Analysis of Proposed Overfishing Tier System for BSAI King and Tanner Crab Stocks

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April 18, 2006

Introduction

The purpose of this analysis is to evaluate the current overfishing definitions and the proposed replacement overfishing definitions, for their consistency with the MSFCMA and National Standard Guidelines. If it is judged that the existing overfishing definitions are lacking in terms of fisheries conservation and utilization goals consistent with governing law, then new definitions need to be established. The analysis presented here can serve to formulate these new definitions through a formal amendment of the current BSAI King and Tanner crab fishery management plan.

Current Tier System for BSAI King and Tanner Crab Stocks (NPFMC 1998)

The existing Tier system is based mostly on the amount of survey information since survey data is used to estimate overfishing definitions. Tier 1 is the least amount of information, Tier 3 the most information. Overfishing is evaluated by comparing MSY (includes mature males and females) to the Guideline Harvest Level (GHL) (includes retained males only, no bycatch). MSST (1/2 B_{MSY}), MSY, OY and MFMT (maximum fishing mortality threshold) values using the current Tier system are shown in Table 1. MFMT was set equal to the assumed Fmsy.

Tier 1. Crab stock is not surveyed. Some catch data available.
Fmsy = M = 0.2 (King), 0.3 (Tanner and snow).
B_{MSY} not estimable.
MSY is estimated from a proxy of mature biomass and stock utilization rate.

Tier 2. Sporadic or limited years of survey data. Catch and effort data on each crab stock is well documented.
Fmsy = M = 0.2 (King), 0.3 (Tanner and snow).
B_{MSY} not estimable.
MSY is estimated from a proxy of mature biomass and stock utilization rate.

Tier 3. Data Available: historical catch, continuous inseason catch and effort data, stock assessment, growth, maturity, limited natural mortality and stock recruitment relationship information.
Fmsy = M = 0.2 (King), 0.3 (Tanner and snow).
B_{MSY} is the average survey biomass of mature males and females from 1983 to 1997.
MSY = B_{MSY} *Fmsy.

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MSY has been estimated for all stocks except Aleutian Islands scarlet king and Eastern Bering Sea scarlet king crabs.

Draft Tier System for BSAI King and Tanner Crab Stocks

The proposed Tier System has five tiers that have analogs to the current NPFMC groundfish Tier System. The different tiers are formulated based on whether reliable estimates are available for biomass (survey or model) and reference points, and whether a model has been implemented for the assessment. In Tiers 1 through 4, three levels of stock status are specified and denoted by 'a', 'b' and 'c'. At stock status level 'a', current stock biomass exceeds the biomass that produces maximum sustainable yield to the fishery (B_{MSY}). For stocks in status 'b', current biomass is less than B_{MSY} but greater than a level specified as the 'critical biomass threshold' (β). Lastly, in stock status 'c', current biomass is below β. For each of these levels of stock status in Tiers 1 through 4, the fishing mortality rate corresponding to the overfishing limit (i.e., F_{OFL}) is specified in the Tier System. In Tier 5, the overfishing limit (OFL) is specified in terms of an average catch value over an historical time period determined to represent the best scientific information.

In the current NPFMC groundfish Tier System, the specified F_{ABC} is the maximum target F to ensure a buffer between the overfishing F_{OFL} and the target F as required by National Standard Guidelines 1 (NSG1). In the BSAI King and Tanner Crab Tier System, no F_{ABC} is specified. The setting of the target F is deferred to Alaska Department of Fish and Game with oversight by the Federal Government. The target F corresponding to the annual quota can be set anywhere below the F_{OFL}. To comply with the intent of the NSG1, however, a buffer between the target F and the F_{OFL} is encouraged to insure that the F_{OFL} is not exceeded.

Tiers 1 through 3 are for stocks with length or age structured models which incorporate survey and fishery data. For Tiers 1 through 3, reliable estimates of necessary input data and parameters are needed for models that provide estimates of a time series of B, B_{MSY} and F_{MSY}, or their respective proxy values. Stocks in Tiers 1 through 3 do not necessarily have annual surveys, however, surveys and other information have to be reliable to be used in a stock assessment model. Tiers 1 and 2 are for stocks with a reliable estimate of the spawner recruit relationship thereby enabling the estimation of the limit reference points B_{MSY} and F_{MSY}. Tier 1 is for stock assessments where the probability density function of F_{MSY} is estimated; that pdf is not estimable for Tier 2 stocks. Tier 3 is for stocks where reliable estimates of the spawner recruit relationship are not available, however, proxies for F_{MSY} and B_{MSY} can be estimated. For Tier 3 stocks, maturity and other essential life-history information are available to estimate proxy limit reference points, although there is no stock assessment model per se. The proxy values for B_{MSY} and F_{MSY} can be determined, for example, from a spawning stock biomass per recruit (SPR) analysis or biomass dynamic modeling. The proxy B_{MSY} value may be determined from survey data. Initial proxy values of 50% and 60% (i.e., $B_{50\%}$, $B_{60\%}$, $F_{50\%}$ and $F_{60\%}$)

are recommended for stocks subject to this tier; 50% and 60% correspond to values which appear appropriate for these anomuran and brachyuran crab species given their unique reproductive dynamics and life-history characteristics. The exact percent level should be determined based on analysis where possible, or established otherwise, however, it should provide risk averse outcomes in terms of stock conservation and utilization in either case.

Tiers 4 and 5 are for stocks with no stock assessment model and where essential life-history information and understanding is lacking. In Tier 4, the MSY control rule declines with stock biomass similar to Tiers 1-3 however, since no estimates of the proxy F_{MSY} value exists, a default value of M is used in the calculation of the F_{OFL}. Explicit to Tier 4 are reliable estimates of current survey biomass and the instantaneous natural mortality rate M. A scaler, γ, is multiplied by M to estimate the F_{OFL} for stocks at status levels 'a' and 'b', and γ is allowed to be less than or greater than unity. Hence, the resultant overfishing threshold can be either more or less biologically conservative than fishing at M. Use of the scaler γ is intended to allow adjustments in the overfishing definitions to account for differences in biomass measures. Stocks belonging to Tier 4 are information-poor by definition, hence, γ should never be set to a value that would provide less biological conservation and more risk prone overfishing levels without defensible evidence that the stock could support fishing at levels in excess of M. Tier 5 stocks have no reliable estimates of biomass or natural mortality rate M, but a reliable catch history exists for these stocks. For stocks belonging to Tier 5, the historical performance of the fishery is used to set overfishing limits (OFL) in terms of catch instead of fishing mortality. OFL represents the average catch from a time period determined to be representative of the production potential of the stock. The time period selected for computing the average catch, hence the OFL, should be based on the best scientific information available and provide the required risk aversion in terms pertaining to stock conservation and utilization goals.

For Tiers 1 through 4, an F_{MSY} Control Rule reduces the F_{OFL} as biomass declines (Figure 1). The NPFMC groundfish F_{MSY} Control Rule uses an α of 0.05 (F is zero at 0.05 x B_{MSY}), F35% as a proxy for F_{MSY}, and F40% as a target F when F_{MSY} is not estimable. The proxy limit reference points are need to be determined for crab stocks based on modeling work. Biomass values for groundfish are female spawning biomass. Crab stocks will use measures of spawning stock biomass that incorporate mature females as well as mature males participating in mating (e.g., effective spawning stock biomass which includes female plus male spawning biomass scaled by the mating ratio). In this example, if there are insufficient mature males to fertilize females, then the effective spawning biomass will be lowered. This measure of spawning biomass requires assumptions regarding the optimum mating ratio and the component of the male stock that is effective at mating. All mature males may not be successful at mating depending on their size, molt history and geographic distribution. The proposed Tier System for crabs incorporates a relative critical biomass threshold value (β) below which F is 0. This would result in F=0 at a biomass value most likely above the value implied by α. For example, the current harvest strategy for Bering Sea snow crab (not the overfishing definitions) reduces fishing mortality to 0 at 25% of B_{MSY}.

Incorporating a Limit Reference Point System into the Tier System

The Limit Reference Point system (Caddy 1998) as proposed for crab stocks would result in an overall score based on scores for individual components of the health and status of a stock. This overall score would be used to scale the F_{OFL} values in the Tier System. The scoring system, which tiers to apply it to and the method of application will be recommended by the working group.

Proposed Tier System Assignment of Stocks

Tier 1:
No stocks.

Tier 2:
No stocks.

Tier 3:
Bering Sea snow crab
Bering Sea tanner crab
Bristol Bay red king crab

Tier 4:
Saint Matthew blue king crab
Pribilof Islands blue king crab
Pribilof Islands red king crab

Tier 5:
Pribilof Islands golden king crab
Saint Matthew golden king crab
Western Aleutian Tanner crab
Saint Lawrence Island blue king crab
Aleutian Islands scarlet king crab
Eastern Bering Sea scarlet king crab
Bering Sea triangle tanner crab
Eastern Aleutian Islands triangle tanner crab
Eastern Aleutian Islands grooved tanner crab
Western Aleutian Islands grooved tanner crab
Bering Sea grooved tanner crab
Western Aleutian Islands (Adak) red king crab
Eastern Aleutian Islands (Dutch Harbor) red king crab
Norton Sound red king crab
Aleutian Islands golden king crab
Eastern Aleutian Islands tanner crab

Proposed tier system for crab overfishing definitions.

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

Projection model

A projection model was used to evaluate various harvest control rules from the proposed Tier system, the current OFL, as well as the current ADFG harvest strategies. The population was simulated for 200 years and fishing mortalities applied according to the particular harvest control rule. Mature biomass values, total and retained catch, F, and the percent of the time the biomass was below B_{MSY} (or B%) and ½ B_{MSY} (or 1/2 B%) were calculated. The average values for 1000 runs using the last 100 years of each simulation were calculated to compare control rules. The population was started from the abundance and biomass in 2005 for snow crab, which were near ½ B_{MSY}, to evaluate rebuilding to B_{MSY} in the beginning years of the simulation. Red king crab starting values were also near ½ B_{MSY} to evaluate rebuilding, although the population is currently at higher levels.

Process error was incorporated in recruitment using an autocorrelated lognormal error structure with coefficient of variation = 0.86 for snow crab and 0.6 for red king crab, using variance of recruitment from stock assessment models. The correlation coefficient for autocorrelation was 0.6 for both snow crab and red king crab, also estimated from time series of re recruitment from stock assessment models. Rebuilding times will be less than estimated here for random recruitment (no spawner recruit curve), and for recruitment generated from a spawner recruit curve with lognormal error and no autocorrelation.

Observation and stock assessment errors were simulated with autocorrelated lognormal error applied to abundance. A cv = 0.15 and autocorrelation = 0.6 were used for errors on biomass. Fishing mortality from the harvest control rules was estimated using the biomass with added errors, resulting in the actual F applied to the true population being higher or lower than the F from the control rule, depending on the error in that year. No process errors on growth or natural mortality were simulated.

Harvest control rules

The harvest control rules applied to the simulated population follow the control rules in the proposed Tier system(see above) as well as the current OFL and current ADFG harvest strategies.
The current OFL uses a fixed value (0.3 for snow crab and 0.2 for red king crab) to calculate the retained catch (SY) using the total survey mature biomass in the current year.

For snow crab the calculation is,

SY = 0.3 * total survey mature biomass (males plus females)

The SY is taken as the retained catch (total catch less discards).

The ADFG harvest strategies use fixed values of biomass reference points and harvest rates that will affect their performance depending on the estimated or true values of Fmsy and B_{MSY} or their proxy values. The ADFG harvest strategy is:

$$E = \frac{0.75 * F'msy * \left[\frac{TMB}{B'msy} - \alpha \right]}{(1-\alpha)}$$

TMB is total mature biomass (male plus female), B'msy is average survey total mature biomass from 1983 to 1997 (418,900 tons), and F'msy=0.3.

for TMB ≥ 0.25*B'msy and TMB<B'msy, where α = -0.35, and,

- E = (F'msy * 0.75) = 0.225, for TMB ≥ B'msy, and E = 0 for TMB < 0.25*B'msy.

The maximum retained catch is determined by using the E determined from the control rule as an exploitation rate on mature male biomass (MMB) at the time of the survey,

- Retained Catch = E•MMB.

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

Simulations used a Beverton-Holt spawner recruit curve with steepness = 0.5, and R0 = 3.1 Billion recruits (male+female) for snow crab. Red king crab simulations also used a Beverton-Holt spawner recruit curve with steepness = 0.5 and R0= 16 million recruits (male+female).

In Tier 3, average recruitment estimated from stock assessment models is used with spawning biomass per recruit fishing at F60% and F50% to estimate B60% and B50% respectively. The time period used to estimate average recruitment will influence the B% values. The time period from 1978 to 1999 was used to estimate an average recruitment of 1.8 billion recruits for snow crab. Prior to 1978, the snow crab catch was mainly bycatch in other crab fisheries. The stock declined to an overfished state after 1999. Red king crab average recruitment (12 million) was estimated for the time period after the decline in abundance in the early 1980's to 2005. Average recruitment prior to the early 1980's was higher.

Two measures of effective spawning biomass were used to evaluate the control rules. The first uses a mating ratio equal to the ratio of mature female numbers to old shell male numbers (non-molting males for red king crab) at F=0, to estimate female effective spawning biomass. Biomass and numbers were projected forward to the time of mating in the spring. If the numbers of old shell mature males (NMM_O) at the time mating occurs (accounting for natural mortality and removing the catch from the numbers at survey time) is less than the numbers of mature females (NMF) at the time mating occurs, divided by the mating ratio ($\eta = 1.7$), then the female mature biomass (fspbio) is reduced to estimate effective female spawning biomass (efspbio),

$$efspbio = fspbio * \frac{NMM_O * \eta}{NMF}$$

If the number of old shell mature males at mating time is more than the numbers of mature females at the time mating occurs, divided by the mating ratio ($\eta = 1.7$), then effective female spawning biomass is estimated to be equal to female spawning biomass. effective male spawning biomass is set equal to old shell male mature biomass. The effective female spawning biomass is added to the effective male spawning biomass to obtain total effective spawning biomass.

The second measure of effective spawning biomass was calculated without using a mating ratio as female spawning biomass at the time of mating plus old shell male mature biomass (non-molting mature males for red king crab).

Results

Snow crab

Projection model results for snow crab are summarized in Tables 2 and 5 and Figures 2 and 3. Tables 2 and 3 contain absolute numbers, while tables 4 and 5 are values relative to the Fmsy run. Results for the Tier 2, Fmsy control rule are shown in Figures 6 through 17, for the effective total spawning biomass at mating time with mating ratio 1.7, retained catch, total spawning biomass at survey time, probability of rebuilding and fishing mortality values over the 200 years simulation. Traces of 5 simulation runs are shown to illustrate the variability in recruitment and biomass simulated in the projections. Fishing mortality can exceed the maximum in the control rule due to errors in biomass in a particular year.

The current OFL would result in very high fishing mortality values which drive the stock to very low levels when calculating effective spawning biomass using a mating ratio of 1.7 (about 4% of B_{MSY}) (Table 1 and Figure 2). The catch calculated using the current OFL is not based on the exploitable portion of the stock and results in most cases in very high fishing mortality values (F was capped in the simulations at 5.0). As fishing mortality increases, and large male crabs desired by the fishery decline, discarding may increase resulting in further declines in the stock. Also, the assumption that the

remaining small mature male crabs can be successful at mating and maintaining the stock may not be valid.

The Tier 2, Fmsy control rule results in average catches similar to MSY (fishing at constant Fmsy) and the average biomass is about 10% greater than B_{MSY} (the biomass fishing at constant Fmsy). Catch for the Tier 3, F60% control rule is about 5% less than fishing at the Tier 3, F50% control rule, however, there is a much lower probability of being below B_{MSY} (26% vs 54%). Fishing mortality values average 0.37 for F60% and 0.59 for F50%, B60% = 460,000 tons and B50% = 383,000 tons. The Tier 4, F=M (0.23) is the most conservative, however still results in a catch of about 79% of MSY, due to maintaining higher biomass levels. The Tier 4, F=M policy applied in the simulations was a constant F, with no decline in F with declining biomass. In the case of snow crab, the average catch (Tier 5, 1978-1999) results in dramatic declines of the stock. The average catch is close to the estimated value fishing at Fmsy, and since the stock begins at about ½ B_{MSY}, taking the average catch is a poor strategy. The average catch strategy is sensitive to the fishing mortality that was being applied over the time period and may not be a conservative policy.

Results for effective total spawning biomass defined as female spawning biomass at the time of mating plus old shell male spawning biomass at the time of mating are shown in Table 3. The current OFL rule results in low biomass levels (74% below ½ B_{MSY}), and a catch of about 55% of MSY. An assumption of the current OFL rule is that the remaining small mature males in the population will be adequate to maintain recruitment at some low level, which may not be valid. Fmsy is about 1.24, almost twice the value using effective spawning biomass with a mating ratio of 1.7 (Fmsy=0.67). Tier 3 using F50% and B50%, is almost identical to the Fmsy control rule, while Tier 3 using F60% and B60% results in catches of about 77% of the Fmsy control rule, while maintaining the population at a higher level. The probability of being below B_{MSY} for the Fmsy control rule is 52%, for the Tier 3, F60% rule, 37%, and the Tier 3 F50% rule 54%. The Tier 4, F=M=0.23 constant control rule is the most conservative, resulting in retained catches of about 64% of the average catch for the Tier 2 Fmsy control rule.

Rebuilding –Snow Crab

The probability of rebuilding to B_{MSY} is estimated as the median for all simulations, of the year when the stock first reaches B_{MSY}. The stock may go below B_{MSY} in later years of the simulation after reaching B_{MSY}. The time to rebuild will depend on the recruitment generator, random recruitment without a spawner recruit curve will result in rebuilding faster than using spawner recruit curve, and adding autocorrelation will further extend rebuilding times. The current OFL rule does not result in rebuilding (Table 1 and 2). The Tier 4 F=M control rule results in the shortest rebuilding time (Table 1 and 2, Figure 2). Alternative slopes of the control rule need to be analyzed relative to rebuilding times to determine whether alpha = 0.05 is appropriate for all crab stocks.

Results – Red King Crab

Projection model results for red king crab are summarized in Tables 4 and 5 and Figures 4 and 5. Tables 2 and 3 contain absolute numbers, while tables 4 and 5 are values relative to the Fmsy run. Results for the Tier 2, Fmsy control rule are shown in Figures 18 through 28, for the effective total spawning biomass at mating time, retained catch, total spawning biomass at survey time, probability of rebuilding and fishing mortality values over the 200 years simulation. Traces of 5 simulation runs are shown to illustrate the variability in recruitment and biomass simulated in the projections. Fishing mortality can exceed the maximum in the control rule due to errors in biomass in a particular year.

The current OFL rule results in the stock declining to zero for both measures of effective spawning biomass (Tables 4 and 5). Fmsy is 0.12 for the effective total spawning biomass with mating ratio 2.0 and 0.23 for effective total spawning biomass not using the mating ratio. The Tier 3 control rules resulted in mean catches that were very close to the Tier 2 Fmsy control rule. Mean biomass values were very close for the Tier 3 F50% control rule and the Tier 2 Fmsy control rule, while the Tier 3, F60% control rule biomass values were higher.

Mean catches were similar for all control rules with effective total spawning biomass without using the mating ratio (Table 5). The probability of biomass being below B_{MSY} was lowest for Tier 3, F60%, followed by Tier 3 F50% and F=M. The ADFG control rule probability of being below B_{MSY} was 75%.

Rebuilding –Red King Crab

The probability of rebuilding to B_{MSY} is estimated as the median for all simulations, of the year when the stock first reaches B_{MSY}. The stock may go below B_{MSY} in later years of the simulation after reaching B_{MSY}. The time to rebuild will depend on the recruitment generator, random recruitment without a spawner recruit curve will result in rebuilding faster than using spawner recruit curve, and adding autocorrelation will further extend rebuilding times. The current OFL rule, the ADFG and Tier 4, F=M policy do not rebuild the stock in the 200 year time frame using effective spawning biomass with a mating ratio of 2.0 (Tables 5 and 6). Rebuilding time is shortest for the Tier 3, F60% control rule(27 years). The rebuilding time for effective spawning biomass with no mating ratio used is also shortest for the Tier 3, F60% control rule (30 years).

Alternative slopes of the control rule need to be analyzed relative to rebuilding times to determine whether alpha = 0.05 is appropriate for all crab stocks. A different control rule with lower slope could be used during rebuilding periods, then switch to a control rule with higher slope once the stock is rebuilt.

Conclusions

The proposed Tier system performs better than the current OFL in all cases presented here. Tier 3, F50% and the Tier 3, F60% control rule catches were similar to the Tier 2

Fmsy control rule. For Tier 3, F60% is recommended as a default value. Tier 5 average catch may not be a conservative policy depending on the exploitation history of the stock. One time period over which to calculate average catch for all stocks is not appropriate. Over the contemporary historical record, the development of fisheries for these crab stocks was non-synchronous. As a result, no unique time period exists during which the fisheries were both fully developed for all stocks and during which the stocks were in a sustainable biological condition. The time period for calculation of the average catch value for Tier 5 stocks should be established on a stock-specific basis and represent the production potential of the stock based on the best available scientific information. The average catch used should be some fraction of MSY to account for fluctuation in stock abundance. However, the relationship of the average catch to MSY will be difficult to determine with data poor, Tier 5 stocks.

Table 1. MSST (minimum stock size threshold), MSY, OY, and the MFMT (maximum fishing mortality threshold) values for BSAI king and Tanner crabs. Values in millions of pounds.

Stock	MSST	MSY	OY range	MFMT
WAI red king	NA	1.5	0-1.5	0.2
Bristol Bay red king	44.8	17.9	0-17.9	0.2
EAI red king	NA	NA	NA	0.2
Pribilof Islands red king	3.3	1.3	0-1.3	0.2
Norton Sound red king	NA	0.5	0-0.5	0.2
Pribilof Islands blue king	6.6	2.6	0-2.6	0.2
Saint Matthew blue king	11.0	4.4	0-4.4	0.2
Saint Lawrence blue king	NA	0.1	0-0.1	0.2
Aleutian Islands golden king	NA	15.0	0-15.0	0.2
Pribilof Islands golden king	NA	0.3	0-0.3	0.2
Northern District golden king	NA	0.3	0-0.3	0.2
Aleutian Islands scarlet king	NA	NA	NA	0.2
EBS scarlet king	NA	NA	NA	0.2
Total king crab		**43.9**	**0-43.9**	
Eastern Aleutian Tanner	NA	0.7	0-0.7	0.3
EBS Tanner	94.8	56.9	0-56.9	0.3
Western Aleutian Tanner	NA	0.4	0-0.4	0.3
Total Tanner		**58.0**	**0-58.0**	
EBS snow	460.8	276.5	0-276.5	0.3
Total snow		**276.5**	**0-276.5**	
Eastern Aleutian triangle Tanner	NA	1.0	0-1.0	0.3
EBS triangle Tanner	NA	0.3	0-0.3	0.3
Eastern Aleutian grooved Tanner	NA	1.8	0-1.8	0.3
EBS grooved Tanner	NA	1.5	0-1.5	0.3
Western Aleutian grooved Tanner	NA	0.2	0-0.2	0.3
Total other Tanner		**4.8**	**0-4.8**	

NA: Indicates that insufficient data exists to calculate value.

Table 2. Snow crab average values from 1000 simulations for the last 100 years of a 200 year projection for various harvest control rules (except years to rebuild). Biomass in 1000's of tons. Steepness = 0.5, R0 = 3.1 billion, Beverton-Holt spawner recruit curve, B_{MSY} = 399, Fmsy = 0.67. Effective spawning biomass is female spawning biomass with mating ratio 1.7, plus old shell male spawning biomass at time of mating. F50%=0.66, B50%=383, F60%=0.40, B60% = 460.

Average over 1000 simulations and 100 yrs	Fmsy constant	Current OFL	Proposed Tier 2 Fmsy control rule	Current ADFG	Proposed Tier 4 F=M (0.23)	F=0	Proposed Tier 3, F50%,B50% control rule	Proposed Tier 3, F60%,B60% control rule	Tier 5 avg catch
Recruits	944502	75580	1008213	873552	1315566	1565639	1009744	1184825	73465
total catch bio	75.7	8.6	78.8	75.4	61.6	1.4	78.7	74.6	8.4
retained catch bio	59.5	6.5	61.9	59.6	47.0	0.0	61.7	57.8	6.3
male sp bio	472.4	20.9	515.5	405.3	889.2	1405.2	518.0	703.0	21.0
Female sp bio	253.5	21.5	270.8	234.5	353.3	420.6	271.2	318.2	21.1
total sp bio	725.9	42.5	786.2	639.8	1242.5	1825.8	789.1	1021.2	42.0
eff male sp bio	247.8	8.6	273.4	205.9	538.1	965.8	275.1	399.9	8.8
eff female sp bio	151.8	8.4	164.4	133.7	255.9	340.1	165.1	213.3	8.3
eff total sp bio	399.5	17.0	437.9	339.6	794.0	1305.9	440.2	613.2	17.1
F	0.67	4.86	0.60	0.79	0.23	0.0	0.59	0.37	4.98
percent below 1/2 B_{MSY}	16.7	99.9	5.8	20.3	0.4	0.0	6.0	0.8	99.6
percent below Bmsy	61.7	100.0	54.4	72.8	11.7	0.5	54.0	25.9	99.8
percent F=0	0.0	0.0	0.0	0.8	0.0	100	0.0	0.0	0.0
years to rebuild	29	NA	23	34	14	9	24	16	NA

Table 3. Snow crab average values from 1000 simulations for the last 100 years of a 200 year projection for various harvest control rules (except years to rebuild). Biomass in 1000's of tons. Steepness = 0.5, R0 = 3.1 billion, Beverton-Holt spawner recruit curve, B_{MSY} = 406.7, Fmsy = 1.24. Effective spawning biomass is female spawning biomass (no mating ratio) plus old shell male spawning biomass. F50%=1.23, B50%=383, F60%=0.59, B60% = 460.

Average over 1000 simulations and 100 yrs	Fmsy constant	Current OFL	Proposed Tier 2 Fmsy control rule	Current ADFG	Proposed Tier 4 F=M	F=0	Proposed Tier 3, F50%,B50% control rule	Proposed Tier 3, F60%,B60% control rule
Recruits	957,558	466,779	1,021,125	891,562	1,372,981	1,578,956	1,016,883	1,010,859
total catch bio	91.9	51.4	95.4	77.0	64.2	0	95.2	74.7
retained catch bio	73.2	38.9	75.9	61.0	49.0	0	75.7	58.4
male sp bio	385.6	123.2	427.7	413.1	928.1	1417.1	425.2	541.1
female sp bio	257.0	125.6	274.2	239.4	368.7	424.2	273.1	271.5
total sp bio	642.6	248.8	701.9	652.5	1296.9	1841.3	698.2	812.6
eff male sp bio	183.9	49.9	207.9	209.7	561.6	973.9	206.5	293.4
eff female sp bio	222.8	108.8	237.7	207.5	319.7	367.7	236.7	235.4
eff total sp bio	406.7	158.7	445.7	417.3	881.3	1341.7	443.2	528.7
F	1.24	4.82	1.047	0.79	0.23	0	1.05	0.51
percent below 1/2 Bmsy	15.38	74.47	5.39	10.5	0.2	0	6.5	1.98
percent below Bmsy	59.87	96.10	51.8	58.4	7.7	0.42	54.0	37.48
percent F=0	0.00	0.00	0.06	0.68	0	100	0.04	0.03
years to rebuild	29	160	22	26	12	8	23	17

Table 4. Snow crab using effective total spawning biomass with mating ratio 1.7. Results from simulations as a percent of the values for the constant Fmsy control rule from 1000 simulations for the last 100 years of a 200 year projection for various harvest control rules.

Average over 1000 simulations and 100 yrs	Fmsy constant	Current OFL	Proposed Tier 2 Fmsy control rule	Current ADFG	Proposed Tier 4 F=M	F=0	Proposed Tier 3, F50%,B50% control rule	Proposed Tier 3, F60%,B60% control rule
Recruits	1.00	0.08	1.07	0.92	1.39	1.66	1.07	1.25
total catch	1.00	0.11	1.04	1.00	0.81	0.02	1.04	0.99
retained catch	1.00	0.11	1.04	1.00	0.79	0.00	1.04	0.97
male sp bio	1.00	0.04	1.09	0.86	1.88	2.97	1.10	1.49
Female sp bio	1.00	0.08	1.07	0.93	1.39	1.66	1.07	1.26
total sp bio	1.00	0.06	1.08	0.88	1.71	2.52	1.09	1.41
eff male sp bio	1.00	0.03	1.10	0.83	2.17	3.90	1.11	1.61
eff female sp bio	1.00	0.06	1.08	0.88	1.69	2.24	1.09	1.41
eff total sp bio	1.00	0.04	1.10	0.85	1.99	3.27	1.10	1.53
F	1.00	7.25	0.90	1.18	0.34	0.00	0.88	0.55

Table 5. Snow crab using effective total spawning biomass with no mating ratio. Results from simulations relative to the constant Fmsy run from 1000 simulations for the last 100 years of a 200 year projection for various harvest control rules.

Average over 1000 simulations and 100 yrs	Fmsy constant	Current OFL	Proposed Tier 2 Fmsy control rule	Current ADFG	Proposed Tier 4 F=M	F=0	Proposed Tier 3, F50%,B50% control rule	Proposed Tier 3, F60%,B60% control rule
Recruits	1.00	0.49	1.07	0.93	1.43	1.65	1.06	1.06
total catch	1.00	0.56	1.04	0.84	0.70	0.00	1.04	0.81
retained catch	1.00	0.53	1.04	0.83	0.67	0.00	1.03	0.80
male sp bio	1.00	0.32	1.11	1.07	2.41	3.68	1.10	1.40
Female sp bio	1.00	0.49	1.07	0.93	1.43	1.65	1.06	1.06
total sp bio	1.00	0.39	1.09	1.02	2.02	2.87	1.09	1.26
eff male sp bio	1.00	0.27	1.13	1.14	3.05	5.30	1.12	1.60
eff female sp bio	1.00	0.49	1.07	0.93	1.43	1.65	1.06	1.06
eff total sp bio	1.00	0.39	1.10	1.03	2.17	3.30	1.09	1.30
F	1.00	3.89	0.84	0.64	0.19	0.00	0.85	0.41

Table 6. Red king crab average values from 1000 simulations for the last 100 years of a 200 year projection for various harvest control rules (except years to rebuild). Biomass in 1000's of tons. Effective spawning biomass is female spawning biomass using a mating ratio of 2.0, plus non-molting male spawning biomass at time of mating. Steepness = 0.5, R0= 16 million, Beverton-Holt spawner recruit curve, B_{MSY} = 29.2, Fmsy = 0.12. F50%=0.12, B50%=33.8, F60%=0.08, B60% = 40.6.

Average over 1000 simulations and 100 yrs	Fmsy constant	Current OFL	Proposed Tier 2 Fmsy control rule	Current ADFG	Proposed Tier 4 F=M	F=0	Proposed Tier 3, F50%,B50% control rule	Proposed Tier 3, F60%,B60% control rule
Recruits	5206.7	0.0	5310.3	3320.1	3478.4	7921.0	5299.1	6155.1
total catch bio	3.1	0.0	3.2	2.5	2.5	0.7	3.2	3.1
retained catch bio	2.6	0.0	2.6	2.1	2.1	0.0	2.6	2.5
male sp bio	31.9	0.0	32.7	16.3	17.9	77.2	32.5	42.4
female sp bio	22.5	0.0	23.0	14.1	14.8	35.2	23.0	26.9
total sp bio	54.4	0.0	55.7	30.4	32.7	112.4	55.5	69.3
eff male sp bio	17.8	0.0	18.3	7.9	8.9	54.0	18.2	25.3
eff female sp bio	11.4	0.0	11.8	5.4	6.0	30.1	11.7	15.8
eff total sp bio	29.2	0.0	30.1	13.3	14.9	84.0	29.8	41.1
F	0.12	5.00	0.11	0.19	0.18	0	0.11	0.08
percent below 1/2 Bmsy	3.7	100.0	1.3	72.5	55.8	0	0.9	0.0
percent below Bmsy	56.9	100.0	54.2	100.0	96.6	0	55.8	17.6
percent F=0	0.0	0.0	0.0	5.2	0.0	100	0.0	0.0
years to rebuild	53	NA	42	NA	NA	17	41	27

Table 7. Red king crab average values from 1000 simulations for the last 100 years of a 200 year projection for various harvest control rules (except years to rebuild). Biomass in 1000's of tons. Effective spawning biomass is female spawning biomass plus non-molting male spawning biomass at time of mating. Steepness = 0.5, R0= 16 million, Beverton-Holt spawner recruit curve, B_{MSY} = 34.1, Fmsy = 0.23. F50%=0.29, B50%=34.3, F60%=0.17, B60% = 41.2.

Average over 1000 simulations and 100 yrs	Fmsy constant	Current OFL	Proposed Tier 2 Fmsy control rule	Current ADFG	Proposed Tier 4 F=M	F=0	Proposed Tier 3, F50%,B50% control rule	Proposed Tier 3, F60%,B60% control rule
Recruits	5607.6	33.4	5827.1	5353.2	5984.8	7988.8	5535.9	6263.3
total catch bio	4.4	0.0	4.4	4.5	4.3	0.8	4.5	4.3
retained catch bio	3.6	0.0	3.7	3.6	3.6	0.0	3.7	3.6
male sp bio	26.0	0.0	28.2	22.2	30.8	77.9	24.5	34.3
female sp bio	23.7	0.1	24.7	22.3	25.5	35.5	23.3	26.9
total sp bio	49.7	0.1	52.9	44.5	56.4	113.4	47.8	61.2
eff male sp bio	12.1	0.0	13.5	9.5	15.4	54.4	10.9	17.9
eff female sp bio	22.0	0.1	23.0	20.7	23.8	33.3	21.7	25.1
eff total sp bio	34.1	0.1	36.5	30.2	39.2	87.8	32.6	43.0
F	0.23	5.00	0.20	0.28	0.18	0.00	0.24	0.15
percent below 1/2 Bmsy	1.11	100.00	0.28	1.20	0.65	0.00	0.82	0.015
percent below Bmsy	44.1	100.0	48.0	74.8	39.1	0.0	63.5	25.1
percent F=0	0	0	0	0.08	0	100	0	0
years to rebuild	55	NA	39	58	43	16	47	30

Table 8. Red king crab using effective total spawning biomass with mating ratio 2.0. Results from simulations as a percent of the values for the constant Fmsy control rule from 1000 simulations for the last 100 years of a 200 year projection for various harvest control rules.

Average over 1000 simulations and 100 yrs	Fmsy constant	Current OFL	Proposed Tier 2 Fmsy control rule	Current ADFG	Proposed Tier 4 F=M	F=0	Proposed Tier 3, F50%,B50% control rule	Proposed Tier 3, F60%,B60% control rule
Recruits	1.00	0.00	1.02	0.64	0.67	1.52	1.02	1.18
total catch bio	1.00	0.00	1.01	0.80	0.80	0.24	1.02	0.99
retained catch bio	1.00	0.00	1.01	0.79	0.81	0.00	1.02	0.96
male sp bio	1.00	0.00	1.03	0.51	0.56	2.42	1.02	1.33
female sp bio	1.00	0.00	1.02	0.63	0.66	1.57	1.02	1.19
total sp bio	1.00	0.00	1.03	0.56	0.60	2.07	1.02	1.27
eff male sp bio	1.00	0.00	1.03	0.45	0.50	3.03	1.02	1.42
eff female sp bio	1.00	0.00	1.03	0.47	0.52	2.63	1.02	1.38
eff total sp bio	1.00	0.00	1.03	0.45	0.51	2.88	1.02	1.41
F	1.00	43.37	0.98	1.68	1.56	0.00	0.98	0.68

Table 9. Red king crab using effective total spawning biomass with no mating ratio. Results from simulations as a percent of the values for the constant Fmsy control rule from 1000 simulations for the last 100 years of a 200 year projection for various harvest control rules.

Average over 1000 simulations and 100 yrs	Fmsy constant	Current OFL	Proposed Tier 2 Fmsy control rule	Current ADFG	Proposed Tier 4 F=M	F=0	Proposed Tier 3, F50%,B50% control rule	Proposed Tier 3, F60%,B60% control rule
Recruits	1.00	0.01	1.04	0.95	1.07	1.42	0.99	1.12
total catch bio	1.00	0.01	1.01	1.02	0.99	0.17	1.02	0.98
retained catch bio	1.00	0.00	1.01	1.00	0.99	0.00	1.01	0.98
male sp bio	1.00	0.00	1.08	0.85	1.18	2.99	0.94	1.32
female sp bio	1.00	0.00	1.04	0.94	1.08	1.50	0.98	1.14
total sp bio	1.00	0.00	1.06	0.90	1.13	2.28	0.96	1.23
eff male sp bio	1.00	0.00	1.11	0.79	1.27	4.51	0.91	1.48
eff female sp bio	1.00	0.00	1.05	0.94	1.08	1.51	0.98	1.14
eff total sp bio	1.00	0.00	1.07	0.89	1.15	2.57	0.96	1.26
F	1.00	22.08	0.90	1.22	0.79	0.00	1.07	0.67

Table 10. Red king crab spawning biomass per recruit as a percent of the value at F=0, for two measures of effective total spawning biomass at mating time: 1) female spawning biomass plus non-molting male mature biomass, and 2) effective female spawning biomass applying a mating ratio of 2.0 (the ratio of mature females to non-molting males at F=0). Nonmolting males is the non-molting mature male biomass at mating time per recruit as a percentage of the value at F=0.

red king spr			
F	eff total (female+non-molting males)	eff total (mating ratio 2.0)	non-molting males
0.08	72	60	58
0.12	65	50	48
0.17	60	44	41
0.18(F=M)	56	37	35
0.29	50	30	27

Table 11. Snow crab spawning biomass per recruit as a percent of the value at F=0, for two measures of effective total spawning biomass at mating time: 1) female spawning biomass plus non-molting male mature biomass, and 2) effective female spawning biomass applying a mating ratio of 1.7 (the ratio of mature females to non-molting males at F=0). Nonmolting males is the non-molting mature male biomass at mating time per recruit as a percentage of the value at F=0.

Snow crab			
F	eff total (female+non-molting males)	eff total (mating ratio 1.7)	old shell males
0.23(F=M)	76	71	67
0.4	66	60	54
0.6	60	52	46
0.7	58	50	43
1.2	50	40	32

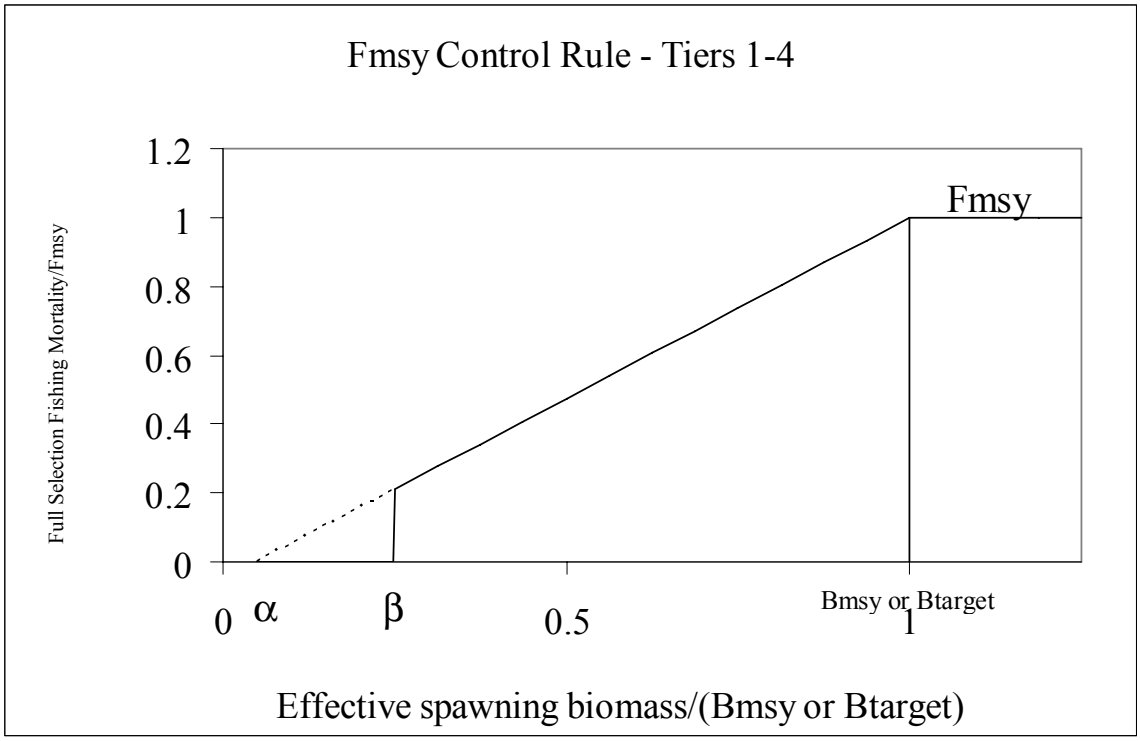

Figure 1. Proposed control rule for overfishing.

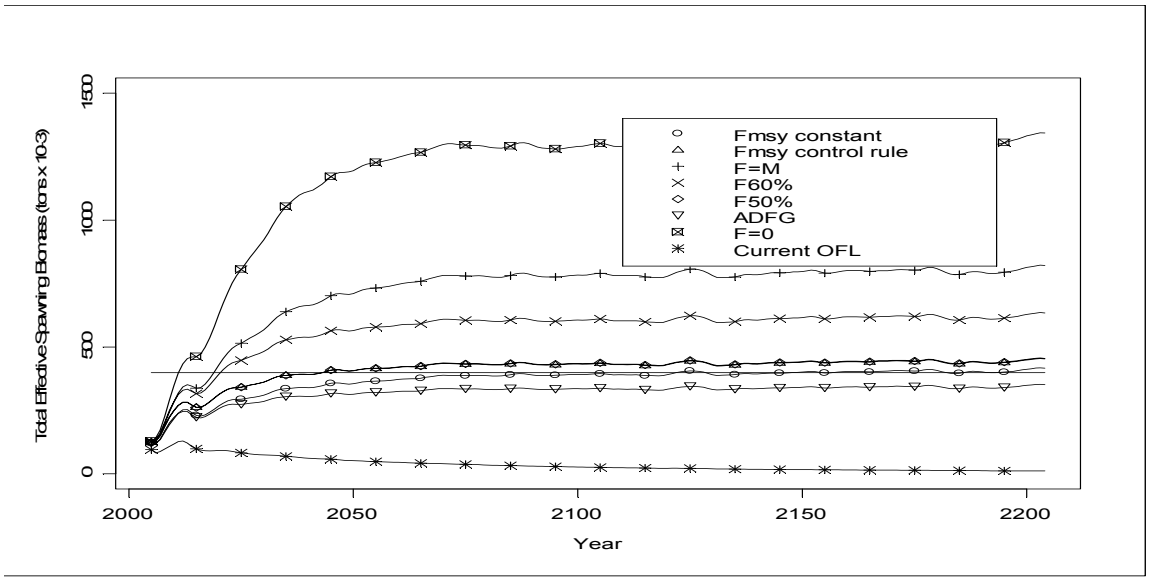

Figure 2. Snow crab total effective spawning biomass with mating ratio 1.7 for various control rules.

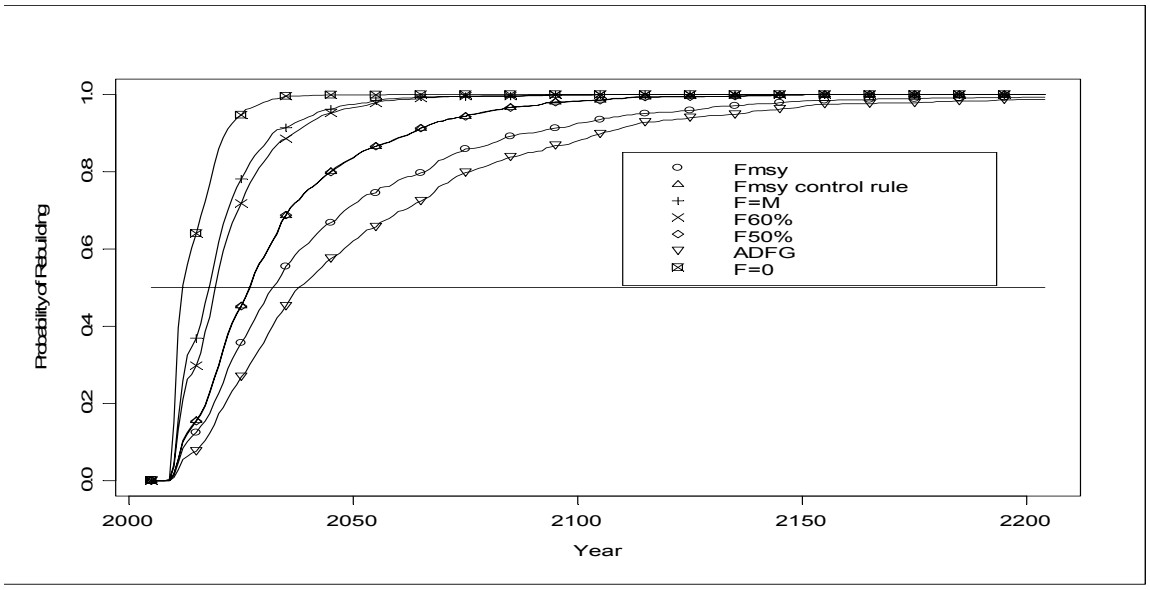

Figure 3. Snow crab probability of rebuilding using total effective spawning biomass with mating ratio 1.7 for various control rules.

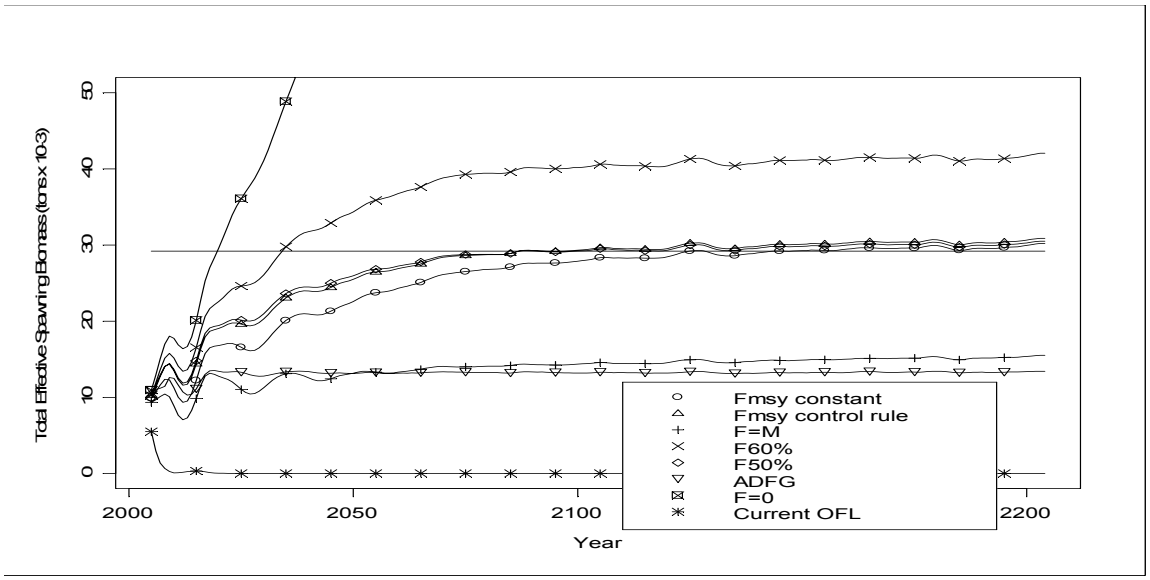

Figure 4. Red king crab mean effective spawning biomass with mating ratio 2 for various harvest control rules.

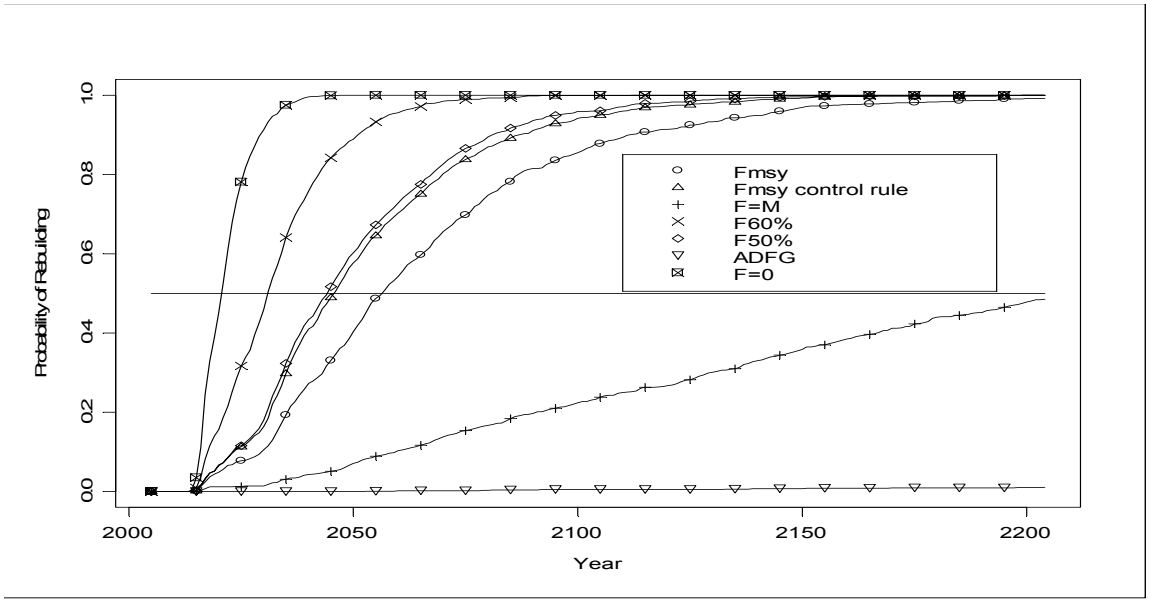

Figure 5. Red king crab probability of rebuilding with effective spawning biomass with mating ratio 2 for various harvest control rules.

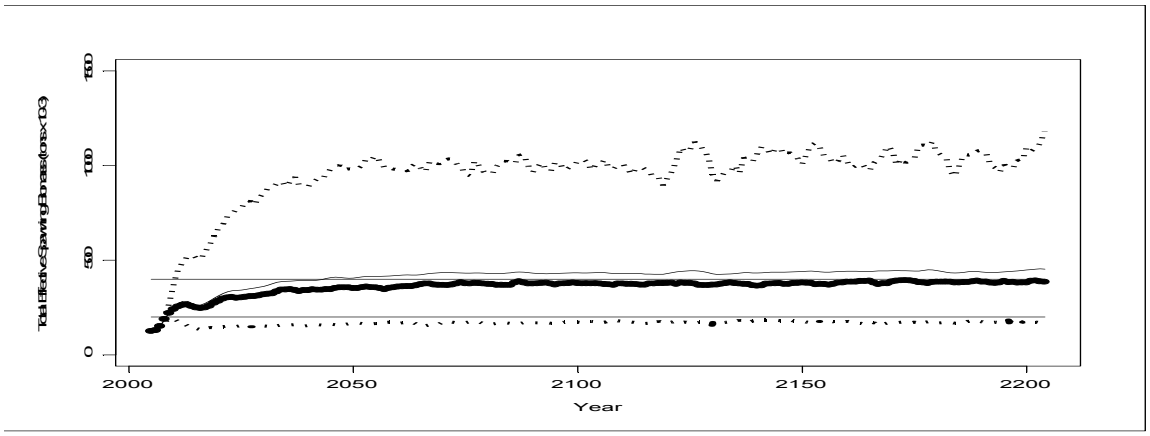

Figure 6. Snow crab, median, mean and 95% probability interval for effective total spawning biomass at mating time using mating ratio of 1.7. Tier 2 Fmsy control rule.

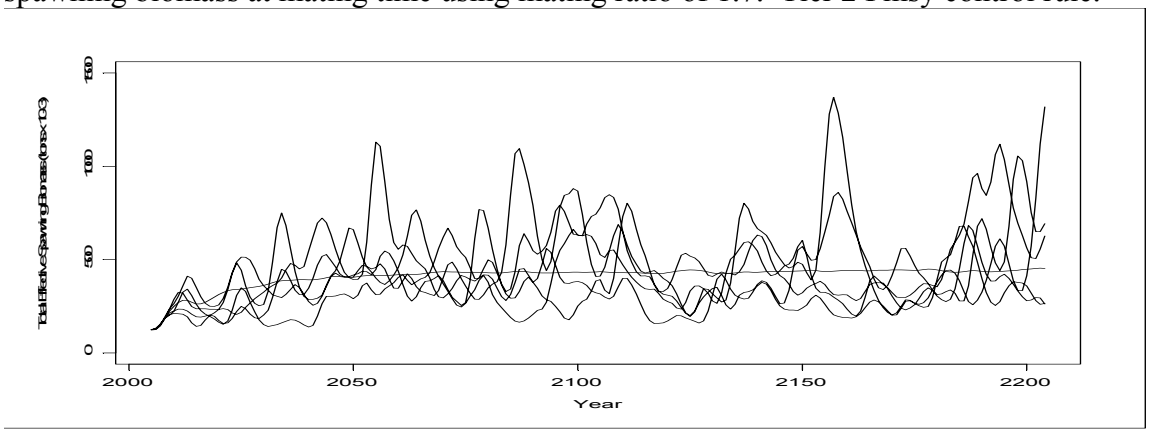

Figure 7. Snow crab, overall mean (1000 runs), and results from 5 simulation runs for effective total spawning biomass at mating time using mating ratio of 1.7. Tier 2 Fmsy control rule.

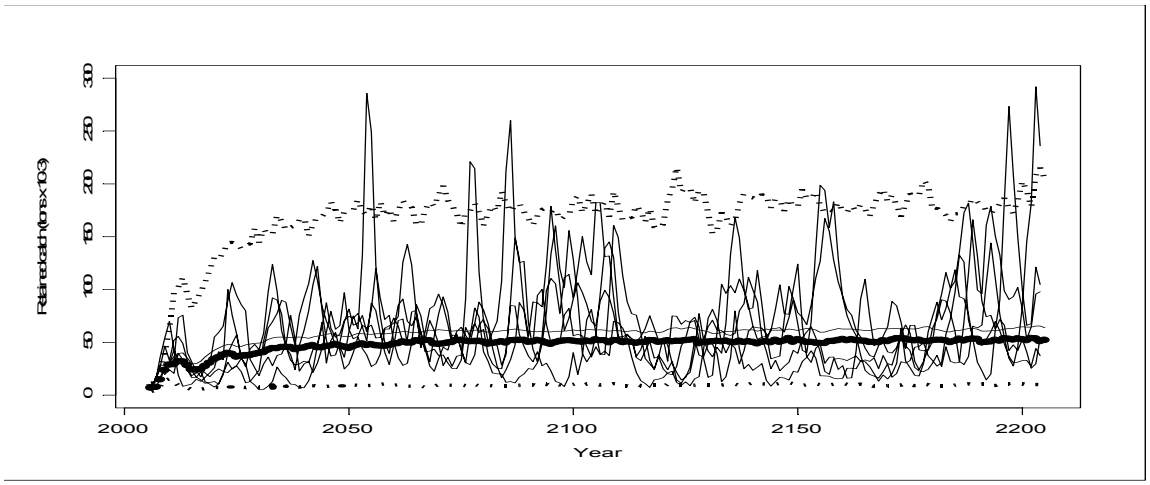

Figure 8. Snow crab retained catch, median, mean, 95% probability intervals, and results from 5 simulation runs for total spawning biomass at survey time using mating ratio of 1.7. Tier 2 Fmsy control rule.

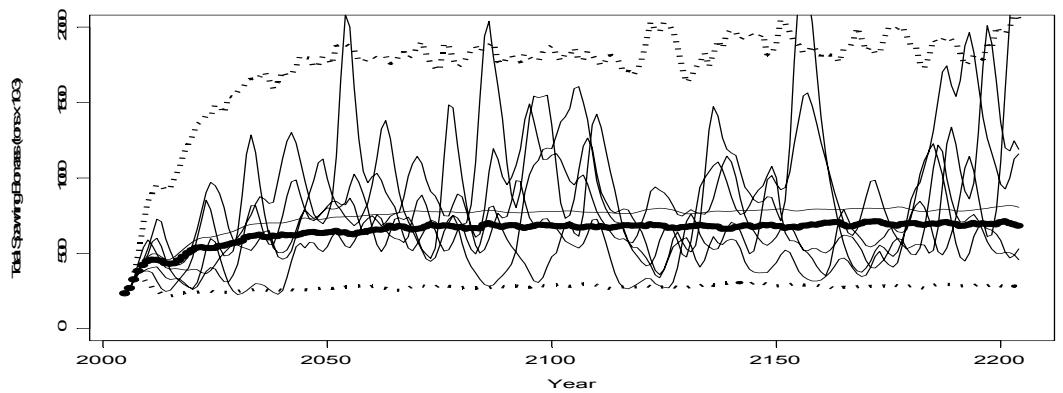

Figure 9. Snow crab, median, mean, 95% probability intervals, and results from 5 simulation runs for total spawning biomass at survey time using mating ratio of 1.7. Tier 2 Fmsy control rule.

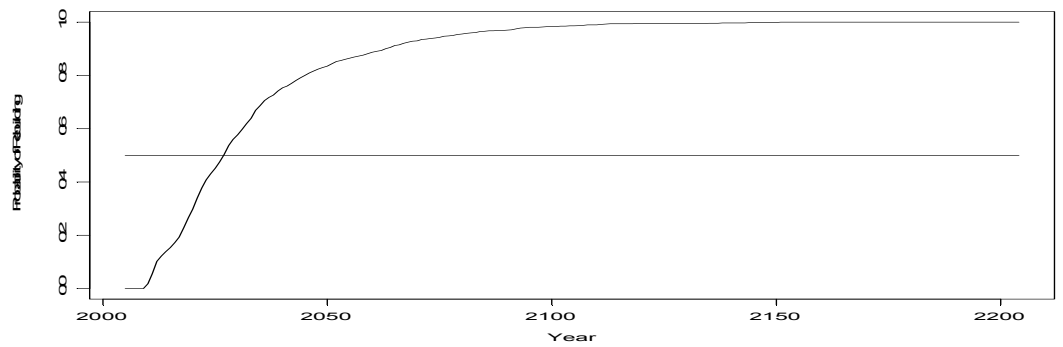

Figure 10. Snow crab, probability of rebuilding, using effective total spawning biomass at mating time with mating ratio of 1.7. Tier 2 Fmsy control rule.

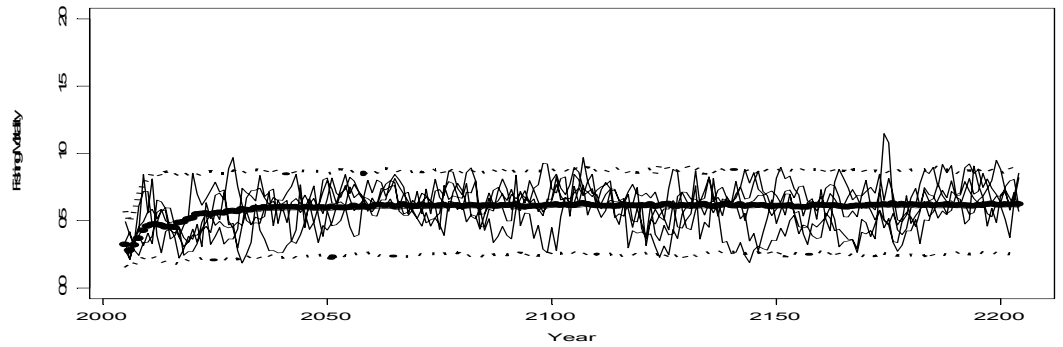

Figure 11. Snow crab fishing mortality, median, mean, 95% probability intervals, and results from 5 simulation runs for effective spawning biomass at mating time using mating ratio of 1.7. Tier 2 Fmsy control rule.

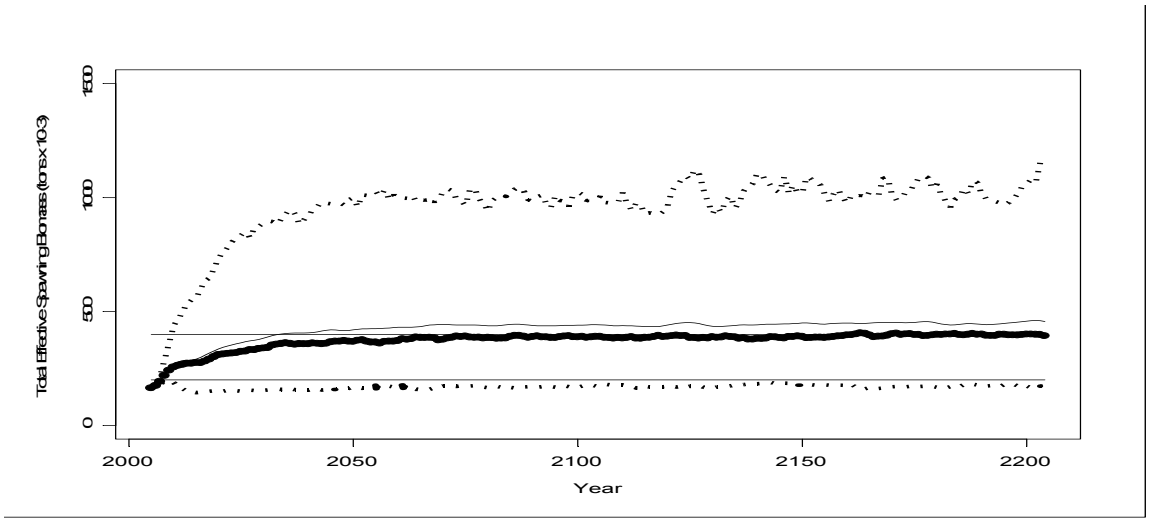

Figure 12. Snow crab, median, mean and 95% probability interval for effective total spawning biomass at mating time, no mating ratio. Tier 2 Fmsy control rule.

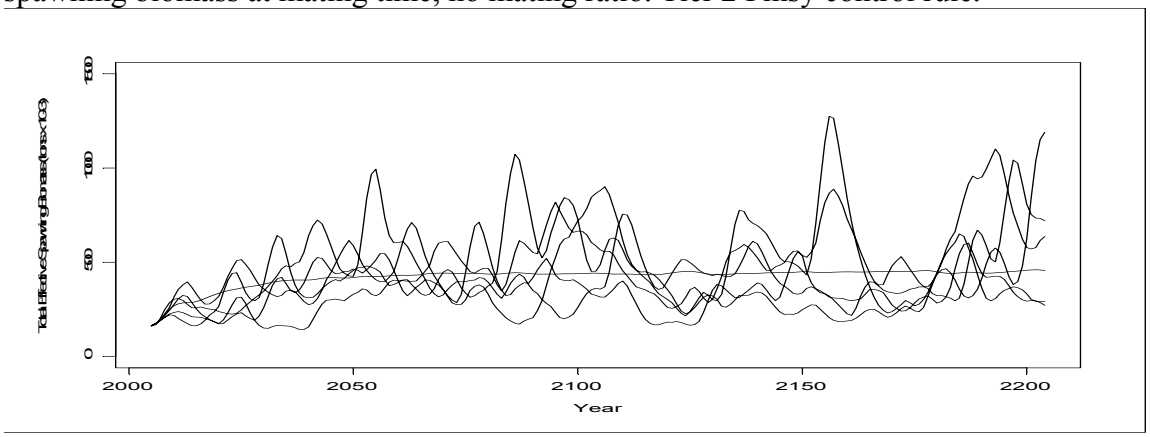

Figure 13. Snow crab, overall mean (1000 runs), and results from 5 simulation runs for effective total spawning biomass at mating time using no mating ratio. Tier 2 Fmsy control rule.

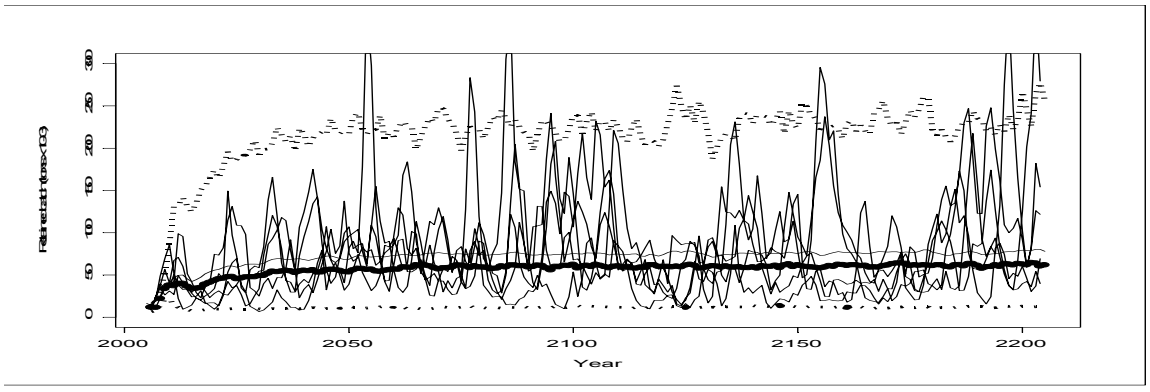

Figure 14. Snow crab retained catch, median, mean, 95% probability intervals, and results from 5 simulation runs for total spawning biomass at survey time using no mating ratio. Tier 2 Fmsy control rule.

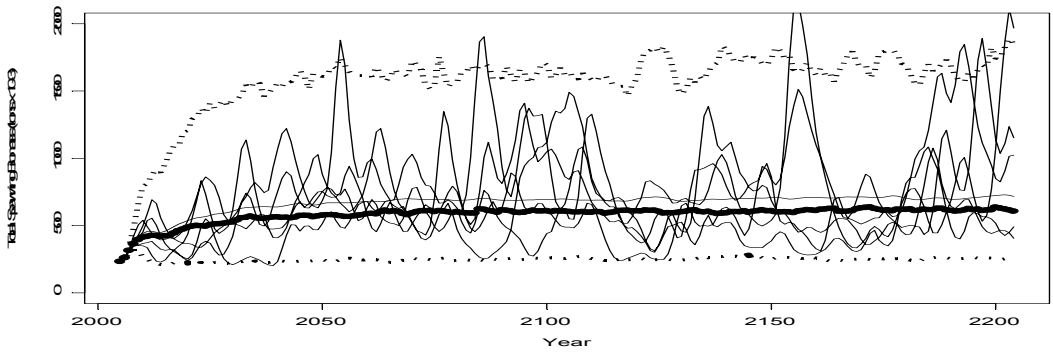

Figure 15. Snow crab, median, mean, 95% probability intervals, and results from 5 simulation runs for total spawning biomass at survey time using no mating ratio. Tier 2 Fmsy control rule.

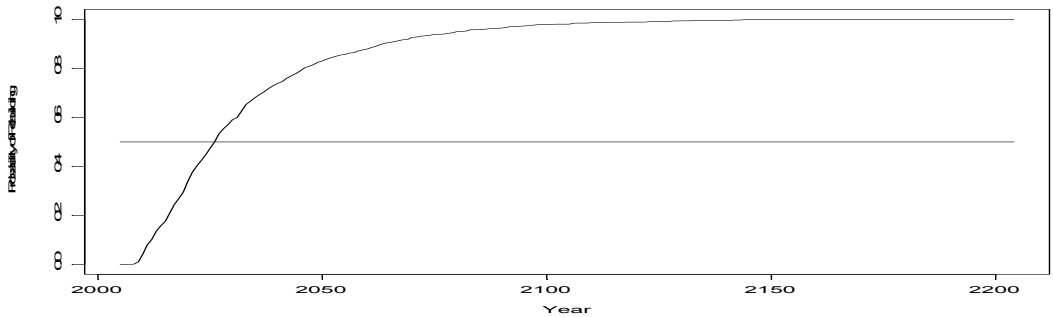

Figure 16. Snow crab, probability of rebuilding, using effective total spawning biomass at mating time with no mating ratio. Tier 2 Fmsy control rule.

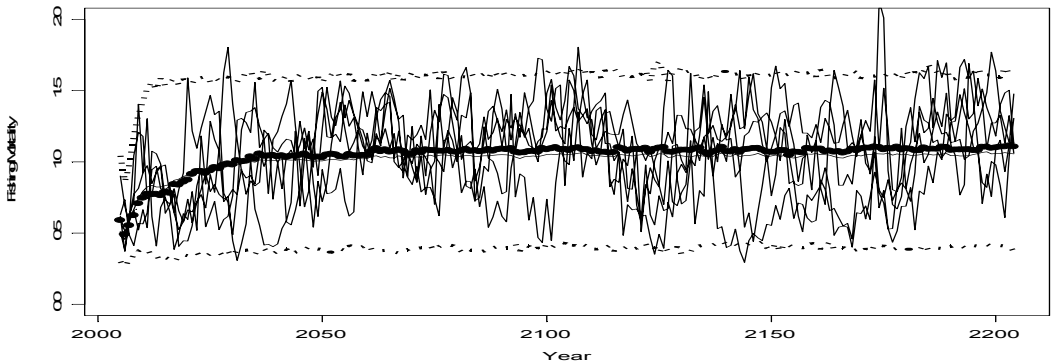

Figure 17. Snow crab fishing mortality, median, mean, 95% probability intervals, and results from 5 simulation runs for effective spawning biomass at mating time using no mating ratio. Tier 2 Fmsy control rule.

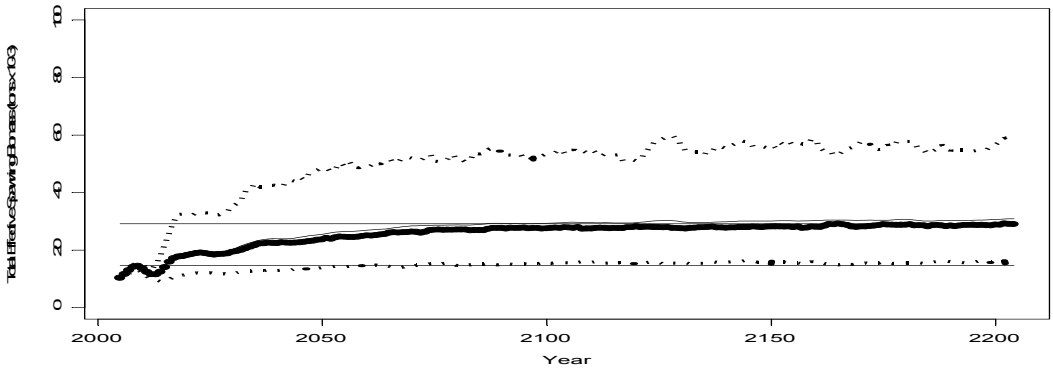

Figure 18. Red king crab, median, mean and 95% probability interval for effective total spawning biomass at mating time using mating ratio of 2.0. Tier 2 Fmsy control rule.

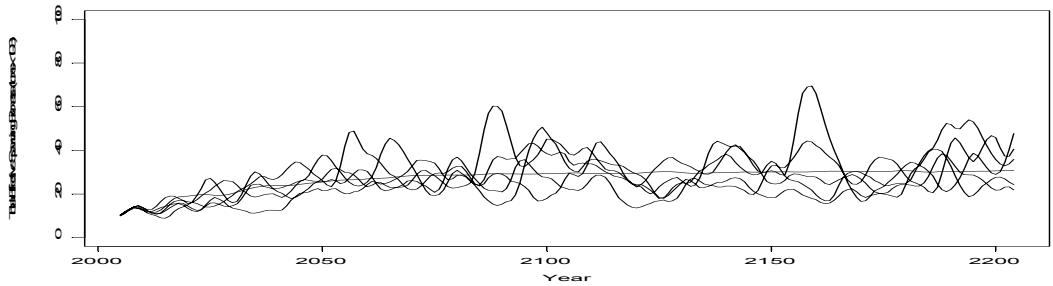

Figure 19. Red king crab, overall mean (1000 runs), and results from 5 simulation runs for effective total spawning biomass at mating time using mating ratio of 2.0. Tier 2 Fmsy control rule.

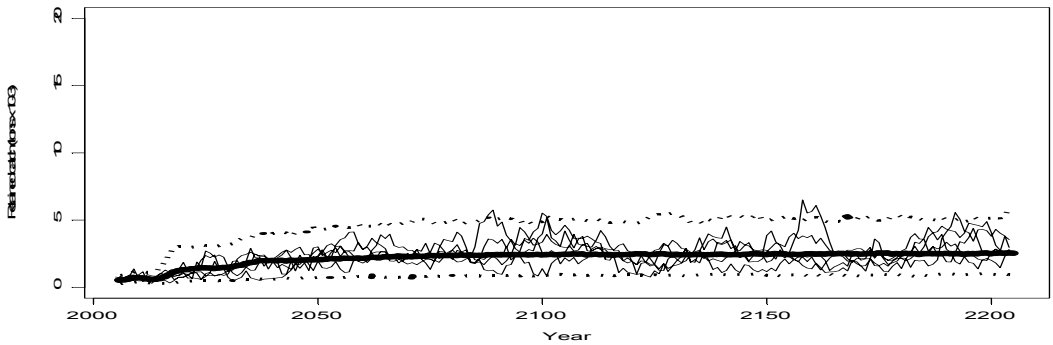

Figure 20. Red king crab retained catch, median, mean, 95% probability intervals, and results from 5 simulation runs for total spawning biomass at survey time using mating ratio 2.0. Tier 2 Fmsy control rule.

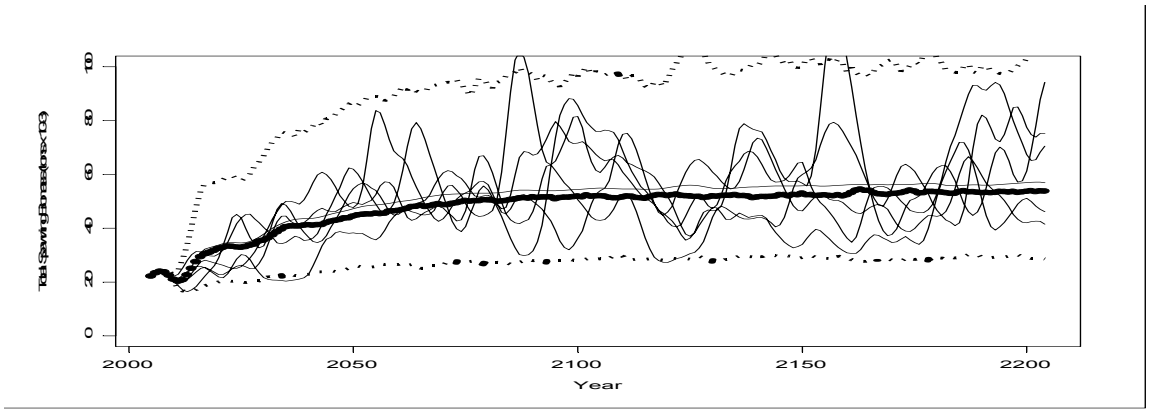

Figure 21. Red king crab, median, mean, 95% probability intervals, and results from 5 simulation runs for total spawning biomass at survey time using mating ratio of 2.0. Tier 2 Fmsy control rule.

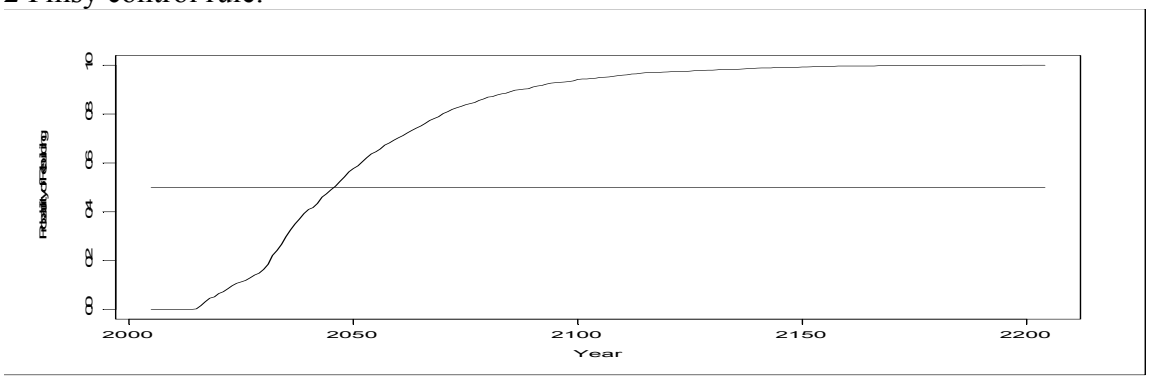

Figure 22. Red king crab, probability of rebuilding, using effective total spawning biomass at mating time with mating ratio of 2.0. Tier 2 Fmsy control rule.

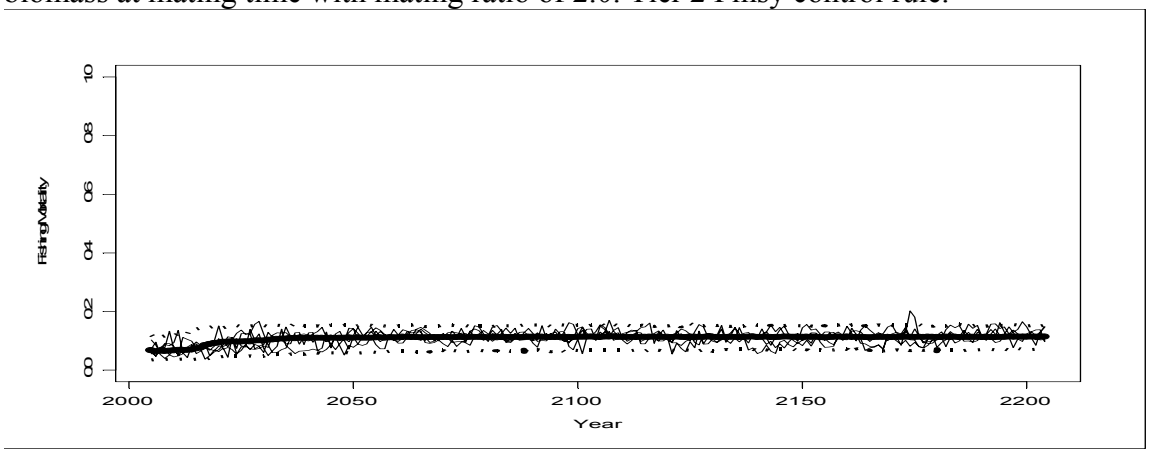

Figure 23. Red king crab fishing mortality, median, mean, 95% probability intervals, and results from 5 simulation runs for effective spawning biomass at mating time using mating ratio of 2.0. Tier 2 Fmsy control rule.

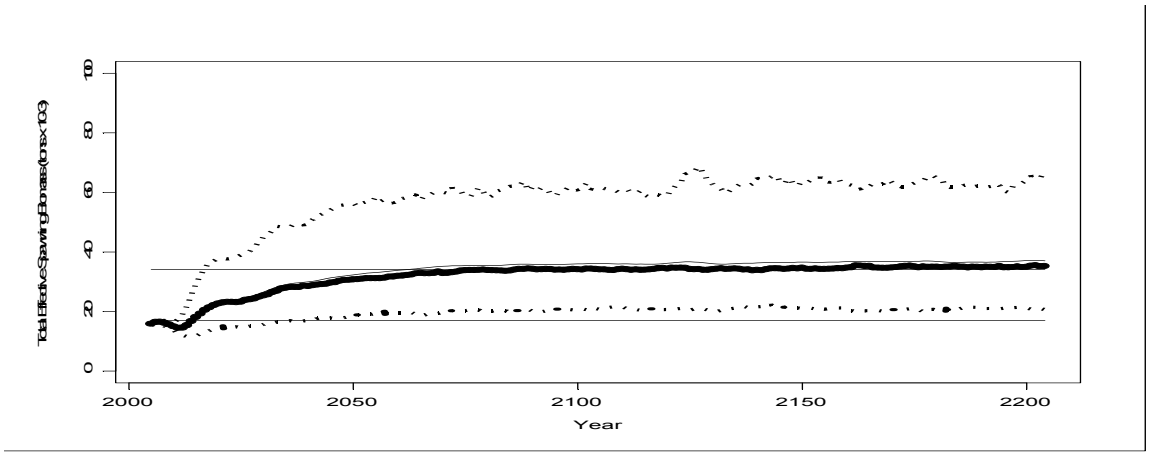

Figure 24. Red king crab, median, mean and 95% probability interval for effective total spawning biomass at mating time using no mating ratio. Tier 2 Fmsy control rule.

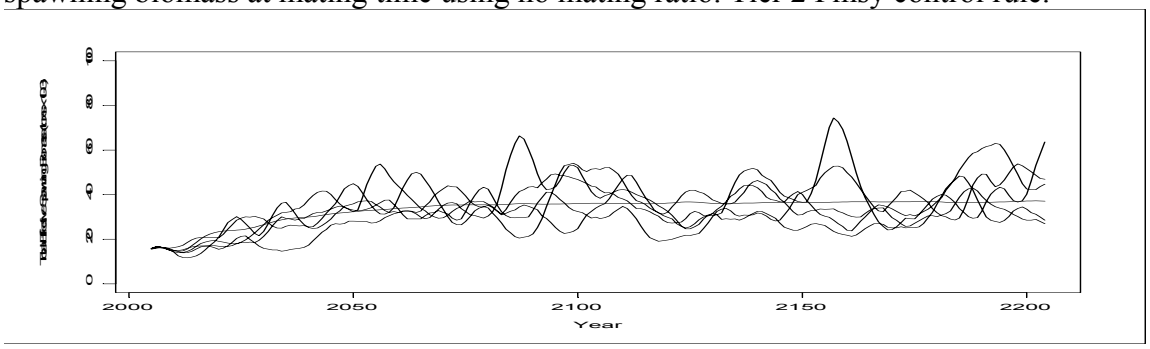

Figure 25. Red king crab, overall mean (1000 runs), and results from 5 simulation runs for effective total spawning biomass at mating time using no mating ratio. Tier 2 Fmsy control rule.

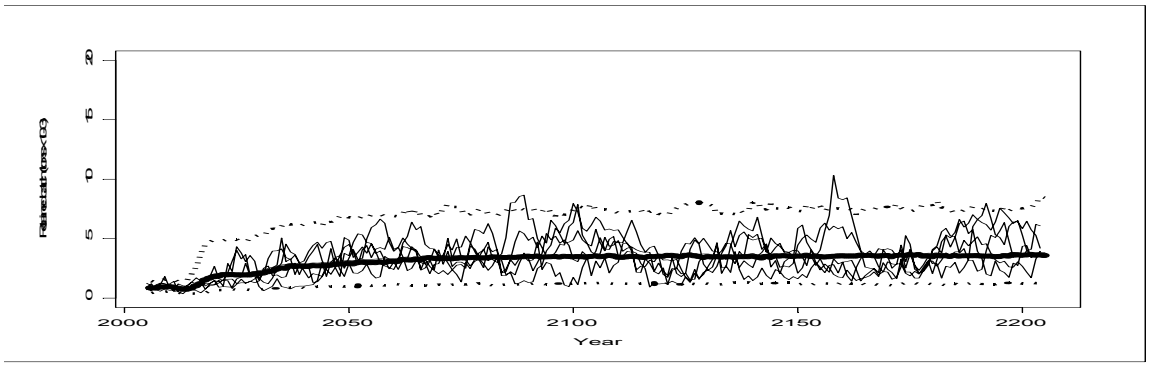

Figure 26. Red king crab retained catch, median, mean, 95% probability intervals, and results from 5 simulation runs for total spawning biomass at survey time using no mating ratio. Tier 2 Fmsy control rule.

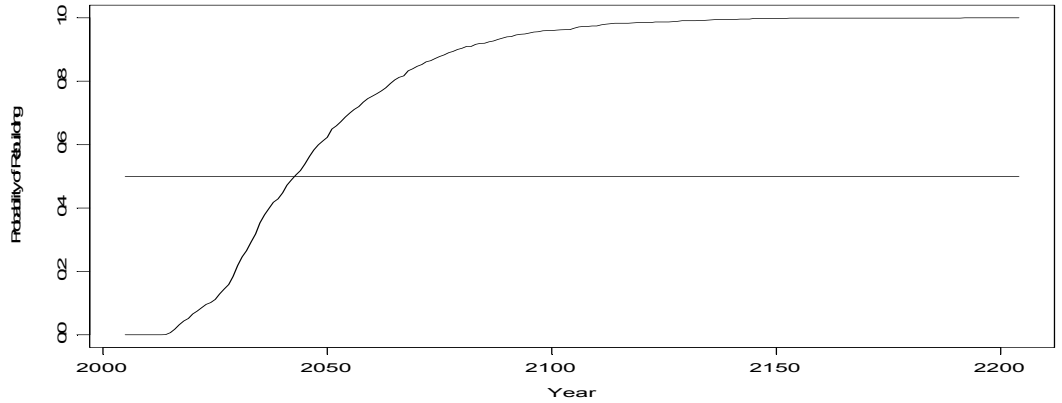

Figure 27. Red king crab, probability of rebuilding, using effective total spawning biomass at mating time with no mating ratio. Tier 2 Fmsy control rule.

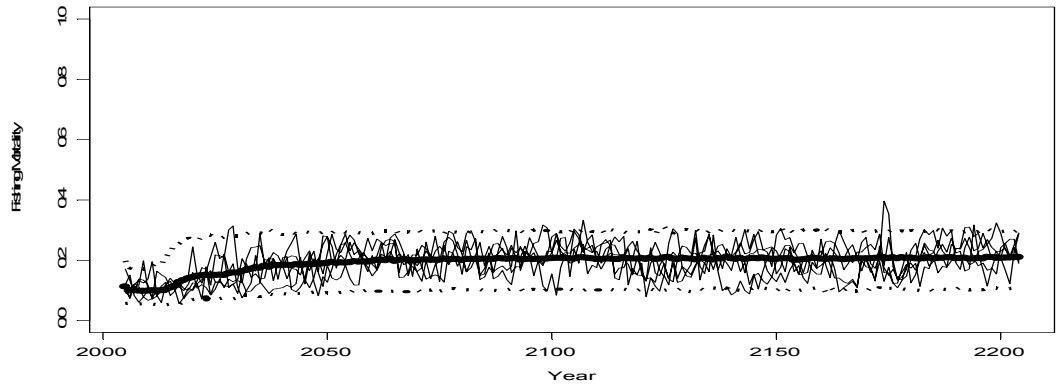

Figure 28. Red king crab fishing mortality, median, mean, 95% probability intervals, and results from 5 simulation runs for effective spawning biomass at mating time using no mating ratio. Tier 2 Fmsy control rule.