OVERVIEW OF RECOMMENDED HARVEST STRATEGY FOR SNOW CRABS IN THE EASTERN BERING SEA

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EXECUTIVE SUMMARY

The Fishery Management Plan for Bering Sea/Aleutian Islands King and Tanner Crabs (FMP; NPFMC 1998) defines an "overfishing" rate and a minimum stock size threshold (MSST) for an "overfished" level for eastern Bering Sea (EBS) snow crabs (*Chionoecetes opilio*). The EBS snow crab stock was classified as "overfished" by the National Marine Fisheries Service (NMFS) in 1999 due to low mature biomass estimated from the NMFS survey. In response, the Alaska Board of Fisheries (Board) adopted an interim harvest strategy for the EBS snow crab fishery in March 2000 as part of a joint Board-Council effort to rebuild the stock, as is required by the Magnuson-Stevens Fishery Conservation and Management Act (NMFS 1996). Due to time constraints imposed by the regulatory process, however, the interim harvest strategy was not thoroughly analyzed prior to adoption. Since March 2000, the Alaska Department of Fish and Game (ADF&G) and NMFS have worked together to perform the analyses needed to better understand snow crab population dynamics and to better evaluate the current harvest strategy against alternatives: ADF&G and NMFS have developed a length-based model (LBA) for EBS snow crabs and ADF&G has also constructed stock-recruitment (S-R) relationships. Based on those analyses, ADF&G has conducted a thorough analysis of alternative harvest strategies based on the current available information. This report summarizes the analysis of alternative harvest strategies and proposes an improved alternative.

Substantial uncertainty remains as to whether male snow crabs in the EBS undergo a terminal molt at maturity. Because that is an issue having important implications for stock assessment and fishery management, we used both terminal molt and non-terminal molt assessment models to evaluate alternative harvest strategies. We recommend using area-swept estimates of population abundance to determine the guideline harvest level (GHL) for the fishery in 2003, testing the LBA in 2003, and using the non-terminal molt model to assess the stock and determine GHLs for later years pending clarification of the terminal molt issue because the terminal molt model, if wrong, leads to a high risk of overfishing. Also, the terminal molt model requires us to assume a questionably high natural mortality for mature males and the model performs poorly in both data fitting and in simulations. Further research efforts will increase our understanding of the terminal molt issue, survey catchability, and natural mortality for mature males, and the assessment model will be improved accordingly.

Annual recruitment of EBS snow crabs alternates between high and low periods in a quasi-cyclic manner and exhibits a very weak density-dependent stock-recruitment relationship. As a result, recruitment appears to be only loosely related to parental abundance levels. Computer simulations and yield per recruit (Y/R) analysis with the non-terminal molt model show that the yield curve is relatively insensitive to high harvest rates and that many alternative harvest strategies show similar results. We recommend a new harvest strategy for the EBS snow crab stock that has four components: (1) a threshold of 25% of B_{msy} (the MSY stock size; B_{msy} is currently defined in the FMP as 921.6 million pounds of total mature biomass), below which the fishery is not opened; (2) a 58% harvest rate on exploitable legal males, which are defined as 100% newshell and a percentage of oldshell males ≥102 mm carapace width (CW), where oldshell selectivity is determined by the historical fishery selectivity and will be updated each year; (3) exploitation rate caps on mature male biomass to be 75% of the fishing mortality that produces maximum sustainable yield (F_{msy}; currently F_{msy}=0.3) when total mature biomass is ≥B_{msy}, one third of F_{msy} when total mature biomass is equal to the threshold, and a linear function of total mature biomass when total mature biomass is greater than the threshold and less than B_{msy}; and (4) a minimum GHL of 25 million pounds in order to open a fishery. Like the status quo strategy, area-swept equivalent abundances and biomasses should be used to determine GHLs. The proposed harvest strategy will result in higher harvest rates than the current rates when the stock abundance is high during high productivity periods and maintain low exploitation rates on mature male biomass for stock rebuilding when the population is depressed. Simulations show that the proposed strategy produces higher mean yields and a better trade-off between high mean yield and low variation in yield than the current strategy. Additionally, the simulations show that expectations for total mature biomass to fall below B_{msy} or MSST are comparable between the proposed harvest strategy and the current strategy. Relative to the harvest strategy in place prior to March 2000, the simulations show that the proposed harvest strategy would produce only a slightly lower mean yield, but would have lower variation in yield and lower expectation for total mature biomass to fall below B_{msy} or MSST.

PURPOSE

The purpose of this report is to provide the basis for a proposed new harvest strategy for the snow crab fishery in the EBS. We provide a brief history of the fishery, an overview of the fishery management goal and management measures, and a summary of problems with the current management strategy. Then, we summarize four analyses of snow crabs in the EBS: (1) terminal molt of mature males; (2) S-R relationships; (3) yield per recruit; and (4) an evaluation of alternative management strategies based on snow crab population dynamics. Finally, our combined analyses lead us to propose a new harvest strategy for snow crabs in the EBS.

HISTORY OF FISHERIES

Snow crabs are widely distributed in the Bering Sea, extending as far north as the Chukchi Sea and Arctic Ocean (Wolotira et al. 1977). Within the EBS, mean sizes of mature males and females increase with decreasing latitude or increasing depth (Zheng et al. 2001). Large males are found in high abundance primarily in the southern part of the EBS and in a band along the outer margin of the continental shelf (Somerton 1981; Zheng et al. 2001) where the snow crab fishery in the EBS occurs.

Snow crabs in the EBS have supported one of the largest and most valuable fisheries in the United States. The Japanese fleet first harvested snow crabs as bycatch in the 1960s; the directed fishery began in 1973, and the catch gradually increased through the 1970s (Otto 1990). Total catch was relatively small until the directed domestic fishery was developed in the late 1970s. No snow crab catch quota has been made available for foreign fishing fleets since 1980 under the provisions of the Magnuson Fishery Conservation and Management Act. The domestic fishery expanded quickly in the late 1980s, and catch peaked in 1991 at 329 million pounds (Morrison 1999). Annual ex-vessel value peaked in 1994 at US$192 million (Morrison 1999). Catch fluctuated widely during recent years, tracking the abundance of large male crabs estimated by the NMFS trawl surveys (Rugolo et al. 2001). Because of the low abundance estimated since the 1999 summer survey, the GHLs for the 2000-2002 fishery seasons were the lowest since 1983.

MANAGEMENT GOAL AND MEASURES

An optimal harvest strategy for any fishery resource depends on fishery management goals. In March 1990 the Board adopted a fishery management policy for king and Tanner crabs (5AAC 35.080; ADF&G 1998). The goal of the policy is to maintain and improve these crab resources for the greater overall benefit to Alaska and the nation. Achievement of this goal is constrained by a need to minimize: (1) risk of irreversible adverse effects on reproductive potential; (2) harvest during biologically sensitive periods; (3) adverse effects on non-targeted portions of the stock; and (4) adverse interactions with other stocks and fisheries. The policy endeavors to maintain a healthy stock, provide for a sustained and reliable supply of high quality product that leads to substantial and stable employment, and provide for subsistence and personal use of the resource. In brief, the Board specified a series of policies to protect the crab stock and provide guidance for optimum utilization:

- Maintain stocks of multiple sizes and ages of mature crabs to sustain reproductive viability and to reduce industrial dependency on annual recruitment;
- Routinely monitor crab resources so that harvests can be adjusted according to stock productivity;
- Minimize handling mortality of non-legal crabs;
- Maintain adequate brood stock to rebuild the population when it is depressed;
- Establish management measures based on the best available information for each area; and
- Establish regulations for an orderly fishery.

The restriction of harvesting only large males and allowing no fishing during molting and mating periods are consistent with these policies. Those measures are based on economic consideration of market value, protection of females, and allowance of at least one mating season for males. A legal size of 78 mm (3.1 in) CW is used for snow crabs in the EBS. However, crab processors currently prefer a minimum size of 102 mm (4.0 in) CW or greater. Accordingly, GHLs have been based on the abundance of males ≥102 mm CW. A constant harvest rate of 58% on large males ≥102 mm CW was used to set GHLs before March 2000. A variable harvest rate strategy has been used since March 2000. The Board's policy on king and Tanner crab management provides specific criteria under which alternative harvest strategies can be evaluated. The Magnuson-Stevens

Fishery Conservation and Management Act provides additional criteria (NMFS 1996). In particular, National Standard 1 states that "conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimal yield from each fishery." The FMP (NPFMC 1998) defines overfishing for EBS snow crab as a fishing mortality in excess of F_{msy} (defined in the FMP as 0.3) for a period of one year or more and defines the EBS snow crab MSST for an overfished level as 460.8 million pounds of total mature biomass (equal to one-half the FMP definition for B_{msy}, 921.6 million pounds of total mature biomass).

PROBLEMS AND APPROACHES

Due to low survey mature biomass, the EBS snow crab stock was classified as "overfished" by NMFS on September 24, 1999. According to the Magnuson-Stevens Fishery Conservation and Management Act (NMFS 1996), a rebuilding plan is needed within one year to rebuild an overfished stock. The Board adopted an interim harvest strategy for the directed EBS snow crab fishery as part of a joint Board-Council effort to rebuild the stock in March 2000. Due to the time constraint imposed by the one-year requirement to implement a rebuilding plan and the Board and Council regulatory meeting schedule, a thorough analysis of the interim harvest strategy could not be completed prior to its adoption. Since March 2000, ADF&G and NMFS have developed a LBA for EBS snow crabs and ADF&G has conducted a thorough analysis of alternative harvest strategies based on the current available information.

ADF&G's proposed new harvest strategy is based on four analyses of the stock and fishery. NMFS, with assistance from ADF&G, developed a LBA to improve abundance estimates of EBS snow crabs. Then, ADF&G estimated the S-R relationships based on the results of LBA and from a review of literature on snow crab reproductive biology to understand the recruitment dynamics. A yield per recruit analysis was also conducted by ADF&G to evaluate the trade-off between growth and mortality (fishing and natural). Finally, based on the results of the LBA and S-R analyses, we conducted computer simulations to evaluate alternative harvest strategies for EBS snow crabs. An overview of these studies follows.

TERMINAL MOLT OF MATURE MALE SNOW CRABS

It has been hypothesized that the maturity molt in majid crabs is the last, or "terminal," molt (Hartnoll 1963). Maturity is often assessed with morphometric data. For males, morphometrically mature crabs are distinguished from morphometrically immature crabs by an increase in chela height for a given CW (Somerton 1980; Conan and Comeau 1986). In this report, the term "morphometric maturity" was operationally defined as large-clawed as opposed to small-clawed males and does not necessarily coincide with physiological or functional maturity. For females, a prominent increase in the width of the abdomen indicates sexual maturity (Somerton 1981). It is commonly accepted that female snow crabs undergo a terminal molt at maturity. The terminal molt assumption for male snow crabs has been accepted for Atlantic stocks (e.g., Conan and Comeau 1986;

Jamieson et al. 1988; Saint-Marie et al. 1995). Although evidence exists that some tagged mature male snow crabs molted in Conception Bay, Newfoundland (Dawe et al. 1991), molting rates were probably very low, and the terminal molt assumption has been accepted for practical application to fishery management (Earl Dawe, Department of Fisheries and Oceans, St. John's, Newfoundland, Canada, pers. comm.).

Whether male snow crabs in the EBS undergo a terminal molt to morphometrically mature remains unresolved. Theoretically speaking, if terminal molt at maturity is species-wide or genus-wide phenomenon as claimed by Conan and Comeau (1986) and Conan et al. (1990), EBS male snow crabs should not be an exception. On the other hand, it is difficult to use the terminal molt theory to interpret the trawl survey and fishery data in the EBS (Zheng 2001; Turnock 2001). If the terminal molt hypothesis is true for male EBS snow crabs, a very high rate of natural mortality for mature males – much higher than that estimated for mature females – would be needed to account for the relatively low proportion of oldshell mature males that occurs in the survey data. Furthermore, because of the relatively low abundance of large immature males caught in the survey, trawl survey catchability has to be very low for these crabs under the terminal molt theory to explain a relatively high proportion of large newshell mature males. In fact, the estimated trawl survey catchability would have to be about 60% for males ≥102 mm CW and much lower for smaller crabs. Research is currently being conducted to understand the terminal molt issue for EBS male snow crabs.

Whether male snow crabs undergo a terminal molt at maturity has important implications on the assessment and management of the commercial fishery. Because the size limit is primarily market-driven for the EBS snow crab fishery, terminal molt has little implication for the legal size limit. However, the existence of terminal molt affects the estimates of growth and natural mortality parameters as well as survey catchability (Zheng 2001), which are important to assess stock size and to determine an optimal harvest strategy. Because of the uncertainty on the terminal molt issue, the LBA was conducted by assuming both terminal molt and non-terminal molt for male crabs (Figure 1). The terminal molt model requires high assumed natural mortality for mature males (M = 1.0 for mature newshell males and M = 1.5 for mature oldshell males) and low survey catchability. In contrast, the non-terminal molt model assumes relatively low natural mortality for mature males (M = 0.37 for mature newshell males and M = 0.7 for mature oldshell males) and high survey catchability. Both models, after adjustments for survey catchability, fit the abundance of large males well and underestimated survey abundance of females although the non-terminal molt model fit the female abundance better than the terminal molt model (Figure 1). Due to the low survey catchability assumed for the terminal molt model, population estimates at the time of the survey are higher from the terminal molt model than from the area-swept or non-terminal molt models (Figure 2). However, due to the high natural mortality assumed for mature males in the terminal molt model, the terminal molt model predicts a greater decrease than the non-terminal molt model in large males remaining at the time of fishing (Figure 2). Both models were used to evaluate alternative harvest strategies.

STOCK-RECRUITMENT RELATIONSHIPS

In this study, we used the results from the LBA (Turnock 2001) to develop S-R relationships for EBS snow crabs. Recruitment of both males and females to the NMFS survey was assumed to primarily occur within 25-39 mm CW with a mean of 30.4 mm CW. Based on the snow crab growth in the Gulf of Saint Lawrence (Sainte-Marie et al. 1995; Alunno-Bruscia and Sainte-Marie 1998), time from mating to recruitment was assumed to be 4 years.

Spawning biomass was estimated as the sum of total biomass of mature females and morphometrically mature males due to several potentially complicating factors, including sperm storage, sperm conservation, and prolonged embryo development. Many similarities exist between the reproductive biology of Tanner (*Chionoecetes bairdi*) and snow crabs, such as storage of sperm by females for future egg fertilization and multiple female mating partners during a given mating season (Paul 1984; Sainte-Marie and Lovrich 1994; Sainte-Marie and Carrière 1995). However, male snow crabs are sperm conservers, partitioning sperm among successive matings, and female snow crabs are polyandrous (Urbani et al. 1998; Rondeau and Sainte-Marie 2001). Both mate-guarding time by males and the quantity of ejaculate stored in a primiparous female's spermatheca were positively related to the sex ratio of males to females, but these relationships may change over time (Rondeau and Sainte-Marie 2001). Therefore, lack of males for mating may rarely occur for snow crabs, but sperm limitation can occur naturally if males allocate their sperm too parsimoniously among females (Rondeau and Sainte-Marie 2001). Because of this sperm economy, it is difficult to use sex ratio to determine effective spawning biomass. Furthermore, depending on temperature, embryo development of snow crabs can take 1 or 2 years (Sainte-Marie 1993; Moriyasu and Lanteigne 1998), and we do not have information to separate the abundance of mature females with different embryo-development times annually.

The association between recruitment and spawning biomass for EBS snow crabs was very weak, and spawning biomass explained very little recruitment variation (Figures 3 and 4). The S–R analyses indicate an existence of a quasi-cyclic annual recruitment pattern (Figures 3 and 4). Recruitment patterns and S–R relationships for EBS snow crabs were similar to those described for snow crabs in the Gulf of St. Lawrence in Atlantic Canada. Periods with strong and weak recruitment alternated every few years, cyclic patterns of S–R relationships existed, and there were very weak density-dependent S–R relationships (Sainte-Marie et al. 1996; B. Sainte-Marie, Maurice Lamontagne Institute, Dept. of Fisheries and Ocean, Canada, pers. comm.). Alternating strong and weak recruitment every few years caused cyclic spawning biomass over time, and the time sequence of recruitment and spawning biomass cycles produced the cyclic patterns of the S–R relationships.

Because of very weak density-dependent effects on recruitment, we modeled the recruitment dynamics with three components (Figures 3 and 4): (1) an S–R curve with a flat line within the estimated range of spawning biomass and a Ricker curve for low spawning biomass levels, (2) random alternation of high and low recruitment patterns (2-3 years of high and 2-10 years of low) estimated from the recruitment residuals, and (3) lognormal noises. For a given year, the recruitment will be equal to the product of these three components (Figure 5).

YIELD PER RECRUIT ANALYSIS

The weak S-R relationship prompted us to employ the traditional Y/R analysis method to determine useful biological reference points (BRPs) for EBS male snow crabs as a comparison to those determined by rigorous computer simulation studies. The reference harvest rates were determined under two models: (1) non-terminal molt for mature males and (2) terminal molt for mature males. The same values of maturity, molting probability, mean growth increment per molt, natural mortality, handling mortality rate, trawl bycatch mortality rate, and fishery selectivity as were used in the harvest strategy simulations (below) were used.

The Y/R analysis computes relevant BRPs considering the fate of a cohort just recruited through its entire life span under a given set of growth and mortality parameters. We considered the fate over 15 years of 1000 male crabs that recruited primarily to the 25-39 mm CW size range. The cohort was modeled to grow within a size range of 25-135 mm CW. The proportions of crabs growing into different size intervals were determined by the normal probability distribution of growth increment and the overall size-specific molting probability. The abundances in each size interval were also affected by mortality.

The Y/R and harvest rate were computed in five steps using the exploitable stock abundance determined by the annual resources survey conducted approximately 7 months prior to the fishery. First, the GHL was estimated at the time of the survey for a given harvest rate (HR_{GHL}), considering 100% newshell and 25% oldshell crabs ≥102 mm CW and their mean weight at each size interval. Second, the total exploitable biomass of males at the fishing time (i.e., after 7 months of natural mortality) was determined as the sum of the product of male biomass by size and fishery size selectivity under the same harvest rate. Third, the GHL was divided by the total exploitable biomass to estimate a harvest rate at the fishing time, and this harvest rate was set at ≤100% and was applied to the exploitable biomass at the fishing time to calculate the yield (Y). This Y was close to the GHL computed in the first step. Fourth, Y/R was determined by dividing Y by 1000. Finally, this Y-producing harvest rate was rescaled to reflect an equivalent harvest rate at the survey time (HR_Y) by the following formula: $HR_Y = (HR_{GHL} * Y)/GHL$.

Figure 6 depicts the Y/R vs HR_Y (harvest rate expressed as a fraction) curves for the non-terminal and terminal molt models. The maximum Y/R-producing harvest rate (HR_{Ymax}) and the more precautionary 0.1 level harvest rate ($HR_{Y0.1}$) were determined from each Y/R vs HR_Y curve. For the non-terminal molt model, the HR_{Ymax} was 80% and $HR_{Y0.1}$ was 57%, which are comparable to past Y/R analysis results (Somerton 1981). For the terminal molt model, the HR_{Ymax} was 97% and $HR_{Y0.1}$ was 84%. Higher reference harvest rates under the terminal molt model than that under the non-terminal molt model were expected because the terminal molt model assumed higher natural mortality and no growth after maturity.

EVALUATION OF ALTERNATIVE HARVEST STRATEGIES

Computer Simulations

The LBA and S–R relationships were combined in a computer simulation model to evaluate alternative harvest strategies for EBS snow crabs. The primary features of the simulations are as follow:

- Two models were used in the simulations: one based on the terminal molt assumption and another on non-terminal molt assumption for mature male crabs. Each model has its own set of parameters.
- The models were initialized with data on the population status for 2000.
- For each harvest strategy, we simulated the population and fishery for 50 years with 2000 replicates. The average population status and yield (i.e., catch in million pounds) from the simulations were summarized to compare the alternative strategies.
- Fishing patterns, including the mid-point of the fishery season and gear selectivity, were assumed to be the same as the last 10 years.
- An assessment error with a standard deviation of 0.2 was assumed. Assessment errors were applied to the abundance in the initial year and the abundance used to compute GHLs.
- The handling mortality rate of captured but discarded females and males was assumed to be 25% for the crab fishery. Sensitivity to assumed handling mortality rate was examined by assuming alternative 0% and 50% handling mortality rates.
- Bycatch from groundfish fisheries was set according to current prohibited species cap regulations, and the bycatch mortality rate was assumed to be 80% (NPFMC 1996).

To evaluate the strategies, statistics were collected on mature biomass, probabilities of fishery closure, and yield. The probability of fishery closure was estimated as the proportion of replicates with estimated mature biomass below threshold or estimated GHL below the minimum GHL such that the fishery is prohibited for a given year. Results were averaged over the simulated time horizon and over all replicates. With respect to the Board's policy on king and Tanner crab management, two important considerations are the ability of a particular strategy to produce relatively large catches and its ability to produce some fishery stability by avoiding recruits-only fisheries. Therefore, to assess optimality, an equal trade-off value between increase in mean yield (a measure of size of catches) and decrease in standard deviation of yield (a measure of fishery variability) was computed as 0.5*yield-0.5*standard deviation (Zheng et al. 1997) for each alternative strategy.

Alternative Harvest Strategies

We examined four kinds of alternative harvest strategies to set GHLs. These approaches ranged from a simple approach to a more complex approach incorporating gear selectivity and shell condition. A minimum GHL threshold of 25 million pounds was applied to all strategies. Alternative minimum GHL thresholds of 15 million and 20 million pounds were also evaluated for harvest strategy 2, below.

1. Constant harvest rate on exploitable legal males ≥102 mm CW. The exploitable males were defined as 100% newshell and 25% oldshell males. Sixteen alternative harvest rates ranging from 0.05 to 0.8 were evaluated. The purpose of evaluating these harvest rates was to establish a yield curve as a function of harvest rate.
2. A 58% harvest rate on exploitable legal males ≥102 mm CW and variable exploitation rate caps on mature male biomass. The 58% harvest rate is similar to the harvest rate at $HR_{Y0.1}$ (57%) from the yield per recruit analysis with the non-terminal molt model (Figure 6). Variable exploitation rate caps on mature male biomass were 0% when total mature biomass was below $0.25*B_{msy}$ (threshold), 75% of F_{msy} (or currently 0.75*0.3=22.5%) when total mature biomass was at or above B_{msy}, and $[F_{msy}/3+(B_t-0.25*B_{msy})*0.417*F_{msy}/(0.75*B_{msy})]*100\%$ when $0.25*B_{msy} \le B_t < B_{msy}$, where B_t is total mature biomass in year t (Figure 7). Area-swept equivalent abundances and biomasses were used to determine GHLs. The exploitable males were defined the same as that in harvest strategy 1 above. Alternative 30% and 50% oldshell male selectivities were also examined. The median and mean selectivities for oldshell males during the past 10 years were 25% and 30%, respectively, and the median selectivity for oldshell males during the past 21 years was 50%. B_{msy} is currently defined as 921.6 million pounds; therefore, the current mature biomass threshold, $0.25*B_{msy}$, is 230.4 million pounds. In addition, alternative harvest rates of 55%, 60%, and 65% on exploitable legal males and alternative maximum caps of exploitation rates of 20% and 25% on mature male biomass were also examined.
3. Status quo. The status quo strategy has a variable mature harvest rate based on total mature biomass and a cap of 50% exploitable legal males. The exploitable legal males were defined as 100% newshell and 25% oldshell males ≥102 mm CW. Trawl survey catchability was assumed to be 1.0 for all sizes of crabs. This interim harvest strategy was adopted by the Board in March 2000.
4. A 58% harvest rate on males ≥102 mm CW. Trawl survey catchability was assumed to be 1.0 for all sizes of crabs. This was the harvest strategy before March 2000.

The Board's policy on king and Tanner crab management specifies the use of a threshold below which the fishery must be closed to maintain adequate brood stock. Because the S–R relationship is weakly density dependent, we did not attempt to estimate an optimal threshold in our simulations. Rather, we used the current threshold that was based on the guidelines of Restrepo et al. (1998) for implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act as applied to the B_{msy} defined for EBS snow crabs in the FMP. The status quo and alternative harvest strategies with variable exploitation rate caps on mature male biomass are in accordance with the guideline that stocks below the size that would produce MSY should be harvested at a lower rate than when they are above the level that would produce MSY.

Results

Strategy 1: Constant harvest rate. Mean yield and standard deviation of yield increased as a function of harvest rate for both models, but the standard deviation of yield increased at a slower rate than mean yield for the non-terminal molt model and at a slightly faster rate than mean yield for the terminal molt model (Figure 8). The gain in mean yield generally decreased as harvest rate increased, especially at the high harvest rates for the non-terminal molt model. The yield curves as a function of harvest rates were very similar to the Y/R curves in Figure 6. Variation in yield, indexed by the standard deviation of yield, was very high for both models. This is a direct result of the periodic recruitment feature of snow crab population dynamics. Mean mature biomass at the time of the summer survey decreased as harvest rate increased, but the mean mature biomass at a harvest rate of 80% was greater than half of the mean mature biomass without fishing for both models (Figure 8).

Strategy 2: A 58% harvest rate on exploitable legal males ≥102 mm CW and variable exploitation rate caps on mature male biomass. Alternative harvest rate strategies generally did not change the results very much within the non-terminal molt model (Table 1). Increases in harvest rate generally caused increases in mean yield and standard deviation of yield, resulting in similar trade-off values between increases in mean yield and decreases in standard deviation of yield among alternative strategies. Higher harvest rates also resulted in slightly lower mature biomasses and slightly higher percentages of years when the mature biomasses were below B_{msy} or MSST (Table 1). It appears that fishery closures were primarily due to the minimum GHL criterion. Reducing the minimum GHL from 25 million pounds generally resulted in a similar mean yield and standard deviation of yield and a slightly lower mean mature biomass but a substantial decrease in percentages of years with fishery closures (Table 1). As expected, a lower handling mortality rate resulted in a higher mean yield and mature biomass, but due to a low catchability of females and small males in the directed pot fishery, a handling mortality rate close to 25% does not greatly affect the population dynamics and yield (Table 1). Reducing the maximum exploitation cap on mature male biomass from 22.5% to 20% or increasing to 25% slightly decreased or increased mean yield (Table 1).

Results differed somewhat between the models assuming terminal molt and non-terminal molt for mature males. Due to the assumption of high natural mortality, mean yield was generally lower for the terminal molt model than for the non-terminal molt model with a low harvest rate (Figure 8). High natural mortality also made the simulated population fluctuate much greater, resulting in much higher variation in yield and higher percentages of years with fishery closures for the terminal molt model than for the non-terminal molt model. The low estimated survey catchability produced much higher estimates of mature biomass for the terminal molt model than for the non-terminal molt model.

Strategies 3 and 4: Status quo and a 58% harvest rate on males ≥102 mm CW. The performance of the current harvest strategy and the previous 58% constant harvest rate strategy depends on the model. With the non-terminal molt model, the current strategy performed reasonably well, having a relatively high mean mature biomass (Table 1). Although the mean yield was relatively high for the previous 58% constant harvest rate strategy with the non-terminal molt model, its mature biomass was much lower than those produced by the alternative strategies and its trade-off value was the lowest among the alternative strategies (Table 1). With the terminal molt model, both the current and previous harvest strategies produced relatively low mean yield due to the great difference between assumed and actual survey catchabilities. The simulated mean yield with the terminal molt model was much lower than the mean yield of 119 million pounds from 1978 to 2000, indicating potential errors for the model.

Comparison of strategies 2, 3 and 4. Although the current harvest strategy allows the mature harvest rate to vary based on mature biomass, the 50% cap on exploitable legal males ≥102 mm CW is usually in effect, making it very close to a harvest strategy with a 50% harvest rate on exploitable legal males. In this sense, the current harvest strategy can be restated as a 50% harvest rate on exploitable legal males with exploitation rate caps on mature male biomass. Increasing this harvest rate to 58% (strategy 2) resulted in trade-offs that generally outperformed both the current and previous harvest strategies (Table 1). This alternative strategy also maintained relatively high mean mature biomass. Although increasing this harvest rate to 60% or 65% slightly increased mean yield and trade-off value, the mean mature biomass decreased and the risk of population collapse also increased (Table 1). Since we were unable to use the sex ratio to compute effective spawning biomass, we might underestimate the risk of population collapse with a high harvest rate in our simulations. Additionally, increasing the harvest rate above 58% increases the risk of violating the Board policy to maintain stocks of multiple sizes and ages (ADF&G 1998) and is a further increase above the precautionary $HR_{Y0.1}$, which we estimated as 57%. A very small increase in mean yield for harvest rates >58% is not worth the higher risk. Like the current harvest strategy, strategy 2 would assure a low exploitation rate on mature male biomass to protect the population when the population is low. However, when the population is high, strategy 2 would have a higher harvest rate to increase yield than the current strategy. In terms of the relatively high mean yield and trade-off value and in the context of the precautionary approach to fisheries management, we considered strategy 2 as the most attractive alternative to the current strategy or the previous 58% constant harvest rate strategy.

Model selection. There remains the question of which assessment model to use in management of the fishery. The risks of using a wrong model are different between the non-terminal molt and terminal molt models. The risk of underharvesting the stock could occur if we wrongly assumed non-terminal molt for males. But this risk of underharvesting with the non-terminal molt model is lower than the risk of underharvesting with the past stock assessment and management practice, because the overall estimated survey catchability for the non-terminal molt model was lower than that assumed for the area-swept estimates. Because the stock was declared “overfished”, the risk of underharvesting based on area-swept estimates before 2000 may not be a concern. The risk of overharvesting or overfishing could occur if we wrongly assumed terminal molt for males with very low estimated survey catchabilities. The overall estimated survey catchability for males ≥102 mm CW was 1.0 for the non-terminal model and about 0.6 for the terminal molt model. Little has been published on trawl survey catchability for EBS snow crabs. Based on a limited trawl survey catchability experiment on EBS snow crabs, net efficiencies for crabs of 110 and 130 mm CW were estimated to be 0.79 and 0.88 (Somerton and Otto 1999). So the survey catchability for males ≥102 mm CW may be between 0.6 and 1.0. Based on the assumed high natural mortality needed for the terminal molt model to fit the survey data, about half of mature males die during the period between the survey and the mid-point of the fishery. A harvest of 50% of the males ≥102 mm CW estimated at the time of the summer survey could approximately represent all male crabs ≥102 mm CW at the fishing time if the natural mortality of males assumed for the terminal molt model was correct. That is not consistent with the policies of the Board for maintaining stocks of multiple sizes and ages of mature crabs to sustain reproductive viability and to reduce industrial dependency on annual recruitment (ADF&G 1998).

The high natural mortality rate for mature males assumed for the terminal molt model is questionable and biologically difficult to justify (Zheng 2001). Estimated natural mortality for mature female snow crabs and assumed natural mortality for all immature crabs was much lower than the assumed natural mortality for mature males with the terminal molt model. It is not clear why natural mortality would increase sharply at maturity for males, but not for females. Estimated natural mortalities for female red king (*Paralithodes camtschaticus*) and Tanner crabs are higher than those for male crabs (Zheng et al. 1995, 1998). Although terminal molt has been accepted for male snow crabs in Atlantic Canada, estimated natural mortality for those crabs does not increase substantially at maturity (E. Wade, Gulf Fisheries Centre, DFO, Canada, pers. comm.). Furthermore, during the last three years when harvest rates in the EBS were relatively low, the area-swept estimates of large male snow crab abundance in the EBS were steady with a high proportion of oldshell crabs, which was not consistent with high natural mortality. High natural mortality was assumed for mature males with the terminal molt model to reduce the systematic errors of fitting the survey data. Without assuming high natural mortality, the systematic errors were too high to use the terminal molt model.

Unreasonable high natural mortality for mature males with the terminal molt model does not mean terminal molt does not exist. Other errors can affect the parameter estimates and performance of the terminal molt model greatly. Small immature and mature male crabs in the EBS were highly overlapping in the CW-chela height plots (Otto 1998), and hardly any visible separation could be detected between these two groups for crabs <80 mm CW for a given year. Abundances of small immature males were much higher than those of small mature males. So for a given percentage (of abundance) in classification error, a lot more immature crabs will be wrongly classified as mature crabs than those mature crabs that are wrongly classified as immature crabs. Due to the overlap and difference in abundance, classification errors could artificially inflate estimates of small newshell mature males, which would cause higher estimates of natural mortality and lower estimates of survey catchability. If immature males were classified as mature, these wrongly classified "mature males" would molt even if there is a terminal molt for true mature males. Errors in classifying shell condition could also greatly affect natural mortality estimates with the terminal molt model. The survey data of two large snow crab stocks in Canada, the southwestern Gulf of St. Lawrence and Newfoundland, for which terminal molt for mature males has been accepted, clearly show separation of immature and mature males in the CW-chela height plots (E. Wade, Gulf Fisheries Centre, DFO, Canada and E. Dawe, DFO, St. John's, Newfoundland, Canada, pers. comm.). A brief look at Canadian data also indicates that the occurrence of large newshell mature males tracks better in multiple years of data than in our data from the EBS.

In summary, terminal molt for mature male snow crabs in the EBS is still an unanswered question, and the performance of the terminal molt model is very sensitive to classification errors of mature males. The terminal molt assessment model shows poor performance in both data fitting and simulations, requires a questionably high natural mortality rate for mature males, and imposes high risks of overfishing. Accordingly, we recommend use of the non-terminal molt model or area-swept estimates alone for stock assessment pending clarification of the terminal molt issue and its influence on stock assessment and population dynamics. Further research efforts will increase our understanding of the terminal molt issue, survey catchability, and natural mortality for mature males, and the assessment model will be improved accordingly. Area-swept estimates of population abundance should be used to determine the GHL for the fishery in 2003, and the LBA should be tested in 2003 and be used to assess the stock and determine GHLs for later years.

RECOMMENDED HARVEST STRATEGY

Our analyses of population dynamics and harvest strategies lead us to recommend three changes to the current harvest strategy for EBS snow crabs. First, we suggest replacing the current 50% cap with a 58% harvest rate on exploitable legal males. Second, we propose a cap on exploitation rates of mature male biomass as a linear function of total mature biomass. Currently, the exploitation rates of mature male biomass are a mixture of a step and linear function of total mature biomass. Finally, we recommend a flexible percentage of oldshell selectivity to compute GHLs versus the current 25% that is set in regulation. This percentage will be determined by the historical fishery selectivity and will be updated each year. These changes will result in higher harvest rates than the current rates when the stock abundance is high during high productivity periods and maintain low exploitation rates on mature male biomass for stock rebuilding when the population is depressed. Like the status quo strategy, area-swept equivalent abundances and biomasses should be used to determine GHLs. There are four components for the recommended strategy:

- **Threshold**: 25% of B_{msy}. The current B_{msy} is 921.6 million pounds of total female and male mature biomass. The fishery will be closed when the stock is below threshold.
- **A harvest rate on exploitable legal males**: 58% of exploitable legal males, which are defined as 100% of newshell and a percentage of oldshell males ≥102 mm CW estimated at the time of the survey. The percentage for oldshell males is based on the fishery selectivity for oldshell versus newshell males. The current value for the oldshell selectivity is 25% and can be changed when the fishery selectivity changes.

- **Exploitation rate cap on mature male biomass**:
  - 75% of F_{msy} (currently 0.75*0.3=22.5%) when total mature biomass is at or above B_{msy};
  - 0% when total mature biomass is below 25% of B_{msy}, or threshold; and
  - a linear function from one third of F_{msy} (currently 1/3*0.3=10%) when total mature biomass is 25% of B_{msy} to 75% of F_{msy} when mature biomass is at B_{msy}, as described by the equation:

    $$[F_{msy}/3+(B_t-0.25*B_{msy})*0.417*F_{msy}/(0.75*B_{msy})]*100\%,$$

    when $0.25*B_{msy} \leq B_t < B_{msy}$, where B_t is total mature biomass in year t in million pounds.
- **Minimum GHL**: 25 million pounds. This minimum GHL for fishery opening is established to maintain fishery manageability. The minimum GHL can be lowered if measures such as pot limits are lowered to increase the fishery manageability when the estimated stock size is low.

In comparison to the current harvest strategy, the recommended strategy has a slightly higher mean yield, higher trade-off values between mean yield and variation in yield, a similar probability of fishery closure, and slightly lower mean mature biomass. By maintaining the fishery threshold and variable exploitation rate caps on mature male biomass, the recommended new harvest strategy has the same features as the current one: consistent with the Board policy to maintain adequate brood stock to rebuild the population when it is depressed and embodying a precautionary approach to fishery management in accordance with National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act (Restrepo et al. 1998). The recommended harvest strategy also takes into account the relationship between shell condition and productivity levels of the snow crab stock. Strong year classes are dominated by newshell crabs. Applying a harvest rate to exploitable legal males, as opposed to all males ≥102 mm CW, adjusts overall harvest rates on total large males according to recruitment strength as indexed by changes in shell condition. Use of 100% newshell and a percentage of oldshell males to determine GHLs according to the fishing selectivity, just as use of 4" (industry preference) rather than 3.1" (legal limit) CW crabs to set GHLs, is also a conservative measure that prevents depleting all large newshell crabs each year during a low recruitment period.

Among the uncertainties in the EBS snow crab population dynamics, the most important ones that affect the harvest strategy are recruitment dynamics and reproductive biology. In our computer simulations, we assumed the past recruitment patterns would repeat and set recruitment periodicity randomly from 4 to 13 years. If this assumption does not hold and periods of poor recruitment last much longer than we expect, our results will not hold and not even fishery closures can protect the stock from collapse or rebuild it. Also due to periodic recruitment, it appears that no harvest strategies can maintain a stable population. However, reducing overall harvest rates and saving some mature crabs for future spawning when recruitment is in the downward cycle will reduce the chance of prolonged stock collapse.

LITERATURE CITED

Alaska Department of Fish and Game (ADF&G). 1998. Commercial shellfish fishing regulations, 1998-1999 edition. Alaska Dept. Fish and Game, Juneau, Alaska.

Alunno-Bruscia, M., and B. Sainte-Marie. 1998. Abdomen allometry, ovary development, and growth of female snow crab, *Chionoecetes opilio* (Brachyura, Majidae), in the northwestern Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. 55: 459-477.

Conan, G.Y., and M. Comeau. 1986. Functional maturity and terminal molt of male snow crabs, *Chionoecetes opilio*. Can. J. Fish. Aquat. Sci. 43: 1710-1719.

Conan, G.Y., R.W. Elner, and M. Moriyasu. 1990. Review of literature on life histories in the genus *Chionoecetes* in light of the recent findings on growth and maturity of *C. opilio* in Eastern Canada. *In* Proceedings of the International Symposium on King and Tanner Crabs. Alaska Sea Grant College Prog. Rep. 90-04. pp.163-179.

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

Hartnoll, R.G. 1963. The biology of Manx spider crabs. Proc. Zool. Soc. Lond. 141: 423-496.

Jamieson, G.S., R. Bailey, G. Conan, R. Elner, W. McKone, and D. Taylor. 1988. Workshop summary. *In* Proceedings of the International Workshop on Snow Crab Biology. *Edited by* G.S. Jamieson and W.D. McKone. Can. MS Rep. Fish. Aquat. Sci. 2005. pp. viii-xii.

Moriyasu, M., and C. Lanteigne. 1998. Embryo development and reproductive cycle of snow crab, *Chionoecetes opilio*, (Crustacea: Majidae) in the southern Gulf of St. Lawrence, Canada. Can. J. Zool. 76(11): 2040-2048.

Morrison, R. 1999. Bering Sea snow crab fishery, 1998: report to the Alaska Board of Fisheries. Alaska Dept. Fish and Game, Reg. Inf. Rep. 4K99-11, Kodiak.

National Marine Fisheries Service (NMFS). 1996. Magnuson-Stevens Fishery Conservation and Management Act as amended through October 11, 1996. National Marine Fisheries Service, NOAA Tech. Memo. NMFS-F/SPO-23.

North Pacific Fishery Management Coucil (NPFMC). 1996. Additional analysis for Amendment 37 (Bristol Bay red king crab savings area) and an environmental assessment/regulatory impact review/initial regulatory flexibility analysis for Amendment 41: Management of red king crab, Tanner crab, and snow crab bycatch limits in Bering Sea groundfish trawl fisheries and establishment of a trawl closure area in nearshore waters of Bristol Bay. A proposed amendment to the Fishery Management Plan for the groundfish fishery of the Bering Sea and Aleutian Islands. North Pacific Fishery Management Council, Anchorage.

North Pacific Fishery Management Coucil (NPFMC). 1998. Fishery Management Plan for Bering Sea/Aleutian Islands King and Tanner Crabs. North Pacific Fishery Management Council, Anchorage.

Otto, R.S. 1990. An overview of eastern Bering Sea king and Tanner crab fisheries. *In* Proceedings of the International Symposium on King and Tanner Crabs. Alaska Sea Grant College Prog. Rep. 90-04. pp. 9-26.

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

Paul. A.J. 1984. Mating frequency and viability of stored sperm in the Tanner crab *Chionoecetes bairdi* (Decapoda, Majidae). J. Crust. Biol. 4: 375-381.

Restrepo, V.R., G.G. Thompson, P.M. Mace, W.L. Gabriel, L.L. Low, A.D. MacCall, R.D. Methot, J.E. Powers, B.L. Taylor, P.R. Wade, and J.F. Witzig. 1998. Technical guidance on the use of precautionary approaches to implementing national standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act. NOAA Tech. Memo. NMFS-F/SPO-31.

Rondeau, A., and B. Sainte-Marie. 2001. Variable mate guarding time and sperm allocation by male snow crabs (*Chionoecetes opilio*) in response to sexual competition, and their impact on the mating success of females. Biological Bulletin vol. 200. In press.

Rugolo, L.J., J.A. Haaga, and R.A. MacIntosh. 2001. Report to industry on the 2001 eastern Bering Sea crab survey. Alaska Fisheries Science Center, Processed Rep. 2001-07. National Marine Fisheries Service, National Oceanic and Atmospheric Administration, P.O. Box 1638, Kodiak, AK 99615, USA.

Sainte-Marie, B. 1993. Reproductive cycle and fecundity of primiparous and multiparous female snow crab, *Chionoecetes opilio*, in the Northwest Gulf of Saint Lawrence.

Can. J. Fish. Aquat. Sci. 50: 2147-2156.

Sainte-Marie, B., and C. Carrière. 1995. Fertilization of the second clutch of eggs of snow crab, *Chionoecetes opilio*, from females mated once or twice after their molt to maturity. Fish. Bull. (U.S.) 93(4): 759-764.

Sainte-Marie, B., and G.A. Lovrich. 1994. Delivery and storage of sperm at first mating of female *Chionoecetes opilio* (Brachyura: Majidae) in relation to size and morphometric maturity of male parent. J. Crustacean Biol. 14(3): 508-521.

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

Sainte-Marie, B., J-M Sévigny, B.D. Smith, and G.A. Lovrich. 1996. Recruitment variability in snow crab (*Chionoecetes opilio*): pattern, possible causes, and implications for fishery management. *In* High latitude crabs: Biology, anagement, and economics. University of Alaska Fairbanks, Alaska Sea Grant College Prog. Report 96-02. pp. 451-478.

Somerton, D.A. 1980. A computer technique for estimating the size of sexual maturity in crabs. Can. J. Fish. Aquat. Sci. 37: 1488-1494.

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

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

Turnock, J. 2001. Bering Sea snow crab. Manuscript.

Urbani, N., B. Saint-Marie, J.-M. Sévigny, D. Zadworny, and U. Kuhnlein. 1998. Sperm competition and paternity assurance during the first breeding period of female snow crab (*Chionoecetes opilio* (Brachyura: Majidae). Can. J. Fish. Aquat. Sci. 55: 1104-1113.

Wolotira, R.J., Jr., T.M. Sample, and M. Morin, Jr. 1977. Demersal fish and shellfish resources of Norton Sound, the southeastern Chukchi Sea, and adjacent waters in the baseline year 1976. U.S. Dep. Comm., NOAA, NMFS, Northwest and Alaska Fisheries Center, Washington, Processed Rep.

Zheng, J. 2001. Uncertainties of natural mortality estimates for eastern Bering Sea snow crab, *Chionoecetes opilio*. Manuscript.

Zheng, J., G.H. Kruse, and M.C. Murphy. 1998. A length-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: 97-105.

Zheng, J., G.H. Kruse, and D.R. Ackley. 2001. Spatial distribution and recruitment patterns of snow crabs in the eastern Bering Sea. Pages 233-255 G.H. Kruse, N. Bez, A. Booth, M.W. Dorn, S. Hills, R.N. Lipcius, D. Pelletier, C. Roy, S.J. Smith, and D. Witherel (eds.). Spatial processes and management of fish populations. University of Alaska Sea Grant, AK-SG-01-02, Fairbanks.

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

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

Table 1. Comparisons of fishery performance for alternative harvest strategies with the non-terminal molt model. Shown are mean yield, standard deviation of yield (SD), equal trade-off between increase in mean yield and decrease in standard deviation of yield, mean mature biomass at the end of February (SB1), mean mature biomass at the time of summer survey (SB2), percentage of years without fishing (Closure), and percentages of years with mature biomass below B_{msy} and MSST. "#" is strategy number described in the section of "Alternative Harvest Strategies" with "2a" being the sensitivity study for strategy 2, "Oldshell Select." is the proportion of oldshell males used to compute GHLs, "HR" is harvest rate on exploitable legal males ≥102 mm CW, "Max Cap" is the maximum exploitation rate cap on mature male biomass, and "HM" is handling mortality rate. The status quo strategy (#3) is underlined, and the proposed new strategy (#2) is in bold. Changes in parameter values for strategy 2 are shaded.

#	Oldshell Select.	HR	Max Cap	Min GHL	HM	Yield (million lbs)	SD (million lbs)	Trade-off	SB1 (million lbs)	SB2 (million lbs)	Closure (%)	<B_{msy} (%)	<MSST (%)
3	0.25	0.50	0.225	25	0.25	110.17	90.66	9.76	643.4	980.7	6.9	56.3	20.3
2	**0.25**	**0.58**	**0.225**	**25**	**0.25**	**113.12**	**91.82**	**10.65**	**625.1**	**960.2**	**6.8**	**57.6**	**20.6**
2a	0.30	0.58	0.225	25	0.25	113.18	91.79	10.69	624.1	959.0	6.8	57.7	20.6
2a	0.50	0.58	0.225	25	0.25	113.33	91.66	10.83	620.5	954.4	7.0	58.0	20.8
2a	0.25	0.58	0.225	15	0.25	112.62	90.58	11.02	617.9	950.1	1.7	58.3	21.5
2a	0.25	0.58	0.225	20	0.25	112.88	91.04	10.92	620.8	954.3	3.8	58.0	21.1
2a	0.25	0.58	0.225	25	0.00	118.93	95.56	11.68	643.6	983.9	6.3	56.0	19.7
2a	0.25	0.58	0.225	25	0.50	107.45	88.14	9.66	607.1	936.8	7.3	59.4	21.6
2a	0.25	0.55	0.225	25	0.25	112.40	91.69	10.36	630.8	966.7	6.7	57.3	20.4
2a	0.25	0.60	0.225	25	0.25	113.53	91.85	10.84	621.7	956.2	6.8	57.9	20.7
2a	0.25	0.65	0.225	25	0.25	114.31	91.78	11.27	614.0	947.2	7.0	58.5	21.0
2a	0.25	0.58	0.200	25	0.25	110.04	85.50	12.27	645.1	982.8	6.8	55.7	19.5
2a	0.25	0.58	0.250	25	0.25	115.16	96.98	9.09	608.8	941.3	6.8	59.3	21.6
4	1.00	0.58	NA	25	0.25	114.34	100.07	7.13	501.4	798.9	5.5	69.3	34.2

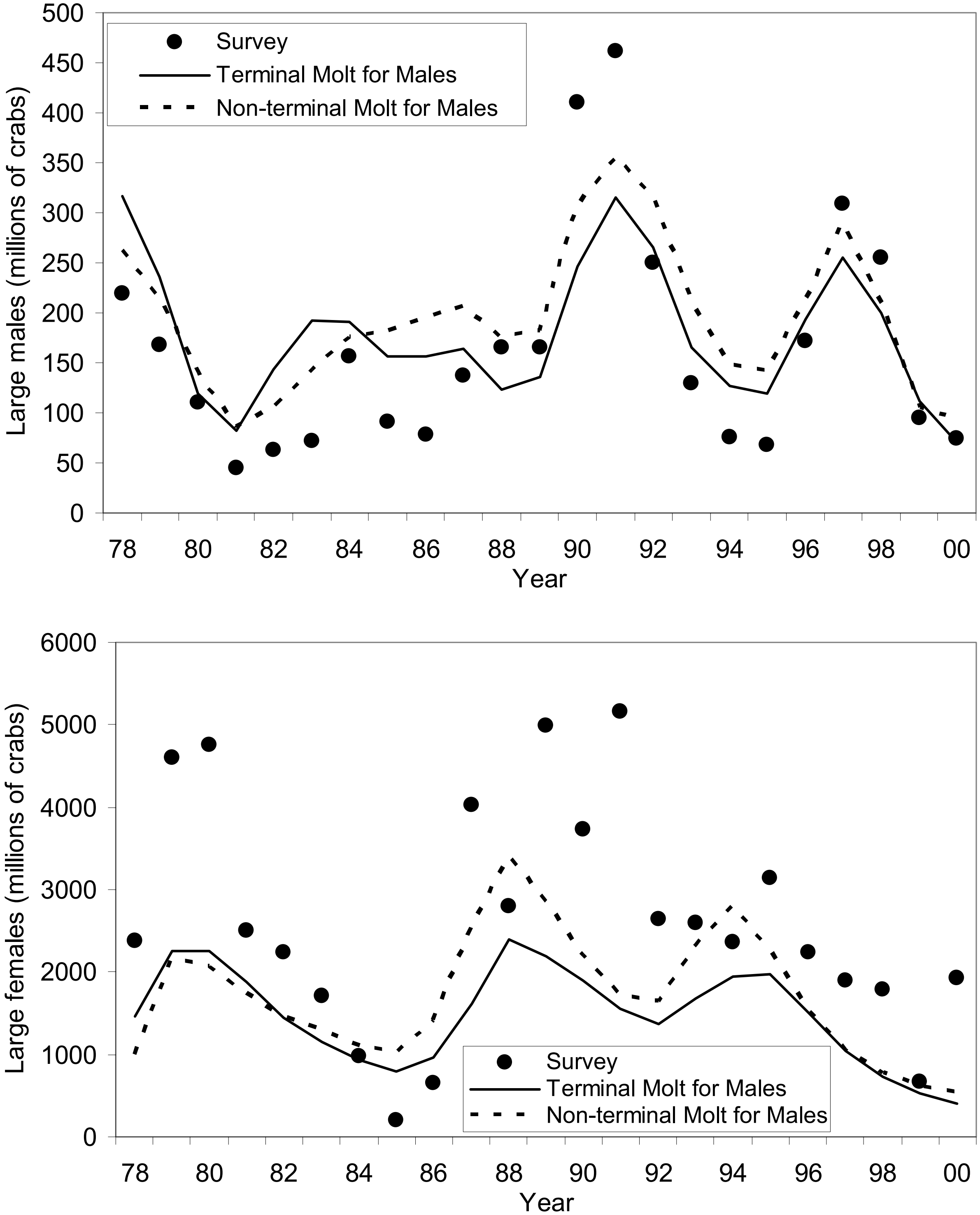

Figure 1. Comparison of area-swept (dots) and catchability-adjusted LBA (solid and dotted lines) estimates of relative male (≥102 mm CW, top panel) and female (>45 mm CW, bottom panel) snow crab abundances in the eastern Bering Sea.

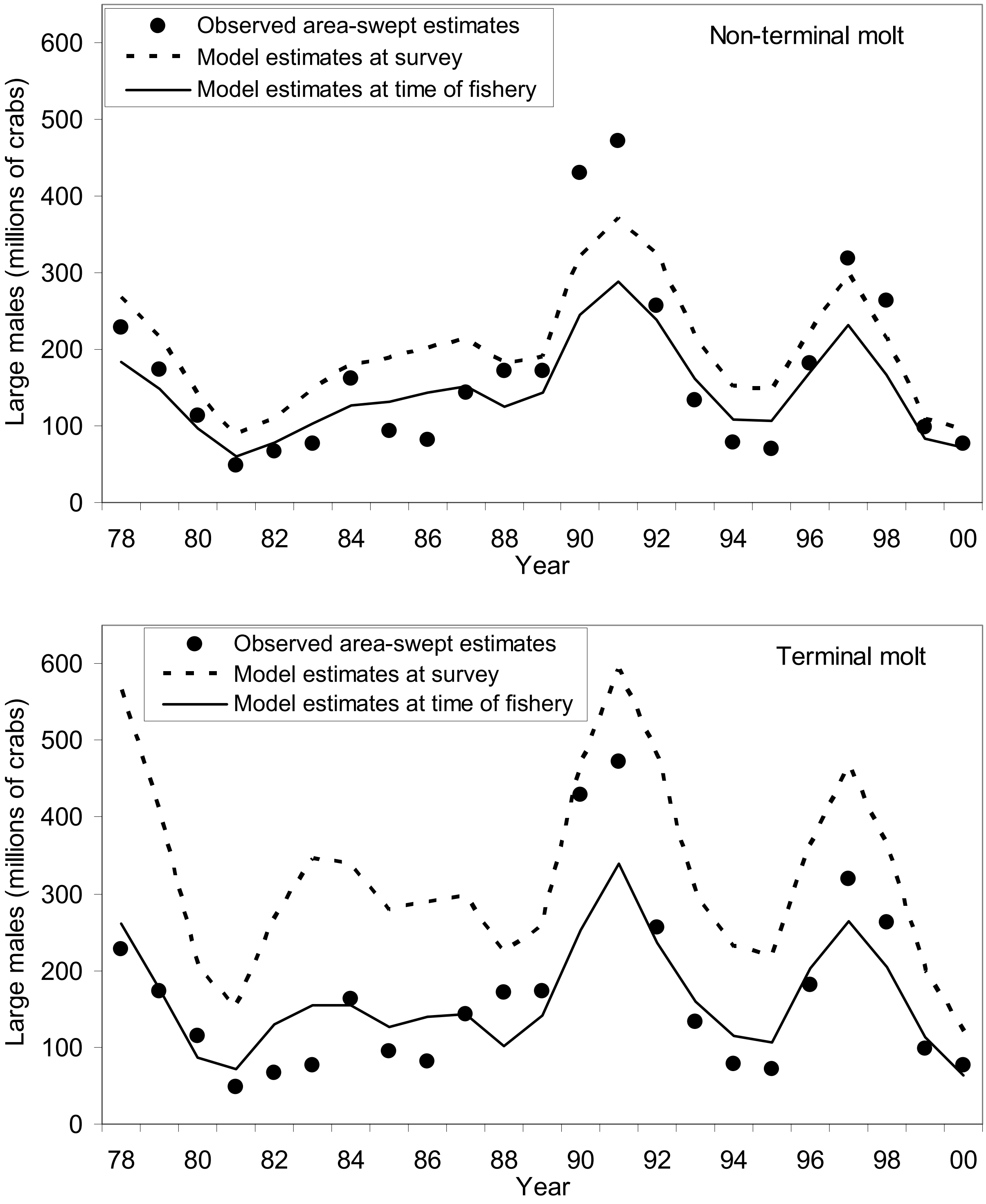

Figure 2. Non-terminal molt (top panel) and terminal molt model (bottom panel) population estimates of male eastern Bering Sea snow crabs ≥102 mm CW at the time of the NMFS trawl survey and of those remaining at the time of the fishery after about 7 months of natural mortality as compared to area-swept estimates from the survey data.

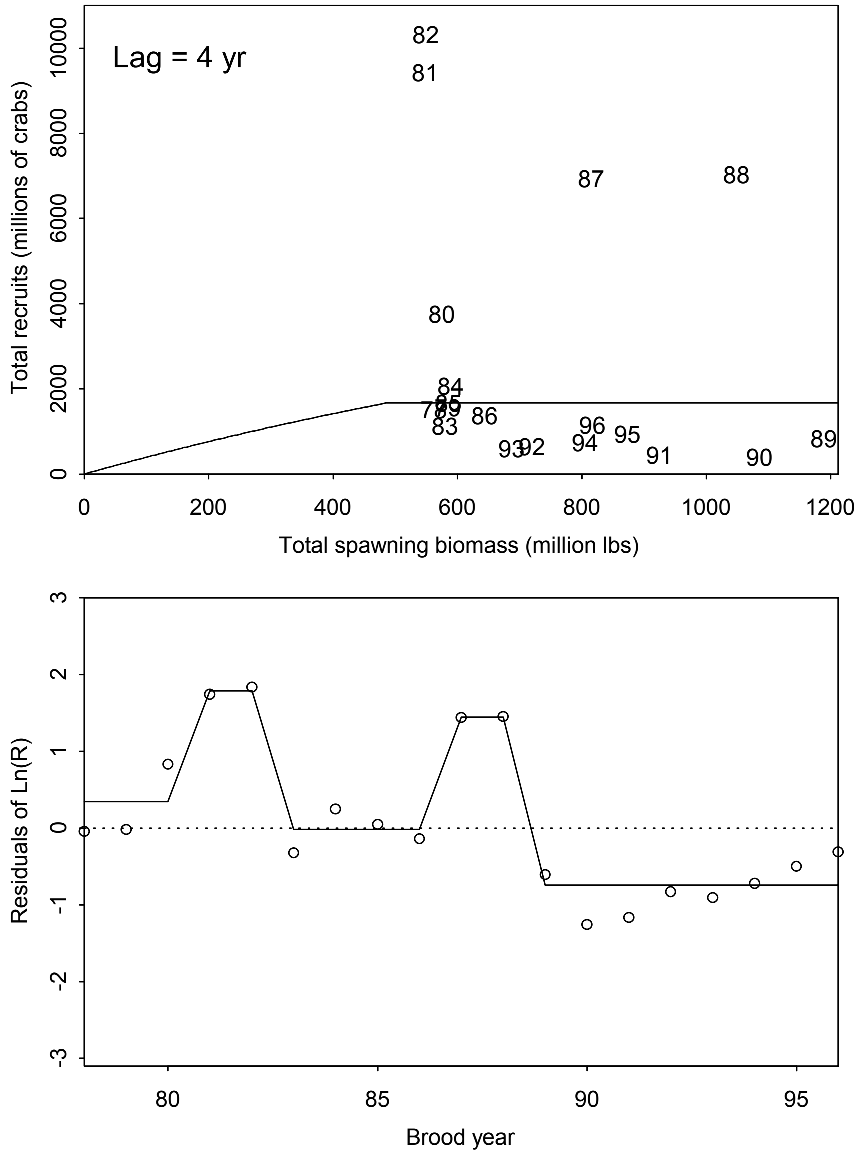

Figure 3. Relationship between total spawning biomass and total recruits at age 3 (i.e., 4-year time lag; top panel) and residuals of logarithm of recruits for eastern Bering Sea snow crabs without the terminal molt assumption. In the top panel, numerical labels are brood year (year of mating), and the solid line is a suggested curve. In the bottom panel, the solid line represents alternation of high and low recruitment patterns.

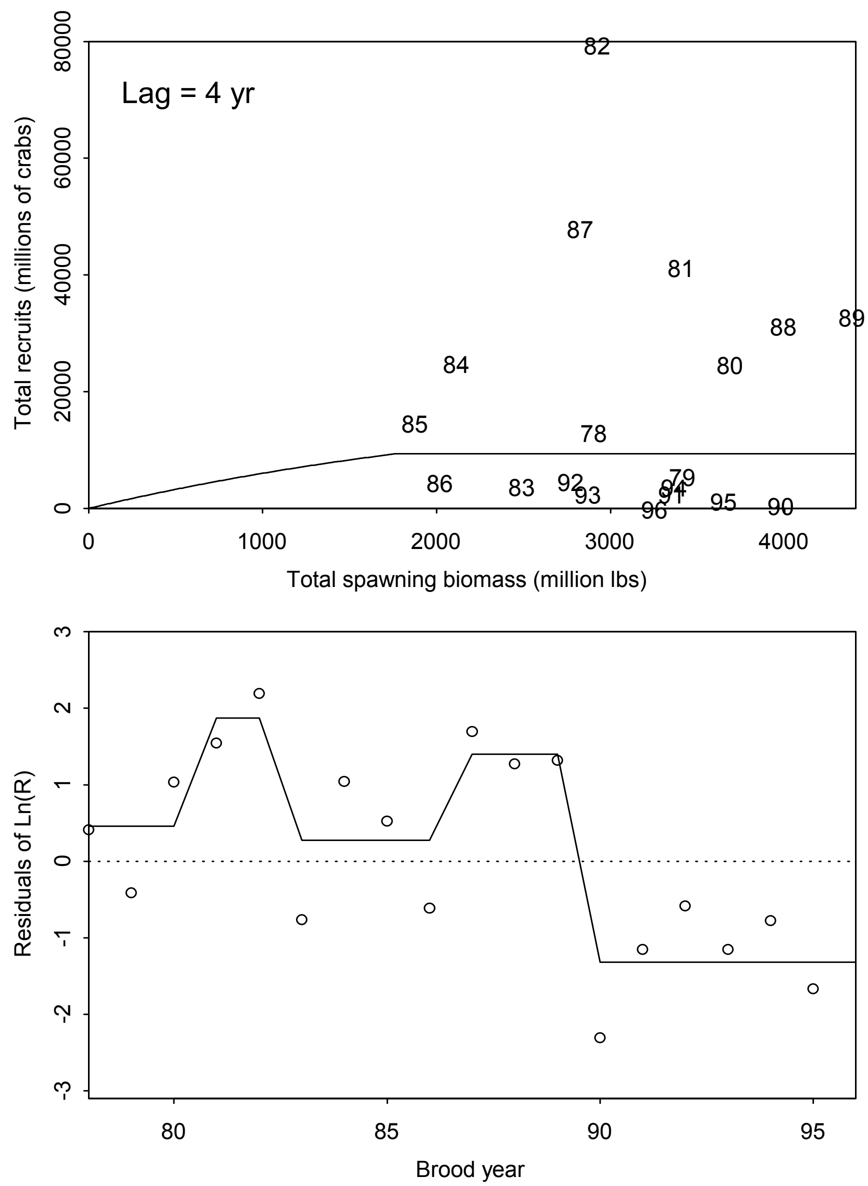

Figure 4. Relationship between total spawning biomass and total recruits at age 3 (i.e., 4-year time lag; top panel) and residuals of logarithm of recruits for eastern Bering Sea snow crabs with the terminal molt assumption. In the top panel, numerical labels are brood year (year of mating), and the solid line is a suggested curve. In the bottom panel, the solid line represents alternation of high and low recruitment patterns.

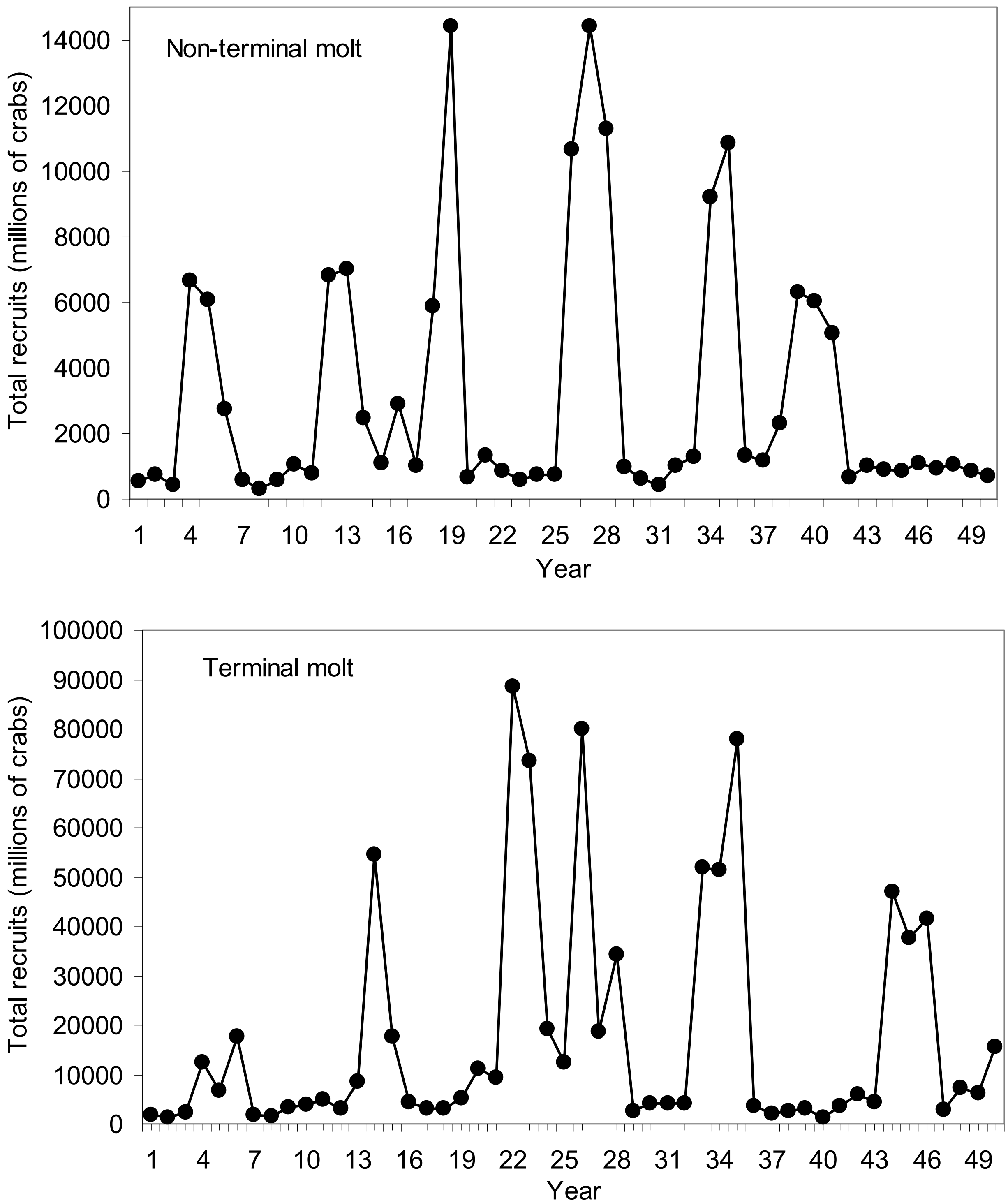

Figure 5. Examples of total recruits generated for one of 2000 replicates for a 50-year period. Top panel is for the non-terminal molt model, and bottom panel is for the terminal molt model.

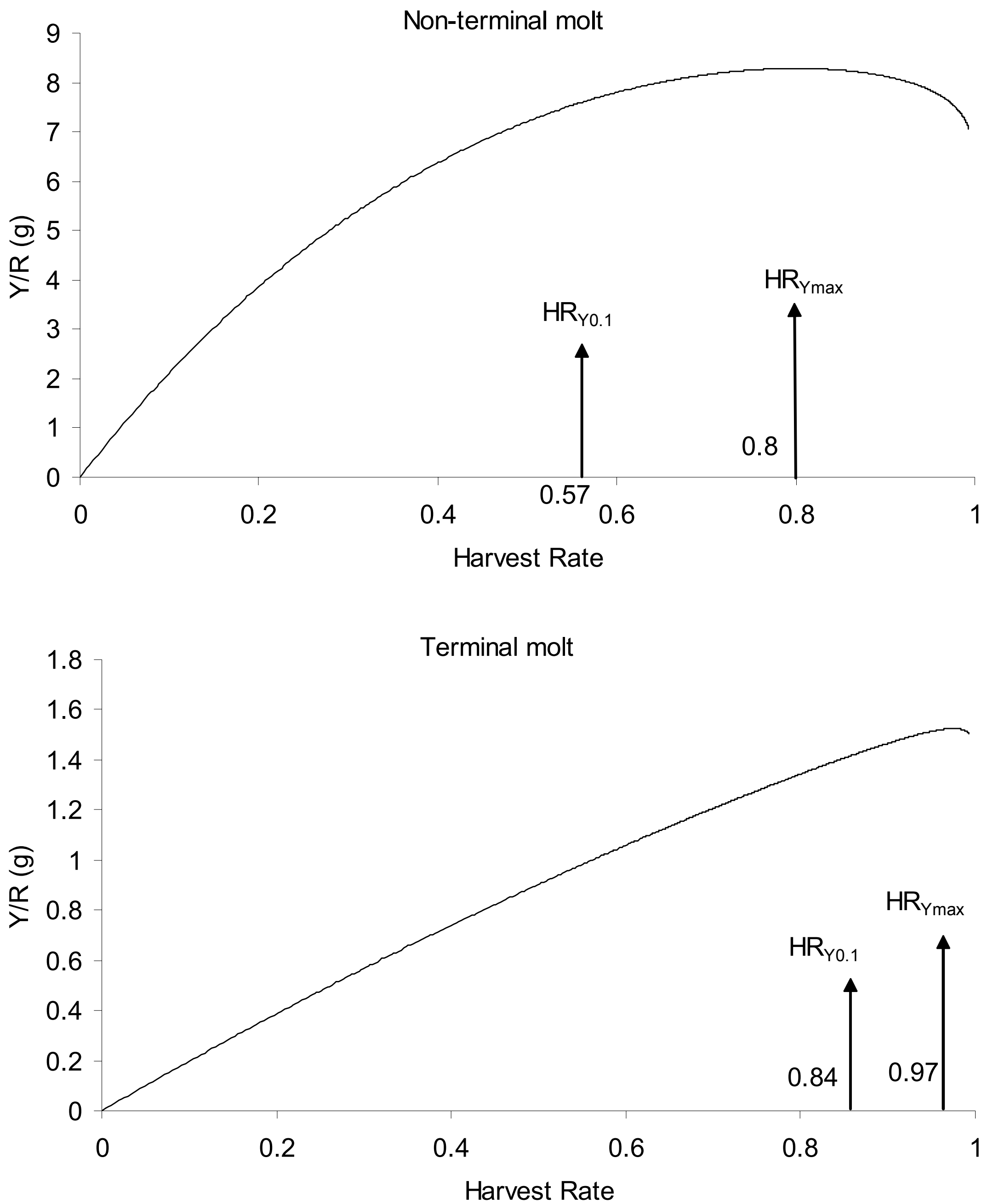

Figure 6. Yield per recruit (Y/R) as a function of fishery harvest rate for eastern Bering Sea snow crabs. Top panel is for the non-terminal molt model, and bottom panel is for the terminal molt model.

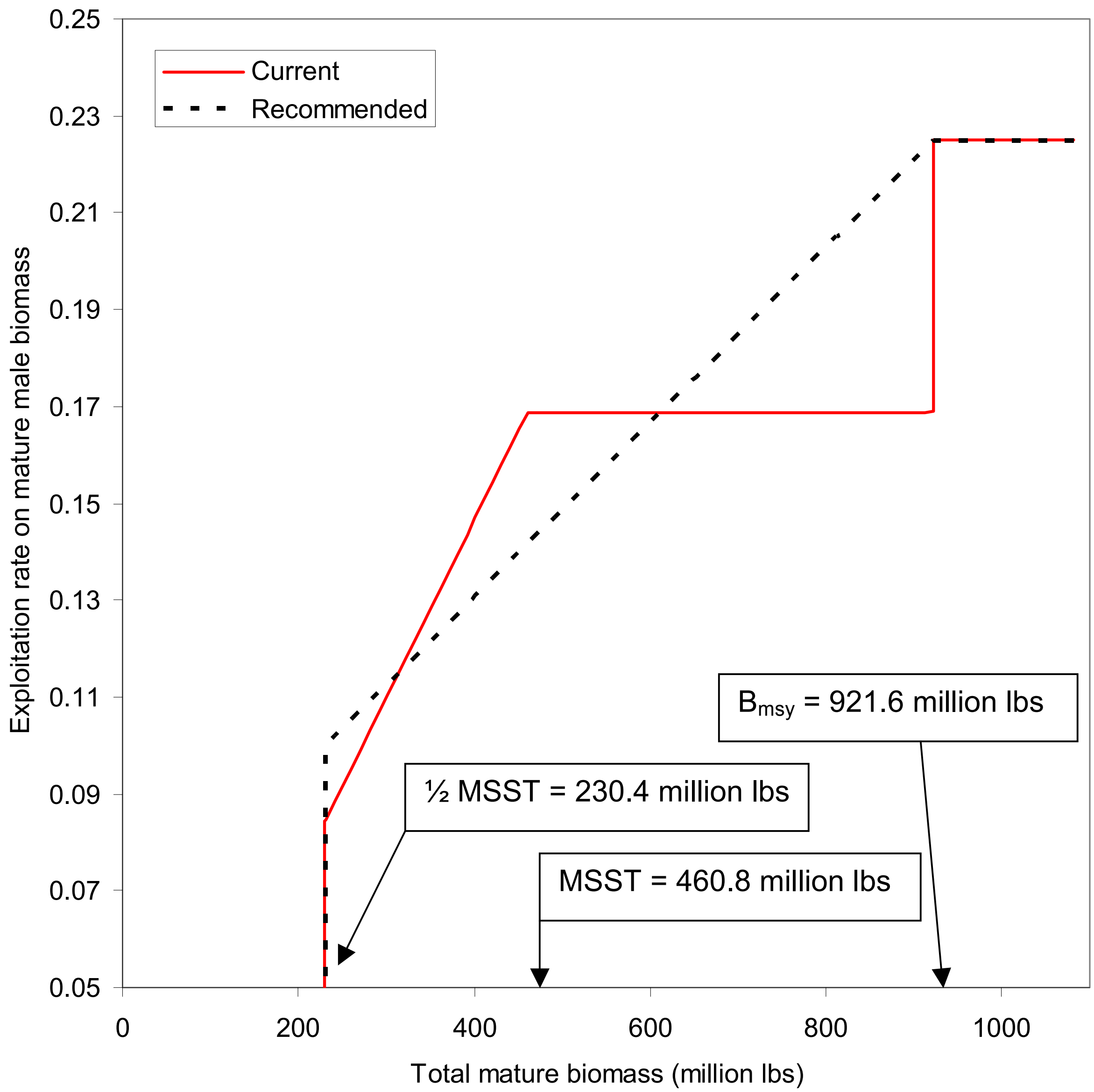

Figure 7. Comparison of current mature exploitation rates and recommended mature exploitation rate caps as a function of total mature biomass for eastern Bering Sea snow crabs.

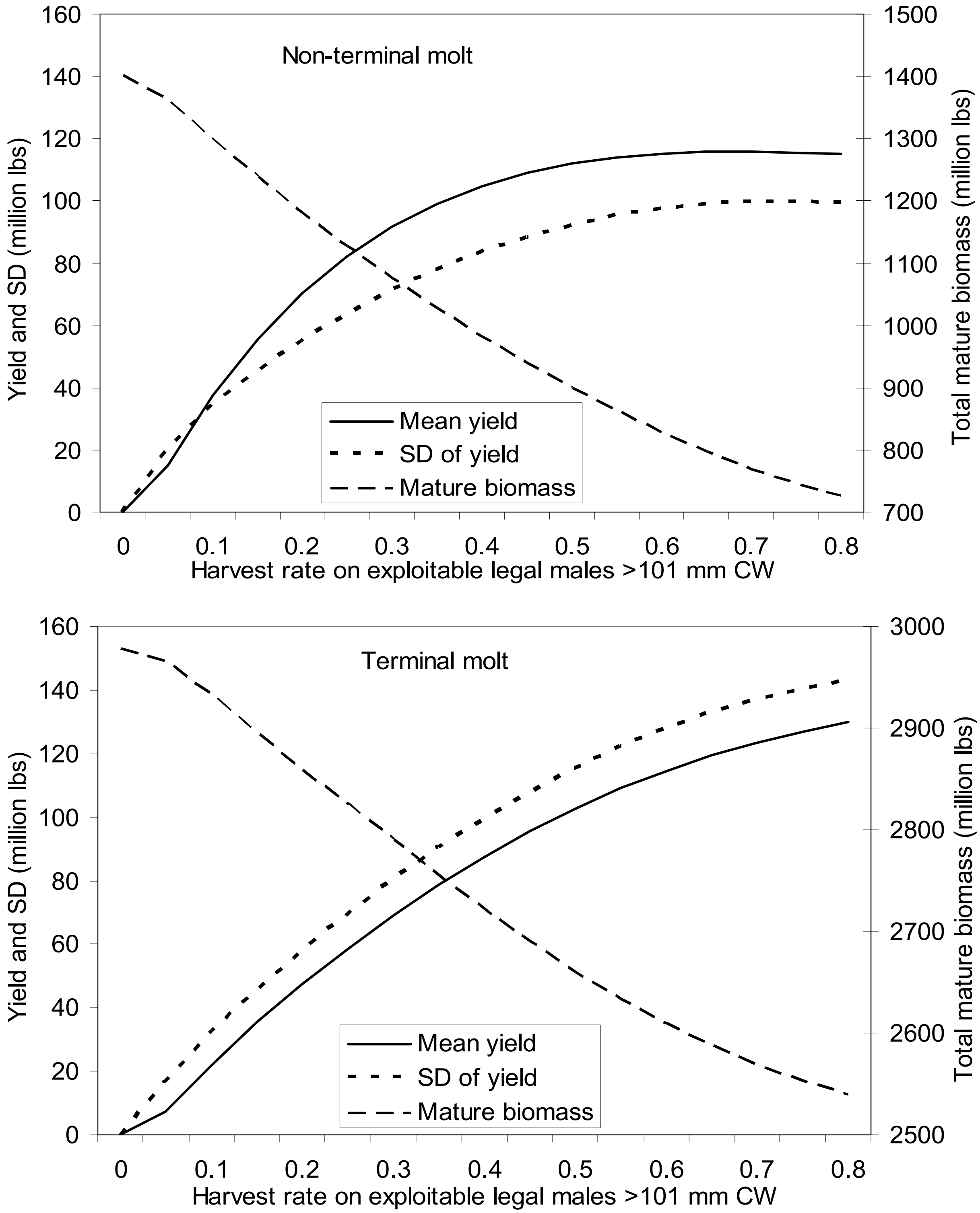

Figure 8. Mean yield (solid lines), standard deviation of yield (dotted lines), and mean mature biomass (dashed lines) as a function of constant harvest rate for eastern Bering Sea snow crabs with and without the terminal molt assumption.