REFERENCE POINT ESTIMATION ANALYSIS
FOR THE BERING SEA AND ALEUTIAN ISLANDS (KING AND TANNER) CRAB
REVISED FISHERIES MANAGEMENT PLAN

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Glossary

a, b, c, d = parameters in auxiliary models,

e = base of natural logarithms.

B = biomass, generally mature biomass,

BYM = constant annual instantaneous trawl and other fishery bycatch mortality (applicable to certain stocks),

CPT = Crab Plan Team,

CPUE = catch-per-unit-effort,

ESB and ESB_0 = effective spawning stock biomasses (adjusted for male to female mating ratio) corresponding to a fishing mortality *F* and *F* = 0, respectively,

ESB_{MSY} = effective spawning stock biomass at MSY producing level,

$ESB_{x\%}$ = effective spawning stock biomass at $F_{x\%}$,

esbfr, esbfr0, esbmr, esbmr0, esbtr, esbtr0 = effective spawning stock biomass-per-recruit of female, male and combined sexes corresponding to a fishing mortality *F* and *F* = 0, respectively,

esbr = effective spawning stock biomass-per-recruit without referring to any sex,

et = average time elapsed between the mid molting date (stock enumeration date; i.e., start of a biological year) and start date of a fishing period as a fraction of a year,

F = instantaneous full-selection fishing mortality for a biological year t,

FMP = Fishery Management Plan,

F_{MSY} = instantaneous full-selection fishing mortality that will produce MSY at the MSY-producing biomass,

F_{mmy} = instantaneous full-selection fishing mortality that will produce OY under Clark's method of determination,

F_{OFL} = 'overfishing' level instantaneous fishing mortality,

F_{ABC} = 'acceptable biological catch' level instantaneous fishing mortality,

$F_{x\%}$ = instantaneous full-selection fishing mortality that results in x% equilibrium spawning potential ratio,

GHL = Guideline Harvest Level,

h = proportion of discarded males and females died due to capture and release to sea,

HR_F = harvest rate at a given *F,*

l_2 and l_1 = lower and upper limits, respectively, of a receiving length interval *l* for $P_{l',l}$ estimation,

$\bar{l}$ = mean of growth increment,

M = annual instantaneous natural mortality,

MB_n = average total mature biomass available in year n,

MFMT = Maximum Fishing Mortality Threshold,

MSFCMA = Magnuson-Stevens Fishery Conservation and Management Act

MSY = Maximum Sustainable Yield,

MSST = Minimum Stock Size Threshold,

n = total number of length intervals available in a cohort for $P_{l',l}$ estimation,

$N_{l,t}$ = abundance in numbers in a length-class l, and age t of a cohort corresponding to a fishing mortality F,

OY = Optimum Yield, expected to be less than MSY,

$P_{l',l}$ = probability of crabs in a length group l' growing into a length group l (estimation methods are described in Appendix B),

s = standard deviation of growth increment,

sp = steepness parameter of the stock-recruitment curve, which can be estimated by setting sp*Rmax = R, where R is estimated at x% ESB_0 from the *S-R* model (usually x % = 20%)

SSB_{MSY} = mature stock biomass at MSY producing level,

S-R = spawner-recruit relationship,

SSC = Scientific and Statistical Committee,

TAC = Total Allowable Catch,

t_r = relative age at recruitment in year,

W_l = mean weight of crabs in a length-class l,

x = a random variable representing the annual growth increment,

$Z = F + M$, constant instantaneous total mortality,

$\tau_{l'}$ = mid length of a providing length interval l' for $P_{l',l}$ estimation,

$\alpha, \beta, \gamma,$ and θ = parameters in the *S-R* models,

λ = relative maximum age of a cohort in year,

δ = duration of average fishing period as a fraction of a year (handling and fishing mortality occur during this time period),

τ = a parameter estimated from a spawning biomass-per-recruit ratio, which influences the steepness near the origin and overall shape of the *S-R* curve, which is related to the steepness parameter, sp.

Executive Summary

Following the 1996 amendments of MSFCMA, the 1989 crab fisheries management plan (FMP) was substantially revised by the Crab Plan Team (CPT) in 1999 (NPFMC, 1999) and has been used since then. The review of this FMP was due five years later in 2004. The CPT appointed a working group consisting of four members in September 2003 to review the FMP with particular attention given to revising the crab overfishing and overfished definitions. Following the groundfish harvest control rule (NPFMC, 1998), a tier system consisting of five groups is proposed for Bering Sea and Aleutian Islands (BSAI) crab stocks (Appendix A). This draft report proposes HR_{MSY} and ESB_{MSY} proxies to tie to the tier system based on analysis of five major BSAI crab stocks (Bristol Bay red king crab, Bering Sea Tanner and snow crab, St. Mathew Island and Pribilof Islands blue king crab). It also suggests a number of improvements to the crab FMP.

The following two alternatives are considered:

Alternative 1. Status Quo. No revision to the 1999 crab FMP would be made, and the FMP would not be updated.

Alternative 2. (Preferred) Revise the 'overfishing' and 'overfished' definitions, their analysis methods, and implementation.

(2.1) Implement the Tier system given in Appendix A for BSAI crab management.

(2.2) As a proxy for F_{OFL} in the Tier formulas, use the following $F_{x\%}$ as legal harvest rate value at the fishing time:

(a) Red king crab: F_{50} (legal harvest rate = HR_{31}, mature harvest rate at the survey time = HR_{17})

(b) Blue king crab: F_{60} (legal harvest rate = HR_{31}, mature harvest rate at the survey time = HR_{17})

(c) Snow crab: F_{60} (legal harvest rate = HR_{57} mature harvest rate at the survey time = HR_{19})

(d) Tanner crab: same as those for snow crab

(e) For other crab stocks: if ESB/R and ESB are not estimable, then γM or average catch during an ecologically stable period should be used as proposed in the Tier system (Appendix A).

Implement a threshold spawning biomass of 25% of ESB_{MSY}. Mean recruitment during a selected period is used to estimate ESB_{MSY} or SSB_{MSY} for Tier 1 and 2 stocks. The selected period is an ecologically stable period for the stock, which is determined by the stock assessment scientist responsible for analysis in concurrent with the CPT and SSC.

(2.3) Target F_{TAR}:

Target legal harvest rate for F_{TAR} must be below HR_{OFL} and are determined by the State of Alaska crab harvest strategies.

Note: The harvest rates are applicable to the total legal abundance at the fishing time. Therefore, the abundance during summer surveys is projected to the start of the fishing period by discounting for M as well as trawl and other fishery bycatch mortality to compute TAC.

Under Alternative 1, the MSY is estimated considering the total of male and female mature crab biomasses from survey data. Consequently, this MSY can be compared only with the total harvest of male and female crabs. However, only males are harvested in the BSAI crab fisheries. In addition, MSY and B_{MSY} are estimated assuming $F_{MSY} = M$. However, simulation results indicate that F_{MSY} is different from M. Furthermore, equating current mature stock biomass to a fraction of the static average size of the total mature biomasses for 1983-1997 (i.e., MSST) for determining 'overfished' status is not appropriate with varying ecological conditions during different productivity periods.

Under Alternative 2, the F_{MSY} or its proxy ($F_{x\%}$, γ^*M, or average catch) is estimated for F_{OFL} to incorporate into the harvest control rule formulas listed in the Tier system (Appendix A). Whether the stock is in the 'overfishing' or 'overfished' status is determined by comparing the estimated equivalent legal harvest rate and the effective spawning biomass (or total mature biomass) with F_{OFL} and critical effective spawning biomass (or total mature biomass). A default 25% value to determine critical effective spawning biomass (or total mature biomass) from an effective spawning biomass at the MSY level during a selected period is suggested based on limited analysis with red king and snow crab stocks.

1 Introduction

Management of fishery resources in the Exclusive Economic Zone (EEZ, 3 to 200 nautical miles) waters of the US is based on the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA), first passed by the U.S. Congress in 1976 and amended several times, with the last substantial amendment made in 1996. The 1996 amendments to the MSFCMA were concerned with redefining OY and stressing a precautionary approach to managing fisheries (Restrepo et al., 1998; Restrepo and Powers, 1999). Eight regional fishery management councils (Councils) were established under MSFCMA to manage EEZ fishery resources. They are entrusted with developing Fisheries Management Plans (FMP) in accordance with MSFCMA policy guidelines to manage fish stocks or stock complexes in their regions of Federal waters. The North Pacific Fishery Management Council (NPFMC) is responsible for managing fishery resources in the EEZ off Alaska and has been managing the king and Tanner crab fisheries in the EEZ of the Bering Sea and Aleutian Islands (BSAI) by implementing FMPs since 1984. Following the 1996 amendments of MSFCMA, the 1989 FMP was substantially revised by the NPFMC Crab Plan Team (CPT) in 1999 (NPFMC, 1999) and has been used since then.

The CPT appointed a four member committee in September 2003 to review the current FMP. This report proposes new 'overfishing' and 'overfished' definitions based on rigorous length-based assessment of five major BSAI crab stocks: Bristol Bay red king crab, Bering Sea Tanner and snow crab, and St. Mathew Island and Pribilof Islands blue king crab. Recent biological and fishery data on these stocks were used in deterministic and stochastic simulation models to determine F_{MSY}, F_{OFL}, HR_{OFL} and critical biomass reference points.

2 Purpose of and the Need for the Review

When the 1999 report on revised overfishing definitions and updates of BSAI crab FMP was prepared, it was agreed by the CPT to review the 'overfishing' and 'overfished' estimates on a five-year cycle or in the event that environmental conditions signal a regime shift. Therefore, the current review of FMP is timely. The 1999 report did not fully utilize the technical guidelines on precautionary management prepared by Restrepo et al. (1998). The analyses for the current review followed a number of Restrepo et al.'s suggestions.

Alternative 2 in NPFMC (1999) defines the overfishing level by a constant fishing mortality MSY Control Rule equating F_{MSY} on mature population abundance to M. When the current F is greater than M, the stock is considered to be in an overfishing status. It defines the overfished status by the MSST, which is equal to half of the MSY stock size in most cases. If the current biomass is less than MSST, the stock is considered overfished. The MSY stock size is estimated as the average biomass observed over a 15-year period from 1983 to 1997, which is considered to be an ecologically stable period. These surrogates (M for F_{MSY} and mean annual total mature biomass for MSY stock size) are identified for crab management because the BSAI crab stocks are poorly understood and rigorous stock assessment methods for a number of stocks are yet to be developed. Furthermore, assessment of crab fisheries has been complicated by the fact that only males are harvested and that recruitment, in many instances, is largely driven by environmental factors rather than density-dependent responses. During the 1990s, catch survey analysis (CSA), catch length analysis (CLS), and length-based analysis (LBA) have been developed and applied on a number of BSAI crab stocks to determine historical stock trends, size distributions, and alternative harvest strategies (e.g., Zheng et al., 1995a; Turnock, 2004). Length-based assessment methods have been used to determine biological reference points for some BSAI crab stocks (e.g., Siddeek, 2002, 2003a, 2003b; Siddeek et al., 2004). Besides redefining the 'overfishing' and 'overfished' levels, this report simplifies the application of reference points on crab stock status determination and management.

3 Current BSAI Crab Fishery Management Strategies

Major king and Tanner crab stocks in the Federal EEZ waters in the BSAI are managed under the Federal FMP for king and Tanner crab fisheries in the BSAI. The FMP is developed by the NPFMC under the MSFCMA. The MFMT (= F_{MSY}) and MSST (=1/2 SSB_{MSY} in most cases) in the MSY Control Rule are used as bench marks for determining the status of a stock. If the stock is overfished a Target Control Rule is used for rebuilding the stock to the MSY producing level. Because of the lack of reliable F_{MSY} estimates for crab stocks, M is used as a surrogate for F_{MSY}. Furthermore, because of the lack of plausible M estimates for each crab stock, an M of 0.2 for the king crab group and an M of 0.3 for the *Chionoecetes* group have been adopted.

In addition, ADF&G on its own or with the help of NMFS and the CPT has developed harvest strategies for king (red and blue), Tanner, and snow crab stocks in selected fisheries of the Bering Sea in accordance with the Alaska Board of Fisheries (Board) policy on king and Tanner crab resources management. The harvest strategies aim at keeping sufficient spawning biomass for

stock productivity by controlling the removal of mature males. According to the Board's policy, harvest rate and the guideline harvest level (GHL) are determined for each exploitable portion of a stock, and threshold stock size level (mainly of mature portion) and threshold GHL for a few stocks (ADF&G, 2001) are also estimated for assessing stock viability and manageability under continued fishing. The stock size threshold levels are determined only for those stocks having sufficient fisheries and biological data and adequate stock assessment analysis. If the preseason standing stock size goes below the threshold levels, and in some fisheries, if the preseason estimates of GHL are lower than the minimum acceptable GHL, the fishery is closed for the entire season. If it is above the threshold levels, a harvest rate, in some cases a stair-step, is applied, depending on the standing stock size, to calculate GHL. To avoid over harvest of legal males within the GHL, up to a 50% cap on harvest of legal males is enforced in most fisheries (Pengilly and Schmidt, 1995). Incidental mortality of crabs in other fisheries (trawl, fish pot, and dredge) is reduced by enforcing closed areas and a maximum allowable crab bycatch percentage (of the crab abundance) in those fisheries (ADF&G, 2001; NPFMC, 2001).

Currently, Bristol Bay red king crab, Bering Sea Tanner and snow crabs, Pribilof Islands red and blue king crabs, and St. Matthew Island blue king crab are managed under a Federal FMP along with the State harvest strategies. All the other crab stocks are managed by the State harvest strategies. A new rationalized crab fishery system was introduced in August 2005, in which a total allowable catch (TAC) is set by the State of Alaska harvest strategies and the fishery is conducted by an individual fishery quota (IFQ) system with an extended season.

Annual trawl surveys are conducted in BSAI Federal waters by the NMFS and in some State waters by ADF&G to determine crab stock abundance by sex, size, maturity, and shell age using an area swept method of analysis. Because trawl surveys are subject to sampling errors, catch survey analysis (CSA) is used in some stocks to obtain better stock abundance estimates. For those stocks having long time series of length frequency and trawl survey abundance data (e.g., Bristol Bay red king crab, Bering Sea snow crab), length-based analysis (LBA) is used for fine-tuning stock abundance estimates. The abundance estimates are used to compare the status of standing stock size with the Federal overfishing and State threshold levels for opening the fishery and to determine the TAC on an annual basis. Some crab stocks are not surveyed annually (e.g., the Norton Sound red king crab stock is surveyed triennially using trawl gear and annually using pot gear; and the Aleutian Islands golden king crab stock is surveyed triennially by pot gear), while some others are not surveyed at all (e.g., deepwater grooved and triangular Tanner cab

stocks). For those stocks having no annual stock abundance estimates, TACs are determined based on either the very recent abundance estimates or historical average harvests. In addition, the current stock status of un-surveyed stocks is determined by fisheries performance analysis (FPA). The FPA involves examining CPUE, size, sex, maturity, and shell age compositions, amount of sub-legal crab discards, amount of other crab bycatch, and prohibited areas of fishing in the recently concluded fisheries.

Most BSAI crab fisheries are managed by sex, size, and season with a TAC determined from either stock biomass or long-term mean harvest. Only male crabs above minimum legal size are allowed to be retained for marketing. Single sex harvest has been in force since the late 1940's to protect mature females for sufficient recruit production. Specific fishing seasons are set to avoid harvesting crab during mating and molting (soft-shell) periods.

4 Alternatives Considered

Alternative 1. Status Quo. No revision to the 1999 crab FMP would be made, and the FMP would not be updated.

Alternative 2. (Preferred) Revise the 'overfishing' and 'overfished' definitions, their analysis methods, and implementation.

(2.1) Implement the Tier system given in Appendix A for BSAI crab management.

(2.2) As a proxy for F_{OFL} in the Tier formulas, use the following $F_{x\%}$ as legal harvest rate value at the fishing time:

(a) Red king crab: F_{50} (legal harvest rate = HR_{31}, mature harvest rate at the survey time = HR_{17})

(b) Blue king crab: F_{60} (legal harvest rate = HR_{31}, mature harvest rate at the survey time = HR_{17})

(c) Snow crab: F_{60} (legal harvest rate = HR_{57} mature harvest rate at the survey time = HR_{19})

(d) Tanner crab: same as those for snow crab

(e) For other crab stocks: if *ESB/R* and *ESB* are not estimable, then γM or average catch during an ecologically stable period should be used as proposed in the Tier system (Appendix A).

Implement a default threshold spawning biomass of 25% of ESB_{MSY}. Mean recruitment during a selected period is used to estimate ESB_{MSY} or SSB_{MSY} for Tier 1 and 2 stocks. The selected period is an ecologically stable period for the stock, which is determined by the stock assessment scientist responsible for analysis in concurrent with the CPT and SSC.

(2.3) Target F_{TAR}:

Target legal harvest rate for F_{TAR} must be below HR_{OFL} and are determined by the State of Alaska crab harvest strategies.

4.1 OY

(i) OY Definition

The term "optimum," with respect to the yield from a fishery, means the amount of crab which- (a) will provide the greatest overall benefit to the Nation, particularly with respect to food production and recreational opportunities, and taking into account the protection of marine ecosystems; (b) is prescribed as such on the basis of MSY from the fishery, as reduced by any relevant economic, social, or ecological factor; and (c) in the case of an overfished fishery, provides for rebuilding to a level consistent with producing the MSY in such fishery.

(ii) Estimation of OY

The BSAI crab regulatory process considered social (e.g., desire for stabilized economy) and economic factors (e.g., low marketability of females and small males) as well as biological (e.g., growth, mortality, abundance) factors in formulating harvest strategies and hence harvests reflected the OY concept. Crab in the BSAI are currently managed to optimize yield. As a result, the following set of Control Rules is already in operation to reduce MSY by appropriate factors:

(ii.a) no harvest of female crabs (sex restriction);
(ii.b) only crabs greater than or equal to a minimum size limit may be harvested (size restriction);

(ii.c) TAC estimated from exploitation rate strategy or fishery performance data;
(ii.d) non-retained catch of directed fishery harvest; and
(ii.e) non-directed fishery harvest including subsistence, sport, and bycatch.

(iii) Management Practice to Achieve OY

The ADF&G in consultation with NMFS recommends appropriate management measures for a given year and geographical area consistent with the Board's policy on king and Tanner crab resource management, the FMP, the MSFCMA, and other State and Federal laws. In addition, the Board has established state harvest strategies that are consistent with the Board's policy on king and Tanner crab management. The harvest strategies aim at minimizing the risk of overfishing and obtaining OY below MSY (NPFMC, 1999).

4.2 MSY

(a) Alternative 1

(i) MSY Definition

The largest long-term average catch or yield (of crab) that can be taken from a stock or stock complex under prevailing ecological and environmental conditions.

(ii) Estimation of MSY

Several BSAI crab stocks have insufficient scientific data to estimate management reference points. The MSY is computed as the 15-year mean harvest at F_{MSY} (=M) from the biomass of the male and female portion of the mature population or total mature biomass (MB_n) of a stock. This choice resulted in lower MSY estimates for many stocks compared to those obtained by considering fully developed fishery periods defined in previous FMPs (see NPFMC 1999). The M is estimated by taking the largest crab size, converting this to age, and then computing M from Hoenig's (1983) M to longevity formula. An annual M value of 0.2 for king crabs and an M value of 0.3 for *Chionoecetes* species are used.

For reference point estimation, the 15-year period from 1983 to 1997 is considered adequate to satisfy both terms, "long-term" and "current environmental conditions," specified in the National Standard guidelines for estimating MSY. The CPT considered this period as representative of current environmental conditions because: (1) many crab stocks seem to have declined until the early 1980s and then stabilized; (2) finfish populations that increased sharply during the late 1970s (regime shift) seem to have stabilized somewhat by 1983; (3) recruitment from the generally high crab populations of the 1970s would have been evident or have dissipated by 1983; and (4) conditions in crab populations (particularly red and blue king crabs) are relatively stable over this period.

The MB_n for surveyed king crab stocks is computed by considering the catchability in survey trawl of each 5 mm carapace length (CL) size group of crabs, the proportion mature, the mean weight, and unadjusted survey index abundance for each size and sex group. The MB_n for surveyed Tanner and snow crabs is computed by considering the proportion mature, the mean weight, and unadjusted survey index of abundance (i.e., assuming a catchability value of 1) for each 5 mm carapace width (CW) size group of crabs and sex group. The MB_n for year n is taken as the sum of biomass over size and sex and considered as the annual average biomass available for a single stock. The sustainable yield for year n is estimated using the equation $SY_n = M*MB_n$ and MSY is determined as the average of SY_n estimates over 15 years (1983-1997).

For stocks that are not surveyed or only have limited time series of survey data, MB_n is estimated in part using a ratio of legal biomass to mature biomass and corresponding utilization rate for representative stocks (see NPFMC (1999) for the details). The MSY is estimated using this MB_n in the MSY estimation equation described in the previous paragraph. The Bristol Bay red, Pribilof Islands red and blue, and St. Matthew Island blue king crab stocks are selected to estimate the proxy mature biomass and utilization rates for the Western Aleutian Islands stock of red king crabs. These stocks are also used as the proxy stocks for the deep water king crabs: Aleutian Islands and Bering Sea scarlet king crabs, and the Aleutian Islands, Pribilof Islands and St. Matthew Island golden king crab stocks. Both Tanner and snow crabs are used as representative proxy stocks for the Eastern and Western Aleutian Islands Tanner crab stocks and deep water Tanner crabs (*Chionoecetes tanneri* and *C. angulatus*) stocks in the Eastern and Western Aleutian Islands and Eastern Bering Sea.

In the current FMP, MFMT is represented by a proxy, SY_n , in a given year, which is the MSY rule applied to the current estimated spawning biomass (the MSY control rule is $F_{MSY} = 0.2$ for king crabs, and $F_{MSY} = 0.3$ for Tanner crabs). Overfishing occurs if the estimated GHL (or TAC) exceeds the SY_n in one year (SAFE 2004).

(b) Alternative 2

The MSY definition for BSAI crab stocks under Alternative 1 follows the NMFS National Standard 1 guidelines and complies with the MSFCMA. Therefore, the definition remains the same under Alternative 2. However, the estimation method requires modifications.

First, The MSY is currently estimated considering the total male and female mature crabs. Consequently, this MSY can be compared only with the total harvest of male and female crabs. However, only males are legally harvested in the BSAI crab fisheries. Therefore, for fishery performance determination, MSY should be estimated considering only legal male biomass or retained male biomass. Furthermore, because of spatial segregations and behavior of sexes, trawl survey catchability and pot fishery catchability for females are very low compared to the same size group of males for a number of crab stocks. For example, snow crab female catchability is much lower than that of sublegal males (Zheng, 2003). Therefore, estimation of mature female abundance will be somewhat biased and may introduce errors in the MSY estimation.

Second, M is currently used as a proxy for F_{MSY} in estimating SY_n. Maintaining F at the M value on mature stocks is believed to produce yields near MSY (Alverson and Pereyra, 1969; Gulland, 1970). However, M is rarely equal to F_{MSY} under many different stock conditions (Francis, 1974; Deriso, 1982; Thompson, 1992, Quinn et al., 1999). For the five BSAI crab stock analyses (Bristol Bay red, St. Matthew Island blue, Pribilof Islands blue; and Bering Sea Tanner and snow crabs) reported here, F_{MSY} could take any value - above, equal, or below M, depending on the steepness of the S-R curves near the origin and other life history parameters.

Under Alternative 2, either direct estimation of F_{MSY} or HR_{MSY} (if possible) or estimation of its proxy, $HR_{x\%}$, to incorporate into the Tier system (Appendix A) is proposed. The HR_{MSY} can be used to estimate the MSY knowing the MSY biomass. A default 25% of the MSY level spawning biomass is suggested for threshold minimum biomass below which the fishery is closed.

The length-based analysis procedure cannot be applied to stocks lacking many life history parameters. Those stocks include Tier 1 (data-poor) and some Tier 2 (limited-data) stocks as defined in the old Tier system (NPFMC, 1999). In this case, it is recommended to assign them to appropriate Tier levels (Tiers 4 and 5) in the new Tier system (Appendix A), which do not require F_{MSY}, ESB_{MSY}, $F_{x\%}$, and $ESB_{x\%}$ estimates.

5 Determination of 'Overfishing' and 'Overfished' Reference Points for Five BSAI Crab Stocks

5.1 Overfishing Level Fishing Mortality, Harvest Rate, and Effective Spawning Biomass by Deterministic Simulations

Deterministic simulations were carried primarily for sensitivity analysis of the input parameters. Mace (1994) derived a set of formulas based on total mature biomass per recruit (*SSB/R*) to investigate trends in various mortality and biomass reference points for finfish types of stock parameters under deterministic Beverton and Holt (1957) and Ricker (1954) *S-R* models. Clark (1991, 1993) derived the $F_{x\%}$ harvest rate for groundfish types of stock parameters under deterministic and stochastic Beverton and Holt, and Ricker *S-R* models. The deterministic and stochastic simulations for BSAI crab stocks follow the same approaches proposed by these two researchers, but with a number of modifications and improvements suitable for crab life history (see the flow chart of the analytical methods in Appendix B and computation formulas in Appendix C). The Clark's method was used only to locate an approximate $F_{x\%}$ and detail simulation analyses were carried to identify appropriate $F_{x\%}$ values for each stock. The simulation models were developed in FORTRAN with IMSL subroutine (IMSL, 2000) to determine F_{MSY}, HR_{MSY}, $F_{x\%}$, and threshold *ESB*. In this section, results from deterministic simulations for base input parameter values (Appendix D) are provided.

5.1.1 Bristol Bay Red King Crab

Male crabs are fully mature by 120 mm CL (Zheng et al., 1995a). Approximately 50% of females mature by 89 mm CL and 80% by 95 mm CL (Otto et al., 1990). A size range of 65-200 mm CL for males and a size range of 65-165 mm CL for females were considered in the simulations. This was to include immature sizes of crabs as initial recruits to the cohorts. Appendix D(a) provides the input base parameter values.

Table 1 provides results of various reference point estimates for steepness parameter (*sp*) values in the range of 0.51 to 0.79 (= τ values of 0.1 to 0.4), and at three mating ratio values, 1:2, 1:3 and 1:4, under Beverton-Holt and Ricker S-R models with female *ESB*. Although mating ratios from 1:2 to 1:4 were possible depending on the male size, a mating ratio of 1:3 was a plausible average value and appeared to be conservative for reference point estimation. The Ricker models have been fitted to the Bristol Bay red king crab stock with female *ESB* (Zheng et al, 1995a, 1995b).

The 1968- 1996 spawner–recruit data provided the following τ and equivalent steepness (*sp*) estimates from the Ricker model using 1968-2005 data:

$$\hat{\alpha} = e^{ln(\alpha) + \frac{\sigma^2}{2}} = 1.74$$

$$\tau = \frac{1}{esbfr0 \times \hat{\alpha}} = \frac{1000}{4241.283 \times 1.67} = 0.14$$

$$sp = \frac{1}{5} \times e \times \tau^{0.2} \; ln(\frac{1}{\tau}) = 0.72$$

On the other hand, when only the 1977-2005 data (i.e., after the regime shift) were used, the τ and steepness (*sp*) parameter values were, 0.21 and 0.62, respectively.

The F_{MSY} and HR_{MSY} decreased with reduced steepness. On the other hand, the percentage of effectively mated female increased with reduced steepness. The F_{MSY} at a plausible steepness value of 0.63, Ricker *S-R* curve with female *ESB*, ranged 0.38 to 0.68, and the corresponding legal male harvest rate at the time of the fishery, HR_{MSY} *%,* ranged 26 to 40 for 1:2 to 1:4 mating ratios.

The $F_{x\%}$ estimate following Clark's method (1991) resulted in F_{51} for deterministic Beverton-Holt and Ricker *S-R* curves with base parameter values, female *ESB*, a mating ratio of 1:3, and a steepness range of 0.51-0.79 (Table 2). The corresponding fishing mortality, $F_{mmy,}$, and legal male harvest rate, HR_{mmy}*%,* were 0.44 and 29, respectively. At this harvest rate, 84% of MSY was achieved with 60% effectively mated females.

5.1.2 Bering Sea Snow Crab

Approximately 50% of males mature by 75 mm CW and 50% of females mature by 50 mm CW (Otto, 1998). A size range of 25-135 mm CW for both sexes was considered in the simulations. As mentioned before, this was to include immature sizes of crabs as initial recruits to the cohort. Appendix D (b) provides the input base parameter values. Terminal molt at maturity was assumed for both sexes in all simulations. In the *ESB* calculation, the primiparous spawning biomass was discounted by 20% to account for reduced reproductive output by primiparous compared to multiparous females.

Tables 3 provides results of various reference point estimates for steepness values in the range, 0.41 to 0.79, and at three mating ratio values, 1:2, 1:3 and 1:4, under deterministic Beverton-Holt and Ricker S-R models with combined sexes (i.e., total) ESB. Even though the Beverton-Holt model has been fitted in a snow crab assessment (Turnock, 2004), the model does not explain much variation of recruitment. Because of the high steepness value near the origin of the Beverton-Holt S-R curve, a Ricker model was fitted to estimate τ (see Clark, 2002). The 1978-2003 S-R data provided τ and *sp* estimates of 0.07 and 0.85 respectively for combined sexes ESB. On the other hand, when only the data after 1990 (low production period) were considered, the corresponding estimates were 0.28 and 0.54, respectively.

The trends in F_{MSY}, $HR_{MSY}\%$, %MSY achieved, and mated female proportion were similar to those for the red king crab, but the fishing mortality and harvest rate values were higher due to different life history and fishery parameter values (Table 3). The estimates of F_{MSY} and HR_{MSY} *%* at the plausible steepness value of 0.79 and for the mating ratio of 1:2 were, 1.26 and 59 respectively for the Beverton-Holt S-R model, and 2.71 and 85 respectively for the Ricker S-R model with combined sexes *ESB*.

The $F_{x\%}$ estimate following Clark's method (1991) resulted in F_{59} under Beverton-Holt and Ricker S-R curves with base parameter values, combined sexes *ESB*, a mating ratio of 1:2, and a steepness range of 0.51-0.79 (Table 4). The corresponding F_{mmy} and HR_{mmy} *%* were 1.26 and 59, respectively. At this harvest rate, 92% of MSY was achieved.

5.1.3 Sensitivity Analysis of Reference Point Estimation Using Red King Crab Life History and Fishery Information

Table 5 provides the estimates of F_{MSY}, HR_{MSY} *%*, and percentage of effectively mated females for changes in various input parameter values. The minimum legal size was kept at the current size (135 mm CL) for the sensitivity analysis. When the effective *ESB* unit was changed from female to combined sexes, F_{MSY} and HR_{MSY} *%* reduced very slightly. When the female *M* value was increased by 25%, the F_{MSY} and HR_{MSY} *%* increased from 0.53 and 34 to 0.73 and 42, respectively. Changing the fishing period to October 15-January 15 (i.e., the new fishing period (0.2548 yr) under crab rationalization policy) did not appreciably affect the reference point estimates. But increasing the handling mortality rate from 20% to 50% reduced the F_{MSY} and HR_{MSY} *%* estimates. Changing the start date of the fishery from October 15 to December 15 (i.e., lapsed time from

molting to start of fishery increased to 0.7096 yr) did not affect the reference point estimates. Changing the female spawning biomass computation procedure by assuming pre-molt size in the length-weight calculation did not affect the reference point estimates as well. However, changing the mating ratio from 1:3 to 1:2.209, calculated as the sex ratio at F=0, substantially reduced the F_{MSY} , HR_{MSY} %, and % mated female estimates.

5.2 Overfishing Level Fishing Mortality, Harvest Rate, and Effective Spawning Biomass by Stochastic Simulations

5.2.1 Stochastic Simulation Method

Stochastic simulations were carried out with random recruitments to explore the viability of the $F_{x\%}$ and critical biomass ratio under different scenarios**.** The stochastic simulations with a range of $F_{x\%}$ (mainly a range of F_{50} to F_{60}, as suggested by the expert work shop in February 2006, was used) were performed to choose appropriate $F_{x\%}$ for each stock.

Simulations were initiated with 2000 immature new-shell recruits divided equally between males and females and distributed to each length bin by a probability function (gamma or normal). Full age structure was established by projecting the initial recruits through its entire life span up to a maximum age (26+ years for king crabs, and 20+ years for males and 15+ for females *Chionoecetes* species) with a given set of mortality and growth parameter values. Once the full age-structure has been achieved, the same population structure was repeated for a number of years, equivalent to the recruitment year. Then the mature component of each full age-structured population was used in a *S-R* model (Beverton-Holt or Ricker) to generate the number of recruits entering the simulated population with a time lag equivalent to the recruitment age (6 years for king and 5 years for Tanner and snow crabs). Each full-age-structured population was projected successively for a number of years with constant mortality, growth, and deterministic recruitment to stabilize the age structure (77 years for king and 76 years for Tanner and snow species appeared sufficient for stabilization) and thereafter the predicted number of recruits were randomized with a log-normal random error for a 100-year fishing period. The random error structure consisted of an overall recruit variance (σ^2) and a serial correlation (ρ). A base value of 0.7 for σ and 0.5 for ρ (Zheng et al., 1995b, Siddeek et al. 2004) were used in the simulations. The stochastic program codes were first checked to produce deterministic results with a deterministic Beverton-Holt S-R model and found to be satisfactory. A number of statistics, mean relative yield, CV of yield, proportion of years overfished, rebuilding possibility from a low *ESB*

level, were determined from this 100-year fishery to explore the viability of $F_{x\%}$ and critical biomass ratio. A set of hundred trials of 100-year fishery simulations with a given $F_{x\%}$ was also carried out to determine the distribution of the rebuilding time from a low *ESB* level.

Intensity of analysis for different stocks varied with the availability and reliability of base input parameter values in the following order: Bristol Bay red king crab, Bering Sea snow crab, St. Mathew Island blue king crab, Pribilof Islands blue king crab, and Bering Sea Tanner crab. Only one set of stochastic simulations was carried for each of the Tanner and blue king crab stocks to determine $F_{x\%}$. The flow chart of the stochastic method is depicted in Appendix B and the model equations are provided in Appendix C.

5.2.2 Bristol Bay Red King Crab

The $F_{x\%}$ estimate following Clark's method resulted in F_{55} for stochastic Beverton-Holt and Ricker S-R curves with base parameter values, female *ESB*, a mating ratio of 1:3, and a steepness range of 0.51-0.79 (Figure 1(a)). The corresponding F_{mmy} and HR_{mmy} % were 0.39 and 27%, respectively. At this harvest rate, 82% of MSY was achieved. A range of $F_{x\%}$ values from F_{50} to F_{60} were tried in the diagnostic tests described in section 5.2.7 to choose a precautionary $F_{x\%}$ value for the red king crab stock.

5.2.3 Bering Sea Snow Crab

The $F_{x\%}$ estimate was F_{58} for stochastic Beverton-Holt and Ricker S-R curves with base parameter values, combined sexes *ESB*, a mating ratio of 1:2, and a steepness range of 0.51-0.79 (Figure 1(b)). The corresponding F_{mmy} and HR_{mmy}% were 1.29 and 60%, respectively. At this harvest rate, 93% of MSY was achieved. A range of $F_{x\%}$ values from F_{50} to F_{60} were tried in the diagnostic tests described in section 5.2.7 to choose a precautionary $F_{x\%}$ value for this stock.

Because of limitation (or inadequate) of biological and fisheries input parameter values for the other stocks, Tanner and blue king crab stocks, the high end of the $F_{x\%}$ range considered for the first two stocks was used for the diagnostic tests. The $F_{x\%}$ estimates for these stocks following Clark's approach (Figure 1) justified the choices.

5.2.4 Bering Sea Tanner Crab

Approximately 50% of males mature by 115 mm CW and 50% of females mature by 80 mm CW (Zheng et al. 1998). Therefore, the size ranges 50-170 mm CW for both sexes were considered.

This was to include immature sizes of crabs as initial recruits to the cohorts. Appendix D(c) provides the input base parameter values. Terminal molt at maturity was assumed for both sexes in all simulations. In the *ESB* calculation, the primiparous spawning biomass was discounted by 30% to account for reduced reproductive output by primiparous compared to multiparous females.

The $F_{x\%}$ estimate was F_{66} for stochastic Beverton-Holt and Ricker S-R curves with base parameter values, combined sexes *ESB*, a mating ratio of 1:2, and a steepness range of 0.51-0.79 (Figure 1(c)). The corresponding F_{mmy} and HR_{mmy}% were 1.64 and 72%, respectively. At this harvest rate, 95% of MSY was achieved.

5.2.5 Pribilof Islands Blue King Crab

Approximately 50% of males mature by 108 mm CL and 50% of females mature by 96.3 mm CL (Somerton and MacIntosh 1983). Therefore, the size ranges 65-170 mm CL for both sexes were considered. This was to include immature sizes of crabs as initial recruits to the cohorts. Appendix D(d) provides the input base parameter values. Some important life history parameter estimates were lacking for this stock and they were borrowed from the St. Mathew stock, e.g., growth increment and pot selectivity parameter values. For blue king crab stock simulations in 5.2.5 and 5.2.6, biennial spawning characteristics of females was used by assuming that the mated females molt once in two years.

The $F_{x\%}$ estimate was F_{64} for stochastic Beverton-Holt and Ricker S-R curves with base parameter values, female *ESB*, a mating ratio of 1:3, and a steepness range of 0.51-0.79 (Figure 1(d)). The corresponding F_{mmy} and HR_{mmy} % were 0.37 and 29%, respectively. At this harvest rate, 83% of MSY was achieved.

5.2.6 St. Mathew Island Blue King Crab

Approximately 50% of males mature by 77 mm CL and 50% of females mature by 80.6 mm CL (Somerton and MacIntosh 1983). Therefore, the size ranges 60-155 mm CL for both sexes were considered. This was to include immature sizes of crabs as initial recruits to the cohorts. Appendix D (e) provides the input base parameter values.

The $F_{x\%}$ estimate was F_{58} for stochastic Beverton-Holt and Ricker S-R curves with base parameter values, female *ESB*, a mating ratio of 1:3, and a steepness range of 0.51-0.79 (Figure

1(e)). The corresponding F_{mmy} and HR_{mmy}% were 0.47 and 32%, respectively. At this harvest rate, 82% of MSY was achieved.

5.2.7 Evaluation of Tier System Parameters: α, β, γ

Tiers 1 to 3 require values of α and β parameters whereas Tier 4 requires these two and the γ parameter. Probable values for the first two parameters were investigated by considering three steps values for α (0.0, 0.05, and 0.1) and β (0.2, 0.25, and 0.3). The Bristol Bay red king and Bering Sea snow crabs' life history and fishery parameter values were used to investigate these parameters. On the other hand, at this time, only the Bristol Bay red king crab's life history and fishery parameter values were used to investigate the γ parameter. A range of values, 0.4, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, and 5.0, was considered in the investigation of the γ parameter. For simplicity, the α and β values were fixed at selected values from their separate investigation.

The parameters were evaluated by rebuilding analyses. A stock is rebuilt from a low level (i.e., β*ESB_{MSY} level) to the ESB_{MSY} level under a given $F_{x\%}$ with a stochastic recruitment and various statistics were computed during the rebuilding process: mean rebuilding time, median rebuilding time, confidence interval of rebuilding time (CI), percentage of times the rebuilding occurred within 10 years; mean yield, coefficient of variation of yield, and percentage of years the stock is depleted (overfished). The first four statistics were estimated from 100 simulations of 100-yr fishery with random recruitment; and the last three statistics were computed from a single simulation of a 100-yr fishery with random recruitment (see Appendix C for the stochastic formulation of the *S-R* models).

5.2.7.1 Bristol Bay Red King Crab

The simulated population produced an ESB_{MSY} of 3795.3 kg for the Ricker S-R curve with the steepness value 0.62 and 3275.2 kg for the Beverton and Holt S-R model with the steepness value 0.51 (we intentionally selected low productivity *S-R* curves in the rebuilding analysis).

For evaluating the Tier system parameters, rebuilding the stock from the β* ESB_{MSY} stock level to the MSY level, under the proposed harvest-control rule (Appendix A) with a selected constant $F_{x\%}$, was investigated by simulating one hundred of 100-year fishery under stochastic Ricker *S-R* model with a steepness value of 0.62, female *ESB*, and a mating ratio of 1:3. $F_{x\%}$ values at a step of 5 from F_{50} to F_{60} as well as different combinations of β and α at a step of 0.05 were used. The

trends of results were similar for different $F_{x\%}$ values; therefore, only the results for F_{50} are given in Table 6. Mean and median rebuilding times tend to be lower as β and α values tend to be higher. There are overlaps in the confidence intervals of mean rebuilding time and no much difference among the CV of yields although mean yield tends to be higher at higher β and α values. There is no much of a choice between β and α combinations, 0.25, 0.1 and 0.3, 0.1 (Table 6). We chose the former as a default value because the rebuilding analysis with much lower productive Beverton and Holt model with a steepness value of 0.51 under F_{50} and these β and α values rebuilt the stock within a reasonable time period (~ 11 years) compared to the mean generation time (14.2 years) estimated following Restrepo et al.'s (1998). The latter analysis was also a diagnostic test for choosing F_{50} (Table 6).

A number of additional diagnostic investigations were carried out for the suitability of selected F_{OFL}. Although variability of the coefficient of variation of yield (CV) among different steepness values reduced with increasing $F_{x\%}$ values, the F_{50} harvest rate produced somewhat tight CV values for steepness > 0.51. The mean yields were also not dramatically increased with increasing $F_{x\%}$ beyond F_{50} for different steepness values > 0.51 (Figure 2). The proportion of years *ESB* was depleted to < 25% ESB_{MSY} (overfished level) was < 0.15 for all steepness values under F_{50} (Figure 3).

The rebuilding time and yield statistics were also computed for higher σ and ρ parameter values under Beverton and Holt S-R curve with a steepness value of 0.51 (a low productive *S-R*). There were increasing trends in all statistics with increasing σ and ρ values (Table 8).

Table 6a provides the rebuilding statistics under F_{OFL} equated to various proportions (i.e., γ value) of *M* for different types of *S-R* model and *ESB*. When the female *ESB* in the Ricker *S-R* model with a low productive *sp,* 0.62, was considered, γ values up to 2.0 rebuilt the stock within 10 years; and when combined sexes *ESB* was used in the same *S-R* model, the γ value up to 1.0 rebuilt the stock within 10 years. On the other hand, when a low productive Beverton-Holt *S-R* model with a low productive *sp*, 0.51, was considered, a γ value of 0.4 rebuilt the stock around the mean generation time (14.2). Thus, the choice of γ value is dependent on the type of *ESB* and *S-R* model used. Therefore, determination of γ value should be left to the stock assessment author.

5.2.7.2 Bering Sea Snow Crab

The simulated population produced an ESB_{MSY} of 307.7 kg for the Ricker S-R curve with the steepness value 0.53 and 214.8 kg for the Beverton and Holt S-R model with the steepness value 0.51 (we intentionally selected low productivity S-R curves in the rebuilding analysis). Table 7 provides the evaluation of β and α parameters for the snow crab stock. The trends in results are similar to those of the red king crab stock. We chose the β and α combination of 0.25 and 0.1 as a default for Snow and Tanner crab stocks.

The rebuilding analysis with Ricker *S-R* model with a steepness value of 0.53 under F_{60} and these β and α values rebuilt the stock with somewhat a longer rebuilding time period (~ 14 years) than the estimated mean generation time (9.5 years). The latter analysis was also a diagnostic test for choosing F_{60} for the snow crab stock (Table 7).

The rebuilding time and yield statistics were also computed for higher σ and ρ parameter values under Beverton and Holt S-R curve with a steepness value of 0.51. Similar to the red king crab stock, there were increasing trends in all statistics with increasing σ and ρ values (Table 8).

5.2.7.3 Bering Sea Tanner Crab

The input parameter values for the Tanner crab assessment were chosen from Zheng et al. (1998), which has not been updated because of a prolonged closure of this fishery. Because of the deficiency of input parameter values, detail stochastic analysis was not carried out and the conclusions made for snow crab stocks were assumed to apply to this stock as well because of similar life history parameters. Analyses of blue king crab described in the following sections were also restricted for the same reasons.

5.2.7.4 Pribilof Islands Blue King Crab

The simulated population produced an ESB_{MSY} of 1132.4 kg (assuming the same ESB_{MSY} to ESB_0 ratio of 0.58 as for the red king crab stock) for the Beverton and Holt *S-R* curve with the steepness value 0.51 (we intentionally selected a low productivity *S-R* curve in the rebuilding analysis). The rebuilding analysis with F_{60} under this low productive *S-R* curve and the same β and α values (0.25 and 0.1) as for the red king crab stock rebuilt the stock within a reasonable time period (Table 8).

5.2.7.5 St. Mathew Island Blue King Crab

The simulated population produced an ESB_{MSY} of 934.1 kg (assuming the same ESB_{MSY} to ESB_0 ratio of 0.58 as for the red king crab stock) for the Beverton and Holt *S-R* curve with the steepness value 0.51. The rebuilding analysis with F_{60} under this low productive *S-R* curve and the same β and α values (0.25 and 0.1) as for the Pribilof blue king crab stock rebuilt the stock within a reasonable time period (Table 8).

6 Discussion

Since *S-R* relationships were lacking for many BSAI crab stocks and is a difficult relationship to establish, a plausible range of steepness parameter (*sp*: 0.51 – 0.79 equivalently τ : 0.1 – 0.3) was considered to derive yield curves for reference point estimation (Mace, 1994; Clark, 1991). Deterministic and stochastic simulations were used in the analysis. The steepness range was chosen following *S-R* fits to Bristol Bay red king, Bering Sea Tanner, and snow crab stock data. The three stocks provided the steepness estimates of 0.72, 0.85, and 0.83, respectively. A conservative steepness parameter value of 0.79 was chosen as the lower limit in all simulations.

Because of uncertainty in the *S-R* models, steepness values, mating ratio, *M*, and many other vital stock parameters, the estimated $F_{x\%}$ values were compared with a few stock productivity and viability features to select a conservative one: rebuilding time and probability from a very low stock level, yield variation, and frequency of overfished status. The suitability of a particular $F_{x\%}$ or $HR_{x\%}$ was assessed, with a low productive *S-R* curve within a plausible range. The reason behind this choice was that if a particular $F_{x\%}$ could rebuild a stock from a depleted level (*25%* ESB_{MSY}) under an S-R relationship with this steepness value, it could very well rebuild the stock under any higher steepness parameter value.

In the simulations certain stock specific characteristics were recognized: Terminal molt at maturity for both sexes in Tanner and snow crabs and biennial spawning in blue king crabs (Otto and Cummiskey, 1985). The consequence of blue king crabs is that multiparous females molt once in every two years to hatch and mate.

Unlike finfish, mating ratio plays a great role in crabs when computing *ESB* for fitting *S-R* models. Lab Studies have shown variation in mating ratio by size and stage among different crab species (Paul and Paul, 1997; Zheng et al., 1995a, Siddeek et al., 2004). For red king crab a mating ratio up to 1:3 with both newshell and oldshell mature males has been used (Zheng et al.,

1995a) and for snow crab a mating ratio up to 1:9 has been used (Siddeek et al., 2004). In the current analysis a 1:3 mating ratio for king crabs and 1:2 mating ratio for Tanner and snow crabs were used, as a conservative measure, to compute reference points. Whether to use female *ESB* or combined sexes *ESB* or total mature *SSB* to fit *S-R* models depends on which unit more appropriately explains the *S-R* relationship for a particular stock. Unfortunately, there were very few *S-R* relationships established for BSAI crab stocks. Zheng et al (1995a, b) derived a Ricker *S-R* model with varying *ESB* units for red king crab. The one with female *ESB* provided a good fit. Turnock (2004) fitted the Beverton-Holt *S-R* model with combined sexes *ESB* for snow crab. He did not choose any other unit for comparison. Reference point mortality estimates under a combined sexes *ESB* assumption were generally lower than those under a female *ESB* assumption. Some questionable parameter estimates from the snow crab model, e.g., male growth increment per molt and fishery selectivities of "oldshell" males, may explain these differences.

In the stochastic analysis, random variation in recruitment was introduced to the model using overall recruitment noise of 0.7 and an autocorrelation parameter of 0.5. These values of recruitment errors have been observed in some crab *S–R* model fittings (e.g., Bristol Bay red king crab, updated from Zheng et al. 1995b). A high value of 0.9 was also considered for the recruitment noises (Table 8), which produced variable rebuilding time and yield statistics.

7 Conclusions

Table 9 lists the selected $F_{x\%}$, legal male harvest rate at the time of fishing, $HR_{mmy}\%$, mature male harvest rate at the mid survey time. The rebuilding analysis with these harvest rates provided lower probability of stock being overfished. The Tanner crab input parameter values did not produce reliable estimate of mature harvest rates. Since the biological characteristics of Tanner crab is similar to that of snow crab, the mature harvest rate selected for snow crab is recommended as tentative overfishing mortality for the Tanner crab stock.

Limit Fishing Mortality (F_{OFL}) and Harvest Rate (HR_{OFL}):

The analysis of five major BSAI crab stocks suggested the following $F_{x\%}$, legal harvest rate at the fishing time, and mature harvest rate at the survey time as a precautionary limit reference points in the *F*-control rule (Appendix A):

(a) Red king crab: F_{50} (legal harvest rate = HR_{31}, mature harvest rate at the survey time = HR_{17})

(b) Blue king crab: F_{60} (legal harvest rate = HR_{31}, mature harvest rate at the survey time = HR_{17})

(c) Snow crab: F_{60} (legal harvest rate = HR_{57} mature harvest rate at the survey time = HR_{19})

(d) Tanner crab: same as those for snow crab

(e) For other crab stocks: if *ESB/R* and *ESB* are not estimable, then γM or average catch during an ecologically stable period should be used as proposed in the Tier system (Appendix A).

Implement a default threshold spawning biomass of 25% of ESB_{MSY}. Mean recruitment during a selected period is used to estimate ESB_{MSY} or SSB_{MSY} for Tier 1 and 2 stocks. The selected period is an ecologically stable period for the stock, which is determined by the stock assessment scientist responsible for analysis in concurrent with the CPT and SSC.

Target F_{TAR}:

Target legal harvest rate for F_{TAR} must be below HR_{OFL} and are determined by the State of Alaska crab harvest strategies.

The harvest rates are applicable to the total legal abundance at the fishing time. Therefore, the abundance during summer surveys is projected to the start of the fishing period discounting for *M* and trawl as well as other fishery bycatch mortality to compute TAC.

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10 Tables:

Table 1. Estimates of limit reference points for the base input parameter values for Bristol Bay red king crab for a range of stock-recruitment model steepness parameter (*sp*) values at three mating ratio values. The recruits are generated from **deterministic** Beverton and Holt (BH) and Ricker (RC) stock-recruitment (S-R) models under **female** effective spawning biomass with an initial sex ratio of 1:1. Estimates marked bold are closer to the estimated *sp* value. Other parameters are defined in the glossary section.

Mating Ratio	1:2	1:2	1:2	1:2	1:2	1:2	1:2	1:2
S-R	BH	BH	BH	BH	RC	RC	RC	RC
sp	0.79	**0.63**	0.51	0.41	0.79	**0.63**	0.51	0.41
F_{MSY}	0.42	**0.26**	0.18	0.12	0.83	**0.38**	0.22	0.15
HR_{MSY} %	28	**19**	14	10	46	**26**	17	12
%Mated Females	52	**57**	64	70	50	**52**	59	67

Mating Ratio	1:3	1:3	1:3	1:3	1:3	1:3	1:3	1:3
S-R	BH	BH	BH	BH	RC	RC	RC	RC
sp	0.79	**0.63**	0.51	0.41	0.79	**0.63**	0.51	0.41
F_{MSY}	0.47	**0.32**	0.24	0.18	1.08	**0.53**	0.34	0.24
HR_{MSY} %	31	**23**	18	14	54	**34**	24	18
%Mated Females	59	**68**	77	85	51	**57**	67	77

Mating Ratio	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4
S-R	BH	BH	BH	BH	RC	RC	RC	RC
sp	0.79	**0.63**	0.51	0.41	0.79	**0.63**	0.51	0.41
F_{MSY}	0.52	**0.37**	0.28	0.23	1.3	**0.68**	0.44	0.32
HR_{MSY} %	33	**26**	21	17	60	**40**	29	23
%Mated Females	68	**79**	90	100	53	**61**	73	85

Table 2. Comparison of various limit reference points estimated for the Bristol Bay red king crab under **deterministic** Beverton and Holt (BH) and Ricker (RC) stock-recruitment (S-R) models with an initial sex ratio of 1:1 and base input parameter values. $F_{x\%}$ are determined by Clark's (1991) method. The estimates are given for a plausible range of steepness (*sp*). Other parameters are defined in the glossary section.

Mating Ratio	1:2	1:3	1:4
ESB	Female	Female	Female
S-R	BH&RC	BH&RC	BH&RC
sp range	0.51-0.79	0.51-0.79	0.51-0.79
$F_{x\%}$	44	51	57
F_{mmy}	0.32	0.44	0.55
HR_{mmy} %	23	29	35
Yield as %MSY	81	84	85
%Mated Females at F_{mmy}	54	60	66

Table 3. Estimates of limit reference points for the base input parameter values for Bering Sea snow crab for a range of steepness parameter (*sp*) values at three mating ratio values. The recruits are generated from **deterministic** Beverton and Holt (BH) and Ricker (RC) stock-recruitment (S-R) models under **total** effective spawning biomass with an initial sex ratio of 1:1. Other parameters are defined in the glossary section.

Mating Ratio	1:2	1:2	1:2	1:2	1:2	1:2	1:2	1:2
S-R	BH	BH	BH	BH	RC	RC	RC	RC
sp	0.79	0.63	0.51	0.41	0.79	0.63	0.51	0.41
F_{MSY}	1.26	0.94	0.70	0.53	2.71	1.63	1.04	0.70
HR_{MSY} %	59	49	39	31	85	68	52	39
%Mated Females	76	81	87	92	63	71	79	87

Mating Ratio	1:3	1:3	1:3	1:3	1:3	1:3	1:3	1:3
S-R	BH	BH	BH	BH	RC	RC	RC	RC
sp	0.79	0.63	0.51	0.41	0.79	0.63	0.51	0.41
F_{MSY}	1.57	1.47	1.35	1.19	3.29	1.81	1.64	1.43
HR_{MSY} %	67	65	62	57	90	72	69	64
%Mated Females	100	100	100	100	89	100	100	100

Mating Ratio	1:4	1:4	1:4	1:4	1:4	1:4	1:4	1:4
S-R	BH	BH	BH	BH	RC	RC	RC	RC
sp	0.79	0.63	0.51	0.41	0.79	0.63	0.51	0.41
F_{MSY}	1.59	1.51	1.41	1.26	1.92	1.79	1.66	1.47
HR_{MSY} %	68	66	63	59	74	72	69	65
%Mated Females	100	100	100	100	100	100	100	100

Table 4. Comparison of various limit reference points estimated for the Bering Sea snow crab under **deterministic** Beverton and Holt (BH) and Ricker (RC) stock-recruitment (S-R) models with an initial sex ratio of 1:1 and base input parameter values. $F_{x\%}$ are determined by Clark's (1991) method. The estimates are given for a plausible steepness (*sp*) range. Other parameters are defined in the glossary section.

Mating Ratio	1:2	1:3	1:4
ESB	Total	Total	Total
S-R	BH&RC	BH&RC	BH&RC
sp range	0.51-0.79	0.51-0.79	0.51-0.79
$F_{x\%}$	59	77	81
F_{mmy}	1.26	2.08	1.64
HR_{mmy} %	59	77	69
Yield as %MSY	92	98	100
%Mated Females at F_{mmy}	76	100	100

Table 5. Comparison of reference point estimates for Bristol Bay red king crab for different input parameter values. The recruits are generated from deterministic Ricker stock recruitment model with a steepness parameter (*sp*) value of 0.63 and an initial sex ratio of 1:1. The bycatch mortality rate is kept at the base value of 80%. Figures in bold refer to changes in input parameter values. Total = combined sexes, and other parameters are defined in the glossary section.

ESB	Female	**Total**	Female	Female	Female	Female	**Female, Pre-molt Length-Weight**	**Female, Pre-molt Length-Weight**
Mating Ratio	1:3	1:3	1:3	1:3	1:3	1:3	1:3	**1:2.209 at F=0**
Lc in mm CW	135	135	135	135	135	135	135	135
M	0.18, 0.18	0.18, 0.18	**0.18, 0.225**	0.18, 0.18	0.18, 0.18	0.18, 0.18	0.18, 0.18	0.18, 0.18
T	0.5417	0.5417	0.5417	0.5417	0.5417	**0.7096**	0.5417	0.5417
δ	0.0112	0.0112	0.0112	**0.2548**	0.0112	0.0112	0.0112	0.0112
h	0.2	0.2	0.2	0.2	**0.5**	0.2	0.2	0.2
F_{MSY}	0.53	0.52	0.73	0.53	0.42	0.53	0.52	0.27
Legal HR_{MSY} *%*	34	33	42	33	29	34	33	20
%Mated Females	57	57	63	57	61	57	56	41

Table 6. Evaluation of α and β parameters for Tiers 1 to 4 F-control rule formula based on rebuilding time (RBT) and catch statistics from 100 of 100-year fishery simulations with F_{50} fishing mortality under stochastic Ricker stock-recruitment model with female *ESB*, steepness parameter (*sp*) = 0.62, σ = 0.7, ρ = 0.0, mating ratio = 1:3, and initial sex ratio = 1:1. Red king crab base parameter values are used in the simulations. CV = coefficient of variation of yield. Other parameters are defined in the glossary section.

α	0.0	0.05	0.1	0.0	0.05	0.1	0.0	0.05	0.1
β	0.2	0.2	0.2	0.25	0.25	0.25	0.3	0.3	0.3
Mean RBT (yr)	13.1	12.8	12.4	11.9	11.5	11.0	11.2	10.9	10.5
Median RBT (yr)	13.0	13.0	13.0	12.0	11.0	10.5	10.0	9.0	9.0
95% Confidence Interval RBT (yr)	11.1-15.1	10.8-14.8	10.4-14.5	9.8-14.0	9.4-13.6	8.9-13.1	8.4-13.9	8.2-13.7	7.73-13.2
%Times RBT<10 years	27	29	29	38	39	43	48	51	55
Mean Yield (kg)	645.2	647.8	662.6	668.8	655.3	672.8	683.8	685.6	671.6
CV of Yield (%)	44	45	43	41	43	42	40.	40	42
% year Stock Overfished	1	1	1	1	1	1	1	1	1

Table 6a. Evaluation of γ parameter for Tiers 4 *F*-control rule formula based on rebuilding time (RBT) statistics from 100 of 100-year fishery simulations with $F_{OFL} = \gamma M$, $\alpha = 0.1$, $\beta = 0.25$, stochastic stock-recruitment (*S-R*) model, female/combined sexes *ESB*, two low productivity steepness parameter (*sp*) values, $\sigma = 0.7$, $\rho = 0.0$, mating ratio = 1:3, and initial sex ratio = 1:1. Red king crab base parameter values are used in the simulations. RC = Ricker *S-R* model, BH = Beverton-Holt *S-R* model, Total = combined sexes. Estimated generation time for red king crab = 14.2 years.

γ	0.4	0.8	1.0	1.5	2.0	2.5	3.0	4.0	5.0
S-R Type	RC	RC	RC	RC	RC	RC	RC	RC	RC
ESB	Female	Female	Female	Female	Female	Female	Female	Female	Female
Steepness, *sp*	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Mean RBT (yr)		5.4	7.9	9.2	**10.1**	11.0	13.6	21.1	30.7
Median RBT (yr)		2.5	8.0	10.0	**11.0**	11.0	11.0	13.5	19.5
95% Confidence Interval RBT (yr)		4.5-6.4	6.8-8.9	8.2-10.2	**9.1-11.0**	8.9-13.1	10.4-16.8	16.1-26.1	24.8-36.5
%Times RBT<10 years		78	56	45	**38**	43	39	31	21
%Times no rebuilding occurred		0	0	0	**0**	1	3	8	11
ESB	Total	Total	Total	Total	Total	Total	Total	Total	Total
Mean RBT (yr)		8.8	**9.3**	11.2	11.7	12.0	13.4	16.1	23.9
Median RBT (yr)		10.	**11.0**	12.0	12.0	12.0	13.0	13.0	17.0
95% Confidence Interval RBT (yr)		7.8-9.7	**8.3-10.3**	10.5-12.0	10.9-12.5	11.2-12.8	11.4-15.4	13.3-19.0	19.4-28.4
%Times RBT<10 years		44	**39**	25	20	19	20	24	20
%Times no rebuilding occurred		0	**0**	0	0	0	1	2	4
S-R Type	BH	BH	BH	BH	BH	BH	BH	BH	BH
ESB	Female	Female	Female	Female	Female	Female	Female	Female	Female
Steepness, *sp*	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
Mean RBT (yr)	**14.3**	15.6	16.2	16.7	25.3	43.9	53.9		
Median RBT (yr)	**14.0**	15.0	15.0	16.5	20.0	31.0	46.0		
95% Confidence Interval RBT (yr)	**13.8-14.8**	15.0-16.3	15.4-17.0	15.3-18.1	21.1-29.4	37.4-50.4	46.9-60.8		
%Times RBT<10 years	**1**	1	2	11	12	10	11	0	0
%Times no rebuilding occurred	**0**	0	0	0	4	13	22	100	100

Table 7. Evaluation of α and β parameters for Tiers 1 to 4 F-control rule formula based on rebuilding time (RBT) and catch statistics from 100 of 100-year fishery simulations with F_{60} fishing mortality under stochastic Ricker stock-recruitment model with combined sexes *ESB*, steepness parameter (*sp*) = 0.53, σ = 0.7, ρ = 0.0, mating ratio = 1:2, and initial sex ratio = 1:1. Snow crab base parameter values are used in the simulations. CV = coefficient of variation of yield. Other parameters are defined in the glossary section.

α	0.0	0.05	0.1	0.0	0.05	0.1	0.0	0.05	0.1
β	0.2	0.2	0.2	0.25	0.25	0.25	0.3	0.3	0.3
Mean RBT (yr)	19.	18.7	18.4	16.5	16.4	16.0	15.7	15.4	14.8
Median RBT (yr)	14.5	14.0	14.0	14.0	14.0	13.5	14.0	14.0	13.0
95% Confidence Interval RBT (yr)	15.6-22.5	15.2-22.2	15.0-21.9	14.6-18.5	14.5-18.4	14.0-18.0	14.6-16.9	14.3-16.4	13.7-15.9
%Times RBT<10 years	5	6	6	4	4	5	6	6	8
Mean Yield (kg)	43.0	43.3	43.7	42.5	42.7	43.0	42.8	43.0	43.2
CV of Yield (%)	58	59	60	57	58	59	55	56	56
% year Stock Overfished	1	1	1	1	1	1	1	1	1

Table 8. Performance of selected $F_{x\%}$ for red king crab, snow crab, Pribilof blue king crab, and St. Mathew blue king crab stocks under stochastic Beverton and Holt stock recruitment model with a steepness parameter (*sp*) value of 0.51 (i.e., under a low productive *S-R* and *sp*) and an initial sex ratio of 1:1. For red king and snow crab stocks, rebuilding time statistics are provided for different σ and ρ values. The figures in bold are preferred estimates. Total = combined sexes, and other parameters are defined in the glossary section.

Stock	Red King	Red King	Red King	Snow	Snow	Snow	Pribilof Blue King	St. Mathew Blue King
ESB	Female	Female	Female	Total	Total	Total	Female	Female
Mating Ratio	1:3	1:3	1:3	1:2	1:2	1:2	1:3	1:3
σ, ρ	0.7, 0.0	0.7, 0.5	0.9, 0.9	0.7, 0.0	0.7, 0.5	0.9, 0.9	0.7, 0.5	0.7, 0.5
Mean Rebuilding Time	45.0	**42.4**	53.7	22.9	**23.5**	40.2	**29.9**	**29.2**
Median Rebuilding Time	32.5	**25.5**	45.5	18.5	**19.5**	29	**22.5**	**20.5**
Confidence Interval of Rebuilding Time	38.4-51.0	**35.5-49.3**	45.6-61.9	20.2-25.6	**20.7-26.2**	33.8-46.6	**24.9-34.8**	**23.6-34.9**
% Times < 10 year rebuilding period	11	**17**	25	1	**1**	15	**14**	**20**

Table 9. Selected reference point estimates for red king, snow, Pribilof Islands blue king, and St. Mathew Island blue king crab stocks. The estimates are based on female *ESB* with a mating ratio of 1:3 except for the snow crab stock. Selected reference points for the snow crab stock were based on total *ESB* with a mating ratio of 1:2. Other parameters are defined in the glossary section.

Stock	Red King Crab	Snow Crab	Pribilof Islands Blue King Crab	St. Mathew Island Blue King Crab
Type of Spawners	Female *ESB*	Total *ESB*	Female *ESB*	Female *ESB*
M	0.18	Male 0.23, Female 0.31	0.18	0.18
h	0.2	0.5	0.2	0.2
Legal size	≥ 135 mm CL	≥ 102 mm CW	≥ 135 mm CL	≥ 120 mm CL
Assumed Mature Size	≥ 120 mm CL	≥90 mm CW	≥ 120 mm CL	≥ 105 mm CL
$F_{x\%}$	50	60	60	60
F_{mmy}	0.46	1.19	0.40	0.45
Legal Male HR_{mmy} *% at Fishing Time*	31	57	0.31	31
Mature Male HR_{mmy} *% at Mid Survey Time (June 15)*	17	19	17	18

11 Figures:

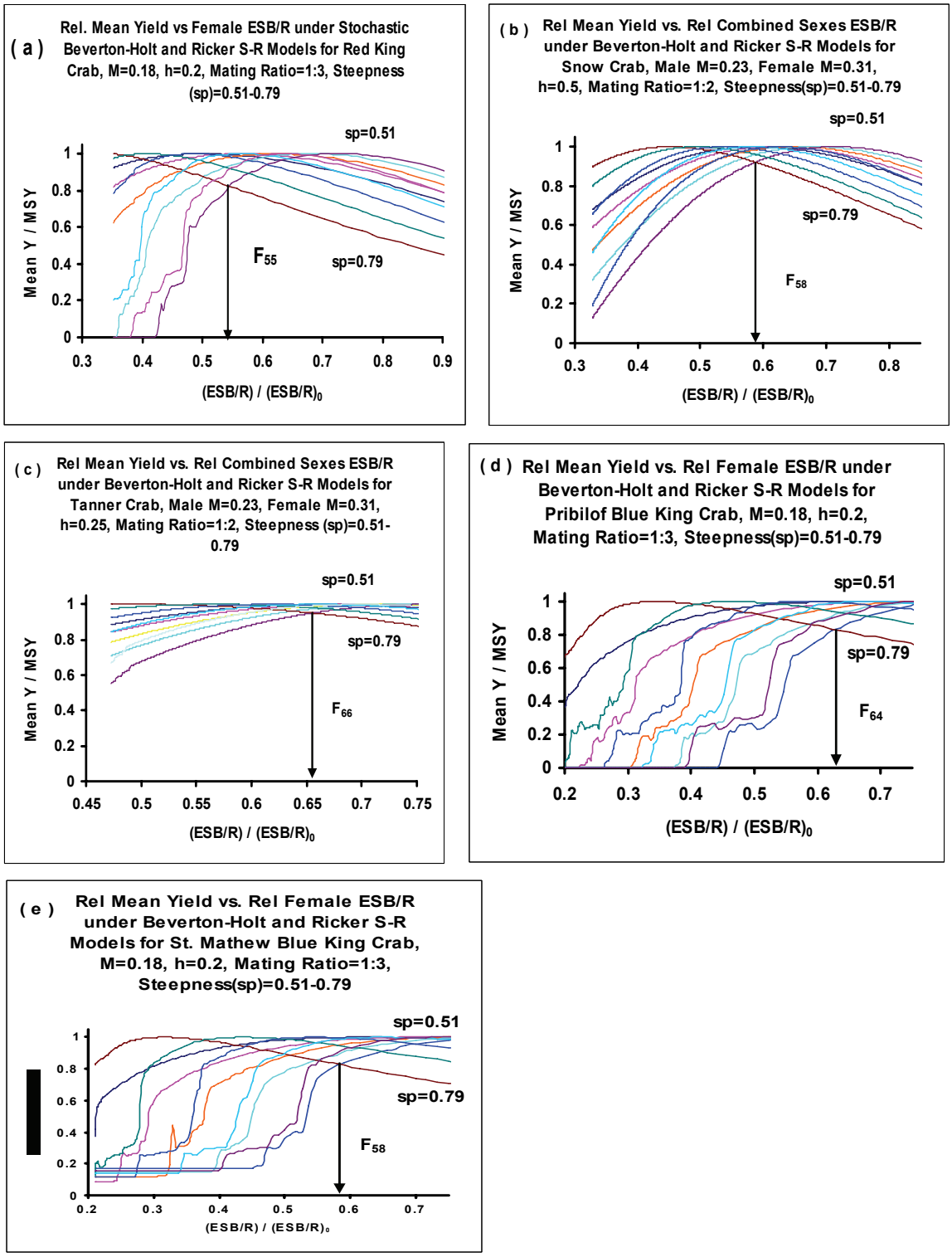


Figure 1. Estimates of $F_{x\%}$ under stochastic stock-recruitment models with overall stock-recruitment variability, $\sigma = 0.7$, and serial correlation, $\rho = 0.5$, for (a) red king, (b) snow, (c) Tanner, (d) Pribilof Islands blue king, and (e) St. Mathew Island blue king crabs using base values of input parameters.

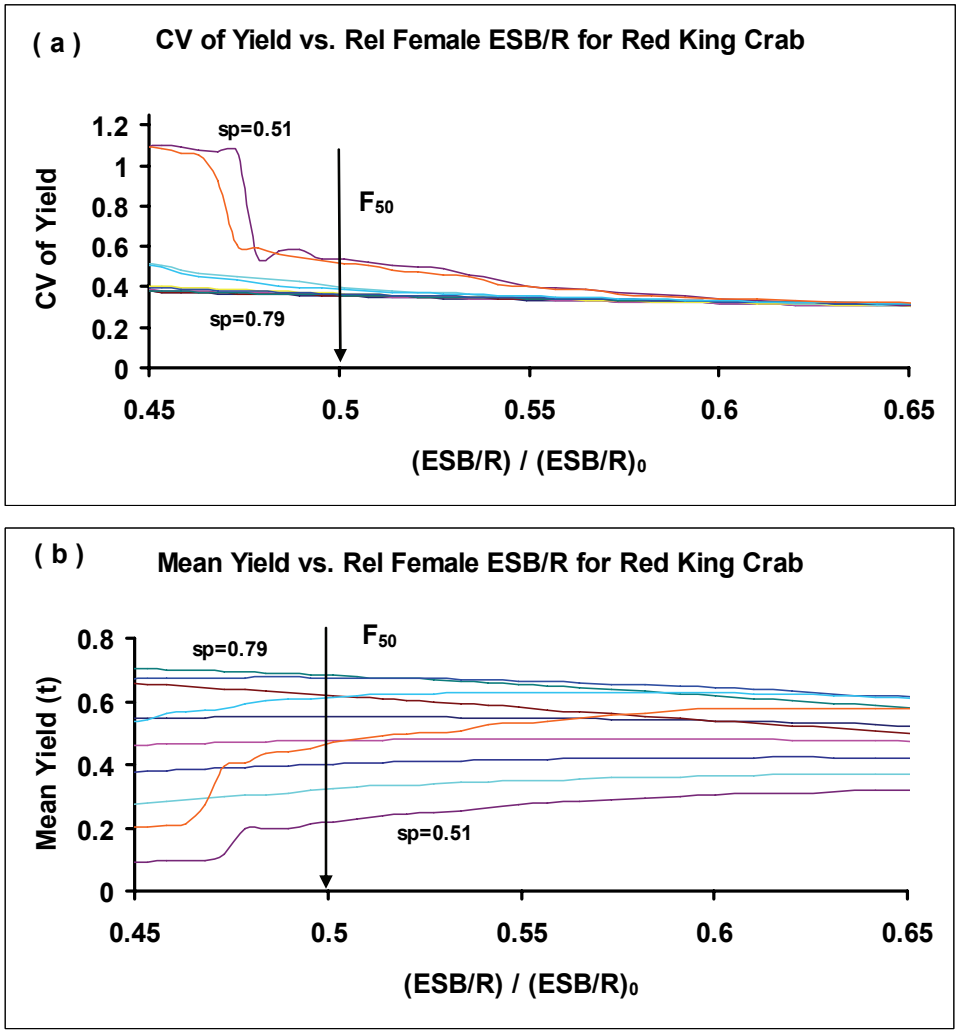


Figure 2. (a) CV and (b) mean yield vs. relative *ESB/R* from 100-year fishery for the red king crab stock. The estimates are made under stochastic Beverton-Holt and Ricker stock-recruitment models with female *ESB*, *M*=0.18, *h*=0.2, mating ratio=1:3, overall recruitment variability, σ = 0.7, serial correlation, ρ = 0.5, and steepness (*sp*) = 0.51-0.79.

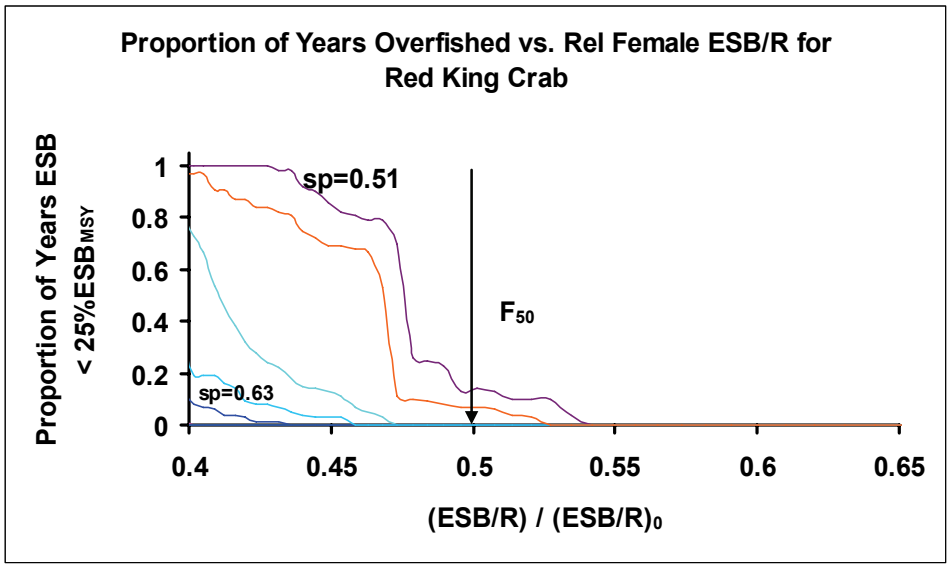


Figure 3. Proportion of years *ESB* has depleted below 25%ESB_{MSY} vs. relative *ESB/R* from 100-year fishery for the red king crab stock. The estimates are made under stochastic Beverton and Holt and Ricker stock-recruitment models with female *ESB*, $M = 0.18$, $h = 0.2$, mating ratio = 1:3, overall recruitment variability, $\sigma = 0.7$, serial correlation, $\rho = 0.5$, and $sp = 0.51$-0.79.

12 Appendix A. New Tier system for BSAI King and Tanner crab stocks

Five Tiers modified from the current groundfish Tier system (NPFMC, 1998) are proposed for the 22 BSAI crab stocks. Tiers are based on whether reliable estimates are available for spawning biomass (by survey or model) and harvest rate reference points. Tiers 1 and 2 are for stocks with a reliable estimate of the S-R relationships. Tier 3 is for stocks with proxy ESB_{MSY} and F_{MSY}. Tier 4 stocks have no estimates of proxy F_{MSY}, so a default value of $\gamma * M$ is used instead, provided that a reliable estimate of current *ESB* and *M* are available. Tier 5 stocks have no biological information to compute proxies for F_{MSY} and no reliable estimates of *ESB* and/or *M*; consequently, catch history is used to set limit and target reference points.

The proposed Tier system for crabs incorporates a relative *ESB* threshold value (β) (relative to an ESB_{MSY}) below which *F* is set to 0 (Figure A.1). The default β value is set to be 0.25. The five Tiers are defined below:

Information available	Tier	Stock status	F_{OFL}
B, B_{msy}, F_{msy}, and pdf of F_{msy}	1a	$\frac{B}{B_{msy}} > 1$	$F_{OFL} = \mu_A$ =arithmetic mean of the pdf
	1b	$\beta < \frac{B}{B_{msy}} \leq 1$	$F_{OFL} = \mu_A \frac{B/B_{msy} - \alpha}{1-\alpha}$
	1c	$\frac{B}{B_{msy}} \leq \beta$	$F_{OFL} = 0$
B, B_{msy}, F_{msy},	2a	$\frac{B}{B_{msy}} > 1$	$F_{OFL} = F_{msy}$
	2b	$\beta < \frac{B}{B_{msy}} \leq 1$	$F_{OFL} = F_{msy} \frac{B/B_{msy} - \alpha}{1-\alpha}$
	2c	$\frac{B}{B_{msy}} \leq \beta$	$F_{OFL} = 0$
B, F_{msy}, $B_{msy^{prox}}$	3a	$\frac{B}{B_{msy^{prox}}} > 1$	$F_{OFL} = F_{msy}$
	3b	$\beta < \frac{B}{B_{msy^{prox}}} \leq 1$	$F_{OFL} = F_{msy} \frac{B/B_{msy^{prox}} - \alpha}{1-\alpha}$
	3c	$\frac{B}{B_{msy^{prox}}} \leq \beta$	$F_{OFL} = 0$
B, M, $B_{msy^{prox}}$	4a	$\frac{B}{B_{msy^{prox}}} > 1$	$F_{OFL} = \gamma M$
	4b	$\beta < \frac{B}{B_{msy^{prox}}} \leq 1$	$F_{OFL} = \gamma M \frac{B/B_{msy^{prox}} - \alpha}{1-\alpha}$
	4c	$\frac{B}{B_{msy^{prox}}} \leq \beta$	$F_{OFL} = 0$
Reliable catch history from a time period to be determined (groundfish uses 1978 through 1995).	5		OFL = the average catch from a time period to be determined, unless an alternative value is established by the SSC on the basis of the best available scientific information

Preliminary assignment of stocks to the Tier system

<u>Tier 1 and 2 stocks:</u>

None.

Tier 3 stocks:

1. Bristol Bay red king crab (*Paralithodes camtschaticus*)
2. Eastern Bering Sea Tanner crab (*Chionoecetes bairdi*)
3. Eastern Bering Sea snow crab (*Chionoecetes opilio*)

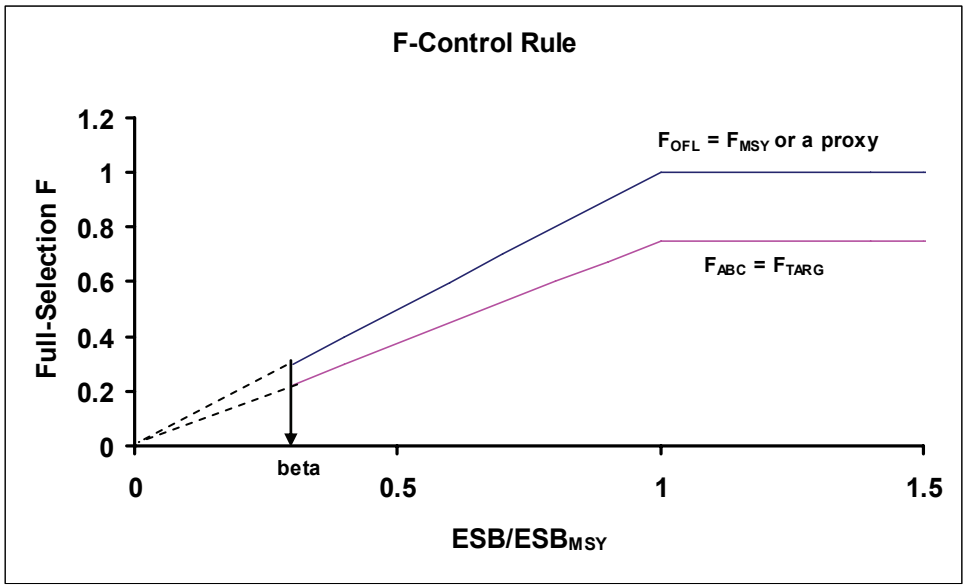
Tier 4 stocks:

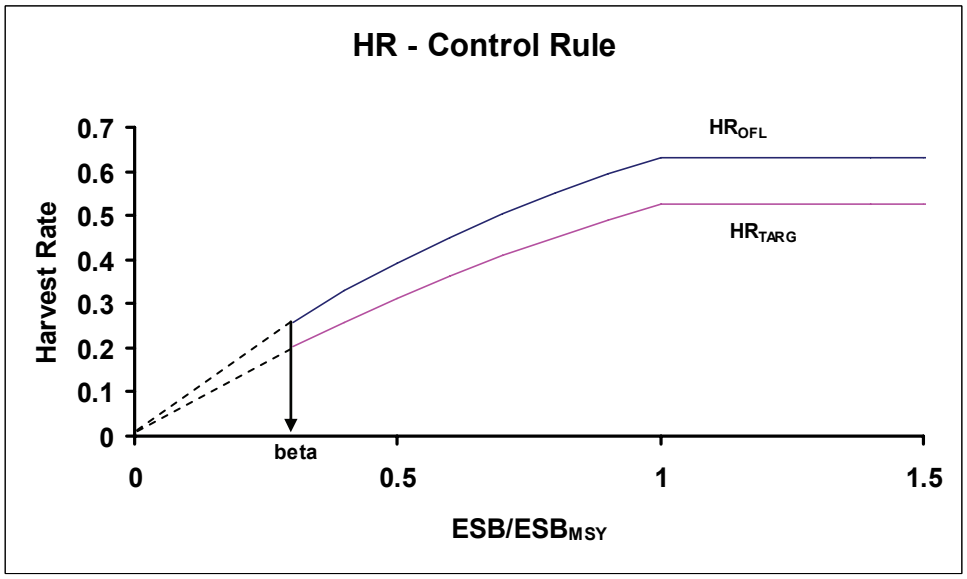
4. Pribilof Islands red king crab
5. Pribilof Islands blue king crab (*Paralithodes platypus*)
6. Saint Matthew Island blue king crab
7. Dutch Harbor red king crab
8. Norton Sound red king crab
9. Eastern Aleutian Islands Tanner crab

Tier 5 stocks:

10. Adak red king crab
11. Pribilof Islands golden king crab (*Lithodes aequispinus*)
12. Saint Matthew golden king crab
13. Aleutian Islands golden king crab
14. Western Aleutian Tanner crab
15. Saint Lawrence Island blue king crab
16. Aleutian Islands scarlet king crab (*Lithodes couesi*)
17. Eastern Bering Sea scarlet king crab
18. Bering Sea triangle Tanner crab (*Chionoecetes angulatus*)
19. Eastern Aleutian Islands triangle Tanner crab
20. Eastern Aleutian Islands grooved Tanner crab (*Chionoecetes tanneri*)
21. Western Aleutian Islands grooved Tanner crab
22. Eastern Bering Sea grooved Tanner crab

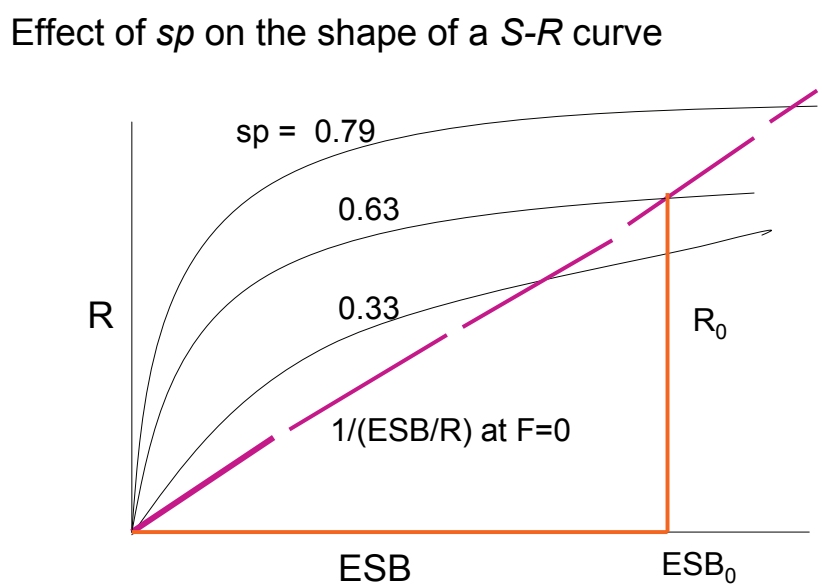
Figure A.1. Harvest Control Rule. When the relative *ESB* reaches the β level, fishery will be closed (F = 0). Top figure is fishing mortality control rule and the bottom figure is the corresponding harvest rate control rule.



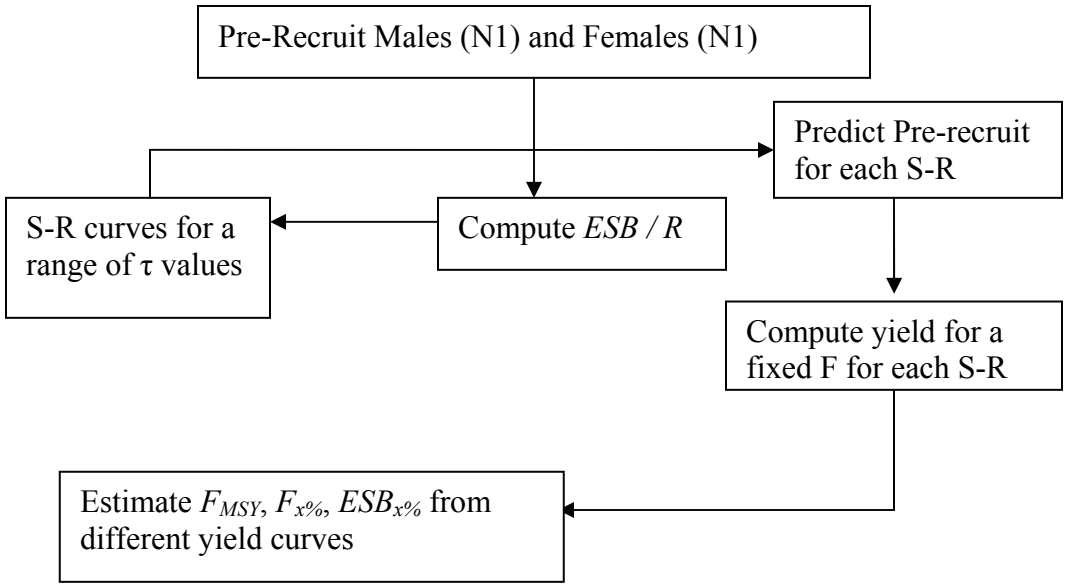


Appendix B: Effect of steepness parameter value on the shape of a S-R curve and flow charts of the deterministic and stochastic models.

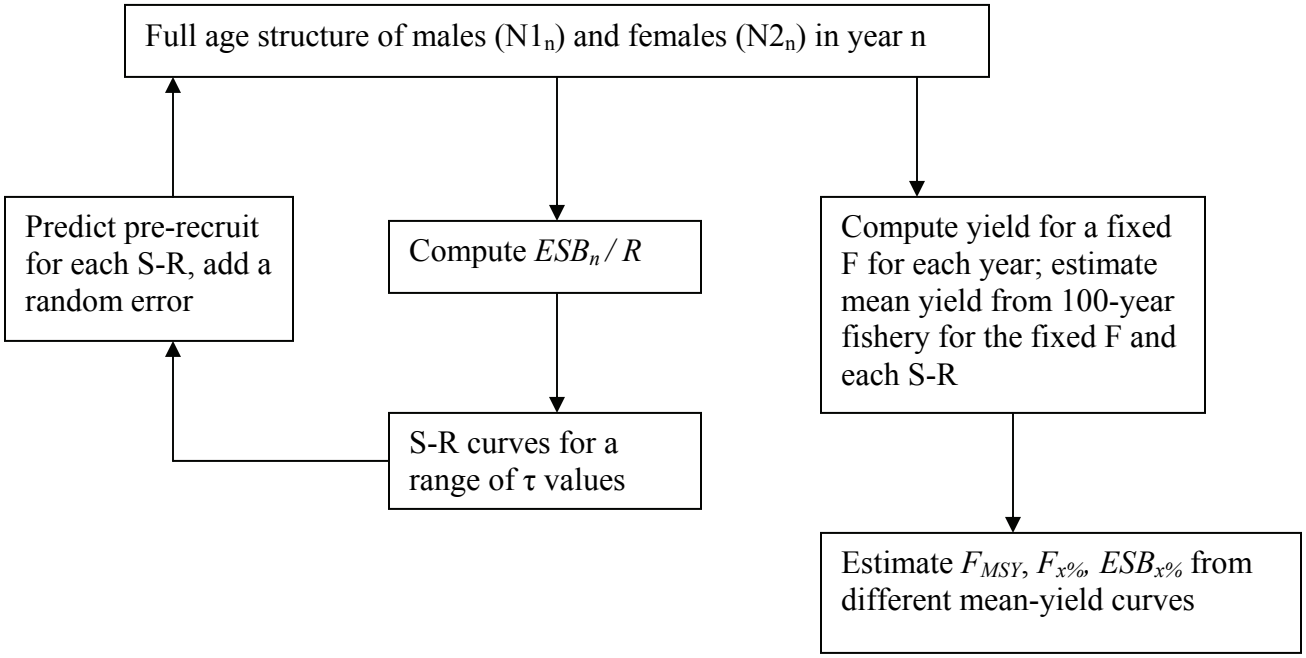
B.1 Effect of steepness (*sp*) parameter value on the shape of a Beverton-Holt S-R curve:



B.2. Flow Chart for reference point estimation by the deterministic *S-R* model:



B.3. Flow Chart for reference point estimation by the stochastic S-R model:



Appendix C: Simulation model equations

The length-based method is used in all simulations. The simulation is started with 1000 male crabs and 1000 female crabs at pre-recruit size as immature new-shell crabs. The *ESB/R* for each sex and yield for only males are estimated in most simulations. The *ESB/R* used in the S-R model to predict number of recruits, whereas the yield is used to obtain F_{MSY} and other mortality reference points.

All female red king crabs are assumed to molt annually (Zheng et al., 1995a); On the other hand, all male and female *Chionoecetes* crabs are assumed to undergo terminal molting when they reach maturity (Otto, 1998 and Tamone et al., 2005 for snow crab; Donaldson et al., 1981 for Tanner crab). Most blue king crabs are biennial spawners (Otto and Cummiskey, 1990). The length-based models used to capture these characteristics are given below:

The following assumptions were made to simplify the derivation in all analyses:

1. Mortality takes place immediately before growth.
2. Instantaneous natural mortality, *M*, is constant.
3. April 1: Mid molting time; February 15: Mating with primiparous female; and May 1: Mating with multiparous female.
3. Recruits generated from *S-R* models have 1:1 sex ratio.

When the fishery selectivity is independent of the shell age (new-shell or old-shell) (red king crab, blue king crab, Tanner crab), the abundances of crab growing into the same or any larger length intervals were determined by,

<u>Stock abundance in number:</u>

$$mat\,N_{l,t+1} = \sum_{l'=1}^{l} \left[\begin{array}{l} (mat\,N_{l',l} + mat\,O_{l',l})\,mmolt_{l'}\,P_{l',l} + \\ (immat\,N_{l',l} + immat\,O_{l',l})\,immolt_{l'}\,mat_{l}\,P_{l',l} \end{array} \right] e^{-(M + F_T s'_{l'} + (F s_{l'} + HM_{l'})\delta)}$$

(C.1)

$$mat\,O_{l,t+1} = \sum_{l'=1}^{l} [(mat\,N_{l',l} + mat\,O_{l',l})(1 - mmolt_{l'})]\, e^{-(M + F_T s'_{l'} + (F s_{l'} + HM_{l'})\delta)}$$

(C.2)

$$immat\,N_{l,t+1} = \sum_{l'=1}^{l} [(immat\,N_{l',l} + immat\,O_{l',l})\, immolt_{l'} (1 - mat_l) P_{l',l}]\, e^{-(M + F_T s'_{l'} + (F s_{l'} + HM_{l'})\delta)}$$

(C.3)

$$immat\,O_{l,t+1} = \sum_{l'=1}^{l} [(immat\,N_{l',l} + immat\,O_{l',l})(1 - immolt_{l'})]\, e^{-(M + F_T s'_{l'} + (F s_{l'} + HM_{l'})\delta)}$$

(C.4)

The abundances in the last age group are estimated as plus group, for example:

$$mat\,O_{l,t+1} = \sum_{l'=1}^{l} [(mat\,N_{l',l} + mat\,O_{l',l})(1 - mmolt_{l'})]\, e^{-(M + F_T s'_{l'} + (F s_{l'} + HM_{l'})\delta)} \div$$

$$[1 - e^{-(M + F_T s'_{l'} + (F s_{l'} + HM_{l'})\delta)}]$$

(C.5)

where,

$mat\,O_{l,t}$ = old-shell mature abundance,

$mat\,N_{l,t}$ = new-shell mature abundance,

$mmolt_l$ = mature crab molt probability,

$immolt_l$ = immature crab molt probability,

mat_l = maturity probability,

F_T = bycatch fishing mortality by the trawl and other fishery, a fixed value of 0.01 is used,

s'_l = trawl and other fishery bycatch selectivity, and

s_l = pot fishery retained/discard selectivity. For convenience, same notation is used in the above formulas, but the function takes different forms and/or parameter values in each case.

Note:

1. For snow and Tanner crabs, new- and old-shell abundances are estimated separately because of different selectivity patterns.
2. For Tanner and blue king crabs, a constant trawl and other fishery bycatch mortality is used.

<u>Effective spawning biomass estimation:</u>

1. Sum the abundance of mature males/mature females and project the total mature abundance to a selected mating time, discounting for intervening mortality to get,

$$MSSN = \sum_{t,l} (mat\ N_{l,t} + mat\ O_{l,t}) \times e^{-a\ z_{l,t}} \tag{C.6}$$

$$FSSN1\ or\ FSSN2 = \sum_{t,l} (mat\ N_{l,t} + mat\ O_{l,t}) \times e^{-a\ z_{l,t}} \tag{C.7}$$

Where,

MSSN = total mature male abundance in number,

FSSN1 = total primiparous female abundance in number,

FSSN2 = total multiparous female abundance in number,

a = lapsed time between molting and mating times, and

$Z_{l,t}$ = intervening total mortality.

Note:

a. Female abundances are computed separately as immature, primiparous, and multiparous, whereas male abundances are computed separately as immature and mature.

b. The following age-at-recruitment and maximum ages are considered for each stock:

Red king crab: age-at recruitment to the model = 6 years; maximum age = 26 years;

Snow crab: age-at recruitment to the model = 5 years; maximum age for males = 20 years, for females = 15 years;

Tanner crab: age-at recruitment to the model = 5 years; maximum age for males = 20 years, for females = 15 years;

Pribilof blue king crab: age-at recruitment to the model = 6 years; maximum age = 26 years;

St. Mathew blue king crab: age-at recruitment to the model = 6 years; maximum age = 26 years.

2. Mating ratio multiplier for effective spawning biomass calculation:

Let the effective spawning biomass multiplier for male be *EMSSN* and that for the female be *EFSSN*.

When $MSSN \times MATING\,RATIO < (FSSN1 + FSSN2)$, *EFSSN* and *EMSSN* are calculated as follows:

$$EFSSN = \frac{MSSN \times MATING\,RATIO}{FSSN1 + FSSN2}$$

$$EMSSN = 1$$

When $MSSN \times MATING\,RATIO > (FSSN1 + FSSN2)$, the following formulas are used to estimate *EFSSN* and *EMSSN*:

$$EFSSN = 1$$

$$EMSSN = \frac{FSSN1 + FSSN2}{MSSN \times MATING\,RATIO}$$

The effective spawning biomass of male (*MSSB*) is calculated as follows:

$$MSSB = \sum_{t,l} (matN_{l,t} + matO_{l,t}) \times w_l \times EMSSN \times e^{-a\,z_{l,t}} \tag{C.8}$$

The effective spawning biomass of female (*FSSB*) is calculated as follows:

$$FSSB = \sum_{t,l} (matN_{l,t} + matO_{l,t}) \times w_l \times EFSSN \times e^{-a\,z_{l,t}} \tag{C.9}$$

Female *ESB/R* is calculated as

$$ESB/R = FSSB/R_{female} \tag{C.10}$$

Combined sexes *ESB/R* is calculated as

$$ESB/R = (FSSB + MSSB)/(R_{male} + R_{female}) \tag{C.11}$$

<u>Stock-recruitment models:</u>

$$R = \frac{ESB}{\alpha + \beta\ ESB} \qquad \text{(Beverton and Holt, 1957)} \qquad \text{(C.12)}$$

$$R = \gamma\ ESB\ e^{-\theta\ ESB} \qquad \text{(Ricker, 1954)} \qquad \text{(C.13)}$$

Asymptotic (maximum) recruitment (R_{max}) for Beverton and Holt *S-R* relationship is $1/\beta$, and that for the Ricker *S-R* relationship is $\frac{\gamma e^{-1}}{\theta}$.

Mace (1994) defined the S-R steepness parameter, τ, as

$$\tau = \frac{(ESB/R)_{ESB=0}}{(ESB/R)_{F=0}} \qquad \text{(C.14)}$$

where $(ESB/R)_{F=0} = ESB/R$ estimated at $F = 0$, and

$(ESB/R)_{ESB=0}$ = reciprocal of the slope at the origin of the *S-R* curve, equal to α for the Beverton and Holt *S-R* model and $1/\gamma$ for the Ricker *S-R* model.

Therefore,

$$\alpha = \tau\ (ESB/R)_{F=0} \qquad \text{for Beverton and Holt S-R curve, and} \qquad \text{(C.15)}$$

$$\gamma = \frac{1}{\tau\ (ESB/R)_{F=0}} \qquad \text{for the Ricker } S\text{-}R \text{ model.} \qquad \text{(C.16)}$$

Thus, for a given τ and a fixed R_{max}, all parameters of the *S-R* relationships can be determined from an estimate of $(ESB/R)_{F=0}$.

The τ can be related to another definition of *S-R* steepness parameter, *sp*,

$$sp = 0.2 \times e \times \tau^{0.2}\ ln(\frac{1}{\tau})$$

for Ricker S-R model with sp defined as $sp \times R_{max} = R$, where R is estimated from the *S-R* curve with $0.2 * ESB_0$.

$$sp = \frac{1}{1+4\tau}$$

For Beverton-Holt S-R model, where $sp \times R_0 = R$, where R is estimated from the *S-R* curve with 0.2**ESB*$_0$.

For reference point determination, the number of recruits are predicted by recasting the S-R models in terms of *ESB/R* as follows:

$$R = \frac{ESB/R - \alpha}{\beta\ ESB/R} \quad \text{(Beverton and Holt S-R model)} \qquad \text{(C.17)}$$

$$R = \frac{ln(\gamma\ (ESB/R))}{\theta\ (ESB/R)} \quad \text{(Ricker S-R model)} \qquad \text{(C.18)}$$

The stochastic form of the S-R models are:

$$R = \frac{ESB/R - \alpha}{\beta\ ESB/R} e^{\varepsilon_t - \sigma^2_{\varepsilon_t}/2} \quad \text{(Beverton and Holt S-R curve)} \qquad \text{(C.19)}$$

$$R = \frac{ln(\gamma\ (ESB/R))}{\theta\ (ESB/R)} e^{\varepsilon_t - \sigma^2_{\varepsilon_t}/2} \quad \text{(Ricker S-R model)} \qquad \text{(C.20)}$$

where,

$\varepsilon_t = \rho * \varepsilon_{t-1} + e_t$ and $e_t \sim N(0, \sigma^2_e)$
(ρ is the autocorrelation)

<u>Estimation of catch and abundance at the fishing time:</u>

Retained catch:

$$c_t = \left(\frac{Fs_j}{(M+F_T s'_j + Fs_j + HM_j)}\right)\left(\sum_{j=p+1}^{p+q} N_{j,t} e^{-(M+F_T s'_j)et}\left(1 - e^{-(M+F_T s'_j + Fs_j + HM_j)\delta}\right)\right) \qquad \text{(C.21)}$$

$$y_t = \left(\frac{Fs_j}{(M+F_T s'_j + Fs_j + HM_j)}\right)\left(\sum_{j=p+1}^{p+q} N_{j,t} e^{-(M+F_T s'_j)et}\left(1 - e^{-(M+F_T s'_j + Fs_j + HM_j)\delta}\right)\right) w_j \qquad \text{(C.22)}$$

The total retained catch in numbers, *C*, and weight, *Y*, for the average fishery life span of the cohort, is obtained by:

$$C = \sum_{t=t_r}^{\lambda} c_t \tag{C.23}$$

$$Y = \sum_{t=t_r}^{\lambda} y_t \tag{C.24}$$

Discarded catch:

Discard catch is computed using the same equations (C.21 and C.22) replacing $F\ s_j$ in the numerator by HM_j (i.e., size specific handling mortality). Total retained and discarded catches are summed up to get the gross yield (Y) for optimization for red king and snow crabs. There are insufficient information for other crab stocks to compute retained and discarded catches separately, consequently, only retained catches are optimized for other crab stocks.

Total abundance of crabs that contribute to the catch are also estimated as,

$$N_t = \sum_{j=p+1}^{p+q} N_{j,t} e^{-(M+F_T s'_j)et} \tag{C.25}$$

$$N = \sum_{t=t_r}^{\lambda} N_t \tag{C.26}$$

The harvest rate (HR) for a given F is estimated as

$$HR = \frac{C}{N} \tag{C.27}$$

Note: In the stochastic simulations, the catches and abundances are averaged for 100 years to estimate relevant reference points.

<u>Auxiliary Models:</u>

1. The instantaneous handling mortality for size j, HM_j, is defined as a function of F with discard selectivity s_j, ignoring M and trawl and other bycatch mortality as follows:

$$1 - e^{-HM_j \delta} = h(1 - e^{-F\ s_j \delta})$$

Where s_j = discard selectivity.

2. The molt probability for a given size class *j* is described by the function:

$$mmolt_j = 1 - \frac{1}{1+e^{-a(j-b)}}$$ (red king and St. Mathew blue king crabs)

$$femlae\ molt_j = 1$$ (red king crab female)

$$immolt_j = 1$$ (immature male and female snow crab)

$$mmolt_j = 0$$ (mature male and female snow and Tanner crabs, mature female blue king crab alternate with 0 and 1 for biennial spawning)

$$mmolt_j = \frac{1}{1+c\ e^{a(j-b)}}$$ (Pribilof male blue king crab)

3. The maturity probability for a given size *j* is described by the function:

$$mat_j = \frac{1}{1+e^{-a(j-b)}}$$ (male and female red king, snow, Tanner, St. Mathew blue king crabs)

Knife-edge maturity size for Pribilof male blue king crab:

If size < 120 mm CL mat = 0 and for larger sizes, maturity = 1.

4. Retained selectivity for a given length *j* is described by the function:

$$s_j = \frac{1}{1+e^{-a(j-b)}}$$ (red king crab; blue king crab; snow and Tanner crabs (new- and old-shell have different parameter values)).

5. Discard selectivity for a given size *j* is described by the function:

$$s_j = \frac{1}{1+e^{-a(j-b)}} \frac{1}{1+e^{c(j-d)}}$$ (red king crab; snow crab (new- and old-shell have different parameter values)).

$$s_j = \frac{1}{1+e^{-a(j-b)}}$$ (female red king crab)

$$s_j = \frac{0.0012}{1+e^{-a(j-b)}}$$ (female snow crab)

6. Trawl selectivity for a given size *j* is described by the function:

$$s'_j = \frac{1}{1+e^{-a(j-b)}}$$ (red king and snow crabs)

7. Weight at size *j*, following Beyer (1987),

$$W_j = (\frac{1}{5})(\frac{a}{b+1})((j+2.5)^{b+1} - (j-2.5)^{b+1})$$

8.a The expected proportion of molting crabs ($P_{i,j}$) growing from size class *i* to size class *j* during a year is described by the gamma distribution as follows:

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

where

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

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

8.b For some species (blue king crab), the $P_{l',l}$ is determined as follows:

Annual growth increment (x) of crab is assumed to have a normal distribution with a mean growth increment $\bar{l}$ and a standard deviation s. Then,

$$P_{l',l} = \frac{\int_{l_1-\tau_{l'}}^{l_2-\tau_{l'}} e^{\frac{-(x-\bar{l})^2}{2s^2}} dx}{\sum_{l=1}^{n} \int_{l_1-\tau_{l'}}^{l_2-\tau_{l'}} e^{\frac{-(x-\bar{l})^2}{2s^2}} dx}$$

9 Total number of recruits (R) to the pre-recruit size bin i is distributed using a probability distribution function similar to 8.a or 8.b. Thus,

$$R_i = R\, P''_i$$

Appendix D (a). Base parameters of red king crab for simulations. CL=carapace length. Growth matrix, recruit proportion in each length bin, retained and discard selectivity values were directly used from the length-based model outputs.

Parameter	Male	Female	Remarks
Size range (mm CL)	65-200	65-165	
Instantaneous *M*	0.18	0.18	Based on 26-year longevity with 1% survival at maximum age
Pot fishery handling mortality rate (*h*)	0.2[a]	0.2	[a]Kruse et al., 2000; Model estimate of discard selectivity with *M*=0.18 using 1985-2004 data
Trawl fishery bycatch death proportion	0.8	0.8	Model estimate of trawl selectivity with *M*=0.18 using 1985-2004 data
Mean fishing period (yr)	0.0112	0.0112	Mean fishing time during 1996-2004
Lapsed time (yr)	0.542	0.542	Molt time (Apr 1) to start of fishery (Oct 15)
Growth increment: *a, b*	17.542, -0.016	16.7, -0.098	Zheng (unpublished data)
Maturity Probability: *a, b*	0.5, 120.0	0.287, 89.0	Estimates from Otto's unpublished data
Molt Probability: *a, b*	0.115, 134.113[a]	100% molt[b]	[a]Model estimates with *M*=0.18 using 1985-2004 data; [b]Zheng et al.,1995a
Recruit distribution			Model estimates with *M*=0.18 using 1985-2004 data
Pot selectivity	Retained; Discard	Discard	Model estimates with *M*=0.18 using 1985-2004 data
Weight length model: *a, b*	0.0003614, 3.16[a]	0.02286, 2.234[b]	[a]Belsiger, 1974; [b]Zheng et al., 1995a

Appendix D (b). Base parameters of snow crab for simulations. CW=carapace width

Parameter	Male	Female	Remarks
Size range (mm CW)	25-135	25-135	
Instantaneous *M*	0.23	0.31	Based on 20-year and 15-year longevity with 1% survival at maximum age
Pot fishery handling mortality rate (*h*)	0.5	0.5	Model estimate of discard selectivity, Turnock and Rugolo, 2005
Trawl fishery bycatch death proportion	0.8	0.8	Model estimate of trawl selectivity, Turnock and Rugolo, 2005
Mean fishing period (yr)	0.096	0.096	Mean fishing time during 1995- 2004
Lapsed time (yr)	0.792	0.792	Molt time (Apr 1) to start of fishery (Jan 15)
Growth increment: *a, b*	8.47, 0.19	12.29, 0.05	Growth Gamma distribution, β=0.75; Turnock and Rugolo, 2005
Maturity Probability: *a, b*	0.12, 88.	0.16, 49.0	Turnock, unpublished
Molt Probability: Immature Mature	 100% molt 0%	 100% molt 0%	Turnock and Rugolo, 2005
Recruit Distribution	mean 32.5 mm, β_r = 1.5	mean 32.5 mm, β_r = 1.5	Recruit proportion Gamma distribution, β_r from Turnock and Rugolo, 2005
Pot selectivity	Retained new- , old-shell; Discard new-, old-shell	Discard	Retained and discard selectivity curves estimated from Turnock, unpublished data
Weight length model: *a, b*	0.00023, 3.12948	0.00253, 2.56427	Somerton, 1981

Appendix D (c). Base parameters of Tanner crab for simulations. CW=carapace width

Parameter	Male	Female	Remarks
Size range (mm CW)	50-170	50-170	
Instantaneous *M*	0.23	0.31	Based on 20-year and 15-year longevity with 1% survival at maximum age
Pot fishery handling mortality rate (*h*)	0.25	0.25	Applicable to sub-legal
Instantaneous bycatch mortality in the trawl fishery	0.02	0.02	Applicable to all sizes, Siddeek, 2002
Mean fishing period (yr)	0.0425	0.0425	Mean fishing time during 1996- to closure year, Siddeek, 2002
Lapsed time (yr)	0.542	0.542	Molt time (Apr 1) to start of fishery (Oct 15)
Growth increment: *a, b*	15.75, 0.07	25.6, -0.1337	Zheng and Kruse, 1999
Maturity Probability: *a, b*	0.12, 115. 0	0.129, 78.24595	Estimates from Otto's unpublished data
Molt Probability: Immature Mature	 100% molt 0%	 100% molt 0%	Assumed similar to snow crab
Recruit Distribution	mean 72.5 mm, β_r = 1.023	mean 62.5 mm, β_r = 0.955	Recruit proportion Gamma distribution, β_r from Zheng et al., 1999
Pot Selectivity:	New-shell, Old-shell	Combined New-&old-shell	Size-specific selectivity values from Zheng and Kruse, 1999
Weight length model: *a, b*	0.00019, 3.09894	0.00182, 2.70462	Somerton, 1981

Appendix D (d). Base parameters of Pribilof blue king crab for simulations. CL=carapace length

Parameter	Male	Female	Remarks
Size range (mm CL)	65-170	65-170	
Instantaneous *M*	0.18	0.18	Based on 26-year longevity with 1% survival at maximum age
Pot fishery handling mortality rate (*h*)	0.2	0.2	Applicable to sub-legal, Siddeek, 2003b
Instantaneous bycatch mortality in the trawl fishery	0.02	0.02	Applicable to all sizes, Siddeek, 2003b
Mean fishing period (yr)	0.0308	0.0308	Mean fishing time during 1996 to closure year
Lapsed time (yr)	0.542	0.542	Molt time (Apr 1) to start of fishery (Oct 15)
Growth increment distribution: normal with	14.1, 3.1[a]	5.2, 1.04[b]	[a]Otto and Cummiskey, 1990; [b]Somerton and MacIntosh,1985
Maturity Probability: *a, b*	0%, if CL<120; 100%, if CL≥120	0.283515,93.79601[c]	[c]Somerton and MacIntosh, 1983
Molt Probability: Immature Mature: *a, b*	0.000002,0.091[d] 0.000002,0.091[d]	100% Newshell 0%, Oldshell 100%	[d]Otto and Cummiskey, 1990
Recruit distribution: mean, std. dev	97.5, 7.5	90.0, 1.6667	Recruit proportion normal distribution
Pot selectivity	0.080993,114.0782	0.080993,114.0782	Siddeek, 2003b
Weight length model: *a, b*	0.00047, 3.103	0.02065, 2.27	Otto, personal communication, AFSC, Kodiak

Appendix D (e). Base parameters of St. Mathew blue king crab for simulations. CL=carapace length

Parameter	Male	Female	Remarks
Size range (mm CL)	60-155	60-155	
Instantaneous *M*	0.18	0.18	Based on 26-year longevity with 1% survival at maximum age
Pot fishery handling mortality rate (*h*)	0.2	0.2	Applicable to sub-legal, Siddeek, 2002
Instantaneous bycatch mortality in the trawl fishery	0.02	0.02	Applicable to all sizes, Siddeek, 2002
Mean fishing period (yr)	0.026	0.026	Mean fishing time during 1996 to closure year
Lapsed time (yr)	0.542	0.542	Molt time (Apr 1) to start of fishery (Oct 15)
Growth increment distribution: normal with mean, standard	14.1, 3.1[a]	5.2, 1.04[b]	[a]Otto and Cummiskey, 1990; [b]Somerton and MacIntosh,1985
Maturity Probability: *a, b*	0.290876,103.9999	0.266642,89.24575	Estimates from Otto's unpublished data
Molt Probability: Immature Mature *a, b*	 0.097,133.8334 0.097,133.8334	 100% Newshell 0%, Oldshell 100%	[d]Otto and Cummiskey, 1990
Recruit distribution: mean, std.dev	80.0, 6.6667	65.0, 5.0	Recruit proportion normal distribution
Pot selectivity	0.080993,114.0782	0.080993,114.0782	Siddeek, 2003b
Weight length model: *a, b*	0.0004, 3.139	0.02065, 2.27	