AGENDA D-7
(SSC only)
APRIL 2008

MEMORANDUM

ESTIMATED TIME
2 HOURS

TO: SSC Members

FROM: Chris Oliver
Executive Director

DATE: March 26, 2008

SUBJECT: Crab model review

ACTION REQUIRED

Review crab stock assessment models, provide guidance to authors (SSC only)

BACKGROUND

In December of 2007 the Council took final action on amendment 24 to the BSAI king and Tanner Crab FMP to revise the existing overfishing definitions for the crab stocks in the BSAI. In anticipation of the forthcoming review of crab stock assessments for OFL setting at the June 2008 meeting, the SSC is schedule to review and provide comments to stock assessment authors at this meeting. The Crab Plan Team has compiled an initial list of recommendations for crab stock assessments (Item D-7(a)). Draft guidelines for structure of the Crab SAFE chapters is attached as Item D-7(b). The CPT's external review guidelines document detailing the timing and process for external review of crab stock assessments is attached as Item D-7(c). Additional information included for the SSC's consideration at this time are the following: amendment text for Amendment 24 describing the approved Tier system and process for OFL determination (Item D-7(d)), excerpted information on control rule parameters from the EA for Amendment 24 including preliminary information on the gamma parameter for Tier 4 stocks (Item D-7(e)), 2007 stock assessments for Bristol Bay red king crab (Item D-7(f)) and EBS snow crab (Item D-7(g)). A CIE review was conducted on the EBS snow crab model in February 2008. The reports from the CIE reviewers are attached as Item D-7(h).

The Crab Plan Team will meet from May 6-8, 2008 at the Alaska Fisheries Science Center in Seattle to review preliminary stock assessment information for all 10 BSAI crab stocks under the FMP and make recommendations regarding appropriate tier levels and OFLs as necessary for specific stocks. The SSC will receive the preliminary stock assessments, the CPT's report on recommendations for all stocks, and provide their own recommendations accordingly at the June 2008 meeting.

AGENDA D-7(a)
APRIL 2008

Crab Plan Team suggestions for 2008 Crab Stock Assessments

The following suggestions are compiled by Crab Plan Team members to provide additional suggestions to crab stock assessment authors regarding the forthcoming May CPT review of stock assessments for 10 BSAI crab stocks for purposes of OFL setting. The CPT understands that this is the first year of the review of assessments and that in the future their comments will be provided for each individual assessment in the context of the review of that assessment annually. However, given the timing of the first year of implementation, the team chose to make some suggestions in anticipation that to the extent possible, assessment authors will include these or be prepared to discuss them at the May meeting in conjunction with their assessment. The Team intends to develop detailed TOR of each Tier level before April 2009.

General comments (all Tiers)

1. Provide full mathematical specifications for the assessment model and the likelihood function (or the analysis method), with clear and comprehensive definition of all terms involved in the equations (perhaps in an appendix).
2. Include a section in the assessment document summarizing the assumptions made regarding key parameters (e.g., *M*, retained and discard selectivity curves, maturity curves) and the justification, if any, for any pre-specified values for these parameters.
3. Include a section in the assessment document summarizing bycatch information (all sources) and assumptions about handling mortality.
4. Provide (or be prepared to provide at the meeting) alternative Tier level calculations should author-recommended tier level not be accepted by the CPT.

General comments (Tier 1, 2, 3 stocks and Tier 4 stocks which rely on an assessment model)

5. Conduct retrospective analyses: provide time-trajectories of biomass, exploitation rate and other pertinent model outputs for two types of retrospective analysis: (a) based on leaving the data for one year at a time out of the "best" assessment, (b) based on each previous assessment (this captures both new data and changes in methodology over time).
6. Provide and discuss the residuals for the fits to the size-composition and index data.
7. Provide and discuss fishery and survey selectivities, including how they may vary over time.
8. Discuss and justify the approach used for fitting shell condition
9. Discuss and justify how *M* is modeled (time-invariant or time-dependent).
10. Discuss and justify assumptions regarding maturity schedules
11. Plot fits to abundance by length on arithmetic not a log scale, as it is difficult to judge the fit when results are shown on a log scale.
12. Show the fits to discarded catch as well as to retained or total directed fishery catch.
13. Plot the fully-selected fishing mortality at the time of the fishery against the MMB at time of mating.

General comments (Tier 4 stocks)

14. Examine sensitivity to the range of years utilized for estimating mean biomass.

General comments (Tier 5 stocks)

15. Examine sensitivity to the range of years used when calculating average catch.

Specific suggestions for the EBS snow crab model:

- Provide CIE review documentation and the authors response to review

Specific suggestions for Bristol Bay red king crab model:

- Start the model in 1968 so that the pre-1981 recruitments can be used to estimate $B_{35\%}$.
- The minimum length in the model should be selected so that the majority of mature crab (male and female) and the catch (including discard) are captured (e.g. 60mm).
- Show results for constant (0.18yr^{-1}) and variable M for both males and females.
- Explore constant molting probabilities estimated from tagging data without the use of shell condition data (using size measurements to determine whether molting occurred or not) due to uncertainty in shell age using shell condition.
- Estimate survey selectivity in the model with different selectivity patterns for 1968-1981 and 1982 onwards to account for the different nets used, which have different catchability. If the survey area didn't cover the whole Bristol Bay red king crab stock in the early years then another survey selectivity will need to be estimated to account for this.
- Estimate fishery selectivities for discarded and retained catch. The selectivity of old and new shell in the fishery is important due to the increased discarding of old shell legal males in the IFQ fishery. Examine whether it is justified to estimate a separate fishery selectivity (in the model) for the IFQ fishery for assessment purposes and for $F_{35\%}$ determination. Account may have to be taken of some error for new and old shell to do this.
- The maturity schedule currently used is close to knife-edged at 120 mm for male red king crab (based on Kodiak mating pairs and the difference in growth between Kodiak and Bristol Bay). This assumption should be discussed given there are no estimates of male maturity for Bristol Bay red king crab. Based on the sizes of mature males in Kodiak mating pairs, the size at 50% maturity for Bristol Bay red king crab is possibly higher than 120mm. For example, in the Kodiak data only 4% of males were smaller than 130mm, but there is lower growth in the Bering Sea. The mean length of all male crab was 159 mm. The crab in mating pairs would need to be compared with all crab in the population to estimate the length-at-50%-maturity, something which was not done in the Kodiak study; rather males were estimated to be 40% greater than females in grasping pairs, i.e. if the length-at-50%-maturity is 90mm for females in the Bering Sea then this would result in a length-at-50%-maturity for male crab of 126 mm. The sensitivity of the estimates of biomass, exploitation rate, $F_{35\%}$ and $B_{35\%}$ to a higher size at 50% maturity for male red king crab should be examined.

DRAFT

A Guide to the Preparation of Bering Sea and Aleutian Islands Crab SAFE Report Chapters

A chapter should be produced for the SAFE report in all cases, and should include all sections listed in the "Outline of SAFE Report Chapters" below. The Outline is intended to provide a consistent structure and logical flow for stock assessments. Some variation from this outline is permissible if warranted by limitations of data or other extenuating circumstance. However, it is particularly important that all of the items listed under "Projections and Harvest Alternatives" be included to the maximum extent possible, in that many of these are critical to the fishery management process. Careful consideration should be given to all applicable SSC comments from the previous assessment(s). Fishing mortality values (F) are always full selection fishing mortality (the F at fishing selectivity equal to 1.0).

Outline of SAFE Report Chapters

Executive Summary

Stock: species/area

Catches: trends and current levels

Data and assessment: date of last assessment, type of assessment model, data available, new information, and information lacking

Unresolved problems and major uncertainties: any special issues that complicate scientific assessment, questions about the best model scenario, etc.

Reference points: management targets and definition of overfishing

Stock biomass: trends and current levels relative to virgin or historic levels, description of uncertainty

Recruitment: trends and current levels relative to virgin or historic levels

Exploitation status: full selection Fishing mortality, trends, past year and recommended. Other measures of fishing mortality (exploitation rates) if appropriate

Management performance: ABC and OY estimates, overfishing levels, retained catch and discard

Forecasts: normally three-year forecasts of catch and biomass

Decision table: (if available)

Recommendations: research and data collection needs

Summary of Major Changes

Changes (if any) in the input data

Changes (if any) in the assessment methodology

Changes (if any) in the assessment results, including projected biomass, GHL, total catch (including discard mortality and retained catch), and FOFL (the full selection fishing mortality rate (F) that results in overfishing)

Responses to SSC Comments

Responses to SSC comments specific to this assessment (for each comment that is addressed in the main text, list comment and give name of section where it is discussed; if the SSC did not make any comments specific to this assessment, say so)

Responses to SSC comments on assessments in general (for each comment that is addressed in the main text, list comment and give name of section where it is discussed; if the SSC did not make any comments on assessments in general, say so)

Introduction

Scientific name

Description of general distribution

Description of management unit(s) (be sure to include any spatial and/or seasonal management measures).

Evidence of stock structure, if any

Description of life history characteristics relevant to stock assessments (e.g., special features of reproductive biology)

Fishery

- Description of the directed fishery
- Information on bycatch and discards
- Summary of historical catch distributions

Table showing time series of GHL, discards (directed fishery discards and other fishery discards), total catch (discard mortality and retained catch); accompanied by a list of recent relevant management or assessment changes that have influenced choice of GHL; selectivity of commercial fishing gear; or distribution of catch by gear, area, or season (e.g., changes in mesh size, gear allocations, pot limits, harvest strategy, or modeling approach)

Data (Items in this section should be presented in tabular form.)

Data which should be presented as time series :

- Total catch, partitioned by strata used in the assessment model, if any
- Catch at age or catch at length, as appropriate
- Survey biomass estimates and variances, and/or confidence intervals
- Survey numbers at age or numbers at length, as appropriate
- Other time series data (e.g., predator abundance, fishing effort)
- Sample sizes (e.g., numbers of age or length samples by year, gear, and area)

Data which may be aggregated over time:

- Length at age
- Growth per molt
- Weight at length or weight at age

Analytic Approach

Model Structure

Description of overall modeling approach (e.g., age/size structured versus biomass dynamic, maximum likelihood versus Bayesian)

Reference for software used (e.g., Synthesis, AD Model Builder)

Description of, or reference for, population dynamic representations used in the model (e.g., Baranov catch equation, Brody length-at-age equation)

List and description of all likelihood components in the model

Discussion of changes in any of the above since the previous assessment

Parameters Estimated Independently

List of parameters that are estimated independently of others (e.g., the natural mortality rate, parameters governing the maturity schedule)

Description of how these parameters are estimated (methods do not necessarily have to be statistical; e.g., M could be estimated by referencing a previously published value)

Parameters Estimated Conditionally

List of parameters that are estimated conditionally on those described above (e.g., full-selection fishing mortality rates, parameters governing the survey and fishery selectivity schedules, recruitments)

Description of how these parameters are estimated (e.g., error structures assumed, list of likelihood components, constraints on parameters)

Critical assumptions and consequences of assumption failures

Model Evaluation

Description of alternative models, if any (e.g., alternative M values or likelihood weights)

Evidence of search for balance between realistic (but possible over-parameterized) and simpler (but not realistic) models

Use hierarchical approach where possible (e.g. asymptotic vs domed selectivities, constant vs time varying selectivities)

Do parameter estimates make sense, are they credible?

Description of criteria used to evaluate the model or to choose between alternative models, including the role (if any) of uncertainty

Residual analysis (e.g. residual plots, time series plots of observed and predicted values or other approach)

Evaluation of the model, if only one model is presented; or evaluation of alternative models and selection of final model, if more than one model is presented

List of final parameter estimates, with confidence intervals or other statistical measures of uncertainty if possible (if the set of parameters includes quantities listed in the "Results" section below, the values of these quantities should be presented in the "Results" section rather than here)

Schedules, if any, defined by final parameter estimates

Results

Definition of biomass measures used (e.g., biomass at length 50 and above)

Definition of recruitment measures used (e.g., numbers at length 40-70)

Definition of fishing mortality measures used (e.g., full-recruitment F multiplied by selectivity for lengths 80 and above)

Table of estimated abundance and biomass time series, including spawning biomass as one measure, with confidence bounds or other statistical measure of uncertainty if possible. Include estimates from previous SAFE for retrospective comparisons

Table of estimated recruitment time series, including average, with confidence bounds or other statistical measure of uncertainty if possible. Include estimates from previous SAFE for retrospective comparisons

Table of estimated catch/biomass time series, with confidence bounds or other statistical measure of uncertainty if possible.

Graphs of fishery and survey selectivities, molting probabilities, and other schedules depending on parameter estimates

Graph of estimated male, female, total and effective mature biomass time series, with confidence bounds if possible

Include a graph of the estimated fishing morality versus estimated spawning stock biomass, including applicable OFL and maximum F_{target} definitions for the stock. The rationale is that graphs of this type are useful to evaluate management performance.

Graph of estimated full selection F over time.

Graphs of model fits to survey numbers or proportions by age or length.

Graphs of model fits to catch numbers or proportions by age or length.

Uncertainty and sensitivity analyses.

1. The best approach for describing uncertainty and range of probable biomass estimates in stock assessments may depend on the situation. Approaches used previously are:

    a) Sensitivity analyses (tables or figures) that show ending biomass levels or likelihood component values obtained while systematically varying emphasis factors for each type of data in the model.
    b) Likelihood profiles for parameters or biomass levels may also be used.
    c) CVs for biomass estimated by bootstrap, implicit autodifferentiation, or the delta method;
    d) Subjective appraisal of magnitude and sources of uncertainty;
    e) Comparison of alternate models;
    f) Comparison of alternate assumptions about recent recruitment.

2. If a range of model runs (e.g.; based on CV's or alternate assumptions about model structure or recruitment) is used to depict uncertainty, then it is important that some qualitative or quantitative information about relative probability be included. If no statements about relative probability can be made, then it is important to state that all scenarios (or all scenarios between the bounds depicted by the runs) are equally likely.

3. if possible, ranges depicting uncertainty should include at least three runs: (a) one judged most probable; (b) at least one that depicts the range of uncertainty in the direction of lower current biomass levels; and (c) one that depicts the range of uncertainty in the direction of higher current biomass levels. The entire range of uncertainty should be carried through stock projections and decision table analyses.

4. retrospective analysis (retrospective bias in base model or models for each area).

5. historic analysis (plot of actual estimates from current and previous assessments for each area).

6. Simulation results (if available).

Projections and Harvest Alternatives

List of parameter and stock size estimates (or best available proxies thereof) required by limit and target control rules specified in the fishery management plan

Specification of FOFL , OFL, the upper bound on Ftarget, and other applicable measures (if any) relevant to determining whether the stock is overfished or if overfishing is occurring.

List of standard harvest scenarios and description of projection methodology

Table of 12-year projected catches corresponding to the alternative harvest scenarios, using stochastic methods if possible (mean values or other statistics may be shown in the case of stochastic recruitment scenarios)

Table of 12-year 5-year (or 10-year, if the stock is overfished) projected spawning biomass corresponding to the alternative harvest scenarios, using stochastic methods if possible (mean values or other statistics may be shown in the case of stochastic recruitment scenarios)

Table of 12-year projected fishing mortality rates corresponding to the alternative harvest scenarios, using stochastic methods if possible (mean values or other statistics may be shown in the case of stochastic recruitment scenarios)

Discussion of information, if any, that might warrant setting the GHL or total catch below the upper bound

Recommendation of F_{OFL} , OFL total catch, OFL retained catch for coming year.

Include a subsection titled "Area Allocation of Harvests" and provide results and details of any apportionment schemes that are used.

Data gaps and research priorities

Summary

Table showing M, Tier (previous year or recommended), projected total biomass (give age or length range), female spawning biomass, male spawning biomass and total spawning biomass for current year and for next year. Male spawning biomass values at the time of mating for B0 and Bmsy and Fmsy (if available from stock-recruit relationship) or proxy values, FOFL , the maximum allowable value for Ftarget , the recommended value of OFL, the maximum allowable total catch.

Literature Cited

The ecosystem section can be added when time allows

Ecosystem Considerations

Discussion of any ecosystem considerations (e.g., relationships with species listed under the ESA, prohibited species concerns, bycatch issues, refuge areas, and gear considerations).

The following subsections should provide information on how various ecosystem factors might be influencing their stock or how the specific stock fishery might be affecting the ecosystem and what data gaps might exist that prevent assessing certain effects.

Stock assessment authors would be encouraged to rely on information in the Ecosystem Considerations chapter to assist them in developing stock-specific analysis and recommending new information to the Ecosystem Considerations chapter that might be required in future years to improve the analysis. Time-series that are in the Ecosystem Chapter would be referred to by the author and not duplicated in their chapter. In cases where the authors have time series or relationships that are specific to their stock, that information should be in their assessment chapter and not in the Ecosystem chapter.

Ecosystem Effects on Stock

There are several factors that should be considered for each stock in this subsection. These include:

1) Prey availability/abundance trends (historically and in the present and foreseeable future). These prey trends could affect growth or survival of a target stock.

2) Predator population trends (historically and in the present and foreseeable future). These trends could affect stock mortality rates over time.

3) Changes in habitat quality (historically and in the present and foreseeable future). These would primarily be changes in the physical environment such as temperature, currents, or ice distribution that could affect stock migration and distribution patterns, recruitment success, or direct effects of temperature on growth.

Fishery Effects on the Ecosystem

In this section the following factors should be considered:

1) Fishery-specific contribution to bycatch of prohibited species, forage (including herring and juvenile pollock), HAPC biota (in particular, species common to *YourFishery*), marine mammals

and birds, and other sensitive non-target species (including top predators such as sharks, expressed as a percentage of the total bycatch of that category of bycatch.

2) Fishery-specific concentration of target catch in space and time relative to predator needs in space and time (if known) and relative to spawning components.

3) Fishery-specific effects on amount of large size target fish.

4) Fishery-specific contribution to discards and offal production.

5) Fishery-specific effects on age-at-maturity and fecundity of the target species.

6) Fishery-specific effects on EFH non-living substrate (using gear specific fishing effort as a proxy for amount of possible substrate disturbance).

Authors should consider summarizing the results of these analyses into a table as shown below (for example):

Analysis of ecosystem considerations for *YourStock* and the *YourFishery*. The observation column should summarize the past, present, and foreseeable future trends. The interpretation column should provide details on how the trend affects the stock (ecosystem effects on the stock) or how the fishery trend affects the ecosystem (fishery effects on the ecosystem). The evaluation column should indicate whether the trend is of: *no concern, probably no concern, possible concern, definite concern,* or *unknown.*

Ecosystem effects on *YourStock*

Indicator	Observation	Interpretation	Evaluation
Prey availability or abundance trends			
Zooplankton	Stomach contents, ichthyoplankton surveys, changes mean wt-at-age	Stable, data limited	Unknown
Predator population trends			
Marine mammals	Fur seals declining, Steller sea lions increasing slightly	Possibly lower mortality on pollock	No concern
Birds	Stable, some increasing some decreasing	Affects young-of-year mortality	Probably no concern
Fish (Pollock, Pacific cod, halibut)	Stable to increasing	Possible increases to pollock mortality	
Changes in habitat quality			
Temperature regime	Cold years pollock distribution towards NW on average	Likely to affect surveyed stock	No concern (dealt with in model)
Winter-spring environmental conditions	Affects pre-recruit survival	Probably a number of factors	Causes natural variability
Production	Fairly stable nutrient flow from upwelled BS Basin	Inter-annual variability low	No concern

***YourFishery* effects on ecosystem**

Indicator	Observation	Interpretation	Evaluation
Fishery contribution to bycatch			
Prohibited species	Stable, heavily monitored	Minor contribution to mortality	No concern
Forage (including herring, Atka mackerel, cod, and pollock)	Stable, heavily monitored	Bycatch levels small relative to forage biomass	No concern
HAPC biota	Low bycatch levels of (spp)	Bycatch levels small relative to HAPC biota	No concern
Marine mammals and birds	Very minor direct-take	Safe	No concern
Sensitive non-target species	Likely minor impact	Data limited, likely to be safe	No concern
Fishery concentration in space and time	Generally more diffuse	Mixed potential impact (fur seals vs Steller sea lions)	Possible concern
Fishery effects on amount of large size target fish	Depends on highly variable year-class strength	Natural fluctuation	Probably no concern
Fishery contribution to discards and offal production	Decreasing	Improving, but data limited	Possible concern
Fishery effects on age-at-maturity and fecundity	New study initiated in 2002	NA	Possible concern

AGENDA D-7)(c)
APRIL 2008

Draft Guideline for Crab Assessments

Notification:

The appropriate time period for notification of intent to solicit an external stock assessment review would be in October. This would give the public the entire time period between May (when stock assessments are first reviewed by the CPT) and October (when TACS are announced) to determine if they had an issue with the stock assessment that they wished to have reviewed externally

Timing:

In order to alleviate possible complications with staff workloads, the appropriate time period for an external review (inclusive of any interactions with the stock assessment authors as well as any follow up workshop) would be from October-March. This would allow for the normal stock assessment, data analysis and TAC setting process to occur between April and October.

Ideally, the reviewer will work with Assessment Authors in a collegial setting where reviewers would make suggestions to the framework or information used in the assessment. If this procedure is adopted, the Assessment Author would work with the reviewer(s) to find a mutually acceptable time for a pre-assessment workshop.

Responsibilities of External Reviewers and Assessment Authors:

The pre-assessment workshop will allow the reviewer to discuss the stock assessment with the Assessment Author and make requests for model modifications or alternative use of information in the assessment. The External Reviewer should produce a written report of their recommendations. To the extent practicable, the Assessment Author will address the comments and suggestions documented in the External Reviewer's report in their SAFE document. In general it is assumed that the Assessment Author will be able to determine whether any changes in the stock assessment recommended by the External Reviewer are substantial enough to require review by the Plan Teams and SSC. Assessment Authors will have the professional discretion to decide when the External Reviewer's recommendations will be incorporated into the SAFE document. When the External Reviewer's recommendation involves a matter of professional discretion, such as the choice of statistical or computational methods, Assessment Authors will have the ability to decline to implement the recommendation. In addition, Assessment Authors may defer action on an External Reviewer's recommendation when complying with the recommendation would compromise the SAFE schedule. For example, if an External Reviewer made a request that would require extensive re-analysis of existing data that could not be accomplished prior to the Plan Team meeting, that request could be deferred to a subsequent year.

Anticipated results of an external review:

The CPT will receive both comments from the external reviewer (to the extent these are made available) as well as a report from the assessment author at the subsequent May CPT meeting indicating how comments by the external reviewer were addressed in the assessment.

AGENDA D-7(d)
APRIL 2008

Amendment 24
To the Fishery Management Plan for Bering Sea/Aleutian Islands King and Tanner Crabs

(1) Revise the following definitions in 4.0 DEFINITIONS OF TERMS to read:

Maximum sustainable yield (MSY) is the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological and environmental conditions. MSY is estimated from the best information available.

F_{MSY} control rule means a harvest strategy which, if implemented, would be expected to result in a long-term average catch approximating MSY.

B_{MSY} stock size is the biomass that results from fishing at constant F_{MSY} and is the minimum standard for a rebuilding target when a rebuilding plan is required.

Maximum fishing mortality threshold (MFMT) is defined by the F_{OFL} control rule, and is expressed as the fishing mortality rate.

Minimum stock size threshold (MSST) is one half the B_{MSY} stock size.

* * * * *

Overfished is determined by comparing annual biomass estimates to the established MSST. For stocks where MSST (or proxies) are defined, if the biomass drops below the MSST (or proxy thereof) then the stock is considered to be overfished.

Overfishing is defined as any amount of catch in excess of the overfishing level (OFL). The OFL is calculated by applying the F_{OFL} control rule annually estimated using the tier system in Chapter 6.0 to abundance estimates.

* * * * *

(2) Revise the first paragraph of 5.0 DESCRIPTION OF FISHERY MANAGEMENT UNIT to read:

This FMP applies to commercial fisheries for red king crab Paralithodes camtschaticus, blue king crab P. platypus, golden (or brown) king crab Lithodes aequispinus, Tanner crab Chionoecetes bairdi, and snow crab C. opilio in the BS/AI area, except for the following stocks exclusively managed by the State of Alaska: Aleutian Islands Tanner crab, Dutch Harbor red king crab, St. Matthew golden king crab, and St. Lawrence blue king crab.

The common and scientific names used in this FMP are those included in Williams et al. (1988), appropriately amended, with secondary common names sometimes used in the fishery included in parentheses. Members of the genus Chionoecetes are often collectively referred to as Tanner crabs; to avoid confusion, the name Tanner crab is used for C. bairdi and snow crab is used for C. opilio. Through 1989, commercial landings had only been reported for red, blue, and golden king crab; and Tanner, snow, and hybrids of these two species.

(3) Replace Chapter 6.0 SPECIFICATION OF MAXIMUM SUSTAINABLE YIELD, OPTIMUM YIELD, MINIMUM STOCKS SIZE THRESHOLDS, OVERFISHING LEVELS, ANNUAL HARVEST, AND ANNUAL PROCESSING with the following:

6.0 STATUS DETERMINATION CRITERIA

Status determination criteria for crab stocks are annually calculated using a five-tier system that accommodates varying levels of uncertainty of information. The five-tier system incorporates new scientific information and provides a mechanism to continually improve the status determination criteria as new information becomes available. Under the five-tier system, overfishing and overfished criterion are annually formulated and assessed to determine the status of the crab stocks and whether (1) overfishing is occurring or the rate or level of fishing mortality for a stock or stock complex is approaching overfishing, and (2) a stock or stock complex is overfished or a stock or stock complex is approaching an overfished condition.

Overfishing is determined by comparing the overfishing level (OFL), as calculated in the five-tier system for the crab fishing year, with the catch estimates for that crab fishing year. For the previous crab fishing year, NMFS will determine whether overfishing occurred by comparing the previous year's OFL with the catch from the previous crab fishing year. This catch includes all fishery removals, including retained catch and discard losses, for those stocks where non-target fishery removal data are available. Discard losses are determined by multiplying the appropriate handling mortality rate by observer estimates of bycatch discards. For stocks where only retained catch information is available, the OFL will be set for and compared to the retained catch.

NMFS will determine whether a stock is in an overfished condition by comparing annual biomass estimates to the established MSST, defined as ½ B_{MSY}. For stocks where MSST (or proxies) are defined, if the biomass drops below the MSST (or proxy thereof) then the stock is considered to be overfished. MSSTs or proxies are set for stocks in Tiers 1-4. For Tier 5 stocks, it is not possible to set an MSST because there are no reliable estimates of biomass.

If overfishing occurred or the stock is overfished, section 304(e)(3)(A) of the Magnuson-Stevens Act, as amended, requires the Council to immediately end overfishing and rebuild affected stocks.

Annually, the Council, Scientific and Statistical Committee, and Crab Plan Team will review (1) the stock assessment documents, (2) the OFLs and total allowable catches or guideline harvest levels for the upcoming crab fishing year, (3) NMFS's determination of whether overfishing occurred in the previous crab fishing year, and (4) NMFS's determination of whether any stocks are overfished.

Five-Tier System

The OFL for each stock is annually estimated for the upcoming crab fishing year using the five-tier system, detailed in Table 6-1 and 6-2. First, a stock is assigned to one of the five tiers based on the availability of information for that stock and model parameter choices are made. Tier assignments and model parameter choices are recommended through the Crab Plan Team process to the Council's Scientific and Statistical Committee. The Council's Scientific and Statistical Committee will recommend tier assignments, stock assessment and model structure, and parameter choices, including whether information is "reliable," for the assessment authors to use for calculating the OFLs based on the five-tier system.

For Tiers 1 through 4, once a stock is assigned to a tier, the stock status level is determined based on recent survey data and assessment models, as available. The stock status level determines the equation used in calculating the F_{OFL}. Three levels of stock status are specified and denoted by "a," "b," and "c" (see Table 6-1). The F_{MSY} control rule reduces the F_{OFL} as biomass declines by stock status level. At stock status level "a," current stock biomass exceeds the B_{MSY}. For stocks in status level "b," current biomass is less than B_{MSY} but greater than a level specified as the "critical biomass threshold" (β).

Lastly, in stock status level "c," current biomass is below β * (B_{MSY} or a proxy for B_{MSY}). At stock status level "c," directed fishing is prohibited and an F_{OFL} at or below F_{MSY} would be determined for all other sources of fishing mortality in the development of the rebuilding plan. The Council will develop a rebuilding plan once a stock level falls below the MSST.

For Tiers 1 through 3, the coefficient α is set at a default value of 0.1, and β set at a default value of 0.25, with the understanding that the Scientific and Statistical Committee may recommend different values for a specific stock or stock complex as merited by the best available scientific information.

In Tier 4, a default value of natural mortality rate (M) or an M proxy, and a scalar, γ, are used in the calculation of the F_{OFL}.

In Tier 5, the OFL is specified in terms of an average catch value over an historical time period, unless the Scientific and Statistical Committee recommends an alternative value based on the best available scientific information.

OFLs will be calculated by applying the F_{OFL} and using the most recent abundance estimates. The Crab Plan Team will review stock assessment documents, the most recent abundance estimates, and the proposed OFLs. The Alaska Fisheries Science Center will set the OFLs consistent with this FMP and forward OFLs for each stock to the State of Alaska prior to its setting the total allowable catch or guideline harvest level for that stock's upcoming crab fishing season.

Tiers 1 through 3

For Tiers 1 through 3, reliable estimates of B, B_{MSY}, and F_{MSY}, or their respective proxy values, are available. Tiers 1 and 2 are for stocks with a reliable estimate of the spawner/recruit relationship, thereby enabling the estimation of the limit reference points B_{MSY} and F_{MSY}.

- Tier 1 is for stocks with assessment models in which the probability density function (pdf) of F_{MSY} is estimated.
- Tier 2 is for stocks with assessment models in which a reliable point estimate, but not the pdf, of F_{MSY} is made.
- Tier 3 is for stocks where reliable estimates of the spawner/recruit relationship are not available, but proxies for F_{MSY} and B_{MSY} can be estimated.

For Tier 3 stocks, maturity and other essential life-history information are available to estimate proxy limit reference points. For Tier 3, a designation of the form "F_x" refers to the fishing mortality rate associated with an equilibrium level of fertilized egg production (or its proxy) per recruit equal to X% of the equilibrium level in the absence of any fishing.

The OFL calculation accounts for all losses to the stock not attributable to natural mortality. The OFL is the total catch limit comprised of three catch components: (1) non-directed fishery discard losses; (2) directed fishery discard losses; and (3) directed fishery retained catch. To determine the discard losses, the handling mortality rate is multiplied by bycatch discards in each fishery. Overfishing would occur if, in any year, the sum of all three catch components exceeds the OFL.

Tier 4

Tier 4 is for stocks where essential life-history, recruitment information, and understanding are lacking. Therefore, it is not possible to estimate the spawner-recruit relationship. However, there is sufficient information for simulation modeling that captures the essential population dynamics of the stock as well as the performance of the fisheries. The simulation modeling approach employed in the derivation of the annual OFLs captures the historical performance of the fisheries as seen in observer data from the early 1990s to present and thus borrows information from other stocks as necessary to estimate biological parameters such as γ.

In Tier 4, a default value of natural mortality rate (M) or an M proxy, and a scalar, γ, are used in the calculation of the F_{OFL}. Explicit to Tier 4 are reliable estimates of current survey biomass and the instantaneous M. The proxy B_{MSY} is the average biomass over a specified time period, with the understanding that the Council's Scientific and Statistical Committee may recommend a different value for a specific stock or stock complex as merited by the best available scientific information. A scalar, γ, is multiplied by M to estimate the F_{OFL} for stocks at status levels a and b, and γ is allowed to be less than or greater than unity. Use of the scalar γ is intended to allow adjustments in the overfishing definitions to account for differences in biomass measures. A default value of γ is set at 1.0, with the understanding that the Council's Scientific and Statistical Committee may recommend a different value for a specific stock or stock complex as merited by the best available scientific information.

If the information necessary to determine total catch OFLs is not available for a Tier 4 stock, then the OFL is determined for retained catch. In the future, as information improves, data would be available for some stocks to allow the formulation and use of selectivity curves for the discard fisheries (directed and non-directed losses) as well as the directed fishery (retained catch) in the models. The resulting OFL from this approach, therefore, would be the total catch OFL.

Tier 5

Tier 5 stocks have no reliable estimates of biomass or M and only historical data of retained catch is available. For Tier 5 stocks, the historical performance of the fishery is used to set OFLs in terms of retained catch. The OFL represents the average retained catch from a time period determined to be representative of the production potential of the stock. The time period selected for computing the average catch, hence the OFL, would be based on the best scientific information available and provide the appropriate risk aversion for stock conservation and utilization goals. In Tier 5, the OFL is specified in terms of an average catch value over a time period determined to be representative of the production potential of the stock, unless the Scientific and Statistical Committee recommends an alternative value based on the best available scientific information.

For most Tier 5 stocks, only retained catch information is available so the OFL will be estimated for the retained catch portion only, with the corresponding overfishing comparison on the retained catch only. In the future, as information improves, the OFL calculation could include discard losses, at which point the OFL would be applied to the retained catch plus the discard losses from directed and non-directed fisheries.

Figure 6-1 Overfishing control rule for Tiers 1 through 4. Directed fishing mortality is 0 below β.

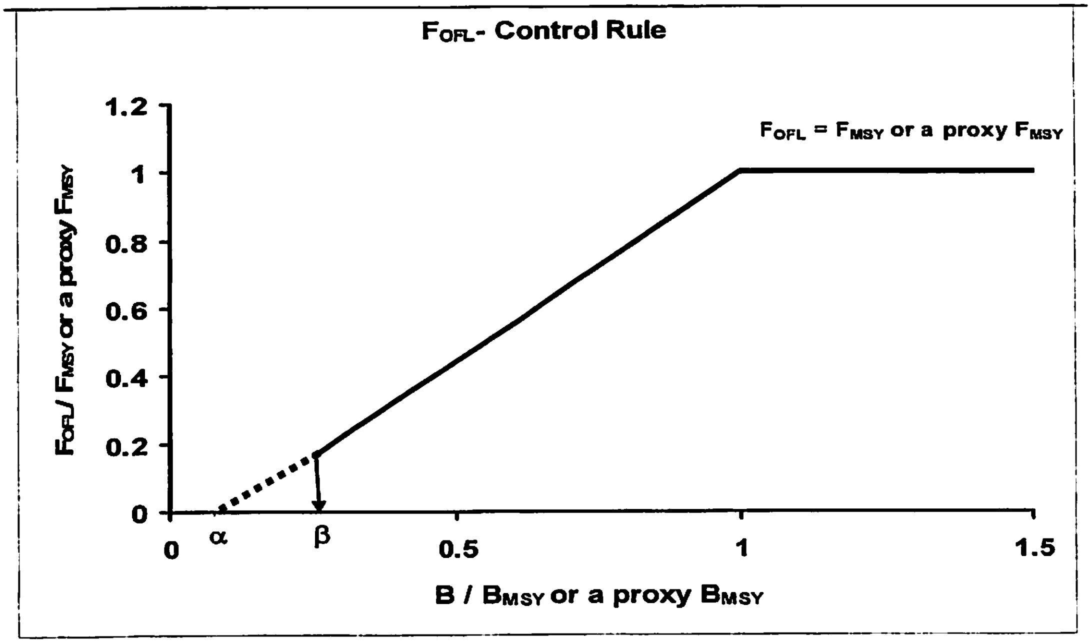

Table 6-1 **Five-Tier System for setting overfishing limits for crab stocks. The tiers are listed in descending order of information availability. Table 6-2 contains a guide for understanding the five-tier system.**

Information available	Tier	Stock status level	F_{OFL}
B, B_{MSY}, F_{MSY}, and pdf of F_{MSY}	1	a. $\frac{B}{B_{msy}} > 1$	$F_{OFL} = \mu_A$ =arithmetic mean of the pdf
		b. $\beta < \frac{B}{B_{msy}} \le 1$	$F_{OFL} = \mu_A \frac{B/B_{msy} - \alpha}{1-\alpha}$
		c. $\frac{B}{B_{msy}} \le \beta$	*Directed fishery F = 0* $F_{OFL} \le F_{MSY}$ †
B, B_{MSY}, F_{MSY}	2	a. $\frac{B}{B_{msy}} > 1$	$F_{OFL} = F_{msy}$
		b. $\beta < \frac{B}{B_{msy}} \le 1$	$F_{OFL} = F_{msy} \frac{B/B_{msy} - \alpha}{1-\alpha}$
		c. $\frac{B}{B_{msy}} \le \beta$	*Directed fishery F = 0* $F_{OFL} \le F_{MSY}$ †
B, $F_{35\%}$*, $B_{35\%}$*	3	a. $\frac{B}{B_{35\%*}} > 1$	$F_{OFL} = F_{35\%}$ *
		b. $\beta < \frac{B}{B_{35\%}*} \le 1$	$F_{OFL} = F^{*}{}_{35\%} \frac{\frac{B}{B^{*}{}_{35\%}} - \alpha}{1-\alpha}$
		c. $\frac{B}{B_{35\%}*} \le \beta$	*Directed fishery F = 0* $F_{OFL} \le F_{MSY}$ †
B, M, $B_{msy^{prox}}$	4	a. $\frac{B}{B_{msy^{prox}}} > 1$	$F_{OFL} = \gamma M$
		b. $\beta < \frac{B}{B_{msy^{prox}}} \le 1$	$F_{OFL} = \gamma M \frac{B/B_{msy^{prox}} - \alpha}{1-\alpha}$
		c. $\frac{B}{B_{msy^{prox}}} \le \beta$	*Directed fishery F = 0* $F_{OFL} \le F_{MSY}$ †
Stocks with no reliable estimates of biomass or M.	5		OFL = average catch from a time period to be determined, unless the SSC recommends an alternative value based on the best available scientific information.

*35% is the default value unless the SSC recommends a different value based on the best available scientific information.

† An $F_{OFL} \le F_{MSY}$ will be determined in the development of the rebuilding plan for that stock.

Table 6-2 A guide for understanding the five-tier system.

- F_{OFL} — the instantaneous fishing mortality (F) from the directed fishery that is used in the calculation of the overfishing limit (OFL). F_{OFL} is determined as a function of:
    - F_{MSY} — the instantaneous F that will produce MSY at the MSY-producing biomass
        - A proxy of F_{MSY} may be used; e.g., $F_{x\%}$, the instantaneous F that results in x% of the equilibrium spawning per recruit relative to the unfished value
    - B — a measure of the productive capacity of the stock, such as spawning biomass or fertilized egg production.
        - A proxy of B may be used; e.g., mature male biomass
    - B_{MSY} — the value of B at the MSY-producing level
        - A proxy of B_{MSY} may be used; e.g., mature male biomass at the MSY-producing level
    - β — a parameter with restriction that $0 \leq \beta < 1$.
    - α — a parameter with restriction that $0 \leq \alpha \leq \beta$.
- The maximum value of F_{OFL} is F_{MSY}. $F_{OFL} = F_{MSY}$ when $B > B_{MSY}$.
- F_{OFL} decreases linearly from F_{MSY} to $F_{MSY} \cdot (\beta - \alpha)/(1 - \alpha)$ as B decreases from B_{MSY} to $\beta \cdot B_{MSY}$
- When $B \leq \beta \cdot B_{MSY}$, $F = 0$ for the directed fishery and $F_{OFL} \leq F_{MSY}$ for the non-directed fisheries, which will be determined in the development of the rebuilding plan.
- The parameter, β, determines the threshold level of B at or below which directed fishing is prohibited.
- The parameter, α, determines the value of F_{OFL} when B decreases to $\beta \cdot B_{MSY}$ and the rate at which F_{OFL} decreases with decreasing values of B when $\beta \cdot B_{MSY} < B \leq B_{MSY}$.
    - Larger values of α result in a smaller value of F_{OFL} when B decreases to $\beta \cdot B_{MSY}$.
    - Larger values of α result in F_{OFL} decreasing at a higher rate with decreasing values of B when $\beta \cdot B_{MSY} < B \leq B_{MSY}$.

(4) Modify sections 8.1.5, 8.3.5. and 8.3.7 to remove references to grooved Tanner crab, St. Matthew golden king crab, AI Tanner crab, St. Lawrence Island blue king crab, scarlet king crab, triangle Tanner crab, and Dutch Harbor red king crab, to read:

8.1.5 Superexclusive Registration in Norton Sound

This FMP establishes the Norton Sound Section of the Northern District of the king crab fishery as a superexclusive registration area. Any vessel registered and participating in this fishery would not be able to participate in other BSAI red and blue king crab fisheries, such as Adak, Bristol Bay, ~~Dutch Harbor~~, Pribilof, ~~St. Lawrence~~, or St.

Matthew, during that registration year. The Norton Sound fishery is the only superexclusive registration area authorized by this FMP.

8.3.5 Gear Modifications

The FMP defers design specifications required for commercial crab pots and ring nets to the State. Pots and ring nets are the specified legal commercial gear for capturing crab in the BS/AI area (see Section 8.1.1). Multiple pots attached to a ground line are currently allowed by the State in the brown (golden) king crab~~, scarlet king crab (Lithodes couesi), grooved Tanner crab (C. tanneri), and triangle Tanner crab (C. angulatus)~~ fisheries. Various devices may be added to pots to prevent capture of other species; to minimize king crab bycatch, the State currently requires tunnel-eye heights to not exceed 3 inches in pots fishing for *C. bairdi* or *C. opilio* in the Bering Sea. Escape mechanisms may be incorporated or mesh size adjusted to allow female and sublegal male crab to escape; the State currently specifies escape rings or mesh panels in regulation for pots used in the BS/AI *C. bairdi*, *C. opilio*, and brown (golden) king crab fisheries, in the Bristol Bay king crab fishery, and in the Pribilof District king crab fishery. State regulations also currently require incorporation of biodegradable twine as an escape mechanism on all pots which will terminate a pot's catching and holding ability in case the pot is lost.

8.3.7 State Observer Requirements

The FMP defers the State Observer requirements to the State. The State may place observers aboard crab fishing and/or processing vessels when the State finds that observers provide the only practical mechanism to obtain essential biological and management data or when observers provide the only effective means to enforce regulations. Data collected by onboard observers in crab fisheries include effort data and data on the species, sex, size, and shell-age/shell-hardness composition of the catch. The State currently requires onboard observers on all catcher/processor or floating-processor vessels processing king or Tanner crab and on all vessels participating in the Aleutian Islands red or brown (golden) king crab fisheries. ~~The State currently may require observers as part of a permit requirement for any vessel participating in the scarlet king crab (Lithodes couesi), grooved Tanner crab (C. tanneri), or triangle Tanner crab (C. angulatus) fisheries.~~ The State currently may require observers on selected catcher vessels taking red or blue king crab in the Norton Sound section, if ADF&G provides funding for the observer presence. ~~The State currently may require observers on vessels taking red or blue king crab in the St. Lawrence Island Section.~~ The State may also require onboard observers in other crab fisheries (e.g., the Pribilof Islands Korean hair crab, *Erimacrus isenbeckii*, fishery) to, in part, monitor bycatch of king or Tanner crab. Observers provide data on the amount and type of bycatch occurring in each observed fishery and estimates of bycatch by species, sex, size, and shell-age/shell-hardness for each observed fishery are currently provided in annual reports by ADF&G.

(5) Revise Appendix E Description of the Fisheries and Stocks to remove references to grooved Tanner crab, St. Matthew golden king crab, Aleutian Islands Tanner

crab, St. Lawrence Island blue king crab, scarlet king crab, triangle Tanner crab, and Dutch Harbor red king crab.

3.2.5 Determination of Tier 1 to 4 Control Rule Parameters

Tiers 1 to 3 control rule formulas consist of four parameters: α, β, B_{MSY} or $B_{X\%}$ and F_{OFL} (F_{MSY} or $F_{x\%}$), while the Tier 4 control rule formula consists of an additional γ parameter associated with *M* to replace F_{OFL}. The deterministic and stochastic simulation analyses were carried out to determine these parameter values first before proceeding into estimating performance statistics for different Tiers

3.2.5.1 $F_{x\%}$, $B_{x\%}$, F_{MSY}, and B_{MSY}

Stock-recruitment relationships were lacking for most BSAI crab stocks for direct estimation of F_{MSY} and B_{MSY} and qualify for Tier 1 or 2. The S-R fits to Bristol Bay red king, Bristol Bay portion of Tanner crab, and snow crab were not considered reliable for Tier 1 or 2. Therefore, reasonable ranges of S-R steepness parameter *h* were considered to determine $F_{x\%}$ and $B_{x\%}$ values as proxies for F_{MSY} (i.e., F_{OFL}) and B_{MSY} respectively in Tier 3 control rule formulas. The steepness ranges were chosen based on *h* estimates from S-R fits to Bristol Bay red king, Bristol Bay portion of Tanner crab, and snow crab stock data during low productivity periods. An *h* range of 0.66 - 1.78 for the Ricker S-R model and a corresponding *h* range of 0.53 - 0.79 for the Beverton-Holt S-R model were chosen for $F_{x\%}$ estimation by Clark's (1991) method for the red king crab. The corresponding *h* ranges for Tanner crab $F_{x\%}$ determination were 0.66-2.2 and 0.53-0.83, respectively; and for the snow crab $F_{x\%}$ determination were 0.52-3.83 and 0.45-0.91, respectively. The $F_{x\%}$ was determined as the 'minimax' point (Clark, 1991) from relative equilibrium yield vs. relative spawning potential ratio curves.

For the red king crab and Tanner crab stocks, the $B_{x\%}$ was estimated at a selected $F_{x\%}$ value from the stochastic simulation of a 100-year fishery with a selected S-R curve and a base *h* value. The average $B_{x\%}/B_0$ ratio was used as a proxy B_{MSY}/B_0 from which the $B_{x\%}$ was determined knowing B_0. The B_0 was estimated at $F = 0$. When the true S-R curve with the estimated *h* value was used the same procedure provided F_{MSY} and B_{MSY} estimates.

For the snow crab stock, MMB per recruit at $F_{x\%}$ was used with the average recruitment estimated from the stock assessment models (Turnock and Rugolo 2006) to estimate $B_{x\%}$ as a proxy for B_{MSY}.

3.2.5.2 α and β

The harvest control rules involve two parameters, α and β. The α parameter in the tier formula determines the slope of the control rule line. The higher the α value the steeper the slope and hence the faster the rebuilding time of an overfished stock. The β parameter value determines the relative biomass level at which the fishery would be closed. The α and β parameters used for the Alternative 2 and 3 status determination criteria are shown in **Error! Reference source not found.**.

A sensitivity analysis of the α and β parameters was investigated by considering a range of values for α (0.0, 0.05, 0.1, 0.25, 0.5) and β (0.0, 0.25, 0.5). An α value of 0.05 is used in the groundfish tier system (NPFMC 1998) whereas a β value of 0.25 is employed as a mature-stock biomass ratio (relative to MSY mature-stock biomass) to determine the fishery closure benchmark in some crab stocks. The parameters were evaluated by rebuilding analyses of a hypothetical overfished stock (10% B_{MSY} and 50% B_{MSY}) under a proxy F_{MSY} ($F_{x\%}$). A number of performance statistics were estimated from 1000 simulations of a 30-year fishery (a few years more than the maximum crab life span) with random recruitment to explore the viability of selected control rule parameter values: median rebuilding time, mean of overfished and $B<25\%B_{MSY}$ proportions, mean and coefficient of variation (CV) of mean yields during the first 10 years and the subsequent 20 years of the rebuilding time period, and the mean of the 30th year B/B_{MSY} ratio. Only red king and snow crabs were considered for these simulations. For the Bristol Bay red king crab a handling mortality rate of 0.2 and for the snow crab a handling mortality rate of 0.25 were used. The results are discussed in Chapters 4 and 5.

3.2.5.3 γ

For Tier 4 stocks, abundance estimates are available, but complete population parameters are not available for computer simulation studies and spawning biomass per recruit analyses needed for Tier 3 stocks.

An important parameter for Tier 4 is γ. A default γ value or a range of γ values can be set for all Tier 4 stocks. In the simulation studies, the ratio of F_{MSY} to M is nearly 2.0 for Bristol Bay red king crab and 3.5 for Bristol Bay portion of the Tanner crab stock, after adjusting the shell condition selectivity. Because Tier 4 is for stocks with limited data, harvest should be more conservative than for these two stocks, which are in Tier 3. This conservation is reflected by the assumption that trawl survey catchability for legal males is equal to 1 for Tier 4 stocks, whereas the survey catchability may be estimated to be less than 1 in a model for Tier 3 stocks. For the five blue king crab and red king crab stocks, the default γ was set to be F_{MSY}/M ($0.3995/0.18 \sim 2.0$) based on Bristol Bay red king crab simulation results. For *Chionoecetes* species, the estimated γ from modified F_{MSY}/M ($0.65574/0.23 \sim 2.85$) was somewhat high. However, for illustrative purpose, this value was used in EBS Tanner crab simulations under Tier 4 control rule. A lower value of 2 or less was suggested for limited data stocks of *Chionoecetes* species. The value for γ is frameworked, depending on the values of F_{MSY} or its proxy ($F_{35\%}$) and M.

Appendix B

BRISTOL BAY RED KING CRAB STOCK ASSESSMENT IN 2007

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EXECUTIVE SUMMARY

A length-based model was applied to eastern Bering Sea trawl survey, catch sampling, and commercial catch data to estimate stock abundance and recruitment of Bristol Bay red king crabs (*Paralithodes camtschaticus*) during 1972-2007. The model was developed in 1994 and assumes the trawl survey selectivities/catchability to be 1 for mature crabs and estimates natural mortality. The model was modified in 2006 to include discarded bycatch. Two levels of male natural mortality and 3 levels of female natural mortality over time were estimated in the model. The model fit the data very well, and its results were used to construct stock–recruitment relationships and determine the preseason total allowable catch (TAC).

Due to above average year classes 1990, 1994, 1997 and 2000, abundances of mature males, legal males, and mature females all increased in 2007 from 2006 and are at the highest levels since 1982. Abundance of mature males increased from 18.9 million in 2006 to 21.0 million in 2007, and legal male abundance increased from 10.6 million in 2006 to 12.3 million in 2007. Mature female abundance increased from 33.4 million in 2006 to 35.7 million crabs in 2007, and effective spawning biomass increased from 67.9 to 72.8 million pounds from 2006 to 2007, above the target rebuilding level of 55 million pounds.

INTRODUCTION

Stock Structure

Red king crabs (RKC), *Paralithodes camtschaticus*, are found in several areas of the Aleutian Islands and eastern Bering Sea. The State of Alaska divides the Aleutian Islands and eastern Bering Sea into three management registration areas to manage RKC fisheries: Aleutian Islands, Bristol Bay, and Bering Sea (ADF&G 2005). The Aleutian Islands area covers two stocks, Adak and Dutch Harbor, and the Bering Sea area contains two other stocks, the Pribilof Islands and Norton Sound. The largest stock is found in the Bristol Bay Area, which includes all waters north of the latitude of Cape Sarichef (54°36' N lat.), east of 168° W long., and south of the latitude of Cape Newneham (58°39' N lat.) (ADF&G 2005). Besides these five stocks, RKC stocks elsewhere in the Aleutian Islands and eastern Bering Sea are currently too small to support a commercial fishery. This report summarizes the stock assessment results for the Bristol Bay RKC stock.

Fishery

The RKC stock in Bristol Bay, Alaska, supports one of the most valuable fisheries in the United States (Bowers et al. 2005). The Japanese fleet started the fishery in the early 1930s, stopped fishing from 1940 to 1952, and resumed the fishery from 1953 until 1974 (Bowers et al. 2005). The Russian fleet fished for RKC from 1959 through 1971. The Japanese fleet employed primarily tanglenets with a very small proportion of catch caught by trawl and pots. The Russian fleet used only tanglenets. U.S. trawlers started to fish for Bristol Bay RKC in 1947, and effort and catch declined in the 1950s (Bowers et al. 2005). The domestic RKC fishery began to expand in the late 1960s and peaked in 1980 with a catch of 59,000 t, worth an estimated $115.3 million ex-vessel value (Bowers et al. 2005). The catch declined dramatically in the early 1980s and has stayed at low levels during the last two decades (Table 1). After the stock collapse in the early 1980s, the Bristol Bay RKC fishery took place during a short period in the fall (usually lasting about a week), and the catch quota is based on the stock assessment conducted in the previous summer (Zheng and Kruse 2002a). As a result of new regulations for crab rationalization, the fishery was longer beginning with the 2005/2006 season, which was open for three months from October 15 to January 15. With the implementation of crab rationalization, historical guideline harvest levels (GHL) were changed to a total allowable catch (TAC). GHL/TAC and actual catch are compared in Table 2. The implementation errors are quite high for some years, and total actual catch from 1980 to 2006 is about 7% less than the GHL/TAC (Table 2).

Fisheries Management

King and Tanner crab stocks in the Bering Sea and Aleutian Islands are managed by the State of Alaska through a federal king and Tanner crab fishery management plan (FMP). Under the FMP, management measures are divided into three categories: (1) fixed in the FMP, (2) frameworked in the FMP, and (3) discretion of the State of Alaska. The State of Alaska is responsible for developing harvest strategies to determine GHL/TAC under the framework in the FMP.

Harvest strategies for the Bristol Bay RKC fishery have changed over time. Two major management objectives for the fishery are to maintain a healthy stock that ensures reproductive viability and to provide for sustained levels of harvest over the long term (ADF&G 2005). In attempting to meet these objectives, the GHL/TAC are coupled with size-sex-season restrictions. Only males ≥6.5-in carapace width (equivalent to 135-mm carapace length, CL) may be harvested and no fishing is allowed during molting and mating periods (ADF&G 2005). Specification of TAC is based on a harvest rate strategy. Before 1990, harvest rates on legal males were based on population size, abundance of prerecruits to the fishery, and postrecruit abundance, and varied from less than 20% to 60% (Schmidt and Pengilly 1990). In 1990, the harvest strategy was modified, and a 20% mature male harvest rate was applied to the abundance of mature-sized (≥120-mm CL) males with a maximum 60% harvest rate cap of legal (≥135-mm CL) males (Pengilly and Schmidt 1995). In addition, a threshold of 8.4 million mature-sized females (≥90-mm CL) was added to existing management measures to avoid recruitment overfishing (Pengilly and Schmidt 1995). Based on a new assessment model and research findings (Zheng et al. 1995a, 1995b, 1997a, 1997b), the Alaska Board of Fisheries adopted a new harvest strategy in 1996. That strategy had two mature male harvest rates: 10% when effective spawning biomass (ESB) is between 14.5 and 55 million pounds and 15% when ESB is at or above 55 million pounds (Zheng el al. 1996). The maximum harvest rate cap of legal males was changed from 60% to 50%. An additional threshold of 14.5 million pounds of ESB was also added. In 1997, a minimum threshold of 4 million pounds was established as the minimum GHL for opening the fishery and maintaining fishery manageability when the stock abundance is low. In 2003, the Board modified the current harvest strategy by adding a mature harvest rate of 12.5% when the stock is between 34.75 and 55 million pounds of ESB. The current harvest strategy is illustrated in Figure 1.

The purpose of this report is to document the stock assessments for Bristol Bay RKC. This report includes (1) all data used to conduct the stock assessments, (2) details of the analytic approach, (3) an evaluation of the assessment results, and (4) the future outlook.

DATA

Catch Data

Landings of Bristol Bay RKC by length and year and catch per unit effort data were obtained from annual reports of the International North Pacific Fisheries Commission from 1960 to 1973 (Hoopes et al. 1972; Jackson 1974; Phinney 1975) and from the Alaska Department of Fish and Game from 1974 to 2006 (Bowers et al. 2005). Bycatch data are available starting from 1990 and were obtained from the ADF&G observer database and reports (Bowers et al. 2005; Burt and Barnard 2006). Sample sizes for catch by length and shell condition are summarized in Table 3. Relatively large samples were taken from the retained catch each year. Sample sizes for trawl bycatch were the annual sums of length frequency samples in the National Marine Fisheries Service (NMFS) database.

Catch Biomass

Retained catch and estimated bycatch biomasses are summarized in Table 1. Retained catch and estimated bycatch from the directed fishery include both the general open access (i.e., harvest not allocated to CDQ groups) fishery and the CDQ fishery. Starting in 1973, the fishery generally occurred during the late summer and fall. Before 1973, a small portion of retained catch in some years was caught from April to June. Because most crab bycatch from the groundfish trawl fisheries occurred during the spring, the years in Table 1 are one year less than those from the NMFS trawl bycatch database to approximate the annual bycatch for seasons defined as June 1 to May 31; e.g., year 2002 in Table 1 corresponds to what is reported for year 2003 in the NMFS database. Catch biomass is shown in Figure 2.

Catch Size Composition

Retained catch by length and shell condition and bycatch by length, shell condition, and sex were obtained for stock assessments. From 1960 to 1966, only retained catch length compositions from the Japanese fishery were available. Retained catches from the Russian and U.S. fisheries were assumed to have the same length compositions as the Japanese fishery during this period. From 1967 to 1969, the length compositions from the Russian fishery were assumed to be the same as those from the Japanese and U.S. fisheries. After 1969, foreign catch declined sharply and only length compositions from the U.S. fishery were used to distribute catch by length.

Catch per Unit Effort

Catch per unit effort (CPUE) is defined as number of retained crabs per tan (a unit fishing effort for tanglenets) for the Japanese and Russian fisheries and number of retained crabs per potlift for the U.S. fishery (Table 4). Although soak time is an important factor influencing CPUE, it is difficult to standardize it. Furthermore, complete historical soak time data from the U.S. fishery are not available. Based on the approach of Balsiger (1974), all fishing efforts from Japan, Russia, and U.S. were standardized as the Japanese tanglenet from 1960 to 1971, and the CPUE was standardized as crabs per tan. The U.S. CPUE data have similar trends as survey legal abundance after 1971 (Figure 3).

Survey Data

NMFS has performed annual trawl surveys of the eastern Bering Sea since 1968. Two vessels, each equipped with an eastern otter trawl with an 83 ft headrope and a 112 ft footrope, conduct this multispecies, crab-groundfish survey during the summer. Stations are sampled in the center of a systematic 20 X 20 nm grid overlaid in an area of $\approx$140,000 nm^2. Since 1972 the trawl survey has covered the full stock distribution. The survey on Bristol Bay area occurs primarily during late May and June. Tow-by-tow trawl survey data for Bristol Bay RKC during 1975-2007 were provided by NMFS.

Abundance estimates by sex, carapace length, and shell condition were derived from survey data using an area-swept approach without post-stratification (Figure 4). If multiple tows were made for a single station in a given year, the average of the abundances from all tows was used as the estimate of abundance for that station. NMFS used a post-stratification approach until the late 1980s and has assumed Bristol Bay as a single stratum since then. If more than one tow is conducted in a station because of high RKC abundance (i.e., the station is a “hot spot”), NMFS regards the station as a separate stratum. Due to poor documentation, it is difficult to duplicate NMFS post-stratifications. A “hot spot” was not surveyed with multiple tows during the early years. Two such “hot spots” affected the survey abundance estimates greatly: station H13 in 1984 (mostly juvenile crabs 75-90 mm CL) and station F06 in 1991 (mostly newshell legal males). The tow at station F06 was discarded in the NMFS abundance estimates (Stevens et al. 1991). In this study, the average abundances from all tows in the 9 stations (the station itself and the 8 adjacent stations) were used as the estimates of abundance for station H13 in 1984 and station F06 in 1991.

The approach here results in estimates close to those made by NMFS with some exceptions (Figure 5). Two surveys were conducted for Bristol Bay red king crabs in 1999, 2000, 2006, and 2007: the standard survey that was performed in late May and early June (about two weeks earlier than historic surveys) in 1999 and 2000 and the standard survey that was performed in early June in 2006 and 2007 and a resurvey of 31 stations (1999), 23 stations (2000), 31 stations (2006, 1 bad tow and 30 valid tows), and 32 stations (2007) with high female density that was performed in late July, about six weeks after the standard survey. The resurveys were necessary because a high proportion of mature females had not yet molted or mated prior to the standard surveys (Figure 6). Tow-by-tow estimates of survey abundance for the 32 valid resurvey stations in 2007 are summarized in Table 5. Differences in area-swept estimates of abundance between the standard surveys and resurveys of these same stations can be attributed to survey measurement errors or, possibly, to seasonal changes in distribution between survey and resurvey. The size distribution of females was significantly larger in the resurveys than during the standard surveys in 1999 and 2000 because most mature females had not molted prior to the standard surveys. Like 2006, area-swept estimates of males >89 mm CL, mature males and legal males within the 32 resurvey stations in 2007 are not statistically significantly different between the standard survey and resurvey (p=0.74, 0.74 and 0.95) based on the t-test of paired two sample for means. However, similar to 2006, area-swept estimates of mature females within the 32 resurvey stations in 2007 are significantly different between the standard survey and resurvey (p=0.03) based on the t-test. NMFS included all survey tows in its estimates in 1999, 2000, 2006 and 2007. To maximize use of the survey data, I used data from both surveys to assess male abundance but only the resurvey data, plus the standard survey data outside the resurveyed stations, to assess female abundance during these four years.

For 1968-1970 and 1972-1974, abundance estimates were obtained from NMFS directly because the original survey data by tow are not currently available. There were spring and fall surveys in 1968 and 1969. The average of estimated abundances from spring and fall surveys was used for those two years. Different catchabilities were assumed for survey data before 1973 because of an apparent change in survey catchability. A footrope chain was added to the trawl gear starting in 1973, and the crab abundances in all length classes in 1973 and beyond were much greater than those estimated prior to 1973 (Reeves et al. 1977).

ANALYTIC APPROACH

To reduce annual measurement errors associated with abundance estimates derived from the area-swept method, the Alaska Department of Fish and Game developed a length-based analysis (LBA) in 1994 that incorporates multiple years of data and multiple data sources in the estimation procedure. Annual abundance estimates of the Bristol Bay RKC stock from the LBA have been used to manage the directed crab fishery and to set crab bycatch limits in the groundfish fisheries since 1995 (Figure 1). The current stock assessment model is named Model A in this report and is the base model used to set TAC. An alternative LBA (research model) was developed in 2004 to include small size groups and extend to the data before 1972. The research model was to fit to the data only from 1985 to 2007. This research model is named Model B in the 2006 SAFE report (Zheng 2006). A stock-recruitment (S-R) relationship, estimated from the results of the base model (Model A), was used to develop the current harvest strategy.

Models

Only stock assessment model (Model A) used since 1995 was reported in this report. Research model (Model B) developed in 2004 was reported in the 2006 SAFE reports and was updated but not reported in this report. The details of the research model can be found in the 2006 SAFE report (Zheng 2006). Three levels of *M* for females and two levels of *M* for males over time were used for Model A.

Population Model

The original LBA model that was described in detail by Zheng et al. (1995a, 1995b) and Zheng and Kruse (2002a) was modified to include fishery discarded bycatch in 2006. Pulse fishing was assumed for the model. Male crab abundances by carapace length and shell condition in any one year are modeled to result from abundances in the previous year minus catch and handling and natural mortalities, plus recruitment and additions to or losses from each length class due to growth:

$$N_{l+1,t+1} = \sum_{l'=1}^{l'=l+1} \{P_{l',l+1} [(N_{l',t} + O_{l',t}) e^{-M_t} - (C_{l',t} + D_{l,t}) e^{(y_t-1)M_t}] m_{l',t}\} + R_{l+1,t+1}, \tag{1}$$

$$O_{l+1,t+1} = [(N_{l+1,t} + O_{l+1,t}) e^{-M_t} - (C_{l+1,t} + D_{l+1,t}) e^{(y_t-l)M_t}](1 - m_{l+1,t}),$$

where

$N_{l,t}$	is newshell crab abundance in length class *l* and year *t*,
$O_{l,t}$	is oldshell crab abundances in length class *l* and year *t*,
M_t	is the instantaneous natural mortality in year *t*,
$m_{l,t}$	is the molting probability for length class *l* in year *t*,
$R_{l,t}$	is recruitment into length class *l* in year *t*,
y_t	is the lag in years between assessment survey and the fishery in year *t*,
$P_{l',l}$	is the proportion of molting crabs growing from length class *l'* to *l* after one molt,
$C_{l,t}$	is the retained catch of length class *l* in year *t*, and
$D_{l,t}$	is the discarded mortality catch of length class *l* in year *t*, including pot and trawl bycatch.

The minimum carapace length for males is set at 95 mm, and crab abundance is modeled with a length-class interval of 5 mm. The last length class includes all crabs ≥160-mm CL. There are 14 length classes/groups (1-14). $P_{l',l}$, $m_{l,t}$, $R_{l,t}$, $C_{l,t}$, and $D_{l,t}$ are computed as follows.

Mean growth increment per molt is assumed to be a linear function of pre-molt length:

$$G_l = a + b\,l, \tag{2}$$

where *a* and *b* are constants. Growth increment per molt is assumed to follow a gamma distribution:

$$g(x \mid \alpha_l, \beta) = x^{\alpha_l - 1}\, e^{-x/\beta} / [\beta^{\alpha_l}\, \Gamma(\alpha_l)]. \tag{3}$$

The expected proportion of molting individuals growing from length class l_1 to length class l_2 after one molt is equal to the sum of probabilities within length range $[l_1, l_2)$ of the receiving length class l_2 at the beginning of the next year:

$$P_{l_1,l_2}=\int_{\iota_1-l}^{\iota_2-l} g(x\,|\,\alpha_t,\beta)dx, \qquad (4)$$

where ι is the mid-length of length class l_1. For the last length class L, $P_{L,L} = 1$.

The molting probability for a given length class l and time t is modeled by an inverse logistic function:

$$m_{l,t}=1-\frac{1}{1+e^{-\beta_t(l-L_{50_t})}}, \qquad (5)$$

where

β_t, L_{50t} are parameters, and

ι is the mid-length of length class l.

Three logistic functions were used to describe the molting probability during different periods for Model A (Zheng et al. 1995a): high molting probabilities with α_1 and β_1 during 1972-1979, low molting probabilities with α_2 and β_2 during 1980-1984, 1992-1995, 1997, and 1999-2001, and intermediate molting probabilities with α_3 and β_3 during 1985-1991, 1996, 1998, and 2002-2007. Grouping of years for molting probabilities is based on the fit of newshell and oldshell crab abundances.

Recruitment is defined as recruitment to the model and survey gear rather than recruitment to the fishery. Recruitment is separated into a time-dependent variable, R_t, and size-dependent variables, U_l, representing the proportion of recruits belonging to each length class. R_t was assumed to consist of crabs at the recruiting age with different lengths and thus represents year class strength for year t. $R_{l,t}$ is computed as

$$R_{l,t}=R_tU_l, \qquad (6)$$

where U_l is described by a gamma distribution similar to equations (3) and (4) with a set of parameters α_r and β_r.

Model A assumes observed retained catch and discarded mortality bycatch to be accurate. Before 1990, no observed bycatch data were available in the directed pot fishery; the crabs that were discarded and died in those years were estimated as the product of handling mortality rate, legal harvest rates, and mean length-specific selectivities. Mean length-specific fishery selectivities for retained males, discarded males and discarded females in the pot fishery were estimated by dividing the catch and bycatch by length by their corresponding estimated abundances and averaging over time.

In the 2005 and 2006 pot fishery, a portion of legal males were also discarded. The selectivity for this highgrading was estimated to be the retained selectivity in 2005 and 2006 times a highgrading parameter, *hg*, each year.

The female crab model is the same as the male crab model except that the retained catch equals zero and molting probability equals 1.0 to reflect annual molting (Powell 1967). The minimum carapace length is set at 90 mm for females for Model A, and the last length class includes all crab ≥140-mm CL, corresponding to length groups 1-11 with 5 mm length intervals for Model A.

Parameters Estimated Independently

Length-weight relationships and mean growth increments per molt were estimated independently outside of the model. Mean length of recruits to the model depends on growth and was assumed to be 95 mm for females and 102 mm for males for Model A.

Length-weight Relationship

Length-weight relationships for males and females were as follows:

$$\begin{aligned} &\text{Immature Females:} && W = 0.010271\, L^{2.388}, \\ &\text{Ovigerous Females:} && W = 0.02286\, L^{2.234}, \qquad (7) \\ &\text{Males:} && W = 0.000361\, L^{3.16}, \end{aligned}$$

where

W is weight in grams, and

L is CL in mm.

Growth Increment per Molt

A variety of data are available to estimate male mean growth increment per molt for Bristol Bay RKC. Tagging studies were conducted during the 1950s, the 1960s and the 1990s, and mean growth increment per molt data from these tagging studies in the 1950s and the 1960s were analyzed by Weber and Miyahara (1962) and Balsiger (1974). Modal analyses were conducted for the data during 1957-1961 and the 1990s (Weber 1967; Loher et al. 2001). Mean growth increment per molt may be a function of body size and shell condition and vary over time (Balsiger 1974; McCaughran and Powell 1977); however, for simplicity, mean growth increment per molt was assumed to be only a function of body size in the models. Tagging data were used to estimate mean growth increment per molt as a function of pre-molt length for males (Figure 8). The results from modal analyses of 1957-1961 and the 1990s were used to estimate mean growth increment per molt for immature females, and the data presented in Gray (1963) were used to estimate those for mature females (Figure 8). To make a smooth transition of growth increment per molt from immature to mature females, weighted growth increment averages of 70% and 30% at 92.5 mm CL pre-molt length and 90% and 10% at 97.5 mm CL were used respectively, for mature and immature females. These percentages are roughly close to the composition of maturity. Once mature, the growth increment per molt for male crabs decreases slightly and annual molting probability decreases, whereas the growth increment for female crabs decreases dramatically but annual molting probability remains constant at 1.0 (Powell 1967).

Parameters Estimated Conditionally

For Model A, the following model parameters were estimated separately for male and female crabs: recruits for each year (year class strength R_t for t = 1973 to 2007), total abundance in the first year (1972), parameters β and β_r, and instantaneous natural mortality M_t (2 to 3 levels of M). Molting probability parameters α_1, α_2, α_3, β_1, β_2, and β_3 were also estimated for male crabs. Total number of parameters to be estimated is 87 for Model A.

To increase the efficiency of the parameter-estimation algorithm, I assumed that the relative frequencies of length and shell classes from survey year 1972 for Model A approximate the true relative frequencies within sexes. Thus, only total abundances of males and females for the first year were estimated; 3n unknown parameters, where n is the number of length-classes, for the abundances in the first year were reduced to 2 under this assumption.

Parameter Estimation

For Model A, measurement errors were assumed to be log-normally distributed, and parameters of the model were estimated using a robust maximum likelihood approach:

$$Ln(L) = -\frac{0.5}{CV^2}\sum_{l,t}\{[\ln(N_{l,t}+\kappa)-\ln(\tilde{N}_{l,t}+\kappa)]^2+[\ln(O_{l,t}+\kappa)-\ln(\tilde{O}_{l,t}+\kappa)]^2\}, \qquad (8)$$

where

$\tilde{N}_{l,t}, \tilde{O}_{l,t}$ are area-swept estimates of abundances of newshell and oldshell crabs in length class *l* and year *t* from trawl survey data, and

κ is a constant set equal to 0.1 millions of crabs (<0.7% and 0.3% of the largest observed male and female abundances by length).

Constant κ was used to prevent taking the logarithm of zero and to reduce the effect of length classes with zero or very low abundances on parameter estimation. A smaller κ gives a heavier weight for low abundances, and vice versa. This constant functions similar to the constant used in the robust likelihood function by Fournier et al. (1990).

S-R MODELS

The results from Model A (base scenario) were used to estimate the parameters of S-R models. I followed Zheng et al. (1995a) and Zheng and Kruse (2003) to estimate effective spawning biomass for Bristol Bay RKC. Male reproductive potential is defined as the mature male abundance by carapace length multiplied by the maximum number of females with which a male of a particular length can mate (Zheng et al. 1995a; Table 6). The maximum mating ratios (Table 6) used in this study are conservative and less than those observed in the laboratory studies (Powell and Nickerson 1965; Powell et al. 1974; Paul and Paul 1990, 1997). If mature female abundance was less than male reproductive potential, then mature female abundance was used as female spawning abundance. Otherwise, female spawning abundance was set equal to the male reproductive potential. The female spawning abundance was converted to biomass, defined as the effective spawning biomass SP_t. The S–R relationships of Bristol Bay RKC were modeled using a general Ricker curve:

$$R_t = SP_{t-k}^{r1}\, e^{r2 - r3\, SP_{t-k} + v_t}, \qquad (9)$$

and an autocorrelated Ricker curve:

$$R_t = SP_{t-k}\; e^{r2 - r3\, SP_{t-k} + \upsilon_t}, \tag{10}$$

where

$\upsilon_t = \delta_t + a1\ \upsilon_{t-1}$,

v_t, δ_t are environmental noises assumed to follow a normal distribution $N(0,\sigma^2)$,

$r1$, $r2$, $r3$, and $a1$ are constants.

Equation (9) was linearized as

$$\ln(R_t) = r2 + r1\ \ln(SP_{t-k}) - r3\ SP_{t-k} + v_t, \tag{11}$$

and equation (10) as

$$\ln(R_t / SP_{t-k}) = r2 - r3\ SP_{t-k} + \upsilon_t. \tag{12}$$

An ordinary linear regression was applied to equation (11) to estimate model parameters $r1$, $r2$ and $r3$, and an autocorrelation regression (procedure AUTOREG, SAS Institute Inc. 1988) with a maximum likelihood method was used to estimate parameters $r2$, $r3$ and $a1$ for equation (12). A time lag of 8 years from mating to recruitment was used (Loher et al. 2001; Zheng and Kruse 2003).

To include the maximum range of available S–R data in the study of S–R relationships, I estimated the effective spawning biomass from 1968 to 1971 using survey abundance and the estimated survey catchability in 1972. The catchability for the survey gear in 1972 was estimated by comparing survey and model estimates. I assumed that the catchability for the survey gears in 1968-1971 was the same as in 1972 because the survey gears and methods were identical during these years (Reeves et al. 1977). Thus, the relative abundances from 1968 to 1971 were divided by the estimated catchability in 1972 to obtain the absolute abundances. The absolute abundances from 1968 to 2007 were used to construct S-R relationships.

Because of the regime shift in climate and physical oceanography that occurred in 1976–77 (Hare and Mantua 2000), it may not be realistic to expect the strong recruitment from hatching years before 1976 to occur in the near future. Also the Crab Plan Team does not consider levels of mature biomass prior to 1983 to be representative of that attainable under the current environmental conditions (NPFMC

1998). Therefore, a normal Ricker S–R curve was also fit to the S–R data after 1976 to estimate an alternative S–R relationship under the current environmental conditions.

As a comparison, mature male biomass on February 15 was also used as an alternative spawning stock index for the S–R relationships. Population abundance at survey time was projected forward to February 15 after adjusting fishing and natural mortalities. February 15 is near the peak of the primiparous female mating, prior to the molting of mature males, and after the fishery. This is about the lowest mature male biomass in a given year and is a conservative spawning biomass index.

RESULTS FOR MODEL A

Stock Assessment Model Evaluation

Model parameter estimates for Model A are summarized in Table 7, and estimated mature male and female abundances are compared in Figures 9 and 10. Common features of the model results were strong recruitment in the 1970s and relatively weak recruitment during the last 20 years. The data fit the model very well. Three scenarios with different levels of *M* were compared in the 2006 assessment, and these comparisons were not repeated this year.

Population Abundance

LBA estimates of Bristol Bay RKC abundance and 95% bootstrap confidence limits for 2007 under the base model (Model A) are shown in Table 8. Mature crab abundance increased to a peak in the late 1970s, decreased dramatically in the early 1980s, remained at low levels during the 1980s and early 1990s, and increased somewhat since the mid 1990s due to the above average year classes (termed the 1990, 1994, 1997 and 2000 year classes in this report based on estimated hatching year). As most male crabs from the first three of these four above average year classes entered the legal-sized population, abundance of large-size groups continued to increase from last year. Mature male abundance increased from 18.943 million to 20.975 million crabs, and legal males increased from 10.647 million to 12.287 million from 2006 to 2007 (Table 8). Due to the above average year class 2000, mature female abundance also continued to increase from last year (35.697 million crabs in 2007 from 33.383 million crabs in 2006). Effective spawning biomass in 2007 (72.844 million pounds) was higher than that in 2006 (67.924 million pounds).

Model A closely fit the survey abundance by length, shell condition, and sex (Figure 11). It appeared that model estimates of oldshell male crabs in 1974, 1980, 1985, 1988, 2001, 2004 and 2006 were much higher than those of the survey. The abundance of newshell males was much higher than the oldshell males in the 1970s.

Molting Probabilities

Three levels of molting probabilities were estimated for different periods. Molting probabilities were very high during 1972-1979, low during 1980-1984, 1992-1995 and 1999-2001, and intermediate during 1985-1991 and 2002-2007 (Figure 12). Estimated molting probabilities during these periods were consistent with that estimated from the 1966-1969 tagging data (Balsiger 1974) but lower than those estimated from the tagging data during 1954-1961 (Balsiger 1974) (Figure 12).

Natural Mortality

Estimated natural mortality overall was much higher for females than males. For the base scenario, estimated natural mortality was very high in the early 1980s (Table 7). The high natural mortality is consistent with survey data (Figure 4), which show a sharp decline of crab abundances in the early 1980s. Factors causing the high natural mortality are not clear. Physical environmental conditions, predation, and disease, or a combination of all these factors may have contributed to high natural mortality (Otto 1986; Blau 1986). Senescence may also play a role for high natural mortality (Stevens 1990); however, high mortality seems to occur for almost all sizes of crabs in the early 1980s.

Exploitation

The RKC fishery in Bristol Bay harvests only legal crabs. Mature male and legal male harvest rates were computed by dividing total catch by the mature male abundance and legal crab abundance estimated in the base scenario at the survey time, respectively. The legal male harvest rates ranged from 0.19 to 0.56 in the 1970s and the early 1980s and fluctuated around 0.22 since the current harvest strategy was adopted in 1996 (Figure 13). After 1995, application of the maximum mature harvest rate of 15% in 1998 and 2003-2006 resulted in a mean legal harvest rate of 0.27 (Figure 13). The mature male harvest rates were close to 0.21 in the 1970s and peaked at 0.33 in 1980 (Figure 13). These high harvest rates and legal crab abundances produced the record catches in the late 1970s and early 1980s, which were followed by the quick collapse of the population. Harvest not only removes legal male crabs but also reduces abundances of sublegal male and female crabs through handling mortality. Although the bycatch mortality biomass was very low relative to the retained catch biomass based on the assumed handling mortality rates (Figure 2), the bycatch handling mortality rate could be higher than those assumed during some extremely cold years (Carls and O'Clair 1990). In summary, it appears that high natural mortality coupled with high harvest rates may have contributed to the collapse of the Bristol Bay RKC population in the early 1980s. The current conservative harvest strategy (low harvest rates) and low natural mortality since the mid 1990s may be assisting the gradual recovery of the stock.

One assumption needed to estimate natural mortality from the survey data is that trawl catchability is equal to 1 during 1973-2007. The recent experiment shows that survey catchability may be less than 1 (Figure 7). Harvest rates would be lower than estimated in Figure 13 if the real catchability is lower than our assumption. Model B assumes a constant natural mortality to estimate survey selectivities/catchability. Detailed results for Model B were described in the 2006 crab SAFE reports (Zheng 2006).

Fishery Selectivities

Fishery selectivities for retained males, discarded males and discarded females in the pot fishery can be estimated by dividing the catch and bycatch by their corresponding estimated abundances and averaging over time (Figure 14). Based on data availability, retained selectivities were averaged from 1972 to 2006, and female bycatch selectivities were averaged from 1990 to 2006, and male bycatch selectivties were averaged from 1990 to 2004. Mean selectivity for female bycatch was generally much lower than those for male bycatch.

S–R RELATIONSHIPS

I estimated S-R relationships for Bristol Bay RKC from the results of the LBA base scenario (Model A) (Figure 15). Generally, strong recruitment occurred with intermediate levels of effective spawning biomass, and very weak recruitment was associated with extremely low levels of effective spawning biomass. These features suggest a density-dependent S–R relationship. On the other hand, strong year classes occurred in the late 1960s and early 1970s, and weak year classes occurred in the 1980s and 1990s. Therefore recruitment is highly autocorrelated, so environmental factors may play an important role in recruitment success. I used the general Ricker curve to describe the density-dependent relationship and the autocorrelated Ricker curve to depict the autocorrelation effects. Because the autocorrelated curve regards the strong recruitment during the late 1960s and early 1970s as a result of autocorrelation, the recruitment associated with intermediate effective spawning biomass is much lower for the autocorrelated curve than for the general curve (Figure 15). Likewise, because the autocorrelated curve is less density-dependent, it has much higher recruitment than the general curve when effective spawning biomass is very high. Overall, the general Ricker curve (R^2=0.48, *df*=29) fit the data slightly better than the autocorrelated curve (R^2=0.47, *df*=29), in contrast to the earlier results when S–R data were fitted up to the 1987 brood year (Zheng et al., 1995a, 1995b). The autocorrelation parameter fit the residuals well only before the 1982 year class and then fit the residuals poorly. As expected, recruitment levels as a function of the spawning stock are lower from the S–R curve estimated with the data after 1976 than those estimated with all data (Figure 15).

The S–R curves estimated with mature male biomass on February 15 have overall lower recruitment levels than those estimated with effective spawning biomass (Figure 15). The S–R curves fit the data better with effective spawning biomass than with mature male biomass (R^2=0.37, *df*=29 for the general curve and R^2=0.44, *df*=29 for the autocorrelated curve).

Egg clutch data collected during summer surveys may provide information about mature female reproductive conditions. Egg clutch data are subject to subjective rating errors as well as sampling errors, but their trends over time may be useful. Proportions of empty clutches for newshell mature females >89 mm CL were high during some years before 1990 and have been very low since 1990 (Figure 16). The highest proportion of empty clutches was in 1986 with 0.20, and they were found with primarily soft shell females (shell condition 1). Clutch fullness fluctuated annually around their average levels during two periods: before 1991 and after 1990 (Figure 16). The average clutch fullness was almost identical for these two periods (Figure 16).

The recruitment strength and the Aleutian Low Pressure index were examined by Zheng and Kruse (2000, 2006) and are compared in Figure 17. The average seasonal index of December-March with a 3-point running average was used. The recruitment trends of Bristol Bay RKC may partly relate to decadal shifts in physical oceanography: all strong year classes occurred before 1977 when the Aleutian Low was weak. The largest year class during the last 20 years, the 1990 year class, was also coincidental with the weak Aleutian Low index during 1989-1991.

Many Alaskan RKC stocks, like Bristol Bay, tend to have periods of weak recruitment that coincide with decades of strong winter Aleutian Lows, the opposite of trends for many fish stocks (Hollowed and Wooster 1992; Beamish and Bouillon 1993). The mechanisms are uncertain, but food availability is hypothesized to be important to RKC (Zheng and Kruse 2000) because their larvae suffer reduced survival and feeding capability if they do not feed within the first 2-6 days after hatching (Paul and Paul 1980). Diatoms such as *Thalassiosira* are important food for first-feeding RKC larvae (Paul et al. 1989) and they predominate the spring bloom in years of light winds when the water column is stable (Ziemann et al. 1991; Bienfang and Ziemann 1995). One hypothesis is that years of strong wind mixing associated with intensified Aleutian Lows may depress RKC larval survival and subsequent recruitment (Zheng and Kruse 2000).

Spatial distributions of Bristol Bay RKC changed profoundly during the last three decades (Hsu 1987; Loher 2001; Zheng and Kruse 2006). Generally speaking, RKC abundance in southern Bristol Bay was high during the 1970s, declined, and was extremely low after 1979 (Zheng and Kruse 2006). Female RKC were found primarily in central Bristol Bay during 1980-1987 and 1992-2007 (Zheng and Kruse 2006). The distribution centers of mature females moved south slightly during 1988-1991 but did not reach the southern locations previously occupied in the 1970s. Loher (2001) hypothesized that changes in near bottom temperatures associated with the 1976/77 regime shift are causes for spatial shifts of RKC female distributions. Because small juvenile RKC are generally located downstream of the mature females (Zheng and Kruse 2006), larval advection appears to be an important process for RKC. The shifts of spatial distributions of mature females make it difficult to supply larvae to the southern range of their spatial distributions. This reduces the number of suitable habitats to which larvae are delivered (Armstrong et al. 1983; Loher, 2001) and may affect recruitment strength.

PROJECTIONS AND FUTURE OUTLOOK

Future population projections primarily depend on future recruitment predictions. Crab recruitment is extremely difficult to predict. Therefore, unless the projections are required for regulatory purposes, no projections are made in the stock assessment report.

The near future outlook for the Bristol Bay RKC stock is stable. Recent three above-average year classes (hatching years 1990, 1994 and 1997) have almost all entered the legal population in 2007 (Figure 18). So the recruitment to the legal population during the next year may not be high. However, year classes 1998 and 1999 are not too weak and entered or will enter the legal population primarily this year and during next two years. Year class 2000 with lengths centered around 102.5 mm CL for males and 97.5 mm CL for females in 2007) appears to be above average in abundance (Figure 18). These crabs will enter the mature male population in 2008 and 2009. Since recent four above-average year classes have entered the mature female population, the mature female population may decline during the next two to three years. The further negative side is that there are no strong cohorts observed in the survey data after year class 2000 (Figure 18). Very few juvenile crabs <70 mm CL were caught in the 2006 and 2007 surveys, which indicates poor recruitment to the mature female population for at least the next two years, followed by at least two years of poor recruitment to the mature male population.

Due to four above average year classes, mature and legal crabs should maintain relatively high levels compared to those during the last 20 years if natural mortality does not increase greatly, as in the early 1980s for this stock and in 1999 for St. Matthew Island blue king crabs (Zheng and Kruse 2002b). Current crab abundance is still very low relative to those in the late 1970s, and without favorable environmental conditions, recovery to the high levels of the late 1970s may be difficult.

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REFERENCES

Alaska Department of Fish and Game (ADF&G). 2005. Commercial king and Tanner crab fishing regulations, 2005-2006. Alaska Department of Fish and Game, Division of Commercial Fisheries, Juneau. 162 pp.

Armstrong, D.A., L.S. Incze, D. Wencker, and J.L. Armstrong. 1983. Distribution and abundance of decapod crustacean larvae in the southeastern Bering Sea with emphasis on commercial species. U.S. Department of Commerce, NOAA, NOS, Anchorage, Alaska. 386 pp.

Balsiger, J.W. 1974. A computer simulation model for the eastern Bering Sea king crab. Ph.D. dissertation, Univ. Washington, Seattle, WA. 198 pp.

Beamish, R.J., and D.R. Bouillon. 1993. Pacific salmon production trends in relation to climate. Can. J. Fish. Aquat. Sci. 50:1002-1016.

Bienfang, P.K., and D.A. Ziemann. 1995. APPRISE: A multi-year investigation of environmental variation and its effects on larval recruitment. Pages 483-487 *In* R.J. Beamish (ed.). Climate change and northern fish populations. Can. Spec. Publ. Fish. Aquat. Sci. 121.

Blau, S.F. 1986. Recent declines of red king crab (*Paralithodes camtschatica*) populations and reproductive conditions around the Kodiak Archipelago, Alaska. Pages 360-

369 *In* G. S. Jamieson and N. Bourne (eds). North Pacific Workshop on stock assessment and management of invertebrates. Can. Spec. Publ. Fish. Aquat. Sci. 92.

Bowers, F.R., Bush, K.L., Schwenzfeier, M., Barnhart, J., Bon, M., Cavin Jr., M.E., Coleman, S., Failor-Rounds, B., & Salmon, M. 2005. Annual management report for the commercial and subsistence shellfish fisheries of the Aleutian Islands, Bering Sea and the westward region's shellfish observer program, 2004. Alaska Department of Fish and Game, Fishery Management Report No. 05-51, Anchorage. 238 pp.

Burt, R., and D.R. Barnard. 2006. Alaska Department of Fish and Game summary of the 2004 mandatory shellfish observer program database for the general and CDQ fisheries. Alaska Department of Fish and Game, Fishery Data Series No. 06-03, Anchorage.

Carls, M.G., and C.E. O'Clair. 1990. Influence of cold air exposures on ovigerous red king crabs (*Paralithodes camtschatica*) and Tanner crabs (*Chionoecetes bairdi*) and their offspring. Proc. Int. Symp. King & Tanner Crabs, Alaska Sea Grant Rep. 90-04: 329-343.

Fournier, D.A., J.R. Sibert, J. Majkowski, and J. Hampton. 1990. MULTIFAN a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii*). Can. J. Fish. Aquat. Sci. 47:301-317.

Gray, G.W. 1963. Growth of mature female king crab *Paralithodes camtschatica* (Tilesius). Alaska Dept. Fish and Game, Inf. Leafl. 26. 4 pp.

Hare, S.R., and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103–145.

Hollowed, A.B., and W.S. Wooster. 1992. Variability of winter ocean conditions and strong year classes of Northeast Pacific groundfish. ICES Mar. Sci. Symp. 195:433-444.

Hoopes, D.T., J.F. Karinen, and M. J. Pelto. 1972. King and Tanner crab research. Int. North Pac. Fish. Comm. Annu. Rep. 1970:110-120.

Hsu, C-C. 1987. Spatial and temporal distribution patterns of female red king crabs in the southeastern Bering Sea. Ph.D. dissertation, University of Washington, Seattle, WA. 300 pp.

Ianelli, J.N., S. Barbeaux, G. Walters, and N. Williamson. 2003. Eastern Bering Sea walleye Pollock stock assessment. Pages 39-126 *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage.

Jackson, P.B. 1974. King and Tanner crab fishery of the United States in the Eastern Bering Sea, 1972. Int. North Pac. Fish. Comm. Annu. Rep. 1972:90-102.

Loher, T. 2001. Recruitment variability in southeast Bering Sea red king crab (*Paralithodes camtschaticus*): The roles of early juvenile habitat requirements, spatial population structure, and physical forcing mechanisms. Ph. D. dissertation. University of Washington, Seattle, WA. 436 pp.

Loher, T., D.A. Armstrong, and B.G. Stevens. 2001. Growth of juvenile red king crab (*Paralithodes camtschaticus*) in Bristol Bay (Alaska) elucidated from field sampling and analysis of trawl-survey data. Fish. Bull. 99:572-587.

McCaughran, D.A., and G.C. Powell. 1977. Growth model for Alaskan king crab (*Paralithodes camtschatica*). J. Fish. Res. Board Can. 34:989-995.

North Pacific Fishery Management Council (NPFMC). 1998. Fishery management plan for Bering Sea/Aleutian Islands king and Tanner crabs. North Pacific Fishery Management Council, Anchorage, Alaska.

Otto, R.S. 1986. Management and assessment of eastern Bering Sea king crab stocks. Pages 83-106 *In* G. S. Jamieson, and N. Bourne (eds.). North Pacific Workshop on stock assessment and management of invertebrates. Can. Spec. Publ. Fish. Aquat. Sci. 92.

Paul, A.J., and J.M. Paul. 1980. The effect of early starvation on later feeding success of king crab zoea. J. Exp. Biol. Ecol. 44:247-251.

Paul, J.M., and A.J. Paul. 1990. Breeding success of sublegal size male red king crab *Paralithodes camtschatica* (Tilesius, 1815) (Decapopa, Lithodidae). J. Shellfish Res. 9:29-32.

Paul, A.J., and J.M. Paul. 1997. Breeding success of large male red king crab *Paralithodes camtschaticus* with multiparous mates. J. Shellfish Res. 16, 379-381.

Paul, A.J., J.M. Paul, and K.O. Coyle. 1989. Energy sources for first-feeding zoea of king crab *Paralithodes camtschatica* (Tilesius) (Decapoda, Lithodidae). J. Exp. Mar. Biol. Ecol. 130:55-69.

Pengilly, D., and D. Schmidt. 1995. Harvest strategy for Kodiak and Bristol Bay red king crab and St. Matthew Island and Pribilof Islands blue king crab. Alaska Dep. Fish and Game, Comm. Fish. Manage. and Dev. Div., Special Publication 7. Juneau, AK. 10 pp.

Phinney, D.E. 1975. United States fishery for king and Tanner crabs in the eastern Bering Sea, 1973. Int. North Pac. Fish. Comm. Annu. Rep. 1973: 98-109.

Powell, G.C. 1967. Growth of king crabs in the vicinity of Kodiak, Alaska. Alaska Dept. Fish and Game, Inf. Leafl. 92. 106 pp.

Powell, G.C., K.E. James, and C.L. Hurd. 1974. Ability of male king crab, *Paralithodes camtschatica*, to mate repeatedly, Kodiak, Alaska, 1973. Fish. Bull., U.S. 72(1):171-179.

Powell, G.C., and R.B. Nickerson. 1965. Reproduction of king crabs, *Paralithodes camtschatica* (Tilesius). J. Fish. Res. Board Can. 22(1):101-111.

Reeves, J.E., R.A. MacIntosh, and R.N. McBride. 1977. King and snow (Tanner) crab research in the eastern Bering Sea, 1974. Int. North Pac. Fish. Comm. Annu. Rep. 1974:84-87.

SAS Institute Inc. 1988. SAS/ETS user's guide, version 6, first edition. SAS Institute Inc., Cary, NC. 560 pp.

Schmidt, D., and D. Pengilly. 1990. Alternative red king crab fishery management practices: modelling the effects of varying size-sex restrictions and harvest rates, p.551-566. *In* Proc. Int. Symp. King & Tanner Crabs, Alaska Sea Grant Rep. 90-04.

Stevens, B.G. 1990. Temperature-dependent growth of juvenile red king crab (*Paralithodes camtschatica*), and its effects on size-at-age and subsequent recruitment in the eastern Bering Sea. Can. J. Fish. Aquat. Sci. 47:1307-1317.

Stevens, B.G., R.A. MacIntosh, and J.A. Haaga. 1991. Report to industry on the 1991 eastern Bering Sea crab survey. Alaska Fisheries Science Center, Processed Rep. 91-17. 51 pp. NMFS, NOAA, 7600 Sand Point Way NE, Seattle, WA 99115.

Weber, D.D. 1967. Growth of the immature king crab *Paralithodes camtschatica* (Tilesius). Int. North Pac. Fish. Comm. Bull. 21:21-53.

Weber, D.D., and T. Miyahara. 1962. Growth of the adult male king crab, *Paralithodes camtschatica* (Tilesius). Fish. Bull. U.S. 62:53-75.

Weinberg, K.L., R.S. Otto, and D.A. Somerton. 2004. Capture probability of a survey trawl for red king crab (*Paralithodes camtschaticus*). Fish. Bull. 102:740-749.

Zheng, J. 2004. Bristol Bay red king crab stock assessment in 2004. An appendix in the 2004 crab SAFE. North Pacific Fishery Management Council, Anchorage, Alaska.

Zheng, J. 2006. Bristol Bay red king crab stock assessment in 2006. An appendix in the 2006 crab SAFE. North Pacific Fishery Management Council, Anchorage, Alaska.

Zheng, J., and G.H. Kruse. 1999. Stock status of king crabs in the eastern Bering Sea in 1999. Alaska Dept. Fish and Game, Commercial Fisheries Division, Reg. Inf. Rep. 5J99-09, Juneau. 19 pp.

Zheng. J., and G.H. Kruse. 2000. Recruitment patterns of Alaskan crabs and relationships to decadal shifts in climate and physical oceanography. ICES J. Mar. Sci. 57:438-451.

Zheng, J., and G.H. Kruse. 2002a. Retrospective length-based analysis of Bristol Bay red king crabs: model evaluation and management implications. Pages 475-494 *In* A.J. Paul, E.G. Dawe, R. Elner, G.S. Jamieson, G.H. Kruse, R.S. Otto, B. Sainte-Marie, T.C. Shirley, and D. Woodby (eds.). Crabs in Cold Water Regions: Biology, Management, and Economics. University of Alaska Sea Grant, AK-SG-02-01, Fairbanks.

Zheng, J., and G.H. Kruse. 2002b. Assessment and management of crab stocks under uncertainty of massive die-offs and rapid changes in survey catchability. Pages 367-384 *In* A.J. Paul, E.G. Dawe, R. Elner, G.S. Jamieson, G.H. Kruse, R.S. Otto, B. Sainte-Marie, T.C. Shirley, and D. Woodby (eds.). Crabs in Cold Water Regions: Biology, Management, and Economics. University of Alaska Sea Grant, AK-SG-02-01, Fairbanks.

Zheng, J., and G.H. Kruse. 2003. Stock-recruitment relationships for three major Alaskan crab stocks. Fish. Res. 65:103-121.

Zheng, J., and G.H. Kruse. 2006. Recruitment variation of eastern Bering Sea crabs: climate-forcing or top-down effects? Prog. Oceanography, 68: 184-204.

Zheng, J., G.H. Kruse, and M.C. Murphy. 1997. Stock status of king crabs in the Eastern Bering Sea in 1997. Alaska Dept. Fish and Game, Commercial Fisheries Division, Reg. Inf. Rep. 5J97-13, Juneau. 21 pp.

Zheng, J., G.H. Kruse, and M.C. Murphy. 1998. Stock status of king crabs in the Eastern Bering Sea in 1998. Alaska Dept. Fish and Game, Commercial Fisheries Division, Reg. Inf. Rep. 5J98-06, Juneau. 18 pp.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1995a. A length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Can. J. Fish. Aquat. Sci. 52:1229-1246.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1995b. Updated length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus,* in Bristol Bay, Alaska. Alaska Fish. Res. Bull. 2:114-124.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1996. Overview of population estimation methods and recommended harvest strategy for red king crabs in Bristol Bay. Alaska Department of Fish and Game, Reg. Inf. Rep. 5J96-04, Juneau, Alaska. 37 pp.

Zheng, J. M.C. Murphy, and G.H. Kruse. 1997a. Analysis of the harvest strategies for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Can. J. Fish. Aquat. Sci. 54:1121-1134.

Zheng, J. M.C. Murphy, and G.H. Kruse. 1997b. Alternative rebuilding strategies for the red king crab *Paralithodes camtschaticus* fishery in Bristol Bay, Alaska. J. Shellfish Res. 16:205-217.

Ziemann, D.A., L.D. Conquest, M. Olaizola, and P.J. Bienfang. 1991. Interannual variability in the spring phytoplankton bloom in Auke Bay, Alaska. Mar. Biol. 109:321-334.

Table 1. Bristol Bay red king crab annual catch and bycatch mortality biomass (million pounds) from June 1 to May 31. A handling mortality rate of 20% for pot and 80% for trawl was assumed to estimated bycatch mortality biomass.

	Retained Catch				Pot Bycatch		Trawl
Year	U.S.	Cost-recovery	Foreign	Total	Males	Females	Bycatch
1970	8.559		12.984	21.543			
1971	12.946		6.134	19.080			
1972	21.745		4.720	26.465			
1973	26.914		0.228	27.142			
1974	42.266		0.476	42.742			
1975	51.326		0.000	51.326			
1976	63.920		0.000	63.920			1.426
1977	69.968		0.000	69.968			2.685
1978	87.618		0.000	87.618			2.757
1979	107.828		0.000	107.828			2.783
1980	129.948		0.000	129.948			2.135
1981	33.591		0.000	33.591			0.448
1982	3.001		0.000	3.001			1.201
1983	0.000		0.000	0.000			0.885
1984	4.182		0.000	4.182			2.316
1985	4.175		0.000	4.175			0.829
1986	11.394		0.000	11.394			0.432
1987	12.289		0.000	12.289			0.311
1988	7.388		0.000	7.388			1.174
1989	10.265		0.000	10.265			0.374
1990	20.362	0.081	0.000	20.443	1.139	1.154	0.501
1991	17.178	0.206	0.000	17.384	0.881	0.142	0.576
1992	8.043	0.074	0.000	8.117	1.191	0.780	0.571
1993	14.629	0.053	0.000	14.682	1.649	1.133	0.836
1994	0.000	0.093	0.000	0.093	0.000	0.000	0.180
1995	0.000	0.080	0.000	0.080	0.000	0.000	0.213
1996	8.406	0.108	0.000	8.514	0.356	0.002	0.238
1997	8.756	0.155	0.000	8.911	0.528	0.034	0.168
1998	14.757	0.188	0.000	14.946	2.074	1.547	0.355
1999	11.670	0.186	0.000	11.856	0.679	0.015	0.408
2000	8.154	0.086	0.000	8.241	0.779	0.078	0.230
2001	8.403	0.120	0.000	8.523	0.902	0.309	0.330
2002	9.570	0.096	0.000	9.666	0.956	0.013	0.245
2003	15.697	0.034	0.000	15.731	1.945	0.709	0.298
2004	15.245	0.202	0.000	15.447	0.746	0.338	0.277
2005	18.309	0.209	0.000	18.518	2.923	0.879	0.403
2006	15.444	0.304	0.000	15.748	1.199	0.067	0.205

Table 2. Comparison of GHL/TAC and actual catch (million pounds) of Bristol Bay red king crabs.

	GHL		Actual		
Year	Range	Mid-point	Catch	Rel.Error	%Rel.Error
1980	70-120	95.00	129.95	34.95	36.79
1981	70-100	85.00	33.59	-51.41	-60.48
1982	10-20	15.00	3.00	-12.00	-79.99
1983	0	0.00	0.00	NA	NA
1984	2.5-6	4.25	4.18	-0.07	-1.59
1985	3-5	4.00	4.18	0.18	4.38
1986	6-13	9.50	11.39	1.89	19.94
1987	8.5-17.7	13.10	12.29	-0.81	-6.19
1988		7.50	7.39	-0.11	-1.50
1989		16.50	10.26	-6.24	-37.79
1990		17.10	20.36	3.26	19.08
1991		18.00	17.18	-0.82	-4.57
1992		10.30	8.04	-2.26	-21.91
1993		16.80	14.63	-2.17	-12.93
1994		0.00	0.00	NA	NA
1995		0.00	0.00	NA	NA
1996		5.00	8.41	3.41	68.11
1997		7.00	8.76	1.76	25.09
1998		16.40	14.76	-1.64	-10.02
1999		10.66	11.67	1.01	9.48
2000		8.35	8.15	-0.20	-2.34
2001		7.15	8.40	1.25	17.52
2002		9.27	9.57	0.30	3.24
2003		15.71	15.70	-0.01	-0.08
2004		15.40	15.25	-0.15	-1.00
2005		18.33	18.31	-0.02	-0.11
2006		15.53	15.44	-0.08	-0.53
Total		440.85	411.01	-29.83	-6.77

Table 3. Annual sample sizes for catch by length and shell condition for retained catch and bycatch of Bristol Bay red king crabs.

	Trawl Survey		Retained	Pot Bycatch		Trawl Bycatch	
Year	Males	Females	Catch	Males	Females	Males	Females
1972	1106	767	15046				
1973	1783	1888	11848				
1974	2505	1800	27067				
1975	2943	2139	29570				
1976	4724	2956	26450			2327	676
1977	3636	4178	32596			14014	689
1978	4132	3948	27529			8983	1456
1979	5807	4663	27900			7228	2821
1980	2412	1387	34747			47463	39689
1981	3478	4097	18029			42172	49634
1982	2063	2051	11466			84240	47229
1983	1524	944	0			204464	104910
1984	2679	1942	4404			357981	147134
1985	792	415	4582			169767	30693
1986	1962	367	5773			62023	20800
1987	1168	1018	4230			60606	32734
1988	1834	546	9833			102037	57564
1989	1257	550	32858			47905	17355
1990	858	603	7218	873	699	5876	2665
1991	1378	491	36820	1801	375	2964	962
1992	513	360	23552	3248	2389	1157	2678
1993	1009	534	32777	5803	5942		
1994	443	266	0	0	0	4953	3341
1995	2154	1718	0	0	0	1729	6006
1996	835	816	8896	230	11	24583	9373
1997	1282	707	15747	4102	906	9035	5759
1998	1097	1150	16131	11079	9130	25051	9594
1999	820	540	17666	1048	36	16653	5187
2000	1278	1225	14091	8970	1486	36972	10673
2001	611	743	12854	9102	4567	56070	32745
2002	1032	896	15932	9943	302	27705	25425
2003	1669	1311	16212	17998	10327	281	307
2004	2871	1599	20038	8258	4112	137	120
2005	1283	1682	21938	55019	26775	186	124
2006	2321	2672	18027	29383	3594	217	168
2007	2252	2499					

Table 4. Annual catch (millions of crabs) and catch per unit effort of the Bristol Bay red king crab fishery.

	Japanese Tanglenet		Russian Tanglenet		U.S. Pot/trawl		Standardized
Year	Catch	Crabs/tan	Catch	Crabs/tan	Catch	Crabs/potlift	Crabs/tan
1960	1.949	15.2	1.995	10.4	0.088		15.8
1961	3.031	11.8	3.441	8.9	0.062		12.9
1962	4.951	11.3	3.019	7.2	0.010		11.3
1963	5.476	8.5	3.019	5.6	0.101		8.6
1964	5.895	9.2	2.800	4.6	0.123		8.5
1965	4.216	9.3	2.226	3.6	0.223		7.7
1966	4.206	9.4	2.560	4.1	0.140	52	8.1
1967	3.764	8.3	1.592	2.4	0.397	37	6.3
1968	3.853	7.5	0.549	2.3	1.278	27	7.8
1969	2.073	7.2	0.369	1.5	1.749	18	5.6
1970	2.080	7.3	0.320	1.4	1.683	17	5.6
1971	0.886	6.7	0.265	1.3	2.405	20	5.8
1972	0.874	6.7			3.994	19	
1973	0.228				4.826	25	
1974	0.476				7.710	36	
1975					8.745	43	
1976					10.603	33	
1977					11.733	26	
1978					14.746	36	
1979					16.809	53	
1980					20.845	37	
1981					5.308	10	
1982					0.541	4	
1983					0.000		
1984					0.794	7	
1985					0.796	9	
1986					2.100	12	
1987					2.122	10	
1988					1.236	8	
1989					1.685	8	
1990					3.130	12	
1991					2.661	12	
1992					1.208	6	
1993					2.270	9	
1994					0.015		
1995					0.014		
1996					1.264	16	
1997					1.338	15	
1998					2.238	15	
1999					1.923	12	
2000					1.272	12	
2001					1.287	19	
2002					1.484	20	
2003					2.510	18	
2004					2.272	23	
2005					2.763	30	
2006					2.477	31	

Table 5. Area-swept estimates of 32 stations for Bristol Bay red king crabs in 2007. Haul numbers <188 are standard survey, and haul numbers >187 are resurvey.

N. Lat.	W. Long.	Station	Haul #	Legal males	Mature males	Males>89mm	Mature females
56.00	-162.23	D10	41	483999	903464	1935994	1774662
55.99	-162.27	D10	206	190325	285487	634417	1110229
56.33	-162.19	E10	40	348438	538495	1045314	823581
56.34	-162.20	E10	207	247148	494296	926806	617870
56.34	-161.63	E11	21	663799	1390816	2876461	3571869
56.33	-161.61	E11	205	153939	523394	1662545	6896483
56.34	-160.99	E12	20	32476	129904	162380	259809
56.33	-161.00	E12	194	127242	127242	222674	1431473
56.66	-163.38	F08	220	0	33073	33073	0
56.66	-162.78	F09	38	92395	123194	123194	0
56.68	-162.80	F09	219	64005	64005	64005	0
56.67	-162.19	F10	36	227743	422952	1529134	195209
56.66	-162.15	F10	208	61345	184035	858829	337397
56.67	-161.59	F11	22	0	127242	127242	190863
56.67	-161.58	F11	204	643903	1195819	2238328	337282
56.68	-160.99	F12	25	486089	777743	1361050	1620298
56.67	-160.99	F12	195	893219	1084623	2552054	4019485
56.66	-160.38	F13	24	217824	280060	466767	1649242
56.66	-160.37	F13	193	62603	62603	187810	500828
57.00	-163.43	G08	46	31856	63711	63711	31856
57.01	-163.37	G08	217	314768	409199	440676	31477
57.00	-162.79	G09	33	91674	122232	702833	763949
57.01	-162.80	G09	218	399969	553803	1015305	892238
56.99	-162.18	G10	35	124000	216999	1332996	1487996
56.99	-162.19	G10	209	216925	309892	1704408	619785
57.00	-161.58	G11	23	190459	412662	1301472	1111012
56.99	-161.56	G11	203	283887	441602	1261720	567774
57.00	-160.98	G12	26	95029	221733	348438	665200
57.00	-160.96	G12	196	471658	597433	754652	1949518
57.00	-160.33	G13	19	250066	281324	531390	1344104
56.99	-160.34	G13	192	312366	624731	1374408	2030376
57.34	-163.39	H08	47	291759	486264	615935	32418
57.34	-163.37	H08	216	157384	314768	440676	94430
57.34	-162.76	H09	32	526093	773666	1392598	1021239
57.33	-162.79	H09	214	124816	187224	249633	873714
57.33	-162.15	H10	34	256844	288949	1284218	1733695
57.33	-162.15	H10	210	31822	95465	286396	1654731
57.33	-161.54	H11	24	94233	125644	1287848	1036561
57.33	-161.53	H11	202	126973	158716	507891	857067
57.34	-160.93	H12	27	155535	155535	248856	373284
57.32	-160.93	H12	197	94167	125556	439446	1475284
57.34	-160.30	H13	18	122232	244464	305580	855623
57.33	-160.31	H13	191	309679	371615	650326	2105819
57.67	-163.39	I08	48	253499	316873	475310	316873
57.67	-163.32	I08	188	123362	154203	185044	1017740
57.66	-162.75	I09	31	640196	914565	1402333	1402333
57.68	-162.73	I09	213	184412	245882	491765	952794
57.66	-162.13	I10	33	284585	411067	1169960	1296443
57.66	-162.13	I10	211	158214	158214	506285	1487211
57.67	-161.52	I11	25	159109	318217	1400157	922831
57.67	-161.51	I11	201	127738	127738	415150	989973
57.67	-160.89	I12	28	62669	156672	313344	407347
57.67	-160.88	I12	198	225947	322781	613285	290503
57.67	-160.27	I13	17	0	0	31215	187289
57.67	-160.27	I13	190	226434	323477	743998	1326257
58.00	-162.11	J10	32	214561	275864	827593	367819
58.00	-162.11	J10	212	0	0	284785	949284
57.99	-161.50	J11	26	253946	380919	666607	571378
57.99	-161.48	J11	200	93321	93321	559927	1057639
58.01	-160.87	J12	29	94069	219494	250850	438987
58.00	-160.84	J12	199	343364	530653	1311025	468223
58.00	-160.22	J13	16	123447	154309	154309	154309
58.00	-160.21	J13	189	189125	315209	630418	1166274

Table 6. Average weight and assumed maximum number of female mates for male red king crabs in Bristol Bay by length-class.

Male Carapace Length (mm)	Average Male Weight (kg)	Number of Female Mates
0-119		0.0
120-124	1.43	1.0
125-129	1.63	1.2
130-134	1.84	1.4
135-139	2.06	1.6
140-144	2.31	1.8
145-149	2.58	2.1
150-154	2.86	2.4
155-159	3.17	2.7
160+	3.50	3.0

Table 7. Summary of parameter estimates for Model A for Bristol Bay red king crabs. The abundance in 1972, N_{72}, and recruits, R_t, are in millions of crabs.

Parameter	Males	Females
N_{72}	38.203	58.801
β	0.583	1.379
β_r	1.662	0.403
L_{501}	155.882	NA
L_{502}	130.557	NA
L_{503}	143.822	NA
β_1	0.0818	NA
β_2	0.0758	NA
β_3	0.0874	NA
M_1	0.197	0.461
M_2	1.060	1.732
M_3	NA	0.217
R_{73}	32.740	34.714
R_{74}	22.366	28.150
R_{75}	33.747	22.152
R_{76}	48.294	34.214
R_{77}	59.571	74.452
R_{78}	26.820	49.486
R_{79}	14.484	19.910
R_{80}	27.839	36.342
R_{81}	18.839	13.602
R_{82}	23.417	17.376
R_{83}	12.820	4.650
R_{84}	18.220	7.422
R_{85}	10.617	4.110
R_{86}	6.782	3.098
R_{87}	7.113	6.246
R_{88}	6.848	4.518
R_{89}	5.956	4.318
R_{90}	1.744	0.861
R_{91}	4.511	3.386
R_{92}	7.432	3.641
R_{93}	2.944	2.393
R_{94}	1.306	0.418
R_{95}	3.475	1.900
R_{96}	4.226	4.944
R_{97}	15.928	17.588
R_{98}	3.751	1.593
R_{99}	1.545	0.560
R_{00}	4.606	4.659
R_{01}	9.600	11.594
R_{02}	2.970	3.074
R_{03}	6.387	10.008
R_{04}	11.883	11.232
R_{05}	9.237	6.555
R_{06}	9.502	5.914
R_{07}	13.852	8.913
$Ln(L)$	-2051.432	-678.108
df	920	345

Table 8. Annual abundance estimates (millions of crabs), effective spawning biomass (ESB, million pounds), and 95% confidence intervals for 2007 for red king crabs in Bristol Bay estimated by length-based analysis from 1972-2007 for the base scenario (Model A). Size measurements are mm CL.

	Males					Females		
Year	Recruits	Small	Prerec.	Mature	Legal	Recruits	Mature	ESB
mm→	(to model)	(95-109)	(110-134)	(>119)	(>134)	(to model)	(>89)	(M lbs)
1972	NA	13.389	14.908	18.331	9.906	NA	58.802	54.940
1973	32.740	21.089	27.457	23.251	10.362	34.714	70.742	63.961
1974	22.366	14.936	35.401	35.239	15.151	28.150	71.682	95.826
1975	33.747	21.735	35.898	41.449	20.934	22.152	66.062	116.797
1976	48.294	31.144	46.743	49.740	25.214	34.214	74.804	128.861
1977	59.571	38.613	63.007	64.085	30.418	74.452	120.272	168.937
1978	26.820	18.513	62.024	78.284	40.617	49.486	123.052	205.336
1979	14.484	9.862	39.319	76.104	48.901	19.910	95.548	171.468
1980	27.839	17.817	28.616	62.368	45.366	36.342	95.232	169.767
1981	18.839	12.657	17.955	18.832	9.561	13.602	71.907	60.919
1982	23.417	15.247	16.115	10.188	2.796	17.376	29.535	23.854
1983	12.820	8.787	12.969	8.787	2.394	4.650	9.762	16.368
1984	18.220	11.831	12.463	8.049	2.290	7.422	9.138	13.711
1985	10.617	7.230	10.192	6.650	1.695	4.110	5.672	8.499
1986	6.782	4.643	12.241	11.343	4.214	3.098	7.518	12.039
1987	7.113	4.699	10.694	13.030	6.382	6.246	12.114	19.548
1988	6.848	4.543	9.995	13.806	7.809	4.518	14.032	23.923
1989	5.956	3.980	9.535	15.289	9.484	4.318	15.471	27.622
1990	1.744	1.318	7.294	15.227	10.317	0.861	13.156	25.899
1991	4.511	2.888	5.176	12.285	8.939	3.386	13.511	26.739
1992	7.432	4.807	6.830	10.744	7.190	3.641	14.423	28.752
1993	2.944	2.418	7.933	11.282	6.622	2.393	13.591	28.131
1994	1.306	1.103	6.027	9.836	5.660	0.418	10.858	24.310
1995	3.475	2.305	5.028	9.982	6.629	1.900	10.637	23.855
1996	4.226	2.924	5.722	10.402	7.030	4.944	13.486	27.679
1997	15.928	10.110	10.474	11.998	7.013	17.588	28.387	38.046
1998	3.751	3.591	14.247	15.317	7.238	1.593	24.228	46.322
1999	1.545	1.159	8.913	16.255	9.549	0.560	19.381	40.563
2000	4.606	3.017	6.672	13.812	9.192	4.659	20.253	42.190
2001	9.600	6.361	8.904	13.370	8.532	11.594	27.822	47.260
2002	2.970	2.634	10.189	14.370	8.285	3.074	25.219	51.370
2003	6.387	4.131	8.309	15.067	9.713	10.008	30.273	55.080
2004	11.883	7.652	10.473	14.750	9.253	11.232	35.205	53.215
2005	9.237	6.213	13.709	17.277	9.587	6.555	34.636	61.050
2006	9.502	6.287	13.748	18.943	10.647	5.914	33.383	67.924
2007	13.852	9.011	15.298	20.975	12.287	8.913	35.697	72.844
				95% Confidence Limits in 2007				
Lower	11.751	NA	13.423	17.632	10.042	6.511	30.374	NA
Upper	16.892	NA	16.811	22.496	13.377	13.221	42.209	NA

Figure Captions

Figure 1. Current harvest rate strategy (line) for the Bristol Bay red king crab fishery and annual prohibited species catch (PSC) limits (numbers of crabs) of Bristol Bay RKC in the groundfish fisheries in zone 1 in the eastern Bering Sea. Harvest rates are based on current-year estimates of effective spawning biomass (ESB), whereas PSC limits apply to previous-year ESB. In addition to the 14.5 million pound ESB threshold, two additional criteria must be met in order to prosecute the fishery: the abundance of large (>89-mm CL) females must equal or exceed 8.4 million crabs, and the guideline harvest level must be greater than or equal to 4 million pounds.

Figure 2. Retained catch biomass and bycatch mortality biomass (million pounds) for Bristol Bay red king crabs from 1953 to 2006. Handling mortality rates were assumed to be 0.2 for the directed pot fishery and 0.8 for the trawl fisheries.

Figure 3. Comparison of survey legal male abundances and catches per unit effort for Bristol Bay red king crabs from 1968 to 2006.

Figure 4a. Survey abundances by length for male Bristol Bay red king crabs from 1968 to 2007.

Figure 4b. Survey abundances by length for female Bristol Bay red king crabs from 1968 to 2007.

Figure 5. Comparison of survey area-swept abundance estimates by NMFS and ADF&G for Bristol Bay red king crabs from 1975 to 2007.

Figure 6. Comparison of area-swept estimates of abundance in 32 stations from the standard trawl survey and resurvey in 2007.

Figure 7. Estimated capture probabilities for Bristol Bay red king crab trawl survey by Weinberg et al. (2004).

Figure 8. Mean growth increments per molt for Bristol Bay red king crabs.

Figure 9. The length-based analysis fit (lines) to area-swept estimates (dots) of mature male (top panel) and mature female (bottom panel) Bristol Bay red king crab abundance (millions of crabs) for Model A.

Figure 10. The length-based analysis fit (lines) to area-swept estimates (dots) of mature male (top panel) and mature female (bottom panel) Bristol Bay red king crab abundance (millions of crabs) for Model A. Results are illustrated from 1982 to 2007.

Figure 11a. Comparison of area-swept and model estimated length frequencies of Bristol Bay newshell male red king crabs by year for Model A. The first length group is 97.5 mm.

Figure 11b. Comparison of area-swept and model estimated length frequencies of Bristol Bay oldshell male red king crabs by year for Model A. The first length group is 97.5 mm.

Figure 11c. Comparison of area-swept and model estimated length frequencies of Bristol Bay female red king crabs by year for Model A. The first length group is 92.5 mm.

Figure 12. Comparison of estimated probabilities of molting of male red king crabs in Bristol Bay for different periods. Molting probabilities for periods 1954-1961 and 1966-1969 were estimated by Balsiger (1974) from tagging data. Molting probabilities for the other periods were estimated under the base scenario (Model A).

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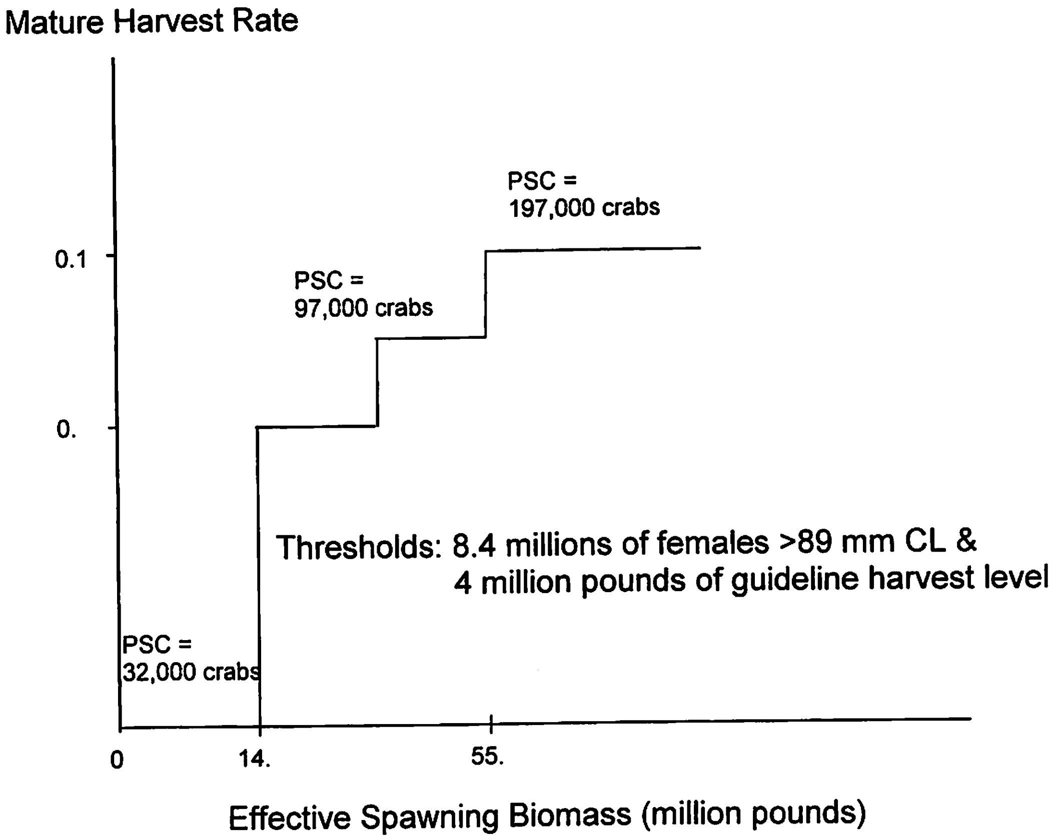

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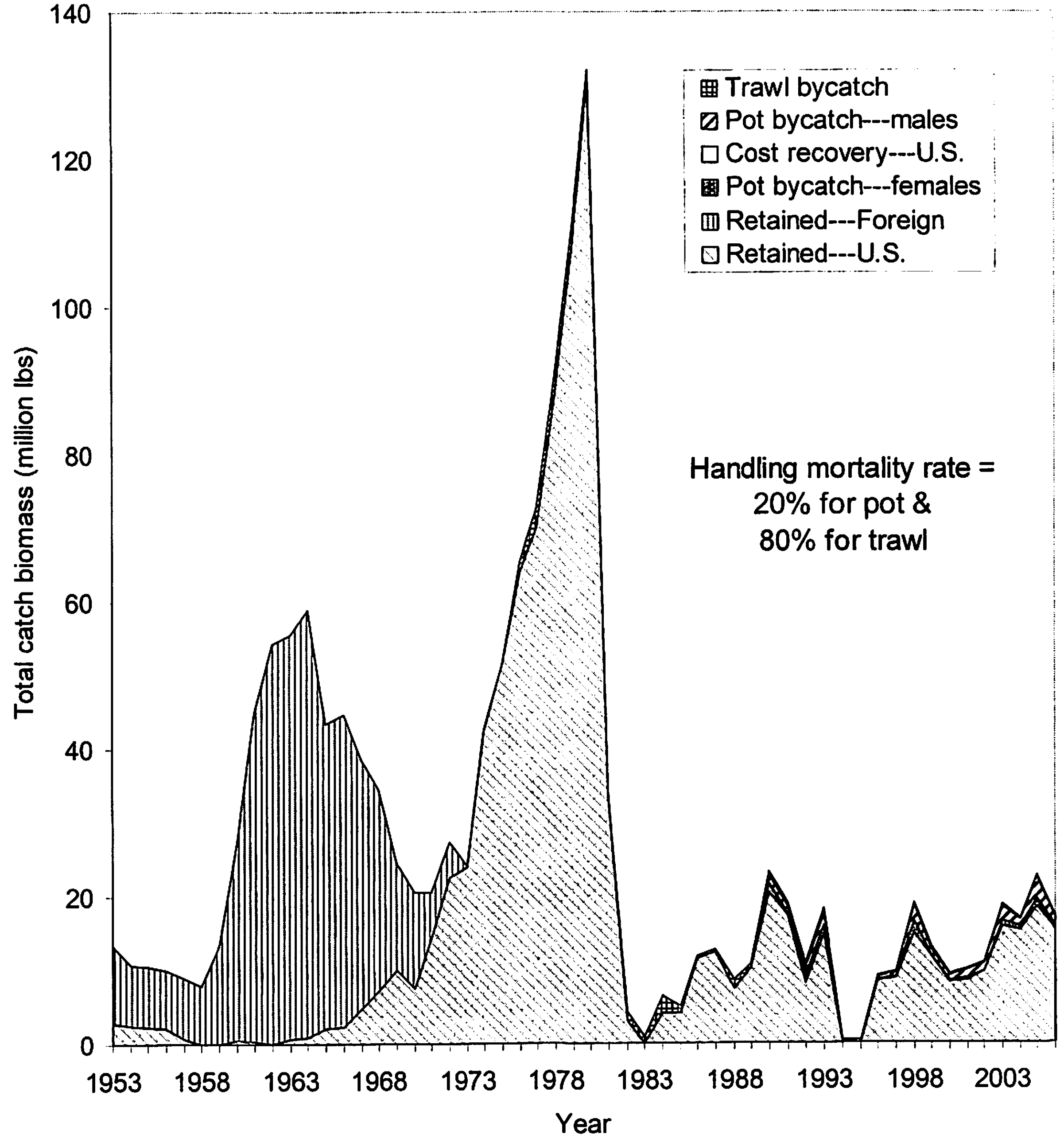

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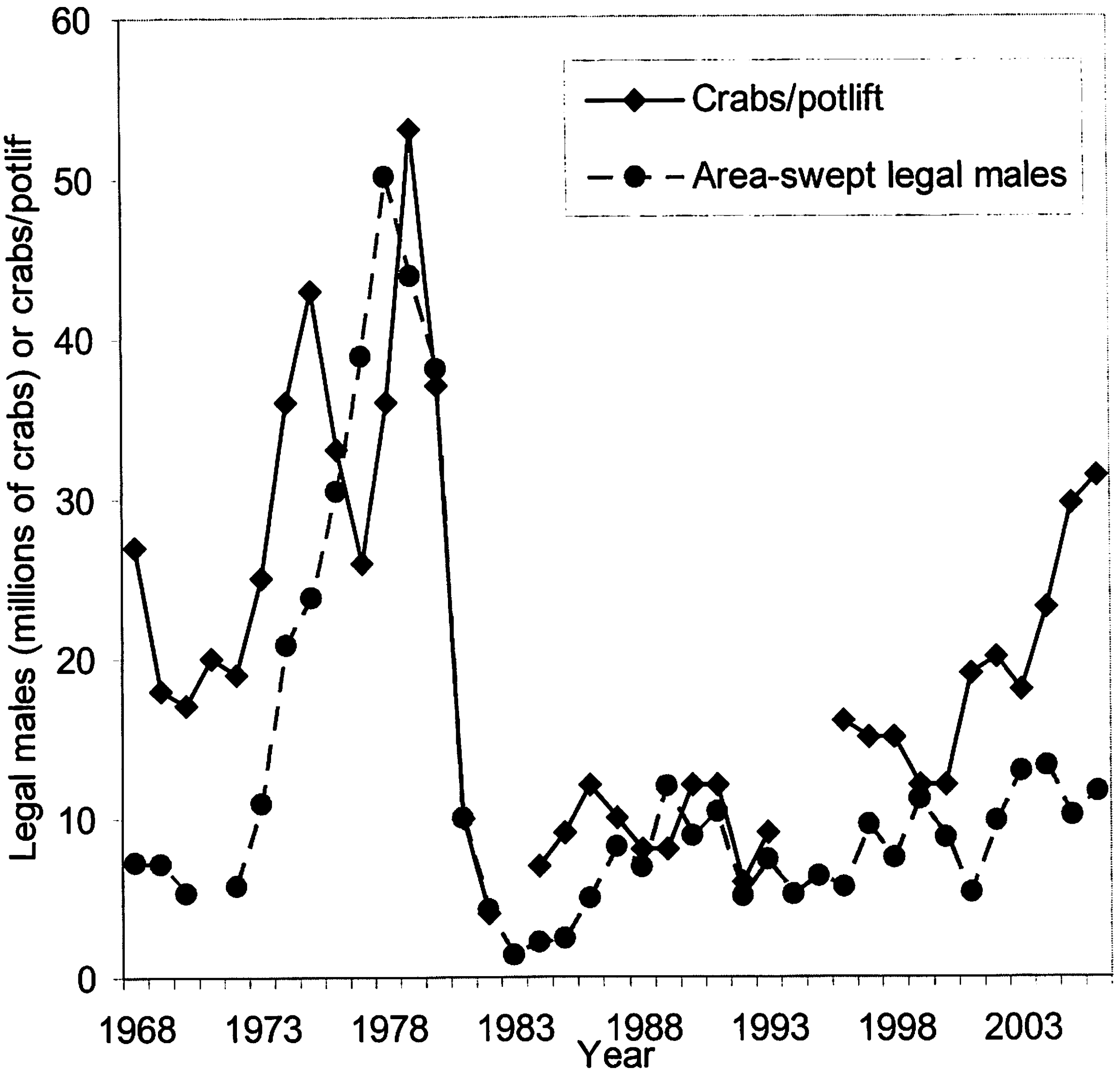

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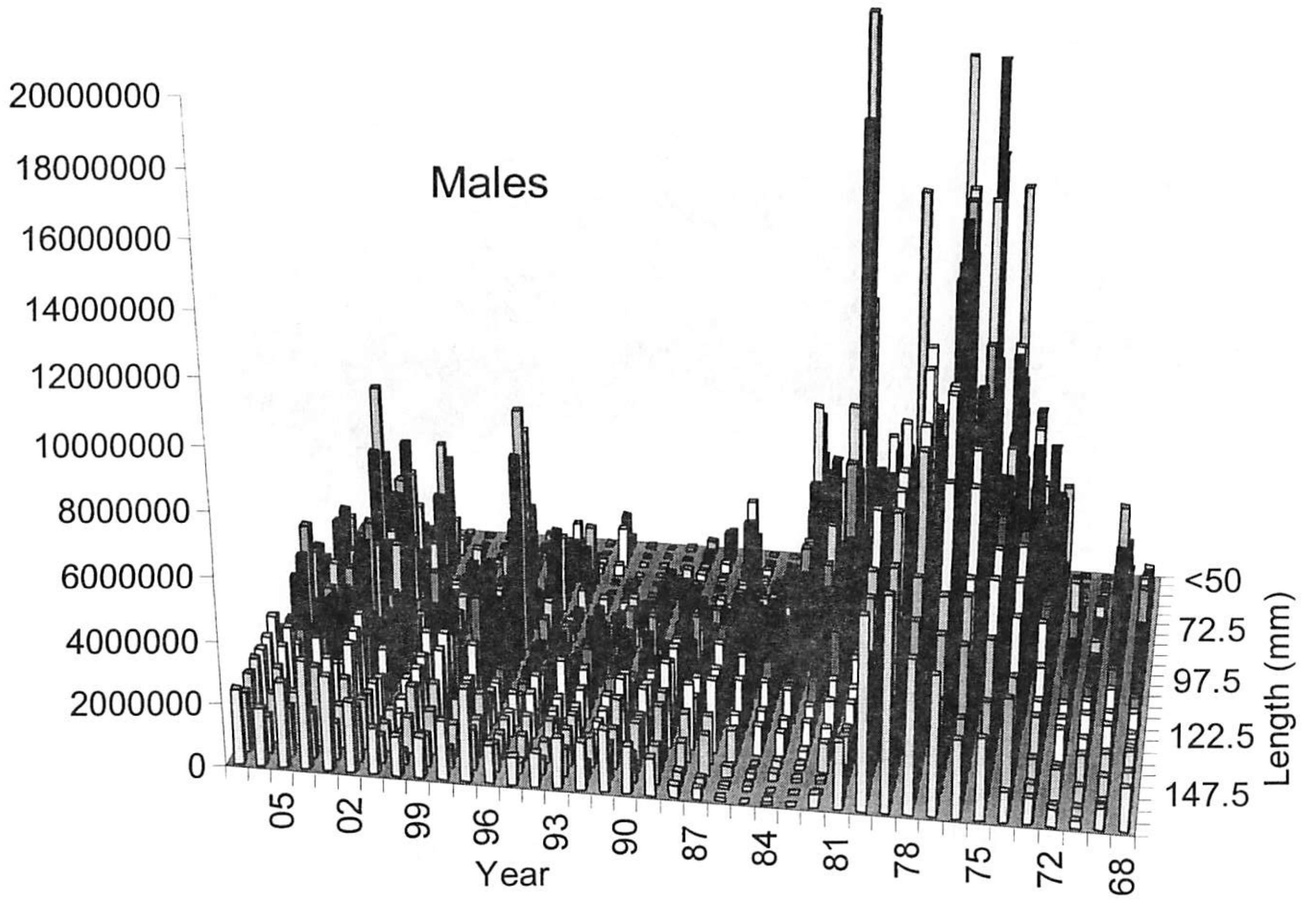

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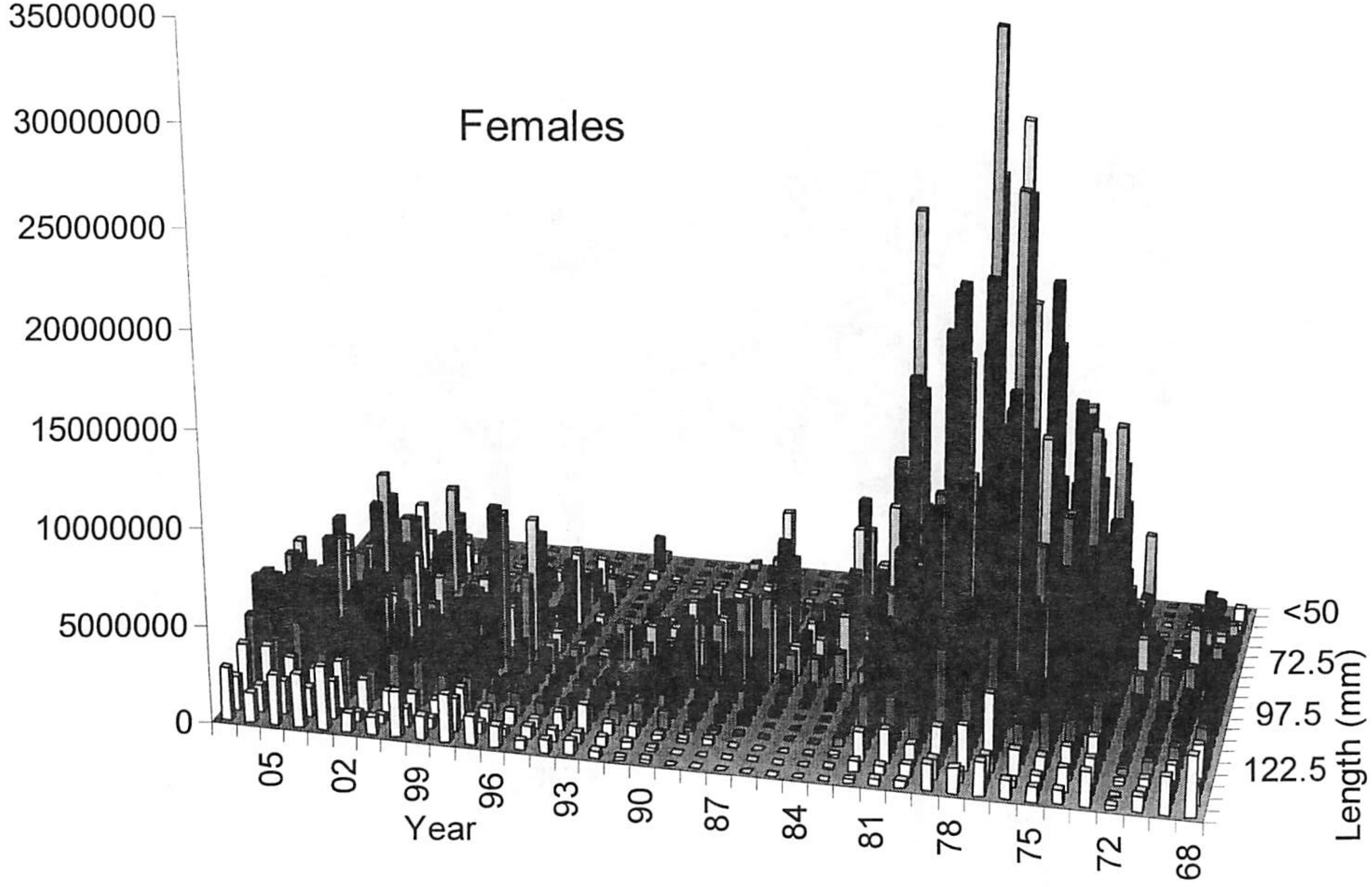

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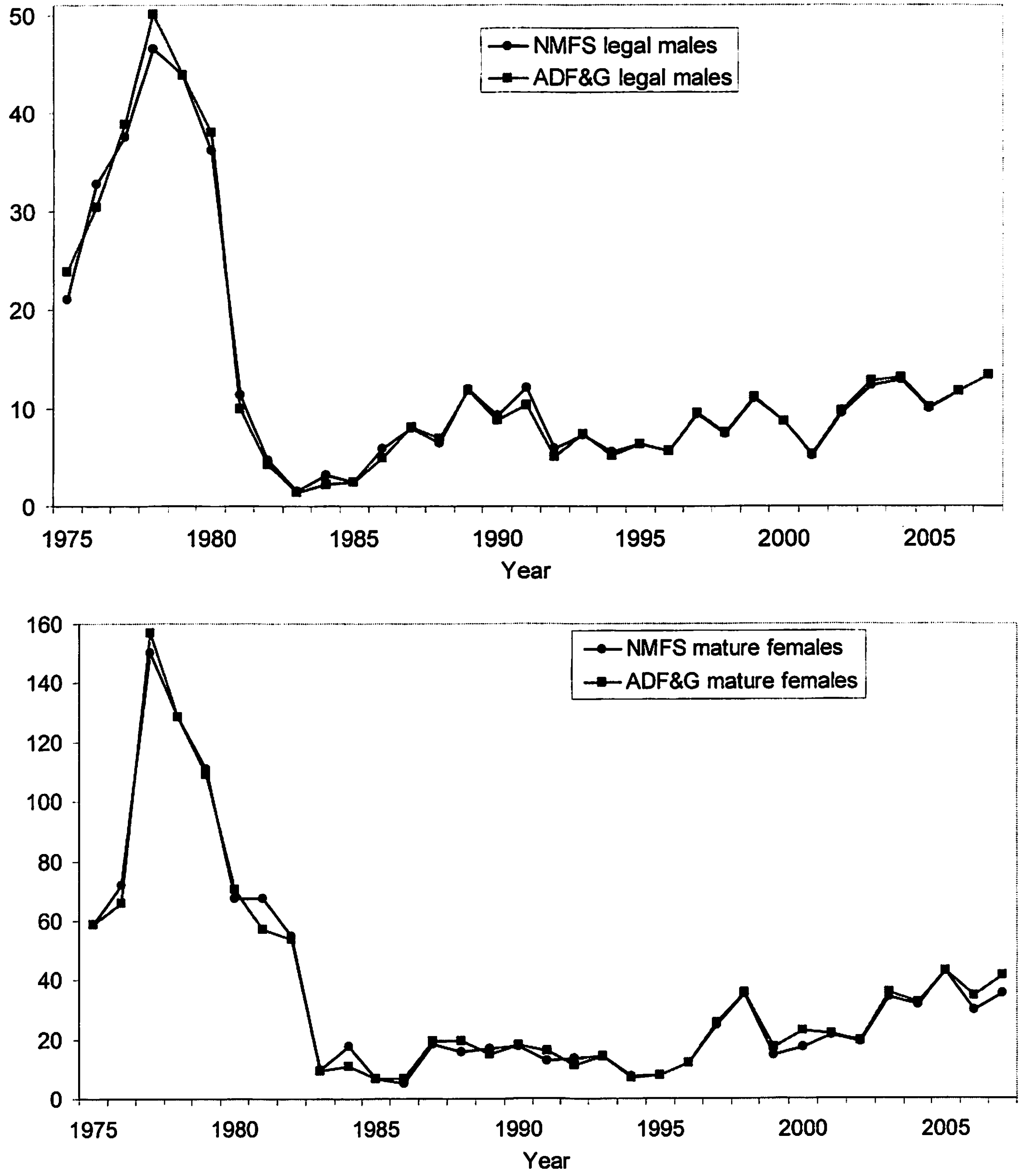

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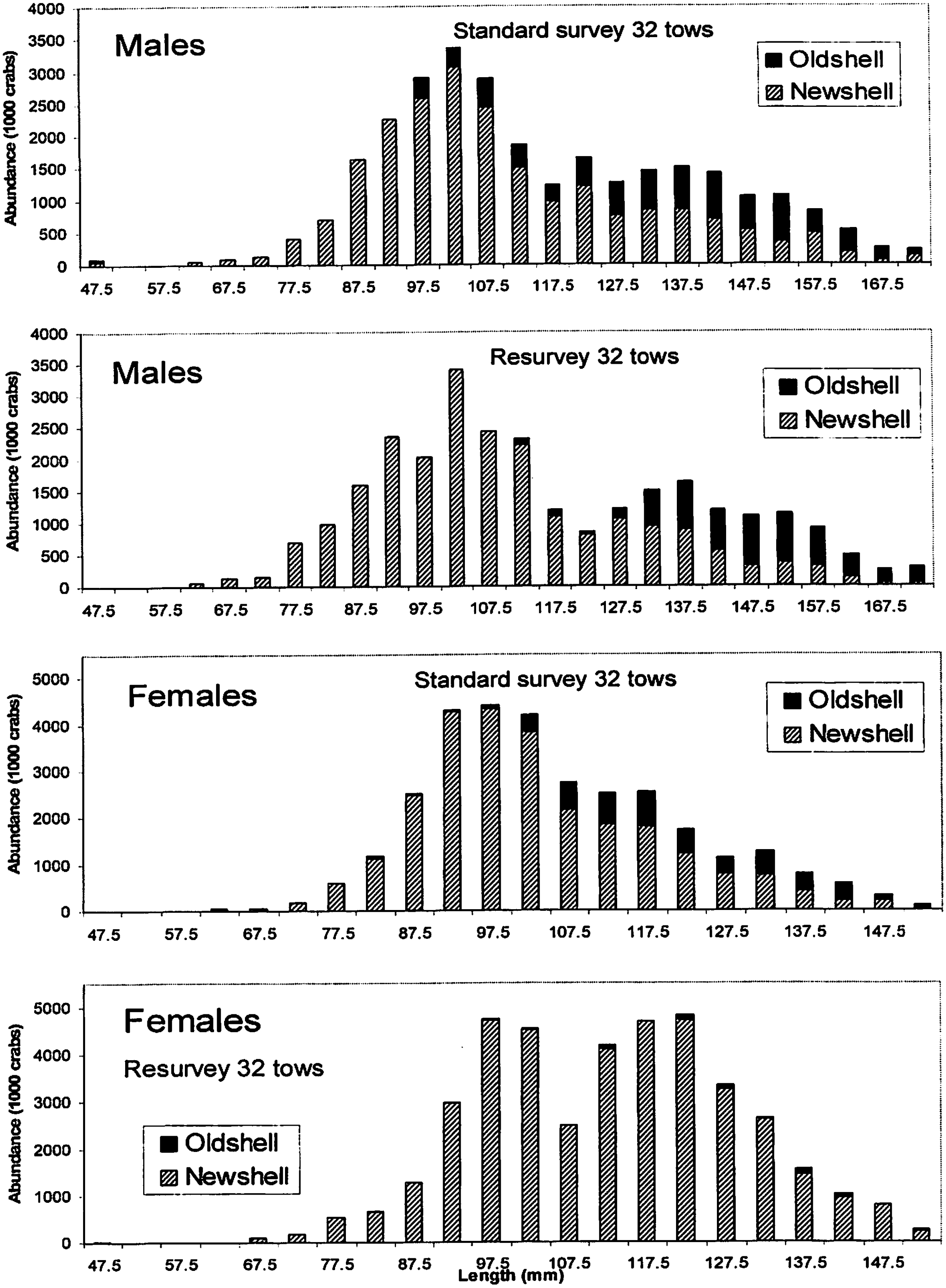

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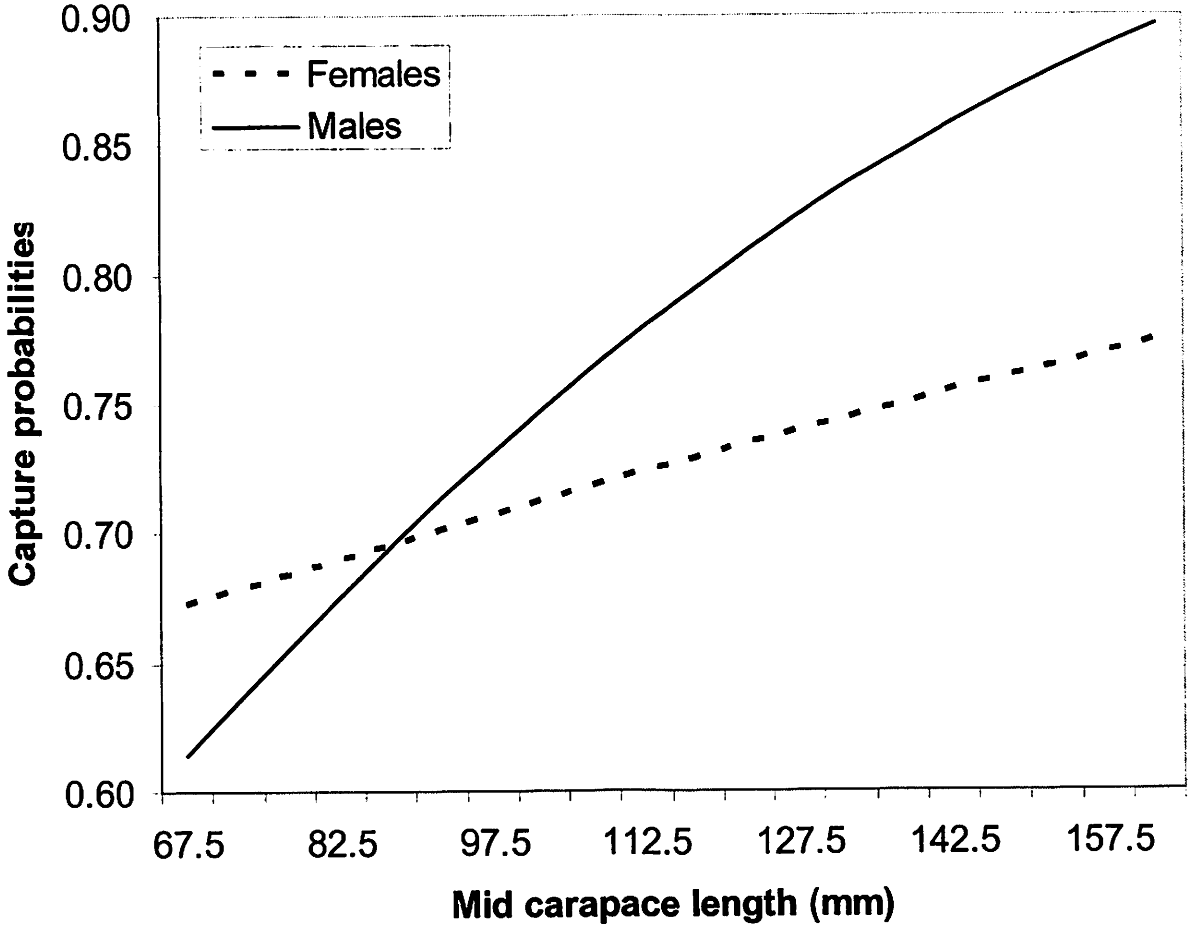

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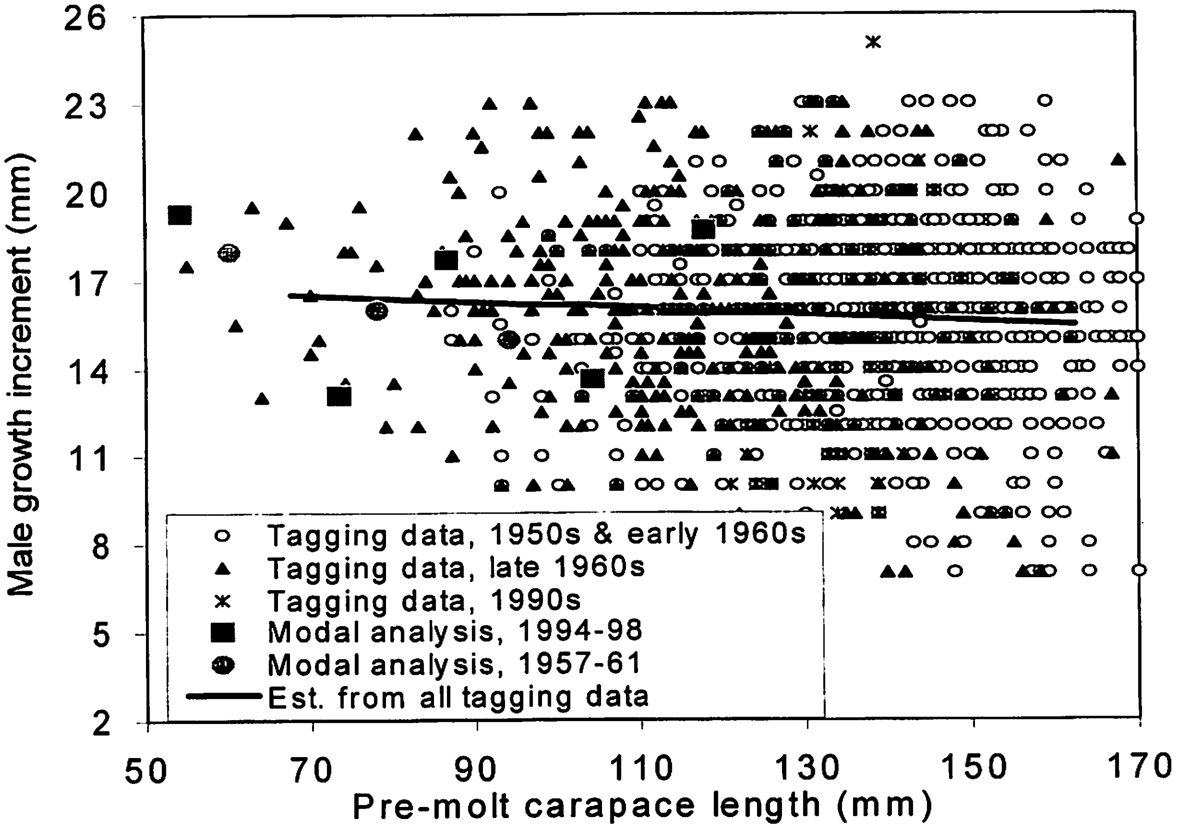

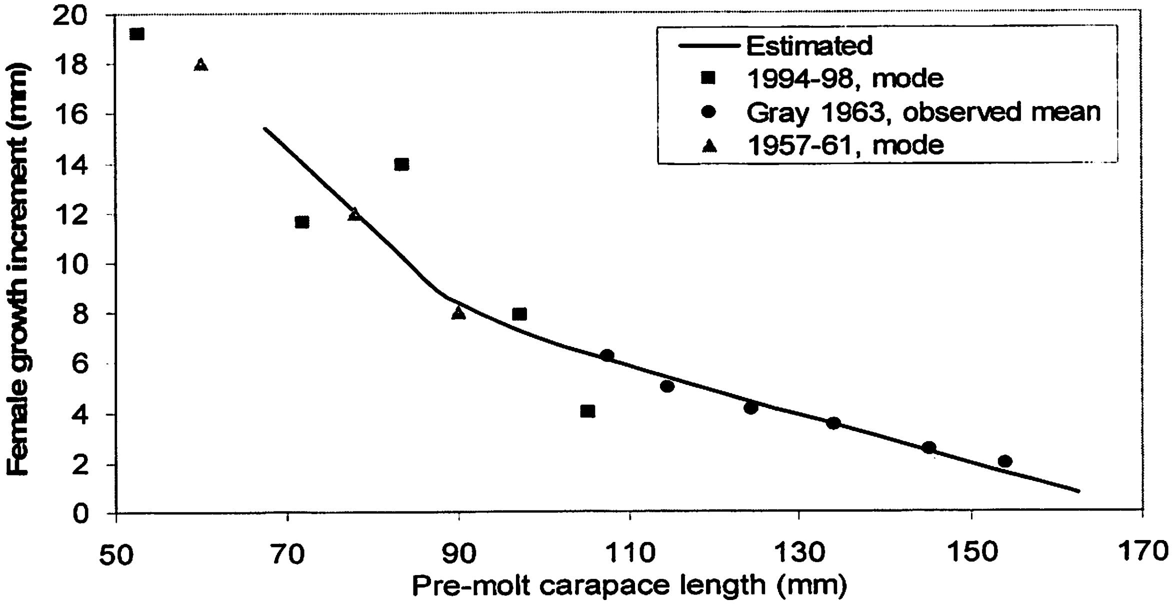

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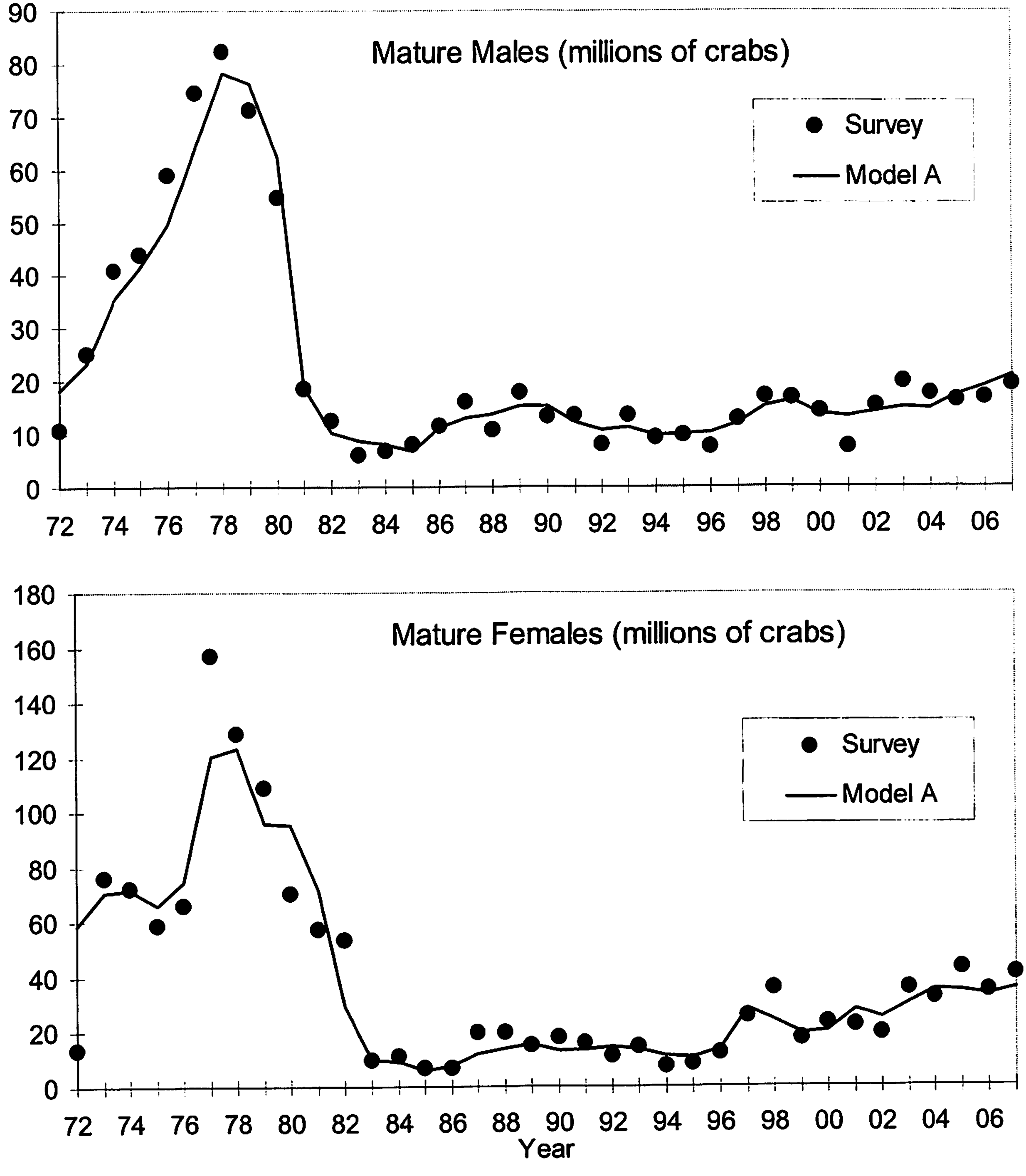

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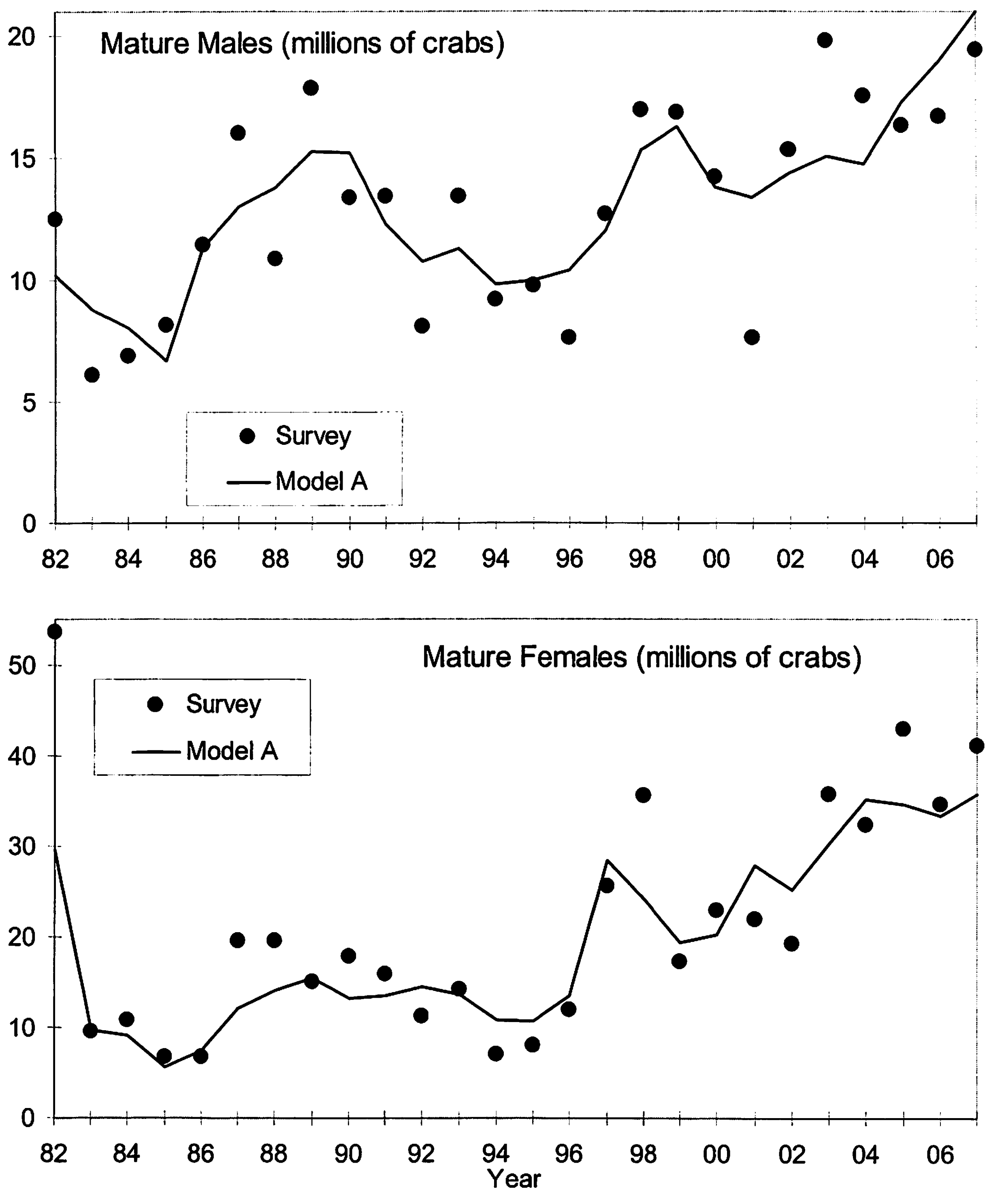

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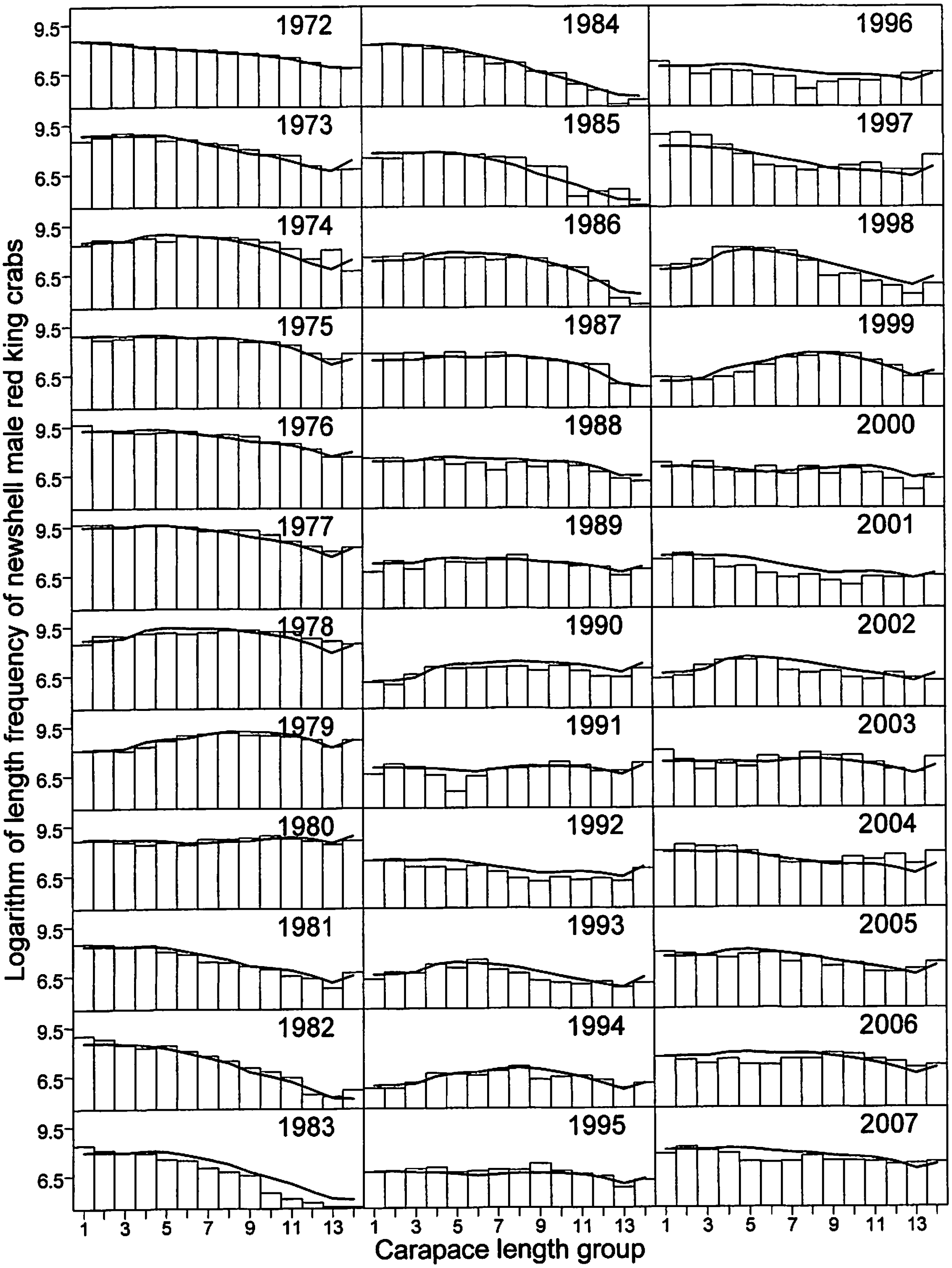

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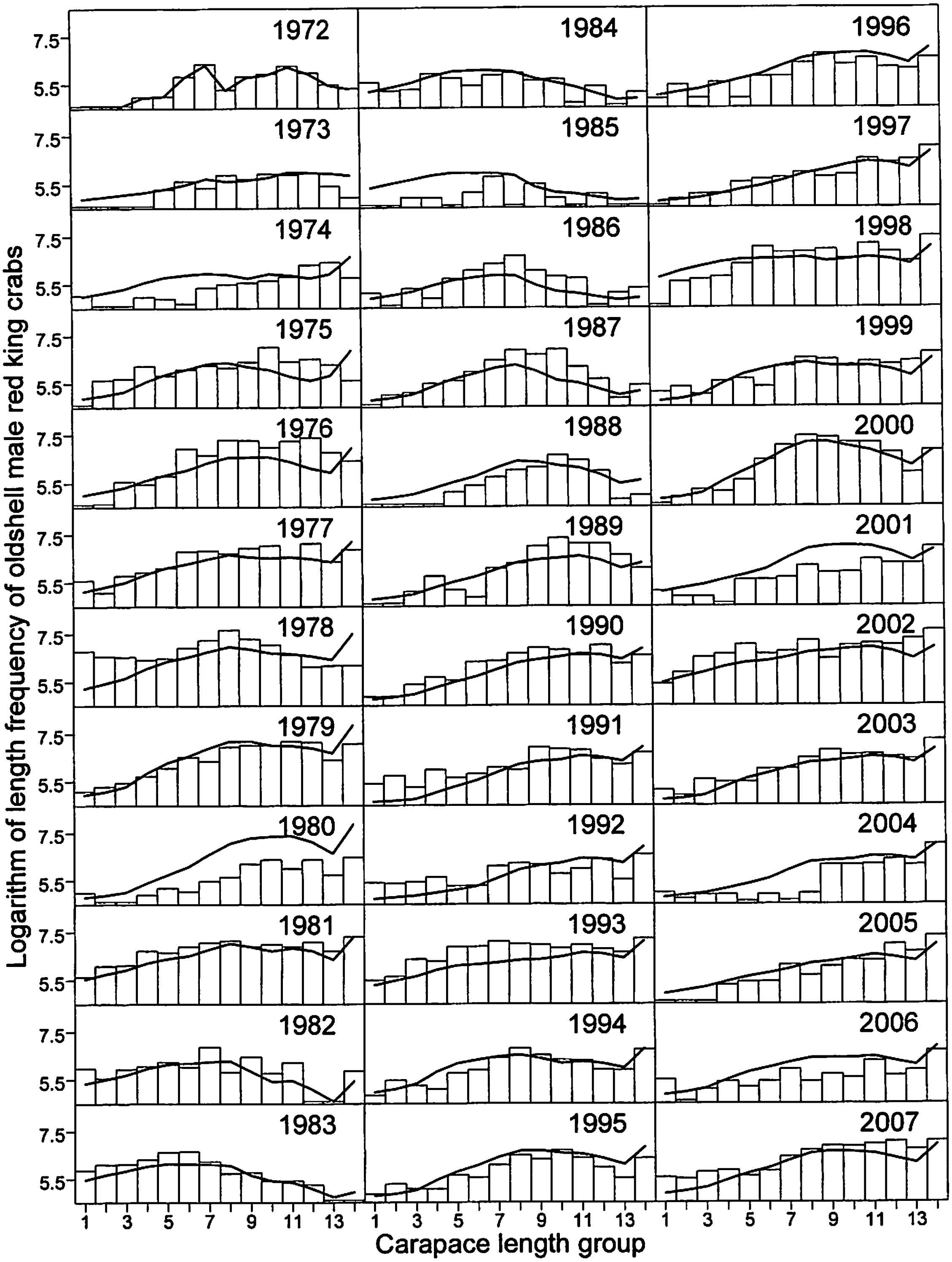

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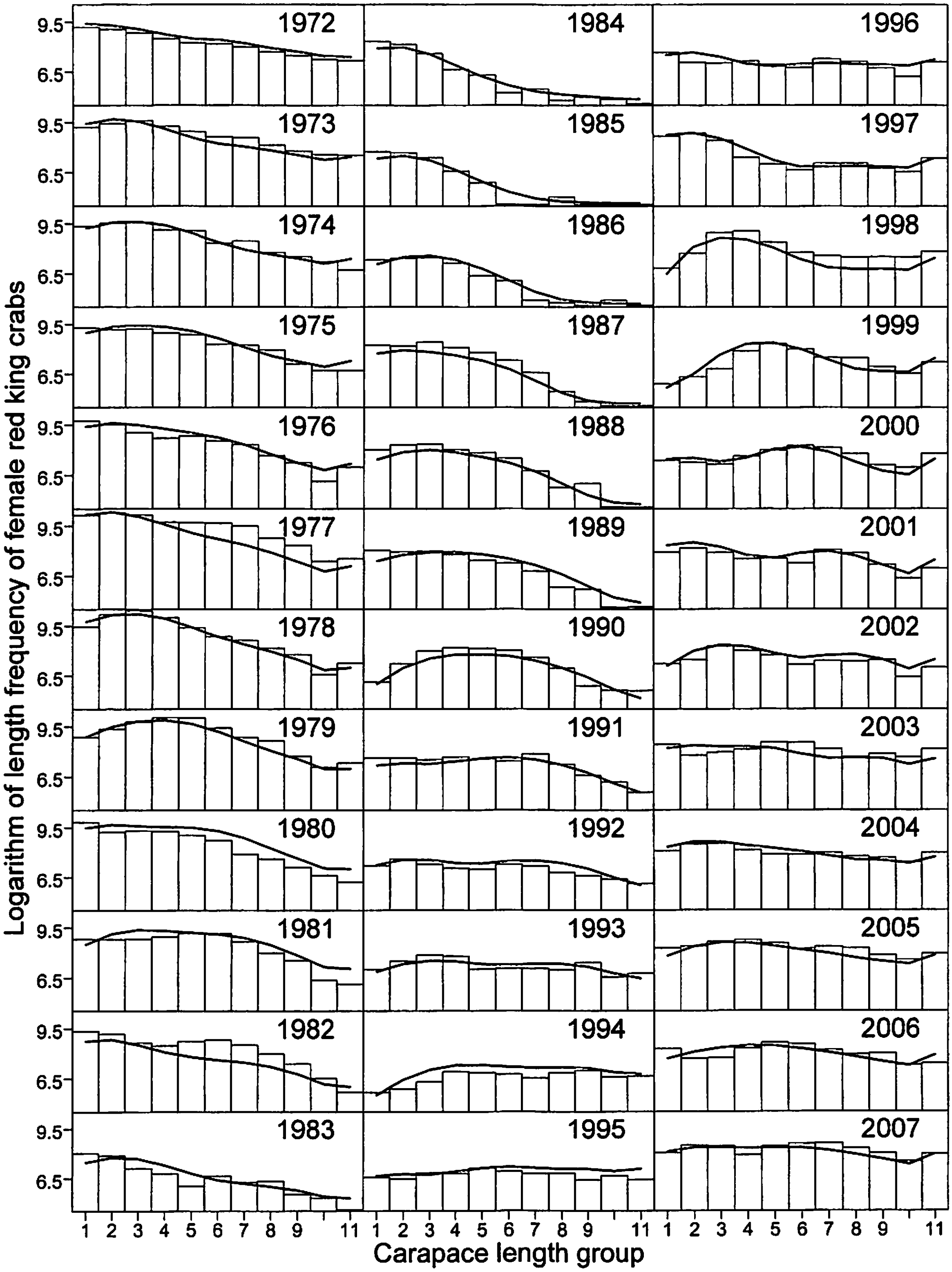

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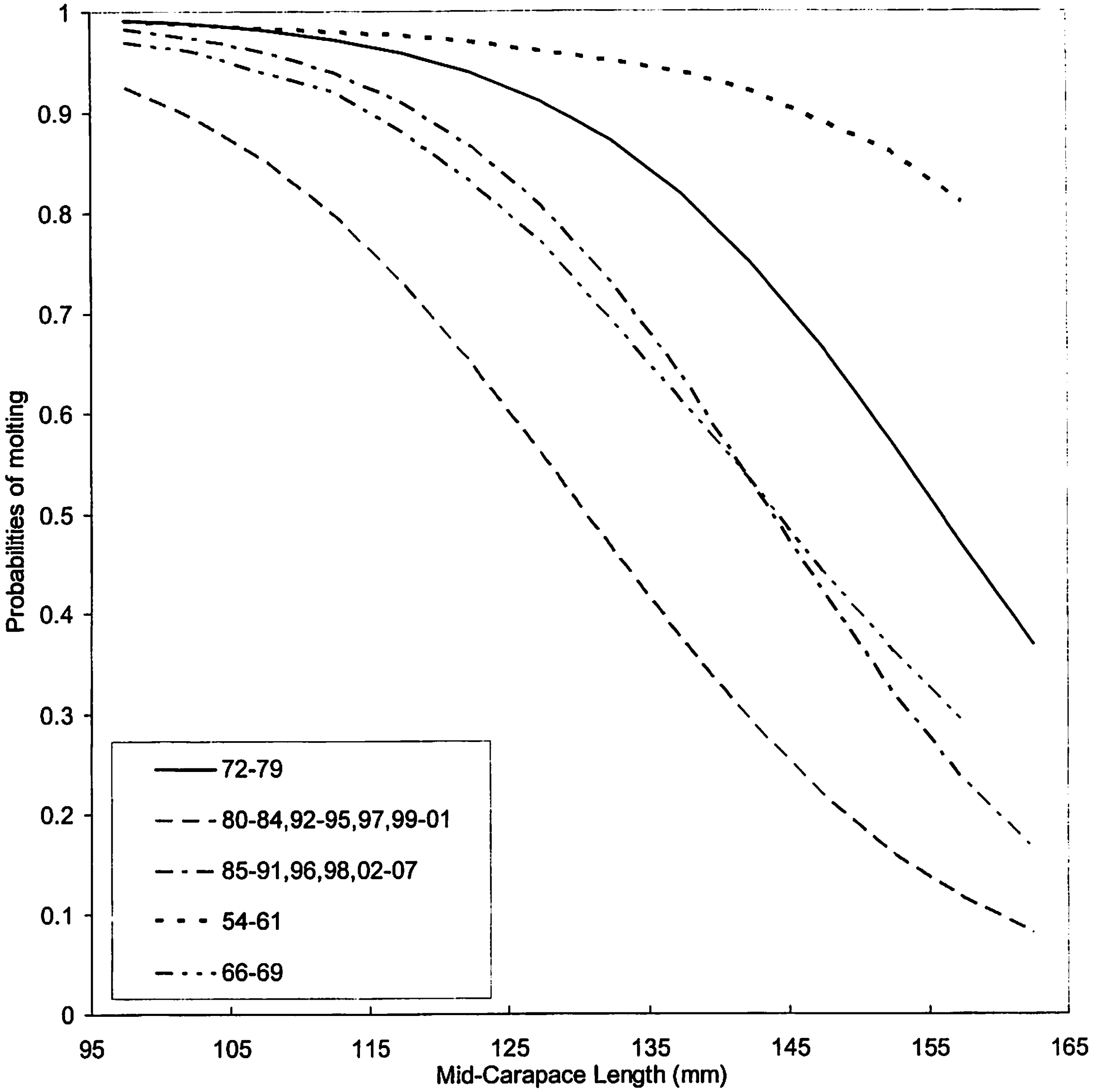

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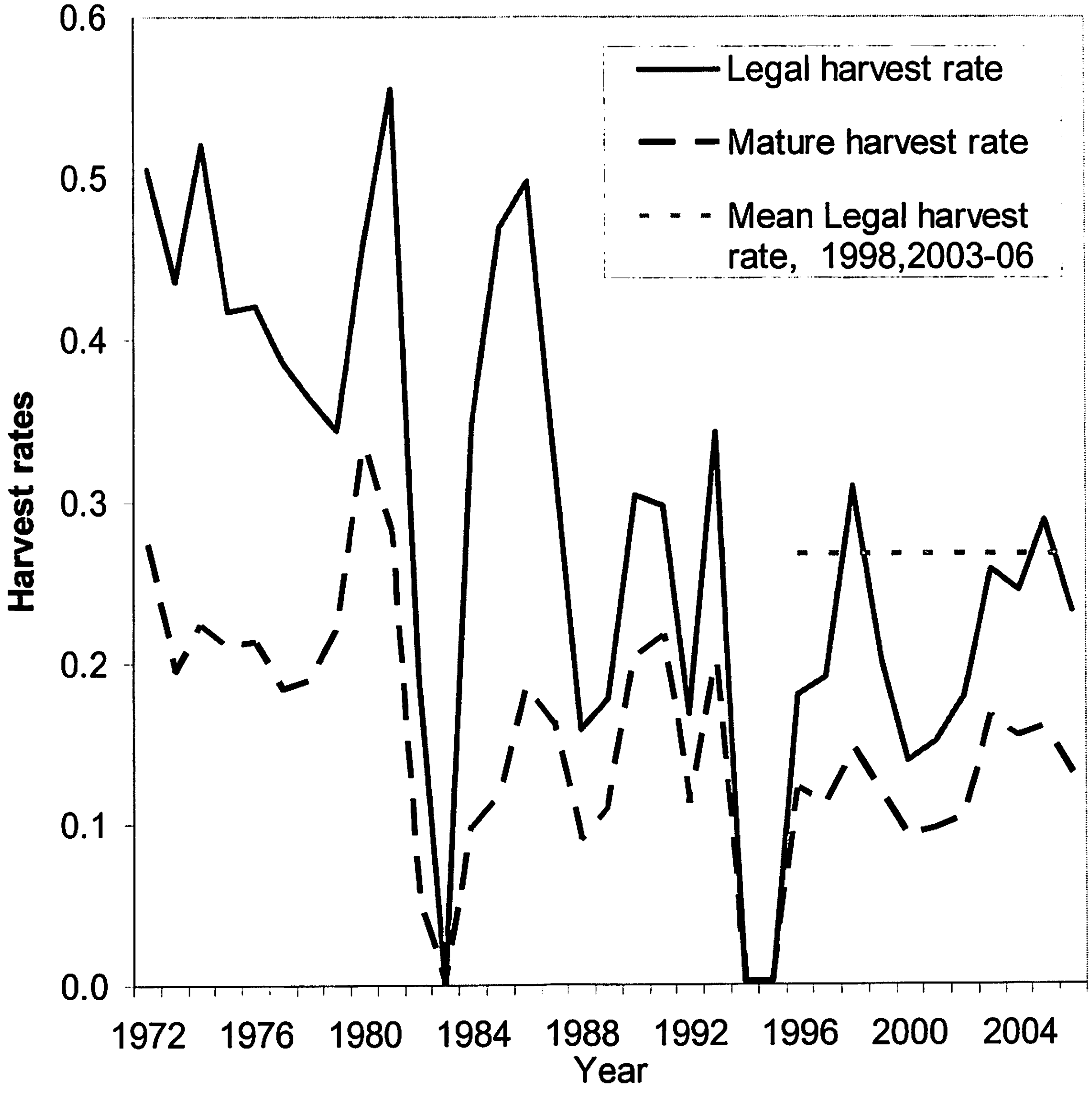

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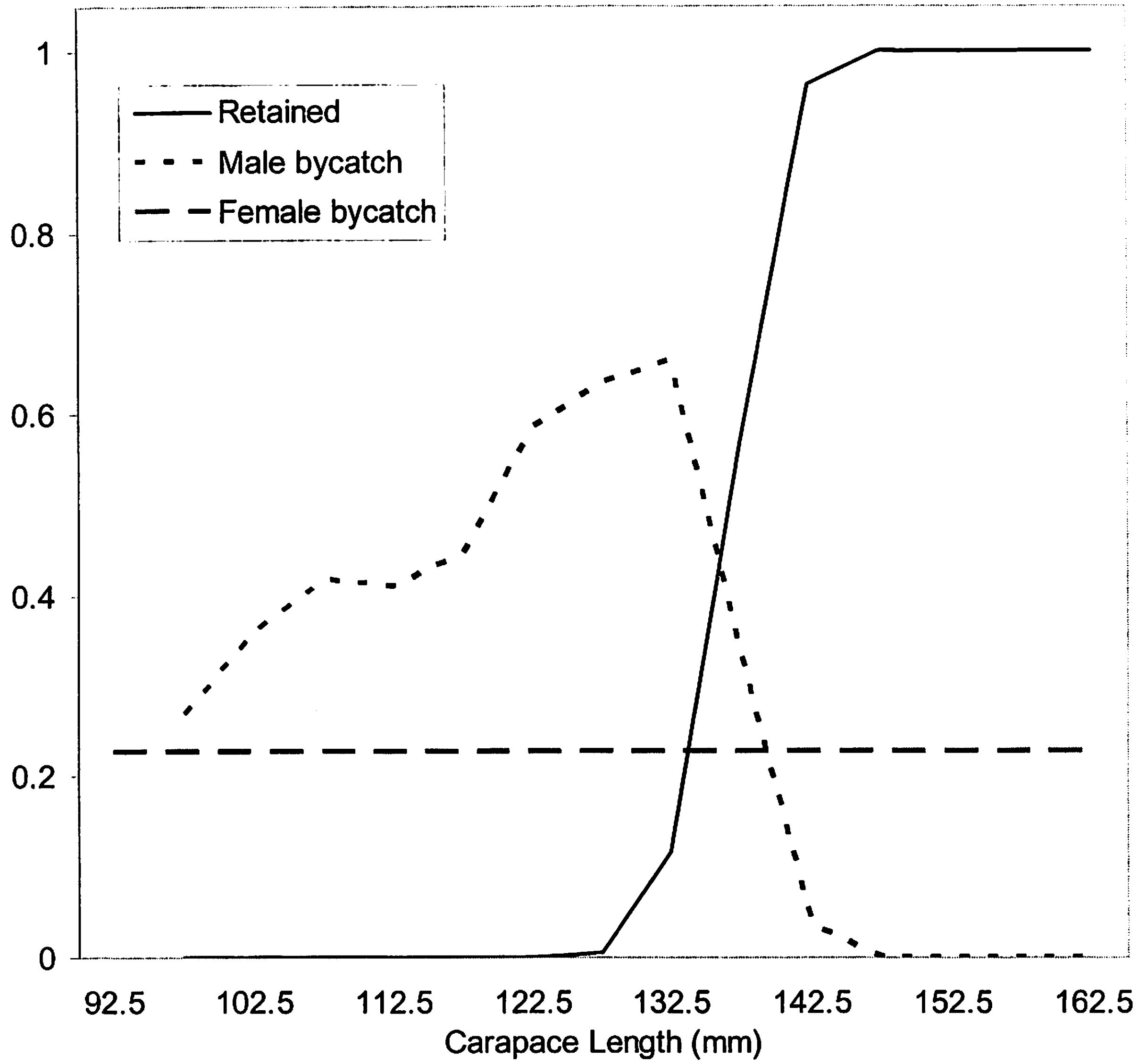

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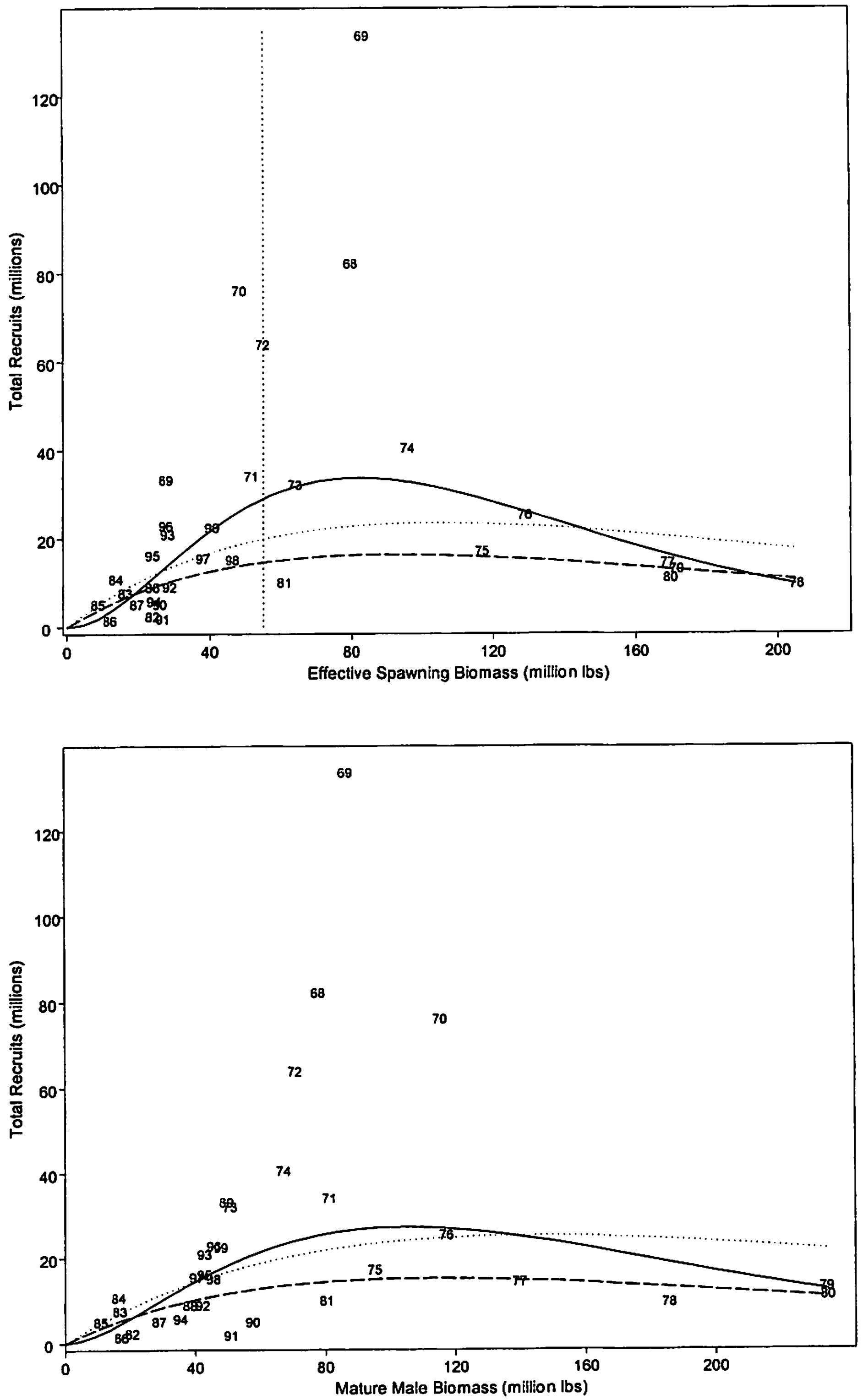

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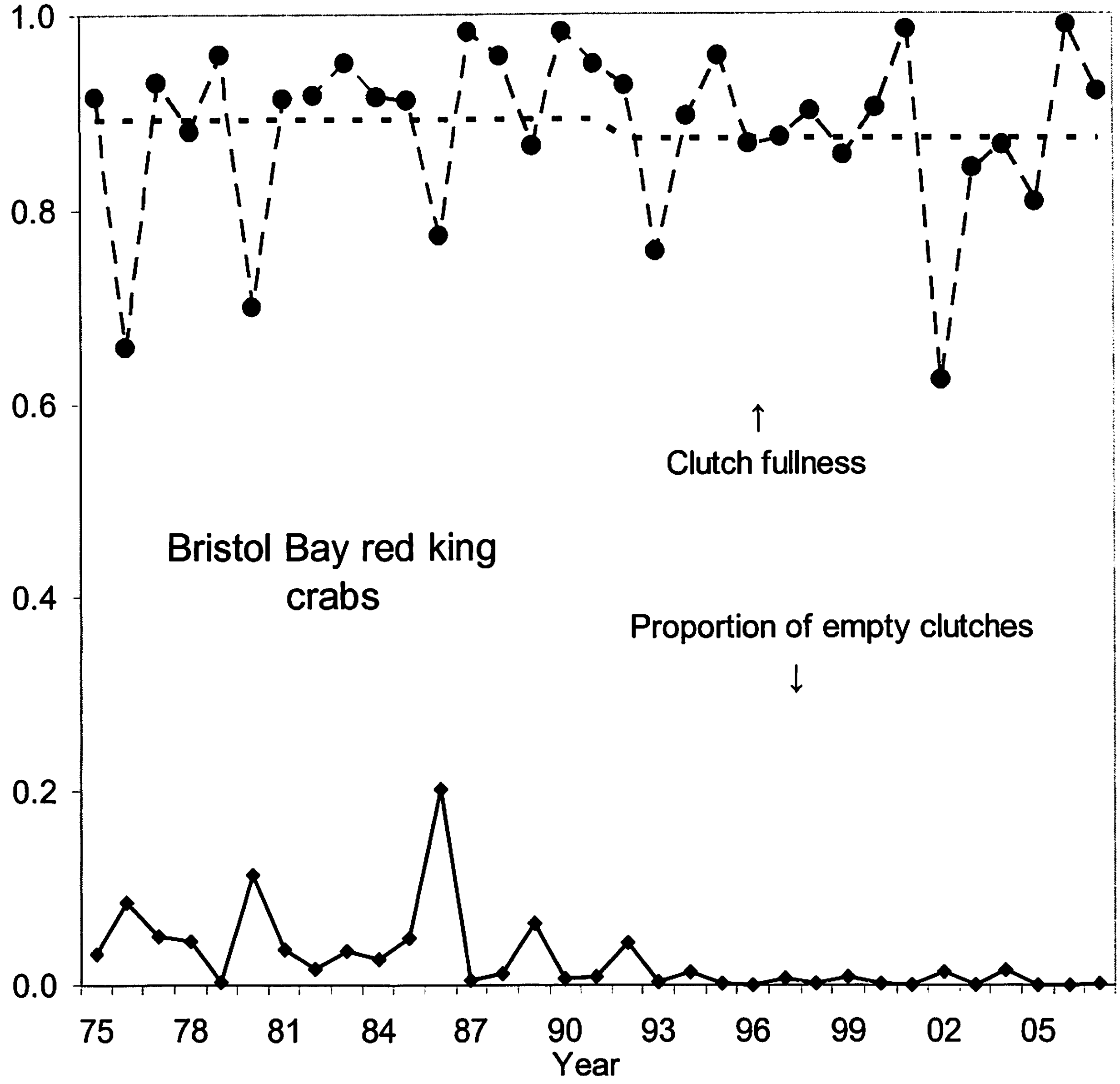

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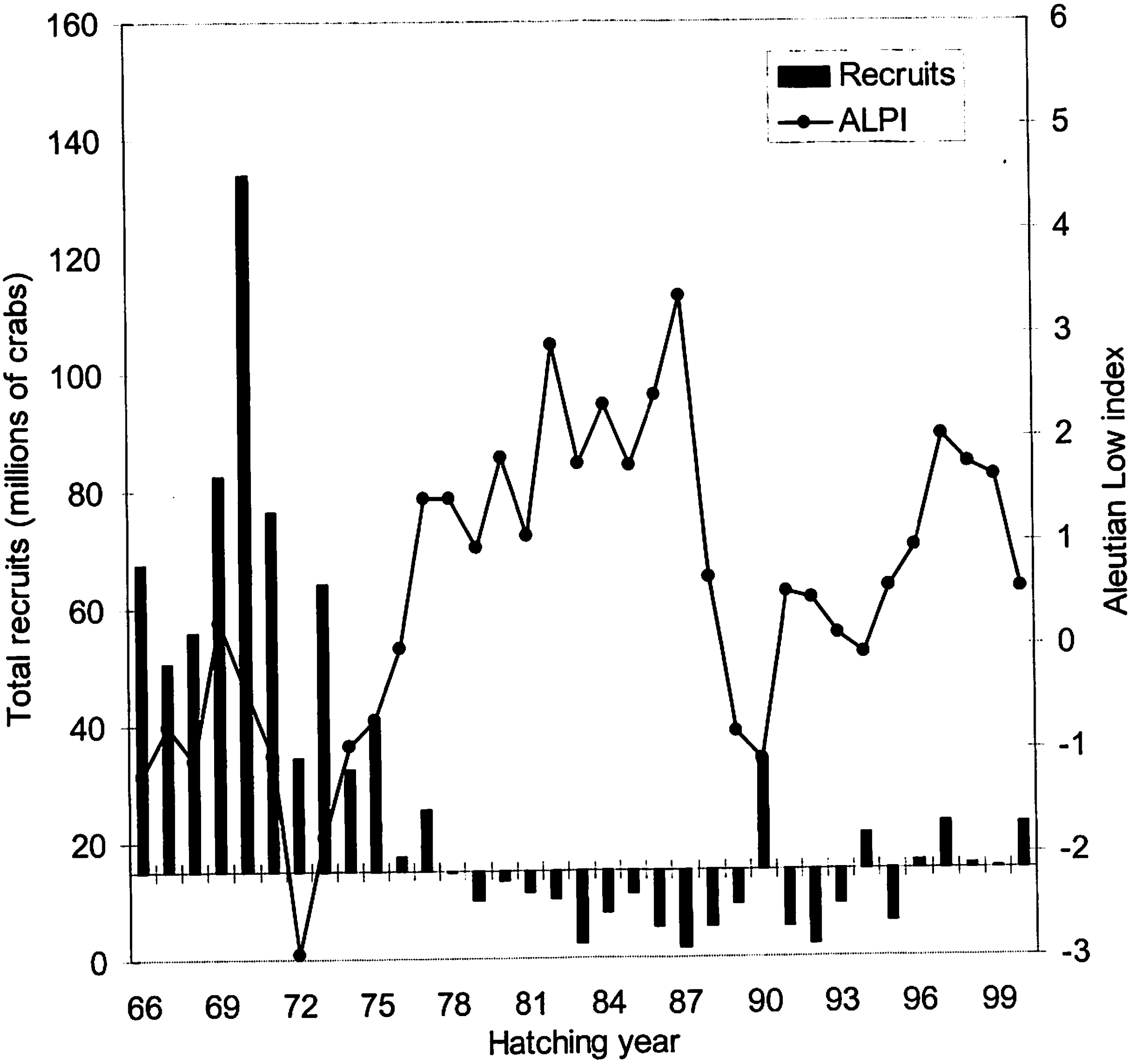

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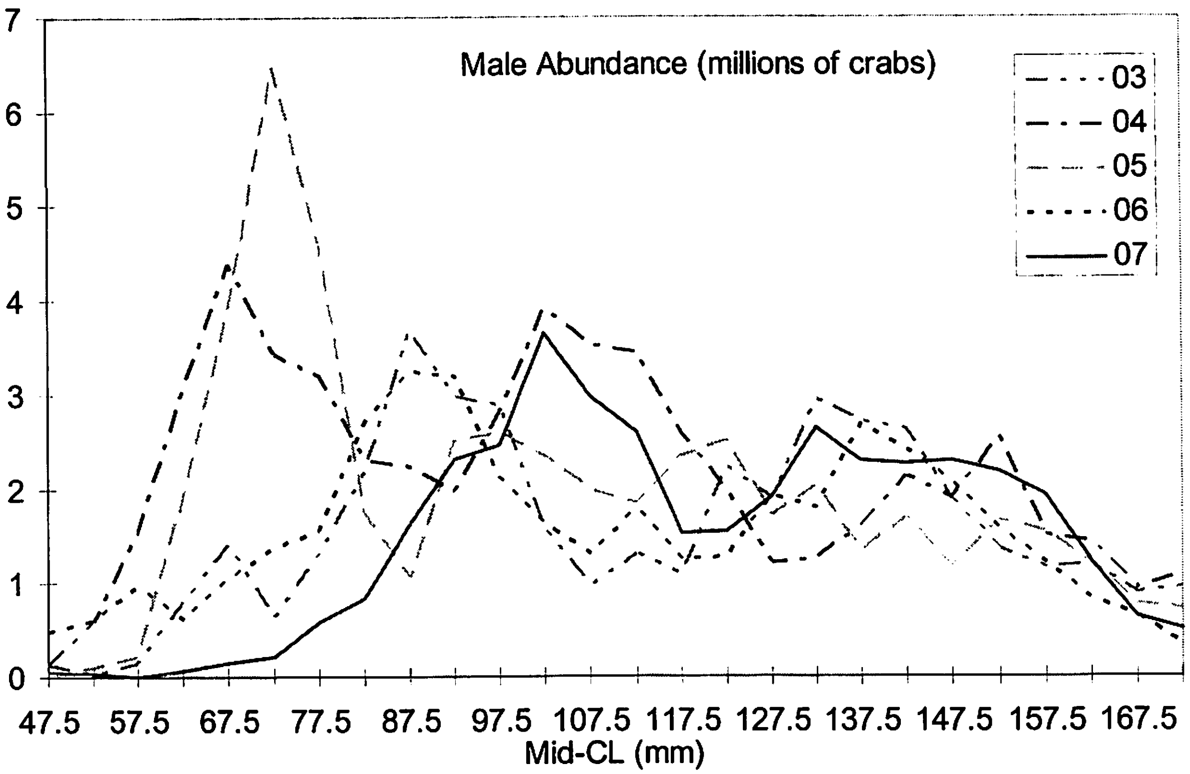

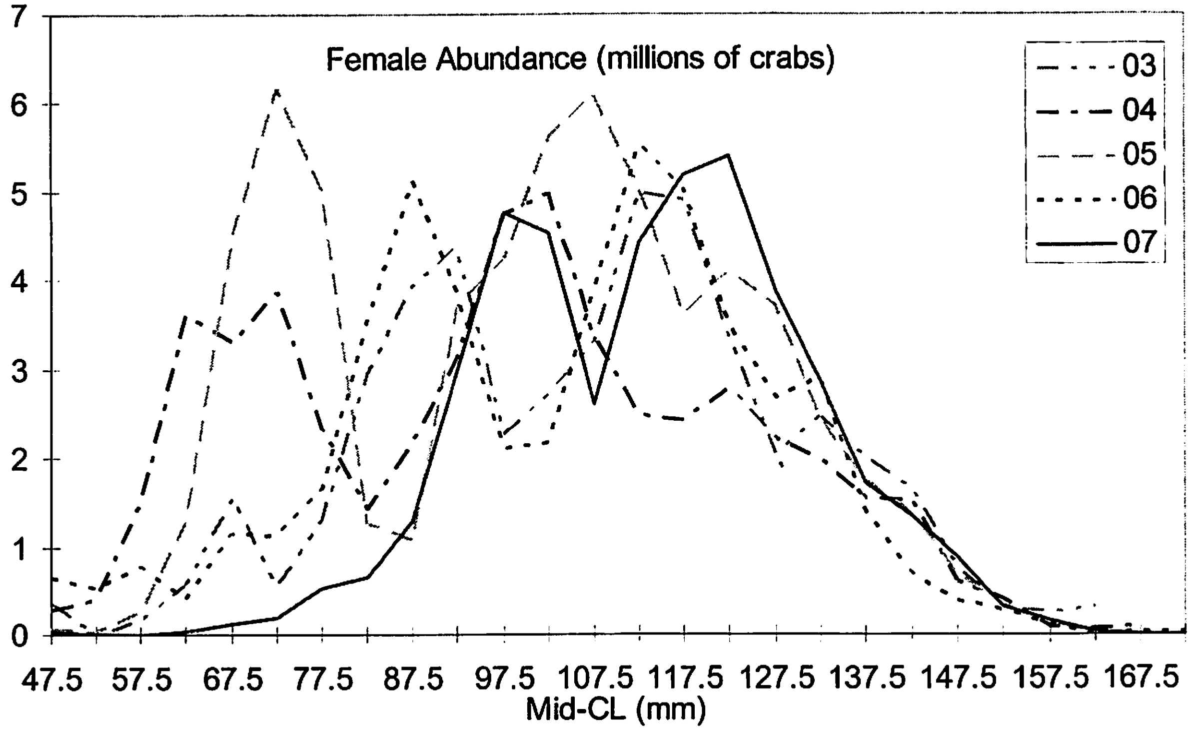

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Appendix A

Stock Assessment of eastern Bering Sea snow crab

Benjamin J. Turnock and Louis J. Rugolo
National Marine Fisheries Service
September 16, 2007

SSC Comments October 2006

The SSC notes that the author was very responsive to SSC comments in June and has devoted a large amount of work to this model since June and has greatly improved the model and its results. While there are remaining improvements to be made, the SSC agrees with the Plan Team that the model should be used this year to provide a more stable biomass estimate than the survey. The SSC notes that the discard mortality rate used in the model (50%) is different than the one used for management (25%), which creates a disconnect. The SSC encourages the stock assessment author to perform a sensitivity study with various discard mortality values including the rate used in the harvest model, in light of the uncertainty in this parameter.

The SSC also notes that there are patterns in the residuals of the fits to survey size frequency data. Jack Turnock noted uncertainty in the practice of using shell condition as a proxy for shell age. The SSC encourages research on growth patterns and shell age to resolve this problem.

Changes to the Model

The model was reconfigured to fit the survey length frequencies for males and females for combined shell condition by immature and mature, due to the uncertainty in shell age with shell condition. Natural mortality was set at 0.29 for mature females, and 0.23 for all other crab, to be consistent with the crab overfishing EA analysis. Sensitivity to discard mortality was investigated in the Crab overfishing EA. The 2007 survey size and abundance and fishery size and catch data were added to the model.

SUMMARY

A size based model was developed for eastern Bering Sea snow crab (*Chionoecetes opilio*) to estimate population biomass and harvest levels. Model estimates of total

mature biomass of snow crab increased from the early 1980's to a peak in 1990 of about 1,660 million lbs. Total mature biomass declined in the late 1990's to about 635 million lbs. in 1999. The stock was declared overfished in 1999 because the survey estimate of mature biomass(330 million lbs) was below the minimum stock size threshold (MSST = 460 million lbs). A rebuilding plan was implemented in 2000. Despite the imposition of the rebuilding plan, model estimates of total mature biomass continued to decline to 407 million lbs in 2003, however, it increased to 654 million lbs in 2007. The 2006 observed survey total mature biomass was estimated at 519.5 million lbs, about 56% of Bmsy (Bmsy = 921.6 million lbs estimated from average survey total mature biomass from 1983 to 1997). The 2007 observed survey total mature biomass increased to 608 million lbs, about 66% of Bmsy. The observed survey estimate of males greater than 101 mm increased from about 69 million in 2005 to 135 million in 2006 and again in 2007 to 151 million. In 2006 there was a high degree of uncertainty in the estimated large male (>101mm) numbers. The 2007 survey estimate of 151 million crab has lower uncertainty than in 2006, with an estimated 95% confidence interval +/-40%. Model estimates of large males (>101mm) were about 97 million crab in 2006 and 142 million in 2007.

Catch has followed survey abundance estimates of large males, since the survey estimates have been the basis for calculating the GHL (Guideline Harvest Level for retained catch). Retained catches increased from about 6.7 million lbs at the beginning of the directed fishery in 1973 to a peak of 328 million lbs in 1991, declined thereafter, then increased to another peak of 243 million lbs in 1998. Retained catch in the 2000 fishery was reduced to 33.5 million lbs due to the low abundance estimated by the 1999 survey. A harvest strategy (Zheng et al. 2002) was developed using a simulation model previous to the development of the current stock assessment model, that has been used to set the most recent GHL's. Retained catch in the 2005 fishery was about 25 million lbs, about 20% above the GHL of 20.9 million lb. Retained catch in the 2006 and 2007 fisheries were 37 million lbs, equal to the preseason TAC.

Estimated discard mortality (mostly undersized males and old shell males) in the directed pot fishery has averaged about 15.5% (with assumed mortality of 50%) of the retained catch biomass since 1992 when observers were first placed on crab vessels. Discards prior to 1992 were estimated based on fishery selectivities estimated for the period with observer data. Discard mortality was assumed to be 50%.

Projected catch and biomass for 2008-2012 was estimated using mature male biomass at the time of mating (February), using F40%, F35% and the current ADF&G harvest strategies. The 2008 mature male biomass at mating time is projected to be at 77% of B40% (fishing at the F40% CR) and 83% of B35% (fishing at F35% CR). Using a harvest control rule with B40% and F40%, the 2008 total catch was estimated at 55.5 million lbs (F = 0.43). Using a harvest control rule with B35% and F35%, the 2008 total catch was estimated at 77.8 million lbs (F = 0.65). The ADF&G harvest strategy 2008 total catch using the projection model was estimated at 80.2 million lbs.

The rebuilding plan developed for snow crab projected a 50% probability of rebuilding by 2010. The probability of rebuilding to the total survey mature biomass Bmsy of 921.6

million lbs in 2010 is less than 1% for all three harvest strategies. Rebuilding to the total survey mature biomass Bmsy is projected to occur by 2021 for the F40% control rule, and about 2024 for the F35% and ADF&G control rules. B35% was estimated using model estimates of mature male biomass at the time of mating (February), a different measure than the current survey based estimate of Bmsy using total mature biomass in summer (males and females). The probability of rebuilding to B35% in 2010 is 10%, 58% and 51% respectively fishing at F35%, F40% and ADF&G control rules.

Biomass is expected to increase in the next few years, then decrease due to recent lower recruitment estimates and using autocorrelation to generate future recruitments. The probability of rebuilding depends on the method of generating future recruitments. The use of random recruitment will result in a higher probability of rebuilding the stock relative to using a spawner recruit curve and autocorrelated recruitment as used in the projections presented here. The trends in future biomass will depend on realized catches and future recruitment and may change in future assessments as more data on the strength of the recent recruitments is obtained.

Exploitation rates in the southern portion of the range of snow crab have been higher than target rates estimated using abundances in the geographic distribution of the stock due the majority of catch occurring in the southern portion of the snow crab range. This prominent feature of the fishery for Bering Sea snow crab has possibly contributed to the shift in distribution to less productive waters in the north. Computing the catch based on the complete survey biomass, then extracting that catch from only the southern component of the stock results in exploitation rates higher than the target rate on crabs in the southern area of the distribution. A biologically meaningful solution would be to split the catch into two regions, north and south, according to the percent distribution of the survey estimate of exploitable males from those regions or the distribution at the time of the fishery if known. In 2003 and 2004, 26% and 24% respectively of male biomass greater than 101 mm measure in the survey was south of 58.5 deg N. The distribution of catch in the 2007 fishery is similar to recent fisheries. Synchronizing the population distribution and catch distribution would result in realized exploitation rate at or close to the target rate in all areas.

INTRODUCTION

Snow crab (*Chionoecetes opilio*) are distributed on the continental shelf of the Bering Sea, Chukchi Sea, and in the western Atlantic Ocean as far south as Maine. In the Bering Sea, snow crab are common at depths less than about 200 meters. The eastern Bering Sea population within U.S. waters is managed as a single stock, however, the distribution of the population may extend into Russian waters to an unknown degree.

CATCH HISTORY

Snow crab were harvested in the Bering Sea by the Japanese from the 1960s until 1980 when the Magnuson Act prohibited foreign fishing. Retained catch in the domestic fishery increased in the late 1980's to a high of about 328 million lbs in 1991, declined to 65 million lbs in 1996, increased to 243 million lbs in 1998 then declined to 33.5 million lbs in the 2000 fishery (Table 1, Figure 1). Due to low abundance and a reduced harvest rate, retained catches remained low and were 32.7 million lbs in the 2002 fishery (36.2 million lbs total catch), 28.3 million lbs of retained catch in 2003 (39 million lbs total catch). Retained catch in the 2005 fishery was 26 million lbs and 37 million lbs in 2006 and 2007.

Discard from the directed pot fishery was estimated from observer data since 1992 and ranged from 11% to 64% (averaged about 33%) of the retained catch of male crab biomass (Table 1). Female discard catch is very low and not a significant source of mortality. In 1992 trawl discard mortality was about 9 million lbs, then declined to about 2 to 3 million lbs until 1998, when it declined to below 1 million lbs (except 2005, 1.4 million lbs). Discard in groundfish fisheries from highest to lowest catch is the yellowfin sole trawl fishery, flathead sole trawl fishery, Pacific cod bottom trawl fishery, rock sole trawl fishery and the Pacific cod hook and line and pot fisheries.

Size frequency data and catch per pot have been collected by observers on snow crab fishery vessels since 1992. Observer coverage was 10% on catcher vessels larger than 125 ft (since 2001), and 100% coverage on catcher processors (since 1992). In the 2002 fishery about 0.5% of the total pot lifts were observed (Neufeld and Barnard 2003).

The average size of retained crabs has remained fairly constant over time ranging between 105 mm and 118 mm, and most recently about 110 mm to 111 mm. The percent new shell animals in the catch has varied between 69% (2002 fishery) to 98% (1999), and was 87% for the 2006 fishery. In the 2007 fishery 98% of the new shell males >101mm CW were retained, while 72% of the old shell males >101mm CW were retained. Only 4% of new shell crab were retained between 78mm and 101 mm CW. The average weight of retained crab has varied between 1.1 lbs (1983-1984) and 1.6 lbs(1979), and 1.3 lbs in the recent fisheries.

Several modifications to pot gear have been introduced to reduce bycatch mortality. In the 1978/79 season, pots used in the snow crab fishery first contained escape panels to prevent ghost fishing. Escape panels consisted of an opening with one-half the perimeter of the tunnel eye laced with untreated cotton twine. The size of the cotton laced panel to prevent ghost fishing was increased in 1991 to at least 18 inches in length. No escape mechanisms for undersized crab were required until the 1997 season when at least one-third of one vertical surface had to contain not less than 5 inches stretched mesh webbing or have no less than four circular rings of no less than 3 3/4 inches inside diameter. In the 2001 season the escapement for undersize crab was increased to at least eight escape rings of no less than 4 inches placed within one mesh measurement from the bottom of the pot, with four escape rings on each side of the two sides of a four-sided pot, or one-half of one side of the pot must have a side panel composed of not less than 5 1/4 inch stretched mesh webbing.

Harvest rates

The Harvest rate used to set the GHL (Guideline harvest level of retained crab only) previous to 2000 was 58% of the number of male crab over 101 mm carapace width estimated from the survey (Anonymous, 2000). The minimum legal size limit for snow crab is 78 mm, however, the snow crab market generally accepts animals greater than 101 mm. In 2000, due to the decline in abundance and the declaration of the stock as overfished, the harvest rate for calculation of the GHL was reduced to 20% of male crab over 101 mm. After 2000, a harvest strategy was developed based on simulations by Zheng (2002).

The actual retained catch typically exceeded the GHL, resulting in exploitation rates for the retained catch (using survey numbers) ranging from about 60% to 100% for most years (Figure 4). The exploitation fraction is calculated using the abundance for male crab over 101 mm estimated from the survey data reduced by the natural mortality from the time of the survey until the fishery occurs, approximately 7 months later, since the late 1980's. The historical GHL calculation did not include the correction for time lapsed between the survey and the fishery. In 1986 and 1987 the exploitation rate exceeded 1.0 because some crabs are retained that are less than 102 mm, discard mortality of small crabs is also included, and survey catchability may be less than 1.0. The exploitation fraction using the total catch divided by the mature male biomass estimated from the model, ranged from 10% to 50% (Figure 5). The exploitation fraction estimated by dividing the total catch by the model estimate of the crabs over 101 mm ranged from about 15% to 80% (Figure 5). The total exploitation rate on males > 101 mm was 50% to 75% for 1986 to 1994 and near 70% for 1998 and 1999 (year when fishery occurred).

Bmsy (921.6 million lbs) is defined in the current crab FMP as the average total mature biomass (males and females) estimated from the survey for the years 1983 to 1997 (BSAI crab FMP 1998). MSST was defined as 50% of the Bmsy value (MSST=460 million lbs of total mature biomass). The current harvest strategy uses a retained crab harvest rate on the mature male biomass of 0.10 on levels of total mature biomass greater than ½ MSST (230 million lbs), increasing linearly to 0.225 when biomass is equal to or greater than Bmsy (921.6 million lbs) (Zheng 2002). The GHL is actually set as the number of retained crab allowed in the harvest, calculated by dividing the GHL in lbs by the average weight of a male crab > 101 mm. If the GHL in numbers is greater than 58% of the estimated number of new shell crabs greater than 101 mm plus 25% of the old shell crab greater than 101 mm, the GHL is capped at 58%. If natural mortality is 0.2, then this actually results in a realized exploitation rate cap for the retained catch of 66% at the time of the fishery, occurring approximately 7 months after the survey. The fishing mortality rate that results from this harvest strategy depends on the relationship between mature male size numbers and male numbers greater than 101 mm. The maximum full selection fishing mortality rate is close to 1.0 under the current harvest strategy at the maximum harvest rate of 0.225 of mature male biomass.

ABUNDANCE TRENDS

Survey Biomass

Abundance is estimated from the annual Bering Sea bottom trawl survey conducted by NMFS (see Rugolo et al. 2003 for design and methods). Since 1989, the survey has sampled stations farther north than previous years (61.2 deg N previous to 1989). In 1982 the survey net was changed resulting in a change in catchability. Juvenile crabs tend to occupy more inshore northern regions (up to about 63 degrees N) and mature crabs deeper areas to the south of the juveniles (Zheng et al. 2001).

The total mature biomass estimated from the survey declined to a low of 188 million lbs in 1985, increased to a high of 1,775 million lbs in 1991, then declined to 330 million lbs in 1999, when the stock was declared overfished (Table 2 and Figure 2). The mature biomass increased in 2000 and 2001, mainly due to a few large catches of mature females. Survey estimates of total mature increased from 519 million lbs in 2006 to 607.8 million lbs in 2007. The total mature biomass includes all sizes of mature females and morphometrically mature males.

The term mature for male snow crab will be used here to mean morphometrically mature. Morphometric maturity for males refers to a marked change in chelae size (thereafter termed "large claw"), after which males are assumed to be effective at mating. Males are functionally mature at smaller sizes than when they become morphometrically mature, although the contribution of these "small-clawed" males to annual reproductive output is negligable. The minimum legal size limit for the snow crab fishery is 78 mm, however the size for males that are generally excepted by the fishery is >101mm. The historical quotas were based on the survey abundance of large males (>101mm).

Survey Size Composition

Carapace width is measured on snow crab and shell condition noted in the survey and the fishery. Snow crab cannot be aged at present (except by radiometric aging of the shell since last molt), however, shell condition has been used as a proxy for age. Based on protocols adopted in the NMFS EBS trawl survey, shell condition class and presumptive age are as follows: soft shell (SC1) (less than three months from molting), new shell (SC2) (three months to less than one year from molting), old shell (SC3) (two years to three years from molting), very old shell (SC4) (three years to four years form molting), and very very old shell (SC5) (four years or longer from molting). Radiometric aging of shells from terminal molt male crabs (after the last molt of their lifetime) elucidated the relationship between shell condition and presumptive age, which will be discussed in a later section (Nevissi et al 1995 and Orensanz unpub. Data).

Survey abundance by size for males and females indicate a moderate recruitment of small crab in 2004 and 2005 (Figures 6 through 9). High numbers of small crab in the late 1970's did not follow through the population to the mid-1980's. The high numbers of small crab in the late 1980's resulted in the high biomass levels of the early 1990's and subsequent high catches. Moderate increase in numbers can also be seen in the mid 1990's.

Spatial distribution of catch and survey abundance

The majority of the fishery catch occurs south of 58.5 deg N., even in years when ice cover did not restrict the fishery moving farther north. In past years, most of the fishery catch occurred in the southern portion of the snow crab range possibly due to ice cover and proximity to port and practical constraints of meeting delivery schedules. In 2003, 66% of the catch was south of 58.5 deg N. (Figure 10), and in 2004 78% of the catch was south of 58.5 deg N. (Figure 11). In 2003 and 2004 the ice edge was farther north than past years, allowing some fishing to occur as far north as 60-61 deg N. Catch in the 2007 fishery was similar to recent years (Figure 12) with most catch south of 58 degrees N. to the west of the Pribilof Islands between about 171 deg. W and 173 deg W.

Summer survey data show that approximately 75% of the mature male snow crab population resides in a region outside of the fishery zone (north of 58.5 deg N Latitude). The 2003 survey estimated about 24% of the male snow crab >101mm were south of 58.5 deg N. About 48% of those males were estimated to be new shell. In 2004 about 26 % of the survey abundance of male snow crab > 101 mm and the mature male biomass were south of 58.5 deg N. latitude (Figures 13 and 15). About 53% of those males south of 58.5 deg N. were estimated to be new shell (which are preferred by the fishery). The 2004 fishery retained about 19 million crab of which about 14.8 million were caught south of 58.5 deg south (about 78%). Although these new shell males are morphometrically mature (i.e., large clawed), at the time of the fishery, they are subject to exploitation prior to recruiting to the reproductive stock. The 2003 survey estimate of new shell male crab > 101 mm was about 7.6 million south of 58.5 deg N. which would have been fished on in the 2004 fishery. In the 2004 survey about 9.5 million new shell males >101mm were estimated south of 58.5 deg N. This indicates that survey catchability may be less than 1.0 and/or some movement occurs between the summer survey and the winter fishery. However, the exploitation rate on males south of 58.5 deg N exceeds the target rate, possibly resulting in a depletion of males from the southern part of their range. Snow crab larvae probably drift north and east after hatching in spring. Snow crab appear to move south and west as they age, however, no tagging studies have been conducted to fully characterize the ontogenetic or annual migration patterns of this stock. High exploitation rates in the southern area may have resulted in a northward shift in snow crab distribution. Lower egg production in the south from lower clutch fullness and higher percent barren females possibly due to insufficient males for mating may drive a change in distribution to the north. The northward shift in mature females is particularly problematic in terms of annual reproductive output due to lowered productivity from the shift to biennial spawning of animals in waters < 1.5 deg C in the north. The lack of males in the southern areas at mating time (after the fishery occurs) may result in insufficient males for mating.

The spatial distribution of large males snow crab in the 2007 survey was similar to 2005 (Figures 16 and 17), however, 2007 had fewer crab in the area to the south and west of

St. Matthew Island. Female crab > 49 mm occurred in higher concentration in generally three areas, just north of the Pribilof Islands, just south and west of St. Matthews Island, and to the north and west of St. Matthew Island. Males > 78 mm were distributed in similar areas to females, except the highest concentrations were between the Pribilof Islands and St. Matthews Island.

Armstrong and Ernst (in press) found the centroids of survey summer distributions have moved to the north over time (Figures 18 and 19). In the early 1980's the centroids of mature female distriubution were near 58.5 deg N, in the 1990's the centroids were about 59.5 deg N. The centroids of old shell male distribution was south of 58 deg N in the early 1980's, moved north in the late 1980's and early 1990's then shifted back to the south in the late 1990's (Figure 19). The distribution of males>101 mm was about at 58 deg N in the early 1980's, then was farther north (58.5 to 59 deg N) in the late 1980's and early 1990's, went back south in 1996 and 1997 then has moved north with the centroid of the distribution in 2001 just north of 59 deg N.(Figure 19). The centroids of the catch are generally south of 58 deg N, except in 1987 (Figure 19). The centroids of catch also moved north in the late 1980's and most of the 1990's. The centroids of the catch were about at 56.5 deg N in 1997 and 1998, then moved north to above 58.5 deg in 2002.

ANALYTIC APPROACH

Data Sources

Catch data and size frequencies of retained crab from the directed snow crab pot fishery from 1978 to the 2007 season were used in this analysis. Observers were placed on directed crab fishery vessels starting in 1990. Size frequency data on the total catch (retained plus discarded) in the directed crab fishery were available from 1992 to 2007. However, the overall rate of observer coverage is low for this fishery – e.g., 0.5% of total snow crab pot lifts were observed in 2002 (Neufeld and Barnard 2003). Total discarded catch was estimated from observer data from 1992 to 2007(Table 1). The discarded male catch was estimated for 1978 to 1991 in the model using the estimated fishery selectivities based on the observer data for the period 1992 to 2007. The discard catch estimate was multiplied by the assumed mortality of discards from the pot fishery. The mortality of discarded crab was assumed to be 50%. The current harvest strategy assumes a discard mortality of 25% (Zheng 2002). The discard mortality assumptions will be discussed in a later section. The estimated discards previous to 1992 may be underestimates due to the lack of escape mechanisms for undersized crab in the pots prior to 1997.

The following table contains the various data components used in the model,

Data component	Years
Retained male crab pot fishery size frequency by shell condition	1978-2007 (Year when fishery actually occurred)
Discarded male and female crab pot fishery size	1992-2007

frequency	
Trawl fishery bycatch size frequencies by sex	1990-2005
Survey size frequencies by sex and shell condition	1978-2007
Retained catch estimates	1978-2007
Discard catch estimates from snow crab pot fishery	1992-2007 from observer data
Trawl bycatch estimates	1973-2007
Total survey biomass estimates and coefficients of variation	1978-2007

Model Structure

The model structure was developed following Fournier and Archibald's (1982) methods, with many similarities to Methot (1990). The model was implemented using automatic differentiation software developed as a set of libraries under C++ (ADModel Builder). ADModel Builder can estimate a large number of parameters in a non-linear model using automatic differentiation software extended from Greiwank and Corliss (1991) and developed into C++ class libraries. This software provides the derivative calculations needed for finding the objective function via a quasi-Newton function minimization routine (e.g., Press et al. 1992). The model implementation language (ADModel Builder) gives simple and rapid access to these routines and provides the ability to estimate the variance-covariance matrix for all parameters of interest.

Details of the population dynamics and estimation equations, description of variables and likelihood equations are presented in Appendix A (Tables A.1, A.2 and A.3). The population dynamics equations, incorporating the growth transition matrix and molting probabilities are similar to other size based crab models (Zheng et al. 1995 and 1998). There were a total of 234 parameters estimated in the model (Table A.4) for the 30 year range of data (1978-2007). The 90 fishing mortality parameters (one set for the male catch, one set for the female discard catch, and one set for the trawl fishery bycatch) estimated in the model were constrained so that the estimated catch fit the observed catch closely. There were 30 recruitment parameters estimated in the model, one for the mean recruitment, 29 for each year from 1979 to 2007 (male and female recruitment were fixed to be equal). There were 12 fishery selectivity parameters that did not change over time as in previous assessments. Survey selectivity was estimated for three different periods resulting in 9 parameters estimated. One parameter was estimated to fit the pot fishery CPUE time series.

Molting probabilities for mature males and females were fixed at 0, i.e., growth ceases at maturity which is consistent with the terminal molt paradigm (Rugolo et al. 2005 and Tamone et al. 2005). Molting probabilities were fixed at 1.0 for immature females and males. The intercept and slope of the linear growth function of postmolt relative to premolt size were estimated in the model using parmeters estimated from growth measurements for Bering Sea snow crab as prior distributions (4 parameters, Table A.5).

A gamma distribution was used in the growth transition matrix with the beta parameters fixed at 0.75 for male and females.

The model separates crabs into mature, immature, new shell and old shell, and male and female for the population dynamics. The model estimate of survey mature biomass is fit to the observed survey mature biomass time series by sex. The model fits the size frequencies of the survey by immature and mature separately for each sex. The model fits the size frequencies for the pot fishery catch by new and old shell and by sex.

Crabs 25 mm CW (carapace width) and larger were included in the model, divided into 22 size bins of 5 mm each, from 25-29 mm to a plus group at 130-135mm. In this report the term size as well as length will be considered synonymous with CW. Recruits were distributed in the first few size bins using a two parameter gamma distribution with the parameters estimated in the model. The alpha parameter of the distribution was estimated in the model and the beta parameter was fixed at 1.5. Eighty-eight parameters were estimated for the initial population size composition of new and old shell males and females in 1978. No spawner-recruit relationship was used in the population dynamics part of the model. Recruitments for each year were estimated in the model to fit the data.

The NMFS trawl survey occurs in summer each year, generally in June-July. In the model, the time of the survey is considered to be the start of the year (July), rather than January. The modern directed snow crab pot fishery has occurred generally in the winter months (January to February) over a short period of time. In contrast, in the early years the fishery occurred over a longer time period. The mean time of the fishery was estimated from the weighted distribution of catch by day for each year. The fishing mortality was applied all at once at the mean time for that year. Natural mortality is applied to the population from the time the survey occurs until the fishery occurs, then catch is removed. After the fishery occurs, growth and recruitment take place (in spring), with the remainder of the natural mortality through the end of the year as defined above.

Weight - Size

The weight (kg) – size (mm) relationship was estimated from survey data, where weight $= a * \text{size}^{b}$. Juvenile female a= 0.00000253, b=2.56472. Mature female a=0.000675 b=2.943352, and males, a= 0.00000023, b=3.12948 (Figure 20).

Maturity

Maturity for females was determined by visual examination during the survey and used to determine the fraction of females mature by size for each year. Female maturity was determined by the shape of the abdomen, by the presence of brooded eggs or egg remnants.

Morphometric maturity for males is determined by chela height measurements, which are available starting from the 1989 survey (Otto 1998). The number of males with chela height measurements has varied between about 3,000 and 7,000 per year. In this report a mature male refers to a morphometrically mature male.

One maturity curve for males was estimated and applied to all years of survey data to estimate mature survey numbers. A two-parameter logistic function fit the fraction mature for larger new shell males well, resulting in size at 50% mature for new shell males of 88 mm CW with a slope of 0.12. The separation of mature and immature males by chela height at small widths may not be adequately refined given the current measurement to the nearest millimeter. Chela height measured to the nearest tenth of a millimeter (by Canadian researchers on North Atlantic snow crab) shows a clear break in chela height at small and large widths and shows fewer mature animals at small widths than the Bering sea data measured to the nearest millimeter. Measurements taken in 2004-2005 on Bering sea snow crab chela to the nearest tenth of a millimeter show a similar break in chela height to the Canadian data (Lou Rugolo et al. 2005).

The average fraction mature for old shell males was used as the maturity curve for all years for old shell males. Maturity for old shell males is zero below 40 mm, increases from 83% at 45 mm to 95% at 115 mm.

The probability of a new shell crab maturing was estimated outside the model to move crab from immature to mature in the model. The probability of maturing was estimated to match the observed fraction mature for all mature males and females observed in the survey data. While the fraction of all animals that are mature is fit well, the fraction of crab that are old shell is greater than in the survey data. The probability of maturing by size for female crab was about 50% at about 50 mm and increased to 100% at 80mm (Figure 21). The probability of maturing for male crab was 20% at 80 mm, increased to 50% at 100mm, about 905 at 120mm and 100% at 135 mm.

Selectivity

Selectivity curves for the retained and total catch were estimated as two-parameter ascending logistic curves (Figure 22). The probability of retaining crabs by size and shell condition was estimated as an ascending logistic function. The selectivities for the retained catch were estimated by multiplying the retention curve by the selectivities for the retained plus discarded size compositions.

The selectivities for the survey and trawl bycatch were estimated with two-parameter, ascending logistic functions (Figure 23). Survey selectivities were set equal for males and females. Separate survey selectivities were estimated for the period 1978 to 1981, 1982 to 1988, and 1989 to the present. The maximum selectivity was estimated in the model. The separate selectivities were used due to the change in catchability in 1982 from the survey net change, and the addition of more survey stations to the north of the survey area after 1988. Survey selectivities have been estimated for Bering Sea snow crab from underbag trawl experiments (Somerton and Otto 1999) (Figure 23). A bag underneath the regular trawl was used to catch animals that escaped under the footrope of the regular trawl, and was assumed to have selectivity equal to 1.0 for all sizes. The selectivity was estimated to be 50% at about 74 mm, 0.73 at 102 mm, and reached about 0.88 at the maximum size in the model of 135 mm.

Growth

Very little information exists on growth for Bering Sea snow crab. Tagging experiments were conducted on snow crab in 1980 with recoveries occurring in the Tanner crab (*Chionoecetes bairdi*) fishery in 1980 to 1982 (Mcbride 1982). All tagged crabs were males greater than 80mm CW, which were released in late may of 1980. Forty-nine tagged crabs were recovered in the Tanner crab fishery in the spring of 1981 of which only 5 had increased in carapace width. It is not known if the tags inhibited molting or resulted in mortality during molting, or the extent of tag retention. One crab was recovered after 15 days in the 1980 fishery, which apparently grew from 108 mm to 123 mm carapace width. One crab was recovered in 1982 after almost 2 years at sea that increased from 97 to 107 mm.

Growth data from 14 male crabs collected in March of 2003 that molted soon after being captured were used to estimate a linear function between premolt and postmolt width (Lou Rugolo unpublished data, Figure 23). The crabs were measured when shells were still soft because all died after molting, so measurements are probably underestimates of postmolt width (Rugolo, pers. com.). Growth appears to be greater than growth of some North Atlantic snow crab stocks (Sainte-Marie 1995). Growth from the 1980 tagging of snow crab was not used due to uncertainty about the effect of tagging on growth. No growth measurements exist for Bering Sea snow crab females. North Atlantic growth data indicate growth is slightly less for females than males.

Growth was modeled using a linear function to estimate the mean width after molting given the mean width before molting (Figure 24),

$$\text{Width}_{t+1} = a + b^{*}\ \text{width}_t$$

The parameters a and b estimated from the observed growth data for Bering sea snow crabs were used as prior means for the growth parameters estimated in the model. Crab were assigned to 5mm width bins using a gamma distribution with mean equal to the growth increment by sex and length bin and a beta parameter (which determines the variance),

$$Gr_{s,l\rightarrow l'} = \int_{l'-2.5}^{l'+2.5} Gamma(\alpha_{s,l}, \beta_s)$$

Where Gr is the growth transition matrix for sex, s and length bin l (premolt size). l' is the postmolt size. The Gamma distribution is,

$$g(x \mid \alpha_{s,l}, \beta_s) = \frac{x^{\alpha_{s,l}-1} e^{-\frac{x}{\beta_s}}}{\beta^{\alpha_{s,l}} \Gamma(\alpha_{s,l})} \quad .$$

Where x is length and alpha and beta are parameters. Beta for both males and females was fixed in the model at 0.75.

Natural Mortality

Natural mortality is an essential control variable in population dynamic modeling, and may have a large influence on derived optimal harvest rates. Natural mortality rates estimated in a population dynamics model may have high uncertainty and it may be correlated with other parameters, and therefore is usually fixed. However, a large portion of the uncertainty in model results (e.g. current biomass), will be attributed to uncertainty in natural mortality, when natural mortality is estimated in the model. The ability to estimate natural mortality in a population dynamics model depends on how the true value varies over time as well as other factors (Fu and Quinn 2000, Schnute and Richards 1995).

Estimation Techniques

Hoenig, 5% Rule and maximum age

In the 2004 snow crab SAFE, natural mortality was assumed to be between 0.2 for males and females. A maximum age of 20 years would result from an M of about 0.21 (Table 5) (Hoenig 1983). A natural mortality of 0.3 would indicate a maximum age of about 14 years (Hoenig 1983). Anthony (1982) proposed that the 95% percentile of age be used to limit the maximum age in yield modeling. This procedure would result in an M of 0.2 for a maximum observed age of 15 years. A natural mortality of 0.3 results in about 5% of animals remaining after 10 yrs of age. Research is currently underway to assess a method using lipofuscin for age determination (Se-Jong, et al. 1999). A maximum age of about 13 years for females and 19 years for males has been hypothesized for North Atlantic snow crab by Comeau, et al (1998) based on size frequency analysis and growth data. Sainte-Marie, et al (1995) estimated an age of about 9 years for a 95 mm male snow crab and 11 years for a 131 mm crab for a different sub-population of Atlantic snow crab than Comeau, et al (1998) using size frequency analysis and growth data. A maximum time at large of 8 years for tag returns of terminally molted mature male snow crab in the North Atlantic has been recorded since tagging started about 1993 (Sainte-Marie, pers. comm.).

Model based

Otto (1998) estimated natural mortality of male snow crab based on survey data and retained catches to be greater than 1.0. The snow crab fishery generally occurs over a short time span, about 7 months after the survey. Otto (1998) overestimates M because the method assumed no time lapse between the survey and the fishery removals (during which natural mortality would be occurring) and no bycatch mortality. Otto (1998) assumed that shell condition is an accurate indicator of age since last molt (new shell less than one year, old shell crabs more than one, but less than two years from molting), and that new and old shell crabs were accurately categorized by shell condition. Radiometric aging and tagging data indicate shell condition is not an accurate measure of shell age (discussed in Maximum post-terminal molt age and shell classification section).

Zheng (unpub) investigated natural mortality of Bering Sea snow crab using a modeling approach, accounting for natural mortality between the time of the survey and the fishery. Estimates of natural mortality ranged from 0.0 to 0.97, depending on assumptions made for molting probabilities, growth per molt and survey selectivities (Zheng unpub.).

Tanner crab

Tanner crab have a similar life history to snow crab and probably have similar longevity. Zheng et al. (1998) estimated natural mortality and bycatch mortality together to be about 0.5 for male and female Bering Sea Tanner crab (*Chionecites bairdi*) in a population dynamics model. He did not estimate bycatch mortality separately, but, natural mortality would have been less than the reported 0.5 value. Somerton (1981) estimated natural mortality for male Tanner crab less than commercial size to be 0.35. M was estimated to be between 0.13 and 0.28 for commercial size male Tanner crab (Somerton 1981).

Maximum age post-terminal molt and shell classification

Crab are classified by shell condition at the time of the survey. SC1 crab are soft shell crab indicating they have recently molted. SC2 crab (new shell) have clean, hard shells. SC3 crab (old shell) show some wear and scratches and encrusting organisms are frequently present. SC4 crab (very old shell) have more wear and growth on the shell and encrusting organisms are almost always present. SC5 (very very old shell) have shells extensively stained and usually with extensive cover of encrusting organisms.

Orensanz (unpub.) used radiometric techniques to estimate shell age from last molt (Table 4). The total sample size was 21 male crabs (a combination of Tanner and snow crab) from a collection of 105 male crabs from various hauls in the 1992 and 1993 NMFS Bering sea survey. Representative samples for the 5 shell condition categories were collected that made up the 105 samples. The oldest looking crab within shell conditions 4 and 5 were selected from the total sample of SC4 and SC5 crabs to radiometrically age (Orensanz, pers comm.). Shell condition 5 crab (SC5 = very, very old shell) had a maximum age of 6.85 years (s.d. 0.58, 95% CI approximately 5.69 to 8.01 years). The average age of 6 crabs with SC4 (very old shell) and SC5, was 4.95 years. The range of ages was 2.70 to 6.85 years for those same crabs. Given the small sample size, crabs older than the maximum age of 7 to 8 years are reasonably expected in the population. Maximum life span defined for a virgin stock is reasonably expected to be longer than these observed maximum ages of exploited populations.

Male snow crab during the mid to late 1980's were subjected to increasing exploitation with the maximum catch occurring in 1991. The maximum age in the sample of 6.85

years would be the result of fishing mortality as well as natural mortality. Using this maximum age would result in an upper bound on natural mortality. If crabs mature at about age 7 to 9, an additional 7 or 8 years gives a maximum total age of about 14 to 17 years. However, due to exploitation occurring at the same time, the maximum age that would occur due to M alone would be greater than 14 to 17 years.

Tag recovery data for Bristol Bay red king crab males in the 1968 Japanese fishery contains shell condition and carapace length at time of tagging and time of recapture (INPFC 1969). Thirty two of 98 animals tagged in July to August, 1967 and recaptured May to October 1968 did not grow, however, were assigned shell condition 2 (new shell) at recapture. Those 32 animals were 12 to 18 months from molting, if they had molted in spring of 1967. This would indicate that about 33% of animals that are clean shell (SC2) are actually more than a year from molting. There were 47 crabs assigned new shell of 52 animals that were at large more than two years that did not grow (tagged in 1966 and recaptured in 1968). These animals would have been at least 2 years from molting. Tagging of Bristol Bay male red king crab was also conducted in 1990, 1991 and 1993. Recoveries occurred in the fishery that took place in October to November of each year. Recovery information was recorded primarily by ADF&G research staff, dockside samplers and observers on board vessels. Only the 1991 tagging data had sufficient recaptures in 1992 and 1993 for analysis. There were 56 animals that were recaptured in November, 1992 that were tagged in September to October, 1991 that had carapace length measured and were recorded as new shell at recapture. Of those 56 new shell animals, 21 did not grow in the 1 year between tagging and recapture. Those 21 animals (37.5 % of the new shell animals) were more than 1 ½ years from molting and were recorded as new shell. This is similar to the results from the 1968 tag recaptures, indicating that shell condition as prescribed is suspect as a rigorously quantified index of shell age. Based on these results, molting probabilities and natural mortality will be overestimated by using shell condition as an index of true shell age.

We examined the empirical evidence for reliable estimates of oldest observed age for male snow crab. Radiometric aging of male snow crab carapaces sampled in the Bering Sea stock in 1992 and 1993, as well as the ongoing tag recovery evidence from eastern Canada reveal observed maximum ages in exploited populations of 17-19 years (Orensanz, et al 20??, St. Marie 2002). We reasoned that in a virgin population of snow crab, longevity would be at least 20 years. Hence, we used 20 years as a proxy for longevity and assumed that this age would represent the upper 99th percentile of the distribution of ages in an unexploited population if observable. Under negative exponential depletion, the 99th percentile corresponding to age 20 of an unexploited population corresponds to a natural mortality rate of 0.23. M=0.23 was used for all immature crab and for mature male crab. M was set at 0.29 for mature female crab assuming that maturity occurs at a younger age and post–mature longevity is similar to mature male crab. Information of longevity of female crab is needed for estimation of M.

Radiometric ages estimated by Orensanz, et al () may be underestimated by several years, due to the continued exchange of material in crab shells even after shells have hardened (Craig Kastelle, pers. comm., Alaska Fisheries Science Center, Seattle, WA).

Molting probability

Female and male snow crab have a terminal molt to maturity. Many papers have dealt with the question of terminal molt for Atlantic Ocean mature male snow crab (e.g., Dawe, et al. 1991). A laboratory study of morphometrically mature male Tanner crab, which were also believed to have a terminal molt, found all crabs molted after two years (Paul and Paul 1995). Bering Sea male snow crab appear to have a terminal molt based on recent data on hormone levels (Sherry Tamone, per. comm., University of Alaska, Juneau, AK) and findings from molt stage analysis via setagenesis. The models presented here have a terminal molt for both males and females.

Male Tanner and snow crabs that do not molt (old shell) may be important in reproduction. Paul, et al (1995) found that old shell mature male Tanner crab out-competed new shell crab of the same size in breeding in a laboratory study. Recently molted males did not breed even with no competition and may not breed until after about 100 days from molting (Paul, et al. 1995). Sainte-Marie (2002) states that only old shell males take part in mating for North Atlantic snow crab. If molting precludes males from breeding for a three month period, then males that are new shell at the time of the survey (June to July), would have molted during the preceding spring (March to April), and would not have participated in mating. The fishery targets new shell males, resulting in those animals that molted to maturity and to a size acceptable to the fishery of being removed from the population before the chance to mate. Animals that molt to maturity at a size smaller than what is acceptable to the fishery may be subjected to fishery mortality from being caught and discarded before they have a chance to mate.

Crabs in their first few years of life may molt more than once per year, however, the smallest crabs included in the model are probably 3 or 4 years old and would be expected to molt annually.

The growth transition matrix was applied to animals that grow, resulting in new shell animals. Those animals that don't grow become old shell animals. Animals that are classified as new shell in the survey are assumed to have molted during the last year. The assumption is that shell condition (new and old) is an accurate measure of whether animals have molted during the previous year. The relationship between shell condition and time from last molt needs to be investigated further. Additional radiometric aging for male and female snow crab shells is being investigated to improve the estimate of radiometric ages from Orensanz (unpub. data).

Mating ratio and reproductive success

Full clutches of unfertilized eggs may be extruded and appear normal to visual examination, and may be retained for several weeks or months by snow crab. Resorbtion of eggs may occur if not all eggs are extruded resulting in less than a full clutch. Female snow crab at the time of the survey may have a full clutch of eggs that are unfertilized, resulting in overestimation of reproductive potential. Male snow crab are sperm conservers, using less than 4% of their sperm at each mating. Females also will mate with more than one male. The amount of stored sperm and clutch fullness varies with sex ratio (Sainte-Marie 2002). If mating with only one male is inadequate to fertilize a full clutch, then females will need to mate with more than one male, necessitating a sex ratio closer to 1:1 in the mature population, than if one male is assumed to be able to adequately fertilize multiple females.

The fraction barren females and clutch fullness observed in the survey increased in the early 1990's then decreased in the mid- 1990's then increased again in the late 1990's (Figures 26 and 27). The highest levels of barren females coincides with the peaks in catch and exploitation rates that occurred in 1992 and 1993 fishery seasons and the 1998 and 1999 fishery seasons. While the biomass of mature females was high in the early 1990's, the rate of production from the stock may have been reduced due to the spatial distribution of the catch relative and the resulting sex ratio in areas of highest reproductive potential. The faction of barren females was low in 2006, however, increased to high levels in 2007. Clutch fullness was high in 2006, then declined in 2007.

The fraction of barren females in the 2003 and 2004 survey south of 58.5 deg N latitude was generally higher than north of 58.5 deg N latitude (Figures 28 and 29). In 2004 the fraction barren females south of 58.5 deg N latitude was greater for all shell conditions. In 2003, the fraction barren was greater for new shell and very very old shell south of 58.5 deg N latitude.

Laboratory analysis of female snow crab collected in waters less than 1.5 deg C and colder from the Bering Sea have been determined to be biennial spawners in the Bering Sea. Future recruitment may be affected by the fraction of biennial spawning females in the population as well as the estimated fecundity of females, which may depend on water temperature.

An index of reproductive potential for crab stocks needs to be defined that includes spawning biomass, fecundity, fertilization rates and frequency of spawning. In most animals, spawning biomass is a sufficient index of reproductive potential because it addresses size related impacts on fecundity, and because the fertilization rates and frequency of spawning are relatively constant over time. This is not the case for snow crab.

The centroids of the cold pool (<2.0 deg C) were estimated from the summer survey data for 1982 to 2003 (Figure 29). The centroid is the average latitude and average longitude. In the 1980's the cold pool was farther south(about 58 to 59 deg N latitude) except for 1987 when the centroid shifted to north of 60 deg N latitude. The cold pool moved north from about 58 deg N latitude in 1999 to about 60.5 deg N latitude in 2003. The cold pool was farthest south in 1989, 1999 and 1982 and farthest north in 1987, 1998, 2002 and 2003.

The clutch fullness and fraction of unmated females however, does not account for the fraction of females that may have unfertilized eggs. The fraction of barren females observed in the survey may not be an accurate measure of fertilization success because females may retain unfertilized eggs for months after extrusion. To examine this hypothesis, RACE personnel sampled mature females from the Bering Sea in winter and held them in tanks until their eggs hatched in March of the same year. All females then extruded a new clutch of eggs in the absence of males. All eggs were retained until the crabs were sacrificed near the end of August. Approximately 20% of the females had full clutches of unfertilized eggs. The unfertilized eggs could not be distinguished from fertilized eggs by visual inspection at the time they were sacrificed. Indices of fertilized females based on the visual inspection method of assessing clutch fullness and percent unmated females may overestimate fertilized females and not an accurate index of reproductive success.

McMullen and Yoshihara (1969) examined female red king crab around Kodiak Island in 1968 and found high percentages of females without eggs in areas of most intense fishing (up to 72%). Females that did not extrude eggs and mate were found to resorb their eggs in the ovaries over a period of several months. One trawl haul captured 651 post-molt females and nine male red king crab during the period April to May 1968. Seventy-six percent of the 651 females were not carrying eggs. Ten females were collected that were carrying eggs and had firm post-molt shells. The eggs were sampled 8 and 10 days after capture and were examined microscopically. All eggs examined were found to be infertile. This indicates that all ten females had extruded and held egg clutches without mating. Eggs of females sampled in October of 1968 appear to have been all fertile from a table of results in McMullen and Yoshihara(1969), however the results are not discussed in the text, so this is unclear. This may mean that extruded eggs that are unfertilized are lost between May and October.

Discard mortality was assumed to be 50% for this assessment. The fishery for snow crabs occurs in winter when low temperatures and wind may result in freezing of crabs on deck before they are returned to the sea. Short term mortality may occur due to exposure, which has been demonstrated in laboratory experiments Zhou and Kruse (1998) and Shirley (1998), where 100% mortality occurred under temperature and wind conditions that may occur in the fishery. Even if damage did not result in short term mortality, immature crabs that are discarded may experience mortality during molting some time later in their life.

RESULTS

The total mature biomass increased from about 963 million lbs in 1978 to the peak biomass of 1,663 million lbs in 1990. Biomass declined sharply after 1997 to about 407 million lbs in 2003, then increased to 654 million lbs in 2007 (Table 3 and Figure 2). The model is constrained by the population dynamics structure, including natural mortality, the growth and selectivity parameters and the fishery catches. The low observed survey abundance in the mid-1980's were followed by an abrupt increase in the survey abundance of animals in 1987, which followed through the population and resulted in the highest catches recorded in the early 1990's.

Average discard catch mortality for 1978 to 2007 was estimated to be about 16.7% of the retained catch (with 50% mortality applied), similar to the observed average observed discards from 1992 to 2007 (15.5%) (Table 1 and Figure 31). Parameter estimates for the 50% discard mortality model are in Table 7. During the last four years (2004 to 2007 fishery seasons) model estimates of discard mortality averaged 15% of the retained catch. Estimates of observed discard mortality ranged from 6% of the retained catch to 32% of the retained catch (assuming 50% discard mortality).

Mature male and female biomass show similar trends (Table 3, Figures 32 and 33). Mature male biomass increased from 320 million lbs in 2006 to 420 million lbs in 2006 (adjusted by survey selectivity), while observed survey mature male biomass increased from 331 million lbs to 385 million lbs. Model estimates of mature female biomass increased from 229 million lbs in 2006 to 244 million lbs in 2007. Mature female biomass observed from the survey increased from 189 million lbs in 2006 to 223 million lbs in 2007.

Fishery selectivities and retention curves were estimated using ascending logistic curves (Figure 22, 23 and 34). Selectivities for trawl bycatch were estimated as ascending logistic curves (Figure 35). Plots of model fits to the survey size frequency data are presented in Figures 36 and 38 by sex for shell conditions combined. The model estimates higher numbers of mature old shell male and female crabs and lower numbers of new shell mature male and female crabs than observed from the survey. This could be due the size at maturity, which determines when males and females stop growing, or that shell condition is not an accurate estimator of shell age. Tagging results presented earlier indicate that animals that are more than one year from molting may be underestimated by using shell as a proxy for shell age.

Survey selectivities for the period 1978 to 1981 were estimated at about 50% at 30 mm and reached 100% at about 60-70mm (Figure 23). Survey selectivities for the period 1982 to 1988 were estimated at 50% at about 40 mm and reached a maximum of 82% at greater than 70 mm. Survey selectivities for the period 1989 to the present were estimated at 50% at about 31 mm and reached a maximum of 92% at greater than 60 mm. These selectivities were the best fit determined by the model. An underbag experiment estimated survey selectivity of 50% at 78 mm and a maximum of about 89% at 135 mm (Somerton and Otto 1998) with the survey net in use since 1982. The survey selectivities are multiplied by the population numbers by length to estimate survey numbers for fitting to the survey data.

The estimated number of males > 101mm generally follows the observed survey numbers except for a few peak survey years where the model estimates are lower than the survey estimates (Figure 40). The observed survey estimate of males greater than 101 mm increased from about 69 million in 2005 to 135 million in 2006 and 151 million in 2007. The estimated 95% confidence interval for the observed survey large males in 2007was +/-40% of the estimate. Model estimates of large males were about 96 million crab in 2006 and 142 million crab in 2007.

Two main periods of high recruitment were estimated by the model, in 1980-1983 (fertilization year) and in 1986-1987 (Figure 41). Recruits are 25mm to about 40 mm and may be about 4 years from hatching, 5 years from fertilization (Figure 42, although age is approximated). Low recruitments were estimated from 1990 to 1996 and in 2000 to 2002. The 1999 year class appears to be a medium size recruitment that has resulted in an increase in biomass in 2006 and 2007. The estimated recruitments lagged by 5 years (approximate fertilization year) from the model are close to the higher survey estimates of abundance of females with eggs and abundance of females with eggs multiplied by the fraction full clutch from 1975 to 1988 (Figure 43). Recruitment was low from 1990 to 1996, showing little relationship to the reproductive index. Exploitation rates were generally higher in 1986 to 1994, and in 1998-99 than prior to 1986 (Figure 4).

The size at 50% selected for the pot fishery was 102 mm for new shell males and 122 mm for old shell males (Figure 22). Retention for old shell males was higher than for new shell males, however, fishery selectivity was lower for old shell males than new shell, indicating the fishery is able to target areas where new shell crab are more abundant (Figure 34). The fishery generally targets new shell animals with clean hard shells and all legs intact. The fits to the fishery size frequencies are in Figures 44 through 48. Fits to the trawl fishery bycatch size frequency data are in Figures 49 and 50.

Fishing mortality rates ranged from about 0.26 to 3.0 (Figure 51). Fishing mortality rates were 0.75 to 1.9, for the 1986 to 2003 fishery seasons (except F=3.0 in 1999). Full selection fishing mortality was estimated at 0.53 for 2005, 0.90 for the 2006 and 0.61 for 2007 (year fishery occurred).

Harvest Strategy and Projected Catch

Current Harvest Strategy

Harvest strategy simulations are reported by Zheng et al. (2002) based on a model with structure and parameter values different than the model presented here. The harvest strategy by Zheng et al. (2002) was developed for use with survey biomass estimates and was applied to survey biomass estimates to calculate the 2008 fishery season catch. Bmsy is defined in the current crab FMP as the average total mature survey biomass for 1983 to 1997. MSST is defined as ½ Bmsy. The harvest strategy consists of a threshold for opening the fishery (230.4 million lbs of total mature biomass(TMB), 0.25*Bmsy), a minimum GHL of 15 million lbs for opening the fishery, and rules for computing the GHL.

Under current FMP (Fishery Management Plan) definitions for MSY biomass (B_{MSY} = 921.6 million pounds TMB) and overfishing rate (F_{MSY} =M=0.3), the exploitation rate to apply to current mature male biomass (MMB), is determined as a function of TMB as,

$$E=\frac{0.75*Fmsy*\left[\frac{TMB}{Bmsy}-\alpha\right]}{(1-\alpha)}$$

for TMB ≥ 0.25*Bmsy and TMB<Bmsy, where $\alpha = -0.35$, and,

- E = (Fmsy * 0.75) = 0.225, for TMB ≥ Bmsy, and E = 0 for TMB < 0.25*Bmsy.

The maximum for a GHL_{max} is determined by using the E determined from the control rule as an exploitation rate on mature male biomass at the time of the survey,

- $GHL_{max} = E \bullet MMB$.

There is a 58% maximum harvest rate on exploited legal male abundance. Exploited legal male abundance is defined as the estimated abundance of all new shell legal males >=4.0-in (102 mm) CW plus a percentage of the estimated abundance of old shell legal males >=4.0-in CW. The percentage to be used is determined using fishery selectivities for old shell males.

Alternative Overfishing Control Rules

An alternative overfishing control rule based on spawning biomass per recruit reference points follows those developed for North Pacific groundfish stocks (SAFE 2004) (Figure 54).

$$F=\frac{F\%*\left[\frac{MMB}{B\%}-\alpha\right]}{(1-\alpha)}$$

MMB is mature male biomass at the time of mating. Two alternatives for the maximum fishing mortality were estimated, F40% and F35% (Table 6). F40% was estimated at 0.77 and B40% at 406 million lbs. F35% was estimated at 0.99 and B35% at 355 million lbs. B40% and B35% were estimated using average recruitment and spawning biomass per recruit for males fishing at F40% or F35% respectively. $\alpha = 0.1$, and the F is set to zero when mature male biomass is below 25% of B40% or B35% (Figure 54).

Estimated fishing mortality from 1980 fishing season to 2005 have been above the F40% control rule except for three years (1979, 1983 and 1984) (Figure 54). The target F historically (pre-2000 fishery season) was about 1.1 which was exceeded in many years. The last two fishery seasons F was estimated at 0.89 and 0.61. The F in 2007 was just below the F35% control rule.

The catch using the control rule is estimated by the following equation,

$$catch = \sum_{s}\sum_{l} (1 - e^{-(F^{*}Sel_{s,l} + Ftrawl^{*}TrawlSel_{l})}) w_{l} N_{s,l} e^{-M^{*}.62}$$

Where $N_{S,l}$ is the 2007 numbers at length(l) for males by shell condition(s) at the time of the survey estimated from the population dynamics model, M is natural mortality, 0.62 is the time elapsed (in years) from when the survey occurs to the fishery, F is the value estimated from the harvest control rule using the 2007 mature male biomass projected forward to the time of mating time (spring 2008), and w_l is weight at length. $Sel_{S,l}$ are the fishery selectivities by length and shell condition for the total catch (retained plus discard) or for the retained catch estimated from the population dynamics model (Figure 24).

Harvest recommendations

Fishing mortality, biomass values and total catches were projected for the 2008 to 2012 fishery seasons (Table 6). The survey biomass estimate for total mature biomass summer 2007 was estimated to be 608 million lbs (66% of Bmsy =921.6 million lbs). The MMB in spring 2008 is estimated to be at 77% of B40% and 83% of B35%. **The 2008 F40% total catch was estimated at 55.5 million lbs. The F35% total catch for 2008 was estimated at 77.8 million lbs. Estimated total catch using the ADF&G harvest strategy(current harvest strategy) was 80.2 million lbs.** Total catch includes retained directed pot fishery, discard pot fishery (with 50% mortality of discards) and trawl bycatch (80% mortality). The observed total catch in 2007 was 43.5 million lbs (with 50% mortality on the directed pot fishery discard).

Computing the catch based on the complete survey biomass may result in exploitation rates higher than the target rate on crabs in the southern area of the distribution. One solution would be to split the catch into two regions, north and south, according to the percent distribution of the survey estimate of large males or mature males from those regions. This would require knowing the location of catch inseason. Two other approaches would not require knowledge on inseason catch location. One approach would be to compute the catch from that portion of the stock where most of the catch is extracted. Another approach would be to compute a catch that would result in the target harvest rate for the southern portion of the stock and increase that catch according to the percent catch in the north.

Projections and Rebuilding Scenarios

Projections and rebuilding trajectories were estimated using simulation with several harvest control rules and lognormally distributed, autocorrelated recruitment from a Beverton-Holt spawner recruit curve (steepness= 0.68, R0=2.0 billion, cv recruitment =0.86, autocorrelation = 0.6). The rebuilding plan developed for snow crab projected a 50% probability of rebuilding by 2010. The probability of rebuilding to the total survey biomass Bmsy of 921.6 million lbs is less than 1% in 2010, fishing at F35%, F40% and the ADF&G harvest strategies (Table 6). Rebuilding to the total survey mature biomass

Bmsy is projected to occur by 2021 for the F40% control rule, and about 2024 for the F35% and ADF&G control rules. The probability of rebuilding to B35% using mature male biomass at the time of mating in 2010 is 10% fishing at F35%, 58% fishing at F40% and 51% fishing at the ADF&G strategy. The probability of rebuilding depends on the method of generating future recruitments. The use of random recruitment will result in a higher probability of rebuilding the stock relative to using a spawner recruit curve and autocorrelated recruitment as used in the projections presented here.

Projections of biomass and catch for the three control rules indicate that biomass is expected to increase through 2009, then to decrease (Table 6 and Figures 55 and 56). The model and observed biomass estimates have followed the expected trends in biomass from the snow crab rebuilding plan for 2002 to 2007. However, projected biomass is projected to decline after 2008 due to low recruitment and catches that may exceed the original expected catch from the rebuilding plan. Catches in the early years of the rebuilding period (2001 to 2006) exceeded the expected catches due to higher realized biomass and to a change in the minimum GHL to open the snow crab fishery. Catches estimated from the F35% and ADF&G harvest strategies are close the expected for the 2008 fishery season. Future survey data will reduce uncertainty in the estimate of the strength of recent recruitments.

Conservation concerns

- The Bering Sea snow crab survey estimates of total mature biomass are currently at 65% of the survey Bmsy. The stock is not expected to rebuilding by 2010 under the F35%, F40% or ADF&G harvest strategies to the total survey biomass Bmsy of 921.6 million lbs.
- Moderate recruitment is estimated in 1997-1998 fertilization year, however, in general recruitment has been at low levels in the last 10 years (since 1994).
- There is uncertainty in discard mortality due to low coverage of total pot lifts and only 10% coverage of catcher vessels which only started in 2001. Higher discard mortality would necessitate lower retained catches.
- Exploitation rates in the southern portion of the range of snow crab may have been higher than target rates, possibly contributing to the shift in distribution to less productive waters in the north.

Research Needs

Research is needed to improve our knowledge of snow crab life history and population dynamics to reduce uncertainty in the estimation of current stock size, stock status and optimum harvest rates.

Tagging programs need to be initiated to estimate longevity and migrations. Studies and analyses are needed to estimate natural mortality. Additional sampling of crabs that are close to molting is needed to estimate growth for immature males and females.

The lower number of mature old shell male crabs in the observed survey compared to what are expected in the model needs to be reconciled. Harvest rates and status of the stock are highly dependent on what the discrepancy is due to. The differences could be due to higher fishery discard mortality, higher natural mortality of mature animals, differential catchability of new and old shell animals in the survey, or the estimation of when maturity occurs, which determines when animals stop growing and subsequently move from new shell to old shell animals. In addition, the assignment of crabs to new and old shell condition used in the survey data may not be an accurate measure of time from the last molt.

Increased observer coverage is needed on catcher vessels in the directed snow crab fishery to improve estimates of discards. Field studies are needed to estimate mortality of discards in the winter snow crab pot fisheries where freezing temperatures and wind chill are important factors.

A method of verifying shell age is needed for all crab species. Current research is being conducted using lipofuscin to age crabs and continued radiometric aging of shells of mature crabs is also being conducted (results may be available the end of 2004). However, at this time it is not known if the lipofuscin method will be successful, and radiometric aging is time consuming, so only small numbers of animals can be aged at present. Aging methods will provide information to assess the accuracy of assumed ages from assigned shell conditions (i.e. new, old, very old, etc), which have not been verified, except with the 21 radiometric ages reported here from Orensanz (unpub data).

Techniques for determining which males are effective at mating and how many females they can successfully mate with in a mating season are needed to estimate population dynamics and optimum harvest rates. At the present time it is assumed that when males reach morphometric maturity they stop growing and they are effective at mating. Field studies are needed to determine how morphometric maturity corresponds to male effectiveness in mating. In addition the uncertainty associated with the determination of morphometric maturity (the measurement of chelae height and the discriminate analysis to separate crabs into mature and immature) needs to be analyzed and incorporated into the determination of the maturity by length for male snow crab.

The experiment to estimate catchability of the survey trawl net needs to be repeated with larger sample sizes to allow the estimation of catchability by length, sex and shell condition for snow crab (and Tanner crab). This is needed to determine if the number of mature old shell crabs in the observed survey (which are lower than expected in the model) are due to mortality (fishery discard or natural mortality) or due to lower catchability in the trawl survey.

Female opilio in waters less than 1.5 deg C and colder have been determined to be biennial spawners in the Bering Sea. Future recruitment may be affected by the fraction of biennial spawning females in the population as well as the estimated fecundity of females, which may depend on water temperature.

Analysis needs to be conducted to determine a method of accounting for the spatial distribution of the catch and abundance in computing quotas.

Literature Cited

Anthony, V.C. 1982. The calculation of F0.1: a plea for standardization. NAFO SCR Doc. 82/VI/64. Serial NO. N557. 16pp.

Bering sea and Aleutian Islands Crab SAFE. 2002. North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

Bering Sea snow crab rebuilding plan, 2000. Bering Sea Crab Plan Team, North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

BSAI SAFE. 2002. Bering Sea and Aleutian Islands stock assessment and fishery evaluation for North Pacific Groundfish.

Comeau, M., Conan, G.Y. Robichaud., G., and Jones, A. 1991. Life history and population fluctuations of snow crab (Chionoecetes opilio) in the fjord of Bonne Bay on the west coast of Newfoundland, Canada—from 1983 to 1990. Can.Tech.Rep.Fish.Aquat.Sci. 1817.

Comeau, M., G.Y. Conan, F. Maynou, G. Robichaud,J. Therriault, and M. Starr. 1998. Growth, spatial distribution, and abundance of benthic stages of the snow crab (Chionoecetes opilio) in Bonne Bay, Newfoundland, Canada. Can.J. Fish. Aquat. Sci. 55: 262-279.

Crab FMP 1998. Bering Sea Crab Plan Team, North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

Dawe, E.G., D.M. Taylor, J.M. Hoenig, W.G. Warren, and G.P. Ennis. 1991. A critical look at the idea of terminal molt in male snow crab (*Chionoecetes opilio*). Can. J. Fish. Aquat. Sci. 48: 2266-2275.

Dorn, M.W. 2002. Advice on west coast rockfish harvest rates from Bayesian meta-analysis of stock-recruit relationships. North American Journal of Fisheries Management 22:280-300.

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

Fu, C. H., and T. J. Quinn II, 2000. Estimability of natural mortality and other population parameters in a length-based model: *Pandalus borealis* in Kachemak Bay, Alaska. Can. J. Fish. Aquat. Sci. 57: 2420–2432.

Gabriel, W.L., M.P. sissenwine, and W.J. Overholtz. 1989. Analysis of spawning biomass per recruit: an example for Georges Bank haddock. North American Journal of Fisheries Management 9:383-391.

Greiwank, A. and G.F. Corliss(eds). 1991. Automatic differentiation of algorithms: theory, implementation and application. Proceedings of the SIAM Workshop on the Automatic Differentiation of Algorithms, held Jan. 6-8, Breckenridge, CO. Soc. Indust. And Applied Mathematics, Philadelphia.

Hoenig, J. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull. 82: 898-903.

INPFC. 1969. Release and recovery information for united states king crab tags recovered by the Japanese in 1968. INPFC Document no. 1171.

Mcbride (1982). Tanner crab tag development and tagging experiments 1978-1982. In Proceedings of the International Symposium of the Genus Chionoecetes. Lowell Wakefield Fish. Symp. Ser., Alaska Sea Grant Rep. 82-10. University of Alaska, Fairbanks, Alaska. Pp. 383-403.

McMullen, J.C. and H.T. Yoshihara. 1969. Fate of unfertilized eggs in king crabs *Paralithodes camtschatica (Tilesius)*. Department of Fish and Game. Informational Leaflet 127. INPFC document no. 1151. 14pp.

Methot, R. D. 1990. Synthesis model: An adaptable framework for analysis of diverse stock assessment data. Int. N. Pac. Fish. Comm. Bull. 50:259-277.

Nevissi, A.E., J.M. Orensanz, A.J.Paul, and D.A. Armstrong. 1995. Radiometric Estimation of shell age in Tanner Crab, Chionoecetes opilio and C. bairdi, from the eastern Bering Sea, and its use to interpret indices of shell age/condition. Presented at the International symposium on biology, management and economics of crabs from high latitude habitats October 11-13, 1995, Anchorage, Alaska.

Neufeld, G and D.R. Barnard. 2003. Alaska department of fish and game summary of the 2001 mandatory shellfish observer program database for the general and cdq fisheries. Regional Information Report No. 4K03-2. Alaska Department of Fish and Game. 160pp.

Otto, R.S. 1998. Assessment of the eastern Bering Sea snow crab, Chionoecetes opilio, stock under the terminal molting hypothesis. In Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. Edited by G.S. Jamieson and A. Campbell. Can. Spec. Publ. Fish. Aquat. Sci. 125. pp. 109-124.

Paul, A.J. and J.M. Paul. 1995. Molting of functionally mature male *Chionoecetes bairdi* Rathbun (Decapoda: Majidae) and changes in carapace and chela measurements. Journal of Crustacean Biology 15:686-692.

Paul, A.J., J.M. Paul and W.E. Donaldson. 1995. Shell condition and breeding success in Tanner crabs. Journal of Crustacean Biology 15: 476-480.

Press, W.H., S.A. Teukolsky, W.T.Vetterling, B.P. Flannery. 1992. Numerical Recipes in C. Second Ed. Cambridge Univ. Press. 994 p.

Rugolo, L.J., D. Pengilly, R. MacIntosh and K. Gravel. 2005. Reproductive dynamics and life-history of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea. Final Completion Report to the NOAA, Award NA17FW1274, Bering Sea Snow Crab Fishery Restoration Research.

Rugolo, L.J., R.A. MacIntosh, C.E. Armisted, J.A. Haaga and R.S. Otto. 2003. Report to industry on the 2003 Eastern Bering Sea crab survey. AFSC Processed Report 2003-11.

Sainte-Marie, B., Raymond, S., and Brethes, J. 1995. Growth and maturation of the male snow crab, *Chionoecetes opilio* (Brachyura: Majidae). Can.J.Fish.Aquat.Sci. 52:903-924.

Sainte-Marie, B., J. Sevigny and M. Carpentier. 2002. Interannual variability of sperm reserves and fecundity of primiparous females of the snow crab (Chionoecetes opilio) in relation to sex ratio. Can.J.Fish.Aquat.Sci. 59:1932-1940.

Schnute, J. and L. Richards. 1995. The influence of error on population estimates from catch-age models. Can. J. Fish. Aquat. Sci. 52: 2063-2077.

Se-Jong, J., D.H. Secor, H.R. Harvey. 1999. Use of extractable lipofuscin for age determination of blue crab *Callinectes sapidus*. Marine Ecology Progress series. Vol 185: 171-179.

Shirley, T.C. 1998. Appendix D: Crab handling mortality and bycatch reduction. In: King and Tanner crab research in Alaska: Annual report for July 1, 1997 through June 30, 1998. Alaska Department of Fish and Game Regional Information Report No. 5J98-07.

Siddeek, M.S.M., B. Sainte-Marie, J. Boutillier and G. Bishop. 2003. Some reference points used in US and Canada crab fisheries and a comparison of a referential system estimated using a length-based method for snow crab (*Chionoecetes opilio*) and Dungeness crab (*Cancer magister*).

Somerton, D.A. 1981. Life history and population dynamics of two species of Tanner crab, Chionoecetes bairdi and C. opilio, in the eastern Bering Sea with implications for the management of the commercial harvest. Ph.D. dissertation. University of Washington, Seattle, Wash. 220 p.

Somerton, D.A. and R.S. Otto. 1999. Net effeciency of a survey trawl for snow crab, *Chionoecetes opilio*, and Tanner crab, *C. Bairdi*. Fish.Bull. 97:617-625.

Tamone, S.L., M. Adams and J.M. Dutton. 2005. Effect of eyestalk ablation on circulating ecdysteroids in hemolymph of snow crab *Chionoecetes opilio*: physiological evidence for a terminal molt. Integr. Comp. Biol., 45(120), p.166-171.

Zheng, J., S. Siddeek, D. Pengilly, and D. Woodby. 2002. Overview of recommended harvest strategy for snow crabs in the Eastern Bering Sea. Regional Information Report No. 5J02-03. Alaska Department of Fish and Game. Juneau, Alaska.

Zheng, J. unpublished. Uncertainties of natural mortality estimates for Eastern Bering Sea snow crab, *Chionoecetes opilio*. Alaska Department of Fish and Game. Juneau, Alaska.

Zheng, J., G.H. Kruse, and D.R. Ackley. 2001. Spatial distribution and recruitment patterns of snow crabs in the eastern Bering Sea. Spatial Processes and management of marine populations. Alaska sea grant college program. AK-SG-01-02, 2001.

Zheng, J., G.H. Kruse, and M.C. Murphy. 1998. A size-based approach to estimate population abundance of Tanner crab, Chionoecetes bairdi, in Bristol Bay, Alaska. In Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. Edited by G.S. Jamieson and A. Campbell. Can. Spec. Publ. Fish. Aquat. Sci. 125. pp. 97-105.

Zheng, J., M.C. Murphy, and G.H. Kruse. 1995. A length-based population model and stock-recruitment relationships for red king crab, Paralithodes camtschatics, in Bristol Bay, Alaska. Can. J.Fish. Aquat. Sci. 52: 1229-1246.

Zhou, S. and G.H. Kruse. 1998. Appendix C: Crab handling mortality and bycatch reduction. In: King and Tanner Crab research in Alaska: Annual Report for July 1, 1997 through June 30, 1998. Alaska Department of Fish and Game Regional Information Report No. 5J98-07.

Table 1. Catch (1,000s of lbs) for the snow crab pot fishery and groundfish trawl bycatch. Retained catch for 1973 to 1981 contain Japanese directed fishing. Observed discarded catch is the total estimate of discards before applying mortality. Discards from 1992 to 2007 were estimated from observer data. Model estimates of male discard include a 50% mortality of discarded crab.

Year fishery occurred	retained catch(1,000s of lbs)	Observed Discard male catch	Retained + discard male catch	Model estimate of male discard	Discard female catch	Year of trawl bycatch	trawl bycatch
1973	6,711					1973	30,046
1974	5,033					1974	41,582
1975	8,250					1975	16,096
1976	10,050					1976	6,975
1977	16,284					1977	4,722
1978-79	52,272			7,090	73	1978	5,422
1979-80	75,025			7,180	91	1979	4,357
1980-81	66,933			7,501	81	1980	3,170
1982	29,355			6,568	46	1981	1,323
1983	26,128			4,706	62	1982	538
1984	26,813			2,715	44	1983	693
1985	65,999			6,416	43	1984	737
1986	97,984			13,929	44	1985	632
1987	101,903			16,692	96	1986	2,716
1988	135,355			18,757	139	1987	8
1989	149,456			32,963	148	1988	974
1990	161,821			43,689	192	1989	1,131
1991	328,647			64,717	204	1990	865
1992	315,302	96,214	402,897	50,605	234	1991	9,578
1993	230,787	124,865	355,652	37,701	481	1992	4,669
1994	149,776	38,922	188,698	21,565	321	1993	3,010
1995	75,253	29,436	104,689	12,297	232	1994	3,393
1996	65,713	42,104	107,817	19,773	63	1995	1,844
1997	119,543	54,391	173,934	28,571	277	1996	2,074
1998	243,342	41,982	294,171	38,561	22	1997	2,906
1999	194,000	34,158	228,358	25,792	26	1998	2,159
2000	33,500	3,790	37,081	3,894	2	1999	796
2001	25,256	4,537	29,794	2,691	2	2000	889
2002	32,722	13,824	46,546	5,886	17	2001	635
2003	28,307	9,938	38,245	5,957	3	2002	384
2004	23,663	4,196	27,859	3,459	6	2003	289
2005	24,560	3,716	28,276	2,741	3	2004	740
2006	37,000	9,965	46,965	5,577	12	2005	1,378
2007	37,000	12,995	49,995	6,847	5	2006	385
						2007	702

Table 2. Observed survey female, male and total spawning biomass(millions of lbs) and numbers of males > 101mm (millions of crab).

Year	Observed survey female mature biomass	Observed survey male mature biomass	Observed survey total mature biomass	Observed number of males > 101mm (millions)
1978	336.6	424.9	761.5	163.4
1979	712.2	528.7	1,240.9	169.1
1980	894.8	385.1	1,279.9	109.0
1981	480.2	262.1	742.3	45.4
1982	507.0	403.0	910.1	65.0
1983	316.6	355.3	671.9	71.5
1984	145.2	387.5	532.6	154.2
1985	21.2	167.2	188.4	78.2
1986	55.8	200.9	256.7	80.0
1987	448.4	462.2	910.6	141.9
1988	556.1	538.8	1,094.9	167.3
1989	1,006.2	712.3	1,718.4	175.4
1990	649.6	905.4	1,555.0	407.2
1991	793.0	981.8	1,774.8	466.6
1992	463.9	574.8	1,038.8	251.4
1993	505.0	545.3	1,050.3	140.8
1994	473.6	379.4	853.0	80.3
1995	622.0	507.8	1,129.8	69.0
1996	435.0	744.9	1,179.9	170.1
1997	387.6	663.5	1,051.2	308.5
1998	285.4	529.3	814.7	244.0
1999	113.5	216.6	330.1	92.2
2000	374.7	227.1	601.8	75.6
2001	318.4	339.2	657.5	79.4
2002	120.5	232.8	353.3	73.5
2003	130.2	197.8	328.0	64.6
2004	194.3	196.6	390.9	65.8
2005	256.7	294.8	551.4	68.9
2006	188.9	330.5	519.5	135.3
2007	222.6	385.2	607.8	150.8

Table 3. Model estimates of population biomass, population numbers, male, female and total mature biomass(million lbs) and number of males greater than 101 mm in millions. Recruits enter the population in the spring of the survey year.

Year	Biomass (million lbs 25mm+)	numbers (million crabs 25mm+)	female mature biomass	Male mature biomass	total mature biomass	Number of males >101mm (millions)	Recruitment (millions, 25 mm to 50 mm)	Male mature biomass at mating time(Feb of survey year)	Ratio mature females to mature males at mating time
1978	1,427	7,716	488	474	963	151			3.6
1979	1,395	6,697	580	450	1,030	149	732	347	4.5
1980	1,297	6,015	595	370	965	110	888	299	4.9
1981	1,217	5,514	565	314	879	76	925	243	4.5
1982	1,246	6,012	510	351	861	104	1,785	233	3.7
1983	1,306	6,255	462	426	888	158	1,613	269	3.0
1984	1,361	5,952	432	486	918	184	1,104	330	2.7
1985	1,489	7,878	410	501	911	179	3,300	337	2.5
1986	1,747	11,117	417	524	941	188	5,036	336	2.3
1987	2,033	11,872	484	587	1,071	211	3,234	355	2.4
1988	2,300	11,500	576	646	1,222	192	2,304	389	2.4
1989	2,483	10,058	638	778	1,417	231	1,221	409	2.2
1990	2,523	8,255	642	1,021	1,663	386	602	528	2.0
1991	2,168	6,741	590	995	1,585	373	670	579	1.9
1992	1,835	7,793	511	828	1,339	281	2,877	561	1.8
1993	1,639	8,686	462	647	1,109	188	2,834	500	1.9
1994	1,568	7,766	463	532	994	120	1,107	428	2.0
1995	1,594	6,350	472	530	1,002	104	364	391	2.0
1996	1,603	5,076	451	640	1,090	182	219	403	1.8
1997	1,457	4,001	395	735	1,130	274	201	454	1.7
1998	1,077	3,388	326	575	901	193	523	427	1.7
1999	761	2,974	266	369	635	83	521	331	1.6
2000	676	2,807	223	316	539	69	529	290	1.6
2001	612	2,350	196	274	470	57	190	240	1.7
2002	605	2,980	173	245	418	54	1,188	206	1.6
2003	631	3,312	163	243	407	64	1,012	187	1.6
2004	754	4,812	169	257	427	77	2,238	191	1.7
2005	849	4,329	200	274	474	77	567	200	1.9
2006	962	4,365	229	320	549	97	1,009	204	1.9
2007	1,030	3,601	244	410	654	142	226	245	1.8

Table 4. Radiometric ages for male crabs for shell conditions 1 through 5. Data from Orensanz (unpub).

				Radiometric age	
Shell Condition	description	sample size	Mean	minimum	maximum
1	soft	6	0.15	0.05	0.25
2	new	6	0.69	0.33	1.07
3	old	3	1.02	0.92	1.1
4	very old	3	5.31	4.43	6.6
5	very very old	3	4.59	2.7	6.85

Table 5. Natural mortality estimates for Hoenig (1983) and the 5% rule given the oldest observed age.

	Natural Mortality	
oldest observed age	Hoenig (1983) empirical	5% rule
10	0.42	0.3
15	0.28	0.2
17	0.25	0.18
20	0.21	0.15

Table 6. Projections using F35%, F40% and the current ADF&G control rules for 2008 to 2012 fishery seasons. Mature male biomass is at time of mating (millions of lbs). Survey total mature biomass is at the time of the survey (millions of lbs). Probability of rebuilding was estimated using total survey mature biomass with a target of 921.6 million lbs and for mature male biomass at the time of mating using B35% (355 million lbs). Total catch includes retained pot fishery catch, discard pot fishery catch (with 50% mortality) and trawl bycatch (with 80% mortality).

F35%	total catch	Lower 95% C.I. total catch	Upper 95% C.I. total catch	F	Mature male biomass at mating time	Total survey mature biomass (summer in fishery year)	Prob. of rebuilding to Bmsy (921.6 mill lbs)	Prob. of rebuilding to B35% (355 mill lbs)
Fishery year								
2008	77.8	56.7	98.5	0.65	296.2	666.5	0.000	0
2009	132.2	91.8	169.3	0.89	321.9	639.3	0.000	0.07
2010	114.6	79.0	149.2	0.87	312.9	584.0	0.001	0.1
2011	81.5	55.0	112.2	0.78	288.9	561.8	0.004	0.102
2012	64.1	39.6	96.4	0.74	274.6	582.8	0.037	0.119
F40%								
Fishery year	total catch	Lower 95% C.I. total catch	Upper 95% C.I. total catch	F	Mature male biomass at mating time	Total survey mature biomass (summer in fishery year)	Probability of rebuilding to Bmsy (921.6 mill lbs)	Probability of rebuilding to B35% (355 mill lbs)
2008	55.5	39.3	71.9	0.43	313.0	687.7	0.000	0
2009	113.1	73.9	152.2	0.67	355.4	676.2	0.000	0.501
2010	104.6	70.2	138.9	0.67	354.5	624.4	0.001	0.58
2011	76.5	50.4	107.7	0.61	329.7	599.8	0.006	0.583
2012	60.6	37.0	91.9	0.57	312.1	617.2	0.044	0.597
ADFG								
Fishery year	total catch	Lower 95% C.I. total catch	Upper 95% C.I. total catch	F	Mature male biomass at mating time	Total survey mature biomass (summer in fishery year)	Probability of rebuilding to TMB Bmsy (921.6 mill lbs)	Probability of rebuilding to MMB B35% (355 mill lbs)
2008	80.2	65.7	96.1	0.68	294.4	664.2	0.000	0
2009	99.3	62.6	146.0	0.62	345.1	668.8	0.000	0.291
2010	101.4	62.1	150.2	0.65	350.5	621.5	0.001	0.512
2011	86.8	55.0	118.1	0.71	318.2	588.2	0.005	0.515
2012	71.4	47.1	93.3	0.73	292.0	597.8	0.040	0.533

Table 7. Parameters values for the model, excluding recruitments and fishing mortality parameters.

Natural Mortality immature both sexes and mature males	0.23
Natural Mortality mature females	0.29
Female intercept (a) growth	5.099108
Male intercept(a) growth	8.432714
Female slope(b) growth	1.071039
Male slope (b) growth	1.125182
Alpha for gamma distribution of recruits	12
Beta for gamma distribution of recruits	1.5
Beta for gamma distribution female growth	0.75
Beta for gamma distribution male growth	0.75
Fishery selectivity total new slope	0.200231
Fishery selectivity total new length at 50%	101.765
Fishery selectivity total old slope	0.135145
Fishery selectivity total old length at 50%	121.688
Fishery selectivity retention curve new shell slope	0.25318
Fishery selectivity retention curve new shell length at 50%	96.13595
Fishery selectivity retention curve old shell slope	0.295845
Fishery selectivity retention curve old shell length at 50%	94.19312
Pot Fishery discard selectivity female slope	0.323016
Pot Fishery discard selectivity female length at 50%	61.83911
Trawl Fishery selectivity slope	0.087106
Trawl Fishery selectivity length at 50%	74.12637
Survey Q 1978-1981	1
Survey 1978-1981 length at 95% selected	55.3925
Survey 1978-1981 length at 50% selected	30.19258
Survey Q 1982-1988	0.815655
Survey 1982-1988 length at 95% selected	61.75275
Survey 1982-1988 length at 50% selected	40.58202
Survey Q 1989-present	0.9227
Survey 1989-present, length at 95% selected	45.44617
Survey 1989-present length at 50% selected	31.18834
Fishery cpue q	0.00097

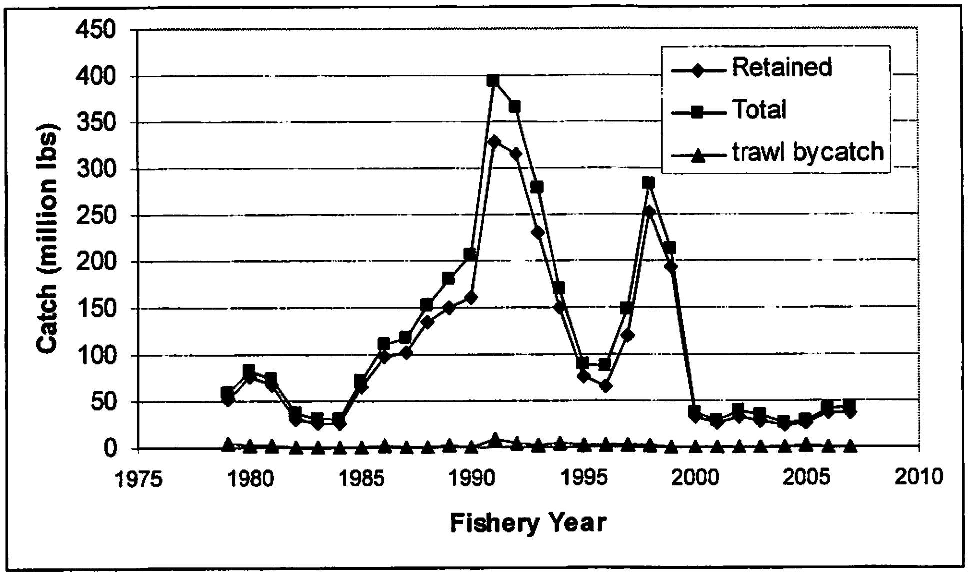

Figure 1. Catch (million lbs) from the directed snow crab pot fishery and groundfish trawl bycatch. Total catch is retained catch plus discarded catch after 50% discard mortality was applied. Trawl bycatch is male and female bycatch from groundfish trawl fisheries with 80% mortality applied.

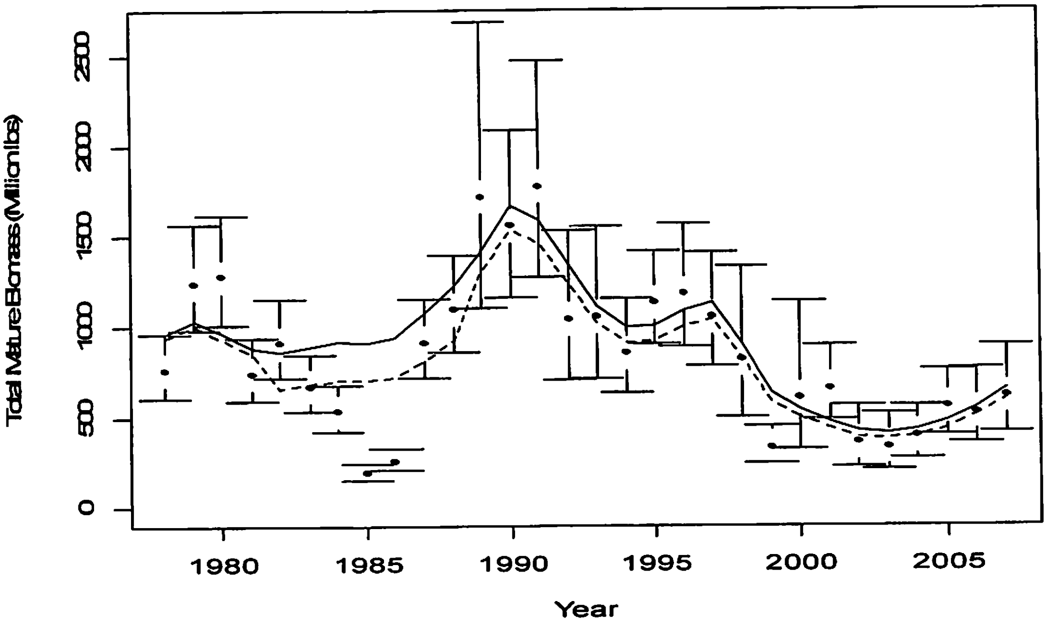

Figure 2. Population total mature biomass (millions of pounds, solid line), model estimate of survey mature biomass (dotted line) and observed survey mature biomass with approximate lognormal 95% confidence intervals.

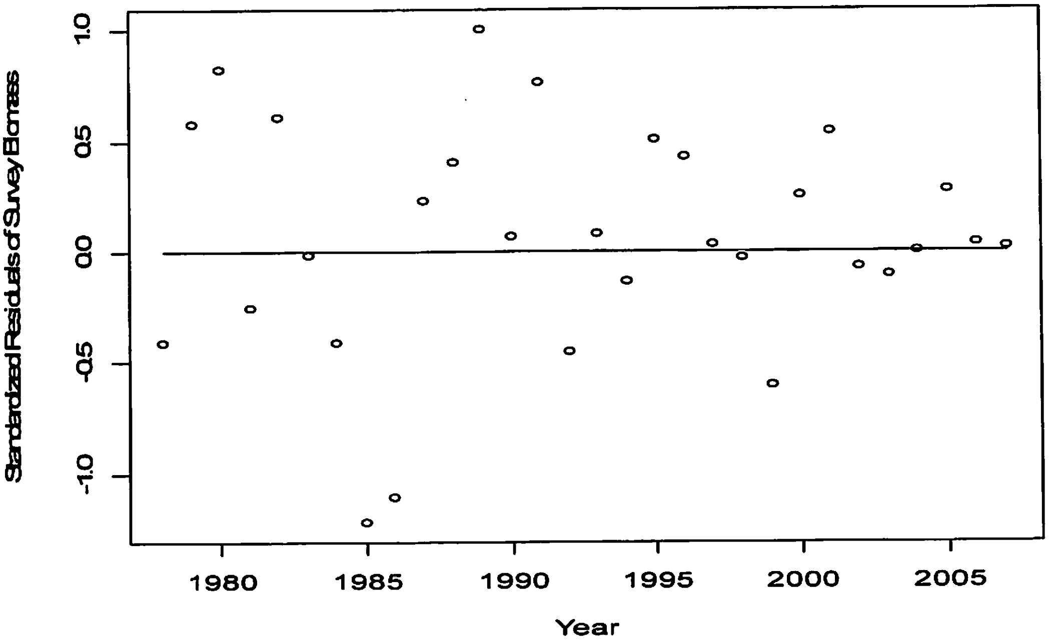

Figure 3. Standardized residuals for model fit to total mature biomass from Figure 2.

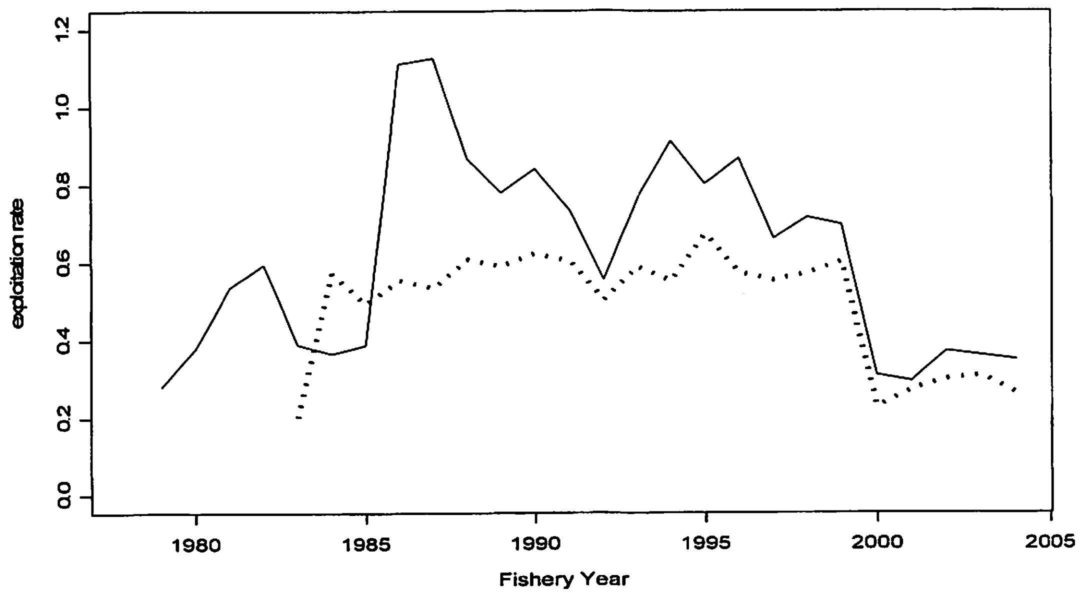

Figure 4. Exploitation rate estimated as the preseason GHL divided by the survey estimate of large male biomass (>101 mm) at the time the survey occurs (dotted line). The solid line is the retained catch divided by the survey estimate of large male biomass at the time the fishery occurs. Year is the year the fishery occurred.

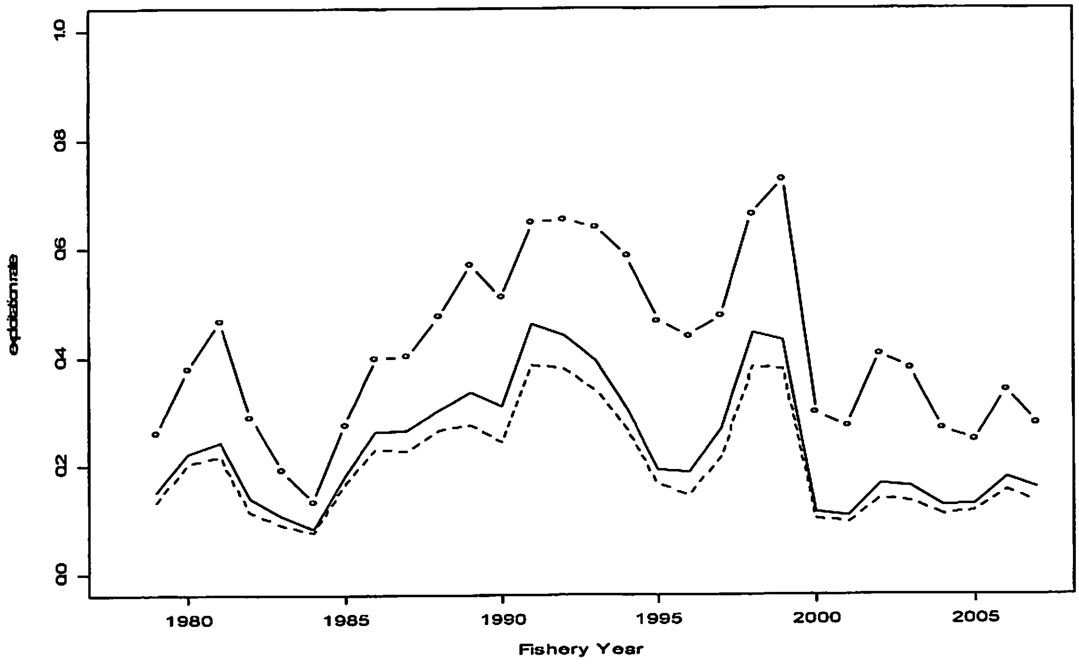

Figure 5. Exploitation fraction estimated as the catch biomass (total or retained) divided by the mature male biomass from the model at the time of the fishery (solid line and

dotted line). The exploitation rate for total catch divided by the male biomass greater than 101 mm is the solid line with dots. Year is the year of the fishery.

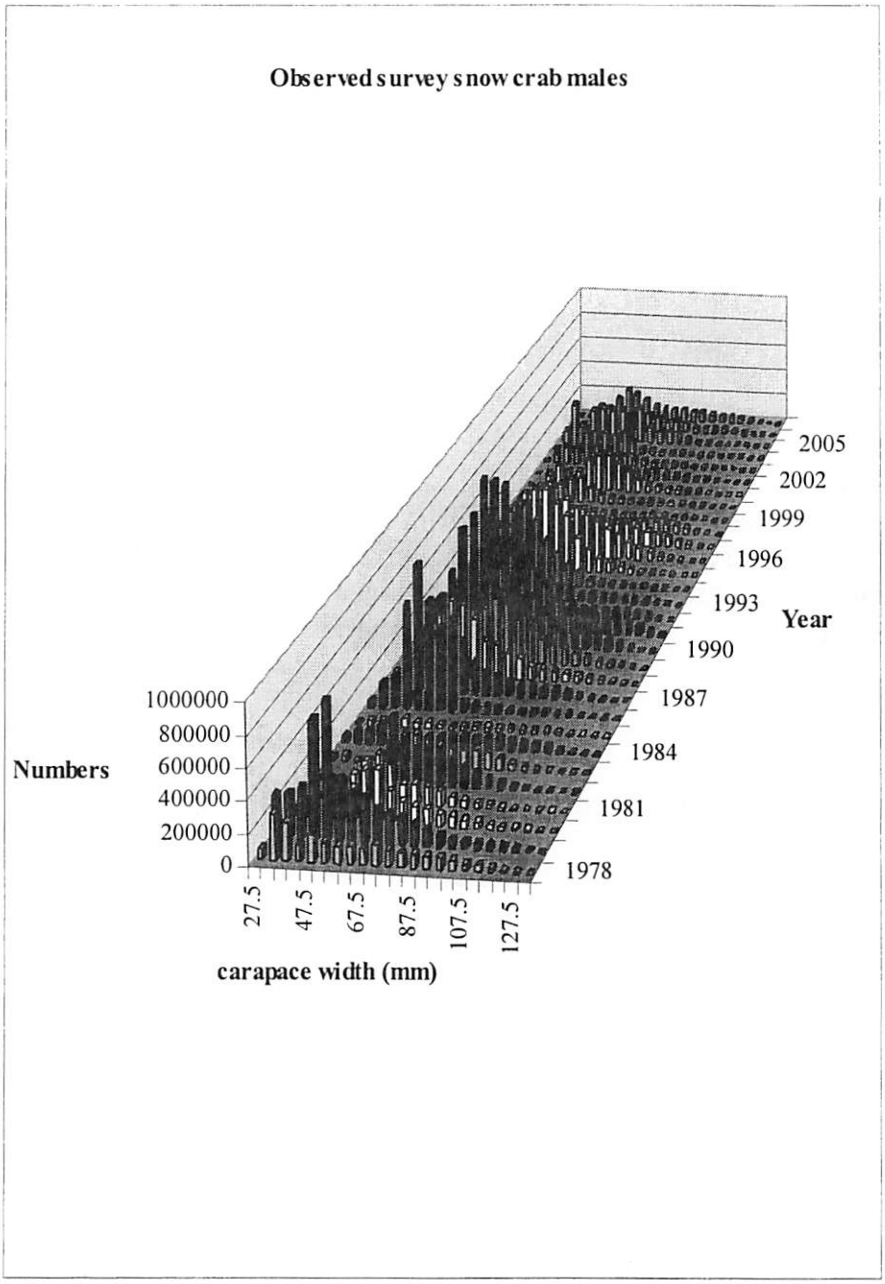

Figure 6. Observed survey numbers (1000's of crab) by carapace width and year fo r male snow crab.

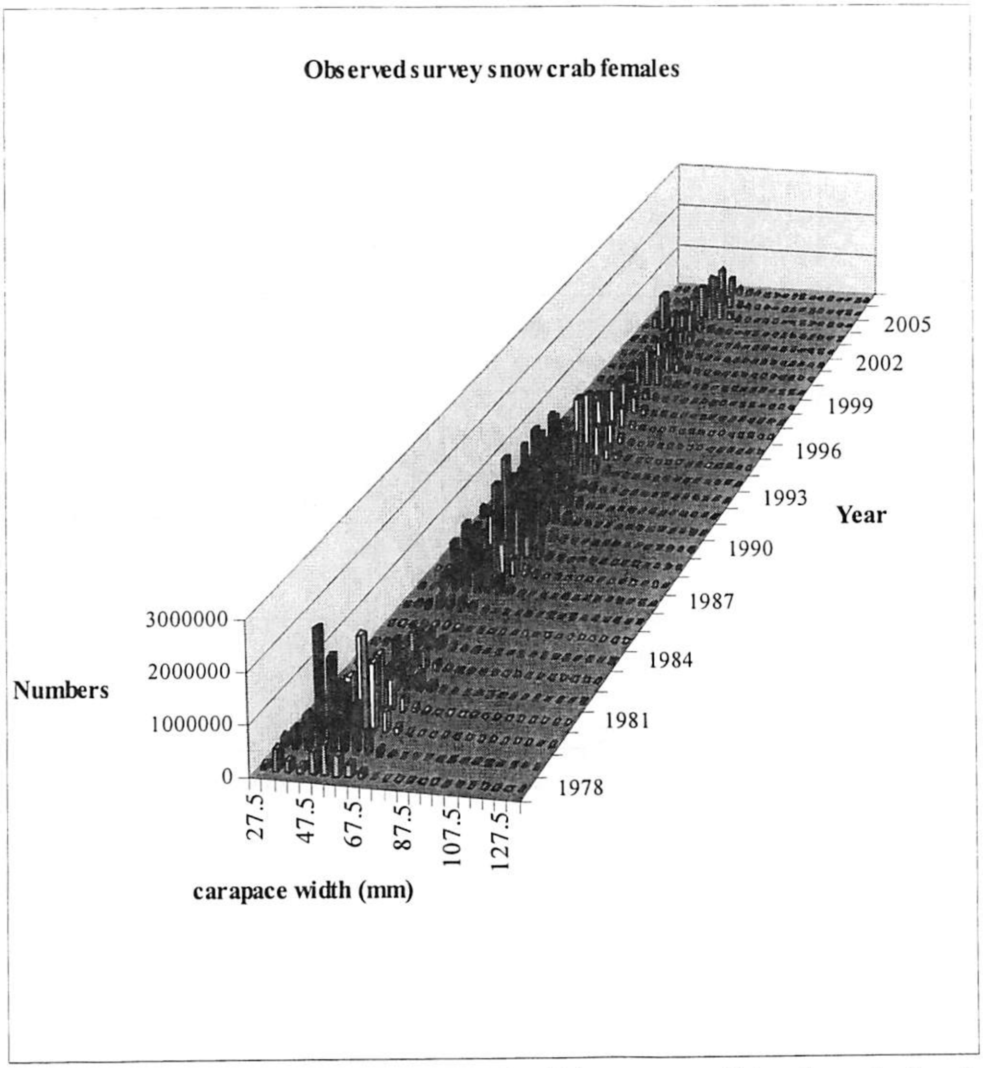

Figure 7. Observed survey numbers (1000's of crab) by carapace width and year for female snow crab.

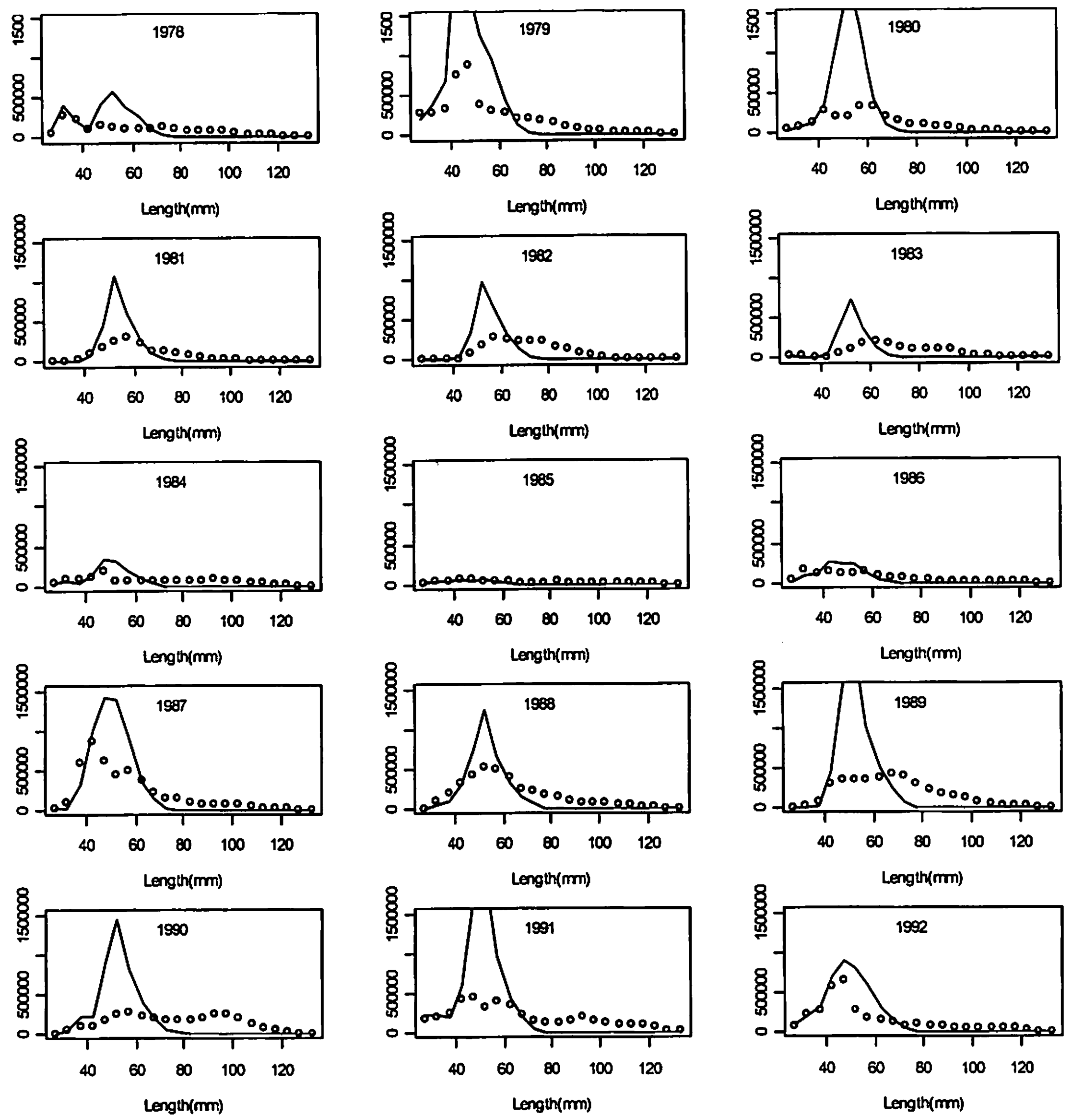

Figure 8. Survey numbers by length, males circles, females solid line.

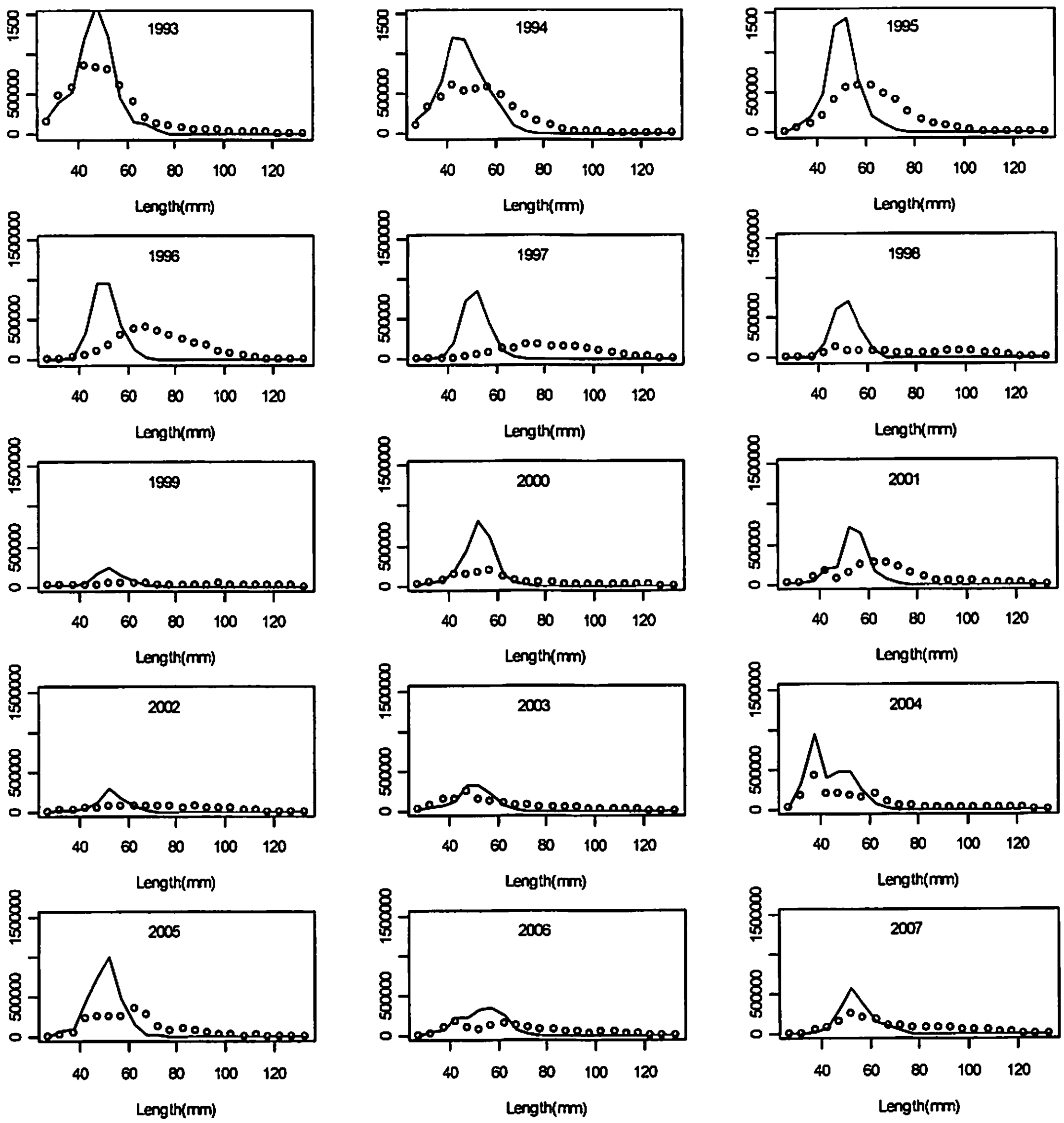

Figure 9. Survey numbers by length, males circles, females solid line.

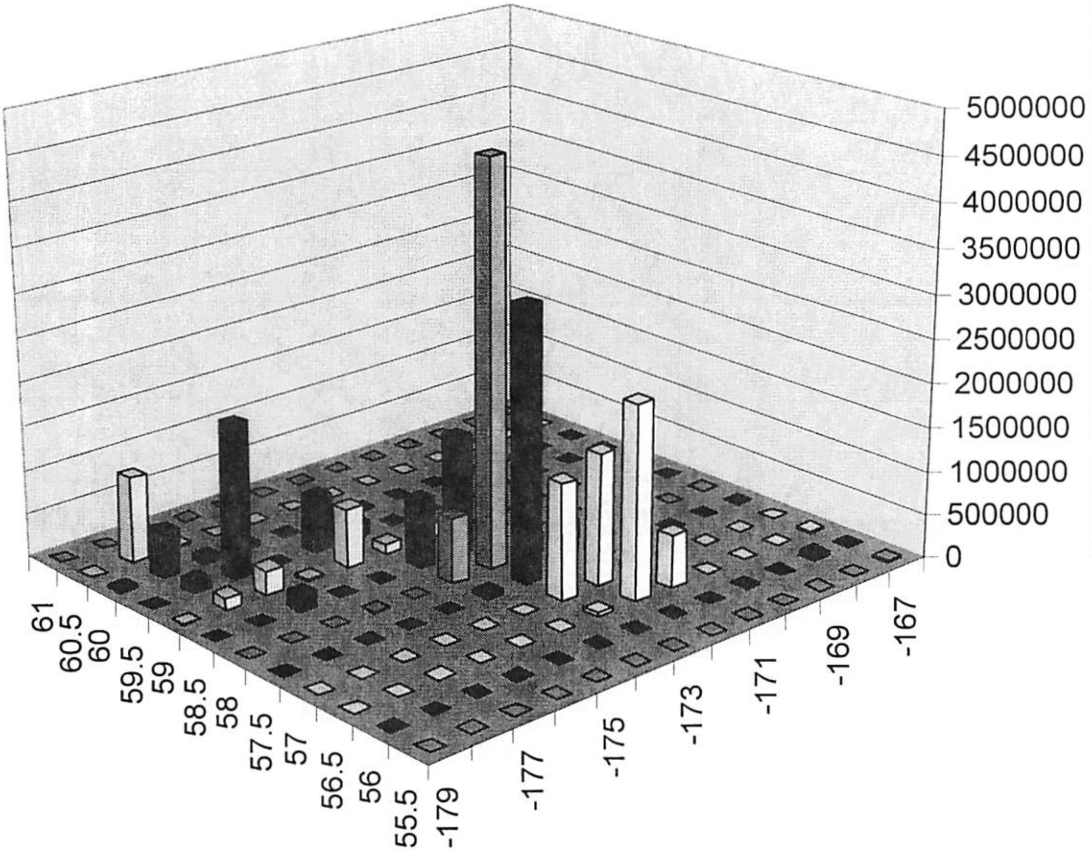

Figure 10. 2003 pot fishery retained catch in numbers by statistical area. Longitude in negative degrees. Areas are 1 degree longitude by 0.5 degree latitude.

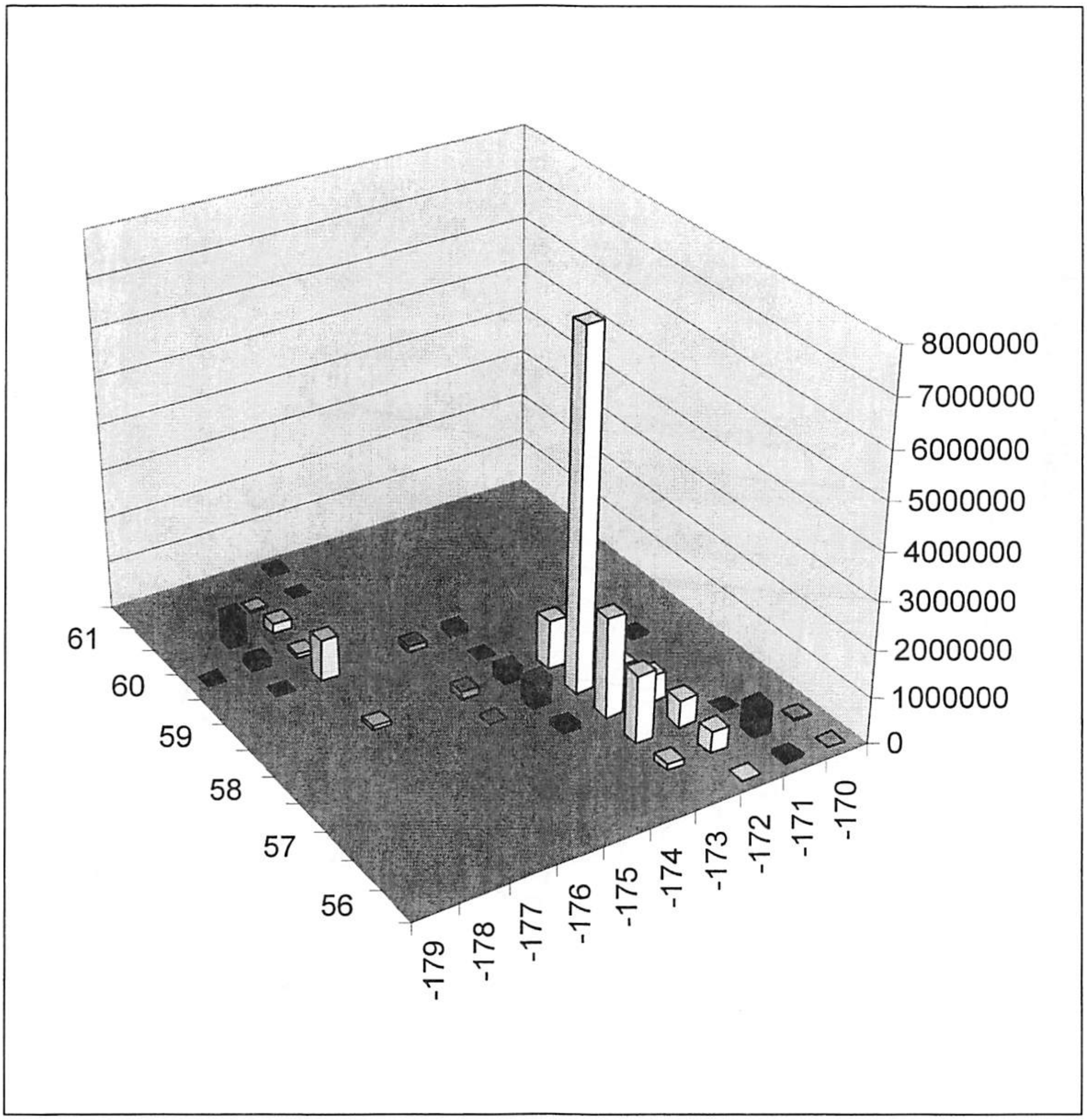

Figure 11. 2004 pot fishery retained catch in numbers by statistical area. Longitude in negative degrees. Areas are 1 degree longitude by 0.5 degree latitude.

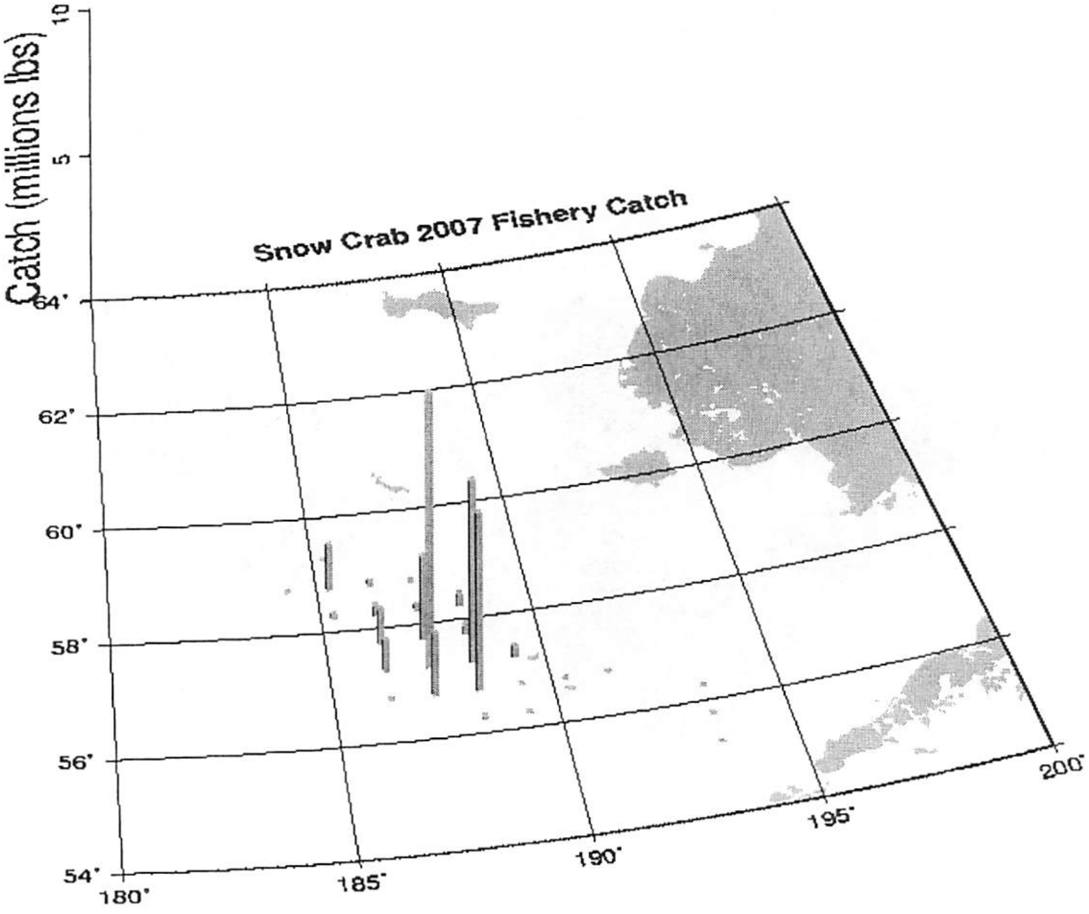

Figure 12. 2007 pot fishery retained catch(million lbs) by statistical area. Longitude increases from west to east (190 degrees = 170 degrees W longitude). Areas are 1 degree longitude by 0.5 degree latitude.

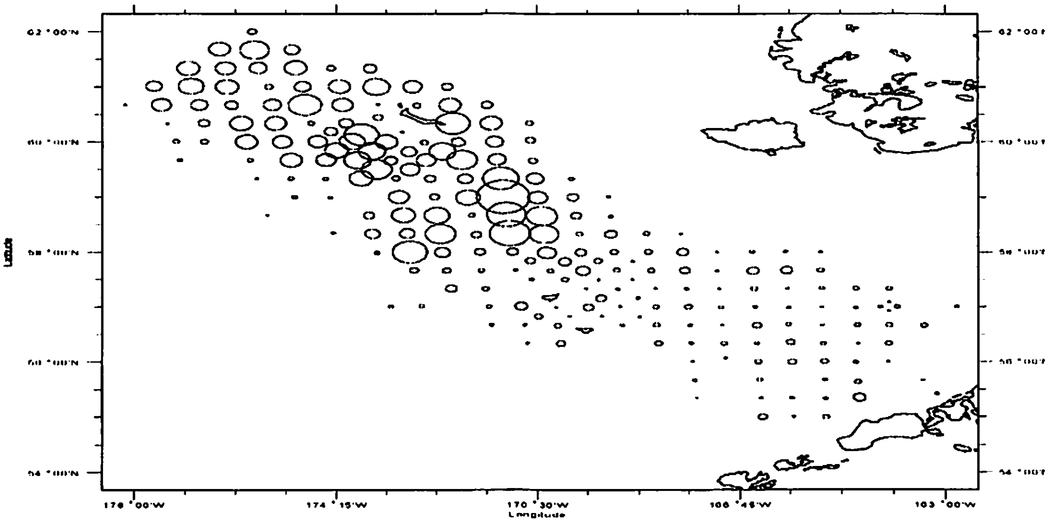

Figure 12. 2004 Survey abundance of males > 79 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle (not on same scale as female abundance in Figure 51).

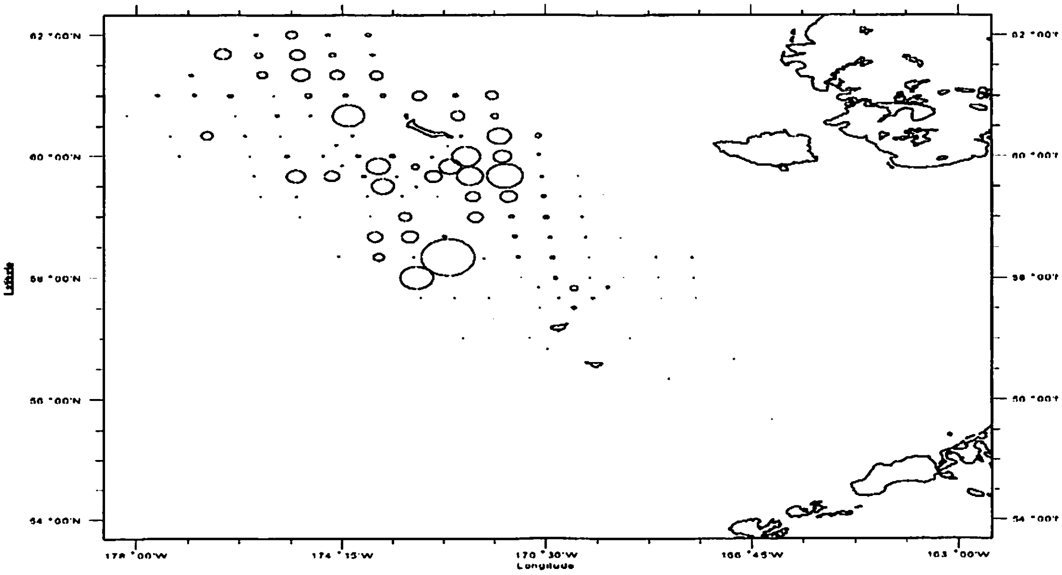

Figure 13. 2004 Survey abundance of females > 49 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle (not on the same scale as male abundance in Figure 9).

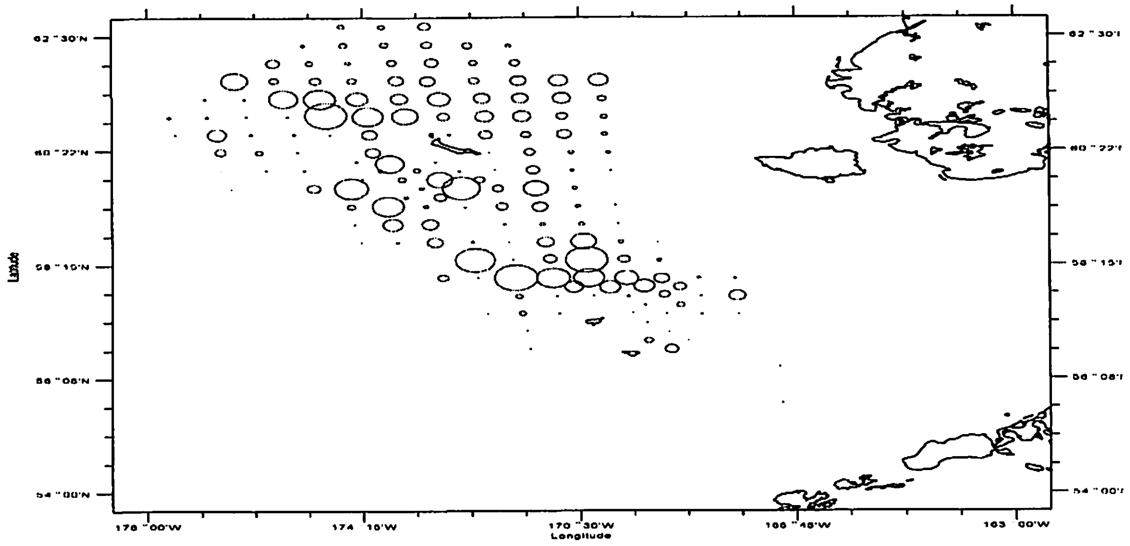

Figure 14. 2005 Survey abundance of females > 49 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle (not on the same scale as male abundance in Figure 54). Includes stations to the north of the standard survey area.

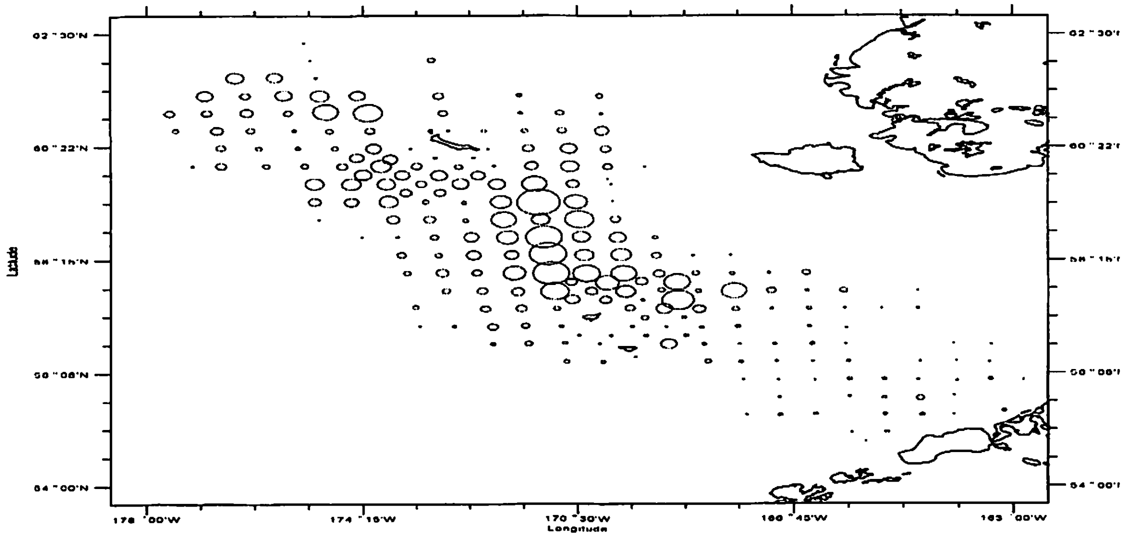

Figure 15. 2005 Survey abundance of males > 79 mm (approximately mature abundance) by tow. Abundance is proportional to the area of the circle (not on same scale as female abundance in Figure 53).

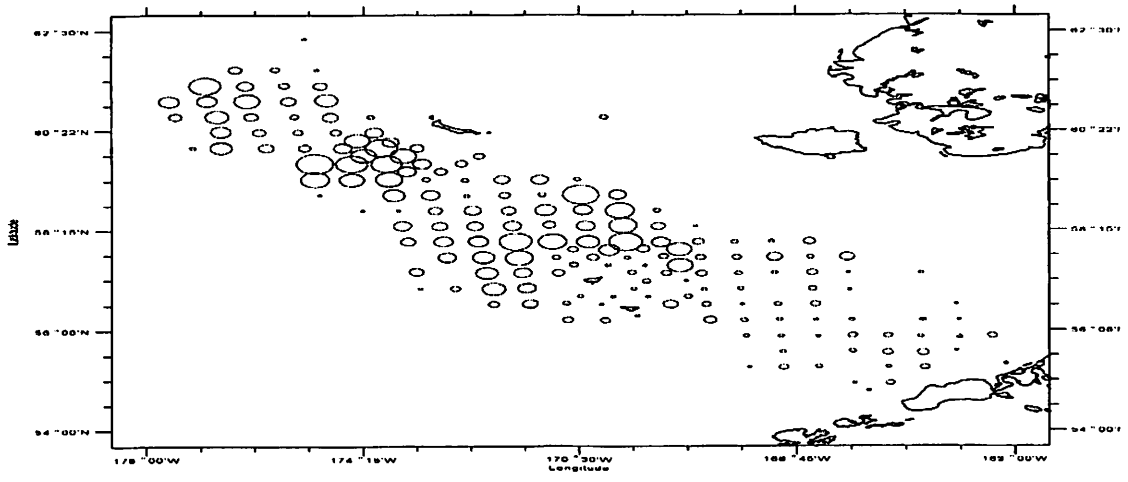

Figure 16. 2005 Survey abundance of males > 101 mm by tow. Abundance is proportional to the area of the circle.

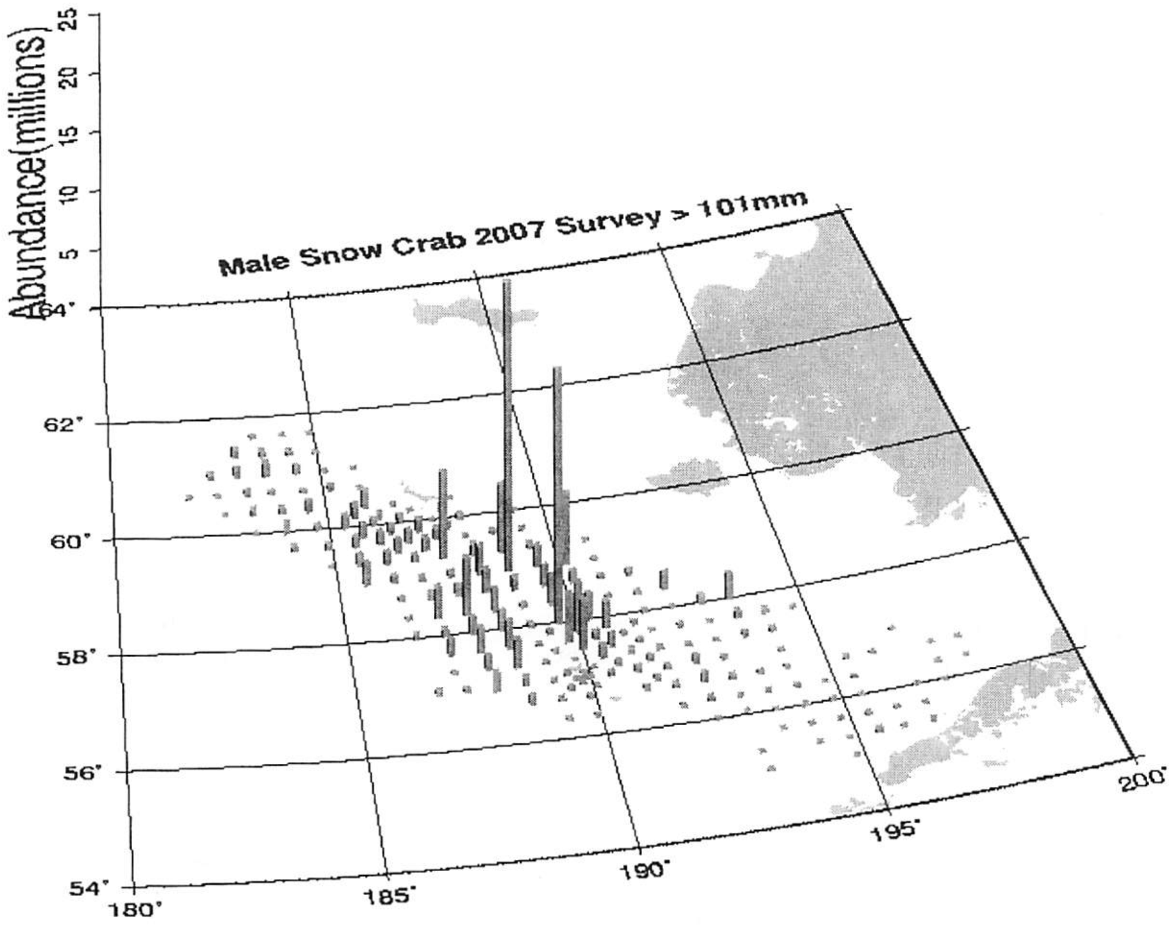

Figure 17. 2007 Survey abundance of males > 101 mm by tow. Abundance is in millions of crab.

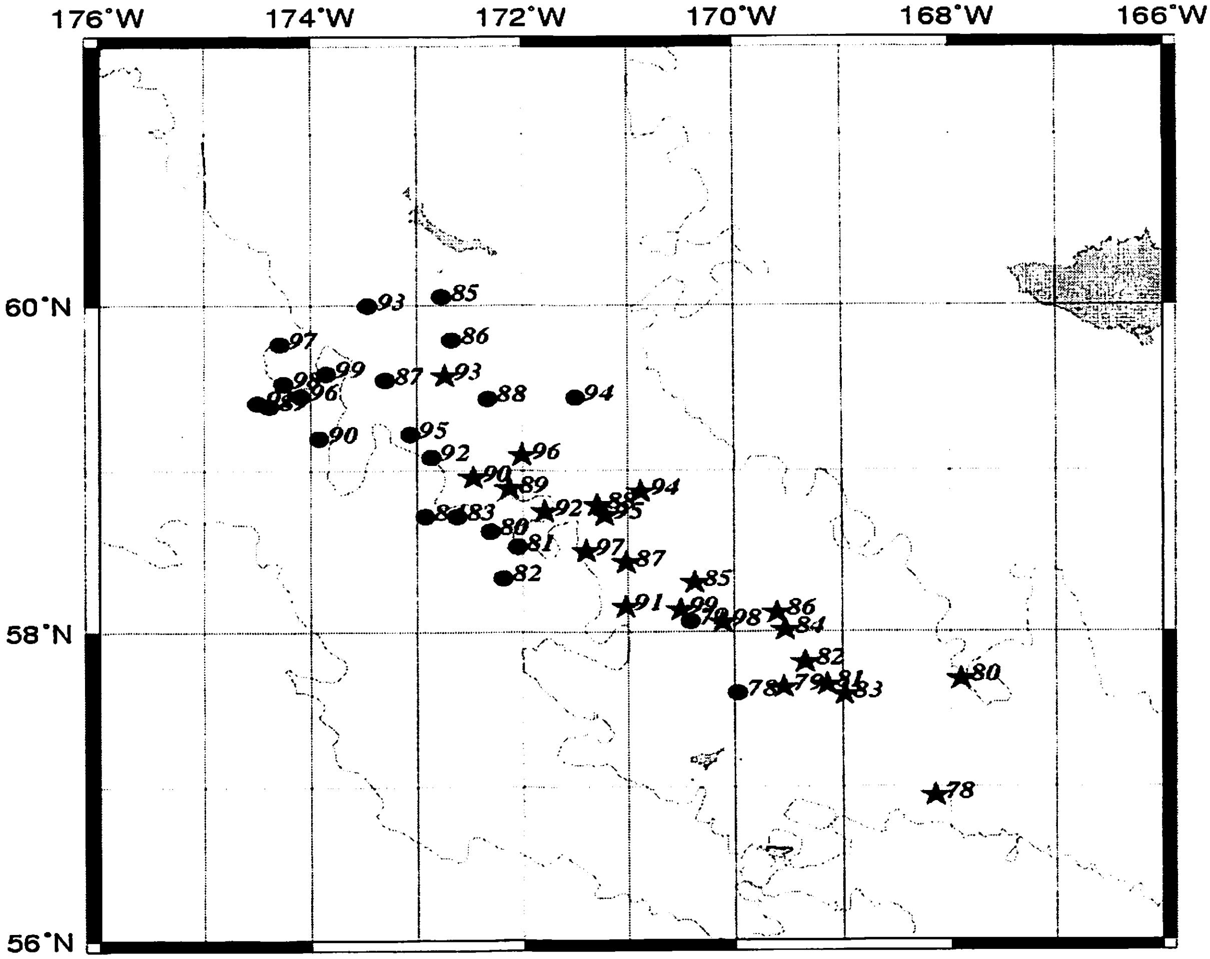

Figure 18. Centroids of abundance of mature female snow crabs (shell condition 2+) in blue circles and mature males (shell condition 3+) in red stars. Reprinted from Orensanz, Armstong and Ernst (in press).

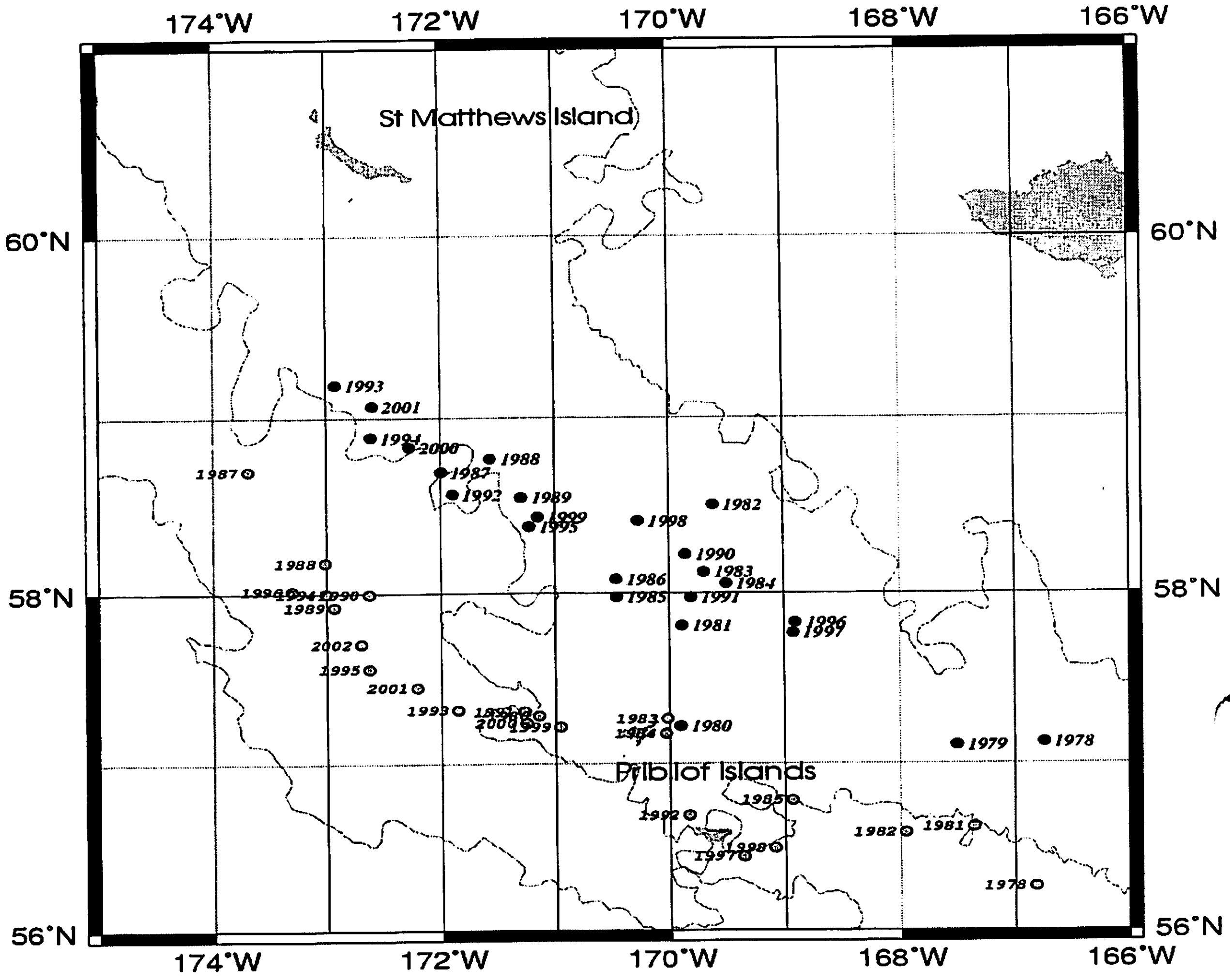

Figure 19. Centroids abundance (numbers) of snow crab males > 101 mm from the summer NMFS trawl survey (red) and from the winter fishery (blue-green), from Orensanz, Armstong and Ernst (in press).

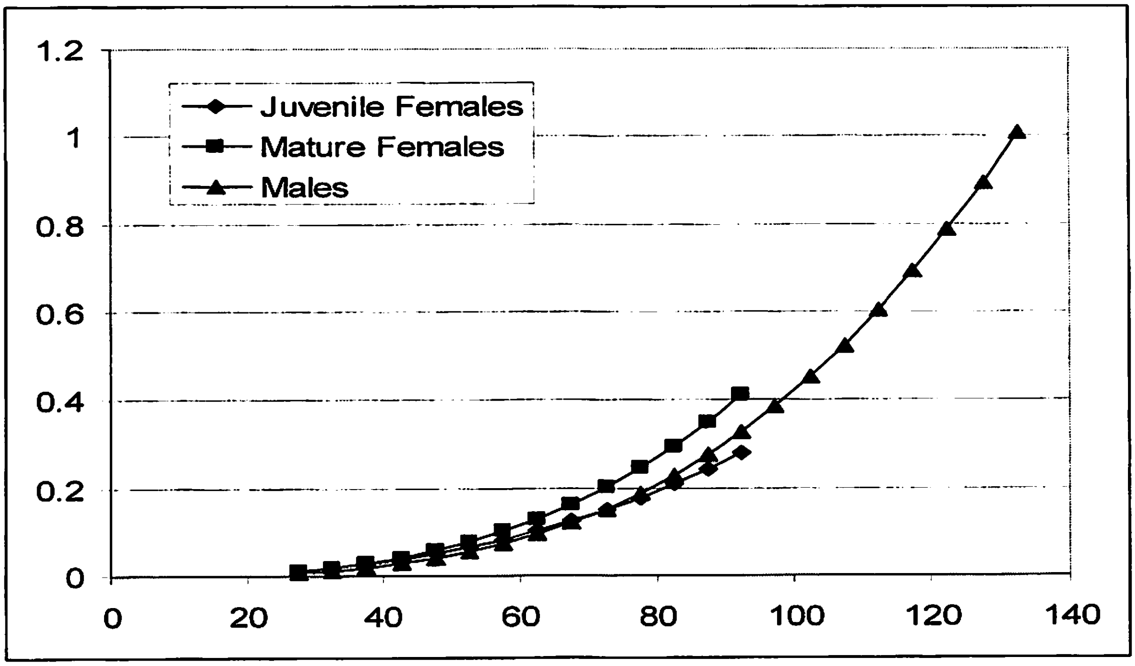

Figure 20. Weight (kg) – size (mm) relationship for male, juvenile female and mature female snow crab.

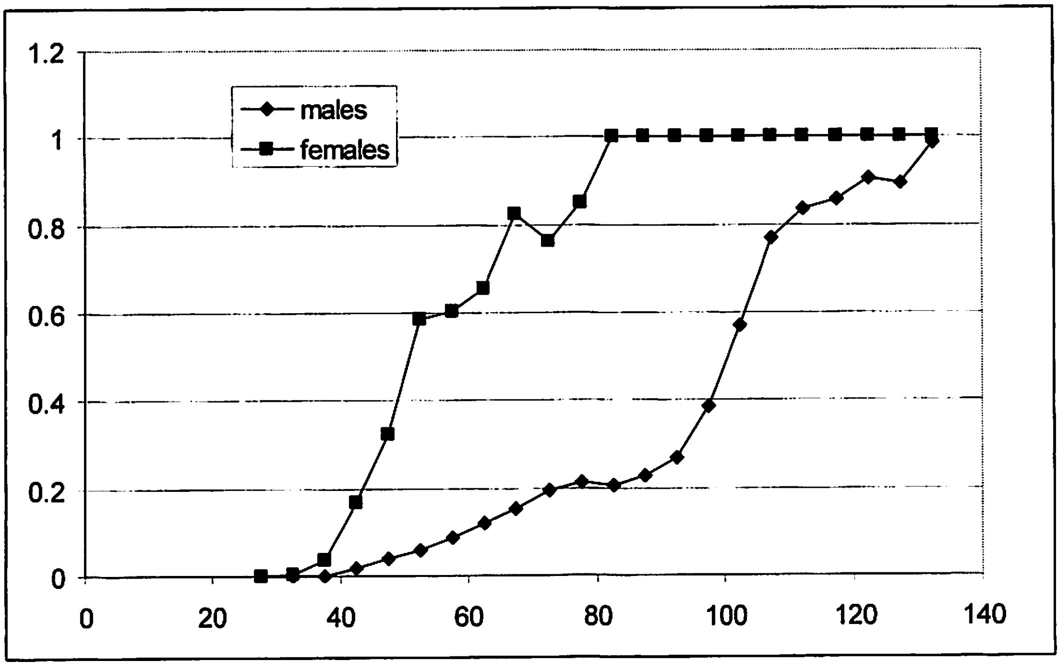

Figure 21. Probability of maturing by size for male and female snow crab (<u>not</u> the average fraction mature).

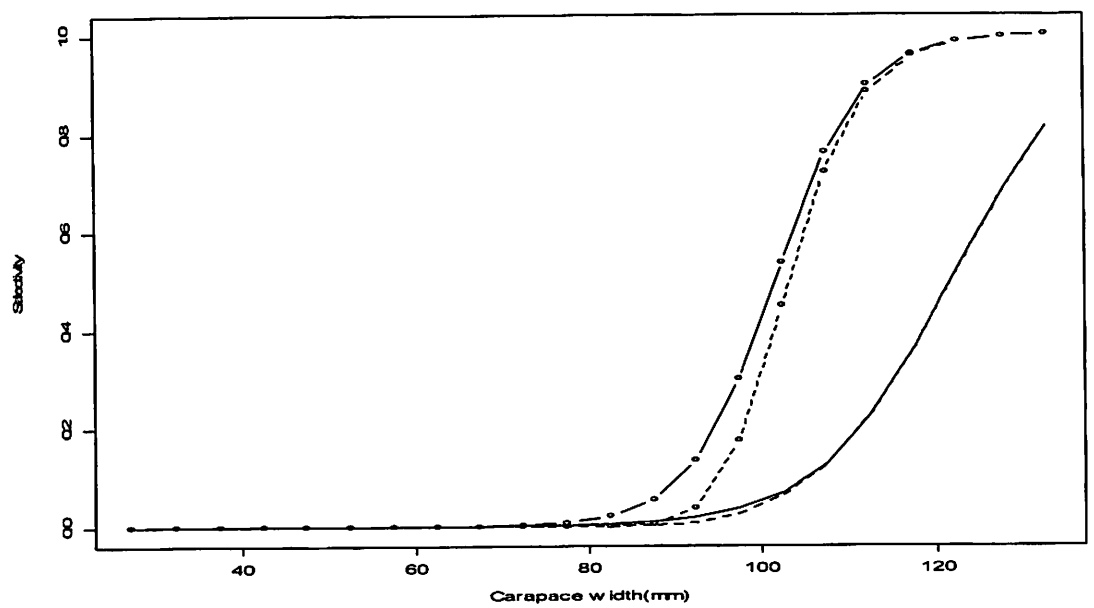

Figure 22. Selectivity curve for total catch (discard plus retained) for new shell males (solid line with filled circles) and retained catch of male snow crab by new (dotted line with filled circles) and old shell condition (dotted line). Solid line is total selectivity (discard plus retained) for old shell males.

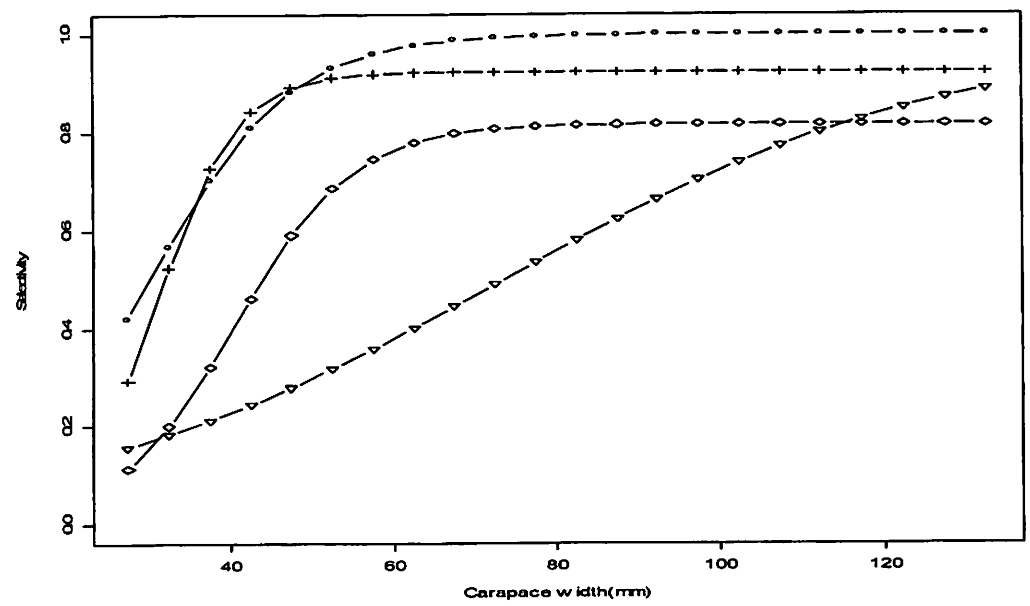

Figure 23. Survey selectivity curves for female and male snow crab estimated by the model for 1978-1981(solid line with circles), for 1982 to 1988 (solid line with diamonds), and 1989 to present (solid line with pluses). Survey selectivities estimated by Somerton and Otto (1998) are the solid line with triangles.

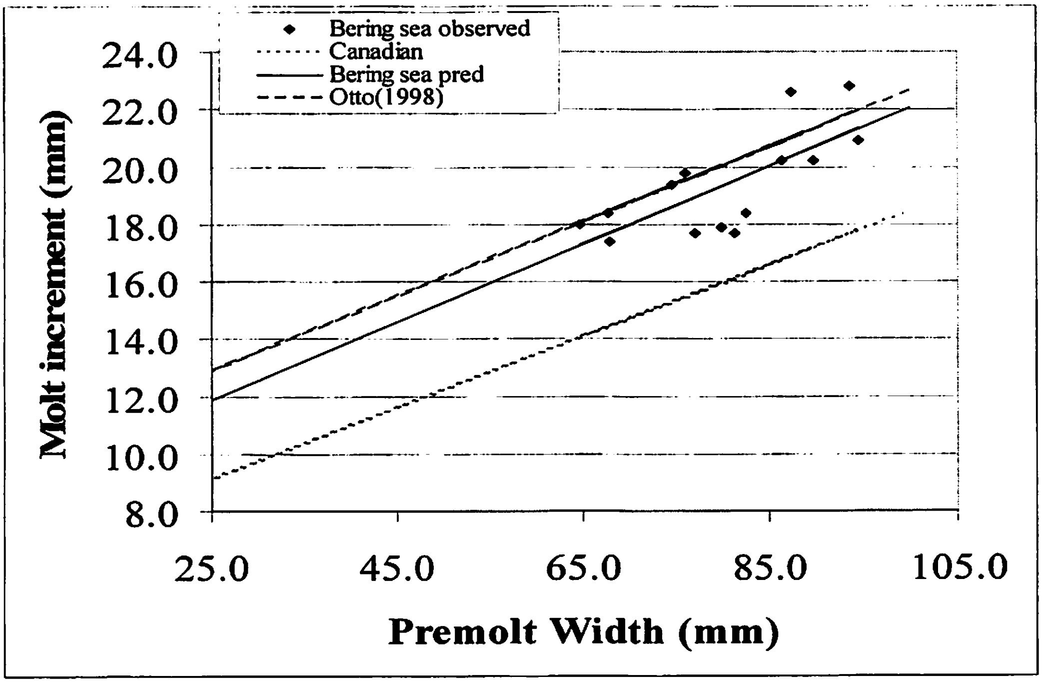

Figure 24. Growth increment as a function of premolt size for male snow crab. Points labeled Bering sea observed are observed growth increments from Rugolo (unpub data). The line labeled Bering sea pred is the predicted line from the Bering sea observed growth, which is used as a prior for the growth parameters estimated in the model. The line labeled Canadian is estimated from Atlantic snow crab (Sainte-Marie data). The line labeled Otto(1998) was estimated from tagging data from Atlantic snow crab less than 67 mm, from a different area from Sainte-Marie data.

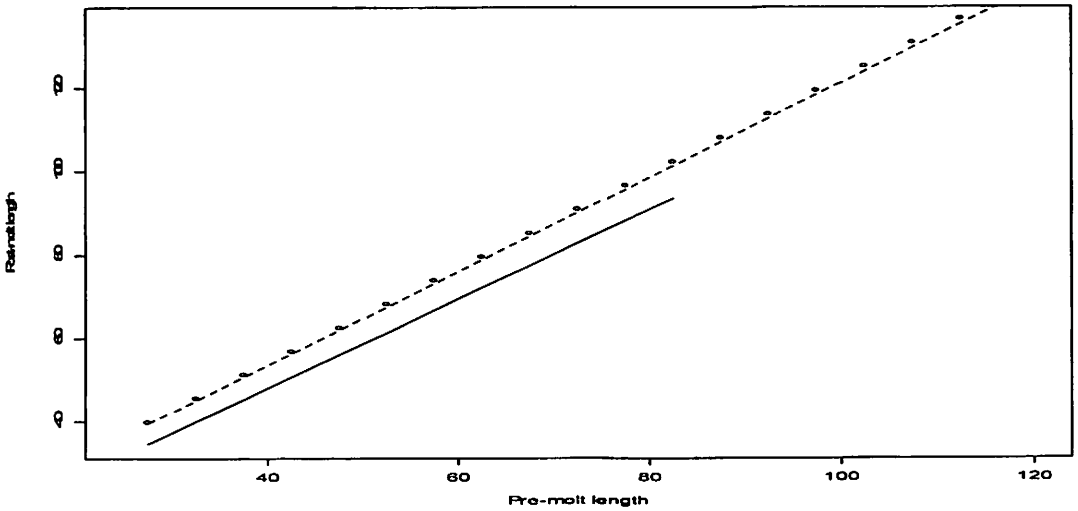

Figure 25. Growth(mm) for male(dotted line) and female snow crab (solid line) estimated from the model. Circles are the observed growth curve.

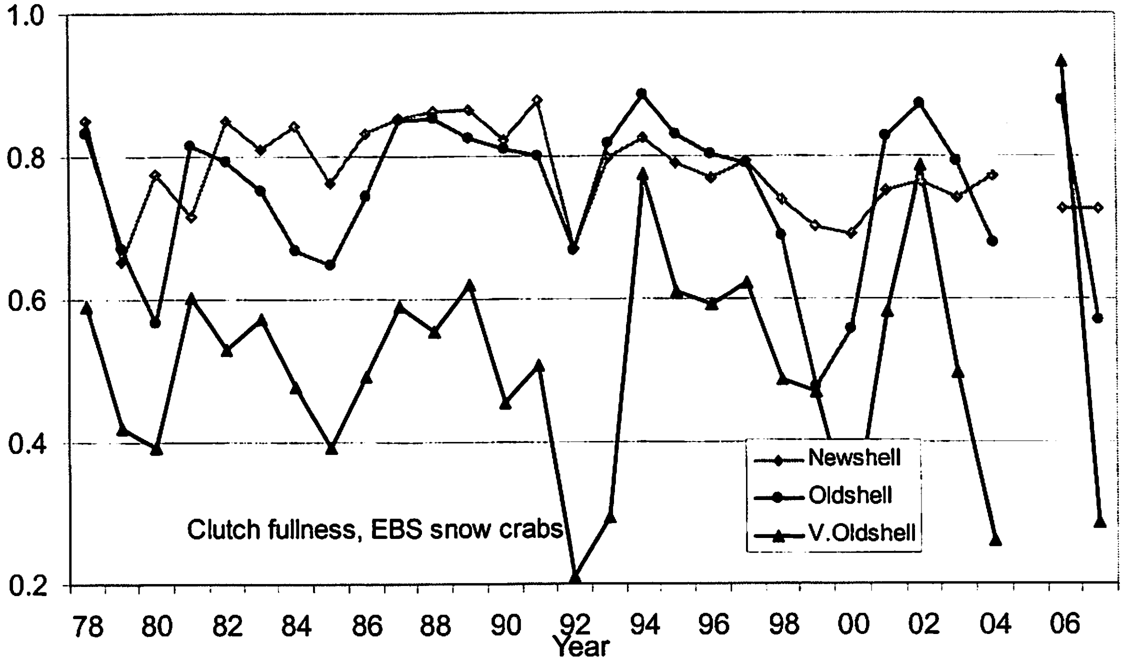

Figure 26. Clutch fullness for Bering sea snow crab survey data by shell condition for 1978 to 2007.

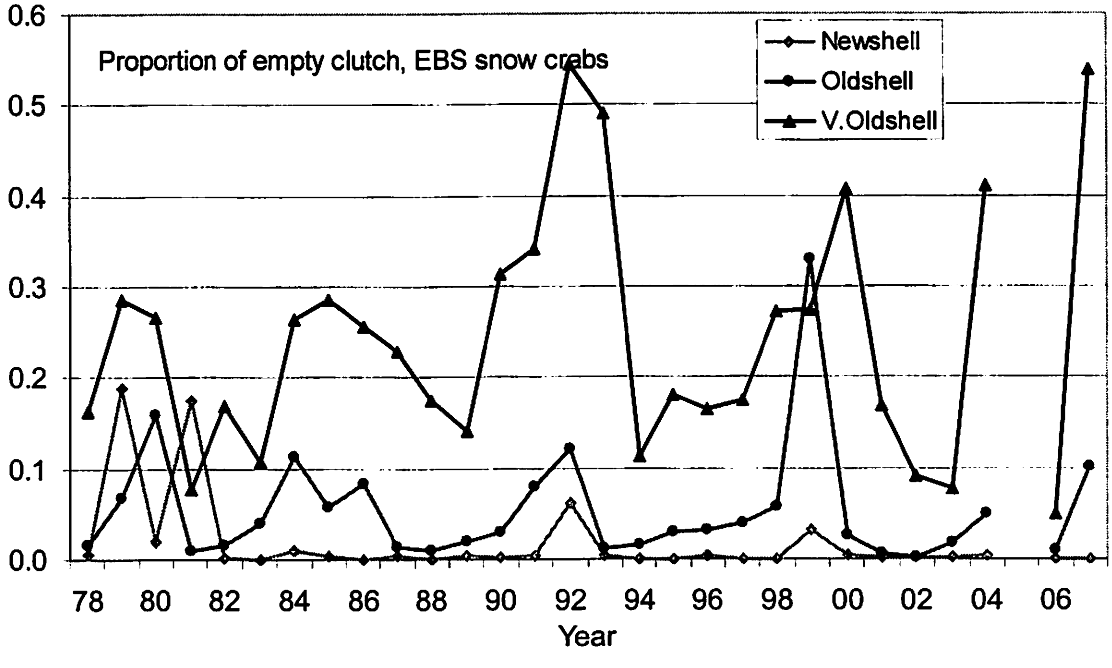

Figure 27. Proportion of barren females by shell condition from survey data 1978 to 2007.

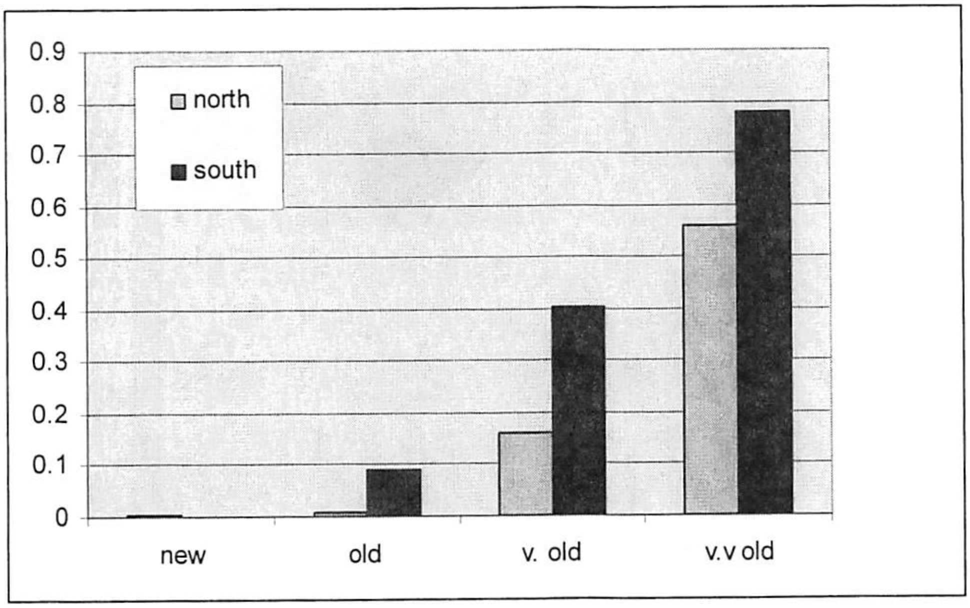

Figure 28. Fraction of barren females in the 2004 survey by shell condition and area north of 58.5 deg N and south of 58.5 deg N.

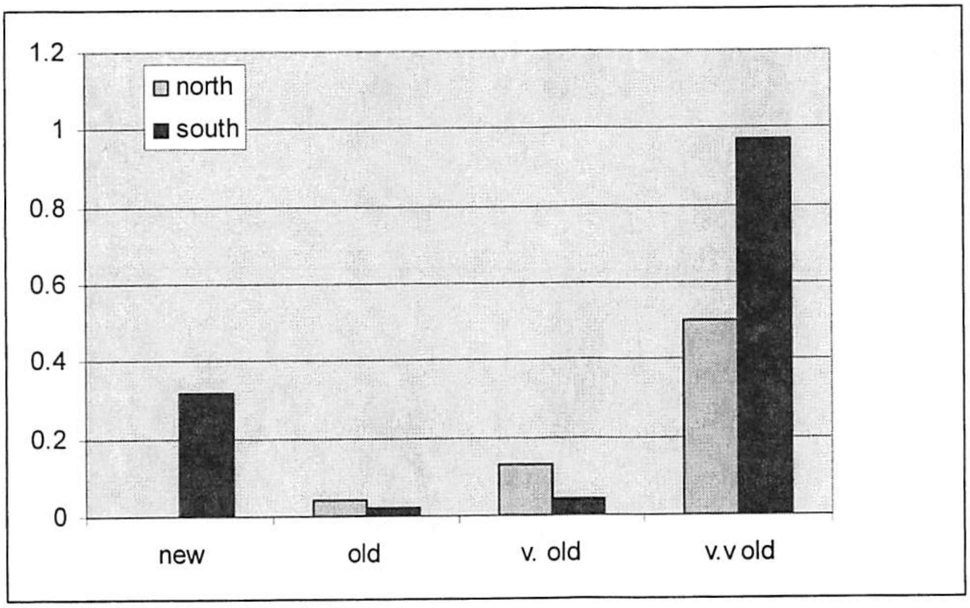

Figure 29. Fraction of barren females in the 2003 survey by shell condition and area north of 58.5 deg N and south of 58.5 deg N. The number of new shell mature females south of 58.5 deg N was very small in 2003.

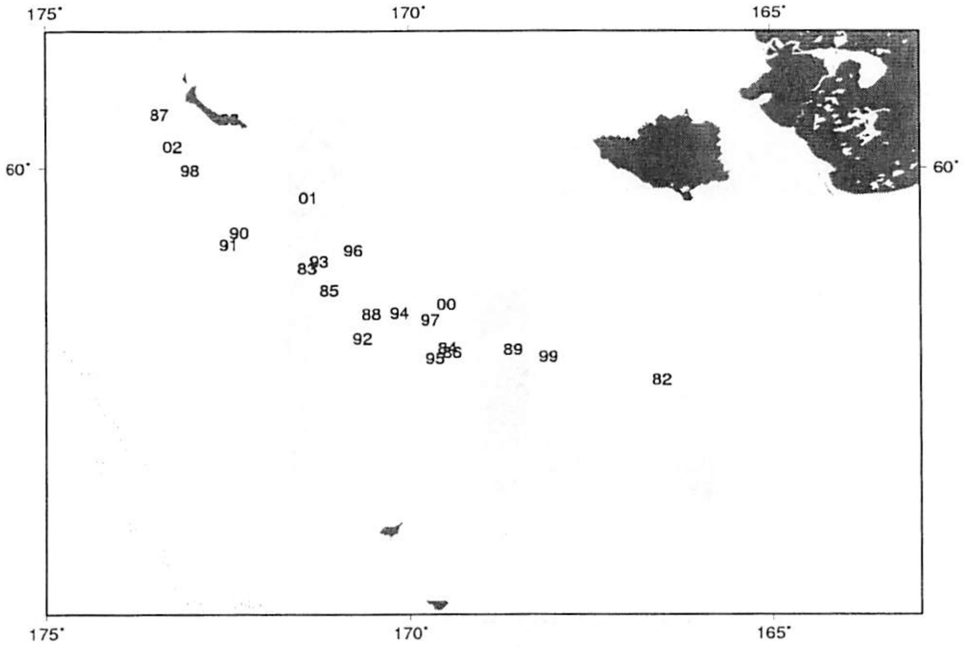

Figure 30. Centroids of cold pool (<2.0 deg C). Centroids are average latitude and longitude.

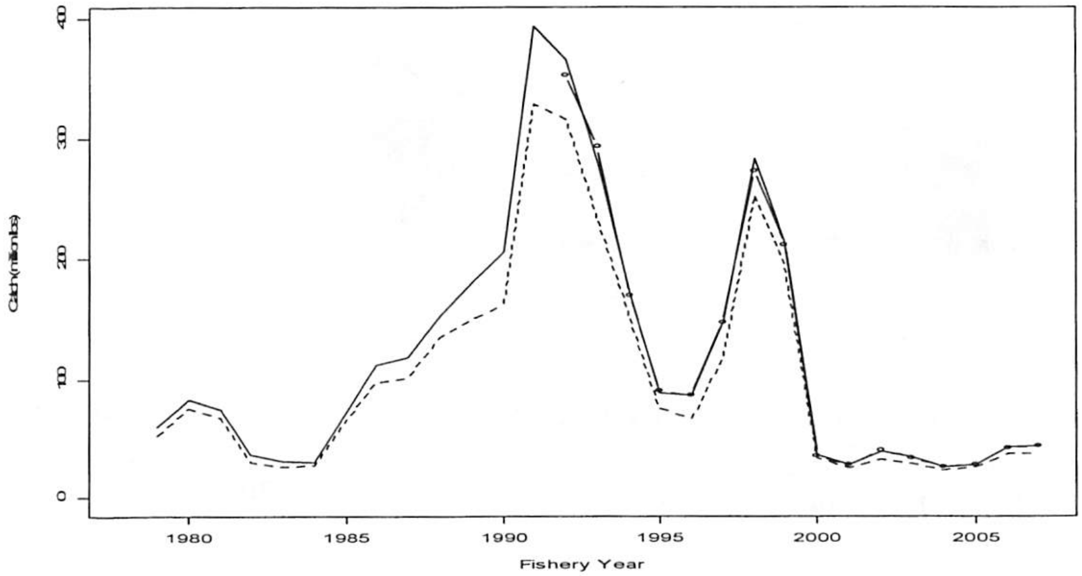

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Figure 31. Estimated total catch(discard + retained) (solid line), observed total catch (solid line with circles) (assuming 50% mortality of discarded crab) and observed retained catch (dotted line) for 1979 to 2007 fishery seasons.

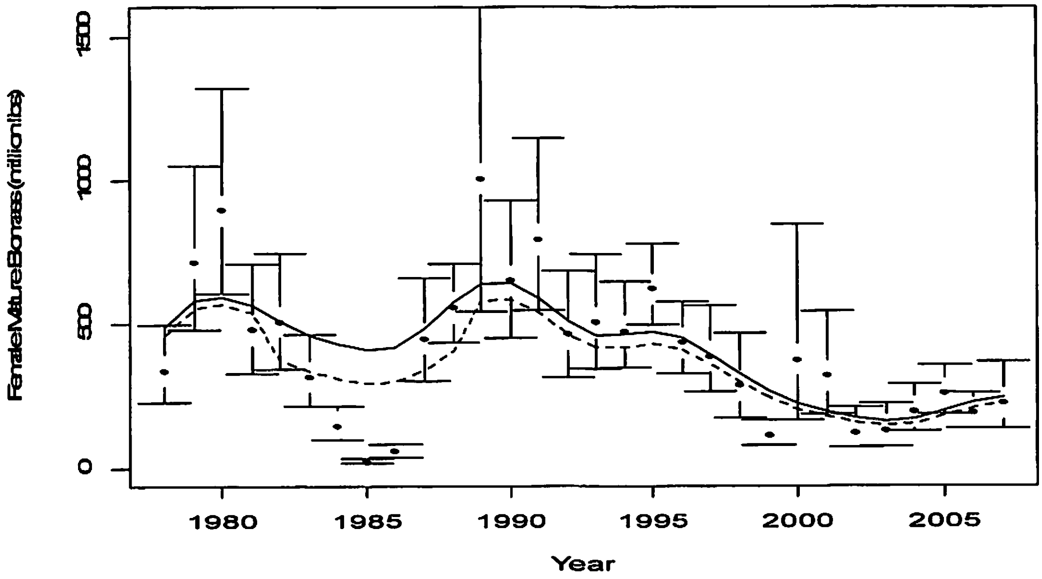

Figure 32. Population female mature biomass (millions of pounds, solid line), model estimate of survey female mature biomass (dotted line) and observed survey female mature biomass with approximate lognormal 95% confidence intervals.

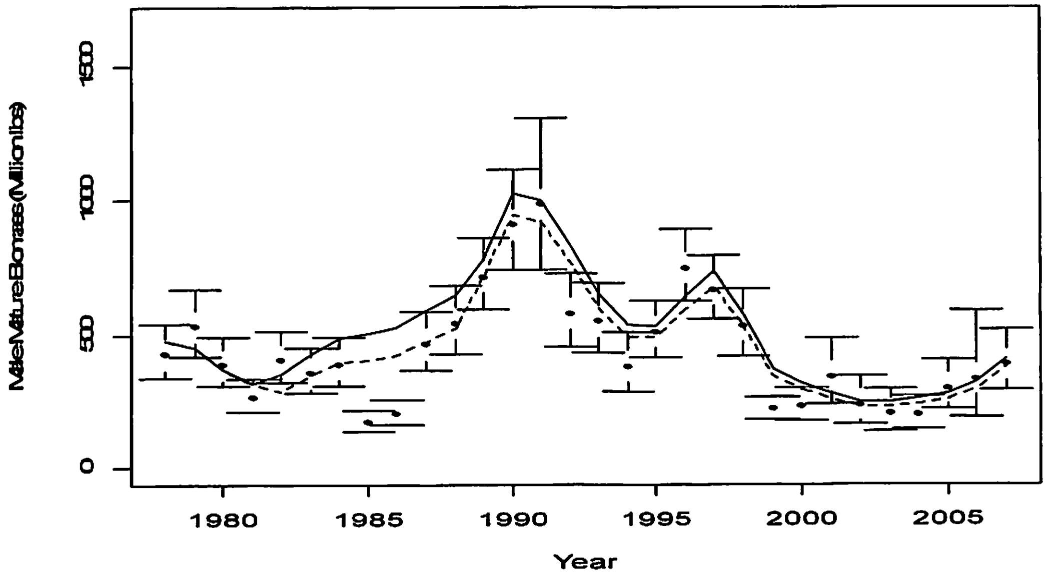

Figure 33. Population male mature biomass (millions of pounds, solid line), model estimate of survey male mature biomass (dotted line) and observed survey male mature biomass with approximate lognormal 95% confidence intervals.

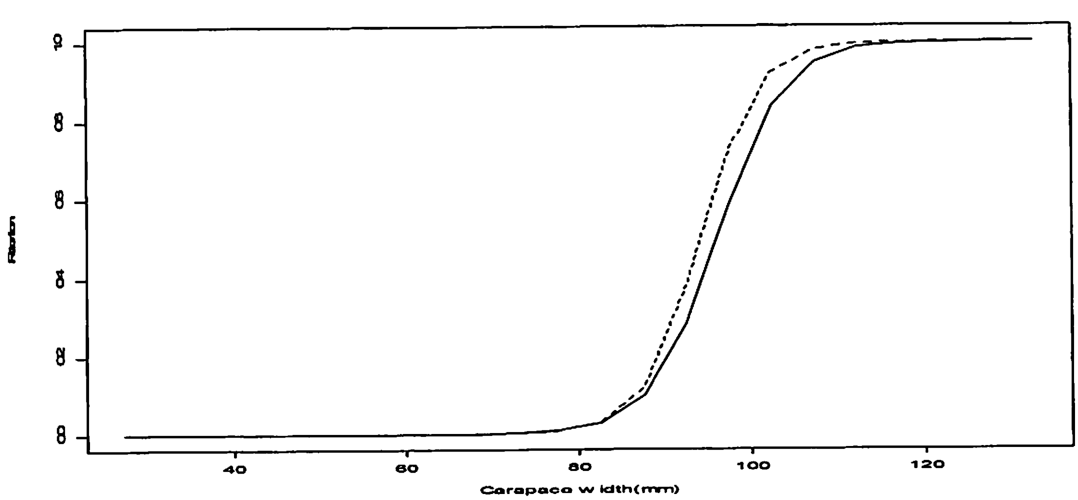

Figure 34. Model estimated fraction of the total catch that is retained by size for new(solid line) and old(dotted line) shell male snow crab.

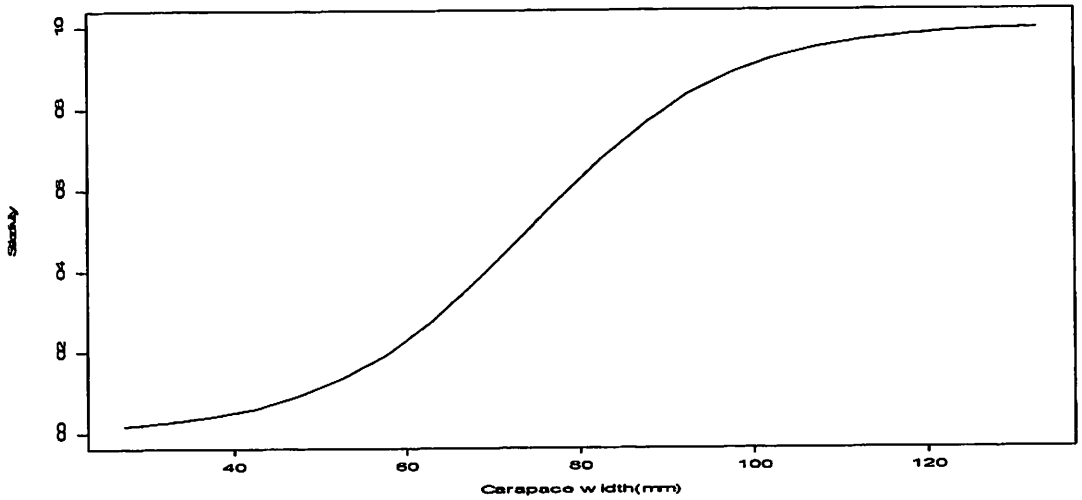

Figure 35. Selectivity curve estimated by the model for bycatch in the groundfish trawl fishery for females and males.

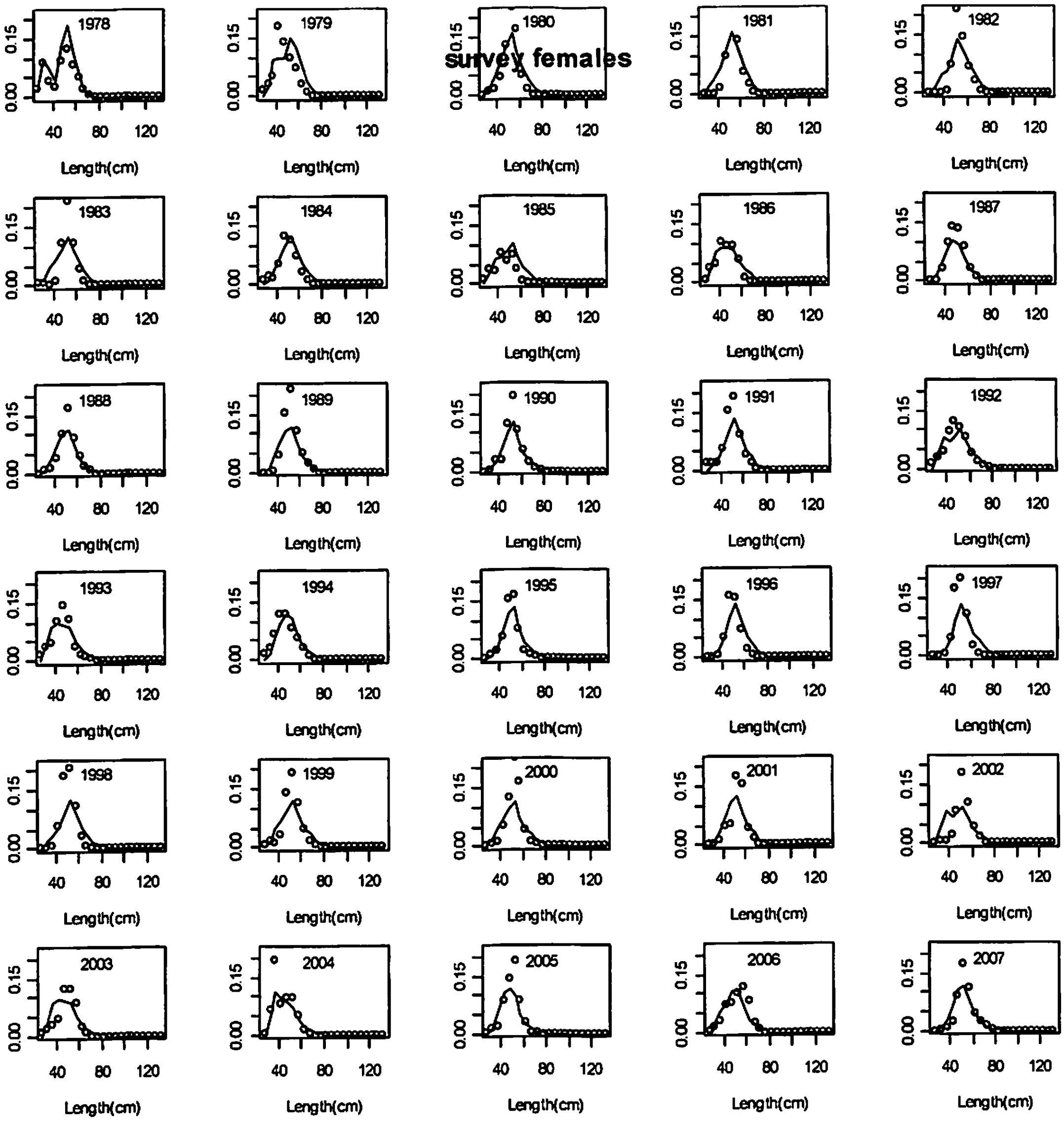

Figure 36. Model fit to the survey female size frequency data. Circles are observed survey data. Solid line is the model fit.

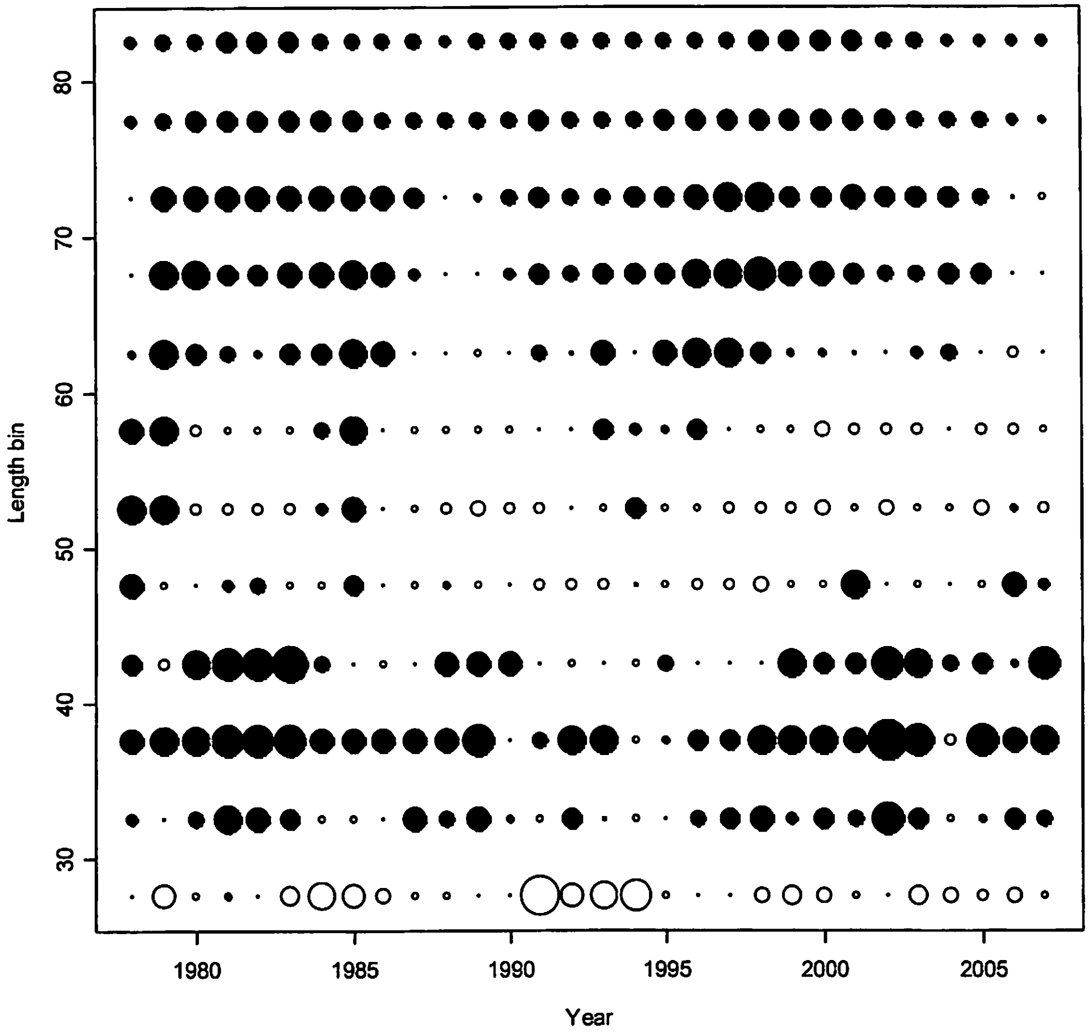

Figure 37. Residuals of fit to survey female size frequency. Filled circles are negative residuals.

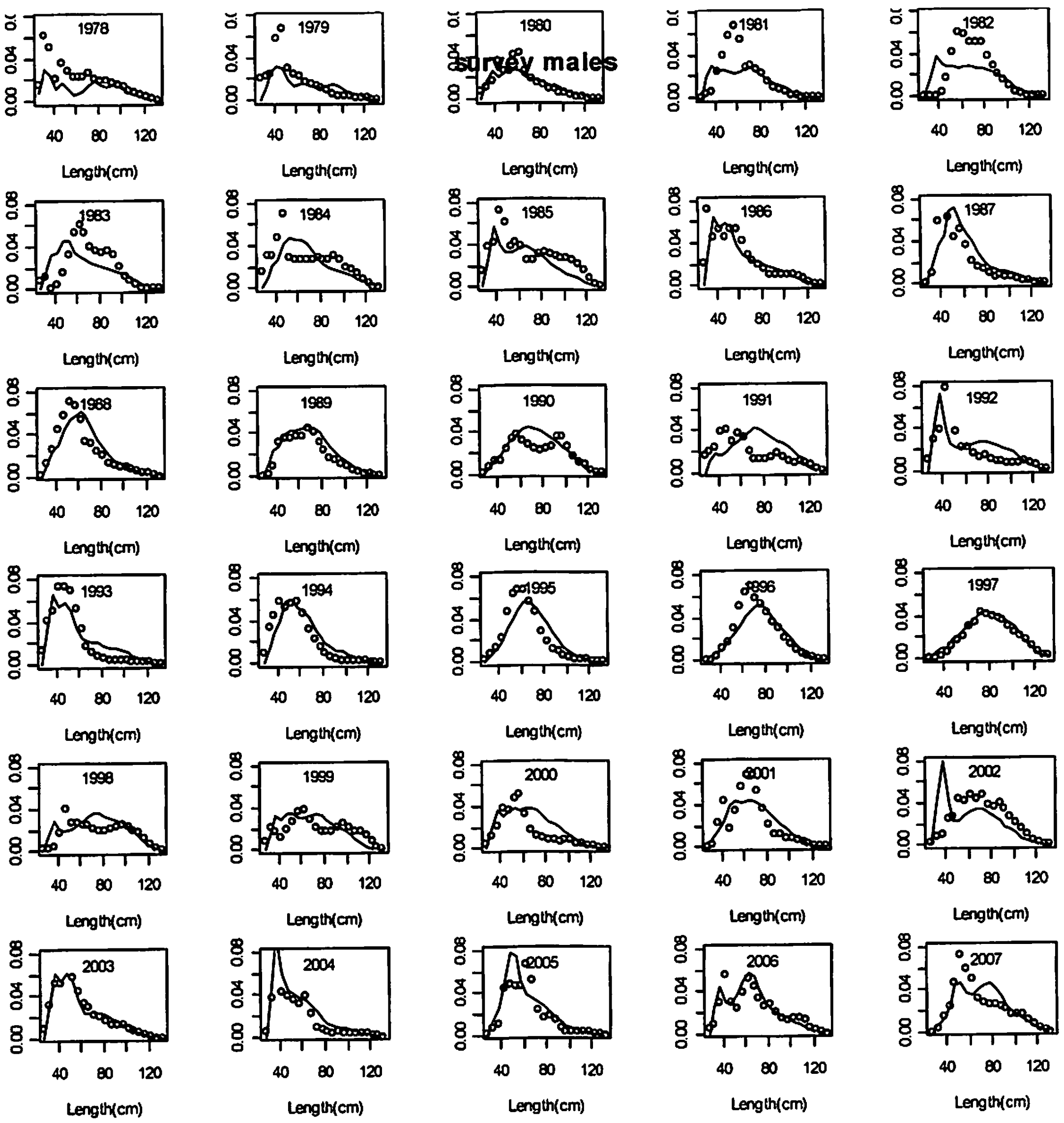

Figure 38. Model fit to the survey male size frequency data. Circles are observed survey data. Solid line is the model fit.

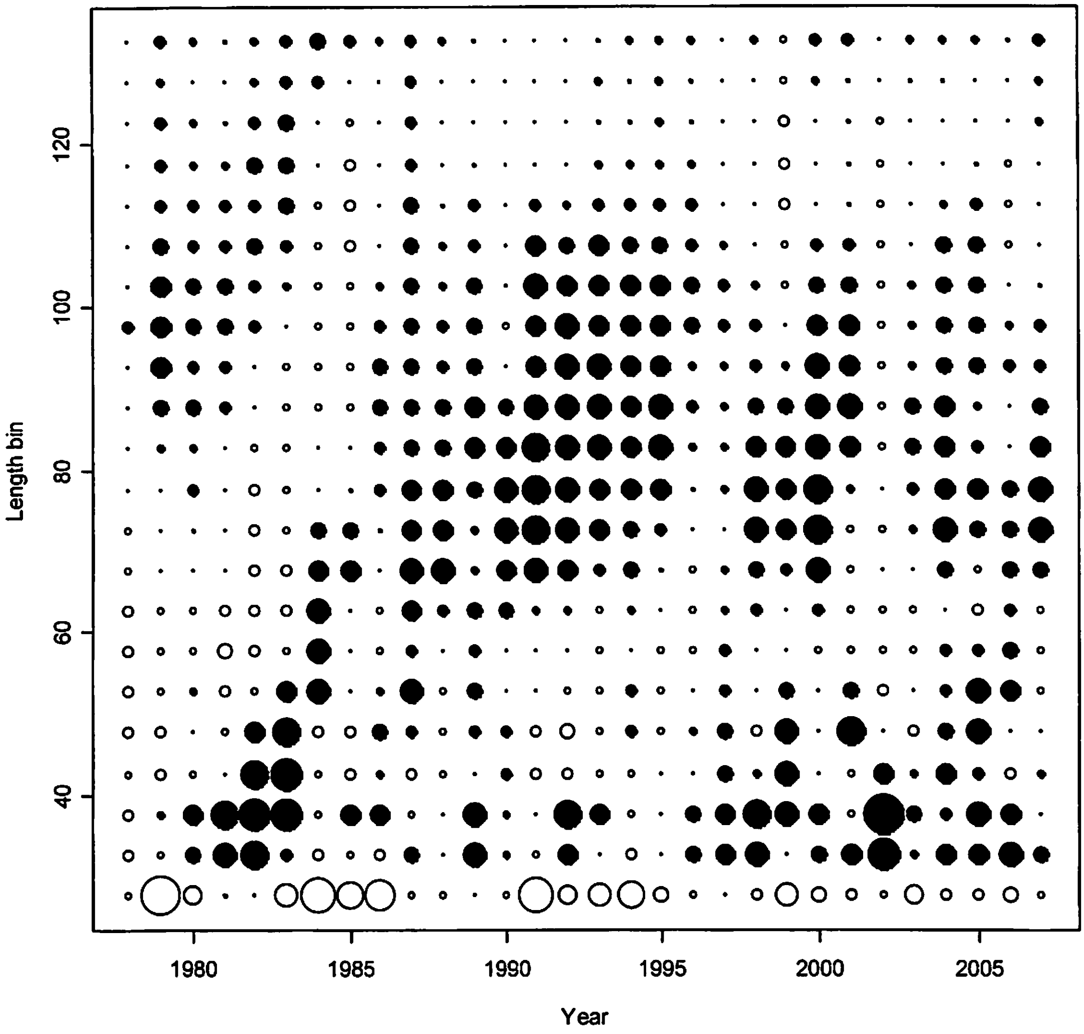

Figure 39. Residuals for fit to survey male size frequency. . Filled circles are negative residuals (predicted higher than observed).

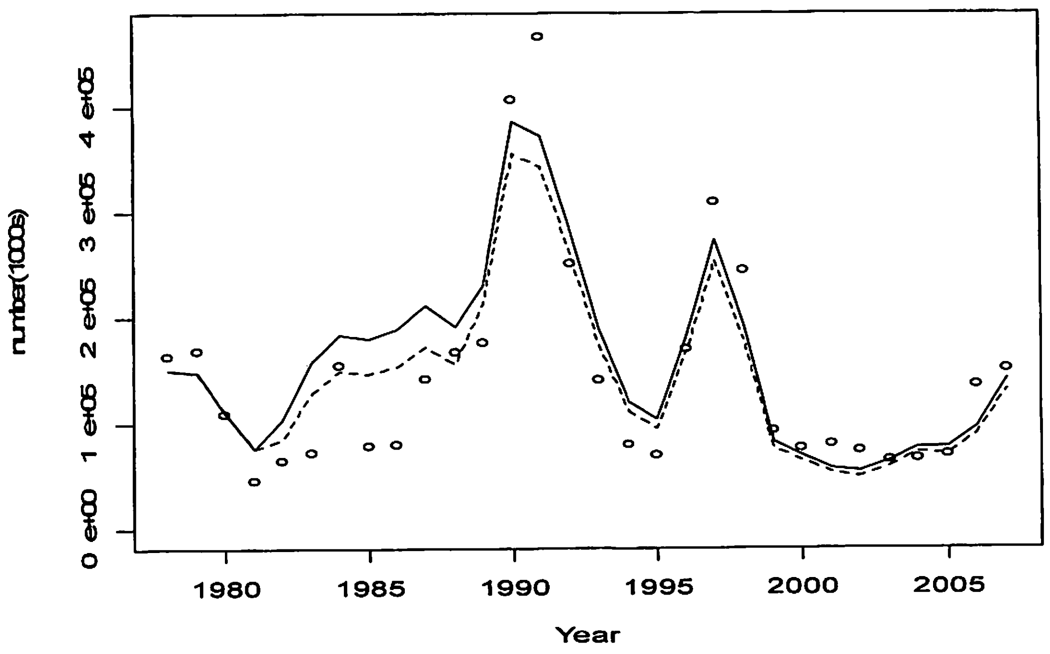

Figure 40. Observed survey numbers of males >101mm (circles), model estimates of the population number of males >101mm(solid line) and model estimates of survey numbers of males >101 mm (dotted line).

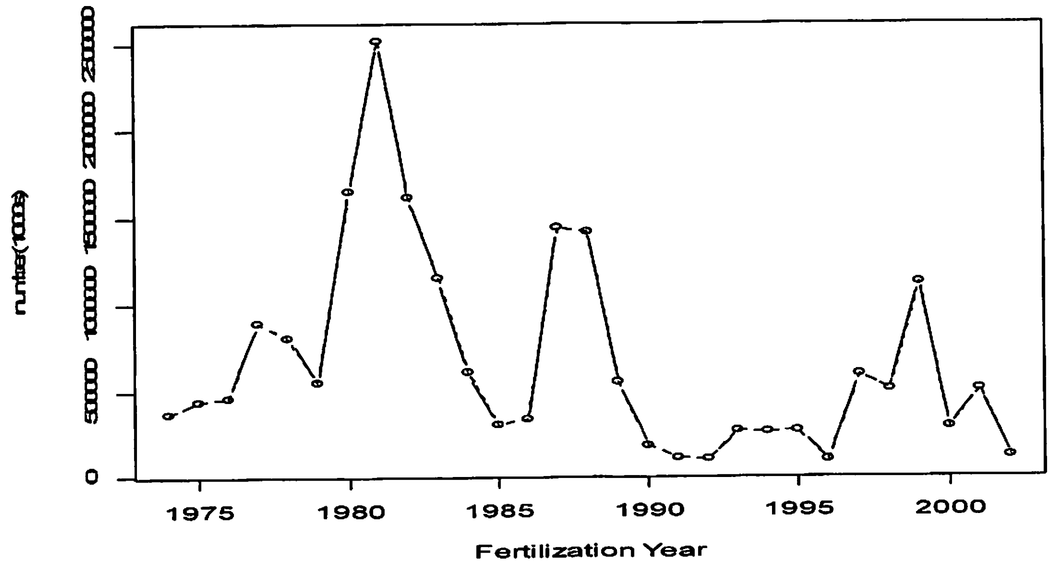

Figure 41. Recruitment to the model for crab 25 mm to 50 mm. Total recruitment is 2 times recruitment. Male and female recruitment fixed to be equal.

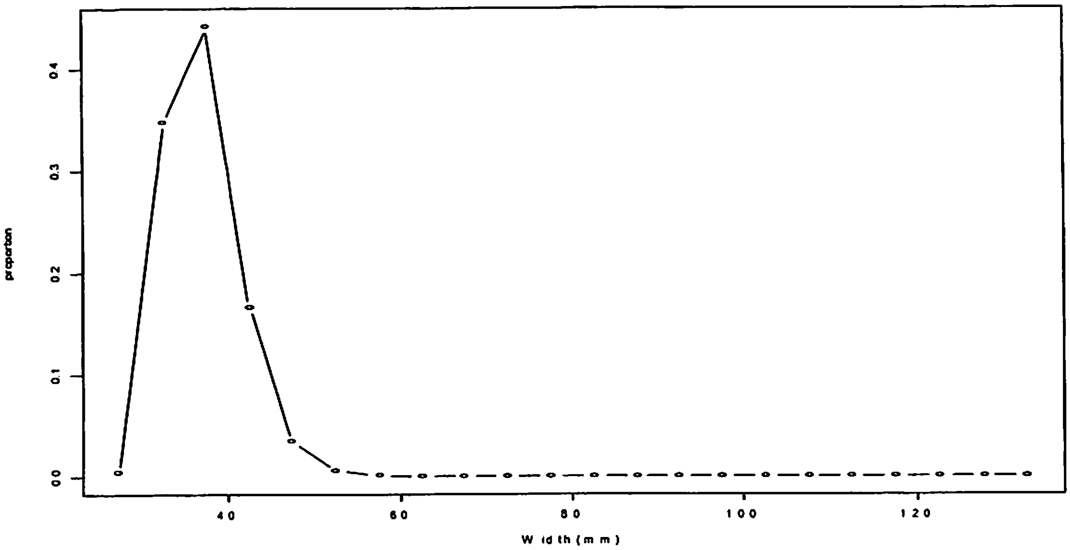

Figure 42. Distribution of recruits to length bins estimated by the model.

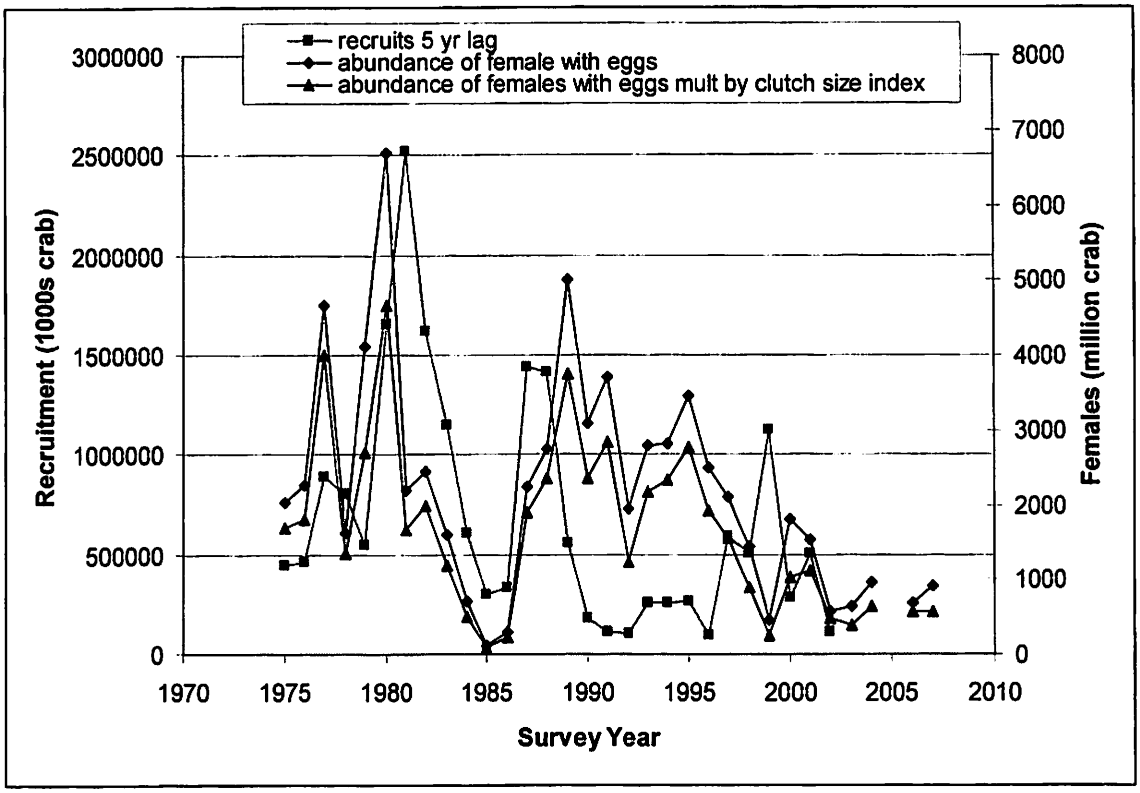

Figure 43. Model estimates of recruitment (fertilization year), survey abundance of females with eggs, and abundance of females with eggs multiplied by the fraction of full clutch from 1975 to 2004.

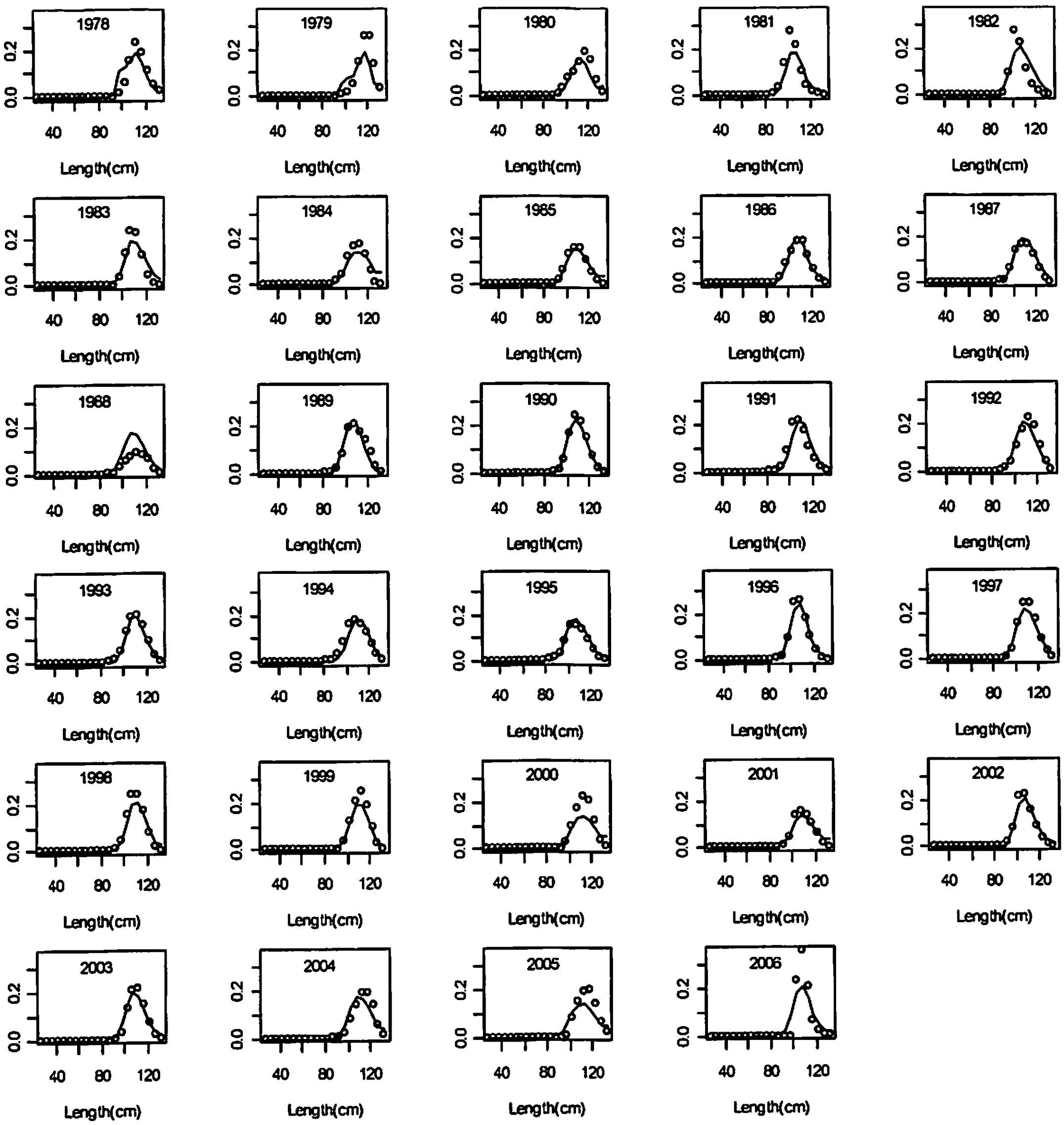

Figure 44. Model fit to the retained male new shell size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

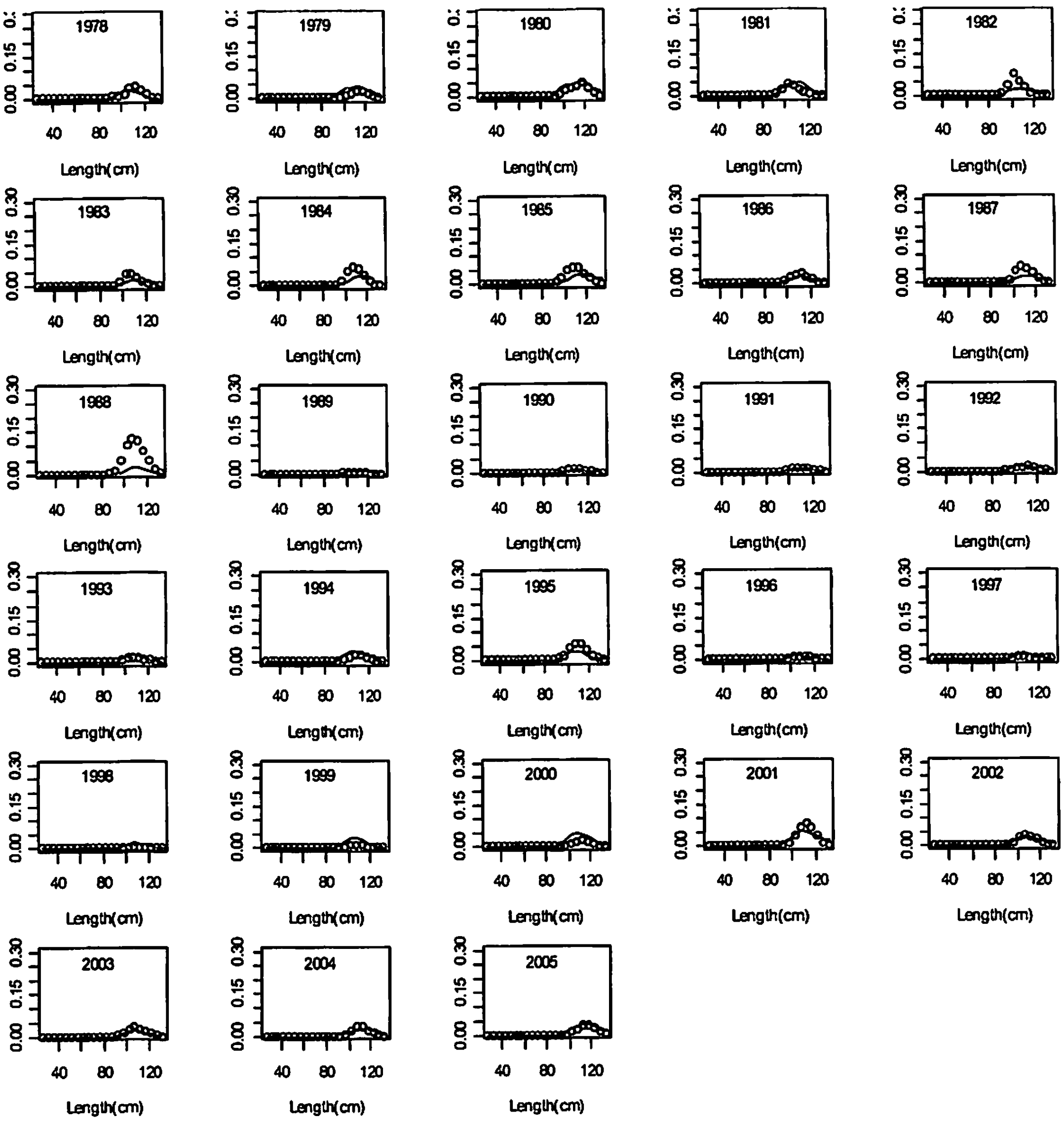

Figure 45. Model fit to the retained male old shell size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

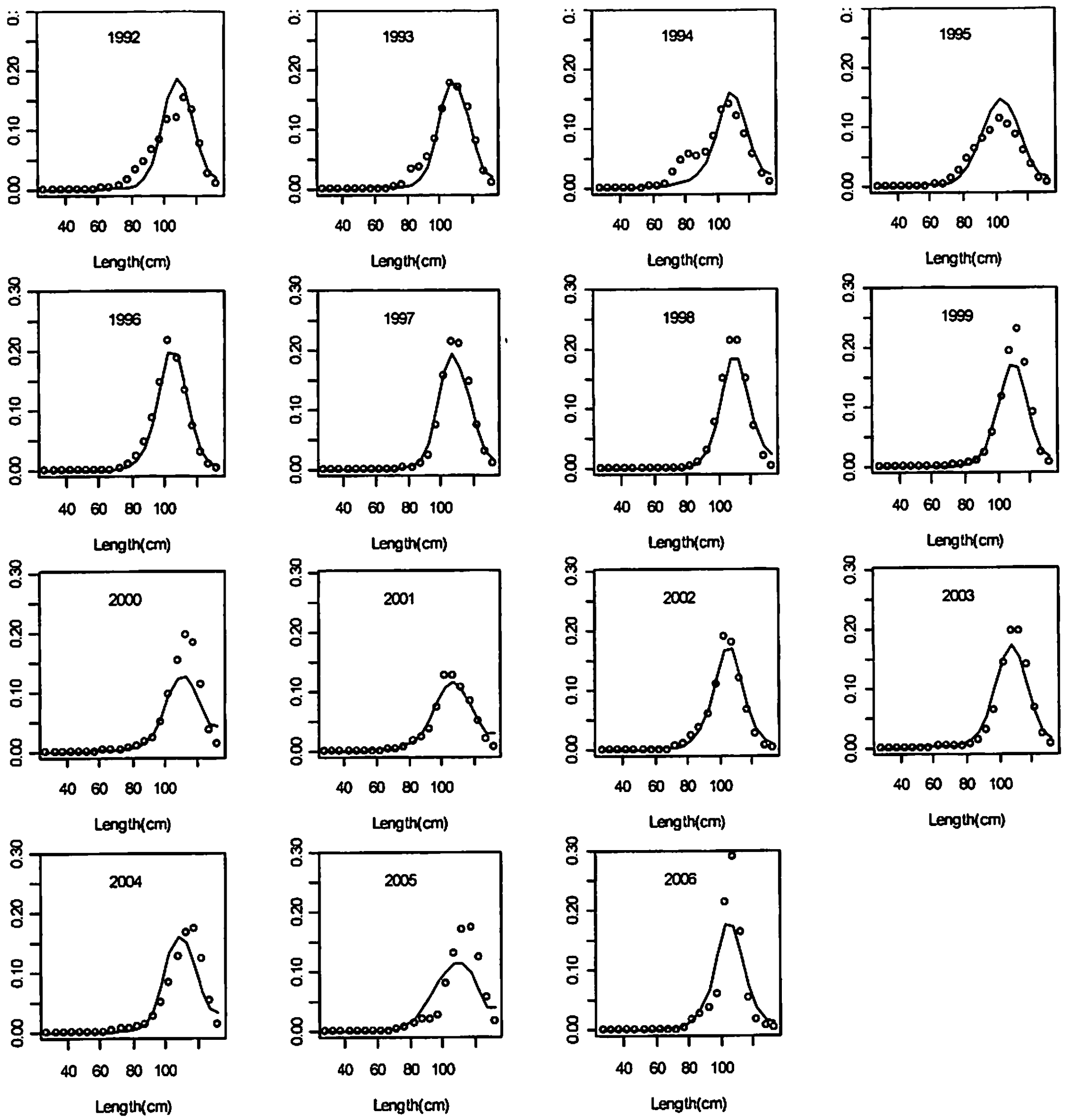

Figure 46. Model fit to the total (discard plus retained) male new shell size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

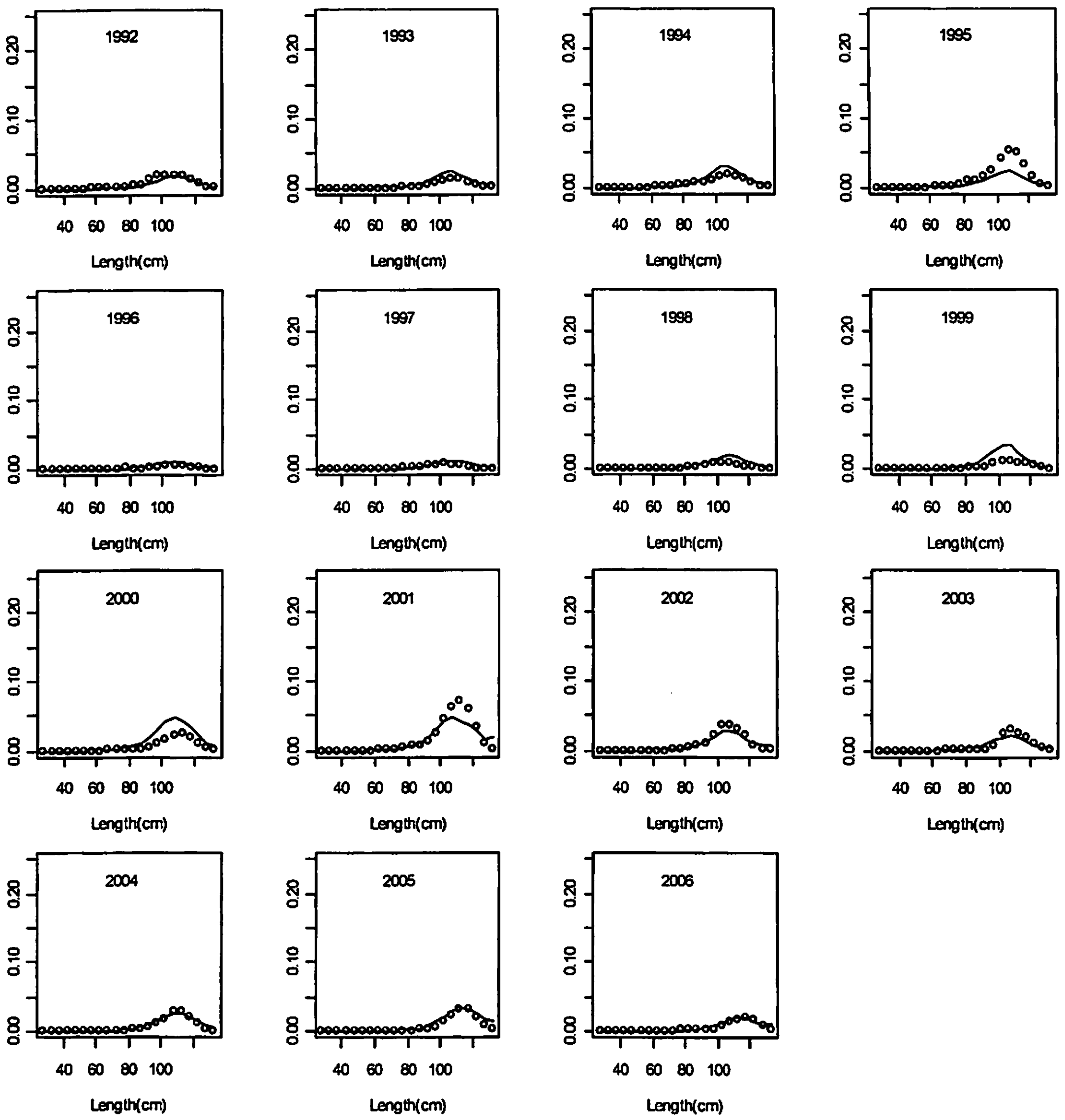

Figure 47. Model fit to the total (discard plus retained) male old shell size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

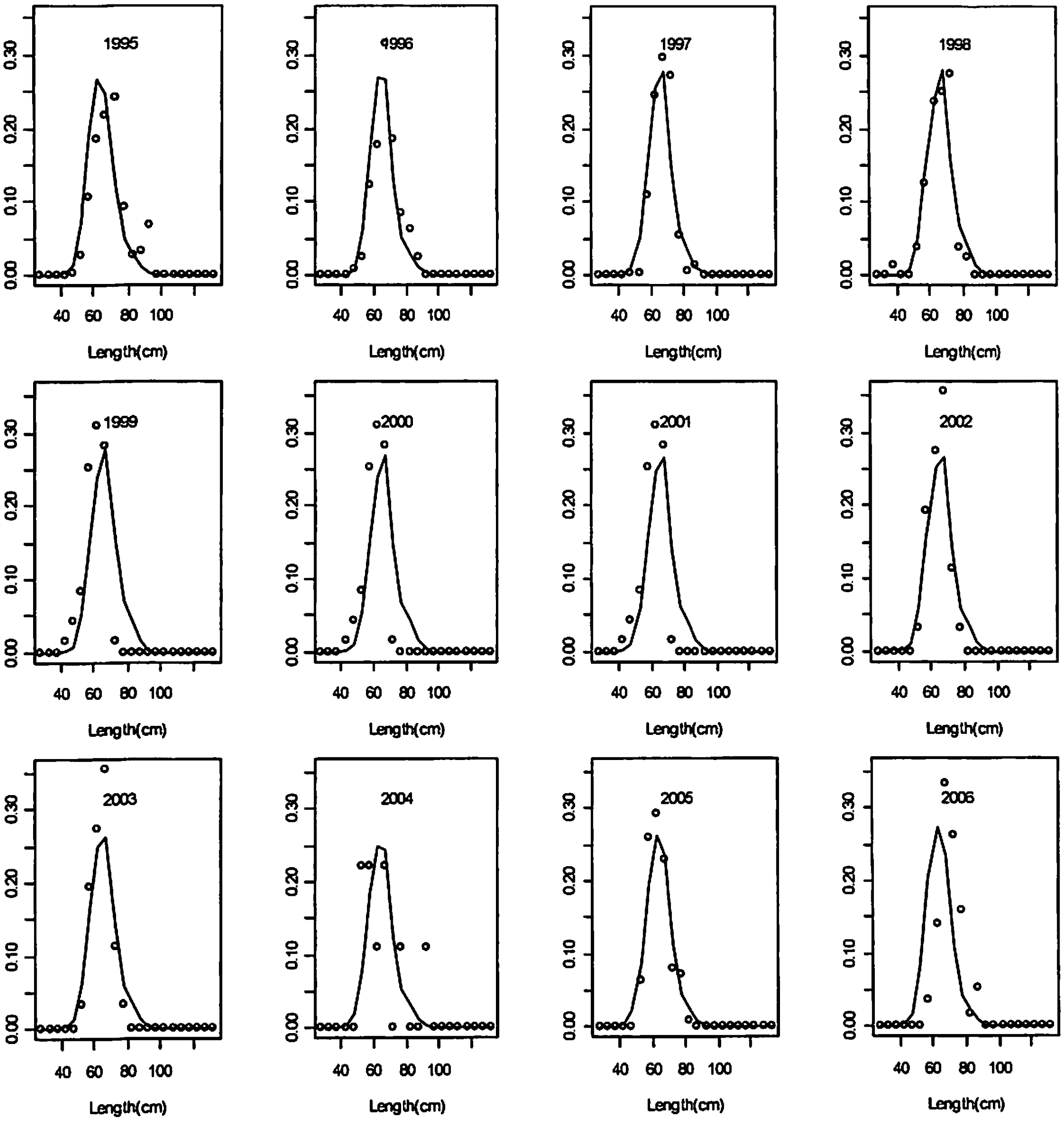

Figure 48. Model fit to the discard female size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

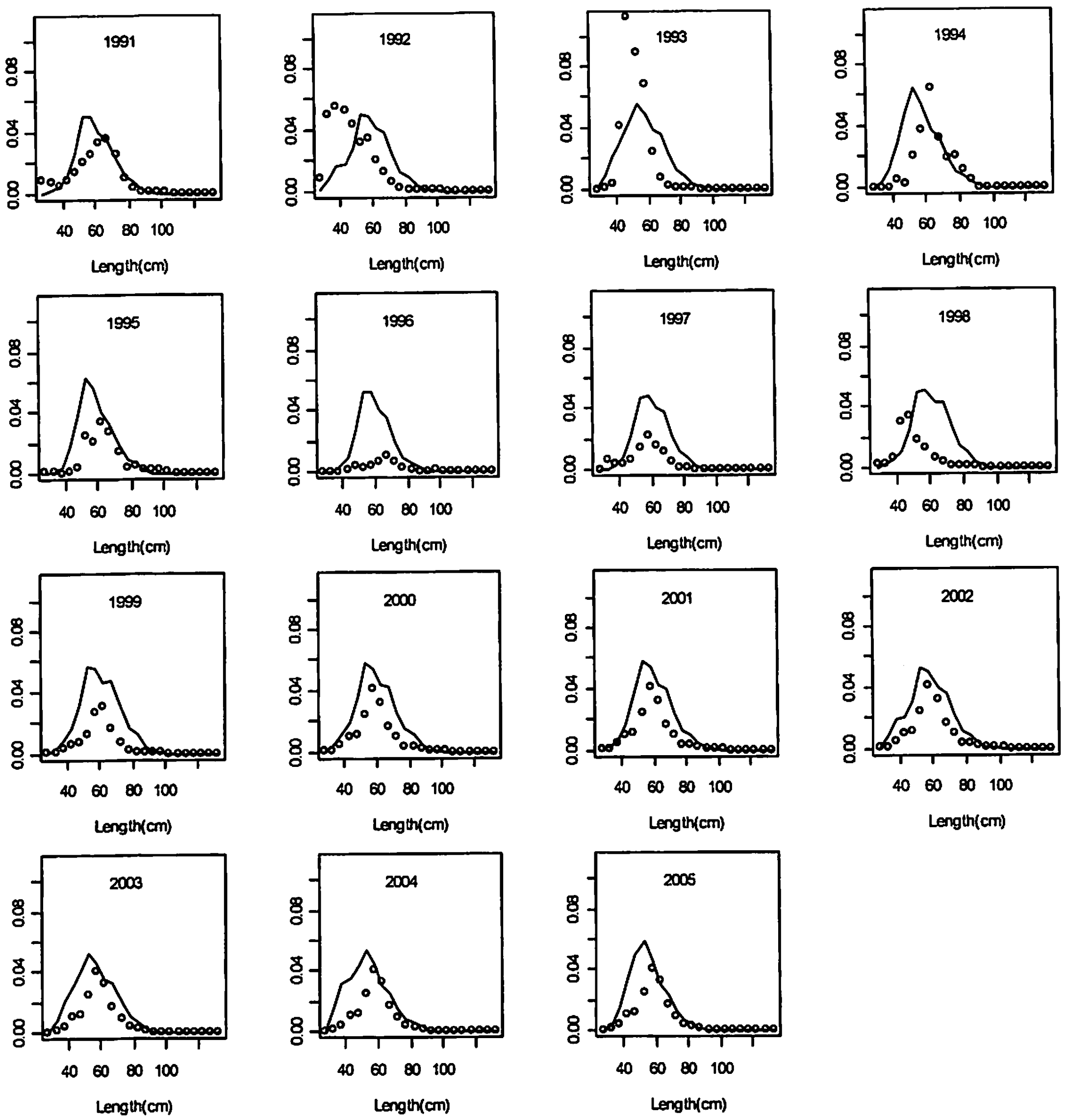

Figure 49. Model fit to the groundfish trawl discard female size frequency data. Solid line is the model fit. Circles are observed data. Year is the survey year.

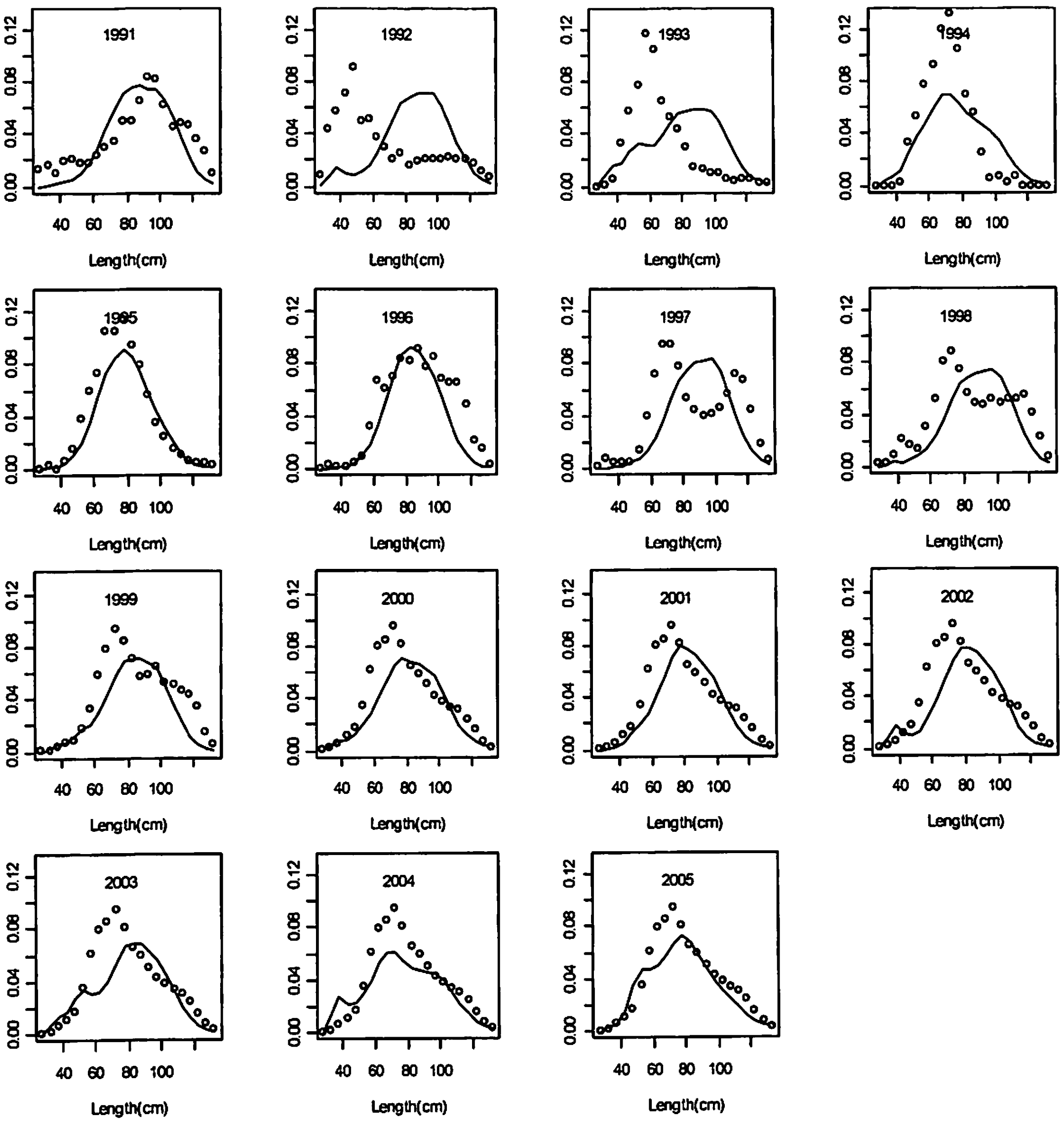

Figure 50. Model fit to the groundfish trawl discard male size frequency data. Solid line is the model fit. Circles are observed data.

Figure 51. Full selection fishing mortality estimated in the model from 1979 to 2007 fishery seasons.

Figure 52. Fit to pot fishery cpue for retained males. Solid line is observed fishery cpue, dotted line model fit.

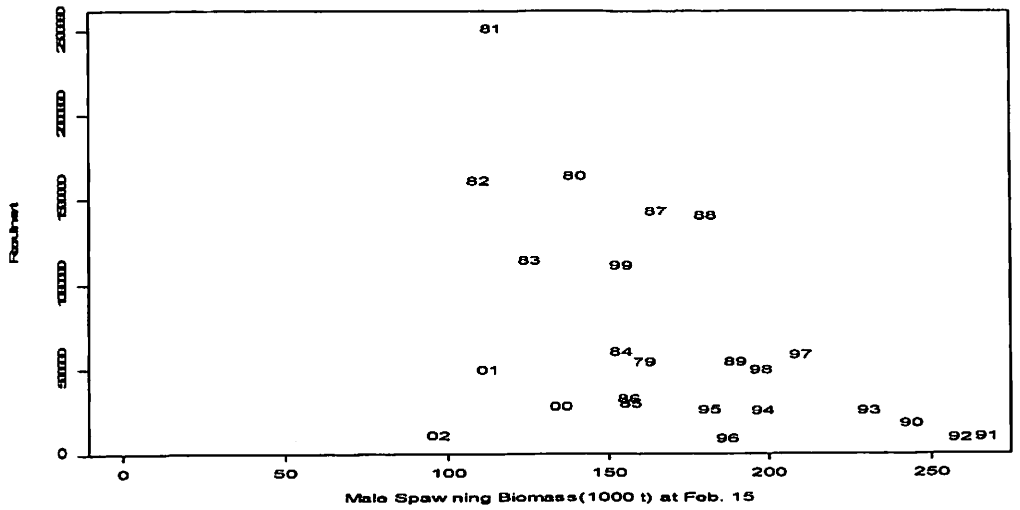

Figure 53. Spawner recruit estimates using male mature biomass at time of mating. Numbers are fertilization year assuming a lag of 5 years. Recruitment is half total recruits in thousands of crab.

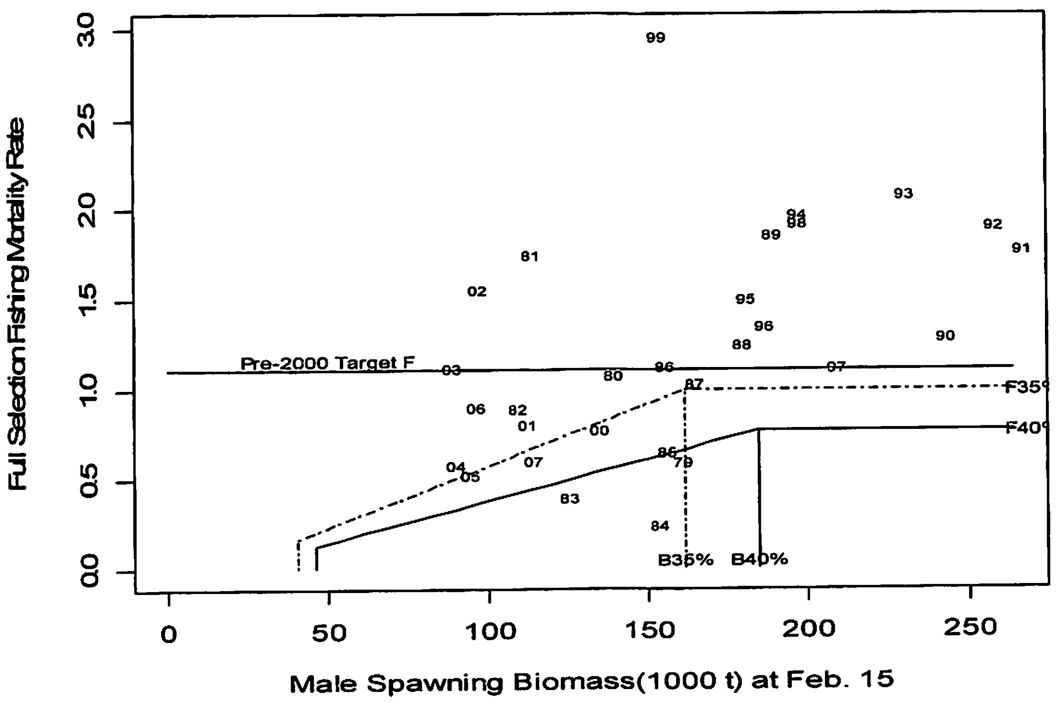

Figure 54. Harvest control rules. Two control rules are shown, one for F40% and one for F35% with alpha = 0.1. The pre-2000 target F of about 1.1 was the target F that resulted from the harvest strategy used before the 2000 fishery season. Vertical lines labeled B40% and B35% are estimated from the product of spawning biomass per recruit fishing at F40% or F35% respectively and mean recruitment from the stock assessment model.

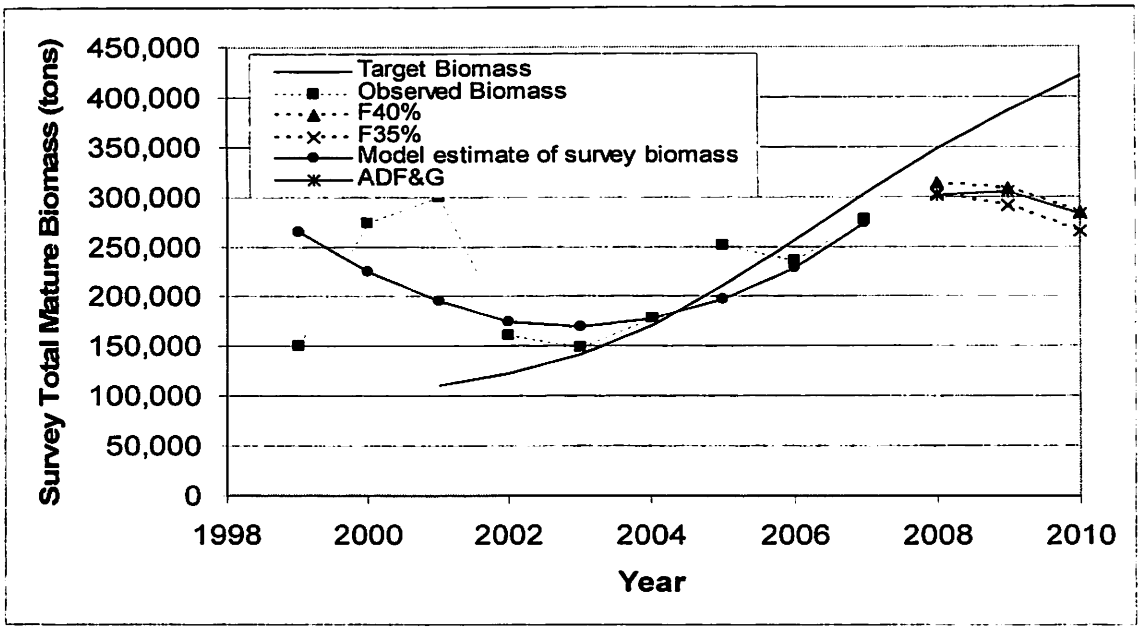

Figure 55. Target survey total mature biomass by year from rebuilding plan simulations, observed survey total mature biomass and model estimates of survey total mature biomass for the current ADF&G harvest strategy, F40% and F35% harvest strategies. 2010 is 10 years from the start of the rebuilding plan

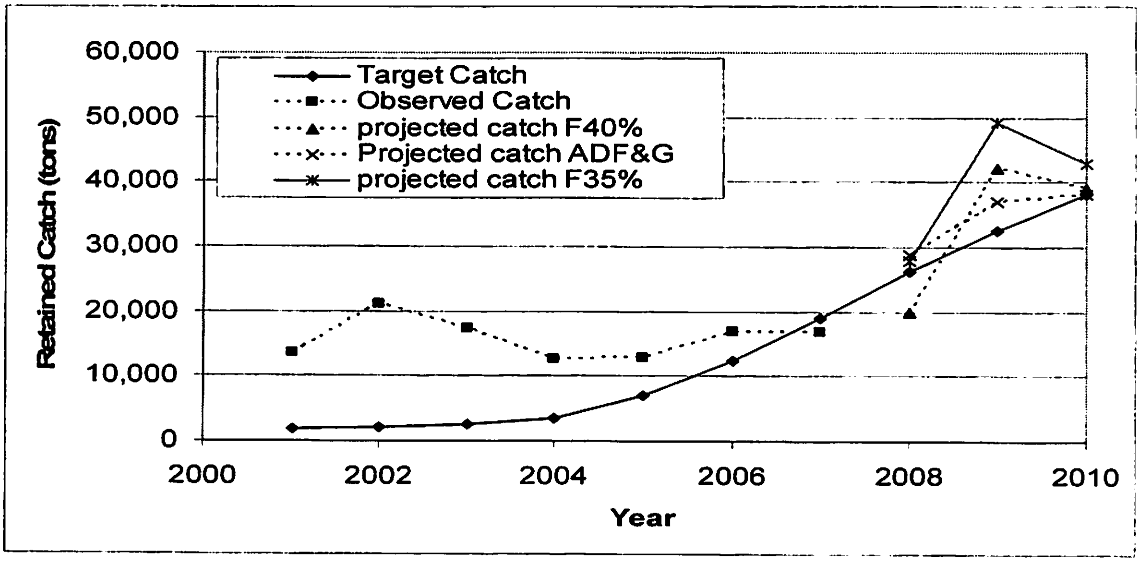

Figure 56. Target average retained catch by year from rebuilding plan simulations, observed retained catch for 2001 to 2007, and projected retained catch for 2008 to 2010 using the current ADF&G harvest strategy, F40% and F35% harvest strategies.

Appendix A.

Table A.1. Model equations describing the population dynamics.

$N_{s,t,1} = pr_l \, R_{0,s} e^{\tau_{s,t}}$	$\tau_{s,t} \sim N(0,\sigma$	Recruitment
TOTAL POT CATCH $C_{t,totalpotfishery,s,sh,l} = \sum_{mature,immature} \frac{F_{s,totalpotfishery,mat,sh,t,l}}{F_{s,mat,sh,t,l}} (1 - e^{-F_{s,mat,sh,t,l}}) e^{-M_{s,mat,sh} Cmid} N_{s,mat,sh,t,l}$ RETAINED POT CATCH $C_{t,retainedfishery,s,sh,l} = \sum_{mature,immature} \frac{F_{s,retainedfishery,mat,sh,t}}{F_{s,mat,sh,t,l}} (1 - e^{-F_{s,mat,sh,t,l}}) e^{-M_{s,mat,sh} Cmid} N_{s,mat,sh,t,l}$ TRAWL BYCATCH $C_{t,trawlfishey,s,sh,l} = \sum_{mature,immature} \frac{F_{s,ftrawlishey,mat,sh,t,l}}{F_{s,mat,sh,t,l}} (1 - e^{-F_{s,mat,sh,t,l}}) e^{-M_{s,mat,sh} Cmid} N_{s,mat,sh,t,l}$	$1 \leq t \leq$ $1 \leq l \leq$	Catch taken as a pulse fishery at midpoint of catch(survey is considered start of the year).
$Nimmature_{new,t+1,s,l+1} =$ $(Nimmature_{new,t,s,l} e^{-Zimmat_{new,t,s,l}}) Gr_{s,l} (1 - \phi_{s,l})$ $Nmature_{new,t+1,s,l+1} =$ $(Nimmature_{new,t,s,l} e^{-Zimmat_{new,t,s,l}}) Gr_{s,l} (\phi_{s,l})$ $Nmature_{old,t+1,s,l+1} =$ $(Nmature_{new,t,s,l} e^{-Zmat_{new,t,s,l}}) + (Nmature_{old,t,s,l} e^{-Zmat_{old,t,s,l}})$	$1 \leq t <$ $1 \leq l \leq$	Numbers at size
$SB_{t,s} = \sum_{l=1}^{L} w_{s,l} (Nmature_{new,t,s,l} + Nmature_{old,t,s,l})$		spawning biomass by sex

Table A.1. continued.

$Z_{t,s,sh,l} = \sum_{fishery} F_{t,fishery,s,sh,l} + M$			Total Mortality
$C_{t,fishery} = \sum_{s} \sum_{sh} \sum_{l} C_{t,fishery,s,sh,l}$			Total Catch in numbers
$p_{t,sh,l} = C_{t,sh,l} / C_t$			proportion at size in the catch
$Y_t = \sum_{l=1}^{L} w_{t,l} C_{t,l}$			Catch biomass
$F_{t,fishery,s,sh,l} = s_{t,s,sh,l} F_{t,fishery}$			Fishing mortality
$F_{t,s,sh,l} = \sum_{fishery} F_{t,fishery,s,sh.l}$			Total F over all fisheries (total pot and trawl fisheries)

$\mathrm{S}_{\mathrm{t,s,sh,l}}=\frac{1}{1+e^{-a_{s,sh}(l-b_{t,s,sh})}}$			Fishery selectivity for total catch sex or shell condition s and size bin l. The 50% parameter changes over time.
$\mathrm{S}_{\mathrm{male,t,sh,l}}=\frac{1}{1+e^{-a_{male,sh}(l-b_{t,male,sh})}}\frac{1}{1+e^{-c_{sh}(l-d_{sh})}}$			Fishery selectivity for male retained catch by shell condition sh and size bin l is the selectivity for total catch multiplied by the retention curve
Table A.1. continued. $\mathrm{S}_{\mathrm{surv,l}}=q\frac{1}{1+e^{-a_{surv}(l-b_{surv})}}$			Survey selectivity by size – same for males and females
$\mathrm{S}_{\mathrm{trawl,s,l}}=\frac{1}{1+e^{-a_{s,trawl}(l-b_{s,trawl})}}$			Trawl bycatch selectivity by size and sex
$SB_{s,t}=\sum_{s}\sum_{l=1}^{L}w_{s,l}s_{surv,l}N_{s,t,l}$			Total Survey biomass
$Gr_{s,l\to l'}=\int_{l'-2.5}^{l'+2.5}Gamma(\alpha_{s,l},\beta_{s})$			Growth transition matrix using a Gamma distribution
$width_{t+1}=a_{s}+b_{s}width_{t}$			Mean post-molt width given pre-molt width

Table A.2. Negative log likelihood components.

$\lambda\sum_{t=1}^{T}\left[\log(C_{t,fishery,obs})-\log(C_{t,fishery.pred})\right]^2$	Catch using a lognormal distribution.
$-\sum_{t=1}^{T}\sum_{l=1}^{L} nsamp_t * p_{obs,t,l}\log(p_{pred,t,l})$ - offset	size compositions using a multinomial distribution. Nsamp is the observed sample size. Offset is a constant term based on the multinomial distribution.
offset = $\sum_{t=1}^{T}\sum_{a=1}^{A} nsamp_t * p_{obs,t,a}\log(p_{obs,t,a})$	the offset constant is calculated from the observed proportions and the sample sizes.
$\sum_{t=1}^{ts}\left[\frac{\log\left[\frac{SB_{obs,t}}{SB_{pred,t}}\right]}{sqrt(2)*s.d.(\log(SB_{obs,t}))}\right]^2$	Survey biomass using a lognormal distribution, ts is the number of years of surveys.
$s.d.(\log(SB_{obs,t})) = sqrt(\log((cv(SB_{obs,t}))^2+1))$	
$\lambda\sum_{s=1}^{2}\sum_{t=1}^{T}(e^{\tau_{s,t}})^2$	Recruitment, where $\tau_{s,t}\sim N(0,\sigma_R^2)$

Table A.3. List of variables and their definitions used in the model.

Variable	Definition
T	number of years in the model(t=1 is 1978 and t=T is end year
L	number of size classes (L =22)
W_l	mean body weight(kg) of crabs in size group l.
ϕ_l	Proportion mature at size l.
R_t	Recruitment in year t
R_0	Geometric mean value of recruitment
τ_t	Recruitment deviation in year t
$N_{l,a}$	number of fish in size group l in year t
pr_l	Fraction of annual recruitment (Rt) distributed to length bin l
$C_{t,l}$	catch number of size group l in year t
$p_{t,l}$	proportion of the total catch in year t that is in size group l
C_t	Total catch in year t
Y_t	total yield in year t
$F_{t,s,sh,l}$	Instantaneous fishing mortality rate for size group l, sex s, shell condition sh, in year t
M	Instantananeous natural mortality rate
E_t	average fishing mortality in year t
ε_t	Deviations in fishing mortality rate in year t
$Z_{t,l}$	Instantantaneous total mortality for size group l in year t
GR	Growth transition matrix
$S_{s,l}$	selectivity for size group l, sex or shell condition s.

Table A.4. Estimated parameters for the model.

Parameter	Description
$\log(R_0)$	log of the geometric mean value of recruitment, one parameter
τ_t $1978 \le t \le 2007$, 30 parameters	Recruitment deviation in year t
Initial numbers by length for each sex and shell condition, 88 parameters.	Initial numbers by length
$\log(f_0)$	log of the geometric mean value of fishing mortality
ε_t $1978 \le t \le 2007$, 30 parameters, one set for retained catch, one set for female discard, and one set for trawl bycatch equals 97 total.	deviations in fishing mortality rate in year t
Slope and 50% selected parameters of the logistic curve	selectivity parameters for the total catch (retained plus discard) of new and old shell males.
Slope and 50% selected parameters of the logistic curve(2 parameters new shell, 2 parameters old shell)	Retention curve parameters for the retained males.
Slope and 50% selected parameters of the logistic curve (6 parameters)	Selectivity parameters for survey male and female crabs for three survey periods (1978-81, 82-88,89 to present).
Slope and 50% selected parameters of the logistic curve(2 parameters male, 2 parameters female)	Selectivity parameters for trawl bycatch male and female
Slope and 50% selected parameters of the logistic curve(2 parameters)	Selectivity parameters for crab fishery female bycatch

M	Natural mortality
Q for survey selectivity, 3 parameters	Survey catchability
Parameters for the linear growth function, intercept a and slope b (2 parameters male, 2 parameters female). Standard deviation of size at the first size bin and standard deviation of size for the last size bin.	Growth parameters estimated from Bering sea snow crab data (14 observations).

Report on the 2007 Bering Sea snow crab assessment

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Prepared for
Center for Independent Experts

1 Contents

2 Executive summary

The Center for Independent Experts and The Alaska Fisheries Science Center (AFSC) requested a review of the snow crab population dynamics and harvest strategy models for the Bering Sea snow crab (*Chionoecetes opilio*) assessment. The review was held in Seattle, Washington, February 11-15, 2008 to consider the stock assessment of the Bering Sea snow crab. Presentations by staff at AFSC were made on the fishery, biology, field experiments, the survey, larval movement, spatial modelling, ecosystem work, the assessment and the forward project model used for calculating the harvest strategy. Additional analyses were requested and carried out, and the results discussed during the week. This report should be read in conjunction with my fellow reviewer, Dr Ewen Bell.

The workshop was well run, and presentations and responses to queries were clear and helpful.

Documentation that describes the model in accurate mathematical detail is poor – particularly when compared to the actual code. This hampered a full review of the mathematical details and accuracy of the model. As a result, the re-modelling of the assessment into Excel by industry consultants, Drs Maunder and Tagart is likely to ultimately be of great benefit to the assessment authors. The healthy debate that will ensue with other parties who have detailed knowledge of the model is likely to produce an improved overall result.

Key issues discussed in the report include, amongst other aspects, the spatial patterns in the data compared to a Bering Sea-wide model, recruitment patterns, strong residual patterns in the fit to size-frequency data, and the value of shell condition data.

Although there is still a lot of process and observation uncertainty in the model, it is an improvement on previous methods and several recommendations from past reviews have been incorporated. The detailed part of this report comments on the various input data, model assumptions and model estimates. Throughout the review, it was clear that a Management Strategy Evaluation should be undertaken so as to help prioritise further research, review key model assumptions and test alternative models. This is the highest priority recommendation. Below is a list of recommendations. They are best read in context.

2.1 Recommendations

Below is a list of recommendations. An attempt has been made to prioritise them starting with the highest.

1. It is strongly recommended that a Management Strategy Evaluation be undertaken. This is the highest priority recommendation. This work should include:

   a. the effects of environmental variables on recruitment and attempt to provide independent data that allows these environmental effects to be modelled internal to the assessment,
   b. investigation of various alternative model options,
   c. investigation of changes to the model that address the strong residual patterns in the fit to the size-frequency data, and
   d. prioritising field research (including growth data) and model change options in terms of their effect on management advice.

   When combined with the spatial work being undertaken by J. Murphy – much should be clarified in the future.

2. A detailed mathematical description of the model is needed. Past reviews have mentioned this as well. Also, figures of model estimates should include parameter variances. I can not emphasise this enough – from investigation of the Turnock and Rugolo (2007) model description and the actual code, there is a large discrepancy between the code and the associated descriptions.

3. It is essential that the raw survey data are transferred onto an accessible system so that detailed analyses and data mining could easily be undertaken by a broader group including the present assessment team.

4. It is recommended that the small spatial distribution of the fishery compared to the size of the survey area needs to be investigated especially in the context of the assessment assumptions.

5. If a size-based model remains the basis of an assessment, reliable growth data need to be collected through a well designed tagging study.

6. It is recommended that the model not use new and old shell categories. This will reduce the number of parameters.

7. It is recommended that an investigation should be undertaken of whether a form of post stratification of the survey data would be useful for the index CVs and the size-frequency data.

8. It is unclear whether there is a time varying trend in the survey catchabilities or selectivities. This would occur, for example, if the distribution of the crab changes over time and the gear catchability or selectivity differs spatially. It is recommended that this needs to be investigated first as part of a desk top exercise.

9. The discussion regarding whether local depletion or large scale movement is occurring should be progressed further. An indirect (and rough) calculation of the scale of movement onto the fishing ground implied by the model can be made by comparing 1) the ratio of mature male biomass in the survey area relative to the whole survey area, and 2) the ratio of the mature male biomass in the catch compared to the mature male biomass estimated in the model at the time of the fishery (provided in this report).

10. It is recommended that studies on Durometer measures of shell hardness and dactyl length should be further investigated. However, it is unlikely that this information will allow re-classification of shell condition data already collected.

11. The survey index uses a simple swept area estimate for animals greater than 25 mm. This index is therefore different to that presented in the annual survey report and it is recommended that this is clarified in the model description.

12. It is recommended that the correct average swept width is used in the input data and the calculation of a clear and obvious catchability and selectivity function is used in the model.

13. For three years in the early 1980s, the actual observed survey index variance inputted into the model is doubled to down weight the importance of those surveys years. In terms of clear communication, this aspect needs to be clearly stated in any stock assessment report text and the appropriate figure legends including the reasons why this step was taken.

14. The plots of size frequency residuals presented in the report uses a method that tends to not show the residuals clearly or accurately. It is recommended that a different method is used to plot the residuals of the model fit to observed size data.

15. As a small model test, it is recommended that the following sensitivity test is undertaken. Test the estimated 9 selectivity parameters by removing the northern sites from the last survey period but still fit the model to 3 survey series. In theory the 2nd and 3rd survey selectivity functions should be comparable.

16. The commercial pot fishery catch rates are included in the model unstandardised. It is also included in the likelihood with low weighting compared to the other components of the likelihood. It is recommended that the fit to pot fishery catch rates is removed from the likelihood while the data remain unstandardised.

17. It is further recommended that the catch rates are standardised and then added to the model with more appropriate weighting. However, this is only suggested at this stage as a sensitivity test, given the added complication that the fishery often covers a much smaller spatial scale relative to the distribution of the crabs.

18. In the case of females, as a minor issue it is recommended that a logistic function is fitted to remove the inconsistency that a larger female may have a lower probability of maturing than a smaller female due to what appears to be noise in the data.

3 Background

The Center for Independent Experts (see Appendix 1) and The Alaska Fisheries Science Center (AFSC) requested a review of the snow crab population dynamics and harvest strategy models for the Bering Sea snow crab (*Chionoecetes opilio*) assessment.

The snow crab assessment model was reviewed by the CIE in 2003 by Dr Maunder. In 2006 there was a three-person CIE review of the Alaskan crab overfishing definitions and simulation models used to evaluate biological reference points for Bering Sea and Aleutian Islands King and Tanner crab stocks. Since that time, several improvements to the model have been undertaken. Drs E. Bell and C. Dichmont reviewed the present Bering Sea snow crab assessment and projection models in Seattle in 2008. The snow crab assessment is a high profile assessment.

This review encompassed the Bering Sea trawl survey data, the stock assessment model structure, assumptions, life history data, the projection model and the harvest control rule.

4 Review activities

4.1 Documentation

The reviewers were provided beforehand and during the meeting with various documents as listed:

Documents received before the workshop

1. Turnock, B.J. and Rugolo, L.J. 2007. Stock assessment of eastern Bering Sea snow crab. (filename snowcrab.assess.sept2007.final.doc)
2. Plan team, 2007. Stock assessment and fishery evaluation report for the king and tanner crab fisheries of the Bering Sea and Aleutian Islands Regions. http://www.fakr.noaa.gov/npfmc/SAFE/2007/CRABSAFE07.pdf
3. Document of the Overfishing Control Rules (http://www.fakr.noaa.gov/npfmc/current_issues/crab/KTC24907.pdf)
4. The 2006 full report on the Bering sea trawl survey http://www.afsc.noaa.gov/Publications/ProcRpt/PR%202006-17.pdf
5. Jadamec, L.S., Donaldson, W.E. and Cullenberg, P. 1999. Chionoecetes Crabs Biological Field Techniques for Chionoecetes Crabs. (Chionoecetes Crabs_Jadamec et al_AK-SG-99-02.pdf)
6. Gravel, K.A., Watson, L.J. and Pengilly, D. 2006. The 2005 Eastern Bering Sea snow crab *Chionoecetes opilio* tagging study. (fmr06-31.pdf)
7. The ad model code for the stock assessment model (scmysrfut2006s3mtbio.tpl), the report files (scmysrfut2006s3mtbio.rep), a control file (sc.ctl), data file (scmysrfut2007allareaimmataugust.dat) and the parameter file (scmysrfut2006s3mtbio.par).

8. Field guide on chionoecetes crab (Chionoecetes Crabs_Jadamec et al_AK-SG-99-02.pdf)
9. An updated agenda,
10. Statement of work including the Terms of Reference of the review.

Documents received during the workshop

1. R code to read ad model report file
2. Presentations of the assessment, new review process for crab stock assessments and OFL determination (Turnock), ageing (Rugolo) and spatial distributions (Murphy)
3. Project application of Punt and Turnock (PlanPunt.doc)

Documents obtained after the workshop

Past CIE reviews relevant to the EBS snow crab:

1. 2003 Bering Sea snow crab Maunder report - final.pdf
2. Bell Alaska king and tanner crab review report - final.pdf
3. Caputi Alaska king and tanner crab review report - final.pdf
4. Cordue Alaska king and tanner crab review report - final.pdf

4.2 Review in Seattle

The review was held in Seattle, Washington, February 11-15, 2008 to consider the 2007 stock assessment of the Bering Sea snow crab. The meeting was chaired by Dr Hollowed. Various presentations from AFSC staff were made (see Appendix 1 for the agenda) – which provided an overview of the fishery, biology, field experiments, age determination, the survey, larval movement, spatial modelling, ecosystem work, economics, the assessment and the forward projection model used for calculating the harvest strategy. Debate and questioning occurred throughout these presentations.

The first two days of the review were open to the public. An independent industry consultant was present who also participated in the debate and questioning. So too were staff from the Alaska Department of Fish and Game, and Dr Punt as a member of the Plan team.

Dr Ewen Bell, CEFAS, Lowestoft, UK was the other CIE member on the review panel. Several requests were made of the assessment team and results of most of these were presented during the week. A draft presentation of Dr Bell and my preliminary findings were provided on 14th February. The final day was spent writing the report. Some small amounts of further interaction by e-mail occurred after the workshop leading up to the final hand-in dates.

5 General comments

The snow crab assessment is data rich but information poor. Data are available from surveys, and from the pot and the trawl fishery. There are sufficient size (carapace width) data, from both the annual summer surveys and industry catch data. On the other hand, the trawl surveys are not directly designed for crabs, nor use gear optimised for the capture of crab. The survey size data do not show clear modal progression even considering that it is a moulting species. These data have therefore not contributed to an understanding of the specie's growth rate nor allow for easy use in an assessment model. There are data on shell condition which should provide shell age but have been shown to be so unreliable that they are practically unusable in their present form. The fishery occurs on a varying spatial scale, in part due to the extent of the sea ice during the season. The actual distribution of Bering Sea snow crabs can at times be much larger than the fishery spatial scale. Little is known about snow crab migration rates. Larval modelling is showing complex movement and environmental influences. The end result is that the Bering Sea snow crab is an extremely complex resource to model given that key information (e.g. growth) is incomplete or unknown.

The daily interactions with the reviewed staff were excellent and there were good discussions during the week. Much was clarified in this process. It was at times difficult to obtain all documentation requested and some have still not been received by the time the report was due (for example, we have not received all the PowerPoint files that were presented by AFSC staff during the review week). The authors kindly made their R code available during the week to assist us to interpret the very large output file produced by the assessment model.

A key issue that has hampered this and past reviews is that there is not an exact and detailed description of the model. For example, the full likelihood (including constraints and restrictions) are not adequately described. This is evident if one compares the text to the code. In some of the plots in the documents provided, parameter variances were not included. Some tests of model sensitivity beyond that provided in the Plan team document should be undertaken. It is essential and recommended that this is provided in the near future. The *AD Model Builder* code we were provided with also had a lot of legacy code within it that has been commented out and was therefore extremely difficult to review.

Another factor that made the process difficult for the reviewers is that the stock assessment team did not themselves have ready access to the raw survey data. It is essential that the data are transferred onto a system so that detailed analyses and data mining could easily be undertaken by the assessment team and others. As a result, certain requests to the assessment team could not be undertaken – not, however, due to the team's error.

6 Stock assessment model

A size-based (carapace width) assessment model, disaggregated by male and female, new and old shell, and immature and mature is fitted to survey, commercial size and catch data. A separate model that describes the same population dynamics as the assessment model is used to forward project the population. The fishery targets clean shell males above 101 mm shell width. Female fishing mortality only occurs through incidental bycatch and subsequent discard mortality.

Comments below are divided broadly into input information and output results.

6.1 Bering Sea trawl survey index

The Bering Sea survey data used in the model start at 1978. Prior to this period, the survey area did not adequately cover the snow crab distribution. It uses trawl gear, different to the targeted pot fishery. The survey targets both crab and fish species and is designed as a simple grid survey with a few extra sites for other species. In 1982, the fishing gear was modified which resulted in a change in catchability. After 1988, the survey was extended further north to capture areas with small snow crabs. This means that the survey index is correctly fitted in the assessment model as 3 separate and distinct series. The model estimates survey catchability and selectivity by size.

The survey index uses a simple swept area estimate for animals greater than 25 mm. This index is therefore different to that presented in the annual survey report and it is recommended that this is clarified in the model description. In the calculation of survey swept area of the raw data, rather than use the actual individual site's trawl width or the actual average trawl width (about 56 ft), a value of 50 ft is used. This was at the time used to adjust the overall trawl catchability. A later experiment where a beam trawl followed the survey trawl confirmed that the survey catchability is less than one. However, the model itself also estimates survey catchabilities and the interpretation of this estimated parameter is complicated by the adjustment in the input data. It is recommended that the correct average swept width is used in the input data and the calculation of a clear and obvious catchability and selectivity function is calculated in the model.

The estimated survey indices are fitted in the model to an inverse variance weighted observed survey index. For three years in the early 1980s, the actual observed survey variance inputted into the model is doubled to down-weight the importance of those survey data points. This is due to anecdotal information (e.g. the catch was greater than survey index) that the surveys were not accurate in those years. In terms of clear communication, this aspect needs to be clearly stated in the figure legend and in the text (that double the variance was used for specific years than was shown) including the reasons why this step was taken.

It is not clear whether the survey data do or do not track the status of the stock, but given that projects are underway to investigate the data, especially the spatial aspects of the survey (e.g. James Murphy), it is recommended that the survey should continue to be used as an index of abundance in the model. We were not given the raw survey data so were unable to explore options ourselves. It is recommended that an investigation should be made of whether a form of post stratification of the survey data would be useful for the index CVs but especially the size-frequency data. The survey is general in respect to target species and area, and not specific to snow crab. It is recommended that the small spatial distribution of the fishery compared to the survey needs to be investigated to show whether it is possible to obtain a more consistent index and better CVs.

Furthermore, it is unclear whether there is a temporal trend in the survey catchabilities or selectivities. This would occur, for example, if the distribution of the crab changes over time and the gear catchability or selectivity differs spatially. It is recommended that this be investigated first as part of a desk top exercise.

There was much discussion as to whether the crab assessment would benefit from a dedicated survey designed for crabs (but then this could only happen every two years) and keeping the present annual grid survey. It is unclear what the trade-offs would be regarding:

a) moving from an annual survey to a bi-ennial one,
b) moving from a grid survey to a specifically designed survey using gear targeting crab, and
c) adding a new survey series into the model and therefore new catchability and size selectivity parameters.

One method to investigate these options prior to making a change, is to investigate these options in a management strategy evaluation (MSE) framework. Also to check whether it is possible to calibrate the new and old trawl survey or overlap the old and new survey methods for a few years.

6.2 Survey size-frequency

Survey size data is entered into the model in 5 mm bin classes. In the model, size frequencies are calculated/fitted for males and females, mature and immature, old and new animals – although not every combination of these are modelled.

The survey size data do not show clear modal progression notwithstanding that the snow crab is a moulting species (e.g. Figure 1). This probably contributes in large part to some of the strong residual patterns evident in the plots of the fitted survey female and male size frequency (e.g. Figure 2) indicating the difference between the observed size frequencies and those predicted by the model.

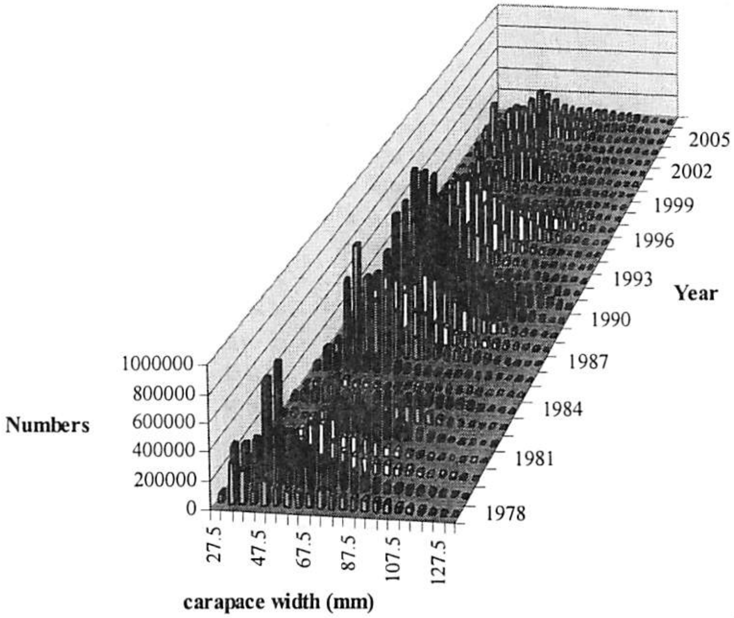

Figure 1: Observed survey male size-frequency in numbers (source: presentation given by J. Turnock during review).

Overall, there are very strong residual patterns in most of the fitted size frequency information (not just the survey data). Given the number of reviews of this model in various forms, it is clear that a MSE would be useful to prioritise research and model change options in light of the sensitivity on management advice. Also, as recommended above, an investigation regarding post stratification (or standardisation) of the survey is needed to see if clearer size distribution data can be obtained (of course without biasing the data). The work being undertaken by James Murphy on the spatial aspects of the survey selectivity and possible migration patterns is therefore crucial.

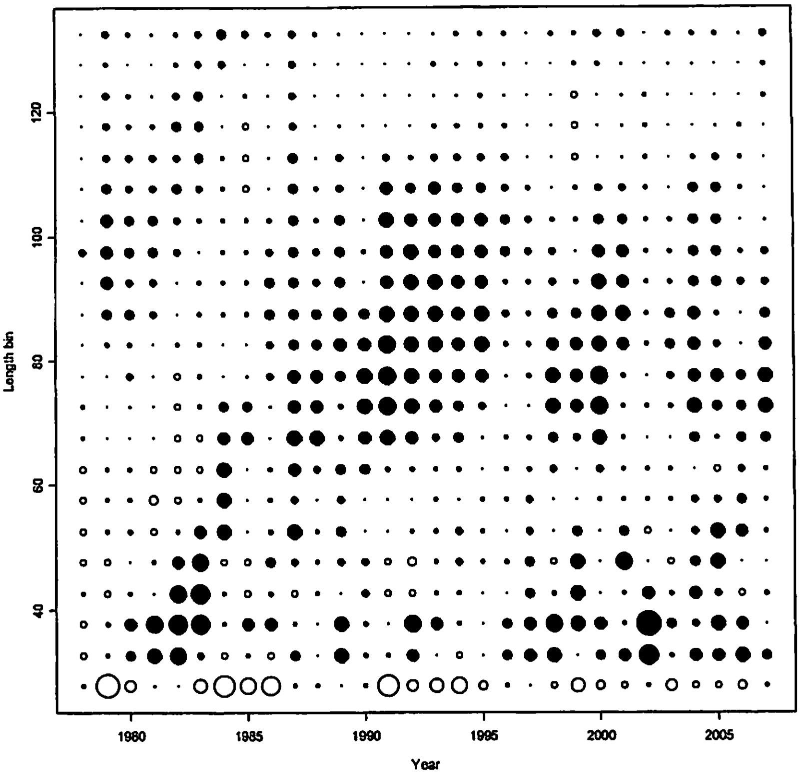

Figure 2: Residuals of the fit to survey male size frequency. Filled circles show predicted higher than observed. (Source: Turnock and Rugolo 2007)

The plots of size frequency residuals presented in the report (and Figure 2) uses a method that tends to not show the residuals clearly or accurately. It is recommended that a different method is used to plot the model residuals to the size data.

6.3 Survey selectivities

There was some discussion during the review week about whether survey selectivities varied within the periods 1978 to 1981, 1982 to 1988, and 1989 to the present. Despite this discussion, it is unlikely the model could estimate any more parameters. Also, given the uncertainty in other input data (such as growth), it is not likely to be a priority area for further modification of the model.

As a small model test, it is recommended that the following sensitivity test is undertaken – to test the estimated 9 selectivity parameters by removing the northern sites but still fitting to 3 survey series. In theory the 2nd and 3rd survey selectivity functions should be comparable.

6.4 Natural mortality

Natural mortality in the model was set at 0.29 for mature females, and 0.23 for all other crab, to be consistent with the crab overfishing analyses. Similar to many other species, there is no reliable external information on natural mortality.

A suggestion was made during the two-day public session that time-varying natural mortality estimates should be implemented in the model. At present, this is not recommended and we support the assessment authors that the model as yet has no further information that could assist in estimating additional selectivities (discussed above) and time-varying natural mortality without seriously confounding in the model.

6.5 Commercial catch rates

The commercial pot fishery catch rates are included in the model as unstandardised data. They are also included in the likelihood calculation with low weighting relative to other components of the likelihood with the result that these data have little influence on the parameter estimates. The argument given by the authors that the low weighting is due to the recent changes in the management of the fishery is supported given that unstandardised data are included. At present, it is recommended that the unstandardised commercial catch rate is removed from the likelihood calculation.

It is further recommended that the catch rates are standardised and then incorporated into the model with more appropriate weighting. However, this is only suggested at this stage as a sensitivity test, given the added complication that the fishery often covers a much smaller spatial range relative to the actual distribution of the crabs and it is unknown how well the commercial catch rate data indicate overall abundance.

6.6 Growth

The growth transition matrix is a crucial input to size-based models. Yet for this fishery there is minimal tagging information. In the model, the growth of females is based on studies undertaken in Canada; that of males is based on 14 observations. The model provided uses a gamma distribution to model growth variance. As explained during the presentations, one of the parameters, beta, is fixed in the model using the same values as used for tanner crab estimates. If a size-based model remains the basis of an assessment, reliable growth data need to be collected through a well designed tagging study. Based on discussions during the review in Seattle, it does not seem feasible to keep snow crab alive long enough in tanks for growth rate studies.

Again, it is also a priority to undertake an MSE that quantifies the impact of using different growth functions and the value of added growth data, and that also investigates using a simpler model that remains applicable to this fishery.

In the model, a 1:1 sex ratio is assumed for recruitment. The growth function used in the model may be incompatible with the assumption of equal recruitment for males and females as females' growth is slower. The assumption that the vector of sizes entering the model are the same for males and females may be incompatible with the above growth function. However, Canadian studies have shown no real differences in the growth of small male and female crabs so this is unlikely to be a major issue.

6.7 Space and its effect on movement, growth, size frequencies and indices of abundance

James Murphy, University of Washington and AFSC, gave a very informative presentation entitled "Spatial dynamics and structure of EBS snow crab". The factors affecting the spatial movement of crabs are not known in any detail. In general terms, using survey data, animals move south-west to deeper waters with mature males moving to deeper waters than females. The degree of movement changes with depth, as shown by the changes in the latitudinal centroids of male and female crabs between 1982 and 2007. The size-frequency distribution also changes between years spatially. Upon visual inspection, there also seems to be some degree of correlation (although this was not tested) between latitude centroids and the relative abundance of new shell mature females (Figure 3). James Murphy also showed spatial patterns in maturity. His study is attempting to identify spatial patterns and relate these to various processes such as oceanography, fishing, regime shifts etc. This work is essential.

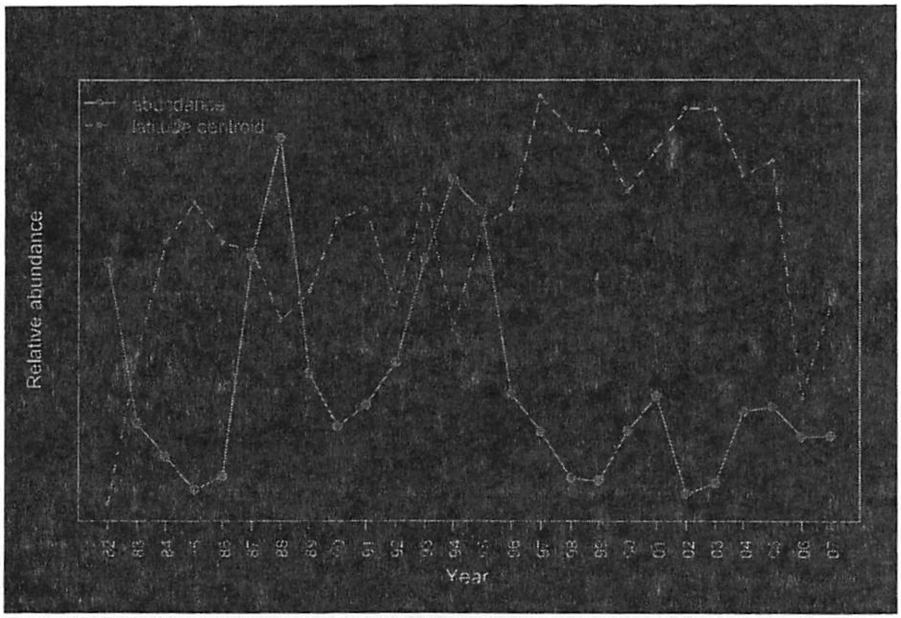

Figure 3: Relative abundance of female relative abundance and latitude centroids of new shell mature females (Source: presentation J. Murphy during review in Seattle).

During the review week, there was much debate about the effect of the lack of spatial assumptions in the model and the strong spatial features apparent in the data. There is also a time gap between the survey and the fishery, which further strengthens the debate as no spatial distribution data beyond the fishery is available at the time the fishery occurs.

There appear to be two points of view regarding the amount of animal movement that occurs between the time of the survey and the fishing season, and therefore the risk of local depletion in the area of the fishery. A plot of the ratio of the commercial catch relative to the relevant population biomass at the time of the fishery was requested during the review (Figure 4). This plot shows that the catch relative to the model large male biomass varies from about 15% to 86%. This was contrary to a statement made by Dr Zheng that the catch is generally about 80% of the model population biomass estimate. Due to lack of access to the raw data, Drs Turnock and Rugolo were unable to provide us with the ratio of the survey biomass in the area of the fishery and the total survey biomass of large males. This would have provided some anecdotal information on how much movement would have to occur to support the model estimates. It is recommended that this still be investigated.

A test was also undertaken where the survey catchabilities were artificially decreased. The fit of this model to the data was poor, although little tuning of the model was undertaken. This did affect the final overfishing/upper catch levels, especially in the short term, contrary to what was argued by Drs Turnock and Rugolo during the discussions in Seattle, but probably not as much as was argued by those with differing views. There was absolutely no basis for the catchability value chosen in the test other than testing the sensitivity of the model to this parameter. It is recommended that these kinds of tests be openly undertaken to progress the debate.

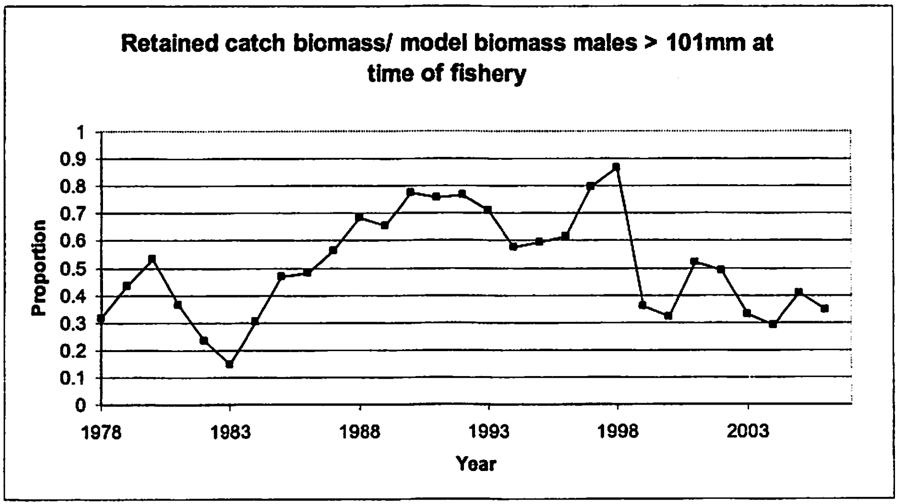

Figure 4: Ratio of the retained catch biomass relative to the model biomass of males greater than 101 mm CW at the time of the fishery (Source: results J. Turnock during review).

There is little information on the movement of snow crabs – a key issue since the fishery occurs in only a very small part of the animals' distribution especially in cold years. Tagging data available are biased as tag returns come from the industry and so only show animals that moved onto the fishing ground and not those that moved elsewhere. I support the assessment authors, Turnock and Rugolo, on this point.

6.8 Maturity

Maturity is assumed in the model to be based on length. In the model, the indicator of spawning biomass is mature male biomass at the time of mating. The model estimated survey mature biomass is fit to the observed survey mature biomass time series by sex. The model also fits the size frequencies of the survey by immature and mature individuals separately for each sex. The fraction of males and females morphometrically mature by year for a given size from survey data is used to calculate the probability of a crab maturing. In the case of new shell males (Figure 5), there is a range of sizes in which the values remain reasonably constant. The actual reason for this remains unclear. This feature appears to be absent for females.

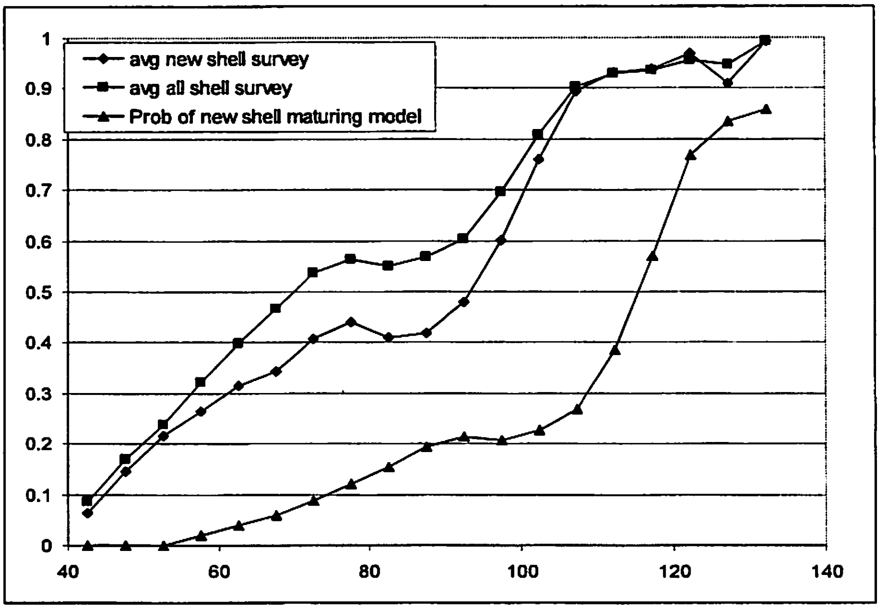

Figure 5: Fraction of males morphometrically mature based on survey data as well as the probability of males maturing (Source: presentation by J. Turnock during review). The x-axis is carapace width and the y-axis is probability or fraction.

In the case of females (Figure 6), as a minor issue it is recommended that a logistic function is fitted to remove the inconsistency that a larger female may have a lower probability of maturing than a smaller female due to what looks more like noise in the data.

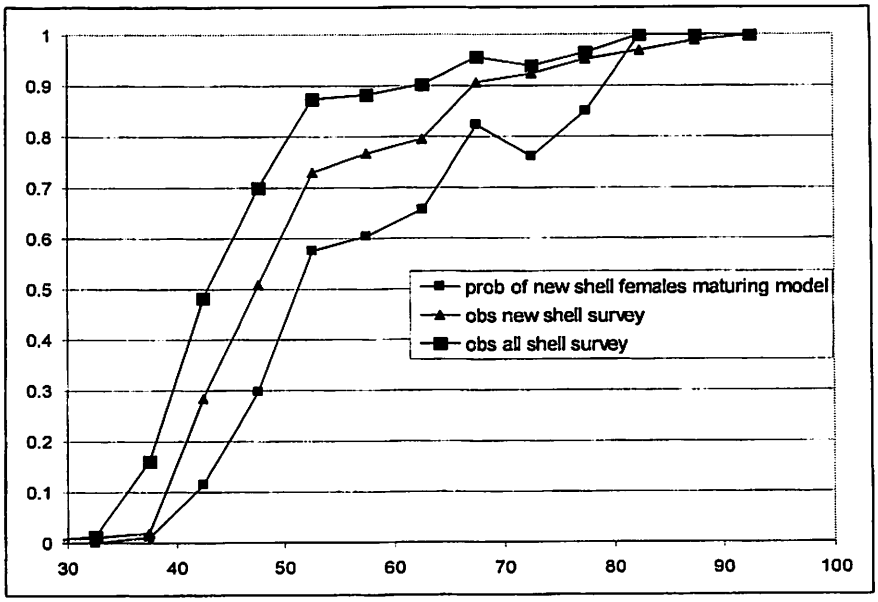

Figure 6: Fraction of new and all shell females morphometrically mature based on survey data and as well as the probability of females maturing (Source: Presentation by J. Turnock during review).

6.9 Shell age

The fishery targets "clean" crab and is only allowed to retain male crabs. As a result, the model separates numbers into males and females, and new and old shell. The model, however, does not fit to new and old shell data separately. In the model, new shell move to old shell after a year. This is a broad assumption and without direct and validated shell age it is unclear how accurate this assumption is.

However, the larger issue is how accurate the definition of shell age is (even at the scale of old and new). For example, studies have shown that biologists themselves incorrectly classify shells (Rugolo presentation). In the model new shells are classified as Shell Condition 2 and Old shell are classified as shell condition 3 to 5. In these studies, the shell mis-classification error also occurs between these new and old shell categories. This error appears to be even larger for the commercial data gathered by observers. Comparisons of observer-rated shell conditions with those made by staff at landing show large discrepancies in both directions. It is not possible with the available data to estimate this error and include this in the model – therefore it is recommended that the model not use new and old shell categories. This issue is particularly highlighted when the calculated fit to new and old shell numbers are shown (Figure 7 and Figure 8). This can not be a great loss in information as the fishery really targets clean shell which may be animals that have a shell age greater than 1 year.

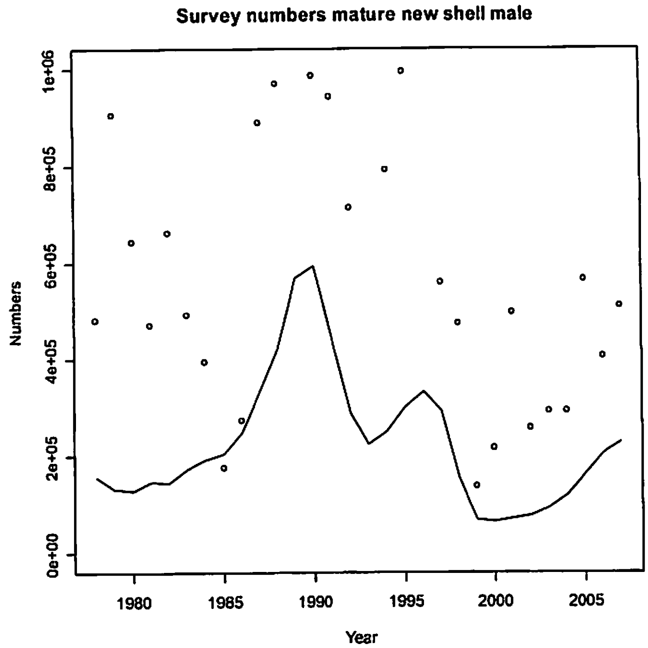

Figure 7: Male mature new shell numbers calculated by the model (solid line) fit to survey data (open circles) (Source: output file from model given by J. Turnock during review).

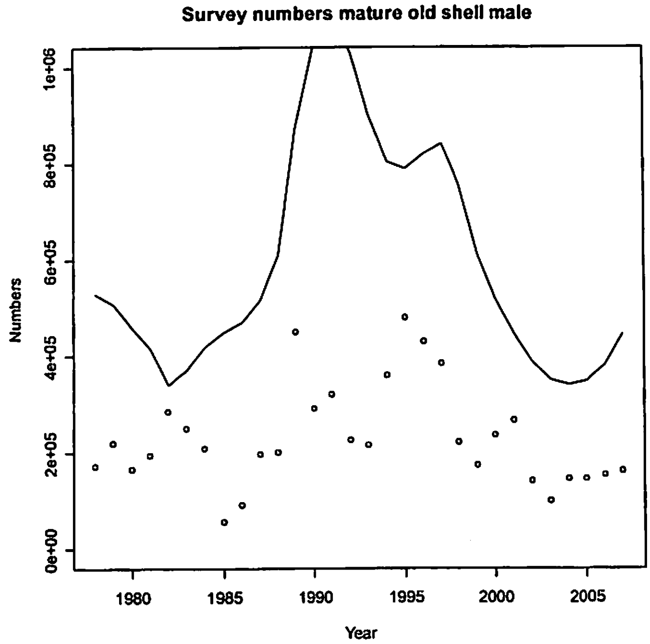

Figure 8: Male mature old shell number calculated by the model (solid line) to survey data (open circles) (Source: output file from model given by J. Turnock during review).

It is recommended that studies on Durometer measures of shell hardness and dactyl length should be further investigated. However, it is unlikely that this information will allow re-classification of data already collected.

6.10 Discard mortality

Industry believes discard mortality is much lower than the 50% mortality assumed with the model. Since independent information does not seem to be available and detailed sensitivity tests were undertaken it is precautionary to retain this feature until alternative information is available.

6.11 Recruitment estimates

The recruitment estimates show large inter-annual variation, autocorrelation as well as a possibility of some form of regime shift. There is also some indication of patterns in recruitment residuals. An investigation of the model output files, the standard deviation on the recruitment deviations are fairly large. In the report, errors around the recruitment estimates are not presented. Studies and presentations during the review week also state that temperature affects, amongst other things, recruitment, larval movement and settlement. Aspects that affect recruitment (including regime shift) should be a large component of an MSE project. This work should include the effects of environmental variables on recruitment and attempt to provide independent data that allows these environmental effects to be modelled internally within the assessment. When combined with the spatial work being undertaken by J. Murphy – much should be clarified in the future.

7 Forward projections

The same population dynamics in the estimation component of the assessment are used in the forward projections, although this is undertaken in separate code. No clear and accurate stock-recruitment model can be estimated from the stock and recruitment output of the estimation component of the assessment model. The Ricker model supports the view by some sectors that the resource is weakly fished but that the resource size is low due to the depensatory effect in the high spawning biomass part of the Ricker stock-recruitment curve. As a result, Ricker estimates of steepness describes a productive stock. On the other hand, the Beverton and Holt function describes an overexploited stock with poor productivity. Recruitment estimates show autocorrelation over time. The results of the forward projections are sensitive to whether autocorrelation is included or not. It is recommended that a Management Strategy Evaluation method should be used to evaluate strategies using existing control rules directly addressing the uncertainty in the trends and variability in future recruitment. The following references comprise a selected list of articles on the method:

Punt, A.E., 1992. Selecting management methodologies for marine resources, with an illustration for southern African hake. S. Afr. J. Mar. Sci. 12, 943-958.

Butterworth, D.S., Punt, A.E., 1999. Experiences in the evaluation and implementation of management procedures. ICES J. Mar. Sci. 56, 985-998.

Punt, A. E., Smith, A.D.M., 1999. Harvest strategy evaluation for the eastern stock of gemfish (Rexea solandri). ICES J. Mar. Sci. 56, 860-875.

Smith, A.D.M., Sainsbury, K.J., Stevens, R.A., 1999. Implementing effective fisheries-management systems - management strategy evaluation and the Australian partnership approach. ICES J. Mar. Sci. 56, 967-979.

Punt, A.E., Smith, A.D.M., Cui, G., 2002. Evaluation of management tools for Australia's South East Fishery 1. Modelling the South East Fishery taking account of technical interactions. Mar. Freshw. Res. 53, 615-629.

Kell, L.T., Mosqueira, I., Grosjean, P., Fromentin, J.M., Garcia, D, Hillary, R., Jardim, E., Mardle, S., Pastoors, M.A., Poos, J.J., 2007. FLR: an open-source framework for the evaluation and development of management strategies. ICES Journal of Marine Science 64, 640 - 646.

There is little in the data and model output that allows any choice between the two stock-recruitment forms. The final steepness values used in the assessment is the average between the two steepness values – with the Ricker curve calibrated so that it also is restrained between 0.2 and 1 and is therefore on the same scale as the Beverton and Holt function. Although this is an agreed value from much negotiation, the average between the two methods does not have much scientific backing and should be clearly stated as the best compromise in a situation where little independent information is available to support either case.

Appendix 1: Statement of Work for Dr. Catherine Dichmont

8 Statement of work

8.1 External Independent Peer Review by the Center for Independent Experts Bering Sea snow crab assessment review

Project Background:

The Alaska Fisheries Science Center (AFSC) requests review of the snow crab population dynamics and harvest strategy models for the Bering Sea snow crab (*Chionoecetes opilio*) assessment. The snow crab assessment model was reviewed by the CIE in 2003. Since that time, the analyst has made several improvements to the model. These changes should be reviewed by an independent panel. In addition, industry has requested a review of the snow crab assessment in FY08. The snow crab assessment is a high profile assessment and with the adoption of revisions to the overfishing definitions it is critical that this assessment provide the best available science on the status of this resource. This review would encompass the Bering Sea trawl survey data, the stock assessment model structure, assumptions, life history data, and harvest control rule. Proposed overfishing definitions for Bering Sea crab stocks, which may be implemented for the 2008-09 fishery seasons, require the use of the snow crab stock assessment model to estimate reference points and the status of the stock relative to those reference points. Management has used estimated survey abundance from the stock assessment to set quotas in the last two years, however, has not used proposed overfishing definitions and reference points estimated from the model. Uncertainty exists in the survey selectivities, maturity functions (which determine size at terminal moult), growth per moult, natural mortality, discard mortality and age post-terminal moult. This review will help in the decision process as to which alternative model is most appropriate, given the current state of knowledge of Bering Sea snow crab.

Overview of CIE Peer Review Process:

The Office of Science and Technology implements measures to strengthen the National Marine Fisheries Service's (NMFS) Science Quality Assurance Program (SQAP) to ensure the best available high quality science for fisheries management. For this reason, the NMFS Office of Science and Technology coordinates and manages a contract for obtaining external expertise through the Center for Independent Experts (CIE) to conduct independent peer reviews of stock assessments and various scientific research projects. The primary objective of the CIE peer review is to provide an impartial review, evaluation, and recommendations in accordance to the Statement of Work (SoW), including the Terms of Reference (ToR) herein, to ensure the best available science is utilized for National Marine Fisheries Service management decisions. The NMFS Office of Science and Technology serves as the liaison with the NMFS Project Contact to establish the SoW which includes the expertise requirements, ToR, statement of tasks for the CIE reviewers, and description of deliverable milestones with dates. The CIE, comprised of a Coordination Team and Steering Committee, reviews the SoW to ensure it meets the CIE standards and selects the most qualified CIE reviewers according to the expertise requirements in the SoW. The CIE selection process also requires that CIE reviewers can conduct an impartial and unbiased peer review without the influence from government managers, the fishing industry, or any other interest group resulting in conflict of interest concerns. Each CIE reviewer is required by the CIE selection process to complete a Lack of Conflict of Interest Statement ensuring no advocacy or funding concerns exist that may adversely affect the perception of impartiality of the CIE peer review. The CIE reviewers conduct the peer review, often participating as a member in a panel review or as a desk review, in accordance with the ToR producing a CIE independent peer review report as a deliverable. The Office of Science and Technology serves as the COTR for the CIE contract with the responsibilities to review and approve the deliverables for compliance with the SoW and ToR. When the deliverables are approved by the COTR, the Office of Science and Technology has the responsibility for the distribution of the CIE reports to the Project Contact.

Requirements for CIE Reviewers:

Two CIE Reviewers are requested for a maximum of 14 days, including pre-review preparations, participation at a 5 day panel review meeting in Seattle WA, and completion of CIE independent peer review reports in accordance to the Terms of Reference (ToR) herein. The CIE reviewers shall have expertise to be thoroughly familiar with various subject areas involved in the stock assessment, including population dynamics, length based models, knowledge of crab life history and biology, harvest strategy models for invertebrates, and the AD Model Builder programming language.

Statement of Tasks for CIE Reviewers:

The CIE reviewers shall conduct necessary preparations prior to the peer review, conduct the peer review, and complete the deliverables in accordance with the ToR and Schedule of Milestones and Deliverables herein. Prior to the Peer Review: The CIE shall provide the CIE reviewers contact information (name, affiliation, address, email, and phone), including information needed for foreign travel clearance when required, to the Office of Science and Technology COTR no later than the date as specified in the SoW. The Project Contact is responsible for the completion and submission of the Foreign National Clearance forms (typically 30 days before the peer review), and must send the prereview documents to the CIE reviewers as indicated in the SoW. Foreign National Clearance: If the SoW specifies that the CIE reviewers shall participate in a panel review meeting requiring foreign travel, then the CIE shall provide the necessary information (e.g., name, birth date, passport, travel dates, country of origin) for each CIE reviewer to the COTR who will forward this information to the Project Contact. The Project Contact is responsible for the completion and submission of required Foreign National Clearance forms with sufficient lead-time (30 days) in accordance with the NOAA Deemed Export

Technology Control Program NAO 207-12 regulations at the Deemed Exports NAO link http://deemedexports.noaa.gov/sponsor.html

Pre-review Documents: Approximately two weeks before the peer review, the Project Contact will send the CIE reviewers the necessary documents for the peer review, including supplementary documents for background information. The CIE reviewers shall read the prereview documents in preparation for the peer review. AFSC will provide:

a) the most recent Stock Assessment Report,
b) a copy of the Environmental Assessment for Crab Overfishing Definitions,
c) copies of relevant articles from peer reviewed journals,
d) a technical memorandum on AFSC crab groundfish trawl surveys,
e) ADMB code for stock assessment and data files.

Panel Peer Review Meeting: The CIE reviewers shall participate and conduct the peer review participate during a panel review meeting as specified in the dates and location of the attached Agenda and Schedule of Deliverable. The Project Contact is responsible for any facility arrangements (e.g., conference room for panel review meetings or teleconference arrangements). The CIE Program Manager can contact the Project Contact to confirm the facility arrangements.

Terms of Reference:

The CIE reviewers shall conduct an impartial peer review in accordance to the Terms of Reference (ToR) herein, to ensure the best available science is utilized for the National Marine Fisheries Service (NMFS) management decisions The CIE reviewers shall travel to Seattle, Washington from February 11-15, 2008 to discuss the stock assessment with the authors of the snow crab assessment. The reports generated by the CIE reviewers should include: a. A statement of the strengths and weaknesses of the snow crab population dynamics and harvest strategy models; b. Recommendations for alternative model configurations or formulations. c. Suggested research priorities to improve the stock assessment. Each CIE reviewer will complete a final CIE independent peer review report after the completion of the meeting in accordance with the ToR and the Schedule of Milestones and Deliverables with a copy each sent to Dr. David Die at ddie@rsmas.miami.edu and Mr. Manoj Shivlani at shivlanim@bellsouth.net no later than February 29, 2008.

Schedule of Milestones and Deliverables:

January 14, 2008 CIE shall provide the COTR with the CIE reviewer contact information, which will then be sent to the Project Contact January 28, 2008 The Project Contact will send the CIE Reviewers the pre-review documents 11-15 February 2008 Each reviewer shall participate and conduct an independent peer review during the panel review meeting February 29, 2008 Each reviewer shall submit an independent peer review report to the CIE March 14, 2008 CIE shall submit draft CIE independent peer review reports to the COTRs March 17, 2008 CIE will submit final CIE independent peer review reports to the COTRs March 31, 2008 The COTRs will distribute the final CIE reports to the Project Contact

Acceptance of Deliverables:

Upon review and acceptance of the CIE reports by the CIE Coordination and Steering Committees, CIE shall send via e-mail the CIE reports to the COTRs (William Michaels William.Michaels@noaa.gov and Stephen K. Brown Stephen.K.Brown@noaa.gov) at the NMFS Office of Science and Technology by the date in the Schedule of Milestones and Deliverables. The COTRs will review the CIE reports to ensure compliance with the SoW and ToR herein, and have the responsibility of approval and acceptance of the deliverables. Upon notification of acceptance, CIE shall send via e-mail the final CIE report in *.PDF format to the COTRs. The COTRs at the Office of Science and Technology have the responsibility for the distribution of the final CIE reports to the Project Contacts.

Request for Changes:

Requests for changes shall be submitted to the Contracting Officer at least 15 working days prior to making any permanent substitutions. The Contracting Officer will notify the Contractor within 10 working days after receipt of all required information of the decision on substitutions. The contract will be modified to reflect any approved changes. The Terms of Reference (ToR) and list of pre-review documents herein may be updated without contract modification as long as the role and ability of the CIE reviewers to complete the SoW deliverable in accordance with the ToR are not adversely impacted.

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ANNEX 1 CIE REPORT GENERATION AND PROCEDURAL ITEMS

1. The report should be prefaced with an executive summary of findings and/or recommendations.

2. The main body of the report should consist of a background, description of review activities, summary of findings, and conclusions/recommendations.

3. The report should also include as separate appendices the bibliography of materials provided by the Center for Independent Experts and the center and a copy of the statement of work.

4. Individuals shall be provided with an electronic version of a bibliography of background materials sent to all reviewers. Other material provided directly by the center must be added to the bibliography that can be returned as an appendix to the final report.

9 Updated agenda

NMFS Alaska Fisheries Science Center
7600 Sand Point Way NE, Building 4
Seattle, Washington
Observer Training Room
Tentative Agenda February 11-12, 2008

Day 1

9:00	Welcome and Introductions
9:15	Overview (species, surveys, fishery, catch levels, bycatch)
10:00	Biology (growth, natural mortality, diets, spawning areas, nursery areas, maturity curves, mating, sperm reserves)
11:00	Field experiments on escapement, discard mortality, tagging
11:30	Age Determination, shell condition
12:00	Lunch
1:00	Biology continued
2:00	Harvest control rules and overfishing definition
3:00	Survey methodology and analysis
4:00	Summary of on-going research
	Egg viability and sperm reserves
	Larval drift
	Spatial modeling
	Management Strategy Evaluation

Day 2

9:00	Ecosystem considerations - Predation, prey
10:00	Description of snow crab assessment model
12:00	Lunch
1:00	Continued discussions

Day 3

9:00	Examination of the harvest control rules and Continued discussion of assessment model
12:00	Lunch

Day 4 and 5

Reviewer discussions with assessment authors

Review of Bering Sea Snow Crab assessment

February 2008, Seattle, Washington

Reviewer's Report

Ewen Bell

Centre for Environment, Fisheries and Aquaculture Science
(Cefas)
Pakefield Road,
Lowestoft
Suffolk IP19 8JH
United Kingdom

Cefas

Executive summary of findings and recommendations

***ToR a:** A statement of the strengths and weaknesses of the snow crab population dynamics and harvest strategy models;*

Strengths:

- The assessment model has been specifically designed to reproduce the complex life-history of Snow Crab, its sexual dimorphism and the selectivity of the fishery.
- The use of ADModelBuilder facilitates estimates of large numbers of parameters and their uncertainty.
- The harvest strategy model suggested for Snow Crab is a vast improvement on the previous model and should help safeguard against stock collapse when viewed at the scale of the whole area.

Weaknesses:

- A consequence of the model's biological complexity is the large amount of data required for parameterisation. Although the model is biologically complex, the considerable spatial structuring of both the stock and the fishery is assumed to be inconsequential. Poor model fits in some areas indicate that the data available for parameterisation are either too uncertain or the spatial structuring is in reality highly significant. The likelihood is that both scenarios are true to some extent.
- The harvest strategy model also assumes that the stock operates as one spatially homogeneous unit. Given the concentration of the fishery on a small sub-area, the harvest strategy model will not prevent local depletion.
- The stock-recruit relationship used in the forecasts is uncertain and there is some evidence of a shift to lower productivity in recent years.

ToR b. Recommendations for alternative model configurations or formulations.

- As there is limited scope for larval movement in a southward direction, the area to the north of the fishery will not contribute significantly to recruitment. I recommend performing an assessment on only the area south of the most northerly extent of the fishery.
- The model could be simplified by removing the new/old shell dimension, because the shell staging data used to parameterise this are unreliable.

ToR c. Suggested research priorities to improve the stock assessment.

- Develop new methods for the ageing/staging of snow crab shells. Measures of shell hardness or dactyl length may give far more objective measures of shell age than the visual staging currently employed.
- Develop tagging studies to understand migration patterns better. Spatial processes in both the fishery and the stock would appear to be crucial to the sustainability of the stock, particularly at smaller scales where significant localised depletion is a realistic possibility.
- Develop studies to determine growth rates. Currently, female growth rates are derived from data on Atlantic stocks of snow crab, and male growth rates are estimated from 14 individuals in the eastern Bering Sea. Although I acknowledge that the operational environment is complex and arduous, considerably more data are required on growth rates for a stock of this commercial importance.
- Explore simpler assessment models. The current assessment model is perhaps too biologically complex considering the quantity of underlying data. Simpler models, although not as biologically realistic, may still yield metrics of stock status sufficient to manage the stock in a sustainable manner.
- Create a Management Strategy Evaluation (MSE) tool for Bering Sea snow crab. Although this recommendation comes last, it is perhaps one of the most important. An MSE would provide an excellent platform upon which to test the whole range of biological assumptions, model formulations and management strategies which have been suggested/recommended here. Given the spatial structuring in the stock and the fishery, the MSE would also ideally need a level of spatial structure.

Other comments

- The program code, model description and input files need re-working to make them easily read and transparent. The program code and input files contain a lot of legacy code, which makes the files somewhat confusing and difficult to read. The accompanying model description is occasionally at odds with what appears in the code.
- The model has been constructed to be biologically complex, reflecting the complexities of the ecology of the species and its fishery. However, strong patterns in the model residuals highlight misspecification with respect to the available input data. The model could be simplified by removing the new/old shell dimension, because the shell staging data used to parameterise this are poor.
- The spatial structuring within the population and fishery is considerable, but assumed irrelevant in the assessment. As there is limited scope for larval movement in a southward direction, the area to

the north of the fishery will not contribute significantly to recruitment. I recommend performing an assessment on only the area south of the most northerly extent of the fishery.

- Shell staging should be dropped from existing sampling protocols. Tests have shown that the shell classification currently employed is too subjective and uncertain to be of any practical use, and continuation of the collection would only serve to give false credence to its utility.
- Mortality estimates from multispecies/ecosystem (ECOPATH) modelling are uncertain, and until some peculiar interactions have been explored/resolved, the values of natural mortality for Eastern Bering Sea snow crab should not be taken from ECOPATH.
- Pathways to facilitate the exchange of survey data between AFSC and the Alaskan Department of Fish and Game should be sought. The apparent unavailability of survey data to the AFSC does not help the common objective of having a sustainably managed snow crab stock.
- Explore the outcomes of assuming an "incorrect" stock–recruit relationship in the forecast. The stock–recruit relationship assumed for the forecast model is the most important element in the model. Sensitivity analyses are required to determine what the risks to the stock are if the wrong relationship, or wrong parameterisation, have been selected. There is evidence of a recent decrease in recruitment productivity, and we need to know what the risk is to the stock of ignoring this issue.

Background

The Alaska Fisheries Science Center (AFSC) requested a review of the stock assessment and harvest strategy models for the Bering Sea snow crab (*Chionoecetes opilio*). The snow crab assessment model was last reviewed by the CIE in 2003, since which time several changes have been made to the model which now require re-evaluation by an independent panel. In addition, industry has requested a review of the snow crab assessment in FY2008. The snow crab is a high-profile assessment and, with the adoption of revisions to the overfishing definitions, it is critical that the stock assessment provides the best available science on the status of this resource. The review is to encompass the Bering Sea trawl survey data, the stock assessment model structure, assumptions, life history data, and harvest control rule.

A panel of two reviewers was selected for the purpose of this review, with the following terms of reference:

- A statement of the strengths and weaknesses of the snow crab population dynamics and harvest strategy models;
- Recommendations for alternative model configurations or formulations.
- Suggested research priorities to improve the stock assessment.

Description of review activities

The following documentation was provided to the reviewers prior to the meeting:

- a description of the model (Appendix 2.1),
- the model code, input and output files (Appendix 2.2)
- the iinitial review draft, Environmental Assessment, for proposed Amendment 24 To the Fishery Management Plan for Bering Sea and Aleutian Islands King and Tanner Crabs to Revise Overfishing Definitions (Appendix 2.3).
- Reproductive Dynamics and Life History of Snow Crab in the eastern Bering Sea. AFSC Quarterly report (Appendix 2.4)
- Biological Field Techniques for *Chionoecetes* Crabs. (Appendix 2.5)

This documentation was sufficient to gain an insight into some of the biological issues and problems concerning the assessment of Bering Sea snow crab, but inconsistencies between the model description and model code meant that understanding the finer workings of the model were only achieved after detailed discussion with the assessment scientists.

The review was held at the ASFC, Sand Point Way NE, Seattle 11th – 14th February 2006, and attended by the two CIE reviewers, staff from both the ASFC and the Alaskan Department of Fish and Game, and an industry representative (Jack Taggart), who attended the first two days of the meeting. The meeting consisted of two days of presentations covering the biology, fishery and assessment of snow crab, from Benjamin Turnock (the principal assessment scientist) and Lou Rugolo (the principal biologist), along with presentations regarding spatial analyses of survey data, the hydrography and ecosystem modelling for the region. Subsequent to this, the reviewers had extensive discussion with the ASFC staff responsible for the assessment, specifically regarding the structure and function of the model.

During the meeting the reviewers made several requests to the assessment team for additional information and model runs, most of which were met. The requests for model runs which not met were due to there being insufficient time to reprocess the basic data.

Following the meeting, copies of the CIE reviews undertaken in 2003 (stock assessment model) and 2006 (overfishing definitions) were received.

Summary of findings

Fishery

The fishery is mainly prosecuted by a potting fleet during winter in the southwest of the region. Historically the fishery was managed as a short-season contest fishery in winter, but has recently undergone a rationalisation programme which has shifted it to a quota-managed fishery. The time constraints have been relaxed, but the requirements of the processing plants are such that the fishery remains a winter fishery. The imposition of a quota system on both capture and processing means that the rigid time constraints are unlikely to change in the near future. The spatial limitations are principally ice-coverage and distance from port. The tight time schedules of the processing plants means that vessels have to keep their allotted slots for unloading and cannot therefore afford to venture further away and risk being unable to return on time.

These constraints on the fishery, particularly the spatial constraint, present significant problems in assessing the stock and the impact of the fishery upon the stock. Stock assessment models assume that the each individual in the population is equally available to the fishing gear (and subsequently subject to gear selectivity) and equally available to all other individuals for the purpose of spawning. The spatially aggregated fishery on eastern Bering Sea snow crab would only satisfy this "dynamic pool" assumption if the crabs happened to aggregate from the whole area into the fished area during winter, but there is no evidence that this is the case.

The theme of spatial structure between the fishery and stock is a crucial element to both understanding and managing fishing mortality, to ensure a sustainable fishery, and it recurs throughout this review report.

Biology/ecology

The reproductive ecology considerably confounds the development of indices of stock status for snow crab. Copulation requires a relatively large size difference between males and females. Males are not thought to be capable of successful copulation in the first year of morphological maturity, whereas this is the stage that the fishery actively seeks. Both male and female reproductive capacity is also considered to change with age past maturity, with first-time spawners (primiparous) having a lower output than multiparous spawners.

It is unclear what minimum sex ratio is required in the population for effective reproduction to take place, because of the polyandrous and polygynous behaviour, and it is further confounded by the ability of females to store spermatophores. Such practice should buffer against increased mortality on the male portion of the stock, but there will still come a point at which the population will become sperm-limited.

Evidence was presented for reduced reproductive capacity in some areas subject to high fishing pressure. This was due to a combination of reduced spermathecal loading in mature females, a reduction in clutch fullness, and an increase in the number of barren females. Although symptomatic of an unsustainable population (and hence fishery), the consequences for the stock as a whole will depend upon the redistribution processes of both larvae and adults.

The results of hydrographic modelling for the area were presented and showed a general drift northwest during the main larval phase for snow crab. Some areas had greater retention probabilities, but there was no evidence for larval transport in a southwesterly direction to repopulate the main fishing grounds.

Some evidence exists for a general movement of snow crab in a southwesterly direction as they grow, which may be a movement to deeper water, but the speed and magnitude of such movement are unknown. Tagging studies are confounded by the recapture effort (i.e. the fishery) being concentrated in the southwest of the area.

As a result of the information provided regarding fishery location and the potential for snow crab redistribution, I am concerned that managing/assessing the stock as a single unit is unlikely to deliver the sustainable fishery being sought. On the scale of multiple generations, the eastern Bering Sea snow crab probably does function as a single stock, and I doubt very much whether genetic studies would find any differences over the region (~1% annual transfer between areas is sufficient to obscure genetic differences). The fishery operates on a much finer time scale and appears able to inflict relatively high rates of mortality on localised areas in short time periods, and the ability of the wider stock to replenish these localised areas appears to be limited. The models used for both assessment and projection have the underlying assumption of a dynamic pool, i.e. the ability of each animal to interact with each another animal and the fishery within the time step being considered (annual) and an equal redistribution of recruiting individuals. These assumptions are almost always violated to some extent, but in this situation the violations are considerable, so the results (particularly the projection of yield) are questionable.

My suggested solution would be to develop a spatially disaggregated model that can model the aggregated fishery in a much more rational manner. A first step would be to assess only that part of the stock which is fished and contributes to the immediate recruitment of the fished area, and I would suggest restricting the assessment area to that south of about 58.5°N. The next development would be to include a model for the remaining area and to parameterise migration rates, which I acknowledge is going to be challenging. As previously mentioned, tagging studies rely upon recapture by the fishery, which is spatially limited by, *inter alia*, winter ice-cover. My suggestion for a tagging study would be to release tagged animals in an area northeast of the main fishery grounds, but which is unlikely to be covered by sea ice. Recapture effort would then be achieved by providing incentives to a vessel (either through direct charter and/or by allowing it to fish off-quota) to fish using a specific search pattern around the release site. This would then provide information regarding movement rates in all directions, rather than biasing detection to the southwest, where the fishery operates. I am unsure as to whether tidal cycles are detectable under ice-cover, but should pressure changes still exist then use of electronic data storage tags (DSTs), coupled to tidal geo-location models, may also provide valuable information regarding movement rates and directions, an approach currently being trialled with *Cancer pagurus* in the UK.

The estimates of natural mortality used have recently changed from a uniform 0.2 to sex-stage-differentiated values of 0.29 (mature females) and 0.23 (all other stages). The presentation of ECOPATH modelling for the eastern Bering Sea suggested that snow crab are preyed upon at a low level by a wide variety of species, but at a much higher rate by one species. Estimates of consumption by this one species are highly variable and much research effort is being expended to understand the reality of this estimate. Until the veracity of the estimate has been established, I do not recommend changing the values of *M* to reflect the ECOPATH estimates of mortality.

Survey

As the fishery is concentrated on a small area, the only information regarding stock status and dynamics for the majority of the eastern Bering Sea snow crab comes from the annual surveys undertaken by AFSC/NMFS. As is often the case, this is a general survey aimed at a wide variety of species; it is therefore not specifically tailored to the measurement of snow crab abundance. The survey design (grid-pattern @ 20 nautical miles) reflects the compromises required to estimate simultaneously the abundance of many species, but it is suboptimal for snow crab, which appears to have a contiguous distribution that is not adequately covered at the 20-mile scale. Attempts have been made to quantify better the highest density stations by incorporating additional stations, but this is inconsistent with the methodology used to raise the survey data.

Aspects of the methodology used to create survey biomass indices caused some concern. During each trawl, data are recorded with respect to the width of the trawlnet, which averages around 60 ft, but when determining the swept area for each station, a fixed value of 50 ft is used. This underestimate is used to compensate for the reduced catchability estimated to exist for smaller snow crabs. It would be far preferable to have a measure of selectivity for the survey gear, and to use the true value of swept area for each tow. This would also be of enormous help to the assessment model, which attempts to estimate survey selectivity, which is one of the crucial factors determining absolute population abundance. Some work on survey selectivity was presented, and it was clear that further work should be afforded high priority.

During the description of the survey gear, it was mentioned that the footrope is unweighted and that a gap exists between the footrope and the belly of the net. This is somewhat surprising given that the survey is used for population estimates of benthic organisms such as crabs and flatfish. Consistency is the key factor in surveys, and it is not therefore advised that the gear be changed to select benthic organisms better unless it is demonstrated that the selectivity of the net is so low that abundance signals are masked by survey noise.

Plots of abundance at length suggest that the survey is poor at tracking cohorts through time; peaks of numbers at larger lengths often appear without having been tracked up through the younger sizes. This presents real problems to the assessment model, which is attempting to fit population estimates to these survey numbers. The apparent inability to track cohorts does change when subareas are investigated, because some lower density subareas appear to track cohorts quite well, indicating that the selectivity of the net is adequate. The apparent relative inability of the higher density areas to track cohorts perhaps reflects the sparseness of the survey station density in relation to the scale of patchiness in snow crab. The spatial analyses of the survey data being undertaken in the PhD programme of James Murphy should generate greater understanding of the spatial structuring of the population, and should then feed directly into the assessment process.

The standard operating procedure for snow crab includes measuring, sexing and staging the individuals. Staging is on a scale of 1–5, 1 being soft, 2 freshly moulted, and 3–5 indicating time since moult, dependent upon the level of shell wear, discolouration and bio-fouling. Stage 5 individuals are considered to be very old and to contribute little to spawning. *Chionoecetes opilio* are considered to have a terminal moult at morphometric maturity, and staging studies were undertaken using tagged animals which were at liberty for up to several years after initial tagging. It should, therefore, have been impossible to reclassify individuals at a lower stage, yet this occurred with alarming regularity. Classification of individuals into shell stages is therefore highly subjective and error-prone, and it is suggested that shell staging is dropped from the protocol for both the survey and market sampling. Reluctance to drop a procedure which has been part of the protocol for a long time is understandable, of course, because it means the end of a long time-series, but given that the data are too unreliable for practical purposes, the continuation of collecting the data simply gives false credence to their utility. There was discussion of two alternatives for the estimation of shell age: measuring shell hardness with callipers and measuring dactyl length. These means of estimation seem to be more promising in terms of deriving an unbiased estimate of age, but their calibration against individuals of known age will still prove to be challenging.

One obstacle to the review process was the inaccessibility of the raw survey data to the AFSC scientists and the resulting inability to reprocess survey indices rapidly. There would appear to be significant communication difficulties between the AFSC and the Alaskan Department of Fish and Game, which for the sake of the resource should be sorted out as a matter of priority. There is no logic for two government departments ostensibly working towards the same goal of sustainably managing a fishery not to share information freely.

Assessment

The use of AD Model Builder as a modelling tool as a platform for stock assessment is an established method, and it should provide robust and reliable parameter estimates with uncertainty estimates and parameter correlations. It was disappointing to see little emphasis of these uncertainties and parameter correlations in the material presented at the meetings.

Program code is rarely written with other users in mind (not an unusual situation worldwide), but in instances where the program is likely to be examined and reviewed by others (such as in stock assessments), care needs to be taken to make comments relevant and names meaningful, and to operate version control, ensuring that only relevant code is retained. The program code supplied was complex and contained much legacy code (which had been commented out), but made the reading of the code difficult. The use of integer names i, j, and k to index arrays is potentially confusing and using "*age*", "*maturity*", and "*sex*" would have made the code slightly lengthier but easier to interpret.

In a similar vein, the input files also contained a lot of legacy code, which was again commented out but made the files difficult to read. Each line of input data is accompanied by a comment line explaining what it was. This practice is to be commended, but unfortunately the comments do not match up with the parallel comments in the input section of the ADModelBuilder code. In order for both code and model to be fully transparent, these problems need to be resolved, because they do not engender confidence that the program is performing as intended. There was not time within the scope of this review process to interpret and check each line of code fully.

The output files from the assessment are complex structures, and specific tools to extract and display the data are required. A routine has been created in the R programming language to extract and display the results, which relies upon the user downloading and installing a number of routines that mimic Unix-style stream editing. Despite the fact that I already use a number of these routines, incompatibility issues that could not be resolved meant that I could not get the R routines to function. It would be preferable to have a stand-alone program that splits the report file into separate files, which R (or any other statistical / plotting program) can then pick up. It was noted that the routine for plotting size-frequency residuals contained an inconsistency, in that the circle size for large negative residuals was not commensurate with that for large positive residuals of the same magnitude.

The assessment model is biologically complex, attempting to track numbers at **length**, **shell stage**, **sex** and **maturity**. Shell stage was limited to new/old, rather than the full 1–5 stages, and was included to capture the fact that the fishery prefers to take clean-shelled animals. It was assumed that individuals moved from shell stage new to old in one year, but there is little evidence that such a distinction is possible from field data. Given the reliability of the basic staging data and the fact that current management does not utilise shell stage, this is an unnecessary dimension, and it should be dropped from the model.

The parameters the model estimates cover:

- Initial numbers at length.
- Mean (log) recruitment and log(annual deviants).
- Mean (log) fishing mortality and log(annual deviants).
- Selectivity of survey and fisheries.
- Linear growth increment model.

The model is fitted to survey biomass estimates, commercial catches, commercial catch rates, and length frequencies from both survey and fishery sources.

The most crucial element of any size-based model is the growth transition matrix. In this model, the matrix is created using a linear shell increment model linked to a gamma function, and parameterised both inside and outside the assessment model. The linear growth parameters for females were taken from Canadian data on Atlantic snow crabs, whereas the parameters for the males came from 14 tagged animals. This level of growth data is unsatisfactory for a length-based assessment model which covers such a large geographical area, and may go some way to explaining the strong residual patterns observed in the model fits.

The model forces the numbers of recruits to be equal for males and females, and although there is no evidence of sex-bias at the egg stage, different growth rates between the sexes have the potential to skew the initial sex ratio.

The catch rate (CPUE) of the pot fishery was not standardised, and given the drastic changes to fishery management in the past couple of years, this is a serious inconsistency. Quotas for the coming year are determined on the current status of the stock, so an artificially inflated (or deflated) CPUE index will push the model away from the true value and potentially result in unsustainable management advice. In the model run presented, the commercial CPUE index was given a very low weight, so would make little impact upon the final assessment. Given the complexity of the model, though, it would be preferable if data which are not considered suitable for inclusion into the objective function were omitted.

The fitting of length frequency data was always going to be problematic given the apparent inability of the survey to track cohorts, and examination of the residuals from these fits confirms the existence of a number of problems with this procedure. There are both temporal and time-invariant patterns within the length-frequency residuals. Both males and females exhibit strong temporal patterns as cohorts' progress through the model. This may be due to the sudden appearance/disappearance of strong cohorts within the survey data, although changes in growth rates would also give rise to similar patterns. There are always negative residuals at the smallest size for both males and females.

Model estimates of survey selectivity appear to be quite high (q_{max}= 0.8–1.0), given the selectivity experiments during which a beam-trawl was towed behind the standard otter trawl and recorded significant numbers of animals missed. During the meeting, a request to run the model with the survey selectivity set at 0.5 was made. It was expected that this change in selectivity would simply have a scaling effect on the population estimates, and that the stock status relative to its historical trajectory would remain unchanged. The results of this alternative assessment were then fed into the forecasting model under the existing Harvest Control Rule. The long-term (~5 year) harvest levels were similar, but the initial harvest levels were considerably different. Examination of the recruitment estimates showed that the pattern and scale of recruitment was significantly altered using the lowered selectivity plateau, resulting in a different picture of relative stock status in the terminal assessment year. There is no information to indicate that one or other level of survey selectivity is more "right" than the other, the purpose of this exercise being rather to test the robustness of the model to different assumptions. Clearly, the model needs careful and extensive sensitivity testing.

I have several proposals for modifications to the model.

- Reduce the dimension space within it by removing the new shell / old shell distinction. It might also be possible to remove the mature/immature dimension within the model. Although the presence of a terminal moult places a cap on the growth of an individual, the instar number at which this occurs is variable, as is the terminal size. One option might be to have an extended "plus group" coinciding with the length at 50% maturity. This would decrease the precision of mature biomass estimates while reducing the bias.
- In order to capture the spatial aspects of the fishery and the data, I suggest performing an assessment using data only from the area south of 58.5° (or the most northern latitude that encompasses the fishery). This would have the advantage of producing an assessment only of the spawning biomass likely to contribute to the recruits arriving in the fished area, and it would also give a better indication of exploitation rates in the fished area. Its downside, however, would be that it would violate the closed population assumption by any migration into the area from the non-assessed area to the north. A solution to this (for the future) would be to create a two-area assessment model linked with migration, but as yet, there are no data available to parameterise such a linkage.
- At present, whole-area survey length frequencies are input for each year and sex. I suggest adjusting the model to take multiple series of length frequencies, inputting more spatially disaggregated datasets.

> The model could then automatically weight the series using some goodness-of-fit criteria. Although this represents an increase in model complexity, it would allow the model to use those parts of the length frequency data which contain genuine information.

There is an obvious attraction for models which capture more biological realism; this model seeks to do just that, and it authors should be commended for attempting to do so. More biologically realistic models allow reference points to be determined with less uncertainty, management can afford to be less precautionary. There is always a price to be paid for such an increase in complexity, an almost exponential requirement for input data. The biology, ecology and habitat of eastern Bering Sea snow crab make the acquisition of such basic data as growth rates and migration rates incredibly time-consuming, costly, and at times dangerous. There would be considerable merit in exploring a range of alternative simpler models which would utilise the available data more effectively, to complement and contrast the biologically complex model presented here.

Forecast

The code for the forecast model was not supplied with the documentation of the review.

The principal component of any fisheries forecast model is the stock–recruit relationship used, and the outcome of the recent OverFishing Level (OFL) debate bears this out.

The stock–recruit plot generated by the assessment model contains no information near the origin, and is therefore inconclusive with regards to what type of stock–recruit relationship to use. There is a scatter of points at mid-range biomasses, whereas the upper range of biomasses has only low recruitment values. It is understandable therefore that some favour a Ricker-type relationship. However, the life history of crabs tends towards later maturity and slower growth, so the Beverton–Holt-type curve seems more ecologically plausible. Although it is currently unclear which is the "better" curve, the practice of taking the mean steepness of the two curves and then applying it to the Beverton–Holt curve seems fundamentally wrong (steepness meaning different things in the two models). Of far greater concern to me is the temporal trend in the data. Most recruitments since 1989 have been low despite a broad spread of biomass, and the possibility of a downward shift in productivity (perhaps a regime shift) appears tangible. If there has been a shift in productivity, then the use of stock–recruit data from outside this period will overestimate potential recruitment, and management will run the risk of advising catch levels that are unsustainable. The flip side to a decrease in productivity is that B_{MSY} will decrease, so the current status of the stock in relation to B_{MSY} would improve, and changes in TAC may therefore not be as drastic as industry may fear.

The results of the HCR simulations showed that the adopted $F_{35\%}$ rule actually results in a slower rebuilding time than a F_{MSY} rule, does not reach B_{MSY}, and is therefore less precautionary than an F_{MSY} regime. In practice, these differences might not be detectable and the system is a substantial improvement upon the previous management plan. What has not been properly explored yet, though, is the risk to the stock when a wrong stock–recruit function is chosen for the forecasts, e.g. a Ricker function is chosen when in fact the true relationship should be Beverton–Holt. This model uncertainty has huge implications for the level of risk to the stock and by excluding this uncertainty from the management projections essentially places the acceptance of this risk onto the scientists. This is a dangerous route for science; a scientist's job is to be completely objective and to provide management with the information and tools that managers require to make decisions based upon **their** acceptance of risk. Once elements of uncertainty are excluded at a scientific level, managers can absolve themselves of blame should problems arise, and science loses credibility in terms of being objective and impartial.

One area the management plan does not explicitly address is the issue of safeguarding against local depletion. Above I have voiced concern that the eastern Bering Sea snow crab population is unlikely to operate as a single stock at the temporal scale at which the fishery is operating, and that more regional assessment should be explored. The current management plan in conjunction with the single-area assessment is incapable of preventing overfishing of localised areas. However, should regional assessments become possible, then the management plan structure should be applicable independently to each area, and therefore better suited to reduce the risk of local depletion.

Conclusions / Recommendations

Much of this report has highlighted areas of uncertainty and requirements for further data, and has suggested changes to programmes and methodologies. It was not, however, my intention to present a negative review of the existing situation. There has obviously been a great deal of work put into the assessment of the stock, and it involved close collaboration between biologists and modellers. The resulting assessment model represents a credible balance between biological complexity, the operational mode of the fishery, and the requirements of stock assessment. The fitting problem which the model seems to have is more likely the result of there being insufficient data for effective parameterisation, and it is for this reason that the exploration of simpler models has been suggested.

There are a number of areas of uncertainty both within the perception of the biological system and the ability to assess the status of the stock(s) of eastern Bering Sea snow crab. By far the best way to formalise these uncertainties and to determine their impact upon the methods used to manage the fishery is to have a Management Strategy Evaluation (MSE) program developed. Essentially MSEs are linked models of the biology, the scientific assessment, management, and the fishery in which the effects of changes in any of the elements can be explored through simulation. I understand that a proposal for the creation of an MSE for eastern Bering Sea snow crab has been submitted, and I sincerely hope that the application is successful, because it offers the best route to exploring the numerous uncertainties surrounding this stock. My only regret is that the proposed MSE will not be designed to explore the spatial structuring of the stock and its fishery, which to me seems to be fundamental in understanding the eastern Bering Sea snow crab better.

ToR a: ***A statement of the strengths and weaknesses of the snow crab population dynamics and harvest strategy models;***

Strengths:

- The assessment model has been specifically designed to reproduce the complex life-history of Snow Crab, its sexual dimorphism and the selectivity of the fishery.
- The use of ADModelBuilder facilitates estimates of large numbers of parameters and their uncertainty.
- The harvest strategy model suggested for Snow Crab is a vast improvement on the previous model and should help safeguard against stock collapse when viewed at the scale of the whole area.

Weaknesses:

- A consequence of the model's biological complexity is the large amount of data required for parameterisation. Although the model is biologically complex, the considerable spatial structuring of both the stock and the fishery is assumed to be inconsequential. Poor model fits in some areas indicate that the data available for parameterisation are either too uncertain or the spatial structuring is in reality highly significant. The likelihood is that both scenarios are true to some extent.
- The harvest strategy model also assumes that the stock operates as one spatially homogeneous unit. Given the concentration of the fishery on a small sub-area, the harvest strategy model will not prevent local depletion.
- The stock-recruit relationship used in the forecasts is uncertain and there is some evidence of a shift to lower productivity in recent years.

ToR b. Recommendations for alternative model configurations or formulations.

- As there is limited scope for larval movement in a southward direction, the area to the north of the fishery will not contribute significantly to recruitment. I recommend performing an assessment on only the area south of the most northerly extent of the fishery.
- The model could be simplified by removing the new/old shell dimension, because the shell staging data used to parameterise this are unreliable.

ToR c. Suggested research priorities to improve the stock assessment.

- Develop new methods for the ageing/staging of snow crab shells. Measures of shell hardness or dactyl length may give far more objective measures of shell age than the visual staging currently employed.
- Develop tagging studies to understand migration patterns better. Spatial processes in both the fishery and the stock would appear to be crucial to the sustainability of the stock, particularly at smaller scales where significant localised depletion is a realistic possibility.
- Develop studies to determine growth rates. Currently, female growth rates are derived from data on Atlantic stocks of snow crab, and male growth rates are estimated from 14 individuals in the eastern Bering Sea. Although I acknowledge that the operational environment is complex and arduous, considerably more data are required on growth rates for a stock of this commercial importance.
- Explore simpler assessment models. The current assessment model is perhaps too biologically complex considering the quantity of underlying data. Simpler models, although not as biologically realistic, may still yield metrics of stock status sufficient to manage the stock in a sustainable manner.
- Create a Management Strategy Evaluation (MSE) tool for Bering Sea snow crab. Although this recommendation comes last, it is perhaps one of the most important. An MSE would provide an excellent platform upon which to test the whole range of biological assumptions, model formulations and management strategies which have been suggested/recommended here. Given the spatial structuring in the stock and the fishery, the MSE would also ideally need a level of spatial structure.

Appendix 1: Statement of Work for Dr Ewen Bell

External Independent Peer Review by the Center for Independent Experts

Bering Sea snow crab assessment review

Project Background:

The Alaska Fisheries Science Center (AFSC) requests review of the snow crab population dynamics and harvest strategy models for the Bering Sea snow crab (*Chionoecetes opilio*) assessment. The snow crab assessment model was reviewed by the CIE in 2003. Since that time, the analyst has made several improvements to the model. These changes should be reviewed by an independent panel. In addition, industry has requested a review of the snow crab assessment in FY08. The snow crab assessment is a high profile assessment and with the adoption of revisions to the overfishing definitions it is critical that this assessment provide the best available science on the status of this resource. This review would encompass the Bering Sea trawl survey data, the stock assessment model structure, assumptions, life history data, and harvest control rule.

Proposed overfishing definitions for Bering Sea crab stocks, which may be implemented for the 2008-09 fishery seasons, require the use of the snow crab stock assessment model to estimate reference points and the status of the stock relative to those reference points. Management has used estimated survey abundance from the stock assessment to set quotas in the last two years, however, has not used proposed overfishing definitions and reference points estimated from the model. Uncertainty exists in the survey selectivities, maturity functions (which determine size at terminal molt), growth per molt, natural mortality, discard mortality and age post-terminal molt. This review will help in the decision process as to which alternative model is most appropriate, given the current state of knowledge of Bering Sea snow crab.

Overview of CIE Peer Review Process:

The Office of Science and Technology implements measures to strengthen the National Marine Fisheries Service's (NMFS) Science Quality Assurance Program (SQAP) to ensure the best available high quality science for fisheries management. For this reason, the NMFS Office of Science and Technology coordinates and manages a contract for obtaining external expertise through the Center for Independent Experts (CIE) to conduct independent peer reviews of stock assessments and various scientific research projects. The primary objective of the CIE peer review is to provide an impartial review, evaluation, and recommendations in accordance to the Statement of Work (SoW), including the Terms of Reference (ToR) herein, to ensure the best available science is utilized for National Marine Fisheries Service management decisions.

The NMFS Office of Science and Technology serves as the liaison with the NMFS Project Contact to establish the SoW which includes the expertise requirements, ToR, statement of tasks for the CIE reviewers, and description of deliverable milestones with dates. The CIE, comprised of a Coordination Team and Steering Committee, reviews the SoW to ensure it meets the CIE standards and selects the most qualified CIE reviewers according to the expertise requirements in the SoW. The CIE selection process also requires that CIE reviewers can conduct an impartial and unbiased peer review without the influence from government managers, the fishing industry, or any other interest group resulting in conflict of interest concerns. Each CIE reviewer is required by the CIE selection process to complete a Lack of Conflict of Interest Statement ensuring no advocacy or funding concerns exist that may adversely affect the perception of impartiality of the CIE peer review. The CIE reviewers conduct the peer review, often participating as a member in a panel review or as a desk review, in accordance with the ToR producing a CIE independent peer review report as a deliverable. The Office of Science and Technology serves as the COTR for the CIE contract with the responsibilities to review and approve the deliverables for compliance with the SoW and ToR. When the deliverables are approved by the COTR, the Office of Science and Technology has the responsibility for the distribution of the CIE reports to the Project Contact.

Requirements for CIE Reviewers:

Two CIE Reviewers are requested for a maximum of 14 days, including pre-review preparations, participation at a 5 day panel review meeting in Seattle WA, and completion of CIE independent peer review reports in accordance to the Terms of Reference (ToR) herein. The CIE reviewers shall have expertise to be thoroughly familiar with various subject areas involved in the stock assessment, including population dynamics, length based models, knowledge of crab life history and biology, harvest strategy models for invertebrates, and the AD Model Builder programming language.

Statement of Tasks for CIE Reviewers:

The CIE reviewers shall conduct necessary preparations prior to the peer review, conduct the peer review, and complete the deliverables in accordance with the ToR and Schedule of Milestones and Deliverables herein.

Prior to the Peer Review: The CIE shall provide the CIE reviewers contact information (name, affiliation, address, email, and phone), including information needed for foreign travel clearance when required, to the Office of Science and Technology COTR no later than the date as specified in the SoW. The Project Contact is responsible for the completion and submission of the Foreign National Clearance forms (typically 30 days before the peer review), and must send the pre-review documents to the CIE reviewers as indicated in the SoW.

Foreign National Clearance: If the SoW specifies that the CIE reviewers shall participate in a panel review meeting requiring foreign travel, then the CIE shall provide the necessary information (e.g., name, birth date, passport, travel dates, country of origin) for each CIE reviewer to the COTR who will forward this information to the Project Contact. The Project Contact is responsible for the completion and submission of required Foreign National Clearance forms with sufficient lead-time (30 days) in accordance with the NOAA Deemed Export Technology Control Program NAO 207-12 regulations at the Deemed Exports NAO link http://deemedexports.noaa.gov/sponsor.html

Pre-review Documents: Approximately two weeks before the peer review, the Project Contact will send the CIE reviewers the necessary documents for the peer review, including supplementary documents for background information. The CIE reviewers shall read the pre-review documents in preparation for the peer review. AFSC will provide: a) the most recent Stock Assessment Report, b) a copy of the Environmental Assessment for Crab Overfishing Definitions, c) copies of relevant articles from peer reviewed journals, d) a technical memorandum on AFSC crab groundfish trawl surveys, e) ADMB code for stock assessment and data files.

Panel Peer Review Meeting: The CIE reviewers shall participate and conduct the peer review participate during a panel review meeting as specified in the dates and location of the attached Agenda and Schedule of Deliverable. The Project Contact is responsible for any facility arrangements (e.g., conference room for panel review meetings or teleconference arrangements). The CIE Program Manager can contact the Project Contact to confirm the facility arrangements.

Terms of Reference:

The CIE reviewers shall conduct an impartial peer review in accordance to the Terms of Reference (ToR) herein, to ensure the best available science is utilized for the National Marine Fisheries Service (NMFS) management decisions

The CIE reviewers shall travel to Seattle, Washington from February 11-15, 2008 to discuss the stock assessment with the authors of the snow crab assessment. The reports generated by the CIE reviewers should include:

a. A statement of the strengths and weaknesses of the snow crab population dynamics and harvest strategy models;
b. Recommendations for alternative model configurations or formulations.
c. Suggested research priorities to improve the stock assessment.

Each CIE reviewer will complete a final CIE independent peer review report after the completion of the meeting in accordance with the ToR and the Schedule of Milestones and Deliverables with a copy each sent to Dr. David Die at ddie@rsmas.miami.edu and Mr. Manoj Shivlani at shivlanim@bellsouth.net no later than February 29, 2008.

Schedule of Milestones and Deliverables:

January 14, 2008	CIE shall provide the COTR with the CIE reviewer contact information, which will then be sent to the Project Contact
January 28, 2008	The Project Contact will send the CIE Reviewers the pre-review documents
11-15 February 2008	Each reviewer shall participate and conduct an independent peer review during the panel review meeting
February 29, 2008	Each reviewer shall submit an independent peer review report to the CIE
March 14, 2008	CIE shall submit draft CIE independent peer review reports to the COTRs
March 17, 2008	CIE will submit final CIE independent peer review reports to the COTRs
March 31, 2008	The COTRs will distribute the final CIE reports to the Project Contact

Acceptance of Deliverables:

Upon review and acceptance of the CIE reports by the CIE Coordination and Steering Committees, CIE shall send via e-mail the CIE reports to the COTRs (William Michaels William.Michaels@noaa.gov and Stephen K. Brown Stephen.K.Brown@noaa.gov) at the NMFS Office of Science and Technology by the date in the Schedule of Milestones and Deliverables. The COTRs will review the CIE reports to ensure compliance with the SoW and ToR herein, and have the responsibility of approval and acceptance of the deliverables. Upon notification of acceptance, CIE shall send via e-mail the final CIE report in *.PDF format to the COTRs. The COTRs at the Office of Science and Technology have the responsibility for the distribution of the final CIE reports to the Project Contacts.

Request for Changes:

Requests for changes shall be submitted to the Contracting Officer at least 15 working days prior to making any permanent substitutions. The Contracting Officer will notify the Contractor within 10 working days after receipt of all required information of the decision on substitutions. The contract will be modified to reflect any approved changes. The Terms of Reference (ToR) and list of pre-review documents herein may be updated without contract modification as long as the role and ability of the CIE reviewers to complete the SoW deliverable in accordance with the ToR are not adversely impacted.

Key Personnel:

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ANNEX 1

CIE REPORT GENERATION AND PROCEDURAL ITEMS

1. The report should be prefaced with an executive summary of findings and/or recommendations.

2. The main body of the report should consist of a background, description of review activities, summary of findings, and conclusions/recommendations.

3. The report should also include as separate appendices the bibliography of materials provided by the Center for Independent Experts and the center and a copy of the statement of work.

4. Individuals shall be provided with an electronic version of a bibliography of background materials sent to all reviewers. Other material provided directly by the center must be added to the bibliography that can be returned as an appendix to the final report.

ANNEX 2

Tentative Agenda

Bering Sea snow crab assessment review

NMFS Alaska Fisheries Science Center
7600 Sand Point Way NE, Building 4, Seattle, Washington
February 11-15, 2008 (Tentative Date)

Day 1

09:00 Welcome and Introductions
09:15 Overview (species, surveys, fishery, catch levels, bycatch)
10:00 Biology (growth, natural mortality, diets, spawning areas, nursery areas, maturity curves)
11:00 Field experiments on escapement, discard mortality, fertilization rate, tagging
11:30 Age Determination
12:00 Lunch
13:00 Harvest control rules and overfishing definition
15:00 Summary of on-going research
    Larval drift
    Spatial modeling
    Management Strategy Evaluation

Day 2

09:00 Ecosystem considerations
    Predation, prey
10:00 Economics
    Crab rationalization
10:30 Description of snow crab assessment model
12:00 Lunch
13:00 Continued discussions

Day 3

09:00 Examination of the harvest control rules
12:00 Lunch

Day 4 and 5

Reviewer discussions with assessment authors