUE, 1990/91 to 2010/11 for standardized pot discard CPUE and pot bycatch biomass and 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; 1985/86 to 2010/11 for standardized retained CPUE, 1990/91 to 2010/11 for standardized pot discard CPUE and pot bycatch biomass and length composition; and 1995/96 to 2010/11 for groundfish fishery male bycatch biomass and size composition.

CPUE Standardization:

I. The four sets (1997, 2000, 2003, and 2006) of survey pot CPUE data came from a standard survey grid in a restricted area (between 52°15' and 53°00' N latitude and 170°00' and 171°30' W longitude), using a standard pot configuration, which may reflect the actual in situ population abundance in that area. The majority of the EAG commercial fishery takes place in this area. The survey CPUE was standardized to soak-time by considering only those pot hauls with soak-time in the range of 30-140 hours. Box plot provided a 95th percentile value of 140-hour soak-time. Very few fell above 140-hour soak-time.

II. We also standardized the observer retained and discard CPUE by soak time by considering only those pot hauls with soak-time below 456 hours for the 1985-2004 period (the 95th percentile) and below 936 hours for the period 2005-2010 (the 95th percentile). The soak-time dramatically increased after rationalization. Very few fell above the 95th percentile or below 48 hours for the two periods in both regions.

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, < 1997, 1998-2004 and >= 2005, because of gear modifications and management procedure changes (e.g., gear web size changes since 1999, rationalization (increased soak time) since 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 used those harvest rates for 1997, 2000, and 2003 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 the CPUE 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 three scenarios with varying weights to important components of negative log likelihood functions (pot survey CPUE, mean CPUE ratio, molt L_{50}, and β) and chose scenario 1 results as the preferred base scenario results (Tables 2 and 9).

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 three scenarios considered dropping some of the data components or 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 - 50 for the retained catch, pot discard, and survey pot catch, and 10 for the groundfish discard length compositions.
f. Do parameter estimates make sense: Number of parameter estimates appears to be reasonable for an *M* of 0.18.
g. Model selection criteria: We used a number of criteria to select the base model (scenario 1) from the other two scenarios (Table 2 and 9 for EAG and WAG, respectively): different components and partial sums of the negative log likelihood values (Tables 3 and 10 for EAG and WAG, respectively), retrospective fits, CPUE fits, and length composition fits. Tables and Figures are provided in the Results section for scenario 1.
h. Residual analysis: We illustrate residual fits by various Figures in the Results section. 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 - 50 for the retained catch, 50 for pot discard, 50 for survey pot catch, and 10 for the groundfish discard length compositions. These weights adequately fitted the length compositions and no further changes were warranted.

Weighting factors for CPUE; catch biomass; recruitment deviation; pot fishery F; groundfish fishery F; mean CPUE ratio; 1997, 2000, and 2003 exploited legal biomass (for EAG only); molt probability L_{50}; and growth function β are provided in Tables 2 and 9 for EAG and WAG, respectively.

2. Tables of estimates:
   a. We provide the parameter estimates for the base model (scenario 1) with one standard deviation in Tables 4 and 11 for EAG and WAG, respectively.
   b. We provide the mature male and legal male abundance time series in Tables 5 and 12 for EAG and WAG, respectively.
   c. We list the recruitment estimates in Tables 5 and 12 for EAG and WAG, respectively.
   d. We provide the time series of catch divided by mature male abundance in Tables 6 and 13 for EAG and WAG, respectively. The harvest rate in EAG appears to be lower than that of WAG in recent years 2002/03 onward) probably due to high abundance in this region.
3. Graphs of estimates:
   a. We provide the fishery total and retained selectivity in Figures 9 and 30 for EAG and WAG, respectively. We provide survey pot selectivity in Figure 10 for EAG, groundfish bycatch selectivity in Figures 11 and 31 for EAG and WAG, respectively. The survey pot and groundfish bycatch selectivity for EAG appear flat indicating all size groups were vulnerable to the gear. This is also shown in the size compositions of survey pot and groundfish bycatch for EAG (Figures 7 and 8). On the other hand, the groundfish bycatch size compositions in WAG showed a different pattern with an S shaped selectivity curve (Figure 31).

      We provide the molt probability curve for EAG in Figure 12 and that for WAG in Figure 32. Molt L_{50} values were 134.6 mm CL for EAG and 138.8 mm CL for WAG.

b. We provide the legal and mature male biomass time series in Figure 20 for EAG and in Figure 39 for WAG. Both legal (a) and mature male biomass (b) 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.

c. We show the full selection F over time for EAG in Figure 21 and for WAG in Figure 40. The F values were high during early years, late 1980s, and systematically declined in the recent years.

d. F vs. MMB: We did not provide this figure because the model has not yet been approved.

e. Stock-Recruitment relationship: None.

   We provide the temporal changes in total number of recruits to the modeled population in Figure 18 for EAG and in Figure 37 for WAG. We also provide the recruitment distribution to the model size group (101-185 mm CL) in Figures 19 and 38 for EAG and WAG, respectively.

4. Evaluation of the fit to the data:

   a. Fits to catches: We present graphs of observed vs. model fitted retained, pot discard, and groundfish discard catches (t) in Figures 22-24 for EAG and in Figures 41-43 for WAG. We also provide graphs of observed vs. model fitted retained and pot discard CPUE in Figure 4 for EAG and in Figure 26 for WAG. The fittings appear good.

   b. Survey data plot: We provide observed vs. predicted plot of EAG survey pot CPUE in Figure 4. The predicted line did not fit the observed points satisfactorily, which is expected because the major likelihood component pot fishery CPUE systematically increased since 1997 while the survey pot CPUE declined. The survey has been conducted in a restricted area perhaps did not fully represent the trend in commercially exploited abundance.

   c. Fit to catch size compositions: We provide retained, pot discard, and groundfish discard length compositions in Figures 5-7 for EAG and in Figures 27-29 for WAG. 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 13 and 33 for EAG and WAG, respectively), for pot discard(Figures 14 and 34 for EAG and WAG, respectively), for groundfish discard (Figures 15 and 35 for EAG and WAG, respectively), and for survey pot CPUE (Figure 16).

d. Fit to survey pot size composition: We provide survey pot length compositions in Figure 8 for EAG. The fittings 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 using the base model with terminal years 2006/07 to 2010/11 in Figure 17 for EAG and in Figure 36 for WAG. The model adequately fit the time series for most of the years (up to 2005/06) and diverges a bit from 2006/07 onward.
6. Uncertainty and sensitivity analysis:

a. We investigated the sensitivity of the model to varying weights on critical likelihood components by computing total OFL, mature male biomass levels every five years including the terminal year 2010/11. For EAG, we considered survey pot CPUE and mean CPUE ratio weights as important whereas for WAG we selected mean CPUE ratio and Molt L_{50} and growth function β weights as critical. One of the scenarios was to consider zero weights for survey pot CPUE and size composition, thus ignoring the influence of survey data. We provide the results in Table 7 for EAG and Table 14 for WAG. A number of scenarios for EAG resulted in a positive Hessian matrix. Nevertheless, those which provided optimized results had similar results for OFL and various levels of mature male biomass. For WAG,

the same conclusion can be made except for the case where the mean CPUE ratio weight was set to 100 and molt L_{50} and growth function β weights were set to 0.6. The OFL and 2010/11 mature male biomass dropped significantly for this case.

b. We provide the likelihood profile for total OFL in Figures 25 and 44 for EAG and WAG, respectively to describe the uncertainty of OFL estimates from current assessment. We rescaled the profile to probability. The distribution is symmetric around the mean OFL estimate and satisfactory.

c. The CV of 2012/13 OFL for EAG is 0.11 and for WAG is 0.22. The CV of mature male biomass for EAG is 0.13 and for WAG is 021.

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, 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 present (2011 Feb 15). This resulted in a MMB_{ref} of 10,583t for EAG and 4,868t for WAG. The current MMB_{2011} was 17,750 t for EAG and 8,033t for WAG, resulting in an F_{OFL} of 0.18 for both regions. The total OFL for EAG was 2,144t and that for WAG was 1,118t. The γ value was set to 1 and an *M* value of 0.18 was used for *OFL* calculation.

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 was 2,045t and that for WAG was 1,073t.
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 upcoming 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 25 and 44 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 estimate for EAG is 2,138t and that for WAG is 1,013t.

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 came from the same exploited stock through growth and mortality. However, there is a possibility that additional recruitment can occur as a result of immigration from neighboring areas and possibly separate sub-stocks; however, the current analysis did not consider this possibility. Extensive tagging experiments are needed to investigate stock distributions.

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.

J. Acknowledgments

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K. Literature Cited

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Table 1. Time series of annual retained catch (number of crabs), discarded catch (handling mortality of 20%), groundfish fishery discarded catch (handling mortality of 50% for pot and 80% for trawl gear, only male portion), observer retained catch-per-unit-effort (CPUE, number of crabs per pot lift), observer discard CPUE, and pot survey CPUE for the EAG golden king crab stock. The data are for the size range 101-185 mm CL. The CPUE are standardized for soak-time. NO = no sampling information. 1985 = 1985/86 fishery.

Year	Retained Catch	Pot Discarded Catch	Groundfish Discarded Catch	Observer Retained CPUE	Observer Discard CPUE	Pot Survey CPUE
1985	1,400,577			9.426		
1986	1,307,032			6.655		
1987	1,029,424			5.554		
1988	1,169,427			5.944		
1989	1,317,833			6.709		
1990	950,008	431,401		6.067	20.101	
1991	1,093,983	290,149		5.319	10.873	
1992	1,118,955	579,201		6.611	21.648	
1993	832,194	148,959		6.154	NO	
1994	1,128,013	266,806		4.657	NO	
1995	1,046,780	247,739	339	5.247	6.968	
1996	731,909	169,407	133	5.560	7.465	
1997	780,610	204,849	25	7.038	9.626	21.2386
1998	740,011	237,249	364	8.803	14.227	
1999	709,332	159,992	648	8.995	10.110	
2000	704,702	191,168	349	9.823	13.359	17.3572
2001	730,030	126,300	132	10.957	10.082	
2002	643,886	100,405	7.620	11.833	9.647	
2003	643,074	92,175	4,277	10.920	7.827	8.0404
2004	637,536	71,086	100	17.404	10.200	
2005	623,971	40,794	114	26.165	8.302	
2006	650,587	42,198	3,063	23.979	8.055	8.6643
2007	633,253	44,507	19,942	30.167	9.824	
2009	679,886	54,180	1,079	25.477	10.301	
2010	670,983	53,702	12,735	24.594	10.387	

Table 2. Optimization scenarios and weighting factors for the eastern Aleutian Islands golden king crab stock (EAG). The molt L_{50} was set to 139.0 mm CL and the growth function β parameter was set to 0.578 in the penalty functions. Both values were independently estimated from tagging data. The mean CPUE ratio for the periods 2005-2010 and 1998-2004, based on observed data, was set to 2.39 in the penalty function. Legal biomasses estimated from observed total pot fishery catches divided by tagging estimates of harvest rate for the fishing years 1997/98, 2000/01, and 2003/04 were used in the legal male biomass penalty functions.

Scenario	CPUE			Recruit	Catch Biomass			Mean CPUE Ratio	Pot Fishery F	Ground-fish Discard F	Legal Male Biomass 1997	Legal Male Biomass 2000	Legal Male Biomass 2003	L_{50}	β
	Retained	Pot Discard	Pot Survey		Retained	Pot Discard	Groundfish Discard								
1	1	1	1	2	600	100	10	200	0.0001	2.0	200	200	200	0.25	0.25
2	1	1	1	2	600	100	10	100	0.0001	2.0	200	200	200	0.25	0.25
3	1	1	0	2	600	100	10	200	0.0001	2.0	200	200	200	0.25	0.25

Table 3. Negative log likelihood component values for the three scenarios for the golden king crab stock in EAG.

Negative Log Likelihood Component	Scenario 1	Scenario 2	Scenario 3
like_retlencomp	-1,224.2700	-1,224.0900	-1,224.4000
like_discdlencomp	-1,008.3900	-1,008.6400	-1,008.1900
like_gdiscdlencomp	-407.8620	-407.9920	-407.8990
like_survcpuelen	-165.6430	-165.7530	-165.6350
like_retcpue	-10.9440	-10.9046	-10.7307
like_discdcpue	-10.2437	-10.0459	-10.0531
like_survcpue	3.3740	3.4093	0
like_retdcatchB	4.0378	4.0480	4.0172
like_discdcatchB	28.4571	28.5208	28.3581
like_gdiscdcatchB	12.8908	12.8404	12.8270
like_rec_dev	8.2247	8.2658	8.3565
like_F	0.0005	0.0005	0.0005
like_gF	63.8404	63.5887	63.5270
like_qq	0.1870	0.1898	0.1943
like_Legal97	3.2294	3.2809	3.2495
like_Legal00	4.1006	3.9689	3.9920
like_Legal03	1.8228	1.6967	1.6962
like_molt50	4.8642	4.7741	4.8977
like_beta	2.1691	2.1351	2.1938
like_meancpue	0.3578	0.5865	0.3953
Sum of catch biomasses negative log likelihood	45.3900	45.4100	45.2000
Sum of length compositions negative log likelihood	-2,806.1700	-2,806.4800	-2,806.1200
Total negative log likelihood	-2,689.8000	-2,690.1200	-2,693.2000

Table 4. Estimates of parameters and 2011 MMB with standard deviations, by the base model (scenario 1) for the golden king crab data from the EAG, 1985/86-2010/11. (altogether 124 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	0.1072	0.0095	log_betar	0.3321	0.3644
log_b	4.9022	0.0072	Log_q	-13.7490	0.2870
log_beta	1.2595	0.2957	logq1	-13.1820	0.0674
c	0.0010	0.0000	logq2	-12.8680	0.0533
log_d	3.5001	0.0812	logq3	-12.0400	0.0682
c1	0.0763	0.1003	log_newsh1	2.3291	0.1387
log_d1	4.2001	1.0038	log_mean_rec	1.0559	0.1150
c2	0.0760	0.0173	log_mean_Fpot	-1.4844	0.0388
log_d2	4.7445	0.0233	log_mean_Fground	-9.1149	0.0808
c3	0.1157	0.0159	mean_qq	3.1973	0.1657
log_d3	4.9100	0.0195	ret_var	0.0230	0.0080
aa1	1.1158	0.3348	discd_var	0.0142	0.0068
log_bb1	4.8993	0.0028	surv_var	0.3132	0.2266
aa2	1.2038	0.2165	2011 MMB	17,750.0000	2,294.2000
log_bb2	4.9040	0.0028			
aa3	2.9999	0.1237			
log_bb3	4.9153	0.0070			
aa4	0.0100	0.0000			
log_bb4	3.9800	0.0008			

Table 5. Annual abundance estimates of recruits to the model (millions of crabs), available legal male biomass (t), and available mature male biomass (t) 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 = 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	11,660	1266.7000	15,043	1166.2000
1986	2.51	8,871	807.9000	10,986	1057.3000
1987	2.22	8,273	657.5400	8,389	741.9700
1988	3.29	7,092	595.0100	7,625	561.1000
1989	4.70	6,575	582.2000	6,519	484.9900
1990	3.15	7,665	595.2000	6,015	451.0000
1991	2.14	8,059	570.5500	6,924	456.2800
1992	4.11	7,940	525.9100	7,284	441.9900
1993	0.78	8,340	476.9800	7,310	407.1300
1994	2.76	7,536	424.2600	7,597	368.8900
1995	1.96	7,001	361.6400	6,980	325.9500
1996	1.92	6,908	328.3000	6,472	276.0100
1997	3.13	6,916	349.3000	6,388	250.1500
1998	4.76	7,773	426.5400	6,437	274.2700
1999	2.27	9,244	514.7900	7,224	324.1500
2000	5.34	10,604	610.2300	8,421	380.0700
2001	1.78	12,035	689.7600	9,828	466.7800
2002	3.39	12,810	763.9800	11,044	546.9200
2003	2.71	13,368	860.7500	11,927	636.4100
2004	2.19	13,661	952.4500	12,503	748.2800
2005	3.64	13,754	1,020.5000	12,792	847.5800
2006	3.33	14,232	1,151.2000	12,959	929.5000
2007	3.57	14,901	1,337.0000	13,352	1,057.5000
2008	3.64	15,604	1,579.6000	13,944	1,242.6000
2009	5.02	16,579	1,915.7000	14,595	1,479.9000
2010	2.96	17,750	2,294.2000	15,541	1,816.8000
2011	2.87			16,532	2,164.2000

Table 6. Time series of catch divided by mature male abundance for EAG. We provide only the 1995/96 to 2010/11 time series because total removals from all sources (pot fishery and groundfish fishery) are available/reliable from 1995/96 to 2010/11.

Year	Total Removal/Mature Male Abundance
1995/96	0.31
1996/97	0.23
1997/98	0.24
1998/99	0.22
1999/00	0.16
2000/01	0.15
2001/02	0.13
2002/03	0.11
2003/04	0.10
2004/05	0.10
2005/06	0.10
2006/07	0.10
2007/08	0.09
2008/09	0.09
2009/10	0.09
2010/11	0.08

Table 7. Influence of different weights on the important likelihood components, pot survey CPUE and mean CPUE ratio for the periods 1998-2004 and 2005-2010 for the golden king crab stock in EAG.

Scenario	Weights			Total OFL (t)	MMB90(t)	MMB95(t)	MMB00(t)	MMB05(t)	MMB10(t)	Max. Gradient	Objective Function
	Pot Survey CPUE	Mean CPUE Ratio	Molt L_{50} and Growth Function β								
	0	0	0.25							$6.3e^{+1}$(Hessian +)	-2,698
	0	100	0.25							$8.5e^{+1}$(Hessian +)	-2,694
3	0	200	0.25	2,170	7,686	7,002	10,638	13,913	18,101	$6.1e^{-7}$	-2,693
	1	0	0.25	2,937	7,550	6,994	11,428	16,542	22,632	$-1.6e^{-5}$	-2,696
2	1	100	0.25	2,207	7,642	6,988	10,640	13,929	18,054	$-1.3e^{-6}$	-2,690
1	1	200	0.25	2,144	7,665	7,001	10,604	13,754	17,750	$5e^{-7}$	-2,690
	10	0	0.25	2,281	7,346	6,887	10,296	13,175	16,192	$-5e^{-5}$	-2,668
	10	100	0.25							$1.4e^{+2}$(Hessian +)	-2,668
	10	200	0.25							$3.9e^{+1}$(Hessian +)	-2,665
	0, 0 (CPUE and length composition)	200	0.25	2,271	7,354	6,874	10,184	13,168	18,075	$-3.4e^{-4}$	-2,506

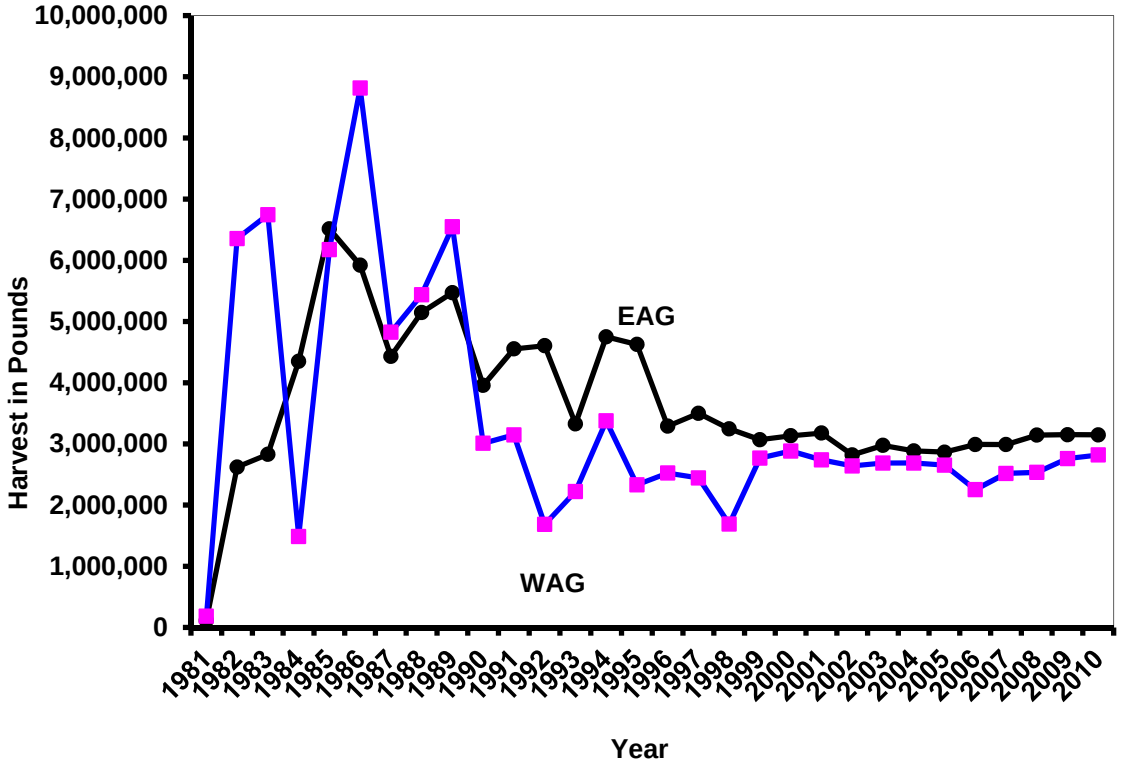

Figure 1. Historical commercial harvest (in pounds) of golden king crab east of 174°W longitude (EAG, Eastern Segment) and west of 174°W longitude (WAG, Western Segment), 1981-2010 (note: 1981 = 1981/82 fishery).

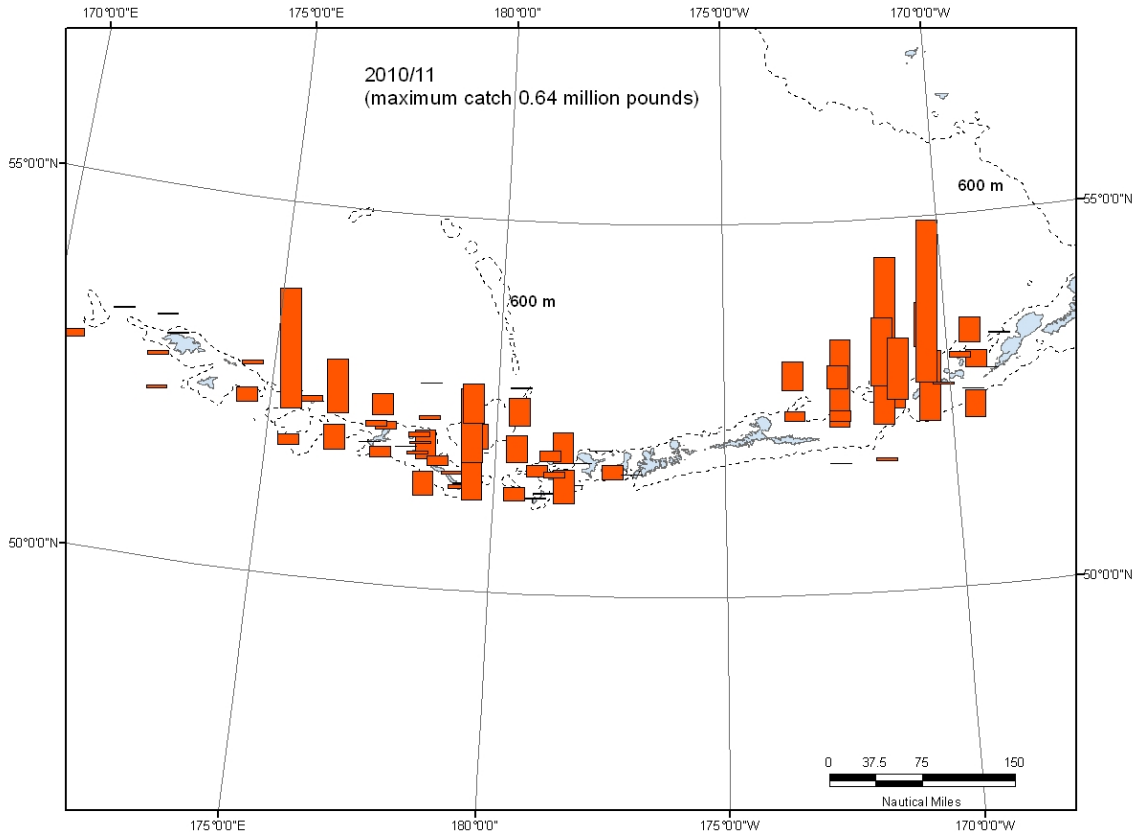

Figure 2. Aleutian Islands golden king crab harvest by ADF&G statistical areas for 2010/11.

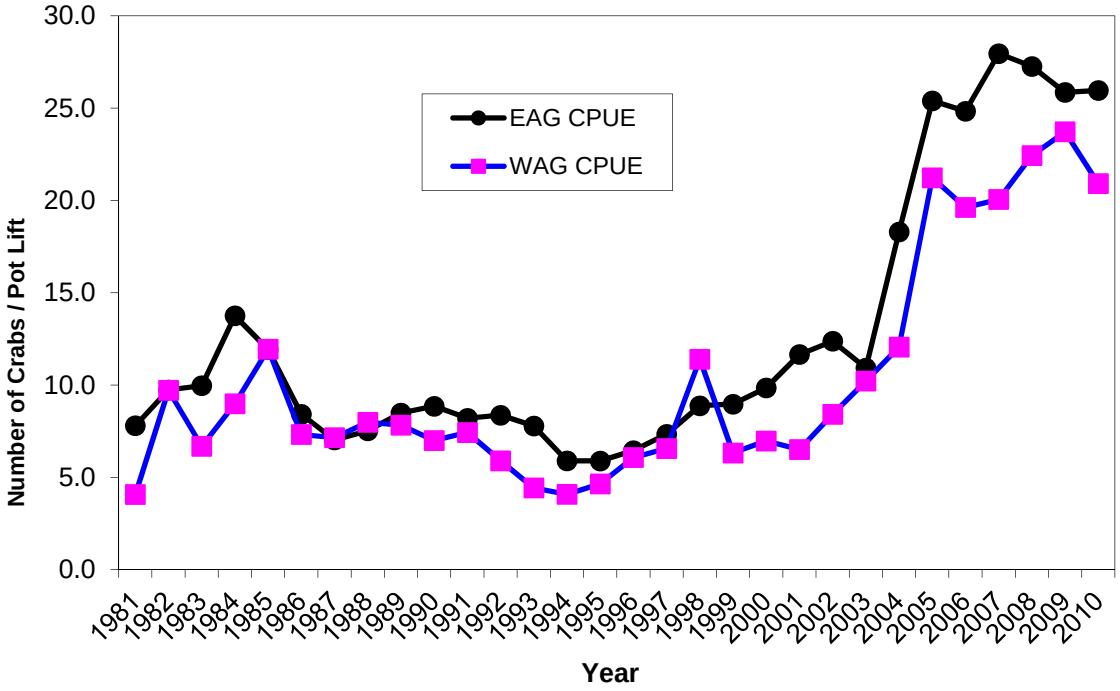

Figure 3. Historical catch-per-unit-effort CPUE (number of crabs per pot lift) in the commercial fishery for golden king crab in the EAG and the WAG, 1981-2010 (note: 1981 = 1981/82 fishery).

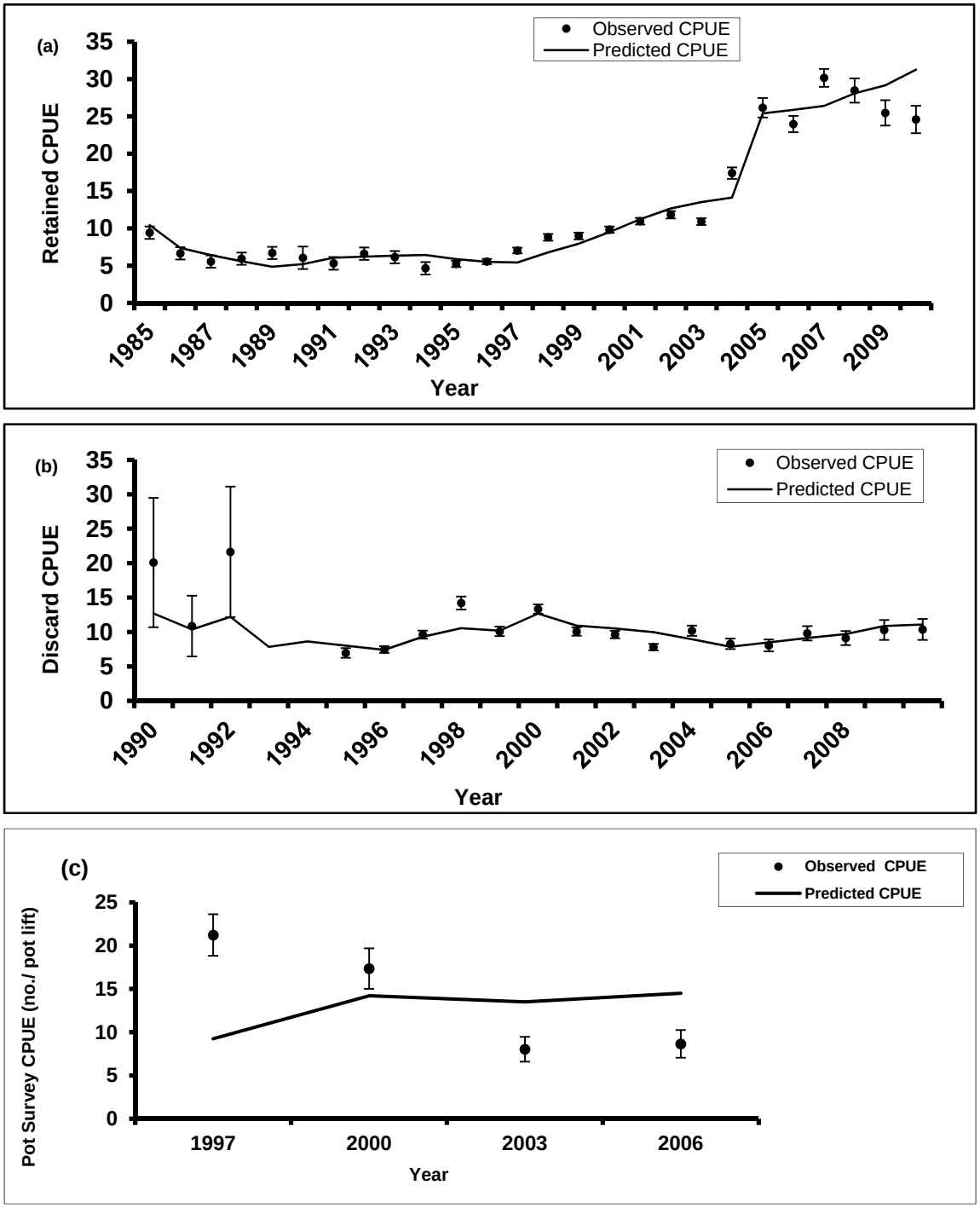

Figure 4. Predicted (line) versus observed (filled circle) (a) retained catch-per-unit-effort (CPUE), (b) discard CPUE, and (c) pot survey CPUE for golden king crab in the EAG. Two Std.Dev. confidence bars are attached to observed points. The fishery CPUE values are 1985-2010 for retained and 1990-2010 for discard (note: 1990 = 1990/91 fishery). The pot survey CPUE values are for 1997, 2000, 2003, and 2006.

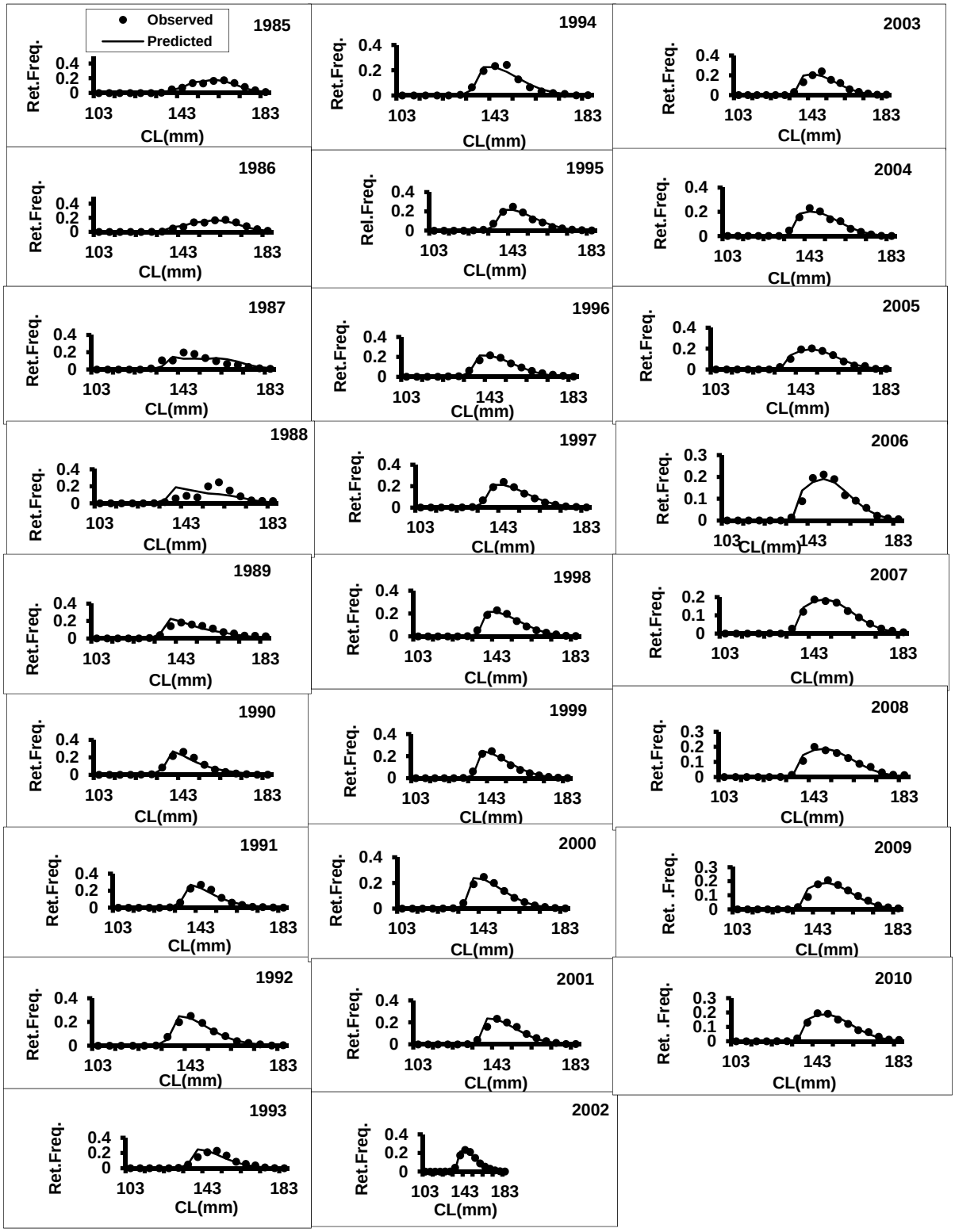

Figure 5. Predicted (line) vs. observed (filled circle) retained catch relative length frequency distributions of golden king crab in the EAG, 1985 to 2010 (note: 1985 = 1985/86 fishery).

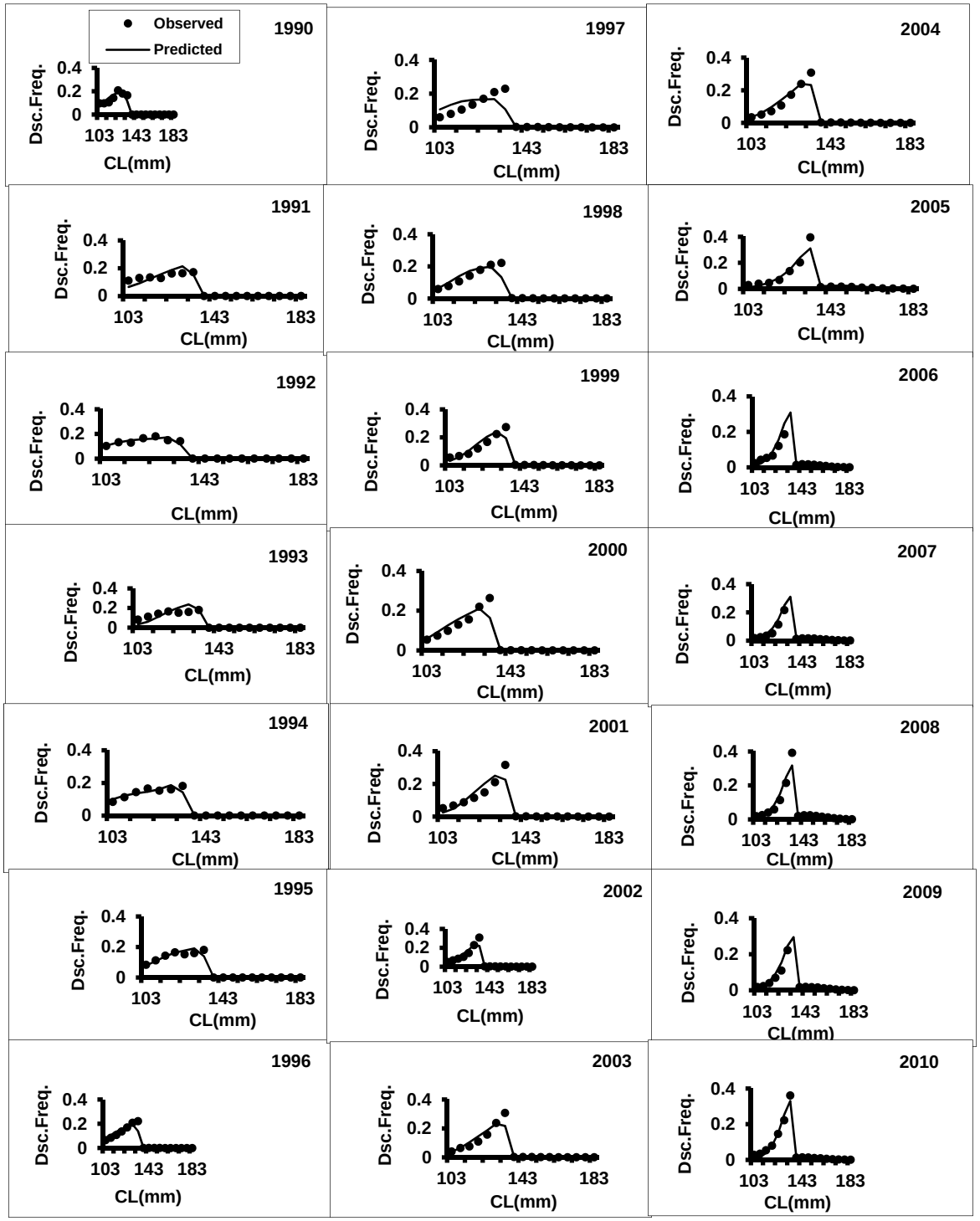

Figure 6. Predicted (line) vs. observed (filled circle) pot discarded catch relative length frequency distributions of golden king crab in the EAG, 1990 to 2010 (note: 1990 = 1990/91 fishery).

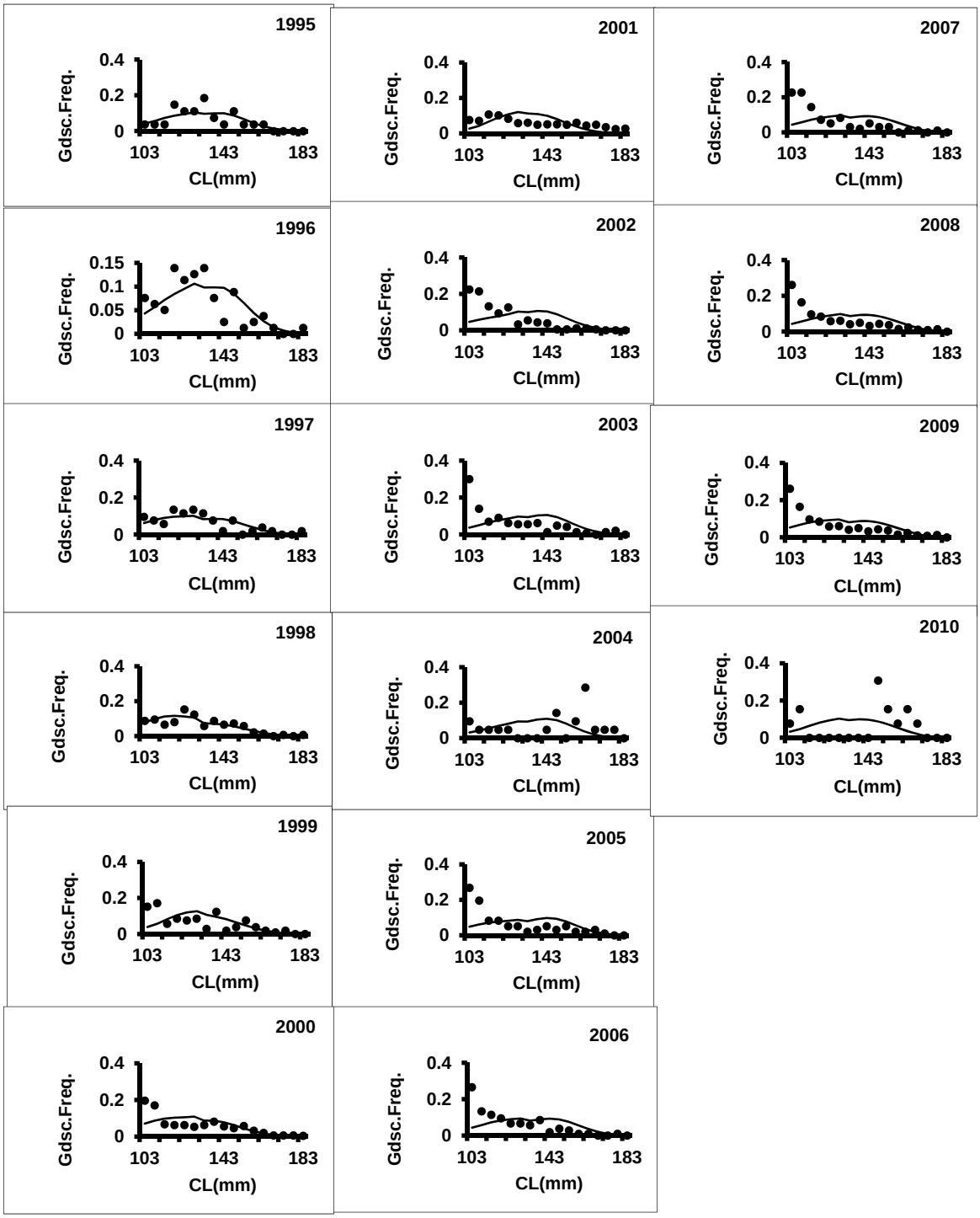

Figure 7. Predicted (line) vs. observed (filled circle) groundfish discarded catch relative length frequency distributions of golden king crab in the EAG, 1995 to 2010 (note: 1995 = 1995/96fishery).

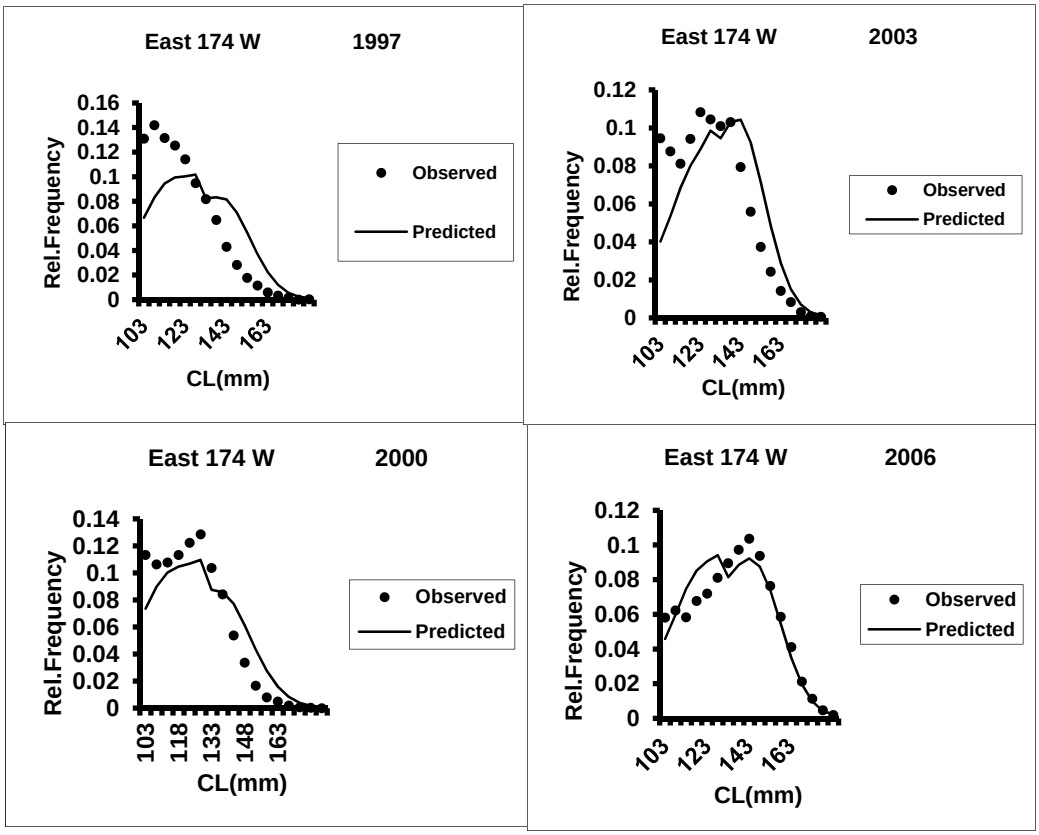

Figure 8. Predicted (line) vs. observed (filled circle) CPUE relative length frequency distributions of golden king crab in the triennial pot surveys in a restricted area in the EAG, 1997 to 2006.

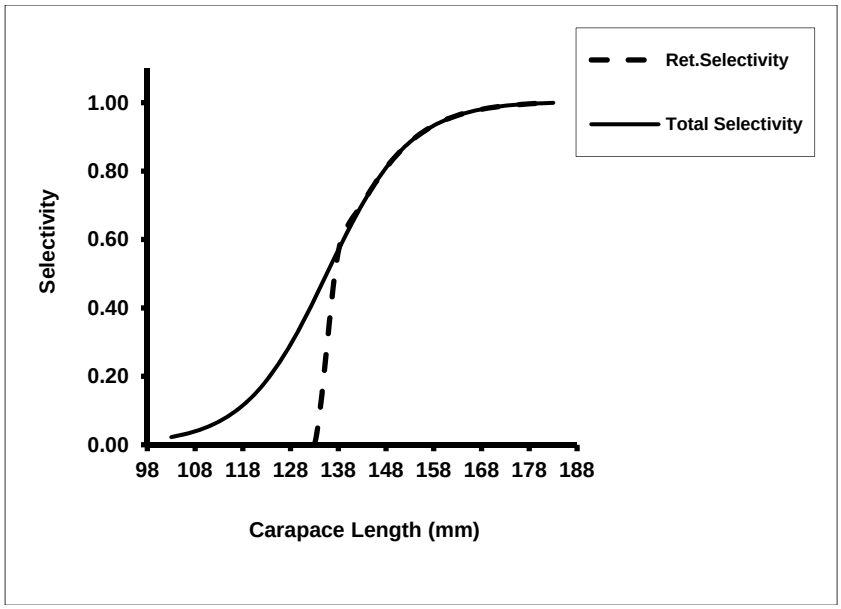

Figure 9. Estimated total selectivity (solid line) and effective retained catch selectivity (total selectivity*retained selectivity, dashed line) during 2005- for EAG golden king crab fishery.

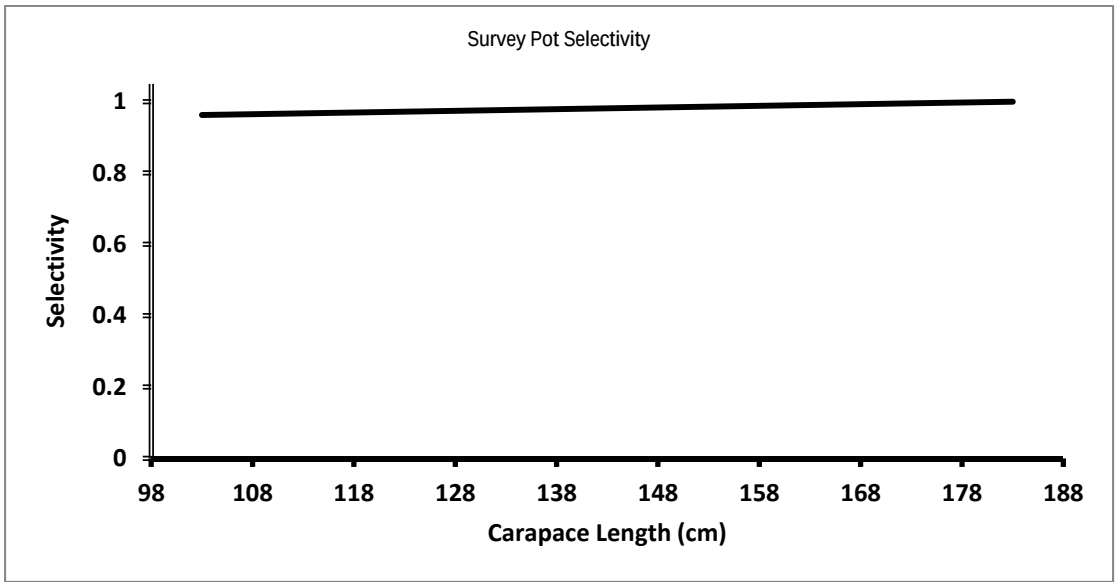

Figure 10. Estimated survey pot selectivity for EAG golden king crab fishery.

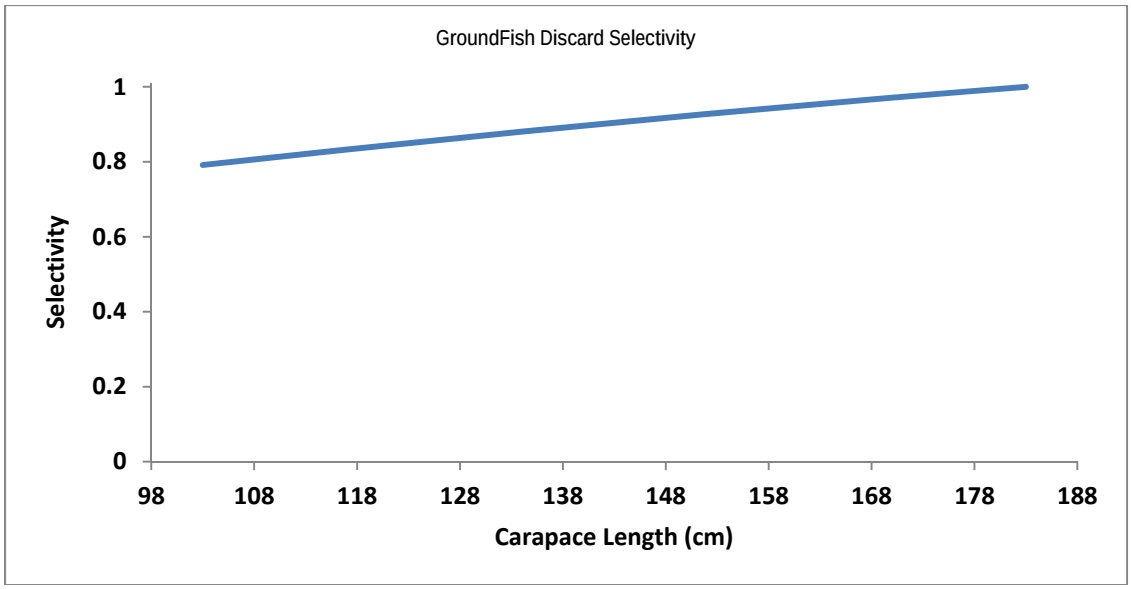

Figure 11. Estimated groundfish bycatch selectivity for EAG golden king crab fishery.

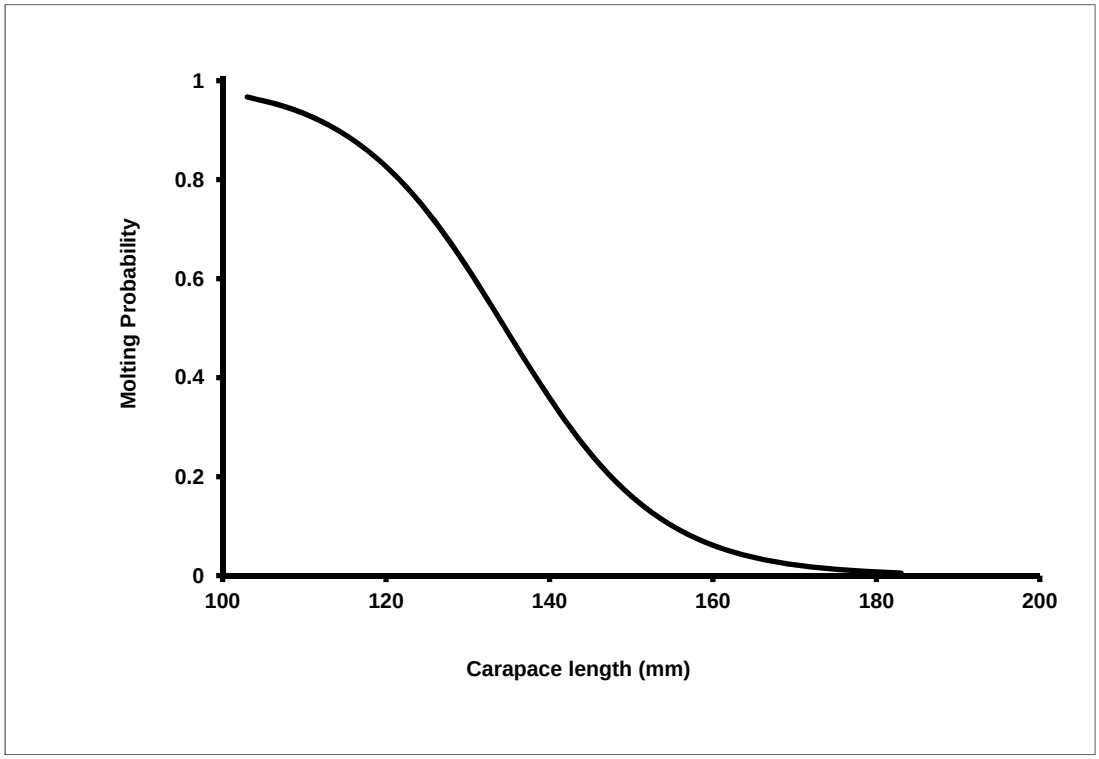

Figure 12. Estimated molt probability of EAG golden king crab.

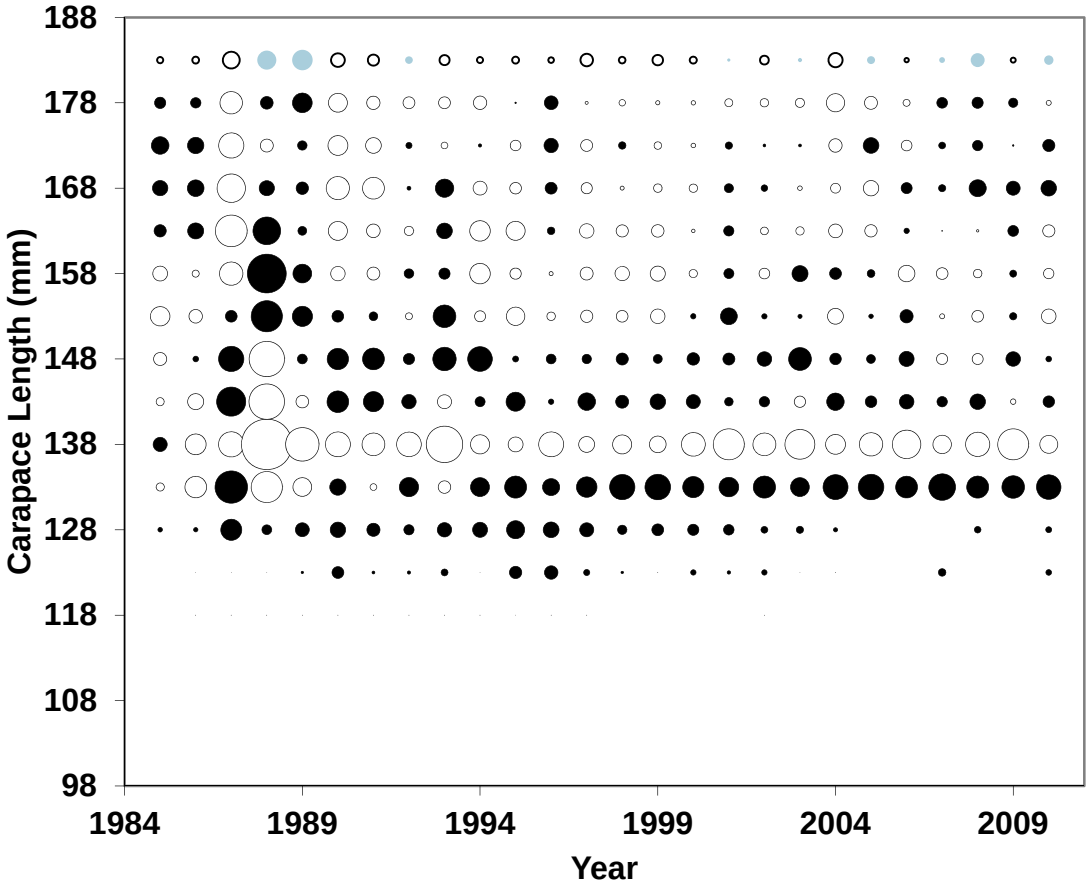

Figure 13. Bubble plot of standardized residuals of retained length composition for EAG golden king crab, 1985-2010 (note: 1985 = 1985/86 fishery).

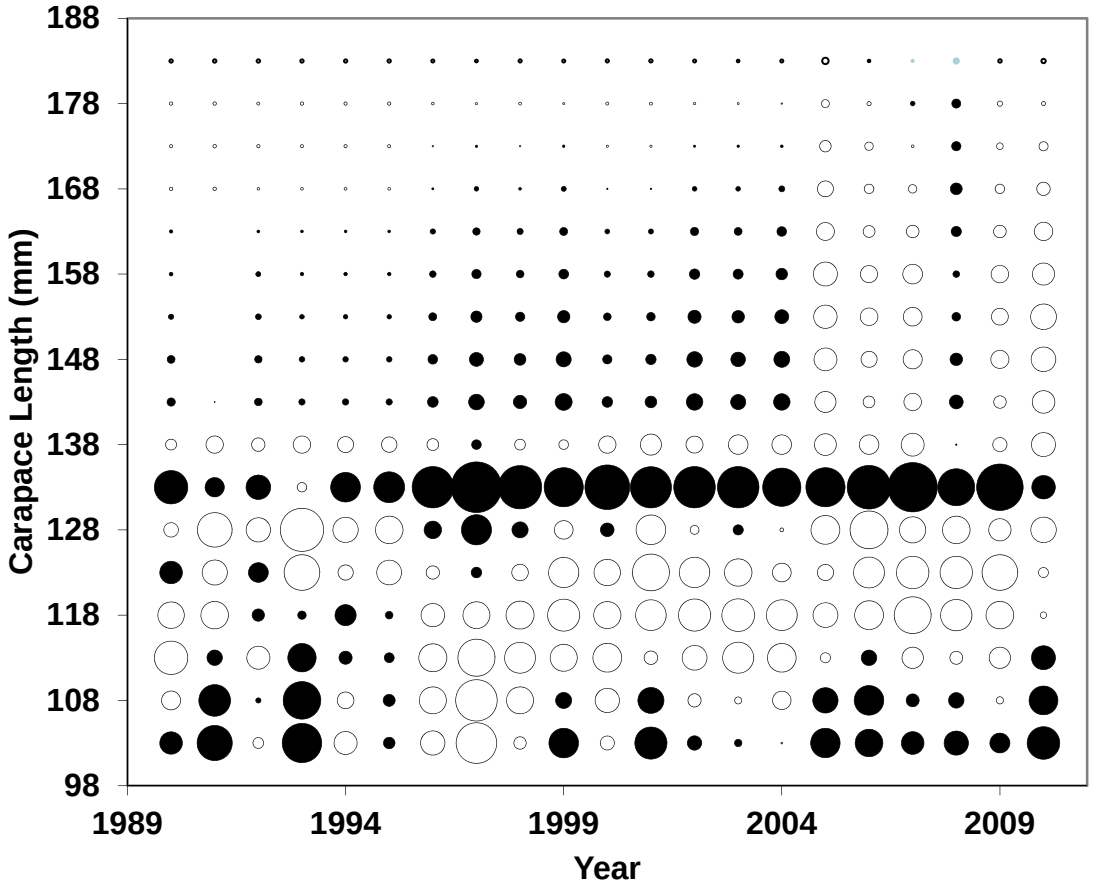

Figure 14. Bubble plot of standardized residuals of pot discarded length composition for EAG golden king crab, 1985-2010 (note: 1985 = 1985/86 fishery).

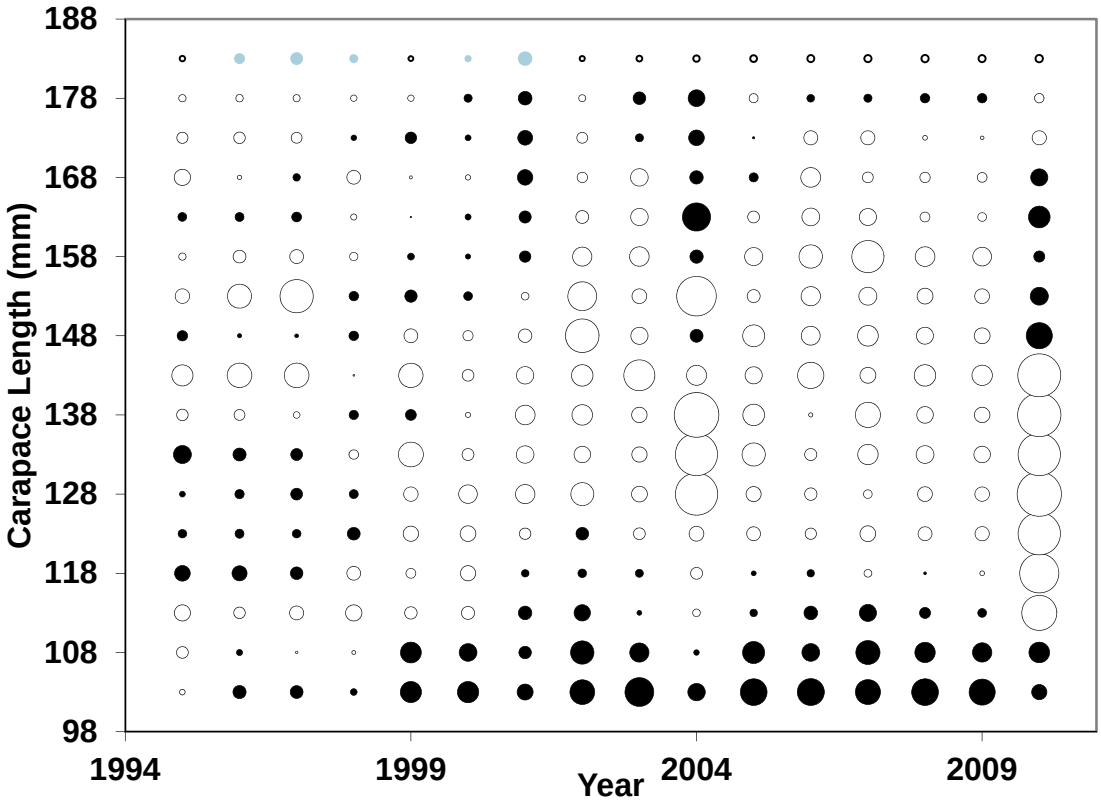

Figure 15. Bubble plot of standardized residuals of groundfish discarded length composition for EAG golden king crab, 1985-2010 (note: 1985 = 1985/86 fishery).

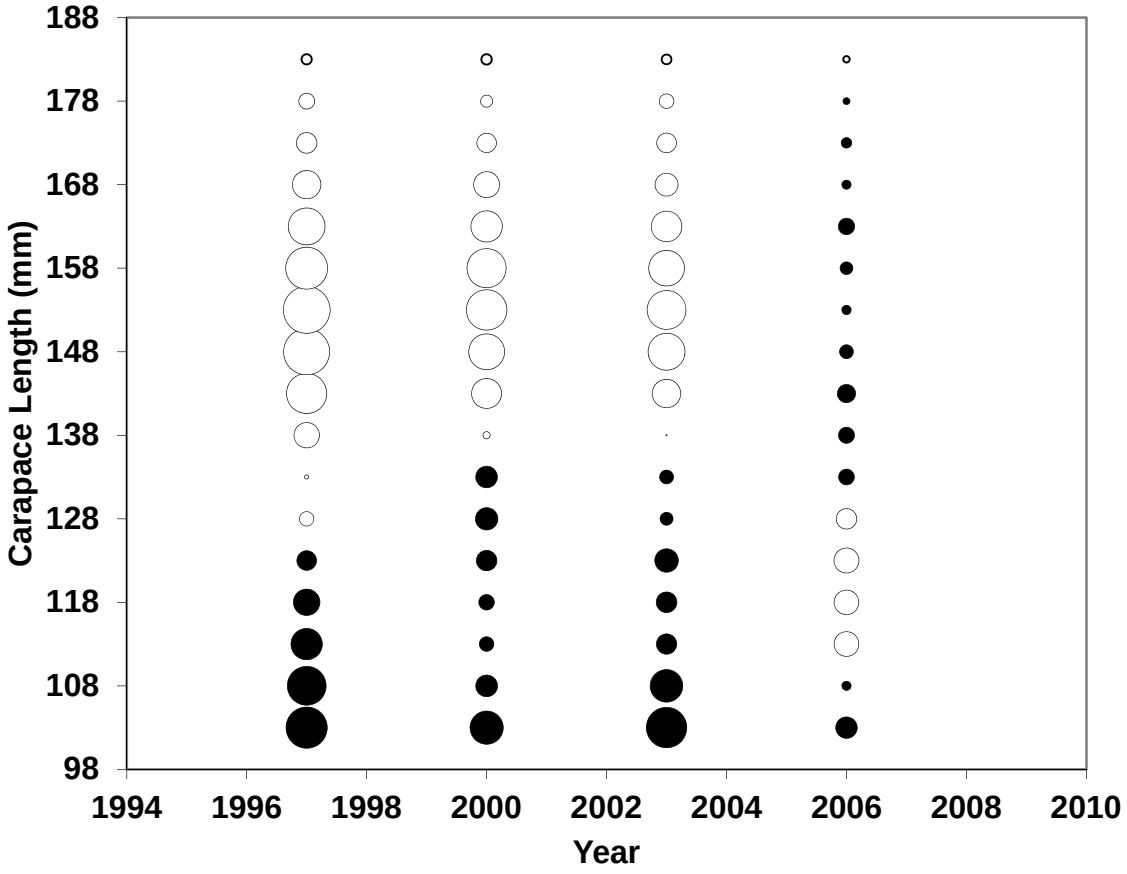

Figure 16. Bubble plot of standardized residuals of survey pot CPUE length composition for EAG golden king crab, 1985-2010 (note: 1985 = 1985/86 fishery).

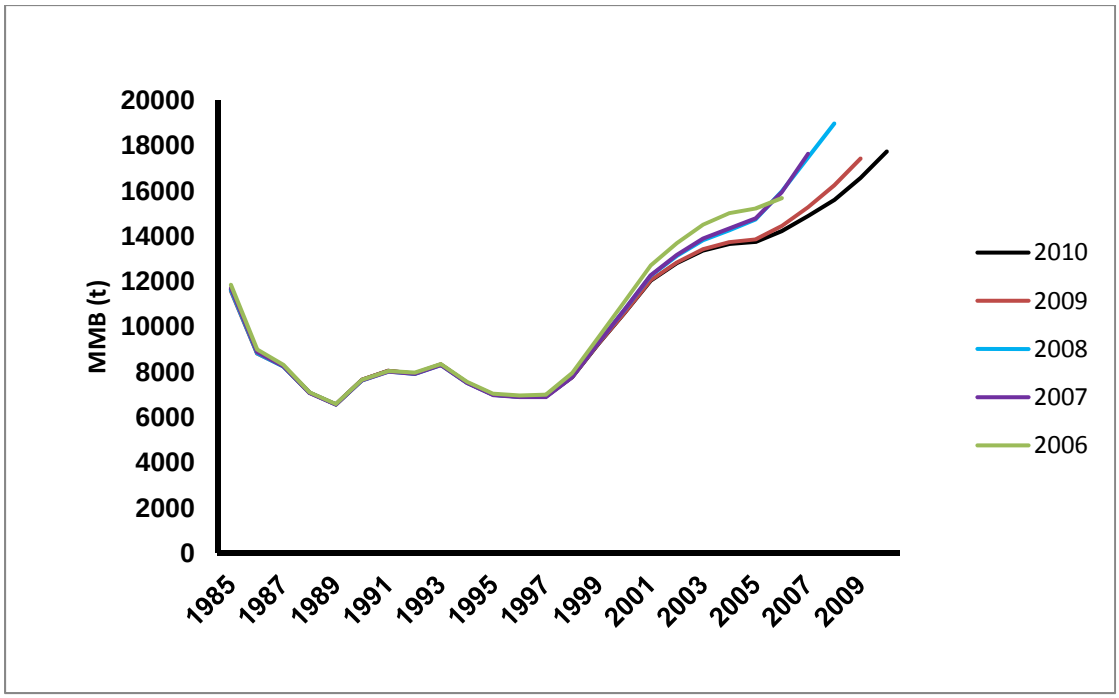

Figure 17. Retrospective fits of mature male biomass with terminal years 2006 to 2010 using the 2011 model for EAG.

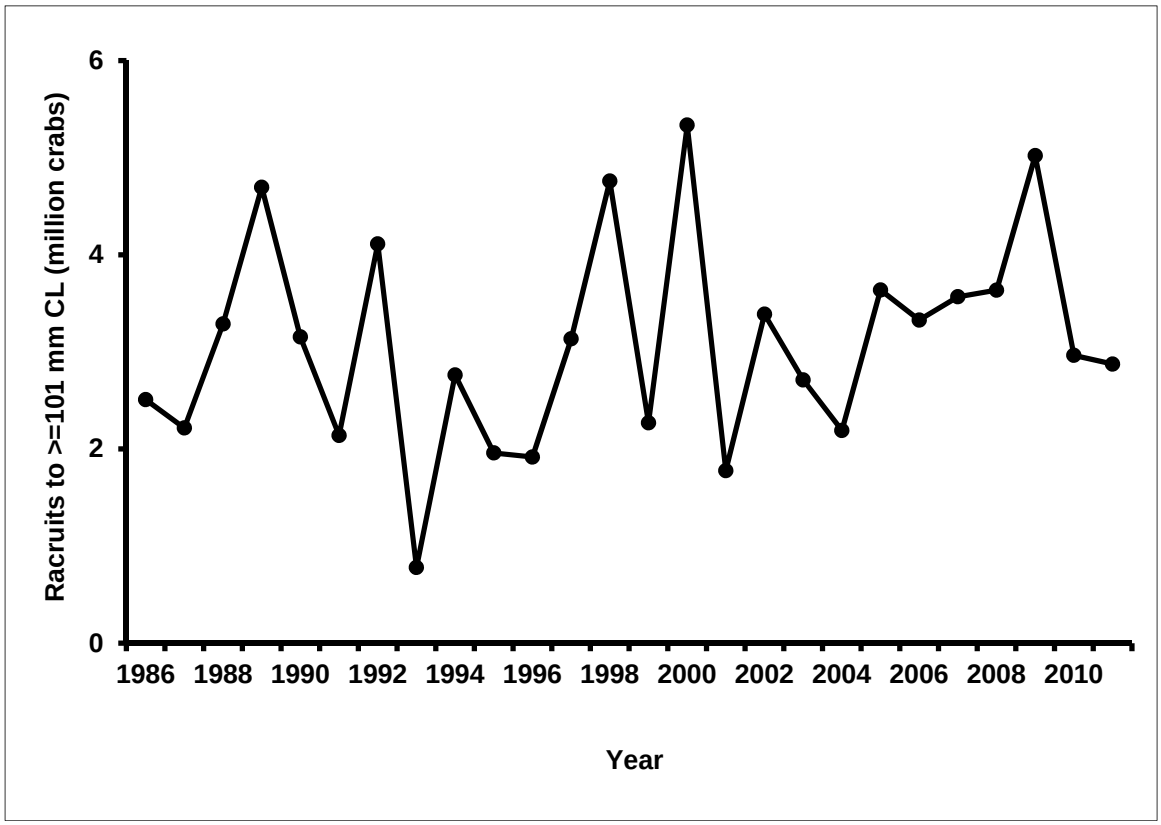

Figure 18. Estimated number of male recruits (millions of crabs ≥ 101 mm CL) to the golden king crab assessment model in EAG, 1986-2011.

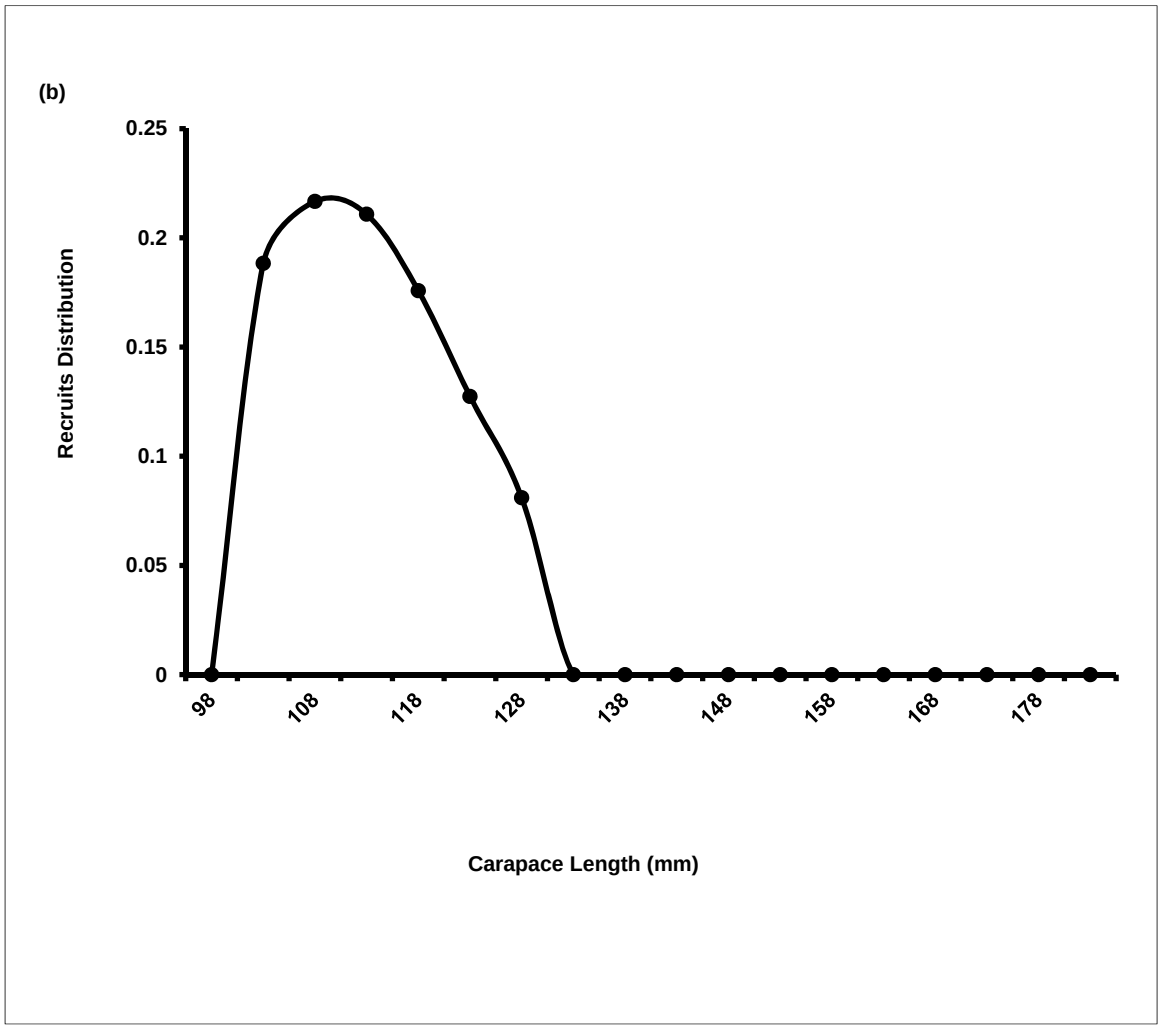

Figure 19. Recruit distribution to the golden king crab assessment model size group in EAG.

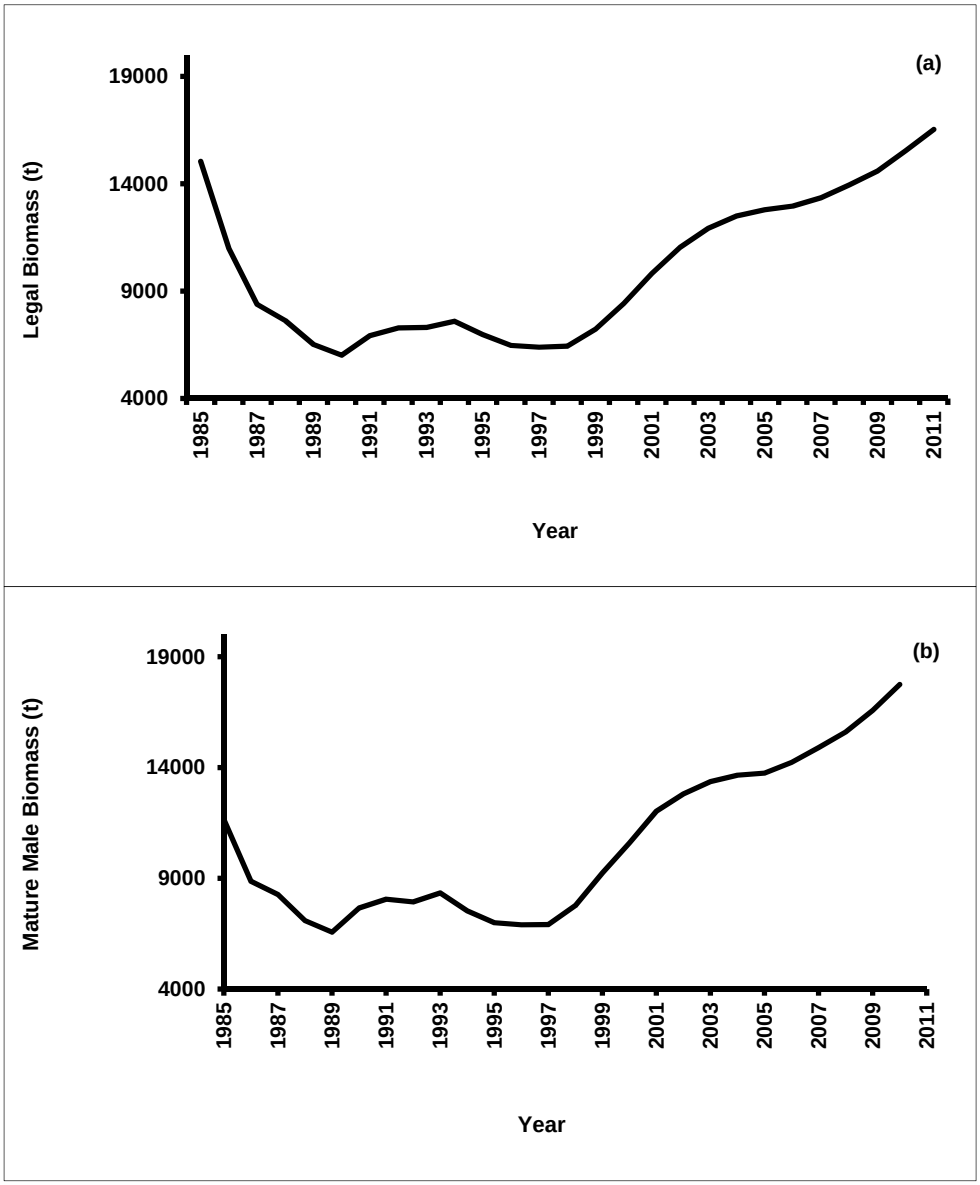

Figure 20. Trends in golden king crab (a) legal male biomass (t) and (b) mature male biomass in the EAG, 1985-2010/11. Legal male crabs are ≥ 136 mm CL and mature male crabs are ≥ 121 mm CL.

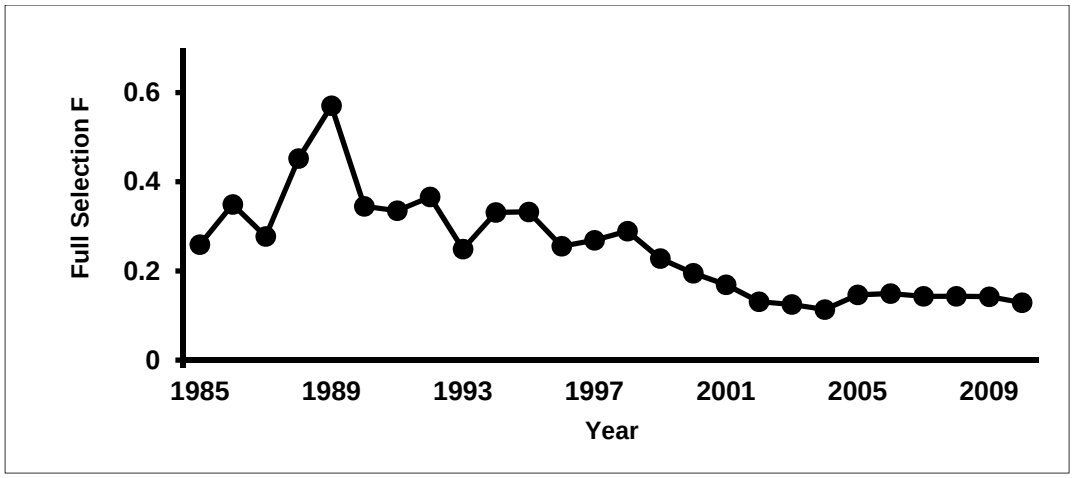

Figure 21. Trend in full selection fishing mortality of golden king crab in the EAG, 1985-2010 (note: 1985 = 1985/86 fishery).

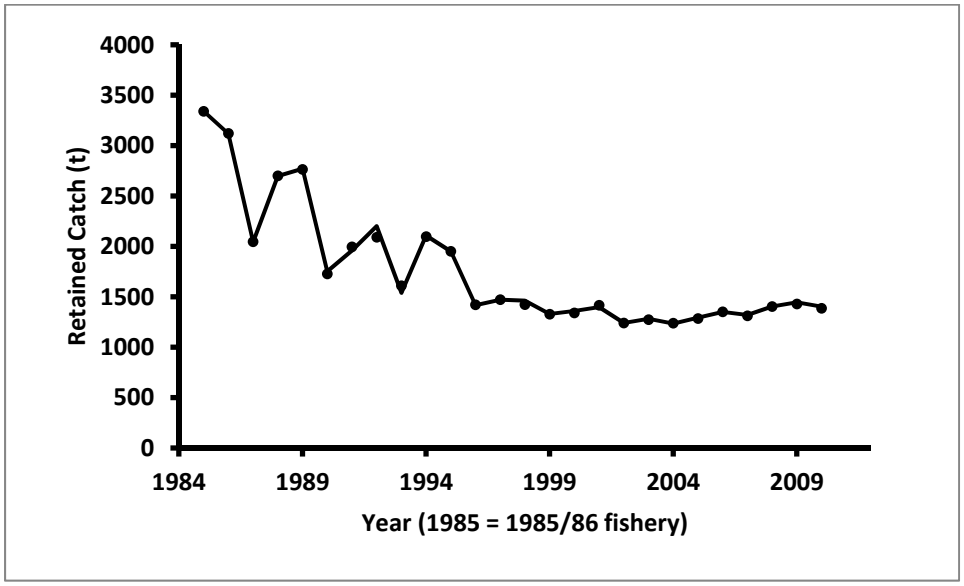

Figure 22. Observed (filled circle) vs. predicted retained catch of golden king crab in the EAG, 1985-2010 (note: 1985 = 1985/86 fishery).

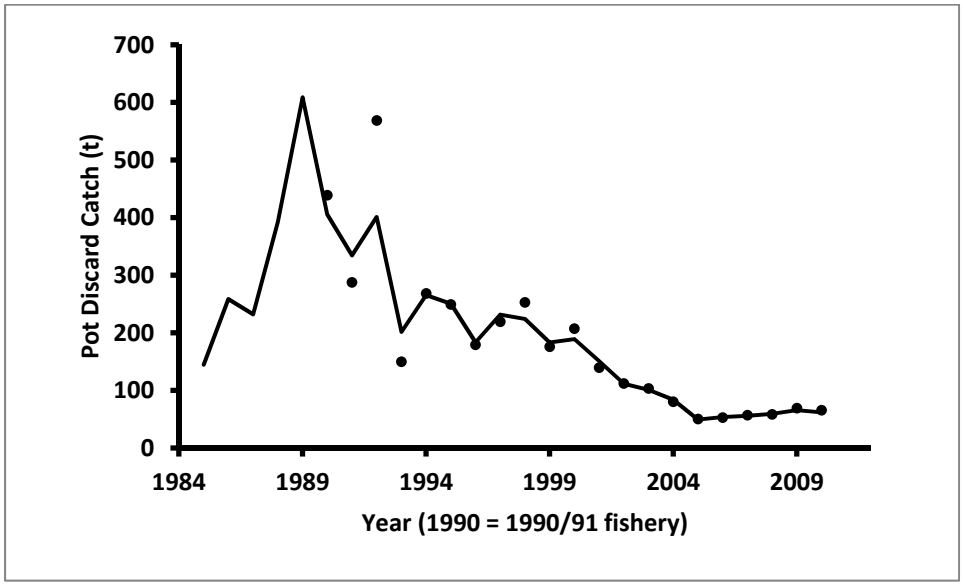

Figure 23. Observed (filled circle) vs. predicted pot discarded dead catch of golden king crab in the EAG, 1985-2010 (note: 1985 = 1985/86 fishery). A handling mortality of 20% was applied.

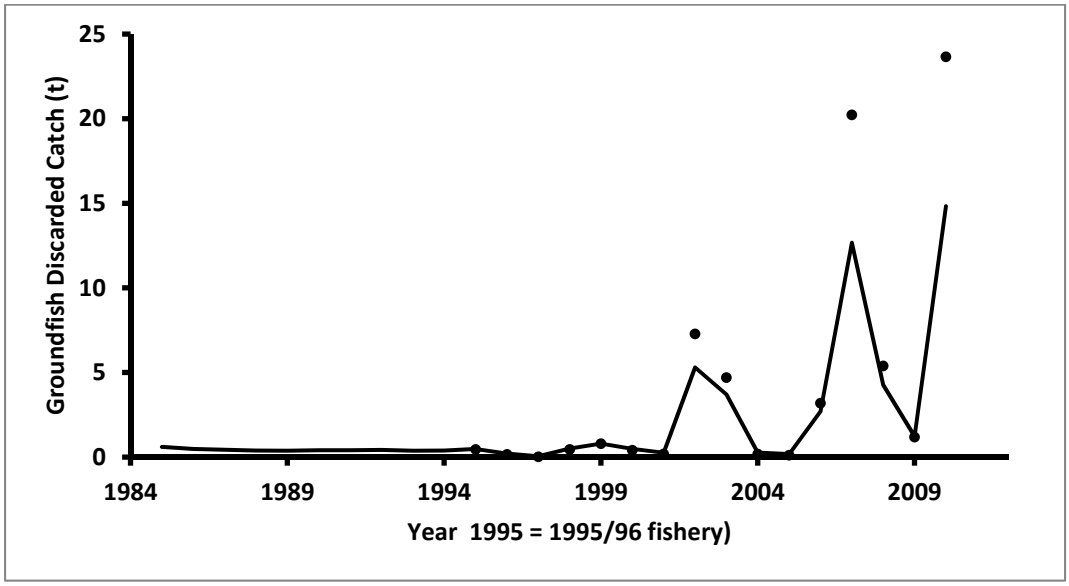

Figure 24. Observed (filled circle) vs. predicted groundfish discarded dead catch of golden king crab in the EAG, 1985-2010 (note: 1985 = 1985/86 fishery). An average handling mortality of 65% (average of 80% and 50%) was applied.

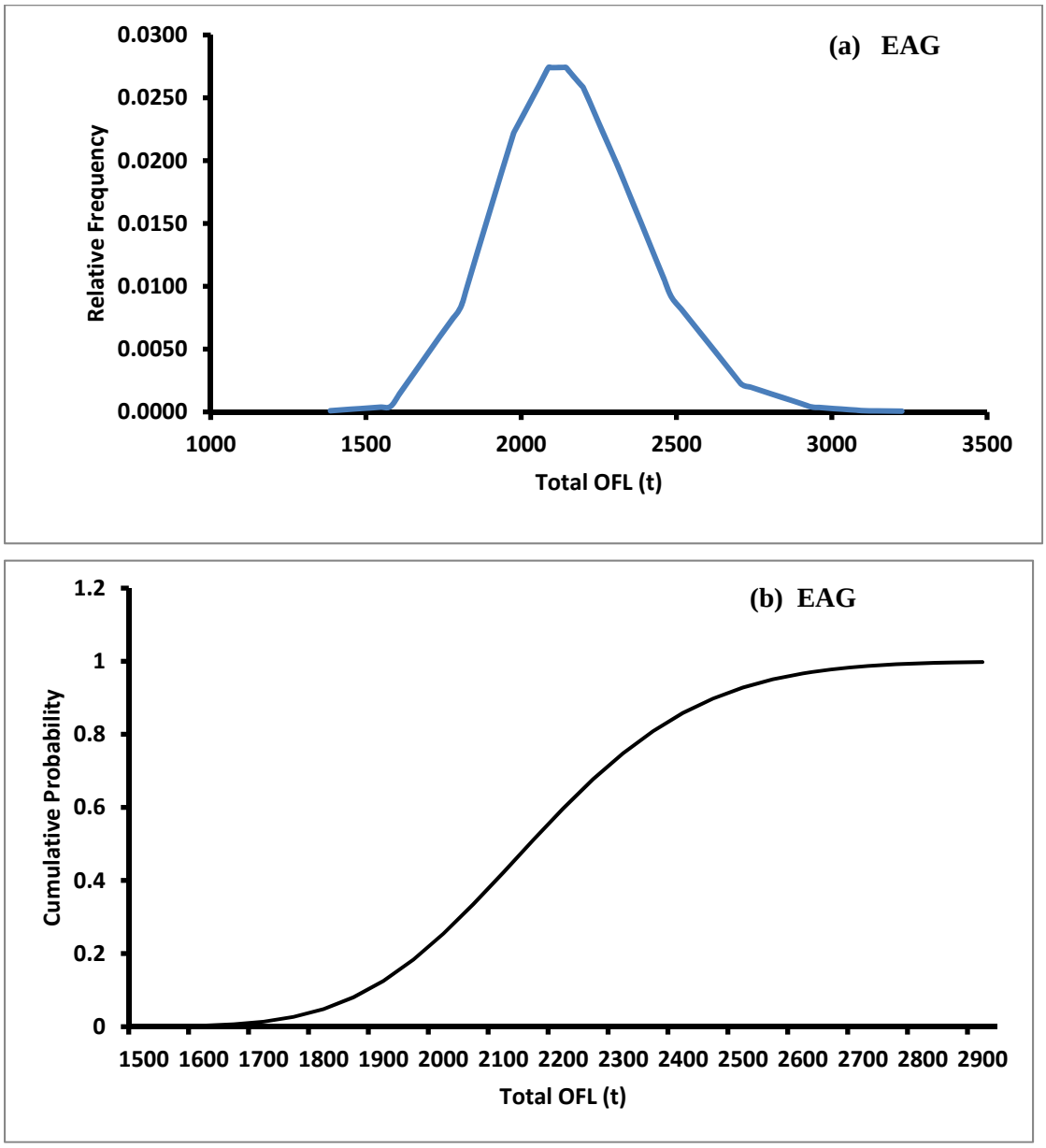

Figure 25. (a) Probability of total OFL based on 1985-2010 data for EAG golden king crab. Profile likelihood was used to create the probability distribution. (b) Cumulative distribution of the lognormal OFL.

Table 8. Time series of annual retained catch (number of crabs), discarded catch (handling mortality of 20%), groundfish fishery discarded catch (handling mortality of 50% for pot and 80% for trawl gear, only male portion), observer retained catch-per-unit-effort (CPUE, number of crabs per pot lift), observer discard CPUE for the WAG golden king crab stock. The data are for the size range 101-185 mm CL. The CPUE are standardized for soak-time. Note:1985 = 1985/86 fishery.

Year	Retained Catch	Pot Discarded Catch	Groundfish Discarded Catch	Observer Retained CPUE	Observer Discard CPUE
1985	1,401,322			10.135	
1986	2,033,595			6.213	
1987	1,145,152			6.065	
1988	1,310,033			6.775	
1989	1,585,080			6.641	
1990	757,610	170,318		4.551	7.865
1991	753,415	172,159		6.389	8.487
1992	409,373	139,183		5.052	10.021
1993	565,336	264,044		3.755	10.333
1994	796,258	402,364		3.463	10.310
1995	535,553	169,119	331	4.441	7.337
1996	603,061	162,478	397	5.445	8.184
1997	569,550	130,136	136	6.299	7.495
1998	409,531	106,290	479	10.715	14.795
1999	676,558	167,595	330	5.764	7.829
2000	705,613	193,385	230	6.166	9.551
2001	686,738	172,718	184	5.773	8.185
2002	664,823	152,054	593	7.271	9.626
2003	676,633	116,365	3,087	9.234	8.784
2004	685,465	128,314	559	10.884	11.286
2005	639,368	80,410	2,145	22.772	13.350
2006	523,701	52,208	1,488	21.131	9.780
2007	600,604	70,513	3,794	20.633	11.772
2008	587,661	73,676	8,953	24.560	14.060
2010	626,246	46,352	1,112	21.083	7.740

Table 9. Optimization scenarios and weighting factors for the western Aleutian Islands golden king crab stock (WAG). The Molt L_{50} was set to 139.0 mm CL and the growth function β parameter was set to 0.578 in the penalty functions. Both values were independent estimates from tagging data. The mean CPUE ratio for the periods 2005-2010 and 1998-2004, based on observed data, was set to 3.45 in the penalty function. The effective sample sizes were kept constant at 50, 50, and 10 for retained catch, pot discard catch, and groundfish discard catch length compositions, respectively.

Scenario	CPUE		Recruitment	Catch Biomass			Mean CPUE Ratio	Pot Fishery F	Groundfish Fishery Discard F	L_{50}	β
	Retained	Pot Discard		Retained	Pot Discard	Groundfish Discard					
1	1	1	2	600	100	10	0.6	0.0001	2.	0.6	0.6
2	1	1	2	600	100	10	10	0.0001	2.	0	0
3	1	1	2	600	100	10	10	0.0001	2.	0.6	0.6

Table 10. Negative log likelihood component values for the three scenarios for the golden king crab stock in WAG.

Negative Log Likelihood Component	Scenario 1	Scenario 2	Scenario 3
like_retlencomp	-1,238.9100	-1,240.2300	-1,238.4400
like_discdlencomp	-1,003.8900	-1,004.2200	-1,003.7100
like_gdiscdlencomp	-416.6180	-414.7790	-415.2500
like_retcpue	-0.6844	-4.5204	-2.5572
like_discdcpue	-2.1220	-2.4439	-2.7119
like_retdcatchB	1.5169	1.6248	1.4739
like_discdcatchB	8.7930	9.3435	8.5164
like_gdiscdcatchB	3.7817	4.4103	4.2795
like_rec_dev	5.9133	6.9273	5.6602
like_F	0.0011	0.0010	0.0008
like_gF	18.8248	21.9530	21.3046
like_qq	0.0561	0.0224	0.0292
like_molt50	0.0179	0	0.0434
like_beta	0.0004	0	0.0001
like_meancpue	0.4895	2.8390	3.4430
Sum of catch biomasses negative log likelihood	14.0916	15.3786	14.2698
Sum of length compositions negative log likelihood	-2,659.4200	-2,659.2300	-2,657.3900
Total negative log likelihood	-2,622.8300	-2,619.0800	-2,617.9100

Table 11. Estimates of parameters and 2011 MMB with standard deviations, by the base model (scenario 1) for the golden king crab data from the WAG, 1985/86-2010/11. (altogether 117 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	0.0579	0.0115	log_betar	-0.6644	0.2811
log_b	4.9332	0.0065	logq1	-11.9330	0.4307
log_beta	-0.5058	0.4014	logq2	-11.9900	0.1935
c1	0.0401	0.0239	logq3	-11.6550	0.1993
log_d1	4.9165	0.2932	log_newsh1	2.6136	0.1128
c2	0.1033	0.0173	log_mean_rec	0.5887	0.0662
log_d2	4.8405	0.0298	log_mean_Fpot	-0.4844	0.2620
c3	0.1594	0.0219	log_mean_Fground	-7.7747	0.1841
log_d3	4.8702	0.0156	mean_qq	3.4910	0.3445
aa1	1.0197	0.1572	ret_var	0.0541	0.0208
log_bb1	4.9031	0.0021	discd_var	0.0446	0.0170
aa2	1.2045	0.1952	2011 MMB	8,032.8000	1,705.1000
log_bb2	4.9050	0.0026			
aa3	0.7917	0.2051			
log_bb3	4.9175	0.0032			
aa4	0.1378	0.0389			
log_bb4	4.8364	0.0282			

Table 12. Annual abundance estimates of recruits to the model (millions of crabs), available legal male biomass (t), and available mature male biomass (t) 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 = 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	6,625	899.9700	7,867	882.2000
1986	1.87	5,199	577.8600	6,694	691.8200
1987	2.48	5,842	424.5800	4,851	529.6800
1988	1.86	5,127	294.5200	5,278	394.7700
1989	1.37	3,414	232.2900	4,662	273.9700
1990	0.98	3,079	212.8100	3,042	218.5000
1991	1.26	2,443	196.0500	2,814	209.4400
1992	2.07	2,598	193.4000	2,246	193.6700
1993	2.64	2,841	191.7000	2,412	183.5900
1994	1.56	2,819	198.1000	2,574	175.7900
1995	1.29	3,104	218.7300	2,461	187.4700
1996	1.28	2,986	236.3900	2,807	210.7500
1997	1.40	2,850	262.6900	2,750	229.8000
1998	2.56	3,208	292.5200	2,640	253.7300
1999	1.62	3,497	311.9200	2,993	280.5500
2000	2.51	3,607	358.4900	3,163	305.1000
2001	2.26	4,103	437.2600	3,289	347.4400
2002	2.61	4,753	538.9500	3,738	422.3500
2003	2.06	5,488	664.7600	4,379	519.2900
2004	2.50	6,013	800.8800	5,088	638.9300
2005	1.52	6,552	922.4400	5,651	767.7900
2006	3.19	7,022	1,021.5000	6,176	887.0900
2007	3.23	7,886	1,219.7000	6,722	982.2500
2008	1.05	8,822	1,483.8000	7,470	1,156.7000
2009	1.17	8,667	1,621.9000	8,331	1,396.3000
2010	1.41	8,033	1,705.1000	8,357	1,548.1000
2011	1.21			7,818	1,636.7000

Table 13. Time series of catch divided by mature male abundance for WAG. We provide only the 1995/96 to 2010/11 time series because total removals from all sources (pot fishery and groundfish fishery) are available/reliable from 1995/96 to 2010/11.

Year	Total Removal/Mature Male Abundance
1995/96	0.38
1996/97	0.44
1997/98	0.43
1998/99	0.27
1999/00	0.42
2000/01	0.44
2001/02	0.36
2002/03	0.29
2003/04	0.25
2004/05	0.24
2005/06	0.20
2006/07	0.16
2007/08	0.17
2008/09	0.15
2009/10	0.16
2010/11	0.18

Table 14. Influence of different weights on important likelihood components, mean CPUE ratio for the periods 1998-2004 and 2005-2010, and molt L_{50} and growth function β for the golden king crab stock in WAG.

Scenario	Weights		Total OFL (t)	MMB90(t)	MMB95(t)	MMB00(t)	MMB05(t)	MMB10(t)	Max. Gradient	Objective Function
	Mean CPUE Ratio	Molt L_{50} and Growth Function β								
	0	0	1,239	3,455	3,597	4,326	7,743	9,222	$6.6e^{-6}$	-2,624
	0.6	0	1,223	3,498	3,658	4,405	7,771	9,143	$8.6e^{-5}$	-2,623
2	10	0	1,081	3,924	4,259	5,131	7,974	8,533	$-6.5e^{-6}$	-2,619
	100	0	828	4,763	5,296	6,162	8,426	8,629	$1.4e^{-4}$	-2,614
	0	0.6	1,103	3,036	3,099	3,550	6,499	7,763	$-3.9e^{-5}$	-2,619
1	0.6	0.6	1,118	3,079	3,104	3,607	6,552	8,033	$3.6e^{-6}$	-2,623
3	10	0.6	893	3,138	3,198	3,669	5,891	6,542	$-3.2e^{-7}$	-2,618
	100	0.6	526	3,120	3,208	3,438	4,534	4,243	$1.8e^{-4}$	-2,625

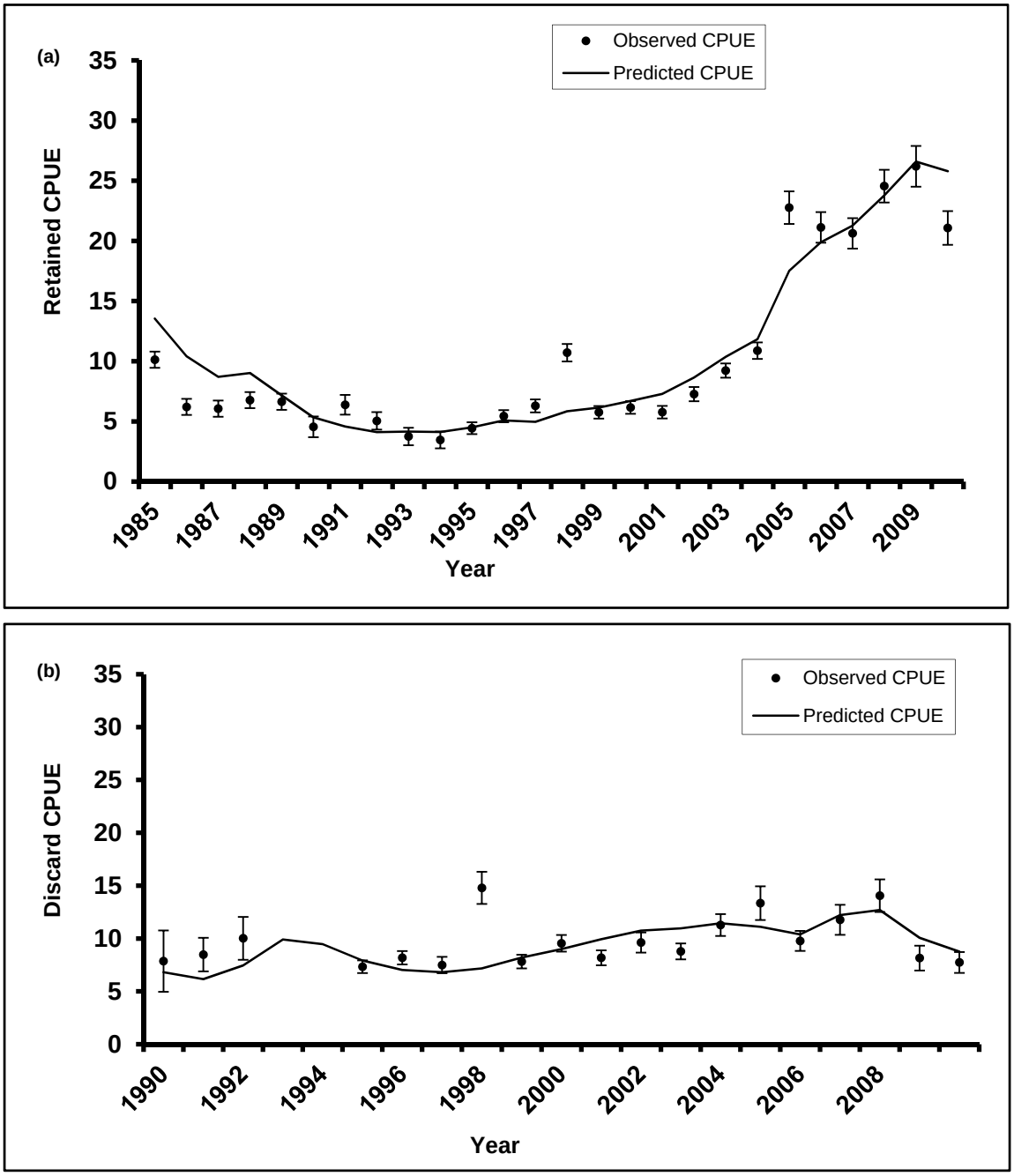

Figure 26. Predicted (line) versus observed (filled circle) (a) retained catch-per-unit-effort (CPUE) and (b) discard CPUE for golden king crab in the WAG. Two Std.Dev. confidence bars are attached to observed points. Fishery CPUE values are 1985-2010 for retained and 1990-2010 for discard (note: 1990 = 1990/91 fishery).

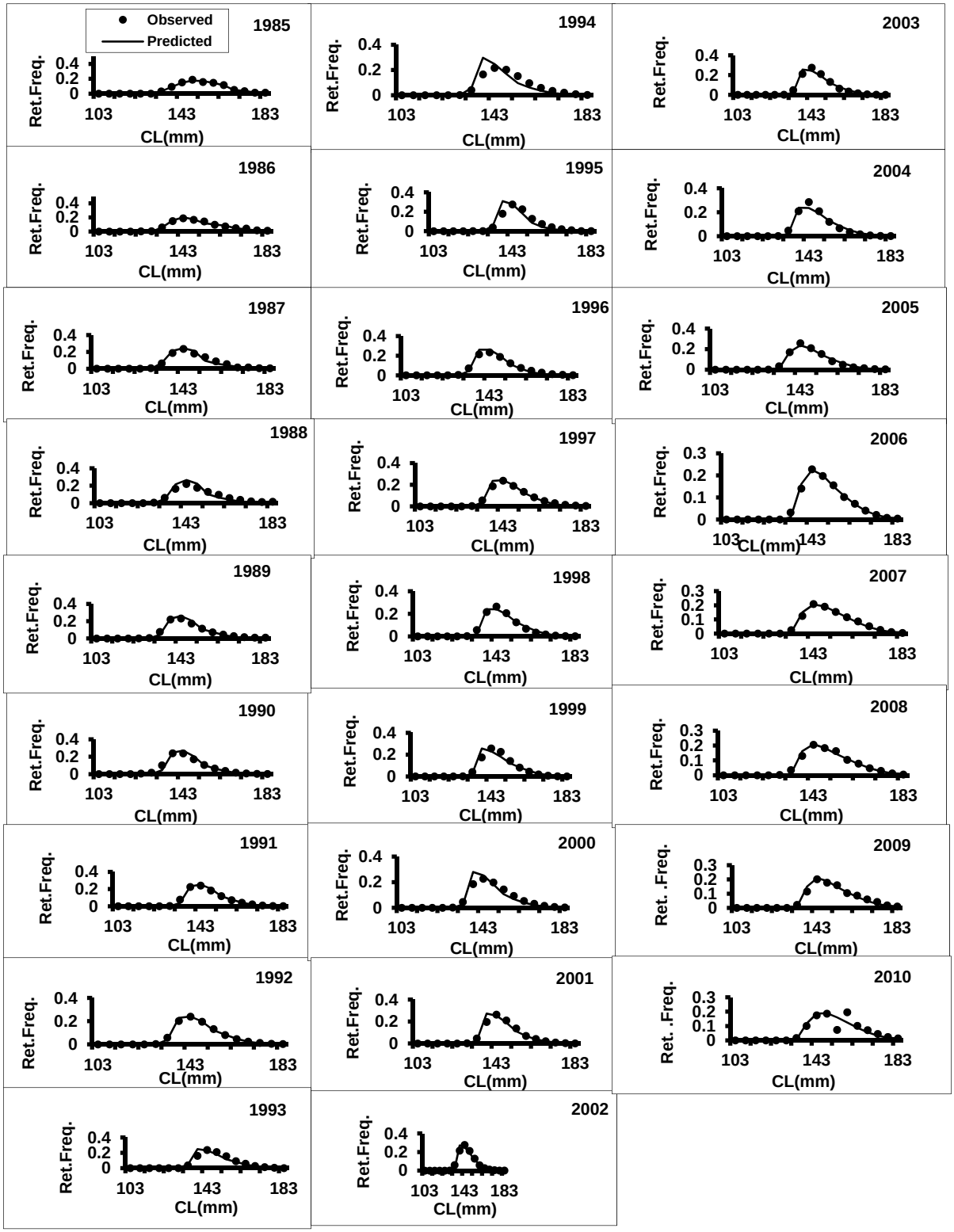

Figure 27. Predicted (line) vs. observed (filled circle) retained catch relative length frequency distributions of golden king crab in the WAG, 1985 to 2010 (note: 1985 = 1985/86 fishery).

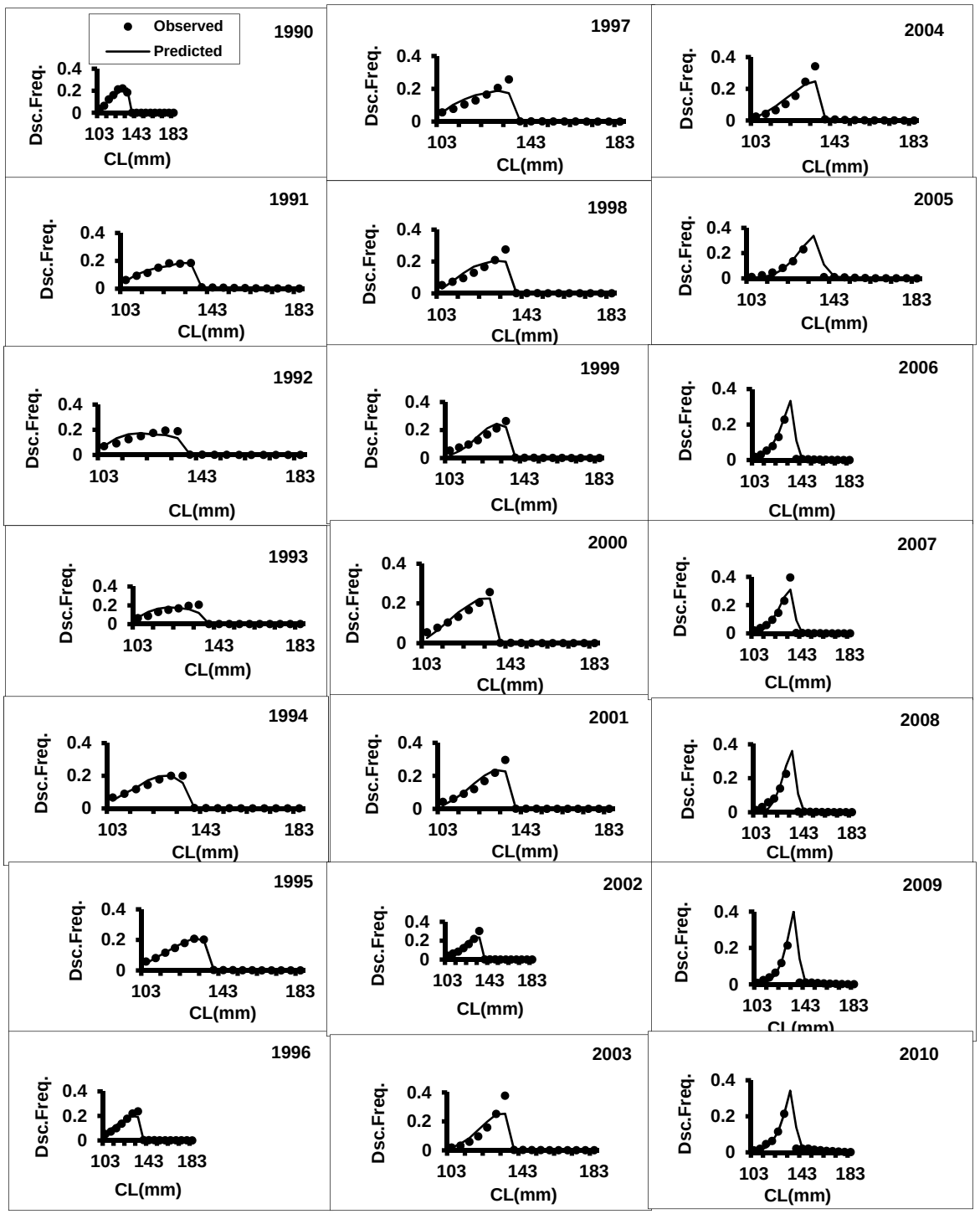

Figure 28. Predicted (line) vs. observed (filled circle) pot discarded catch relative length frequency distributions of golden king crab in the WAG, 1990 to 2010 (note: 1990 = 1990/91 fishery).

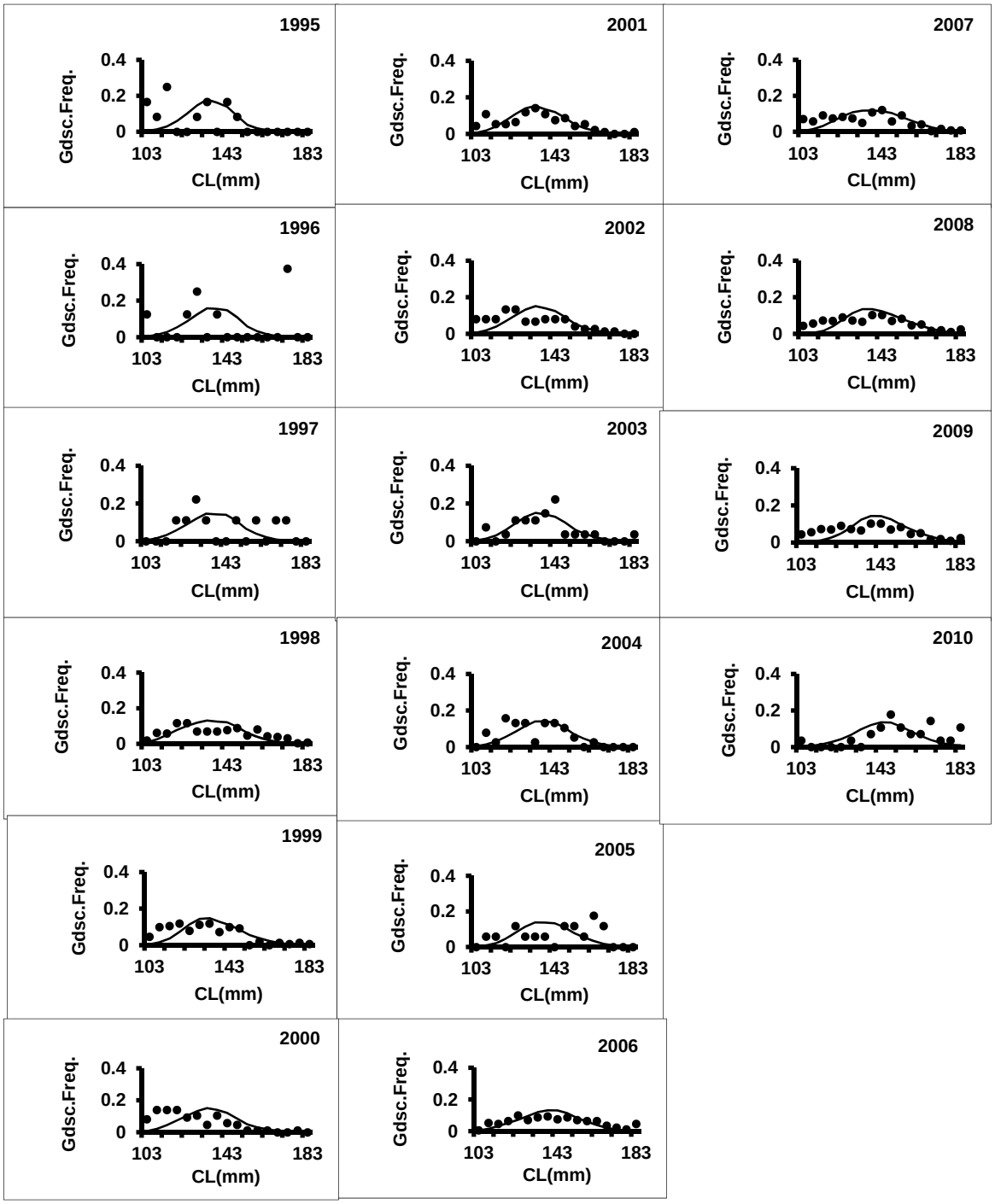

Figure 29. Predicted (line) vs. observed (filled circle) groundfish discarded catch relative length frequency distributions of golden king crab in the WAG, 1995 to 2010 (note: 1995 = 1995/96 fishery).

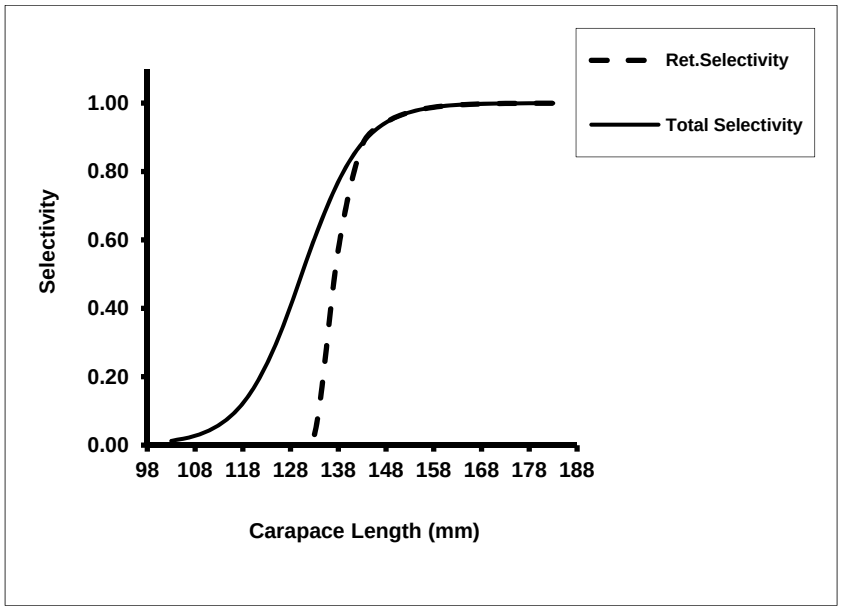

Figure 30. Estimated total selectivity (solid line) and effective retained catch selectivity (total selectivity*retained selectivity, dashed line) during 2005- for WAG golden king crab fishery.

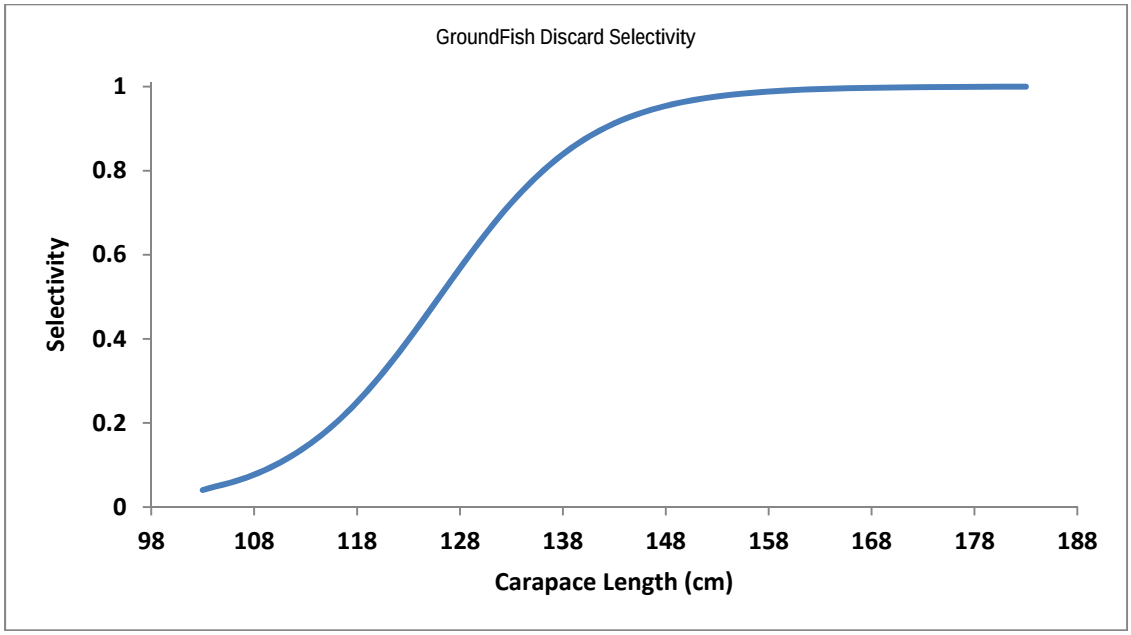

Figure 31. Estimated groundfish bycatch selectivity for WAG golden king crab fishery.

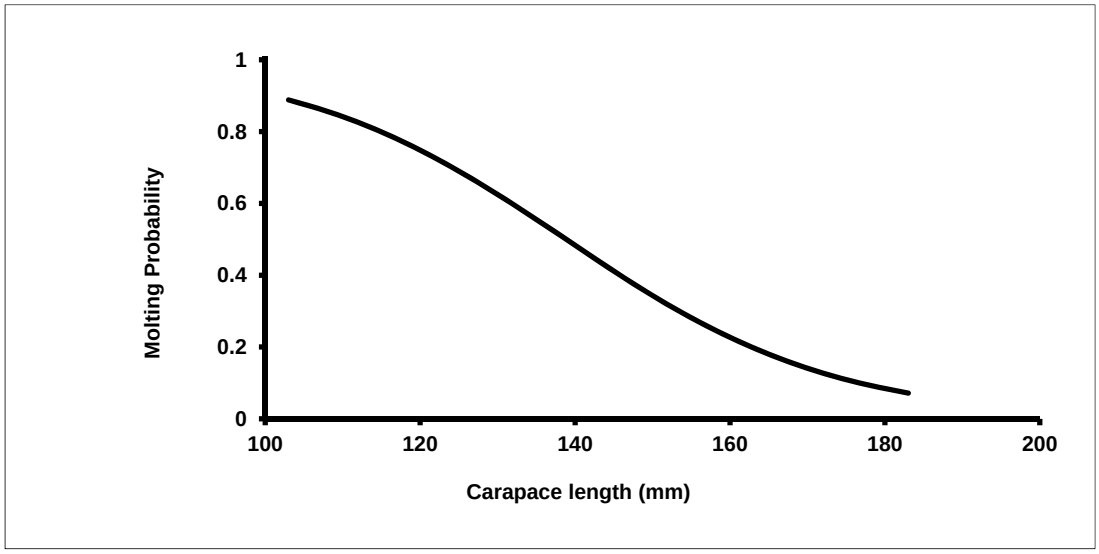

Figure 32. Estimated molt probability of WAG golden king crab.

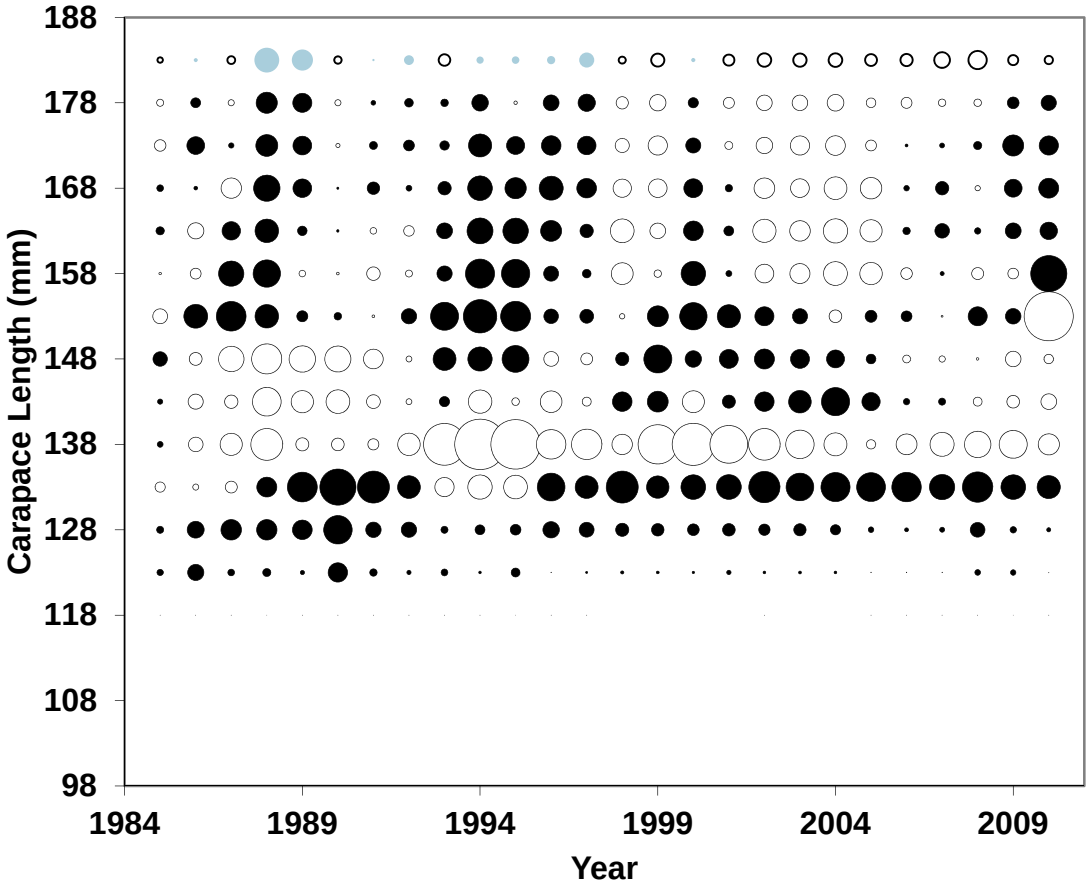

Figure 33 . Bubble plot of standardized residuals of retained length composition for WAG golden king crab, 1985-2010 (note: 1985 = 1985/86 fishery).

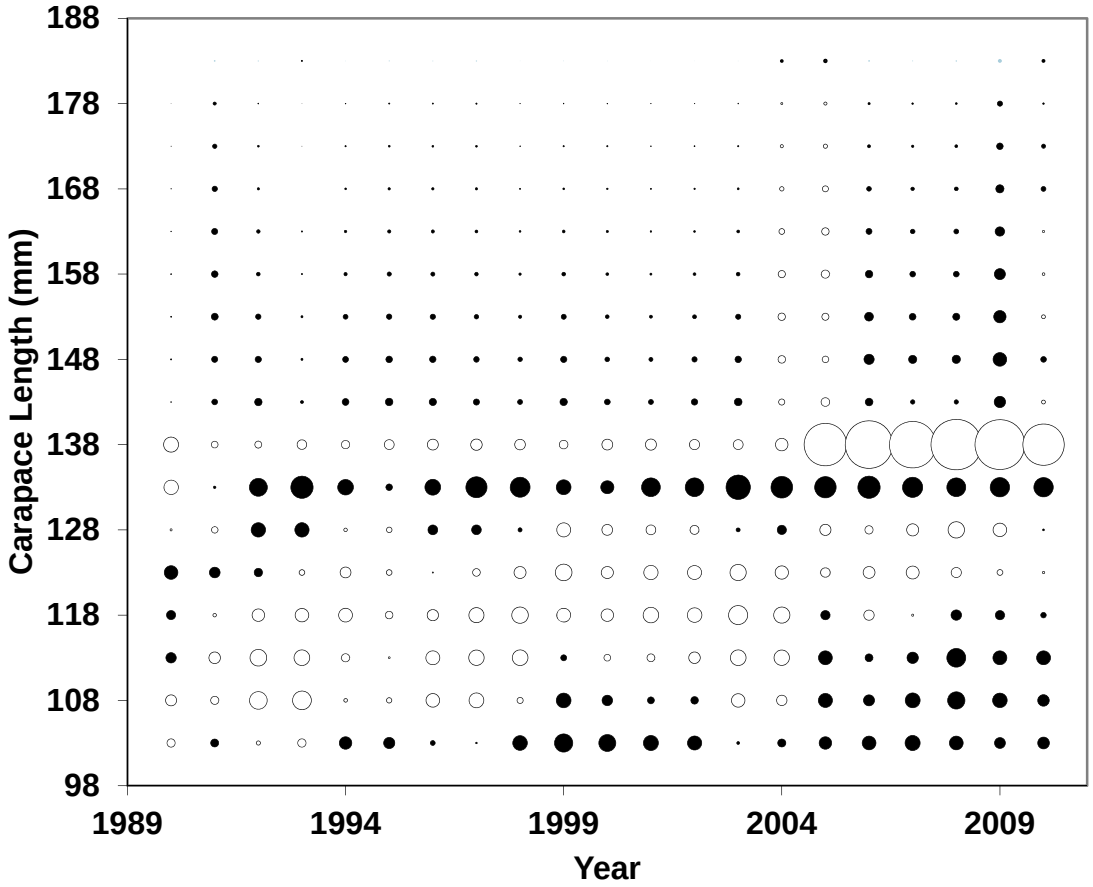

Figure 34. Bubble plot of standardized residuals of pot discarded length composition for WAG golden king crab, 1985-2010 (note: 1985 = 1985/86 fishery).

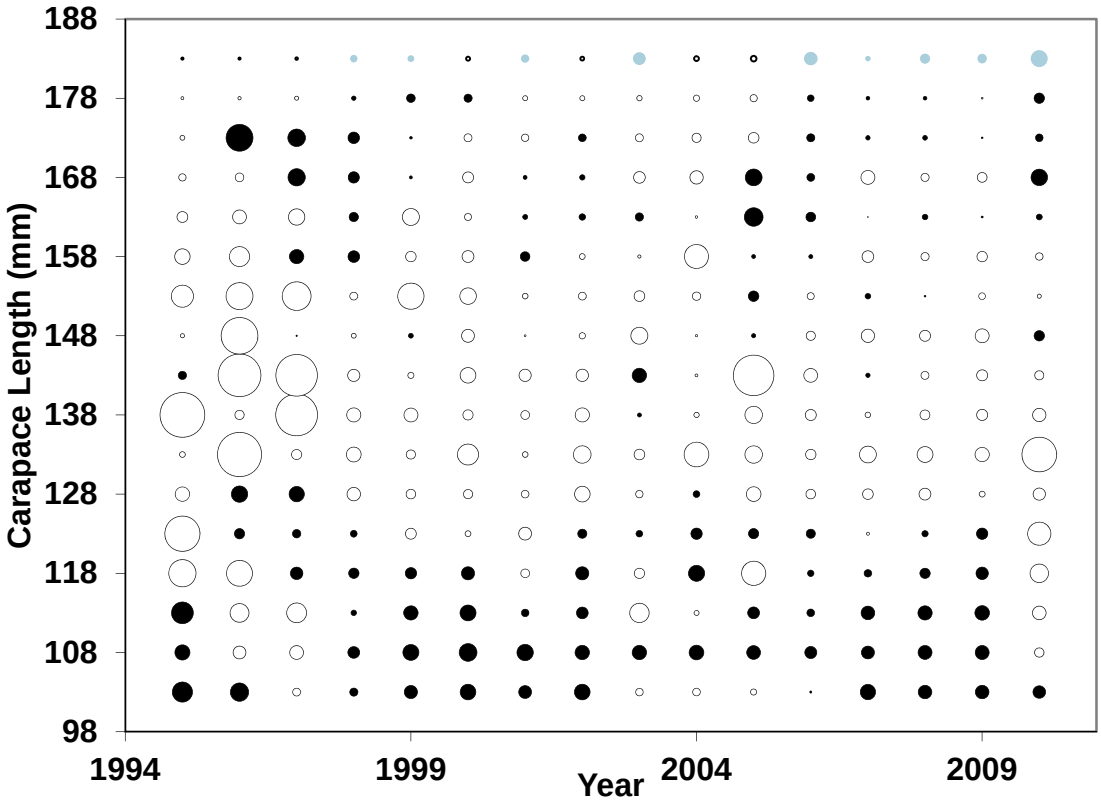

Figure 35. Bubble plot of standardized residuals of groundfish discarded length composition for WAG golden king crab, 1985-2010 (note: 1985 = 1985/86 fishery).

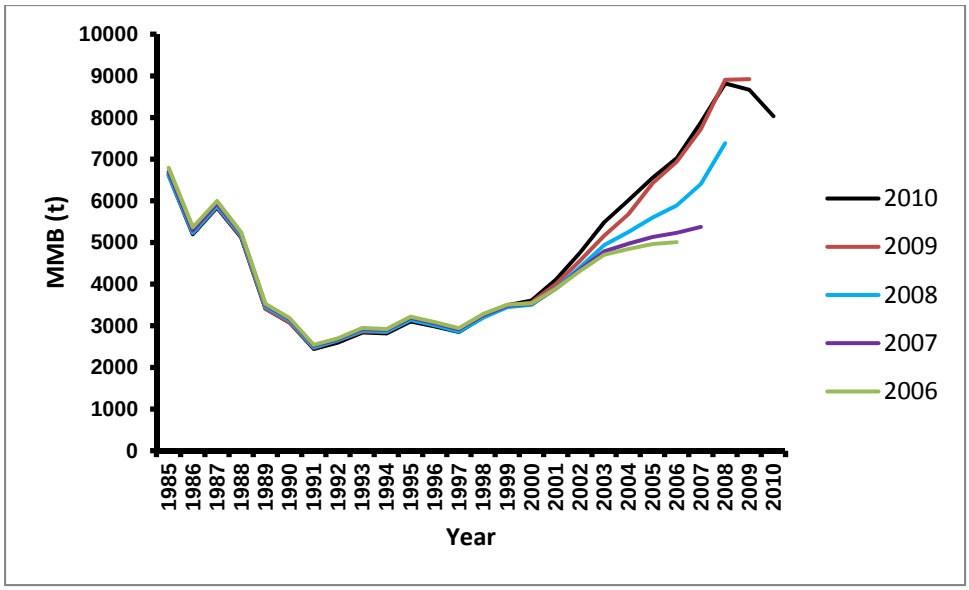

Figure 36. Retrospective fits of mature male biomass with terminal years 2006 to 2010 using the 2011 model for WAG.

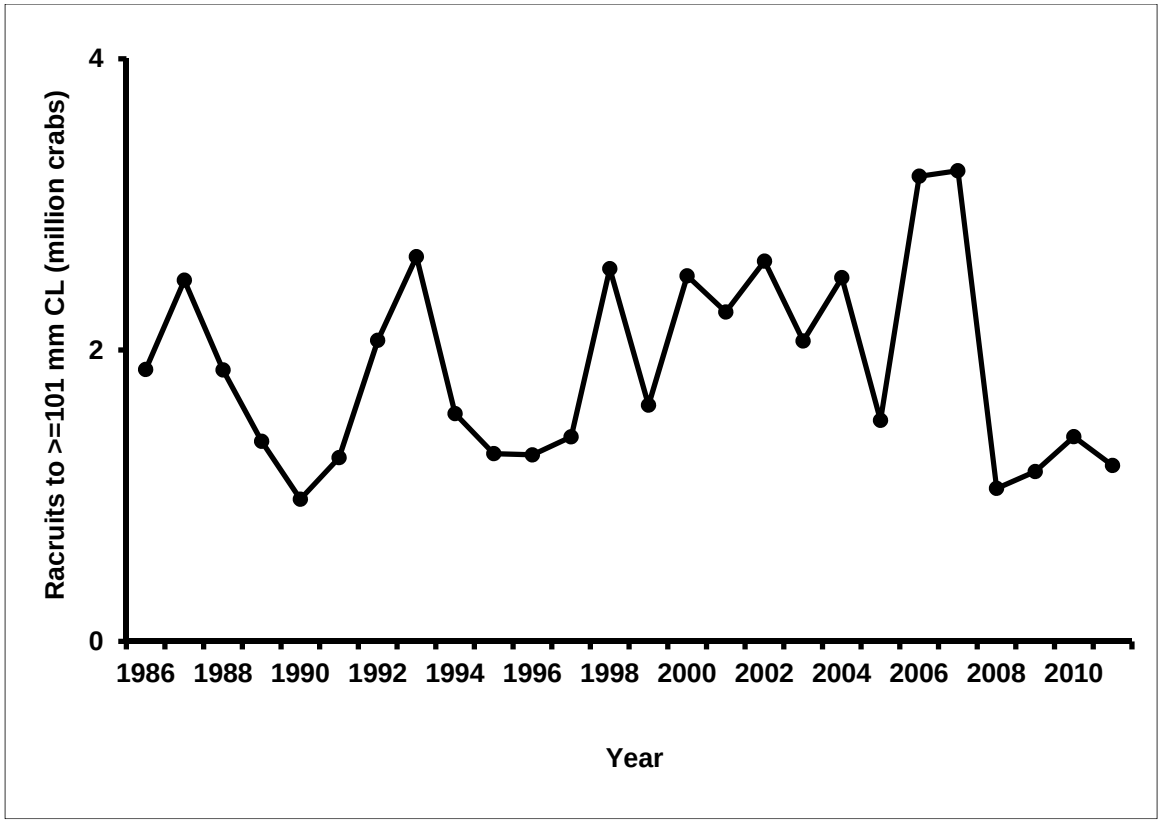

Figure 37. Estimated number of male recruits (millions of crabs ≥ 101 mm CL) to the golden king crab assessment model size group in WAG, 1986-2011.

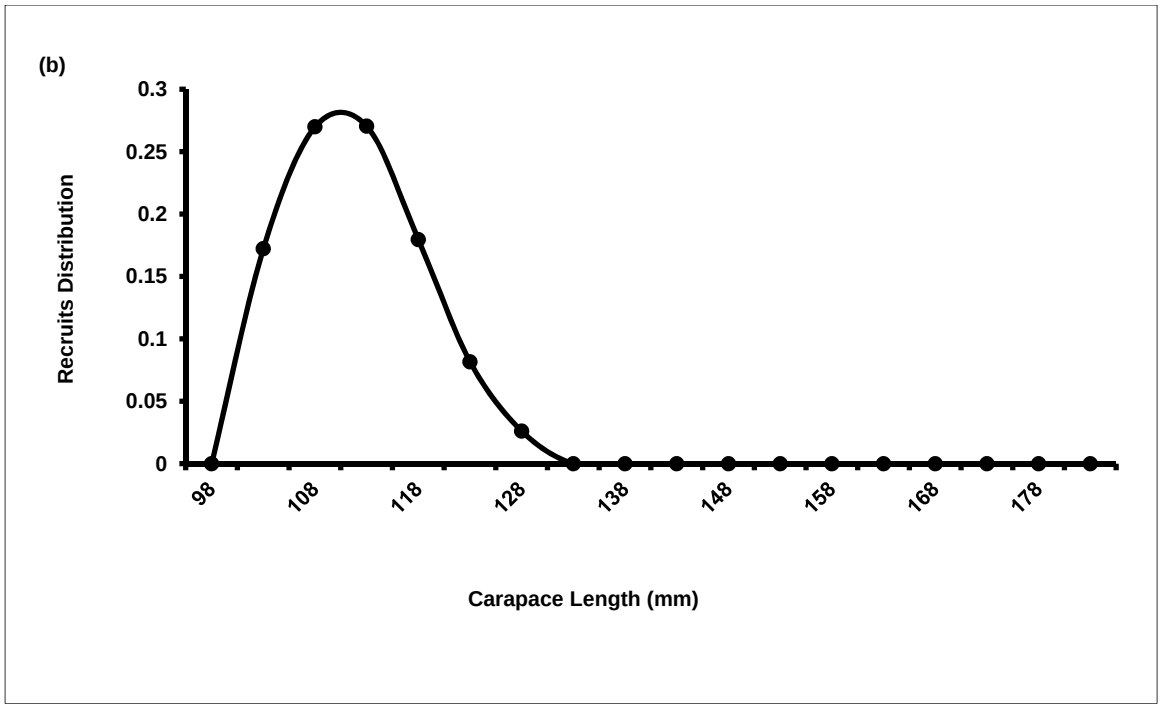

Figure 38. Recruit distribution to the golden king crab assessment model size group in WAG.

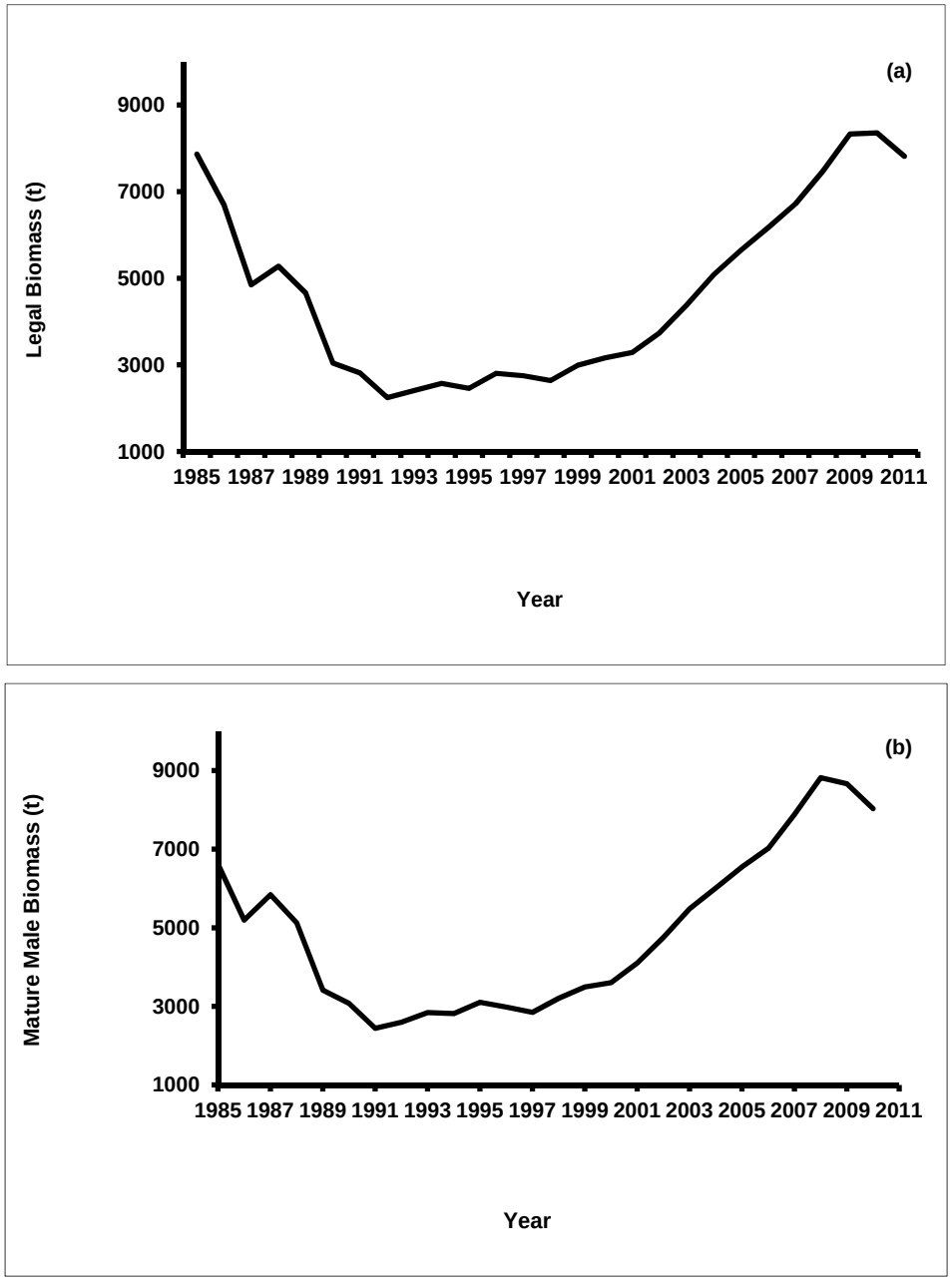

Figure 39. Trends in golden king crab (a) legal male biomass (t) and (b) mature male biomass in the WAG, 1985-2010/11. Legal male crabs are ≥ 136 mm CL and mature male crabs are ≥ 121 mm CL.

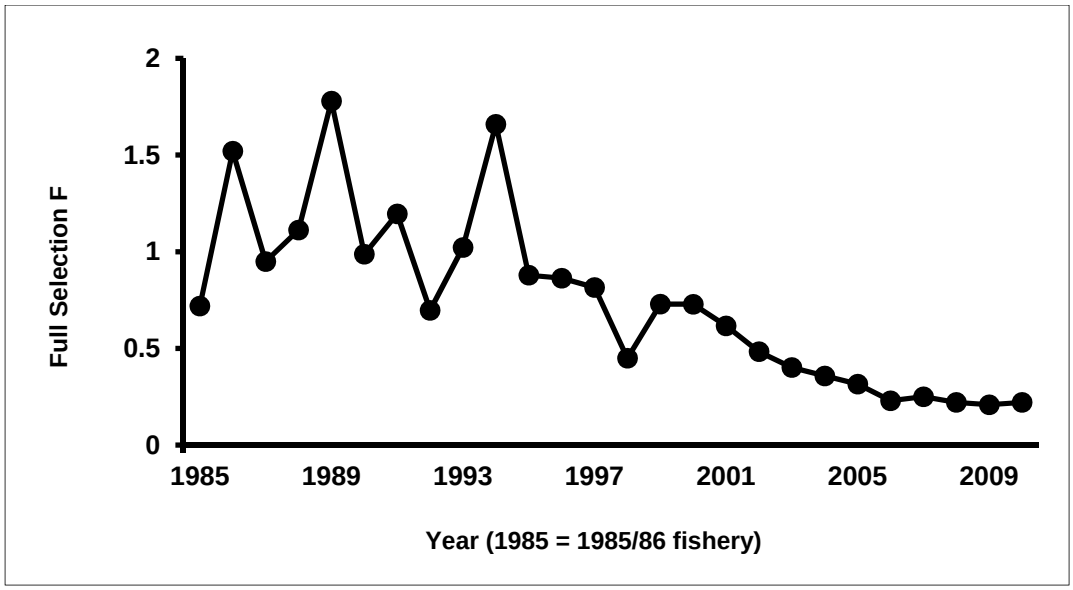

Figure 40. Trend in full selection fishing mortality of golden king crab in the WAG, 1985-2010 (note: 1985 = 1985/86 fishery).

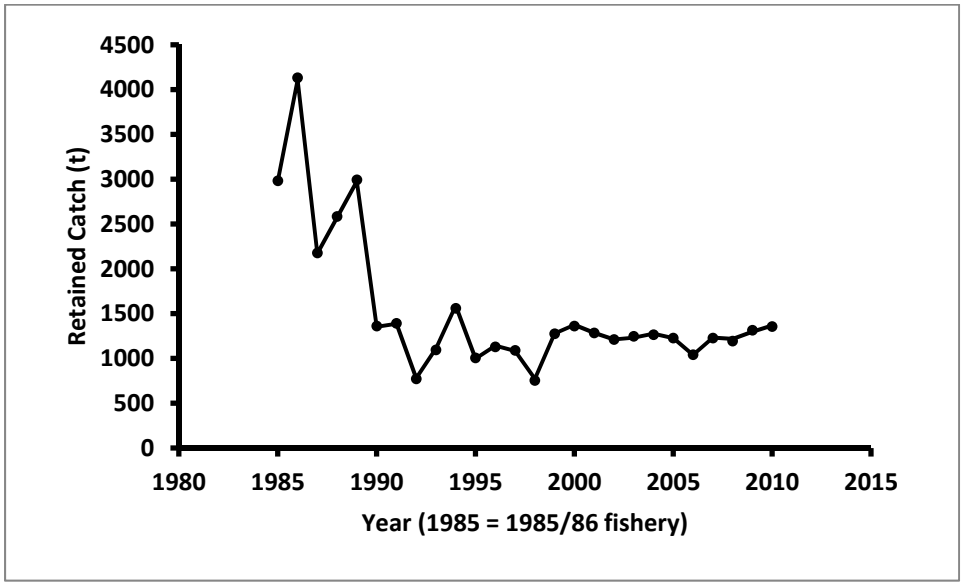

Figure 41. Observed (filled circle) vs. predicted retained catch of golden king crab in the WAG, 1985-2010 (note: 1985 = 1985/86 fishery).

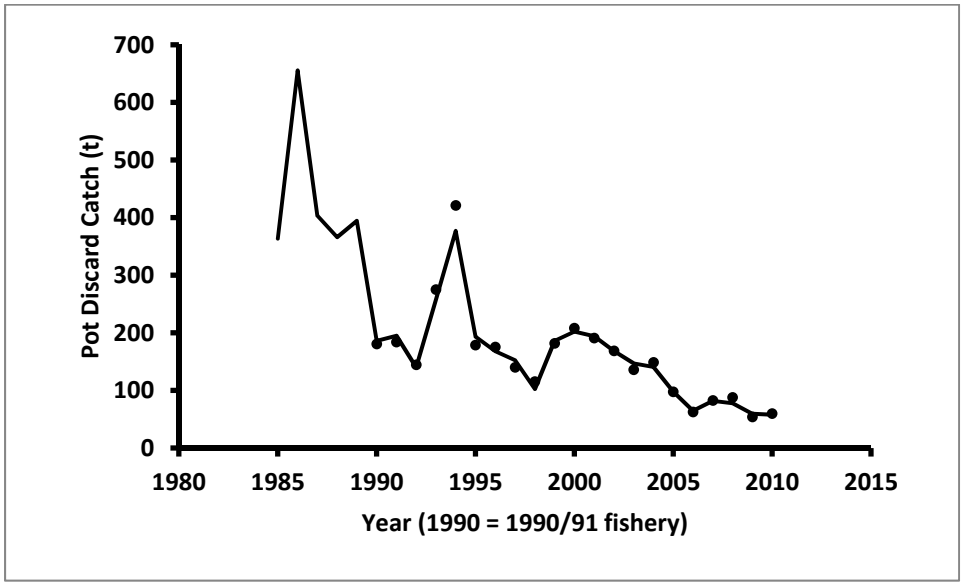

Figure 42. Observed (filled circle) vs. predicted pot discarded dead catch of golden king crab in the WAG, 1985-2010 (note: 1985 = 1985/86 fishery). A handling mortality of 20% was applied.

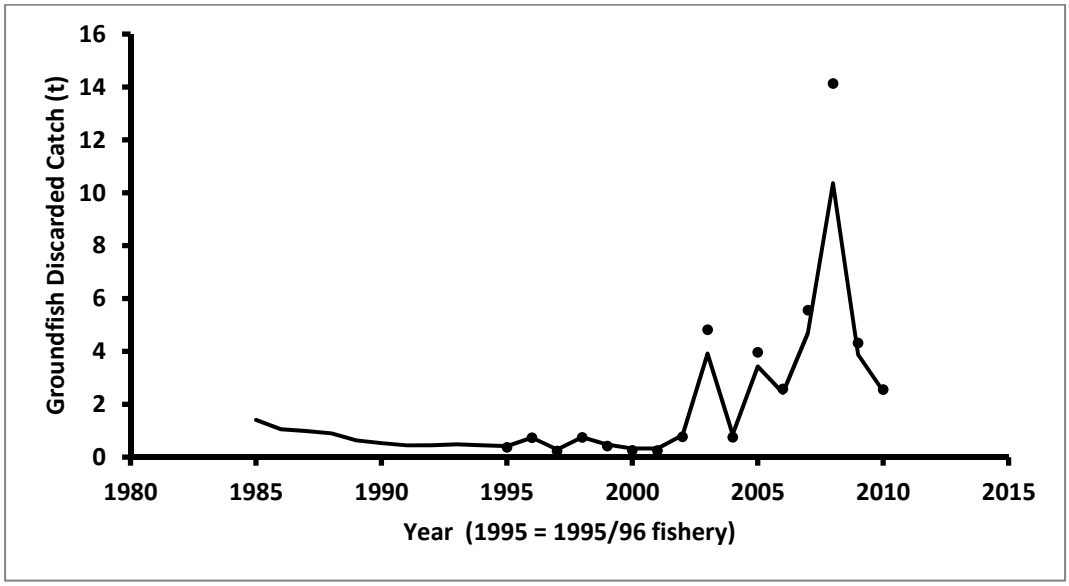

Figure 43. Observed (filled circle) vs. predicted groundfish discarded dead catch of golden king crab in the WAG, 1985-2010 (note: 1985 = 1985/86 fishery). An average handling mortality of 65% (average of 80% and 50%) was applied.

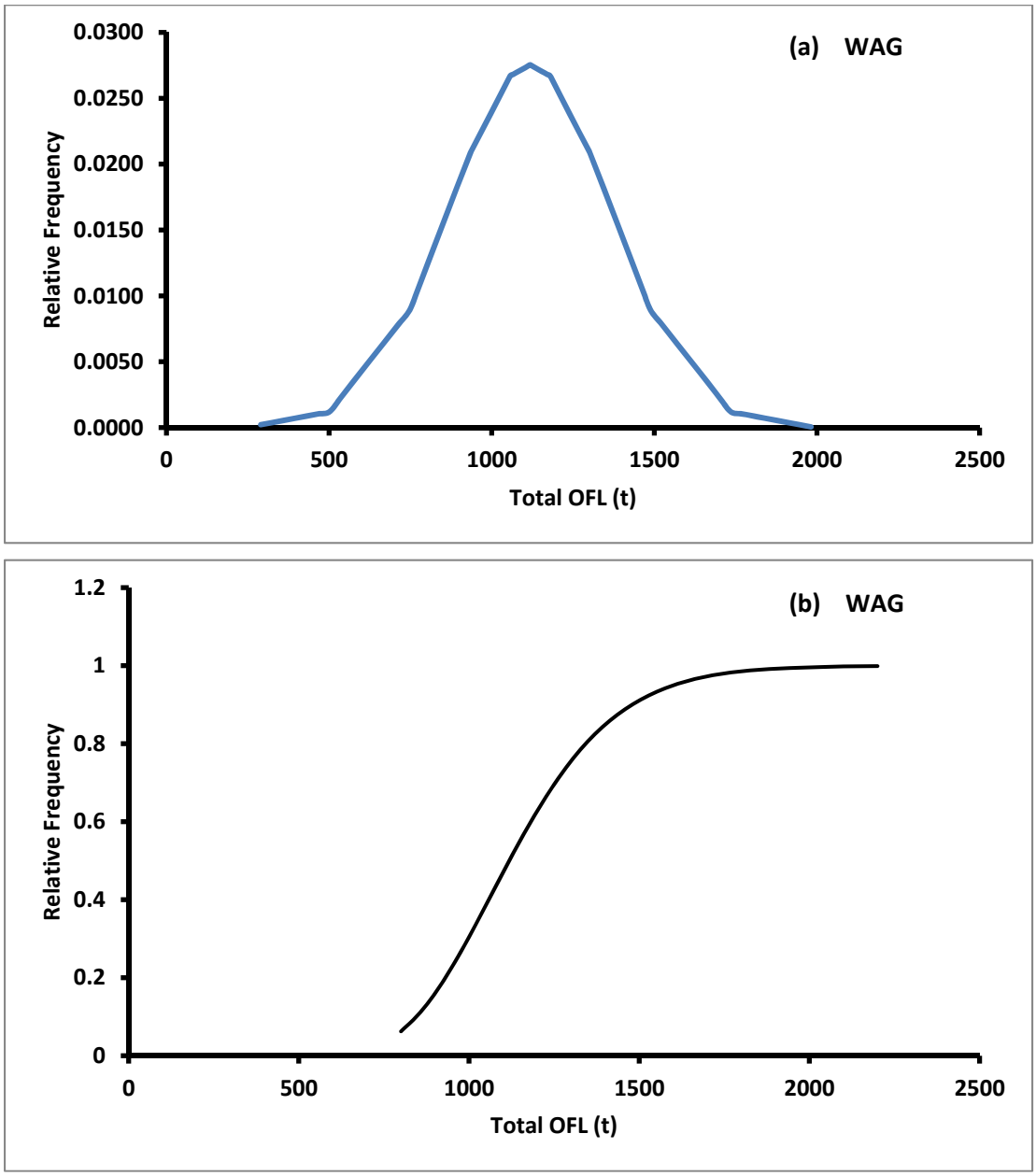

Figure 44. (a) Probability of total OFL based on 1985-2010 data for WAG golden king crab. Profile likelihood was used to create the probability distribution. (b) Cumulative distribution of the lognormal OFL.

Appendix A: Integrated model

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

R_t: total number of male recruits for each year, except the first year, R_{86} to R_{11};
q: survey pot 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, survey pot 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 survey pot.

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

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

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

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

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

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

where ^ sign refers to predicted value.

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, retained, and discarded dead, and groundfish fishery discarded dead catches are estimated as follows:

Total catch,

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

Retained catch,

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

Pot fishery discarded dead catch,

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

Groundfish discarded dead catch,

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

Note: There is an additional discard catchability QQ (t) on legal size crab during the post rationalization period in EAG (2005-2009) and certain years in WAG (1991, 2004, and 2005). Thus, the product

$$QQ(t)s_l^r$$

is used in the retained catch and CPUE formulas. The years were selected based on the observed legal retained/legal discard ratio. The ratios were higher during those fishing seasons than the other years.

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

$$LL_r^{catch} = \lambda_r \sum_t \{log(\sum_j \hat{C}_{t,j} w_j + c) - log(\sum_j C_{t,j} w_j + c)\}^2 \tag{18}$$

$$LL_D^{catch} = \lambda_D \sum_t \{log(\sum_j \hat{C}^D{}_{t,j} w_j + c) - log(\sum_j C^D{}_{t,j} w_j + c)\}^2 \tag{19}$$

$$LL_{GD}^{catch} = \lambda_{GD} \sum_t \{log(\sum_j \hat{T}_{t,j} w_j + c) - log(\sum_j T_{t,j} w_j + c)\}^2 \tag{20}$$

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

$$C\hat{P}UE_{t,j}^s = q_k s_j^{surv} \ (N_{t,j} + O_{t,j}) \tag{21}$$

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

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

(22)

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 $\hat{L}_{t,j}^r$ in year t is computed as

$$\hat{L}_{t,j}^r = \frac{\hat{C}_{t,j}}{\sum_j^n \hat{C}_{t,j}} \tag{23}$$

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

$$LL_r^{LF} = 0.5\sum_t\sum_j log(2\pi\sigma_{t,j}^2) - \sum_t\sum_j log\left[e^{-\frac{(L_{j,t}^r - \hat{L}_{t,j}^r)^2}{2\sigma_{t,j}^2}} + 0.01\right] \tag{24}$$

Where

$$\sigma_{t,j}^2 = \left[(1 - L_{t,j}^r)L_{t,j}^r + \frac{0.1}{n}\right] / S_t$$

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

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

$$\hat{L}_{t,j}^D = \frac{\hat{C}_{t,j}^D}{\sum_j^n \hat{C}_{t,j}^D} \tag{25}$$

Negative log likelihood, LL_D^{LF}, for discard length composition is similar to equation (24) with discard catch effective sample size and length composition replacing the corresponding retained values.

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

$$\hat{L}_{t,j}^{GD} = \frac{\hat{T}_{t,j}}{\sum_j^n \hat{T}_{t,j}} \tag{26}$$

Negative log likelihood, LL_{GD}^{LF}, for groundfish discard length composition is similar to equation (23) with groundfish discard catch effective sample size and length composition replacing the corresponding retained values.

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

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

Negative log likelihood, LL_s^{LF}, for pot survey length composition is similar to equation (24) 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

$$LL_F = \lambda_F \sum_t \{\log(F_t) - \log(\overline{F})\}^2 \tag{28}$$

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

$$LL_{GF} = \lambda_{GF} \sum_t \{log(GF_t) - log(\overline{GF})\}^2 \tag{29}$$

where $\overline{GF}$ 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

$$LL_R = \lambda_R \sum_t \{\log(R_t) - \log(\overline{R})\}^2 \tag{30}$$

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

Legal discard in certain years penalty

$$LL_{QQ} = \lambda_{QQ} \sum_t \{log(QQ_t) - log(\overline{QQ})\}^2 \tag{31}$$

where $\overline{QQ}$ 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

$$LL_{1997\,LMB} = \lambda_{1997\,LMB} \{log(LMB_{1997} + c) - log(\hat{LMB}_{1997} + c)\}^2 \tag{32}$$

where $\hat{LMB}_{1997}$ is the independently estimated exploited legal male biomass based on retained catch and tagging estimated harvest rate (0.204) and $\lambda_{1997\,LMB}$ is the weight for the exploited legal male biomass likelihood.

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

$$LL_{2000\,LMB} = \lambda_{2000\,LMB} \{log(LMB_{2000} + c) - log(\hat{LMB}_{2000} + c)\}^2 \tag{33}$$

where $\hat{LMB}_{2000}$ is the independently estimated exploited legal male biomass based on retained catch and tagging estimated harvest rate (0.200) and $\lambda_{2000\,LMB}$ is the weight for the exploited legal male biomass likelihood..

(c) The weighted negative log likelihood for 2003 LMB is

$$LL_{2003\,LMB} = \lambda_{2003\,LMB}\{log(LMB_{2003} + c) - log(\hat{LMB}_{2003} + c)\}^2 \quad (34)$$

where $\hat{LMB}_{2003}$ is the independently estimated exploited legal male biomass based on retained catch and tagging estimated harvest rate (0.105) and $\lambda_{2003LMB}$ is the weight for the exploited legal male biomass likelihood.

Molt probability L_{50} penalty

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

$$LL_{L50} = \lambda_{L50}\{L_{50} - 139.0\}^2 \quad (35)$$

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

$$LL_{\beta} = \lambda_{\beta}\{\beta - 0.578\}^2 \quad (36)$$

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 CPUE ratio penalty

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

$$LL_{CPUERATIO} = \lambda_{CPUERATIO}\{log(q3/q2) - log(2.3874)\}^2 \quad \text{for EAG, and}$$

$$LL_{CPUERATIO} = \lambda_{CPUERATIO}\{log(q3/q2) - log(3.4526)\}^2 \quad \text{for WAG} \quad (37)$$

where 2.3874 and 3.4526 are observed CPUE ratios for the two periods, respectively for EAG and WAG; and $\lambda_{CPUERATIO}$ is the catchability ratio likelihood weight.

Thus, the objective function for minimization is

$$f = LL_r^{LF} + LL_D^{LF} + LL_{GD}^{LF} + LL_s^{LF} + LL_r^{CPUE} + LL_D^{CPUE} + LL_s^{CPUE} + LL_r^{catch} + LL_D^{catch} + LL_{GD}^{catch} + LL_R + LL_F + LL_{GF} + LL_{QQ} + LL_{1997LMB} + LL_{2000LMB} + LL_{2003LMB} + LL_{L50} + LL_{\beta} + LL_{CPUERATIO} \quad . \quad (38)$$

Following quantities are computed from the estimated parameters:

Harvest rate

Total pot fishery harvest rate:

$$E_t = \frac{\hat{C}_t + \hat{D}_t}{\sum_j^n (N_{j,t} + O_{j,t})} \tag{39}$$

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*:

$$LMB_t = \sum_{j=legal\ size}^{n} s_j^T s_j^r (N_{j,t} + O_{j,t})\, w_j \tag{40}$$

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

$$MMB_t = \sum_{j=mature\ size}^{n} \{(N_{j,t} + O_{j,t})e^{-y'M} - (\hat{C}_{j,t} + \hat{D}_{j,t} + \hat{T}_{j,t})e^{-(y_t - y')M}\}\, w_j \tag{41}$$

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 $MMB_t > 0.25 M\overline{MB}$,

$$F' = \gamma M \frac{(\frac{MMB_t}{M\overline{MB}} - \alpha)}{(1-\alpha)} \tag{42}$$

(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 $M\overline{M}B$ 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 (41) and (42) 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.