Unresolved Issues Concerning Proposed Overfishing Definitions for Bering Sea and Aleutian Islands King and Tanner Crab Stocks

National Marine Fisheries Service
Jack Turnock and Lou Rugolo

February 17, 2006

Introduction: Background Information on aging, shell condition, other biological parameters

I.1 Snow and Tanner crab maximum age post-terminal molt and shell classification

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

These NMFS shell coding instructions were designed to categorize crabs captured during a single time period each year. The NMFS Eastern Bering Sea trawl survey sweeps through crab grounds in June and July. The NMFS protocols for shell condition class are based on the physical appearance of the exoskeleton in terms of discoloration, scratching, shell damage, dactyl sharpness, and epifaunal growth. While there's a general correlation between progressions in these measures of shell condition and shell age, age assessment *per se* is not an objective of the NMFS system. On the annual NMFS trawl survey, male crab have either completed their molt or are near the end of their molting season. In some years, the survey encounters substantial numbers of large males that have just hardened or are still hardening from a recent molt; in most years, molting largely ended one month or two earlier. In either case, males that last molted the previous year (i.e., 12-15 months earlier), can still be very clean and free of scratching and epifauna. There is no doubt that these crabs are sometimes coded as shell condition class SC2 along with crabs that just recently molted in the current spring. Shell condition of similar age crab may also vary geographically.

A similar situation exists with female crab. By and large, the molting, egg extrusion, and mating season is completed for females when sampled by the NMFS trawl survey in June and July. Primiparous females that have molted to maturity in the recent months prior to the survey can be difficult to separate from the brightest and cleanest multiparous females that molted the previous year (12-15 months ago). Similarly, there is no doubt that some mature females coded as SC2 in the NMFS survey are actually multiparous crab in shells that are 1+ year old.

Nevissi, et al. (1995) used radiometric techniques to estimate shell age from last molt for snow and Tanner crab. The total sample size was 21 male crabs (a combination of Tanner and snow crab) from a collection of 105 male crabs from various hauls in the 1992 and 1993 NMFS Bering sea survey. Representative samples for the 5 shell condition categories were collected that made up the 105 samples. The oldest looking crab within shell conditions 4 and 5 were selected from the total sample of SC4 and SC5 crabs (6 crab total) to radiometrically age (Orensanz, pers comm.). Of the 3 SC5 crab aged (SC5 = very, very old shell) the maximum age found was 6.85 years (s.d. 0.58, 95% CI approximately 5.69 to 8.01 years). The average age of 6 crabs with SC4 (very old shell) and SC5, was 4.95 years. The range of ages was 2.70 to 6.85 years for those same crabs. Given the small sample size, crabs older than the maximum age of 7 to 8 years are reasonably expected in the population. Maximum life span defined for a virgin stock is reasonably expected to be longer than these observed maximum ages of exploited populations.

Male snow crab during the mid to late 1980's were subjected to increasing exploitation with the maximum catch occurring in 1991. The maximum age in the sample of 6.85 years would be the result of fishing mortality as well as natural mortality. Using this maximum age would result in an upper bound on natural mortality. If crabs mature at about age 7 to 9, an additional 7 or 8 years gives a maximum total age of about 14 to 17 years. However, due to exploitation occurring at the same time, the maximum age that would occur due to M alone would be greater than 14 to 17 years.

I.2 Red king crab tagging and shell condition indices

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

general progression in the shell class characteristics over time, the interpretation of changes in shell class condition as a basis for assigning presumptive age is inadequate as a method for assigning abundance to age classes and evaluating changes in those abundances between years.

I.3 Natural mortality and longevity

We examined the empirical evidence for reliable estimates of oldest observed age for snow crab. Radiometric aging of carapaces sampled in the Bering Sea stock in 1992 and 1993, as well as the ongoing tag recovery evidence from eastern Canada reveal observed maximum ages in exploited populations of 17-19 years. We reasoned that in a virgin population of snow crab, longevity would be at least 20 years. Hence, we used 20 years as a proxy for longevity and assumed that this age would represent the upper 99th percentile of the distribution of ages in an unexploited population if observable. Under negative exponential depletion, the 99th percentile corresponding to age 20 of an unexploited population corresponds to a natural mortality rate of 0.23. M=0.23 was used in all model runs for snow and Tanner crab. Red King crab natural mortality equal to 0.18 has been agreed on by the work group based on information on longevity from tagging and growth studies (Crab FMP).

Estimates of "M" in the red king crab and Tanner crab stock assessment models include discard mortality and should not be interpreted as representing natural mortality (Zheng et al. 1995, Zheng et al. 1998). Also, in the red king crab stock assessment, M is estimated for different time periods to fit changes in survey abundance, which may represent survey variability and not true changes in M.

I.4 Molting probability

Female and male snow crab have a terminal molt to maturity. Many papers have dealt with the question of terminal molt for Atlantic Ocean mature male snow crab (e.g., Dawe, et al. 1991). A laboratory study of morphometrically mature male Tanner crab, which were also believed to have a terminal molt, found all crabs molted after two years (Paul and Paul 1995). Bering Sea male snow crab appear to have a terminal molt based on recent data on hormone levels (Tamone et al. 2005) and findings from premolt indicators and molt stage analysis via setagenesis (Rugolo et al. 2005). The models presented here have a terminal molt for both males and females for snow and Tanner crab. Molting probability for male king crabs has been estimated in the red king crab stock assessment model based on relative survey abundance of males by shell condition. Female king crabs have to molt every year to mate.

I.5 Mating ratio and reproductive success

Full clutches of unfertilized eggs may be extruded and appear normal to visual examination, and may be retained for several weeks or months by snow crab (Rugolo, pers. comm., Alaska

Fisheries Science Center, Seattle, Wa.). Resorbtion of eggs may occur if not all eggs are extruded resulting in less than a full clutch. Female snow crab at the time of the survey may have a full clutch of eggs that are unfertilized, resulting in overestimation of reproductive potential. Male snow crab are sperm conservers, using less than 4% of their sperm at each mating. Females also will mate with more than one male (polyandry). The amount of stored sperm and clutch fullness varies with sex ratio (Sainte-Marie 2002). If mating with only one male is inadequate to fertilize a full clutch, then females will need to mate with more than one male in a mating season. This would necessitate more males relative to females in the mature population, than if one male is assumed to be able to adequately fertilize multiple females.

The fraction barren females and clutch fullness observed in the survey increased in the early 1990's then decreased in the mid- 1990's then increased again in the late 1990's (Figures 6 and 7). The highest levels of barren females coincides with the peaks in catch and exploitation rates that occurred in 1992 and 1993 fishery seasons and the 1998 and 1999 fishery seasons. While the biomass of mature females was high in the early 1990's, the rate of production from the stock may have been reduced due to the spatial distribution of the catch and the resulting sex ratio in areas of highest reproductive potential.

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

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

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

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

The clutch fullness and fraction of unmated females however, does not account for the fraction of females that may have unfertilized eggs. The fraction of barren females observed in the survey may not be an accurate measure of fertilization success because females may retain

unfertilized eggs for months after extrusion. Rugolo (pers. comm.) sampled mature females from the Bering Sea in winter and held them in tanks until their eggs hatched in March. All females then extruded a new clutch of eggs in the absence of males. All eggs were retained until the crabs were sacrificed near the end of August. Approximately 20% of the females had full clutches of unfertilized eggs. The unfertilized eggs could not be distinguished from fertilized eggs by visual inspection at the time they were sacrificed. Any index of fertilized females using the visual inspection method of assessing clutch fullness and percent unmated females may be an overestimate of fertilized females and not an accurate index of reproductive success.

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

I.6 Discard mortality

The snow and Tanner crab fisheries retains mostly new shell crab with no missing limbs. The fishery for snow crabs occurs in winter when low temperatures and wind may result in freezing of crabs on deck before they are returned to the sea. Short term mortality may occur due to exposure, which has been demonstrated in laboratory experiments Zhou and Kruse (1998) and Shirley (1998), where 100% mortality occurred under temperature and wind conditions that may occur in the fishery. Even if damage did not result in short term mortality, immature crabs that are discarded may experience mortality during molting some time later in their life. The base models used here assume 50% mortality of discarded crab.

I.7 Spawning Biomass Per Recruit Model

Clark's (1991) maximin method of estimating F% proxy value for Fmsy is determined by the intersection of the least productive and most productive sr curves used in the analysis (Figure 1). Clark's method of selecting the range of sr curves was somewhat subjective, he reasoned that the range of F that the typical groundfish stock can sustain was F=M up to F=5M. However, Clark's generalized groundfish stock used fishery selectivity equal to maturity for both sexes; that for the Bering Sea crab fisheries is directed to males. For crab stocks fishery selectivity is at larger sizes than maturity and the majority of the catch is male crab. The range of F that is sustainable for crab stocks is unclear given most stocks have declined to low levels and rebuilding has not yet

occurred for any crab stock. The lack of information on SR relationships for for North Pacific crab stocks makes this choice more difficult.

Forward simulation models projecting the population forward in time are used to examine the effect of fishing on crab dynamics. Spawning biomass per recruit analysis similar to Clark (1991) can be accomplished using these forward simulation models and producing results for one recruit. Inputs to the models are: fishery selectivity for retained and discarded crab by sex and shell condition, mortality of discarded crab, trawl bycatch fishery selectivity and fishing mortality, mortality of trawl bycaught crab, natural mortality, maturity curves for females and males, the growth transition matrix by sex (including mean growth and variability), mean weight by length by sex, molting probabilities by sex and size, mating ratio, and form and steepness of the spawner recruit curve.

Mortality of discarded crab from directed pot fishery has been agreed upon as 50% with runs of 25% and 100% for comparison. There is a high degree of uncertainty in the level of mortality of discarded crab from the directed pot fishery. Mortality depends on how crab are handled on deck and what happens to them as they are thrown back into the sea or down the scuppers. Mortality will depend on exposure time to freezing temperatures and wind. Mortality may be short term, long term, and can occur at the next molting.

The post-release discard mortality rate may depend on temperature induced effects as well as long-term synergistic effects on vision [i.e., foraging] and the fusing of the shell plates in king crab preventing future molting [Otto, pers. comm.] resulting in death at the ensuing molt. Otto in 2005 conducted a laboratory experiment which revealed that dropping of crab to a hard surface at heights greater then 4 feet was almost uniformly lethal. He reported on these results to the Crab Plan Team meeting in September 2005 and on his observations of subsequent ill effects on righting behavior, foraging and outright death resulting from broken shells / infection. On-deck operations in the opilio and red king crab fisheries revealed in the recent Discovery Channel series, that 4 ft. is a minimum distance of a typical drop; many are dropped from the pots to hard surfaces at distances up to 8-10 ft. commonly, or at distances much greater than 4 ft from the sorting table into scuppers or chutes for discarding.

Fishery selectivity curves are estimated in stock assessment models and depend on sampling the length frequency of discarded catch by observers and the estimated population length frequency in the stock assessment model. Parameters of the model (e.g., natural mortality, molting probabilities, etc) may affect the fishery selectivity curves. The number of discarded crab relative to retained crab in the spawning biomass per recruit model should be similar to that observed in the fishery, if selectivity curves have been estimated correctly.

Fishing mortality is estimated at the time that the fishery occurs. Crab fisheries are pulse fisheries where the catch occurs over a relatively short period of time. Numbers and biomass are projected to the time of the fishery and then the F applied to extract the catch. After the fisheries, mating occurs, then molting, which results in new recruits to the population. The survey occurs in early to mid-summer, after the mating and molting seasons. However, for red

king crab in Bristol Bay the mating season may extend into the beginning of the survey depending on temperature conditions.

The reproductive condition of an exploited population is an essential consideration in formulating conservation and management measures that confer stability to stocks and fisheries. The production potential of a stock - e.g., as specified in a formal stock-recruitment relationship - is a principal determinant in setting biomass and exploitation-based reference points that underlie fishery controls. Annual reproductive condition is commonly specified in terms of indices of biomass (mature or total biomass, sex-specific or combined). It is more meaningfully specified as expected or realized population fecundity which is the ultimate expression of the status of the reproductive stock.

For Eastern Bering Sea Chionoecetes (snow and Tanner crabs), the reproductive stock is assessed in terms of effective total spawning stock biomass that incorporates polygynic mating (one male may mate with more than one female in a season). Since this measure is cast in terms of biomass, a formal expectation of proportionality between mature female biomass and total egg deposition is implied. In snow crabs, it's understood that fecundity varies as a function of size and shell class condition, as well as with reproductive history. Adult female snow crab are observed during the NMFS EBS trawl survey with reduced or lacking (barren) egg clutches, and these proportions vary inter-annually. Further complicating the use of a biomass-based index of female reproductive condition are the facts that a varying portion of clutches may contain unfertilized eggs, and that females express both annual and biennial spawning cycles. Mature female biomass is an inadequate index of the annual reproductive condition of this stock. It's further lacking as a measure of parental stock biomass in population dynamic modeling used to derive biological reference points.

Effective fishery conservation and management measures are dependent on the role of population demographics in reproductive success. A key assumption in the management of this stock is that it's protected against the risk of recruitment-overfishing because only males are exploited. Recruitment-overfishing occurs when the spawning stock is sufficiently depressed by fishing such that production cannot replace losses due to fishing and natural causes. Since snow crab exhibit both polygynic and polyandrous mating (a female may mate with more than one male in a season), and female store sperm in spermathecae which can be used to fertilize a new clutch in the absence of mating, management may tend to tolerate male exploitation rates that would otherwise be considered *risk prone* for stocks which don't display such reproductive strategies. In male-only fisheries, it may be possible to assess the effects of recruitment-overfishing by examining changes in the annual reproductive potential and condition of the mature female stock. If declines in total stock abundance occur without concomitant declines in female reproductive condition, then factors other than recruitment-overfishing may be considered (Incze et al., 1987, Orensanz et al., 1998).

Management of EBS Chionoecetes crab relies on an index of effective spawning stock biomass that incorporates polygyny. An implicit assumption is that sufficient mature males are available

to fertilize the mature female stock and, by extension, that female reproductive potential required for stock maintenance will persist inter-annually - i.e., be unaffected by male exploitation. If correct, the female reproductive stock should demonstrate no directional trends that would imply lowered reproductive output. Dramatic declines in the reproductive condition of EBS crab raise concerns about the assumption of protection against recruitment-overfishing. Over the decade of the 1990s, the percentage of full clutches observed in the snow crab stock showed a declining trend, while the proportion of barrenness in multiparous, old shell females is high and inconsistent with the implicit assumption of a sufficient pool of mature males. Particular concerns exist in the removal of males by the fishery that have not yet participated in mating following their molt to maturity. Saint-Marie (1997), Elner and Glass (1998) and Saint-Marie (1993) note that ovigerous western Atlantic snow crab are less fecund in exploited than virgin stocks, and that fecundity in large adult females in exploited populations is abnormally low.

For morphometrically mature and immature males, the schedule will be based on refined morphometric measurements of carapace width and chela height. At the molt to maturity in snow crab, there's a notable change in the relationship between carapace width and chela height. Such morphometrically large-clawed males are said to be functionally mature for reproduction, although Saint-Marie et al. (2002) found that males newly molted to morphometric maturity don't contribute to reproduction.

Understanding the distribution of the reproductive cycle is required if an objective of management is to formulate harvest policies that explicitly protect spawning activity. Studies of *C. opilio* in the western Atlantic have demonstrated that embryogenesis is strongly influenced by sea water temperature, and that annual or biennial egg incubation periods are related to the threshold temperature of 1.5 ^{o}C (Comeau et al., 1998, Moriyasu and Lanteinge 1998, and Sainte-Marie 1993). Ovigerous females inhabiting waters at or below this temperature by early Fall will enter embryonic diapause and retain their eggs for two years before hatching. Embryos that develop under these disparate regimes may have different fitness as well. Those incubated for two years may be of smaller size with decreased nutritional reserves and show poorer survivorship than those incubated in an annual cycle (T. Shirley *pers. comm.*). The current management framework of EBS snow crab assumes that females exhibit only an annual reproductive cycle.

A further consideration in assessing reproductive output from the mature stock is the effective contribution of first-brood (primiparous) and repeat (multiparous) spawners. In addition to having lower fecundity at size, primiparous females may also have embryos that are less fit than those of multiparous females. Management currently does not differentiate between primiparous and multiparous females in the measure of total mature biomass.

Remaining Model Issues to Resolve:

A. Measure of spawning biomass

The usual measure of spawning biomass for fisheries is female spawning biomass since fishing mortality is not restricted by sex. For crab stocks, the retained catch is large males only, however, there is discarding of females, small males, large old shell males and large new shell males missing limbs in the directed crab fisheries. The amount of female and small male discard mortality varies by stock. Female biomass needs to be included in the spawning biomass, however, since there is greater fishing mortality on males, the effect of reducing males on reproduction needs to be accounted for. The calculation of effective spawning biomass incorporates the population sex ratio of mature crab, the mating ratio (the number of females that one male can mate with in a mating season) and the biomass of mature males and females in the population. When the number of males is reduced to below that which results in all females being mated, then the female mature biomass is reduced. Male mature biomass has two main components, the maturity curve by size and the shell age (shell condition is used as a proxy for shell age).

The measure of spawning biomass is used to generate recruitments through the spawner recruit curve and in the estimation of reference points (Bmsy, Fmsy, etc). When fishing is on males and females equally, as with most groundfish fisheries, female spawning biomass is used as a proxy for egg production and in the estimation of the spawner recruit curve. Females are caught as bycatch in directed crab pot fisheries, however, the mortality from fishing is generally less than for males. The retained catch is all males above a certain size, with the fishery timed to maximize meat production and avoid molting and mating periods. Since the effect of fishing is mostly on males, the male spawning biomass could be used to determine the effect of fishing on recruitment. However, the link between male spawning biomass and egg production would need to be established.

Six measures of spawning biomass are considered: 1) total effective spawning biomass, 2) effective female spawning biomass, 3) effective male spawning biomass, 4) total spawning biomass, 5) female spawning biomass and 6) male spawning biomass. The effect of fishing on SPR from the 6 measures depends on the SR curve and mating ratios assumed (examples, Figures 2 through 5). The male spawning biomass declines the most and female spawning biomass the least as fishing mortality increases. Total effective spawning biomass is generally near the middle, however, the F at which TESB is effected by fishing depends on the mating ratio assumed and how EFSB is calculated. At mating ratios of 3 (each male successfully mates with 3 females) TESB does not decline until an F of about 1.7.

Using female effective spawning biomass alone relies completely on the assumed mating ratio for the effect of fishing on reproduction. The mating ratio assumes that every male mates with the specified number of females regardless of any spatial segregation or size dependencies as well as other assumptions. In other words, using the mating ratio per se, to scale male to female biomass assumes the following: 1) a mature male located geographically anywhere is equivalent

to a mature male geographically located everywhere, and 2) a morphometrically mature male at any size represents a mature male of sufficiently large size to mate a female of any size. It is understood that males may need to be some size increment larger than the females to mate successfully.

High fishing mortalities on males that would essentially eliminate all males above a certain size, assumes that males between the size at maturity and the size at which they are caught in the fishery is completely adequate for reproduction, i.e. that, by definition, recruitment overfishing cannot occur.

Due to the high amount of uncertainty in the mating ratio it is more appropriate to use total effective spawning biomass (female effective spawning biomass and effective male spawning biomass(which is old shell male spawning biomass for snow and tanner crabs and nonmolting male spawning biomass for king crabs) in the measure of spawning biomass.

A.1 Calculation of total effective spawning biomass

Female effective spawning biomass was estimated the same as Siddeek, et al. (2003), assuming only old shell males take part in mating. The mating ratio of 1.7 (the number of females one male can mate with in a mating season), was estimated from the ratio of mature females to old shell males fishing at F=0. 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 (MR = 1.7), then the female mature biomass (fspbio) is reduced to estimate effective female spawning biomass (efspbio),

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

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 (MR = 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.

B. Formulation of Effective Male Spawning Biomass

Do not use mating ratio in estimation of effective male spawning biomass (emspbio).
Mspbio is male spawning biomass that includes only those mature males that take part in mating (e.g. old shell mature males for snow and Tanner crab). Without the use of the mating ratio, emspbio = mspbio.

Effective male spawning biomass is calculated from those mature males that will take part in mating, which depends on the stock. King crabs emspbio would consist of mature nonmolting males, snow and Tanner crab stocks emspbio would be old shell mature males.

If an assumed mating ratio is used then emspbio is,

$$emspbio = mspbio * \frac{NMF}{NMM_O * MR} \quad , \text{ if } NMM_0 > (NMF/MR).$$

This is applied only if there are more males than are needed to fertilize the females, that is if $NMM_0 > (NMF/MR)$. The use of the mating ratio reduces the male spawning biomass at F=0, to only the biomass that is needed to fertilize the mature females (at F=0). The effect of fishing is reduced using this method, as emspbio does not decline until the mature male biomass is reduced by fishing to below what would be needed according to the mating ratio to fertilize the existing mature females. Using emspbio that consists of only mature males that take part in mating without using the mating ratio, takes into account the reduction in biomass due to fishing from the old shell male spawning biomass at F=0. The effect of fishing using emspbio with the mating ratio is highly dependent on an assumed and uncertain mating ratio that has many built in assumptions.

C. Mating Ratio

The mating ratio is the number of females one male can mate with in a mating season. There are a number of assumptions inherent in assuming a male can mate successfully with more than one female. There is very little information to estimate the mating ratio.
Data on sex ratios from the annual Bering Sea survey depend on the accuracy of shell condition as a proxy for shell age as well as the accuracy of chela height for estimation of male maturity. As discussed above, shell condition may be highly biased as well as contain high variability as a measure of shell age and so the sex ratios from past survey data may not be an indicator of appropriate mating ratios. This would also assume that past exploitation rates have been appropriate. Data from the summer survey on the fraction of unmated snow crab females and clutch size index appears to be correlated with fishery catch (Figures 7 and 8). This would indicate that past fishery harvests that occurred immediately before the mating season reduced the sex ratio below that needed for full fertilization of females.

One trawl haul in the Gulf of Alaska after the collapse of the red king crab stock, captured 651 post-molt females and nine male red king crab, during the period April to May 1968 (McMullen and Yoshihara 1969). As discussed previously, 76% of the females were barren and all females with eggs examined had infertile eggs. Studies on Canadian snow crab have shown that females mate with multiple males as well as males mating with multiple females. Female snow and Tanner crab can store sperm to fertilize eggs in future years, however female king crabs must mate every year to fertilize eggs.

The practice of recording the presence or absence of eggs and the clutch size at the time of the summer survey may not be a good indicator of reproductive success. Rugolo et al.(2005) found unfertilized eggs that were extruded in the absence of males and carried by females for 6 months that appeared to the naked eye the same as fertilized eggs. Also mating success may depend not only on the total number of mature males that take part in mating (e.g. may be only old shell mature males), but on local sex ratios, the size of males relative to females and the temperature regimes where females reside in the following year.

Due to uncertainty in the mating ratio, one option is to set the MR at the sex ratio in the SPR model at F=0. This would be the sex ratio of the unexploited virgin stock, if other parameters and assumptions of the model are correct. This would be an objective method of setting the MR rather than assuming some value.

D. Applied Mating Ratio

The application of the mating ratio in calculating effective female spawning biomass is also an issue. Mature females can be categorized as primiparous (first brood) and multiparous (second and subsequent brood). It is generally accepted that primiparous crabs mate before multiparous crab since multiparous crabs need to hatch their eggs before they can mate again. However, there also may be spatial segregation of primiparous and multiparous crab. When applying the mating ratio and calculating effective female spawning biomass primiparous and multiparous crabs should be combined. Applying the MR to primiparous and multiparous crabs separately assumes that all mature males are available to mate with primiparous crabs and are also available to mate with multiparous crabs at a later date. For example, if the MR = 3, then each male would be able to mate with 3 primiparous crab and 3 multiparous crab (6 total) in a single mating season. This seems overly optimistic, given the uncertainty in the value of MR and in our knowledge of crab mating behavior and distribution at mating time.

E. Time-Course of Annual Events

The timing of primiparous mating, male molting and multiparous mating is important in the SPR projection modeling. Males that molt to maturity should not be counted in the mature biomass for the mating season during which they molted. Females that molt to maturity should be counted in the mature biomass. The sequence of events in the current fortran code of the SPR projection model from ADF&G has not been reviewed. Previous code was reviewed and logical and computational errors corrected.

F. Pre-Molt Female Size in Spawning Stock Biomass

The pre-molt size of female crabs should be used in spawning biomass calculation, not the post-molt size, which is intended as an index of total egg deposition. The size of a new extruded clutch is keyed to the pre-molt size of the ovaries, not the post-molt size. Primiparous or first-brood females in eastern Canadian waters (Sainte-Marie 1993) and the eastern Bering Sea

(Rugolo et al. 2005) contain clutches of approximately 75% the size of multiparous females of similar body size.

G. Non-Molting Males in Reproduction for King crab

Use only non-molting mature males for spawning biomass and in effective male spawning biomass. Due to the timing of male molting and mating, males that molt will not be able to participate in mating before or after the molt. Post-molt red king crab may take 3-4 months to harden to pre-molt conditions. Spatial separation of male crab that are going to molt from the mating areas is another factor that would preclude newly molted males from mating. Those males that are not going to molt, migrate to mating areas. Japanese tagging studies and information from fisheries in the 1960's show spatial segregation of new shell males and old shell males, and that old shell males predominate in areas where mating was occurring(various INPFC documents).

H. Stock assessment modeling issues: Survey Selectivity, Molting Probability Schedule, M

Survey selectivities estimated in the red king crab stock assessment model may effect fishery selectivities and other parameters estimates used in the SPR modeling. We need different scenarios run for red king crab stock assessment model for input to SPR modeling.

1. Survey selectivity
   a. Use Weinberg selectivities
   b. estimate survey selectivities in the model
2. Handling mortality
   Run two scenarios, 20% and 50% discard mortality
3. Run model for two different times series
   a. whole time series 1968 to 2005
   b. And From early 1980's to 2005(has not got whole time series to converge yet)
4. Use Constant M=0.18 for all crab
5. Molting probability the same over all time.

The issue of molting probability schedule relates to the consistency of the structure and parameters of stock assessment models and the SPR projection models. Parameters such as natural mortality and molting probabilities should be the same in the stock assessment model and the SPR projection model. Parameters estimated in the stock assessment models are inputs to the SPR model, e.g., fishery selectivities, growth (mean growth, variability in growth and molting probabilities), natural mortality (whether fixed or estimated). Values that are fixed in the stock assessment model, such as natural mortality and maturity schedules should also be the same. If natural mortality is believed to vary over time, then a stochastic projection model would be needed with variable M.

I. Old Shell Male in Reproduction for snow and Tanner crab

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

J. Stock-Recruitment Relationship (SRR)

1. SR model Form
   We should consider the Beverton and Holt formulation of the SR curve as the default unless the data strongly suggest a Ricker form.

2. Steepness of SR- range, particular values, Maximin Clark

   If Clark's method is used, then the proxy value for Fmsy depends solely on the intersection of the most and least productive SRRs. The range of steepness to include in this analysis is therefore critical. For groundfish stocks there was some information on SRR and past fishing mortality relative to natural mortality upon which to base a choice of steepness of the SRR. The Clark (1991) method is ad-hoc with some appeal, that is in assisting decisions on SRR steepness in the absence of empirical information. It allows the modeler to acknowledge that we don't know whether the stock is highly productive or not or compensatory or density-dependence mechanisms operate or not, or whether depensation is a feature and thereafter simply base the overfishing definition on the intersection of the most productive Ricker and least Beverton-Holt curves. The biological reference points (BRP) which result from such an application is entirely dependent on the specifications of these least and most productive relationships. It minimizes the opportunity for expert judgment in the analysis and adopting risk aversion in instances where empirical evidence on the SRRs is unavailable. Clark's maximin approach applied to crabs would substitute for informed judgment. If independently derived empirical data are available to formulate the SRR, emphasis should be placed on its use as opposed to the ad-hoc approach, which would simply require selecting the most productive Ricker at tau=0.1 and the least productive Beverton and Holt at tau = 0.5, and graphing them to find the intersection to set BRPs.

The current harvest strategy for Red king crab developed by ADF&G uses a tau of about 0.24 (steepness 0.52) with a Ricker curve. The red king crab SR data used in the ADF&G harvest strategy includes estimates of recruitment from year classes previous to 1976 when a regime shift occurred in the Bering Sea. The Bmsy for red king crab is currently estimated as the average survey mature biomass (females and males) from 1983 to 1997. The use of a SR curve for recruits previous to 1976 is not consistent with a Bmsy estimated from data for year classes after 1976, if we are in a new productivity period. If a Ricker curve is fit to the SR data with year classes after 1976 only, a steepness of 0.38 (tau = 0.45) is estimated (Figure 12). Female effective spawning biomass is used for red king crab and Tanner crab because total effective spawning biomass was not available. The SR relationship may be different if total effective spawning biomass were used.

The snow crab harvest strategy developed by ADF&G uses a curve that was not a fit to the data, but is a straight line from (0,0) to the mean recruitment at the lowest spawning biomass point and a line with 0 slope after that. The 2005 snow crab stock assessment model estimated a Beverton and Holt SR curve with a steepness of 0.54 (tau 0.22) using a constrained fit with the red king crab steepness as a prior mean (0.52). The steepness of 0.54 is lower than the steepness of the SR relationship used in the current harvest strategy for snow crab. A Ricker fit to snow crab total effective spawning biomass and recruitment estimates results in a steepness of 0.7 (tau=0.12) (Figure 10). However, if only the more recent lower recruitment time series is used (1990-1999 year classes), then steepness was estimated at 0.45 (tau = 0.36).

The Tanner crab harvest strategy developed by ADF&G uses a Ricker curve with a tau of about 0.13 (steepness 0.65). Tanner crab spawner recruit estimates result in a Ricker fit with steepness 0.73 (tau=0.09) with all years (Figure 11). The steepness of a Ricker curve for recent lower recruitments (1985-1993 year classes) estimates steepness at 0.52 (tau=0.24).

The above estimates of steepness for crab SR curves support the use of a range of tau values from 0.1 to 0.5 (steepness 0.71 to 0.33) for use in estimating proxy reference points.

3. Changing productivity periods

4. Depensation in SR – amount of depensation.

Crab stocks may fall to levels of abundance where mating is effected due to difficulty of finding mates or some other unknown reason. Crab stocks in the Gulf of Alaska declined to low levels from which they have not recovered even after more than 25 years. If the spawner recruit curve has a shape where expected recruits are below the replacement line at low spawning biomass

then the stock may have difficulty rebuilding from those low spawning biomass levels. Figure 10 shows a comparison of the shape of a standard Beverton and Holt spawner recruit curve and a BV with depensation. The curve with depensation falls below the replacement line at about 25% of B0 in this example. Recruits are generally less than the standard curve below about 40% B0. The level of depensation for crab stocks would have to be determined by examination of stocks that have collapsed. With depensation, a higher level of spawning biomass would need to be maintained.

Literature Cited

Clark, W.G. 1991. Groundfish exploitation rates based on life history parameters. Can.J.Fish.Aquat.Sci. 48:734-750.

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

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

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

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

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

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

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

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

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

Rugolo, L.J., D. Pengilly, R.A. MacIntosh and K.A. Gravel. 2005. Reproductive dynamics and life-history of snow crab (Chionoecetes opilio) in the eastern Bering Sea. Final completion report to the Alaska Department of Fish and Game under NOAA Award NA17FW1274. 271 pp. National Marine Fisheries Service, Alaska Fisheries Science Center, Seattle, Washington.

Sainte-Marie, B. 1993. Reproductive cycle and fecundity of primiparous and multiparous female snow crab, Chionoecetes opilio, in the northwest Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. 50:2147-2156.

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

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

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

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

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

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

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

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

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

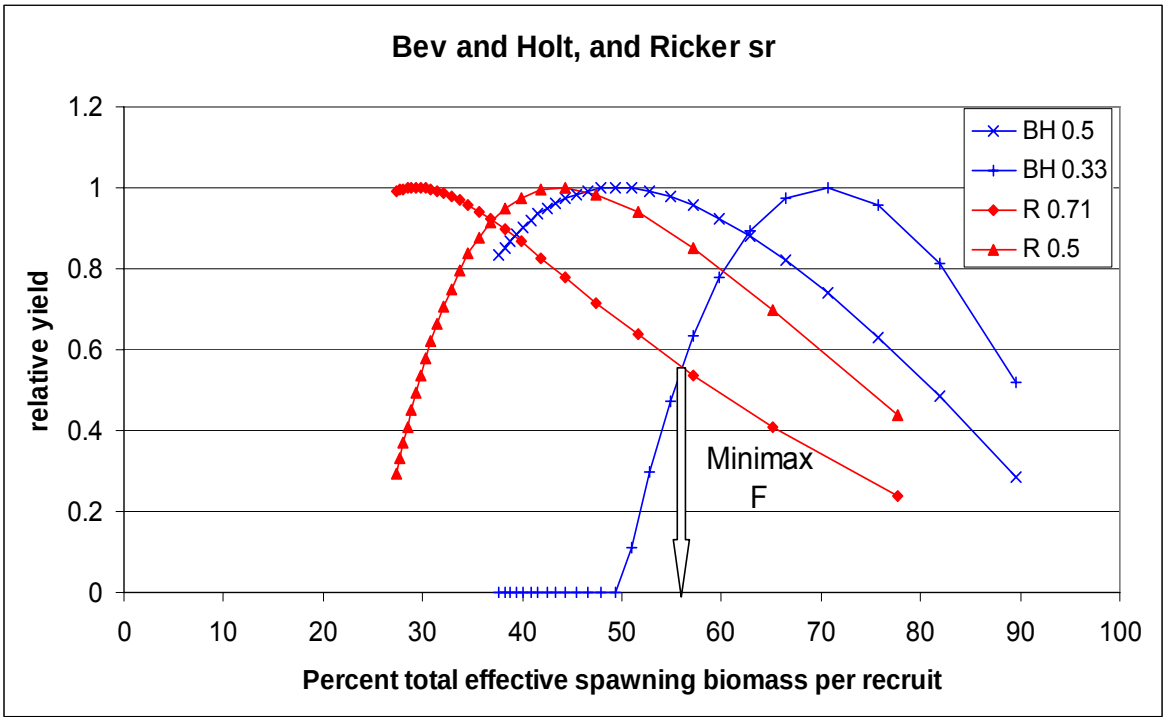

Figure 1. Example of Clark minimax method to determine F% proxy for Fmsy. Numbers are for steepness parameter of the SR curve (steepness of 0.33 is tau 0.5, steepness of 0.71 is tau 0.1).

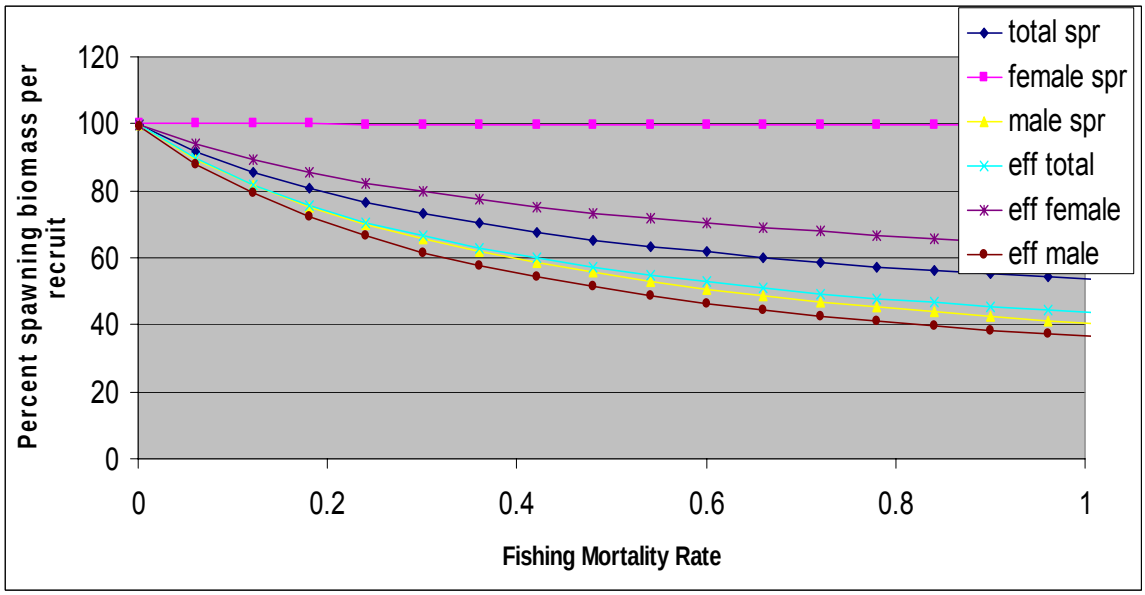

Figure 2. Spawning biomass per recruit model results for snow crab. Mating ratio = 1.7 (sex ratio at F=0). Total effective spawning biomass is female effective spawning biomass plus effective male spawning biomass. Effective male spawning biomass is old shell male spawning biomass with no adjustment for mating ratio.

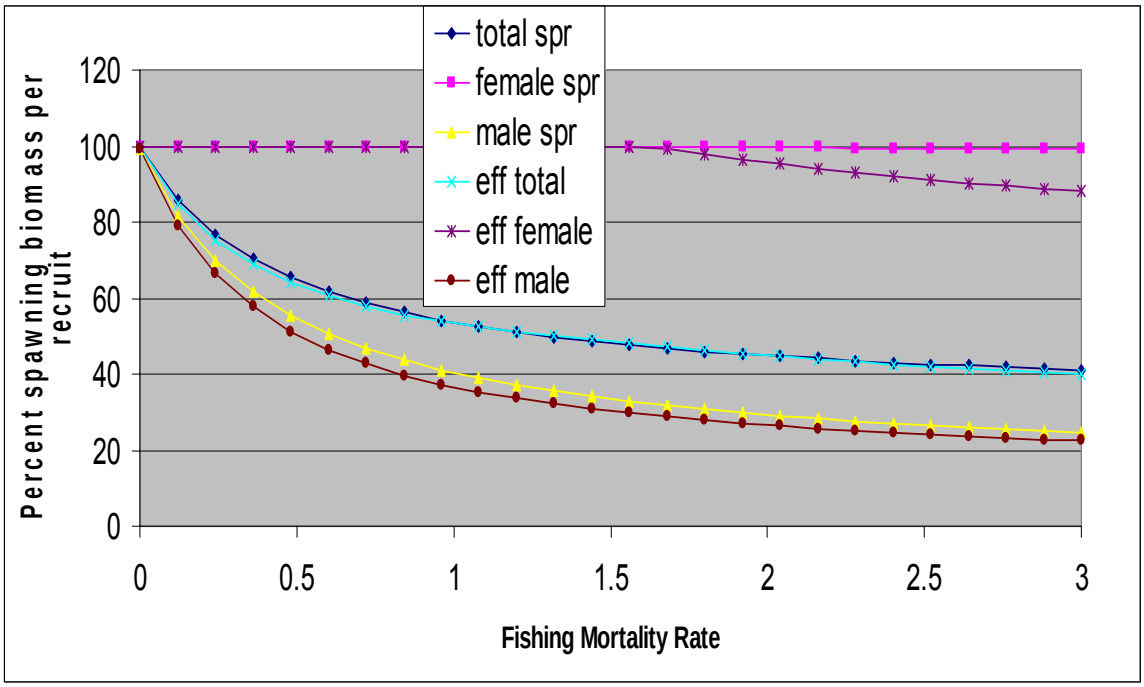

Figure 3. Mating ratio = 3.0. Primiparous and mulitparous separate. Total effective spawning biomass is female effective spawning biomass plus old shell male spawning biomass. Effective males spawning biomass is old shell male spawning biomass with no adjustment for mating ratio.

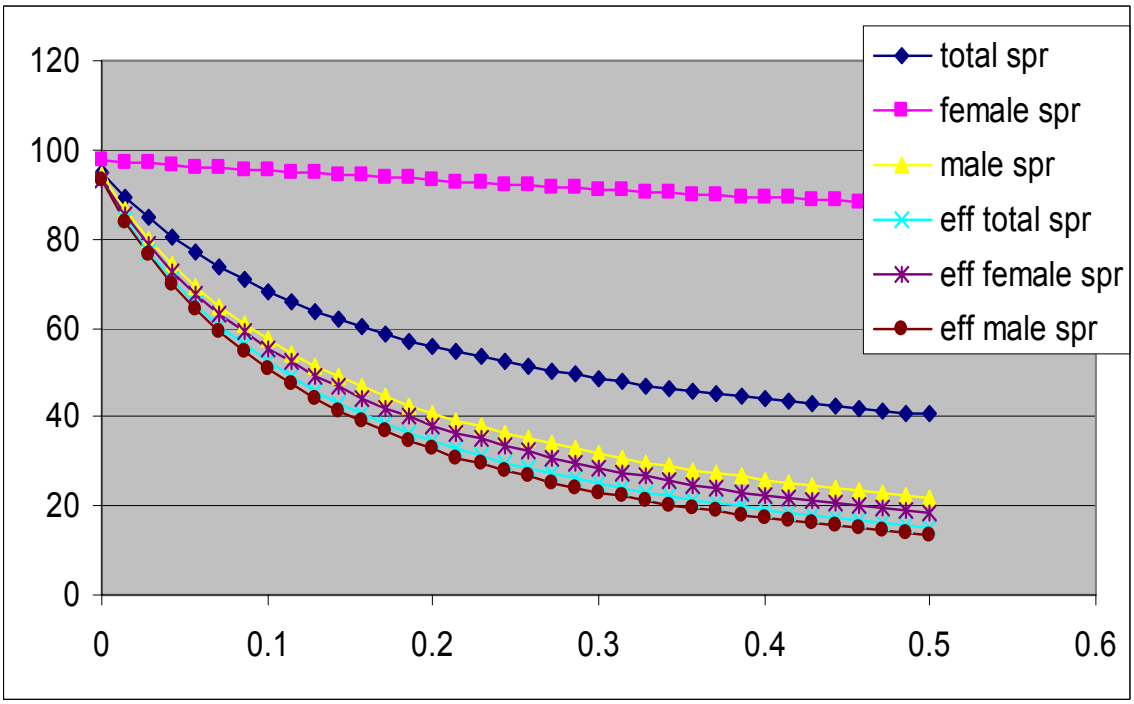

Figure 4. Red king crab mating ratio 2.0, primiparous and multiparous females together in calculation of effective spawning biomass.

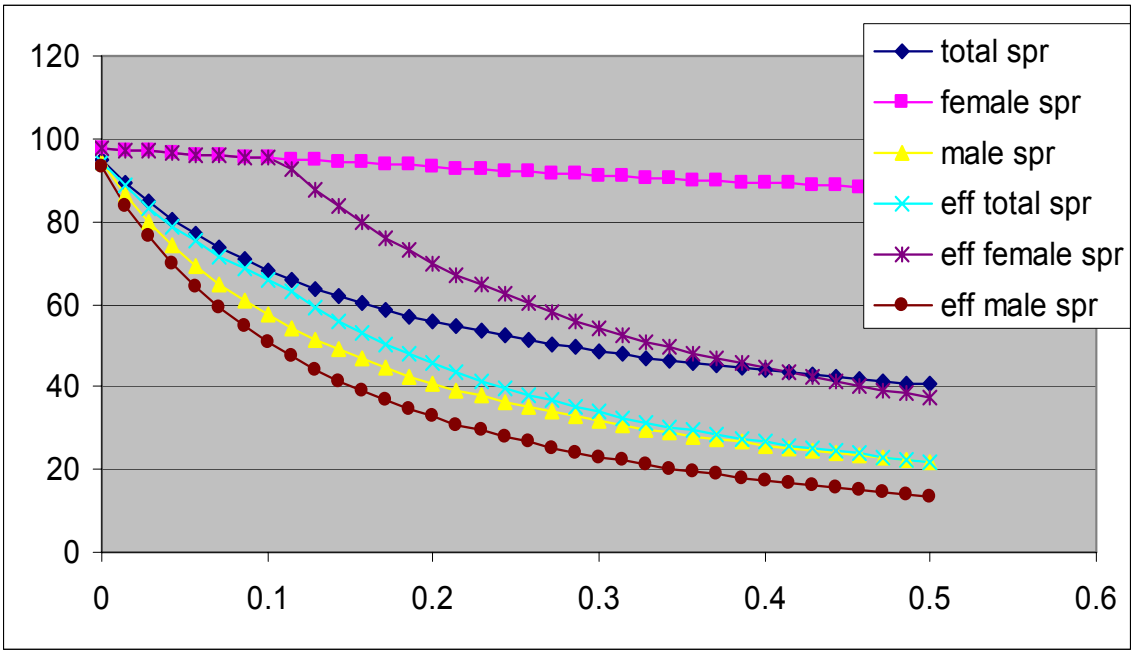

Figure 5. Red king crab mating ratio 3.0, primiparous and multiparous females separate in calculation of effective spawning biomass.

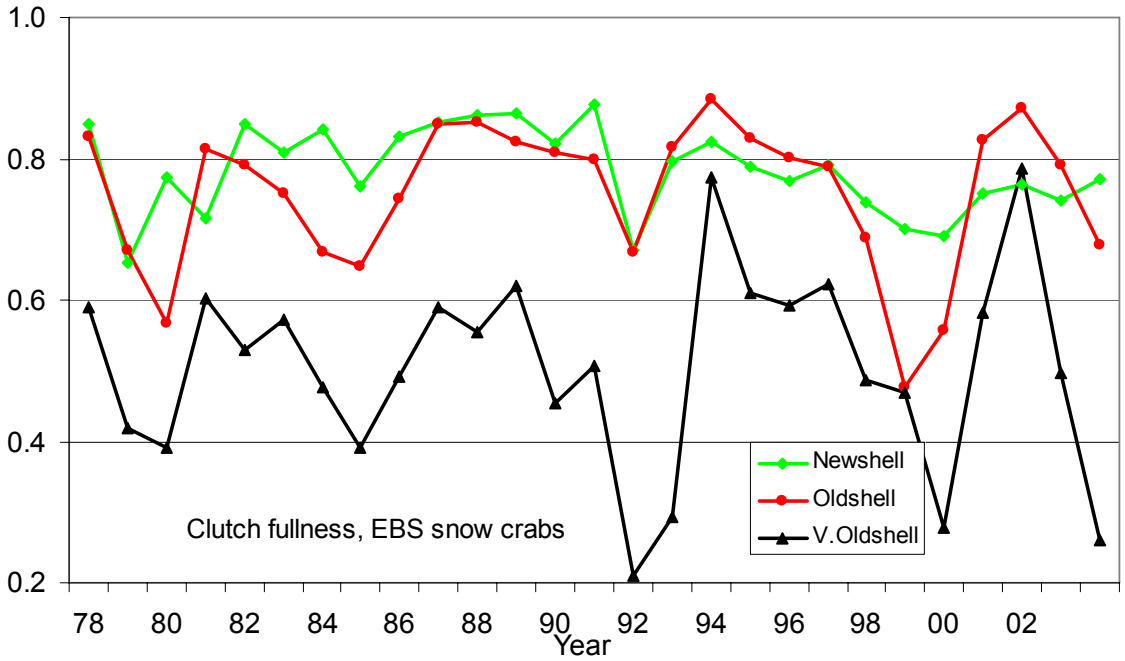

Figure 6. Clutch fullness for Bering sea snow crab survey data by shell condition for 1978 to 2004.

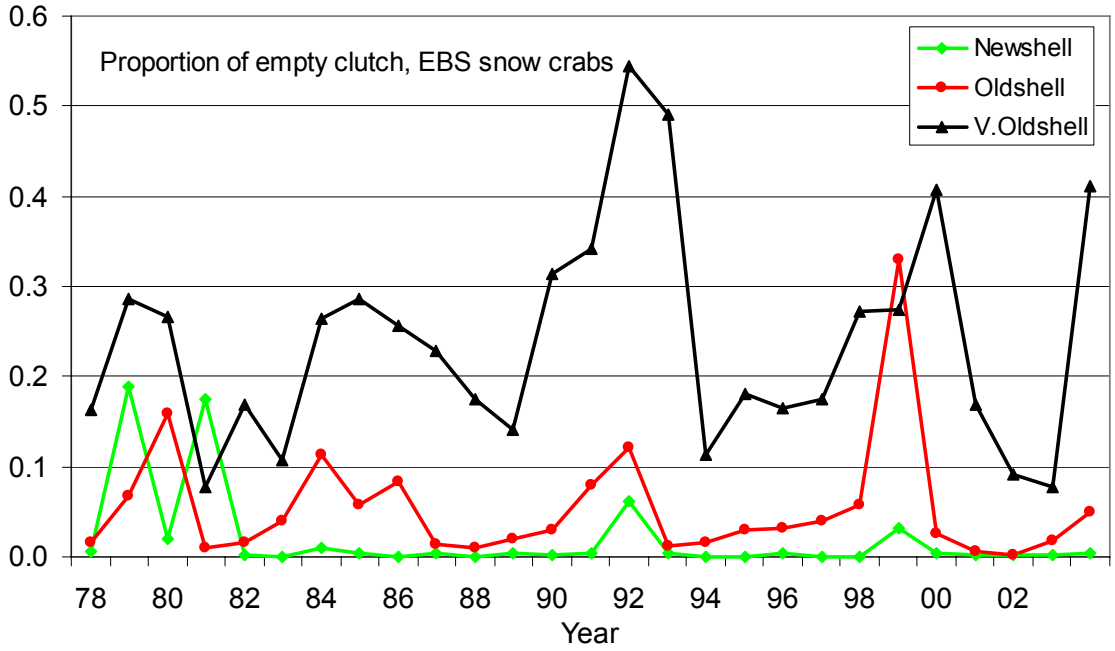

Figure 7. Proportion of barren females by shell condition from survey data 1978 to 2004.

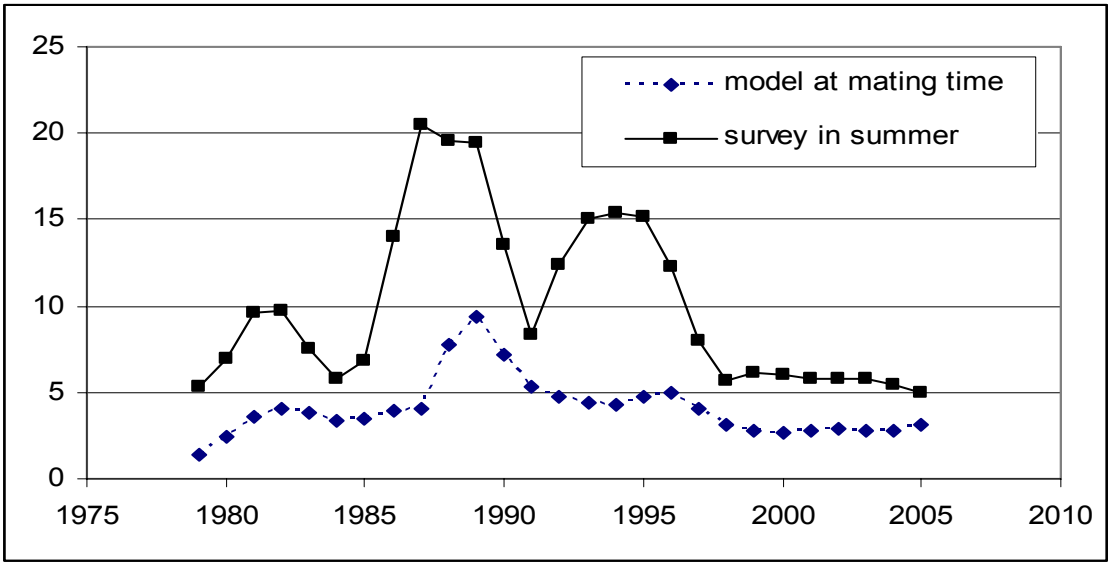

Figure 8. Ratio of mature female snow crab to old shell mature male observed from the survey (summer) and estimated from the stock assessment model at the time of mating (spring, after the fishery).

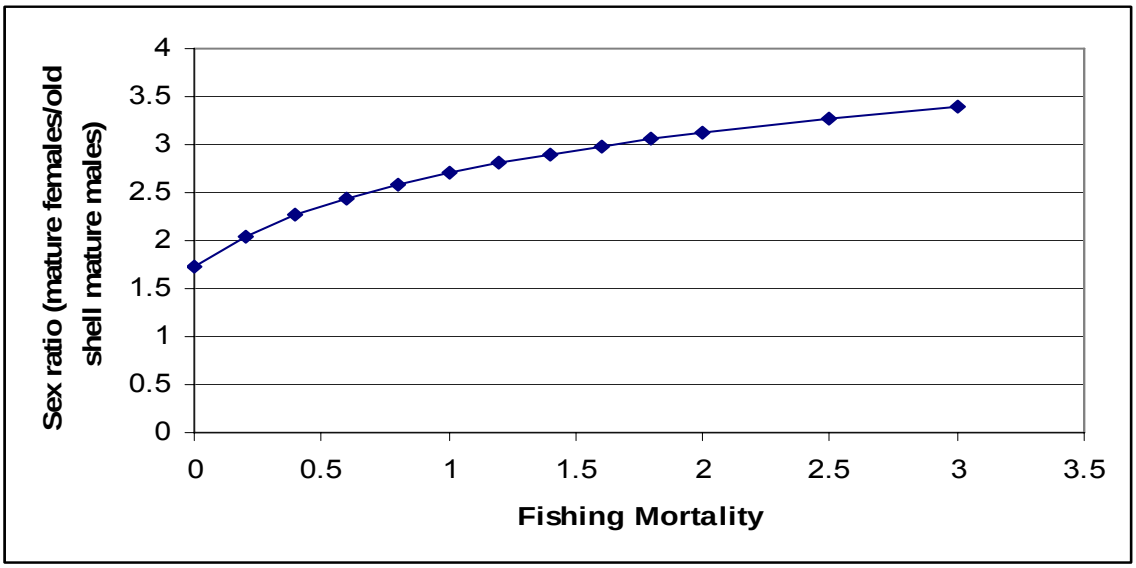

Figure 9. Sex ratio from SPR model for snow crab.

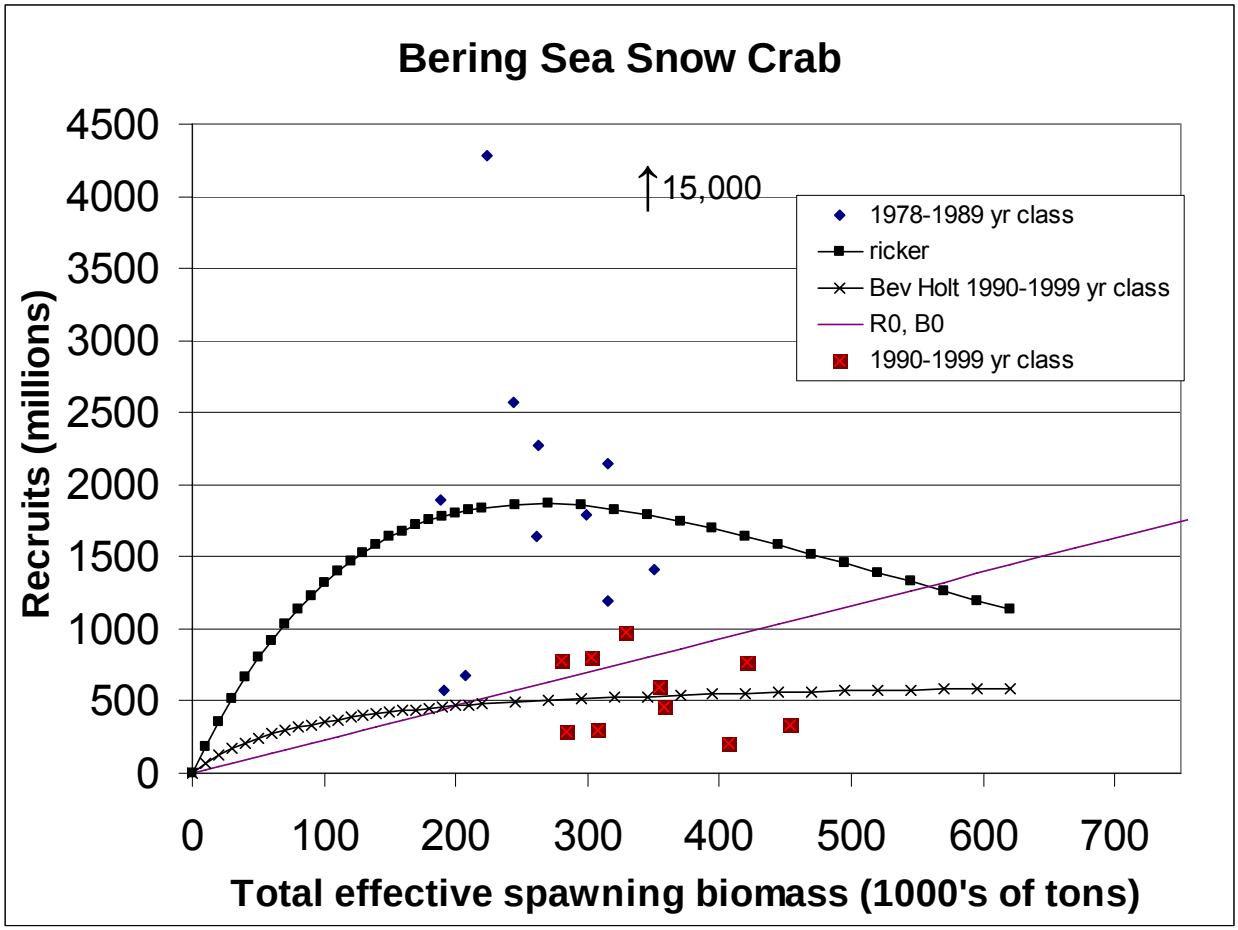

Figure 10. Spawner recruit estimates for snow crab with fits of various SR curves. Ricker curve has steepness 0.7(tau = 0.12) fit to data for all years. A Beverton Holt curve that represents the most current period of low recruitment (1990-1999 year classes) has a steepness of 0.45 (tau = 0.36). The steepness for the Beverton Holt curve was estimated from the slope of the line connecting (0,0) with the point for the lowest spawning biomass with the highest recruitment (280,784).

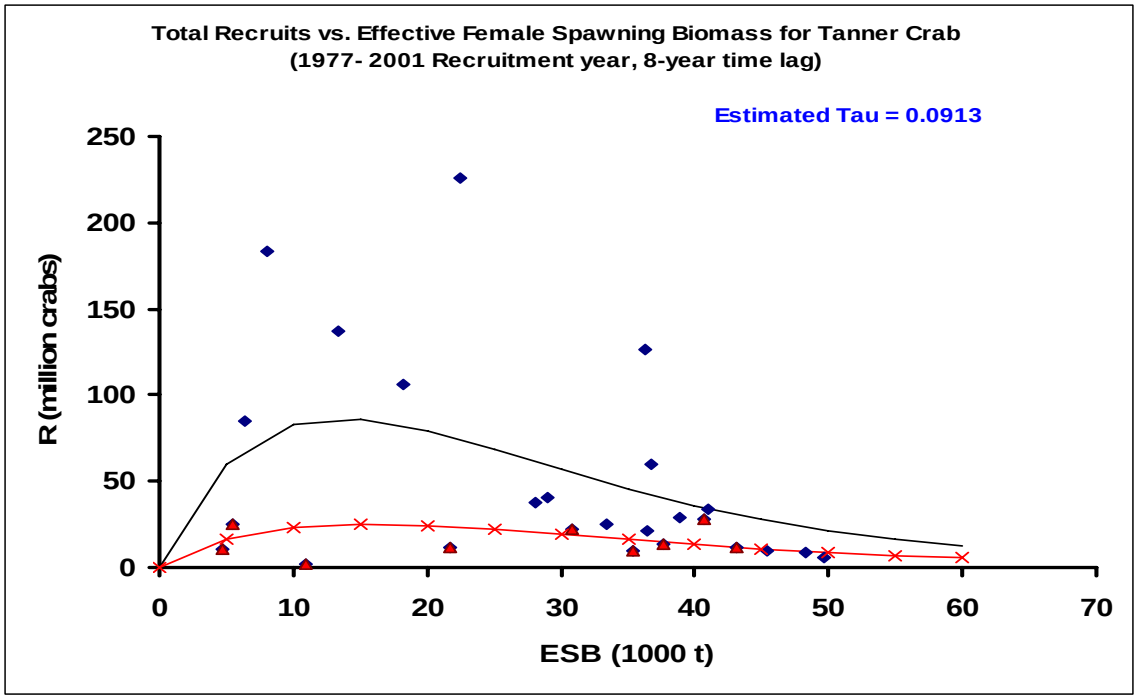

Figure 11. Spawner recruit estimates from the Tanner crab stock assessment model. Ricker curves are fit to all years (steepness 0.73, tau 0.09) and fit to the most recent low recruitments from the 1985-1993 year classes (shown in red) (steepness 0.52, tau 0.24). A ricker curve with steepness = 0.65 (tau = 0.13) was used to develop the current harvest strategy for Tanner crab.

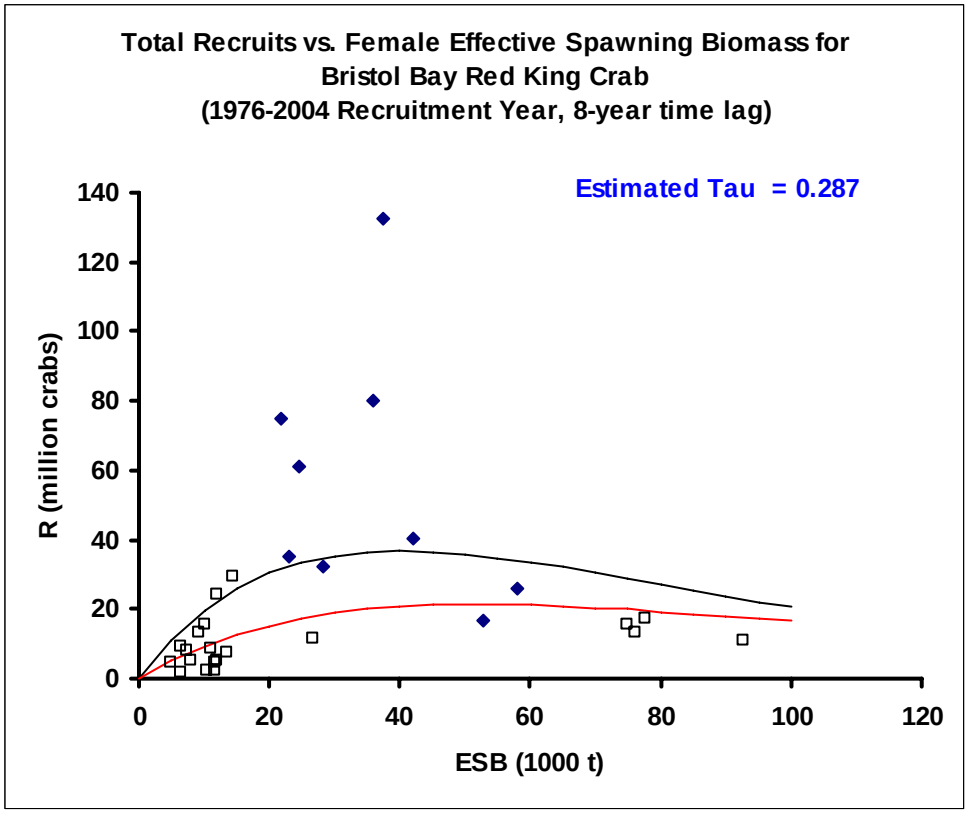

Figure 12. Red king crab recruitment and female effective spawning biomass. A Ricker curve was fit to all years estimated steepness at 0.47 (tau = 0.287). A Ricker curve fit to year classes after from the 1976 regime shift onward estimated steepness at 0.36 (tau=0.45).

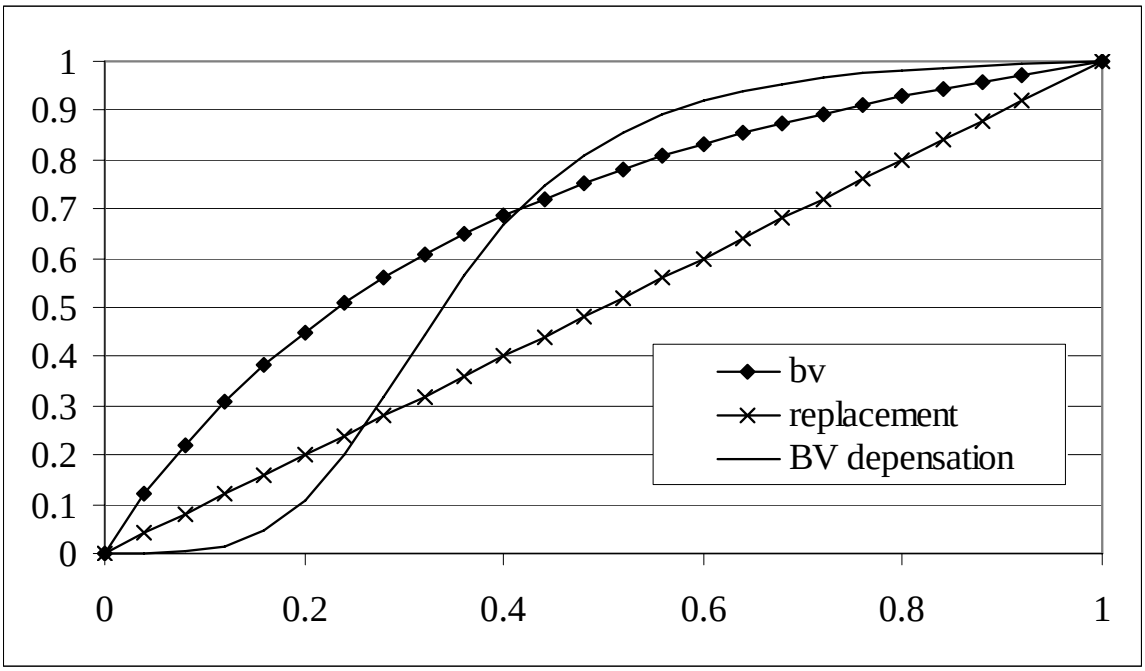

Figure 10. Example of a Beverton and Holt spawner recruit curve with and without depensation. R0 and B0 are 1.0 for both curves.

Appendix A. January 13, 2006 in response to an email from Siddeek.

Doug, Siddeek, and others:

The data you forwarded imply that Guy Powell was able to age crab shells to 12 or 24 months, plus or minus a month, an extremely high precision as Doug duly noted. I don't know anybody who can estimate shell age this accurately, or any technique for doing so. This suggests to me that the "ager" (GP?) held an underlying assumption that the male crabs must have molted at the same month of the previous year. Is this assumption true? On what data is it based? Note that 12 months is the estimated post-molt age of most male crabs, regardless of what month they were observed. Why is this? Those crabs seen mating with primiparous crabs in January through March were predominantly old-shell crabs that had molted the previous year (Maybe 12 months previously, as scored, but more likely sometime between 6 and 18 months previously).

The data do seem to suggest that recently molted crabs were mating with multiparous females in April and May, and those males were scored as being 1-4 months postmolt. Maybe so, but it seems suspect to me for several reasons. In Powell's 1967 tome on growth of RKC, he shows (Table 11, p. 44) that most small crabs (71-109 mm) that were tagged in September 1959 and recovered later were recaptured in April through August after molting once or twice. The first year (1960) is questionable since no recoveries occurred from January to April but the second year show a strong pulse in May-August. Powell concluded that "…molting occurs prior to April". If males were molting in March-April, they would be softshell coincident with the females, and not 1-4 months post-molt, as indicated by the grasping pair data. However, this only addresses crabs that were probably too small to mate.

Powell's data for larger crabs at large more than two years show that molting probability declines with size. These data are somewhat fuzzy because he bases them on "molting opportunities", assuming one per year per crab. I have regrouped his data in 5 mm increments (Fig. 1). Based on these data, the probability of molting in a given year declines to 50% at about 155 mm CL, and goes to zero at 165 mm; the latter is probably incorrect, due to low numbers of large crab recovered. Powell goes on to state that male molting occurs annually up to a size of 158 mm, after which a portion molts biennially, and eventually triennially. But; do they molt only in March-April? Or could they be molting at other times of the year? That is unclear.

I am attaching some additional data collected in our laboratory. These show the shell hardness of 33 female RKC at various periods after molting, and a few before. No crab regained its pre-molt shell hardness in less than a month. Although some crabs did so in as few as 60 days, others may require up to 4 months or more. I interpret this to indicate that it is unlikely that male king crabs molting in March would have a hard enough shell to mate before early May, six weeks later, by which time most mating has been completed. These data are for females and do not necessarily represent males, but I doubt there is that much difference between them.

In summary, the data indicating that recently molted male crabs were grasping females is not quantitative and is therefore questionable. Carapace measurements can be made with a caliper or other quantitative tool, but shell ages are somebody's guess. There is no objective way to measure them, or even compare them between different observers. In my humble opinion, the case is not proven by these data.

Powell, G. C. (1967) Growth of king crabs in the vicinity of Kodiak Island, Alaska. No. 92. Alaska Department of Fish and Game Informational Leaflet. Alaska Department of Fish and Game.

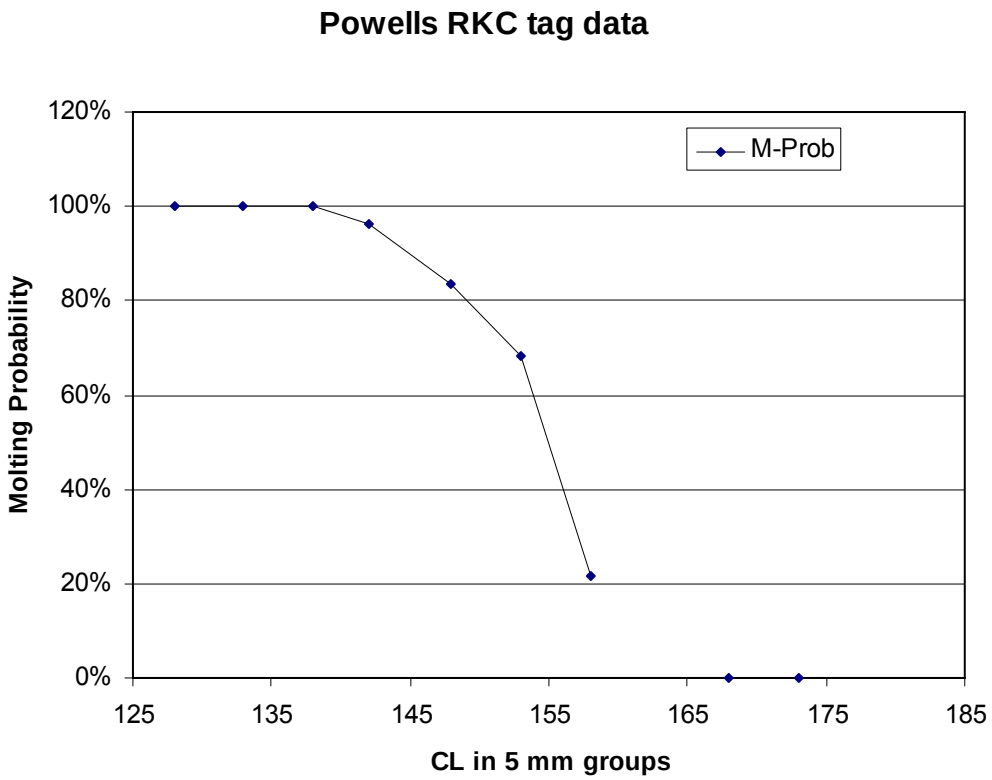

Figure A.1. Probability of molting for male red king crabs at large up to two years, by 5 mm size group. Original data from Powell (1967).

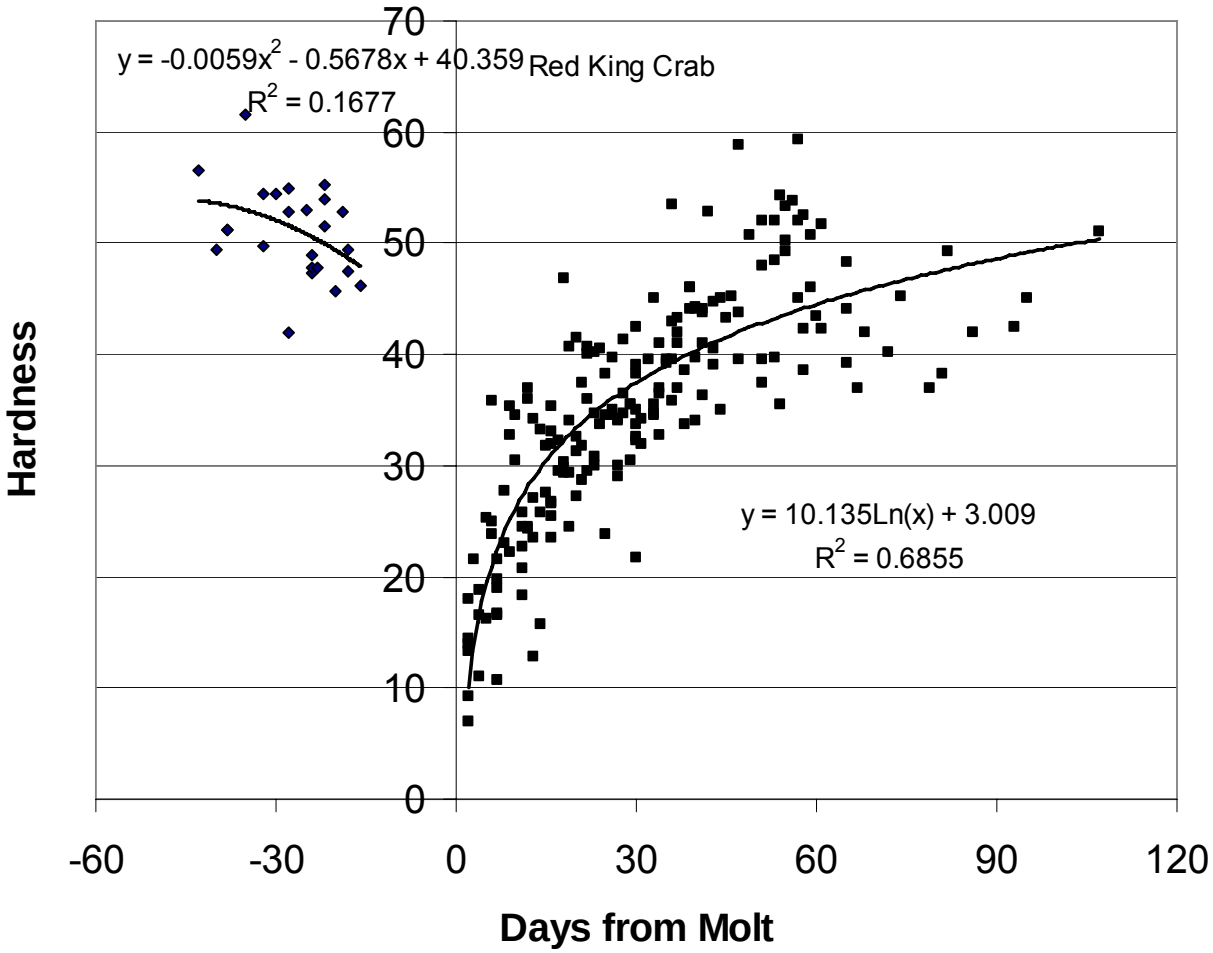

Figure A.2. Shell hardness in durometer units of 33 female king crabs before and after molting. Each point is the mean of 4 measurements at different points on the upper carapace. Data from Brad Stevens (unpublished).