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EXECUTIVE SUMMARY

Due to periodic recruitment, Tanner crab (*Chionoecetes bairdi*) abundance in Alaska fluctuates widely. Currently, most Tanner crab fisheries are closed due to low population levels. Managing Tanner crab fisheries to produce relatively high stable yield with a minimum chance of stock collapses presents a great challenge. In order to evaluate the current harvest strategy against alternative strategies for eastern Bering Sea (EBS) Tanner crabs, we need to understand their population dynamics. We constructed a size-based model to improve population estimates of Bristol Bay Tanner crabs. We also investigated the controversial hypothesis of terminal molt for male Tanner crabs, an issue having great implications for management. We rejected the terminal-molt hypothesis statistically as it failed to provide the most consistent interpretation of field-collected data on size, shell condition, and claw size of the Tanner crab population in Bristol Bay during 1990-1997. Molting probability of male Tanner crabs declines sharply once large claw is obtained, but a large majority of sublegal crabs can grow to legal size. Recruitment is periodic or cyclic for Bristol Bay Tanner crabs, resulting in a weak density-dependent stock-recruitment relationship in which recruitment is only loosely related to parental abundance levels. Computer simulations with a size-based model show that the yield curve is relatively insensitive to high harvest rates and that no harvest strategy can prevent stock collapse when recruitment fluctuates dramatically with long periodicity and high amplitude. A conservative strategy reduces the probability of stock collapse, however. We recommend a new harvest strategy for the EBS Tanner crab stock that is stair-stepped at 0, 10% or 20% of molting mature males (100% of newshell and 15% of oldshell males >112 mm (4.4 in) carapace width (CW)) depending on whether the biomass of females >79 mm CW is <21.0 million lbs, ≥21.0 and <45.0 million lbs, or ≥45.0 million lbs. The strategy also includes a 50% cap on harvest rate for exploitable legal crabs (100% of newshell and 32% of oldshell males >137 mm CW (5.5 in)). Guideline harvest levels (GHL) are determined separately for crabs in areas east of 168°W (Bristol Bay) and west of 168°W (Pribilof Islands) in the Eastern Subdistrict. Total GHL in the Eastern Subdistrict is equal to the sum of these two GHLs. The recommended strategy adjusts legal harvest rates according to changes in stock productivity indexed by recruitment strength: high legal harvest rates during the upward recruitment cycle and low rates that protect large-sized crabs and reproductive potential during the downward recruitment cycle. As compared to the current harvest strategy, the recommended new strategy is easily implemented, has similar trade-offs between high mean yield and relatively low variation in yield while increasing fishing opportunities (few years of closed fisheries) and reducing probabilities of being at overfished levels.

PURPOSE

The purpose of this report is to provide the basis for proposed new harvest strategies for Tanner crab fisheries in Alaska. We provide a brief history of the fisheries, 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 Tanner crabs in the Bristol Bay portion of the EBS: (1) a length (size)-based analysis (LBA) of population changes over time; (2) an analysis of terminal molt – that is, the hypothesis that male crabs stop molting once they reach maturity; (3) stock-recruit (S-R) relationships; and (4) an evaluation of alternative management strategies based on the Tanner crab population dynamics. Finally, our combined analyses led us to propose a new harvest strategy for Tanner crabs in Bristol Bay. We extended these results to Tanner crabs in the EBS and provided a framework to apply our findings and recommendations to Tanner crab stocks in the Gulf of Alaska.

HISTORY OF FISHERIES

Tanner crabs widely distribute in the waters off Alaska, extending as north as Norton Sound and as south as Southeast Alaska. The stocks used to support some of the most important fisheries in Alaska. The fisheries have followed a boom and bust cycle. In the EBS, Tanner crabs were first targeted by Japanese and Russian fleets in 1965. The EBS fishery expanded quickly in the late 1960s, and the catch reached 53 million lbs in 1968. Foreign fishing for Tanner crabs has been prohibited under the Magnuson Fisheries Conservation and Management Act since 1980. Directed fisheries for EBS Tanner crabs by the U.S. fleet began in 1974. Catch peaked in 1978 at 69 million lbs (Otto 1990). The EBS population collapsed in the mid-1980s, and no fishing was allowed in 1986 and 1987. During 1990-1993, catches averaged 33 million lbs and annual ex-vessel values averaged US$46 million. Catches dropped sharply after 1993, and the EBS fishery has been closed since 1997 due to the depressed stock condition.

MANAGEMENT GOAL AND MEASURES

An optimal harvest strategy for any fishery resource depends on fishery management goals. In March 1990 the Alaska Board of Fisheries (Board) adopted a fishery management policy for king and Tanner crabs (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 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.

Current size-sex-season measures, i.e., harvest of only large males and no fishing during spring molting and mating periods, are consistent with these policies. The size-sex-season 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 138 mm (without spines, commercial measurement with spines is 140 mm, 5.5 in) CW is used for Tanner crab fisheries statewide with the exception of Prince William Sound where it is 135 mm (5.3 in) CW. A constant harvest rate strategy is also used to set GHL where abundance estimates are available. For example, for the EBS stock, a harvest rate of 40% is currently applied to the abundance of legal-sized male crabs. Optimal harvest rates have not formally been evaluated for any Tanner crab stocks in Alaska. The Board's policy on king and Tanner crab management provides specific criteria under which alternative harvest strategies can be evaluated. The Maguson-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."

PROBLEMS AND APPROACHES

Tanner crab fishery management is facing a great challenge, and some changes in strategies are needed for several reasons. First, with an exception of a small fishery in Southeast Alaska, all other Tanner crab fisheries in Alaska are currently closed due to depressed stocks. The EBS stock was recently classified as "overfished" by the North Pacific Fishery Management Council (NPFMC 1998). According to the Magnuson-Stevens Fishery Conservation and Management Act (NMFS 1996), a rebuilding plan is needed to rebuild an overfished stock. Second, low stocks aren't necessarily managed more conservatively because the current 40% rate is fixed regardless of stock size provided that the fishery is open. Alternative harvest rates, including reduced rates at low stock sizes, need to be evaluated. Third, GHLs on low stocks often exceed the actual catch because low abundance and the predominance of oldshell crabs lead to poor fishery performance. Finally, although the fishery has been closed from time to time, the current harvest policy does not formally specify fishery thresholds.

To address these problems, ADF&G proposes to revise the harvest strategy for the directed EBS Tanner crab fishery as part of a joint Board-Council effort to rebuild this depressed stock. The Council leads other parts of the rebuilding effort that may include redesign of trawl closure areas and bycatch cap revision on groundfish fisheries. ADF&G's proposed new harvest strategy is based on detailed analyses of Tanner crabs in the Bristol Bay portion of the EBS. The results of our analyses of Bristol Bay Tanner crabs can be extended to the whole EBS with implications to the Gulf of Alaska stocks.

We selected Bristol Bay for study because the longest and most complete data sets were available and because this area supported the most valuable Tanner crab fishery in Alaska. Also, a large majority of mature EBS Tanner crabs are in Bristol Bay. We distinguished Bristol Bay Tanner crabs from those around the Pribilof Islands because there are statistically significant genetic differences between Tanner crabs in the two areas (Merkouris et al. 1997) and survey abundance data are more reliable for Bristol Bay. In addition, Somerton (1981) found an east-west cline of decreasing size at maturity in EBS female Tanner crabs, with the largest mean size of mature females occurring in eastern Bristol Bay. Although Tanner crabs in these two areas are not distinguished as separate stocks for management purposes, modeling Tanner crabs in Bristol Bay alone gives us more reliable results because of these differences.

ADF&G's proposed new harvest strategy is based on several analyses of the stock and fishery. We developed a LBA to improve abundance estimates of Bristol Bay Tanner crabs. The LBA was then modified to investigate a so-called "terminal-molt hypothesis" of male crabs. We also estimated the S-R relationships based on the results of LBA and from a review of literature on Tanner crab reproductive biology to understand the recruitment dynamics. Then, based on the results of the LBA, terminal molt, and S-R analyses, we conducted computer simulations to evaluate alternative harvest strategies for Bristol Bay Tanner crabs. Finally, we extended the simulation results on Bristol Bay Tanner crabs to EBS Tanner crabs and recommended a new harvest strategy. The technical details of our approaches are described in four scientific papers: LBA (Zheng et al. 1998), terminal molt (Zheng and Kruse MSb), S-R relationships (Zheng and Kruse MSa), and harvest strategies (Zheng and Kruse MSc). Copies of these papers are available upon request. An overview of these studies follows.

LENGTH-BASED ANALYSIS

Rationale to Develop the LBA

The annual trawl survey conducted by the National Marine Fisheries Service (NMFS) gathers essential data on the status of crab stocks in the EBS (Stevens et al. 1998). Yet, year-to-year changes in oceanographic conditions lead to changes in crab distributions and availability to survey gear. These changes may cause measurement errors that lead to unexpected shifts in area-swept abundance estimates unrelated to true changes in population size. Data from previous years' surveys and commercial catches provide valuable auxiliary information to help decipher real population changes from survey measurement errors. We developed the LBA (Zheng et al. 1998) to utilize these multiple years of data and multiple data sources to more accurately estimate abundance than using current-year survey data alone. The exact same motivation led to similar age-structured analyses for most important fish stocks off Alaska and elsewhere around the world.

Overview of the LBA

The LBA is an analytical procedure to estimate annual abundance of crab stocks for which extensive high-quality data are available. The LBA makes use of detailed annual data on size, sex, and shell condition from trawl surveys, onboard and dockside catch samples, and annual commercial harvests. Males and females are modeled separately by 5 mm CW intervals as newshell (i.e., those that molted within the past year) and oldshell crabs (i.e., those that have not molted within the past year). The annual abundance of crabs in each width group is a combined result of recruitment, growth, natural mortality, and harvest. Note that this is a size-based analysis, not an age-based analysis that is commonly used for fish stocks.

Comparison of LBA and Area-swept Estimates

LBA estimates of abundance fitted well with NMFS survey area-swept estimates of abundance over the history of the survey in Bristol Bay (Figure 1). Mature female (>79 mm CW) and male (>112 mm CW) abundances generally declined from the mid-1970s to the mid-1980s, increased sharply during the late 1980s, and decreased again in the early 1990s (Figure 1). Currently, Tanner crab abundance is at an extremely low level.

Benefits of the LBA are that it provides relatively precise abundance estimates for male and female crabs for fishery management, yields information needed to estimate S-R relationships, and provides a means to analyze alternative harvest strategies. Another benefit of the LBA is that it smoothes out measurement errors in the survey. Survey measurement errors were very high in some years; for example, the survey appeared to greatly overestimate mature female abundances in 1977, 1991, 1995, and 1996, and mature male abundance in 1975 and to greatly underestimate mature female abundances in 1979 and 1993 (Figure 1). Often, high measurement errors were caused by an extremely high catch in one or two survey stations. By smoothing out survey measurement errors, the LBA provides a more consistent interpretation of stock changes over time than do survey area-swept estimates.

TERMINAL MOLT OF MATURE MALE TANNER CRABS

What Is Terminal Molt and Why Do We Need to Understand It?

In many majid (true) crabs, it has been hypothesized that the maturity molt 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 objectively described 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 Tanner and snow crabs (*Chionoecetes opilio*) undergo a terminal molt at maturity. Based on their snow crab work in the Gulf of St. Lawrence in Atlantic Canada, Conan and Comeau (1986) and Conan et al. (1990) suggested that all males of the genus *Chionoecetes* have a terminal molt at the time they reach morphometric maturity. This assertion led to a considerable debate (Conan and Comeau 1988; Donaldson and Johnson 1988; Jamieson et al. 1988; Conan et al. 1990; Dawe et al. 1991). Scientists around the world as well as within Alaska have not reached a consensus on this issue.

Whether male Tanner crabs undergo a terminal molt at maturity has important implications on the assessment and management of crab fisheries. Terminal molt has implications on legal size limit and yield optimization. If terminal molt occurs before reaching legal size, crabs will never become available for harvest. Conversely, if terminal molt occurs after reaching legal size, crabs may be harvested before having an opportunity to mate, thus reducing reproductive potential and perhaps future recruitment. In terms of yield per recruit, a size limit is not an efficient management measure to optimize harvest of a cohort of crabs that stop growing over a wide range of sizes. Consequently, a conflict exists between management objectives for maximizing physical or economic yield per recruit and adequately protecting a stock's reproductive potential. Additionally, over the long term, use of a size limit on an exploited stock exhibiting terminal molt will result in harvesting the fastest growth segment of the stock with potential adverse genetic consequences (Kruse 1993; Sainte-Marie et al. 1995). The existence of terminal molt also affects the choice of suitable methods to estimate growth and natural mortality parameters, which are important to assess stock size and to evaluate optimal harvest strategy.

Literature Review

Evidence for the terminal-molt hypothesis in *Chionoecetes* species mainly comes from snow crabs in the Gulf of St. Lawrence. Conan and Comeau (1986) observed that large-clawed male snow crabs failed to molt in the laboratory, and in their field studies they did not find large-clawed males with mouth parts indicating imminent molting. Sainte-Marie et al. (1995) also observed in the field that molting of large-clawed male snow crabs was virtually nil over several consecutive years. Nine scientists (Dawe et al. 1991) challenged the idea of terminal molt by critically questioning the methods used by Conan and Comeau (1986) and presenting new data. Among the new data were observations of molting of large-clawed males both in the field and laboratory (Dawe et al. 1991). Sainte-Marie et al. (1995) argued that the observations reported by Dawe et al. (1991) might be caused by exceptions and classification errors and that large claw might not be a strict condition for terminal-molt status. In Alaska, Otto (1998) assessed EBS snow crabs under the assumption of terminal molt.

In their critique of Conan and Comeau's (1986) paper, Donaldson and Johnson (1988) provided evidence contrary to the terminal-molt hypothesis for Gulf of Alaska Tanner crabs. All of the 318 males collected from Women's and Chiniak Bays, Kodiak Island, including several classified as "morphometrically mature," molted in holding pens. Donaldson and Johnson also cited Paul and Paul's (1986) study of encrusting barnacles on Tanner crabs from Cook Inlet. Thirty-nine percent of male crabs 120-180 mm in CW carried barnacles that lived 1-2 growing seasons; no males had barnacles >3 growing seasons. In contrast, 87% of terminal-molt females had barnacles, and 42% of those had lived 3-4 growing seasons. Paul and Paul (1986) cited these results as consistent with Donaldson et al.'s (1981) estimate of an 18-month male intermolt period, and Donaldson and Johnson (1988) expected similar barnacle age distributions on males and females if terminal molt occurred in both sexes.

Conan and Comeau (1988) questioned the conclusiveness of these data and argued that the low proportion (5 of 318) of morphometrically mature males in the sample was consistent with expected misclassification error rates of crabs that might have been morphometrically immature. Regarding the shell-age data from Cook Inlet, Conan and Comeau proposed that a low proportion of oldshell large males was not surprising given (1) large size overlap of morphometrically immature and mature males, and (2) higher mortality rates of males than females due to the large male-only fishery. Conan and Comeau acknowledged that it was not possible to rule out the possibility that terminal molt may not occur in all *Chionoecetes* species, but they suggested that no evidence exists that molting of morphometrically mature males occurs to any significant degree.

Direct evidence now exists that, at least under some conditions for *Chionoecetes bairdi*, the proportion of morphometrically mature males that molt may be very significant, contrary to the terminal-molt hypothesis. Paul and Paul (1995) studied 23 sublegal-sized (110-139 mm CW), functionally mature male Tanner crabs that mated with multiparous females; 74% of these males initiated molting after 26-27 months in the laboratory. According to the criteria of Stevens et al. (1993), 76% of these functionally mature males were morphometrically mature (Paul and Paul 1995). Thus, the generality of the terminal-molt hypothesis remains questionable.

Our Approach

The purpose of our terminal-molt study was to explore the consistency of the terminal-molt hypothesis with field data collected during the annual stock assessments of Tanner crabs in the EBS. We fitted a LBA (Zheng et al. 1998) to trawl survey estimates of male Tanner crab abundance in Bristol Bay from 1990 to 1997 by shell condition (newshell and oldshell) and maturity status (morphometrically mature and immature). We used a non-linear least squares approach to estimate abundance, recruitment, and molting probability and compared model fits with and without an assumption of a terminal molt to evaluate consistency of this hypothesis with field observations. Although comparable data on morphometric maturity status are unavailable for other Tanner crab stocks in Alaska, changes in molting probability can be revealed by the shell conditions of sublegal male crabs which are approximately one molt away from reaching legal size. So, we also examined proportions of sublegal oldshell male Tanner crabs from five stocks in the EBS and the northern Gulf of Alaska to seek evidence that molting probabilities varied over time by region.

Summary of Results

The model fitted observed abundances well, and the fit was best made without assuming a terminal molt at morphometric maturity (large claw size). We rejected the terminal-molt hypothesis statistically as it failed to provide the most consistent interpretation of field-collected data on size, shell condition, and claw size of the Tanner crab population in Bristol Bay during 1990-1997. However, we found that molting probability of male Tanner crabs declines sharply once morphometric maturity is achieved: from 93% to 15% during 1990-1993 and from 61% to 0% during 1995-1996. Although the terminal-molt hypothesis appears valid for 1995 and 1996, a significant percentage of morphometrically mature males appear to have molted in 1990-1993, contrary to the hypothesis. The percentage may have been much higher in previous years. Proportions of oldshell sublegal male crabs during 1990-1997 were about 2.5 times as high as those during 1975-1989, suggesting much higher molting probabilities prior to 1990. However, data were not collected on claw size that would have allowed us to confirm that morphometrically mature crabs molted at higher rates during the 1970s and 1980s than during the 1990s.

An examination of the proportions of oldshell sublegal male Tanner crabs from five major Alaska stocks implies that molting probabilities vary widely by time and area. It appears that the terminal-molt controversy is somewhat a matter of degree. We speculate that the occurrence of terminal molt at morphometric maturity for male Tanner crabs may be stock specific and influenced by recruitment strength and prevailing environmental conditions. We suggest that growth to maximum body size is genetically controlled but modified by environmental conditions.

Implications to Fishery Management

Our results have implications for Bristol Bay Tanner crab fishery management. The current size limit is about 138 mm CW (140 mm CW for commercial fisheries in which the measurements include spines). Many crabs are morphometrically mature prior to attaining legal size, and only a small proportion of legal crabs are immature. The median size at morphometric maturity is 115 mm CW for Bristol Bay Tanner crabs (Somerton 1980), about one molt increment smaller than the size limit. Therefore, almost all males have a chance to mate at least once before they reach the legal size, and the current size limit should adequately conserve male reproductive potential, especially given the sperm retention capabilities of females (Paul 1984). Paul and Paul (1996) reached the same conclusion based on estimates of size of maturity and legal size limit for Kodiak Tanner crabs. That only 22% of all sublegal crabs were oldshell from 1975 to 1989 implies that the large majority of sublegal crabs can grow to legal size during this period. However, the low molting probability since 1990 suggests that a substantial proportion of sublegal crabs may no longer be able to attain legal size. If the current low molting probability continues, management options, such as lowering the current legal size limit or perhaps using a limit based on the ratio of chela height against CW, may need to be considered and evaluated to reduce the loss of harvest opportunity for small-size, large-clawed crabs. Alternatively, the reduced molting probability may provide added reproductive safeguards at low stock sizes. Finally, in our analysis of terminal molt, we found a large difference between the shell conditions of legal crabs from assessment surveys and the commercial fishery in the recent years. This suggested to us that an effective harvest strategy should include both abundance and shell-age composition in setting GHLs.

STOCK-RECRUITMENT RELATIONSHIPS

Overview

An S-R relationship predicts likely recruitment of progeny from a given spawning stock size. Such a relationship can be created by density-dependent predation, cannibalism, and food or space limitation. Inability or difficulty to find mates at low densities can also result in a strong relationship at low spawning stock levels. The commonly used S-R models are dome-shaped curves developed by Ricker (1954) and asymptotic curves by Beverton and Holt (1957).

The S-R relationship has important implications for harvest strategies. If no such relationship exists, i.e., recruitment is not related to the corresponding spawning stock size, then the optimal harvest strategy may be to harvest all crabs that have reached their maximum economic value. But many experiences around the world show that if stocks are heavily exploited, then recruitment will eventually be reduced and fisheries will collapse. Because recruits are survivors from eggs that are spawned by the parent stock, it follows that with a depressed spawning stock, there will be few eggs and few recruits in a closed population. Even if the S-R relationship has not been clearly demonstrated for each stock and species, it is prudent to assume an effect of stock size on recruitment at least at low spawning stock levels to avoid risk of commercial extinction. Due to lack of data, S-R relationships have not been estimated for most crab stocks in Alaska. Our study is the first attempt to estimate S-R relationships for a Tanner crab stock.

Our Approach

In this study, we used updated results from the LBA (Zheng et al. 1998) to develop an S-R relationship for Bristol Bay Tanner crabs. First, we developed a method to compute male reproductive potential, based on a literature review of Tanner crab reproductive biology and data on size at maturity and clutch condition from summer trawl surveys conducted by NMFS. Second, we estimated effective spawning biomass from mature female abundance and male reproductive potential. Finally, we fitted effective spawning biomass and recruitment data to both an ordinary and an autocorrelated Ricker model and examined patterns of residuals from the fits.

In this study, we assumed that female Tanner crabs mature at ≥80 mm CW. Although sizes at 50% maturity are smaller than 80 mm CW during most years from 1975 to 1997, 80 mm CW is the mid-point between the largest and smallest sizes at 50% maturity (Figure 2). Mean size of mature females may be routinely overestimated because it is difficult for the trawl gear to catch small crabs. Although our assumed maturity size of 80 mm CW is much smaller than about 93 mm CW estimated by Somerton (1981) using mean size of mature females, it more accurately represents observed sizes at 50% maturity during the time period we modeled, namely 1975-1997. Use of mean size of mature females as a cutoff size for maturity apparently greatly underestimates female mature abundances during most years.

Results

Recruits are not strongly associated with effective spawning biomass; both weak and strong recruitment occurred with both low and high effective spawning biomass (Figure 3). The strongest recruitment is almost 100 times as large as the weakest recruitment, and the largest effective spawning biomass is more than 10 times as large as the lowest one (Figure 3). Variation of recruitment caused great fluctuation of population abundance over time. Strong year classes occurred in the late 1960s and early 1980s, and weak year classes occurred in the mid and late 1970s and mid and late 1980s. Thus, recruitment is highly autocorrelated; that is, weak years follow weak years and strong years follow strong years. The exponential S-R curve was fit for effective spawning biomass of 14.1 million lbs or less (Figure 3), but the results are highly uncertain because only three pairs of such data are available.

Much variation of recruitment can be explained by autocorrelation or cycle; thus, environmental factors are likely to play a very important role in recruitment success. Some environmental conditions may trigger a switch between weak and strong recruitment from period to period. Rosenkranz et al. (1998) suggested that winds from the northeast are favorable to larval retention and recruitment, but the patterns of winds from the northeast are not consistent with periods of weak and strong recruitment all the time. Alternative explanations include adverse effects of cold bottom temperature on gonad development, beneficial effects of warm surface temperature on larval food (copepod production), groundfish predation and competition, and the possibility that the stock affects recruitment in some ways different than we modeled. Spawning geography, the spatial distribution of spawners, is one possible effect that may confound attempts to estimate S-R relationships.

Autocorrelated, periodic or quasi-periodic recruitment is common in crab stocks and some fish stocks (McKelvey et al. 1980; Koslow et al.1987; Koslow 1989; Zheng et al. 1995; Sainte-Marie et al. 1996; Zheng 1996; Zheng and Kruse in press). Although year classes for Bristol Bay Tanner crabs from 1968 to 1989 showed a strong cyclic behavior with a period of 13 or 14 years (Figure 3), catch data (Otto 1990) indicate that the cycle was weaker or shorter for year classes from late 1950s to late 1960s than from 1968 to 1989. Because of the brevity of available time series, the period length and even the existence of repeatable cycles are not well established. The strong recruitment cycles may also be caused in part by age-class overlap in recruitment estimated by a size-based model. Nevertheless, despite uncertainty about the details, recruitment of Bristol Bay Tanner crabs appears to be at least quasi-periodic.

A strong density-dependent relationship did not emerge after accounting for mates per male, effects of shell condition and size, and sperm retention by females. Based on our current understanding of Tanner crab growth and reproductive biology, we made assumptions about time lag from spawning to recruitment, cutoff size for maturity, average numbers of mates per male, lack of mating by some newshell males, and lack of mating of very large males with newshell females. However, our current understanding of Tanner crab reproductive biology remains quite limited. New knowledge on spawning geography, the proportions of oldshell and newshell males that participate in spawning migrations, and effects of senescence on male and female reproductive capability will be helpful. Additional studies on environmental effects on growth and recruitment would also be valuable. As our understanding of Tanner crab biology increases in the future, we will be able to refine these S-R relationships.

EVALUATION OF ALTERNATIVE HARVEST STRATEGIES

Our Approach

The LBA and S-R relationships described earlier in this report were combined in a computer simulation model to evaluate alternative harvest strategies for Bristol Bay Tanner crabs. The primary features of the simulations are as follow:

- The model was initialized with data on population status for 1997.
- For each harvest strategy, we simulated the population and fishery for 100 years with 1000 replicates. The average population status and yield (i.e., catch in million lbs) from the simulations were summarized to compare the alternative strategies.
- The Ricker S-R curve with cyclic residuals was used, and the recruitment cycle was varied randomly between 10-18 years.
- Annual natural mortality rate was set at 33% (M=0.4) for males and 35% (M=0.43) for females. Handling mortality from the directed Tanner crab fishery and bycatch mortality from all non-pot fisheries were simulated separately from natural mortality. Therefore, natural mortalities for both males and females were lower than those estimated by the LBA (Zheng et al. 1998).
- Handling mortality rate of captured but discarded females and sublegal males was assumed to be 20% for the crab fishery.

- Bycatch from groundfish and scallop fisheries was set according to current prohibited species cap regulations, and handling mortality rate was assumed as 80% for the groundfish fisheries and 40% for the scallop fishery (NPFMC 1996).

We examined three 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. Under the first harvest strategy, the status quo, GHL was set by legal harvest rate times legal male crab abundance. The current legal harvest rate is 40%, but we also evaluated nine other rates ranging from 10% to 60%. Under the second alternative, GHL was set by legal harvest rate times "exploitable" legal male crab abundance. Because the fishery disproportionately harvests newshell crabs over oldshell crabs, we defined exploitable legal males based on fishery selectivity parameters. We estimated 100% selectivity for newshell crabs and 32% selectivity for oldshell crabs based on comparison of catch and survey data from 1975 to 1997. Ten alternative harvest rates for exploitable legal males ranging from 15% to 65% were evaluated. Under the third approach, GHL was set by mature harvest rate times "molting mature males", but only legal males were allowed to be harvested with a catch cap of 50% of exploitable legal male abundance. In other words, the legal harvest rate is equal to the mature harvest rate times "molting mature male" abundance divided by legal male abundance. "Molting mature males" were defined as 100% of newshell males and 15% of oldshell males >112 mm (4.4 in) CW. These mature males have a high probability of molting within a year. Ten alternative mature harvest rates ranging from 10% to 35% were evaluated. This third approach most closely parallels the mature male harvest rate strategy currently used to manage the red king crab (*Paralithodes camtschaticus*) fishery in Bristol Bay. In the case of red king crabs, all mature males are used in the GHL calculation because they continue to molt with a high probability up to legal size, unlike Tanner crabs.

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 set a threshold based partly on past fishery management practice and partly on the S-R relationship. In the past, the effective spawning biomass was always below 15.5 million lbs in the years when the fishery was closed. This level of effective spawning biomass is slightly above the smallest effective spawning biomass with an above average recruitment level (Figure 3).

The Magnuson-Stevens Fishery Conservation and Management Act specifies 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. To accommodate this, we evaluated each approach with a stair-step harvest rate schedule similar to that employed for the Bristol Bay red king crab fishery (Zheng et al. 1997a). We used 48.5 million lbs of effective spawning biomass as a base level, which is the average of simulated effective spawning biomass under the current 40% legal harvest rate. When effective spawning biomass was at or below 50%, 60%, or 70% of this base level, harvest rates would decrease 50% or 40%. A combination of three levels of effective spawning biomass and two levels of reduced harvest rates resulted in six alternative stair-step harvest rate schedules. We evaluated each stair-step schedule in combination with each of the three harvest strategy approaches.

To evaluate the strategies, statistics were collected on effective spawning biomass, probabilities of fishery closure, probabilities that the stock is below the overfished reference point as defined in the fishery management plan (NPFMC 1998), and yield. The probability of fishery closure was estimated as the proportion of replicates with estimated effective spawning biomass below threshold such that the fishery is prohibited for a given year. The overfished level is defined for Tanner crabs in the entire EBS, not just Bristol Bay. Based on the survey data from 1983 to 1997, we approximated the equivalent overfished level for Bristol Bay Tanner crabs as 58.6 million lbs of total mature male and female biomass. 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. 1997a) for each alternative strategy.

Results

Constant harvest rate. The trade-off between mean yield and standard deviation of yield as a function of constant harvest rate (i.e., without the stair-step) was similar among the three approaches (Figure 4). Mean yield, standard deviation of yield, and proportion of years that mature population abundance was below the overfished reference point increased as a function of harvest rate, but the standard deviation of yield increased at a faster rate than mean yield. The increase in mean yield generally slowed down as harvest rate increased, especially with legal harvest rate >40%, exploitable legal harvest rate >45%, and mature harvest rate >20%. Variations in yield, indexed by standard deviations of yield, were very high for all three approaches. This is a direct result of the periodic recruitment feature of Tanner crab population dynamics. Even without a fishery, mature spawning biomass fell below the overfished reference level in 9.4% of years. The legal harvest rate of 40% (status quo) is equivalent to an exploitable legal harvest rate of 45% and a mature harvest rate of 20%. Under equivalent harvest rates, both legal harvest rate and exploitable legal harvest rate approaches had similar mean yield and standard deviation of yield, but the proportion of years at overfished levels was lower for the exploitable harvest rate approach than the harvest rate approach. Mean yield, standard deviation of yield, and proportion of years at overfished levels with the 20% mature harvest rate approach were the lowest among the three equivalent approaches. The 50% cap on exploitable harvest rate for the mature harvest rate approach resulted in relatively flat curves of mean yield, standard deviation, and proportions of years at overfished levels when mature harvest rates were high (Figure 4).

Stair-step harvest rate. Alternative stair-step functions of harvest rate generally did not change the results very much (Table 1). Because standard deviation of yield increased much faster than mean yield at legal harvest rates >40%, exploitable legal harvest rates >45%, and mature harvest rates >20% (Figure 4), we used these harvest rates as the high harvest rate levels in the stair-step functions. The legal harvest rate of 40% also happens to be the status quo harvest rate. For each approach, a decrease from 70% to 60% to 50% in cut-off levels of effective spawning biomass or an increase in low harvest rates from 50% to 60% resulted in slightly higher trade-off values between increase in mean yield and decrease in standard deviation of yield but caused slightly higher percentages of years with fishery closure and with mature biomass being below the overfished reference point (Table 1). Overall, the mature harvest rate approach had slightly higher trade-off values between increase in mean yield and decrease in standard deviation of yield than the other two approaches. It also had slightly lower percentages of years with fishery closure and fewer years being overfished. The harvest strategy with a high mature harvest rate of 20% and a low rate of 10% with a cut-off of 34.0 million lbs of effective spawning biomass had the lowest percentages of years with fishery closure and being overfished among all the alternatives (Table 1). The trade-off value between increase in mean yield and decrease in standard deviation of yield was intermediate among the range in values among all harvest strategies (Table 1). In the context of National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act, we considered this strategy as the most attractive alternative to the status quo strategy.

Sensitivity of the Results

We examined sensitivity of each strategy to changes in natural mortality, handling mortality, and S-R curve. The standard set of population parameters was used in each sensitivity analysis, except that both a normal Ricker S-R curve and a depensatory Ricker S-R curve were used and that the parameter under consideration was assigned one of two opposite and extreme values. For sensitivity studies on recruitment cycles, we used 200 replicates, each for 1000 years. A longer simulated time horizon was needed to examine cycle period.

As expected, higher natural or handling mortality rates resulted in much lower catch and higher percentages of years with fishery closure and at overfished levels for all alternative strategies, and vice versa for lower natural mortality or handling mortality rate. The depensatory S-R curve had a minor effect on the results of simulations except when depensation was combined with high natural mortality, which resulted in extremely low population abundances and few fishing opportunities. Effective spawning biomass rarely fell into the depensatory range under other circumstances.

Under the same test conditions, the status quo harvest strategy had slightly higher mean yield, lower standard deviation of yield, higher percentages of years with fishery closure and at overfished levels than when the status quo harvest strategy included stair-step harvest rates. The status quo harvest strategy also had higher mean yields than those for the proposed new strategy under the same conditions, but its standard deviations of yield and its percentages of years at overfished levels were much higher.

With the normal S-R curve, the status quo and proposed harvest strategies were very sensitive to period length (number of years between the mid-points of two periods of strong year classes) and amplitude (difference between highs and lows) of recruitment cycle, especially for a long period length and high amplitude. Coefficient of variation of yield and proportions of years of fishery closure and at overfished levels increased substantially as period length and amplitude of recruitment cycle increased. For a given combination of period length and amplitude of recruitment cycle, the proposed harvest strategy resulted in only a minor improvement on coefficient of variation of yield and proportion of years of fishery closure over the status quo strategy. The proposed harvest strategy reduced proportions of years at overfished levels considerably when the period length of recruitment cycle was 18 years or less.

In our analysis of alternative harvest rate strategies, we attempted to consider total fishing mortality as the aggregate of landed catch, handling mortality of discards in the directed fishery, and bycatch mortality in groundfish and scallop fisheries. Landings are documented on transaction receipts between processors and fishers called "fish tickets." At-sea observers monitor bycatch aboard vessels fishing for other species. Typically, total bycatch of Tanner crabs by groundfish and scallop fisheries is a small percentage of total crab abundance in the EBS. Whether a significant proportion of the Tanner crab population is adversely impacted by dredges and trawls, but not caught and observed, remains a matter of speculation. Large numbers of Tanner crabs are handled and discarded during crab fisheries due to restrictions on size, sex, season, and target species. In our study of the red king crab fishery in Bristol Bay, increased handling mortality in our model resulted in lower optimal harvest rates and higher optimal threshold levels (Zheng et al. 1997b). For the Bristol Bay Tanner crab fishery, we found that handling mortality had similar, but less pronounced, effects. Female Tanner crabs have much lower catchability during the fishery than legal-sized males. Thus, the impact of handling mortality on female Tanner crabs is smaller than on sublegal male Tanner crabs or female red king crabs. In our sensitivity analysis we bracketed handling mortality rate at 0 and 50% to span low rates from a study that attempted to emulate the fishing process (MacIntosh et al. 1996) and high rates from a laboratory study (Carls and O'Clair 1995) that considered extremely cold air temperatures during winter fisheries. An extensive bibliography of capture and handling effects was compiled by Murphy and Kruse (1995), and reviewed in some detail by Zheng et al. (1997b). Additional research is needed to accurately assess handling mortality rates experienced by Tanner crabs during commercial fisheries in the Bering Sea. Results from ongoing studies of cold windchill effects (Kruse 1998) may significantly affect our estimates of handling mortality rate during winter fisheries. As this research is completed, the implications on crab fishery management need to be analyzed.

In our simulations for the Bristol Bay stock, we set recruitment periodicity randomly from 10 to 18 years. We also examined the sensitivity of harvest strategies to recruitment cycles ranging from 4 to 30 years. We reached the same conclusion for the Bristol Bay Tanner crab stock as Koslow (1989) did for fish stocks: no harvest strategies can protect a stock from collapse if the recruitment cycle is long. This is intuitive from crab biology. Because Tanner crabs mature at about age 6 and few live longer than 12 years (Donaldson et al. 1981), significant numbers of mature Tanner crabs cannot be "banked" for more than 6 years for future spawning. However, reducing 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.

EXTENDING THE RESULTS FROM BRISTOL BAY TO THE EASTERN BERING SEA

Legal-sized Tanner crabs in the EBS primarily occur in two areas: in Bristol Bay and near the Pribilof Islands. As stated in the Problems and Approaches Section, size at maturity in some years, genetics, and survey measurement errors are different between Bristol Bay and Pribilof Islands Tanner crabs. Legal-sized crabs are well separated between these two areas. However, there is no clear geographic separation of small Tanner crabs between these two areas. In addition, mean size of mature females decreases gradually from eastern Bristol Bay to the west rather than a sudden drop at the Bristol Bay regulatory border (168°W) (Bob Otto, NMFS, personal communication). Because Tanner crabs are not separated into Bristol Bay and Pribilof Islands stocks for management purposes and our modeling effort focused on Bristol Bay Tanner crabs, we need to extend the simulation results to Tanner crabs in the EBS.

A large majority of EBS Tanner crabs exist in Bristol Bay (Figure 5). From 1976 to 1998, more than 70% of EBS legal Tanner crabs were from Bristol Bay each year, and more than 90% of legal crabs occurred in Bristol Bay for 9 out of 23 years. Approximately 75% of mature males and female biomass >79 mm CW and 82% of legal males have historically occurred in Bristol Bay. Threshold (15.5 million lbs) and cut-off point (34.0 million lbs) for Bristol Bay crabs can be expanded to the EBS by dividing by 0.75. Because no effective spawning biomass was computed for Pribilof Islands Tanner crabs, we suggest using female biomass >79 mm CW as threshold and cut-off point for simplicity in applying our modeling work to fishery management. Although many females mature at a smaller size, survey abundance of females <79 mm CW is much less reliable than those for larger-sized females. The expanded threshold and cut-off point for EBS Tanner crabs are 21.0 and 45.0 million lbs of female biomass >79 mm CW, respectively. Applying this threshold to survey abundances of EBS Tanner crabs since the complete surveys started (1973) results in only five years of fishery closure: 1985/86, 1986/87, and 1996-1998; in practice, the fishery was closed only during four of these five years with the exception of 1996.

Proportions of EBS Tanner crabs in Bristol Bay were higher for legal crabs than those for mature males and females >79 mm CW, especially during recent years (Figure 5); this suggests that size structures of Tanner crabs in Bristol Bay may be different from the areas to the east. There were hardly any legal crabs in the Pribilof Islands area during the last five years. If molting mature males from Bristol Bay and Pribilof Islands are combined to set GHL for the EBS fishery, the GHL for the Bristol Bay area will be artificially inflated by molting mature males in the Pribilof Islands area. To avoid this problem, we suggest setting separate GHLs for Bristol Bay and Pribilof Islands based on their respective abundances of molting mature males. The 50% cap of exploitable legal males will take effect for either GHL if its relative legal crab abundance is too low. If the GHL in Bristol Bay or Pribilof Islands is too low to manage effectively, the fishery will be closed for that area. The GHL for the EBS fishery will be equal to the sum of GHLs in these two areas.

RECOMMENDED HARVEST STRATEGY

Our analyses on population dynamics and harvest strategies of Tanner crabs lead us to recommend changes in our current harvest strategy for EBS Tanner crabs. These changes will result in low harvest rates for stock rebuilding when the population is depressed and high harvest rates during high productivity periods. GHLs set by the recommend harvest strategy will also be closer to actual catches than the current strategy, especially when the population abundance is low.

There are five components for the recommended strategy as applied to EBS Tanner crabs:

- **Threshold**: 21.0 million lbs of female biomass >79 mm CW. The fishery will be closed when the stock is below threshold.
- **Mature harvest rates**: 20% of molting mature males when biomass of females >79 mm CW is ≥ 45.0 million lbs and 10% of molting mature males when biomass of females >79 mm CW is ≥ 21.0 million lbs and < 45.0 million lbs. Molting mature males are 100% of newshell and 15% of oldshell males >112 mm CW.
- **Legal harvest rate cap**: a 50% cap of exploitable legal males, which are 100% of newshell and 32% of oldshell legal males.
- **GHLs for Bristol Bay and Pribilof Islands**: GHLs are determined separately for crabs east of 168°W (Bristol Bay) and west of 168°W (Pribilof Islands) in the Eastern Subdistrict of the Bering Sea. If the GHL in Bristol Bay or Pribilof Islands is too low to manage effectively, the fishery can be closed for that area. Total GHL in the Eastern Subdistrict is equal to the sum of these two GHLs if the fisheries in both areas are open. If any portion of the Eastern Subdistrict is closed to fishing, the crab abundance in that portion will be excluded from the GHL computation.
- **A precautionary measure**: when the stock is reopened to fishing after having been closed to all commercial fishing in the preceding season due to the depressed stock

condition, the GHL in that season will be reduced to one-half of the value as computed in the above GHL determination. When a stock is reopened to fishing, it is very likely that the ratio of legal crabs to mature male crabs is low, which will result in a high legal harvest rate. This measure will prevent such a high rate. It also serves a protection against survey measurement errors.

Our results and recommended harvest strategy may have implications for the management of the Gulf of Alaska Tanner crab stocks. The framework of the recommended harvest strategy may be applied to these stocks (i.e., threshold and stair-step harvest rate), and detailed components of a harvest strategy may depend on data availability. If mature female biomass is available with an acceptable precision, it can be used to establish a threshold and cut-off point for low harvest rates. Otherwise, mature male biomass or abundance can be used. Molting mature males may need to be defined for each stock because of different molting probabilities.

CONCLUDING REMARKS

Although the current harvest strategy is a constant legal harvest rate of 40%, legal harvest rates actually implemented during the last 24 years were quite different from this level and varied greatly over time (Figure 6). Realized legal harvest rates were higher than 40% from 1977 to 1981 and from 1989 to 1992 and much lower from 1983 to 1988 and from 1994 to 1998. It appears that it is difficult to implement a constant legal harvest rate strategy. Preseason GHLs were generally slightly higher than actual yields for most years but much higher than actual yields when the GHLs were low (Figure 6). The recommended harvest strategy leads to higher legal harvest rates than the historical rates of the current strategy when population abundance is increasing and lower rates when population abundance is decreasing. Historical harvest rates more closely match the recommended new harvest strategy than the current "constant" harvest rate strategy (Figure 6).

The recommended harvest strategy takes into account the relationship between shell condition and productivity levels of Tanner crab stocks. Strong year classes are dominated by newshell crabs. Simulation results show that the recommended new strategy adjusts legal harvest rates according to recruitment strength which is indexed by changes in shell condition. Contrary to the current harvest strategy based on legal male abundance only, use of mature crab abundance and shell condition gives the recommended new strategy a forward-looking feature. When an increase in future legal crab abundance is expected due to increased recruitment to the mature segment of the stock, legal harvest rates are increased. Conversely, during a downward recruitment cycle, reduced legal harvest rates will forestall the decline of large, oldshell males that are most virile (Stevens et al. 1993; Paul et al. 1995).

As a comparison to the current harvest strategy, the recommended strategy has similar trade-off values between mean yield and variation in yield, but it leads to fewer shortages of mates for mature females and reduced probability that population abundance falls below the overfished reference point over a long term. If reproduction can be limited due to a shortage of mature males, it is most likely to occur during periods of low population abundance. As abundance declines, spatial distribution becomes more patchy, thereby potentially reducing mating encounters. By incorporating a fishery threshold and stair-step harvest rates, the recommended new harvest strategy has features more consistent with the Board policy than the current strategy and it embodies a precautionary approach to fishery management (Restrepo et al. 1998). These features reduce mature harvest rates to protect reproductive potential during periods of low abundance when risks of overfishing or falling below the overfished reference point are high due to uncertainties in abundance estimates and population dynamics (i.e., depensation vs. compensation). Due to periodic recruitment, it appears that no harvest strategy can completely prevent stock collapse, but a precautionary approach will reduce the chance of prolonged stock collapse.

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Table 1. Comparisons of mean yield, standard deviation of yield (SD), equal trade-off between increase in mean yield and decrease in standard deviation of yield, mean effective spawning biomass (SP), mean total mature biomass (TMB), percentage of years without fishing (Closure), and percentage of years below the overfished reference point (Overfished) for alternative harvest strategies. "Cut-off" is a level of SP below which the low harvest rate (HR) is used and at or above which the high harvest rate is used. The status quo strategy is underlined and the proposed new strategy is shown in bold. Historical data were included for comparison.

Cut-off (SP)	High HR	Low HR	Yield (million lbs)	SD	Trade-off	SP (million lbs)	TMB	Closure (%)	Overfished (%)
			Harvest Rates Applied to Total Legal Crabs						
15.5	0.4	0.0	16.264	17.635	-0.686	47.752	136.980	14.521	31.847
24.3	0.4	0.2	16.122	17.846	-0.862	48.087	138.177	14.034	30.917
29.1	0.4	0.2	16.021	17.941	-0.960	48.220	138.796	13.848	30.162
34.0	0.4	0.2	15.898	18.012	-1.057	48.332	139.431	13.721	29.385
24.3	0.4	0.24	16.155	17.794	-0.819	48.012	137.904	14.150	31.146
29.1	0.4	0.24	16.081	17.860	-0.890	48.114	138.369	14.018	30.579
34.0	0.4	0.24	15.990	17.906	-0.958	48.197	138.843	13.919	30.004
			Harvest Rates Applied to Exploitable Legal Crabs						
15.5	0.45	0.00	15.406	16.980	-0.787	48.438	140.972	13.598	28.480
24.3	0.45	0.225	15.238	17.198	-0.980	48.696	142.057	13.291	27.483
29.1	0.45	0.225	15.128	17.308	-1.090	48.808	142.641	13.167	26.772
34.0	0.45	0.225	14.991	17.405	-1.207	48.910	143.276	13.059	26.019
24.3	0.45	0.27	15.274	17.152	-0.939	48.645	141.834	13.351	27.706
29.1	0.45	0.27	15.188	17.236	-1.024	48.735	142.297	13.251	27.122
34.0	0.45	0.27	15.082	17.306	-1.112	48.817	142.798	13.158	26.524
			Mature Harvest Rates Applied to Molting Mature Male Crabs						
15.5	0.2	0.0	15.088	16.001	-0.456	48.422	141.268	13.366	27.333
24.3	0.2	0.1	14.943	16.180	-0.618	48.610	142.114	13.121	26.464
29.1	0.2	0.1	14.842	16.272	-0.715	48.698	142.599	13.000	25.754
34.0	**0.2**	**0.1**	**14.718**	**16.354**	**-0.818**	**48.777**	**143.129**	**12.875**	**24.986**
24.3	0.2	0.12	14.983	16.129	-0.573	48.557	141.878	13.188	26.714
29.1	0.2	0.12	14.905	16.195	-0.645	48.621	142.242	13.087	26.192
34.0	0.2	0.12	14.811	16.252	-0.721	48.682	142.646	12.994	25.620
			Estimated Historical Averages from 1975 to 1997						
			15.020	15.093	-0.036	51.998	143.752	13.043	26.087

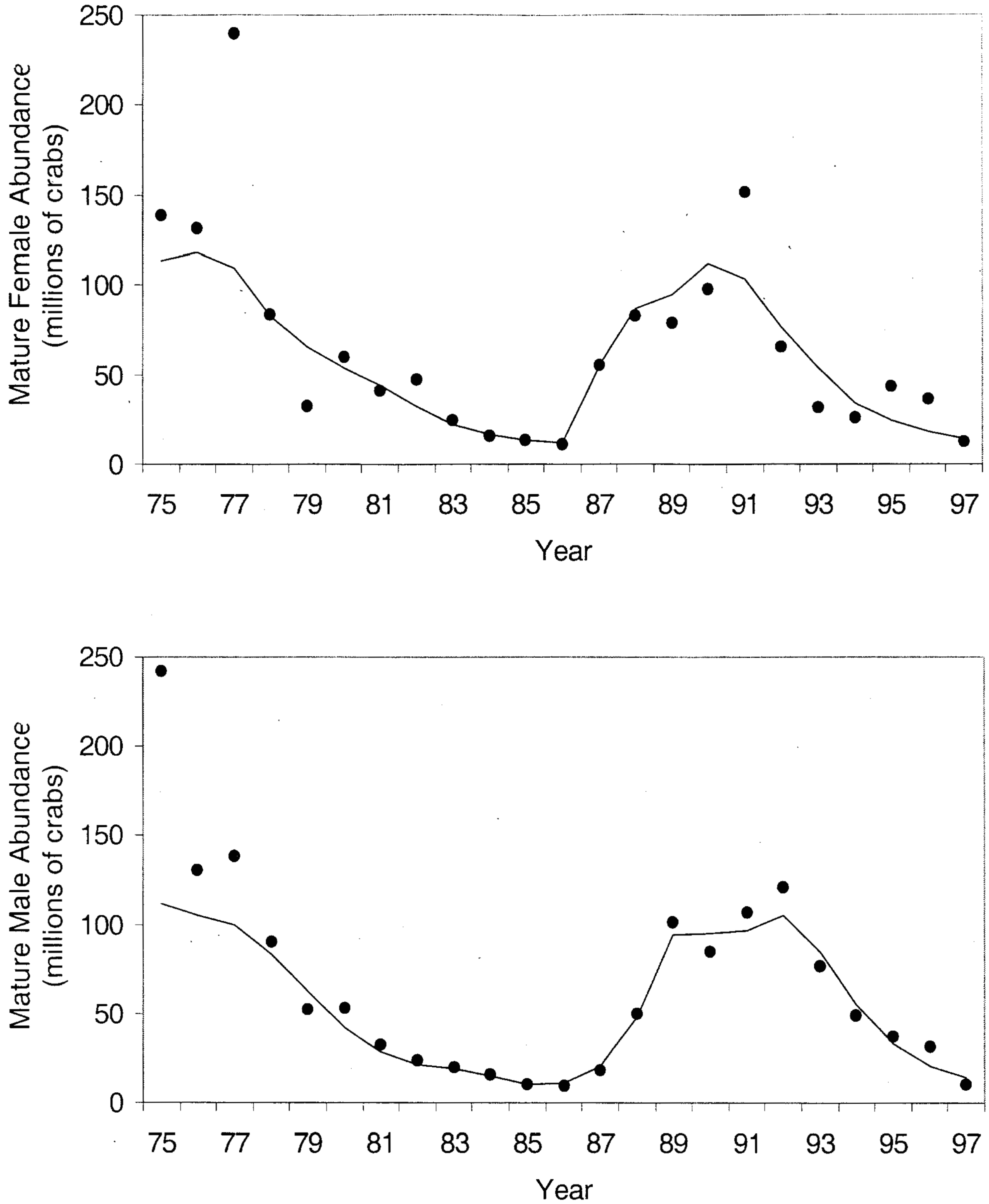


Figure 1. Comparison of area-swept (dots) and LBA (solid line) estimates of mature female (>79 mm CW, top panel) and male (>112 mm CW, lower panel) Tanner crab abundances in Bristol Bay.

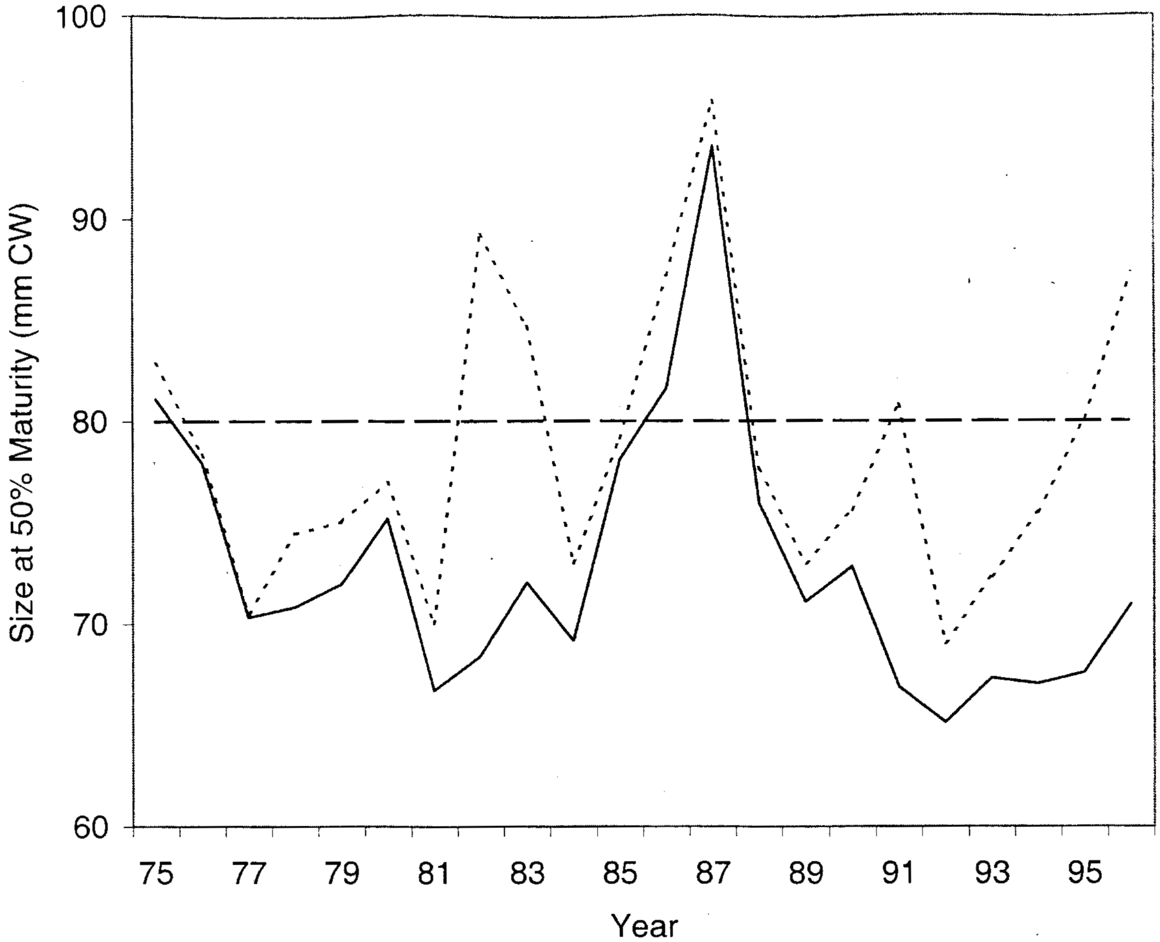


Figure 2. Size at which 50% of females are mature as estimated from clutch data from NMFS surveys for Bristol Bay Tanner crabs.

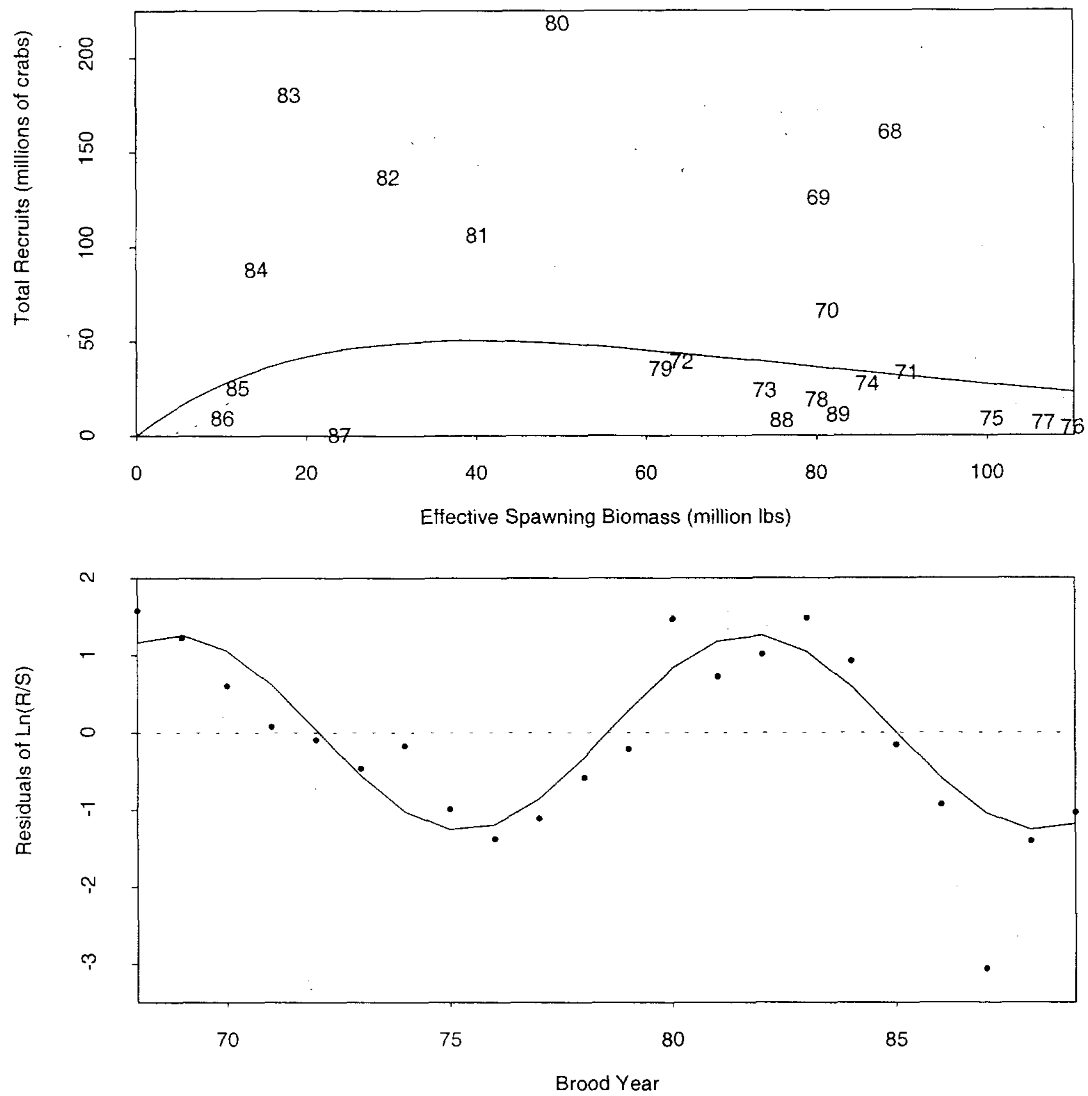


Figure 3. Relationships between effective spawning biomass (S) and total recruits (R) at age 7 (i.e., 8-year time lag, upper plot) and residuals of logarithm of recruits per S from a normal Ricker curve (lower plot) for Bristol Bay Tanner crabs. In the upper plot, numerical labels are brood year (year of spawning), solid line is a normal Ricker curve, and dotted line at low biomass is an exponential S-R curve (depensatory curve). In the lower plot, dots are residuals, and solid line is a sine function estimated from residuals.

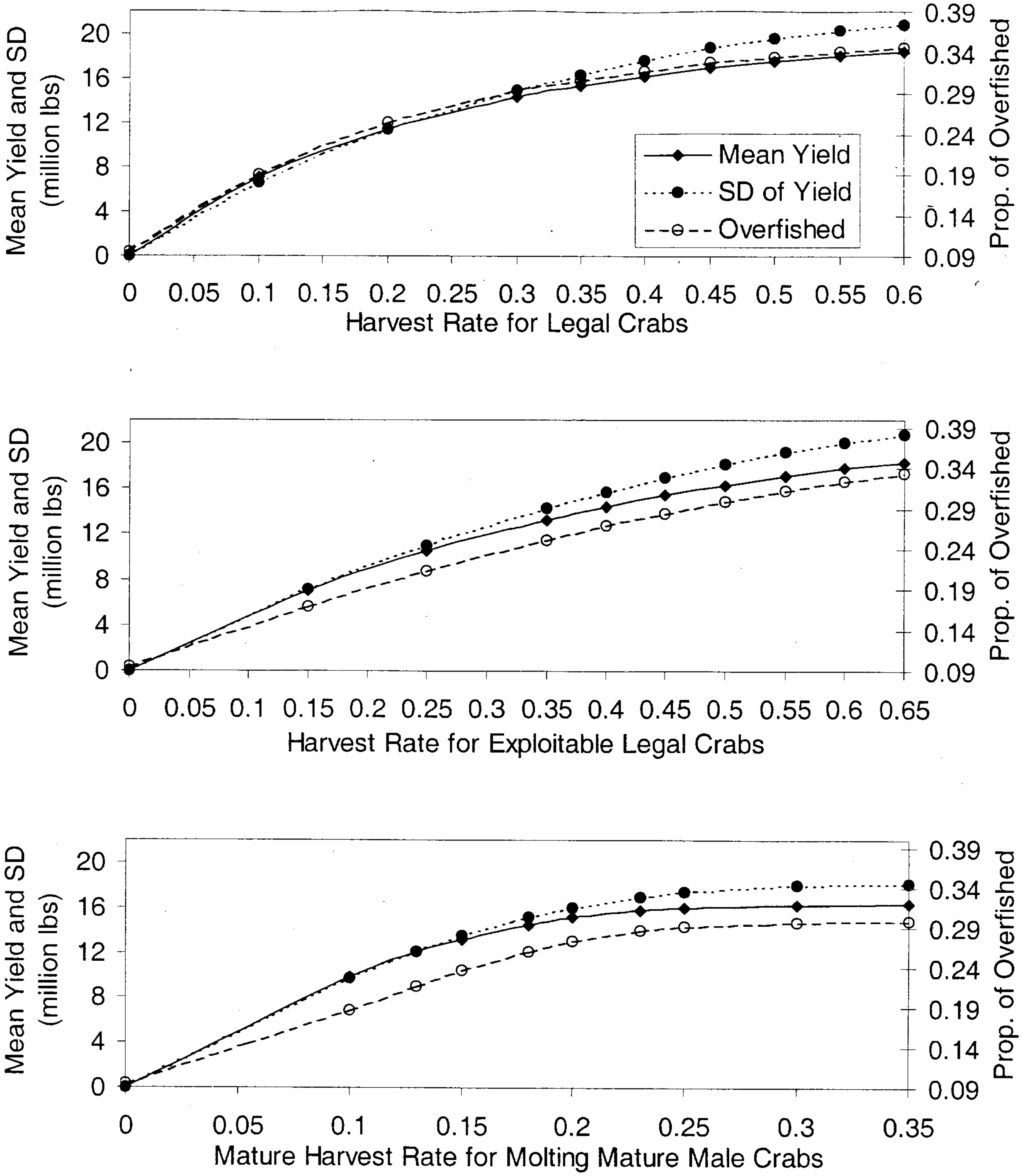


Figure 4. Mean yield (solid lines), standard deviation of yield (dotted lines), and probability of being at overfished levels (dashed lines) as a function of constant harvest rate for Bristol Bay Tanner crabs under the normal S-R curve assuming a 20% handling mortality rate for three harvest approaches.

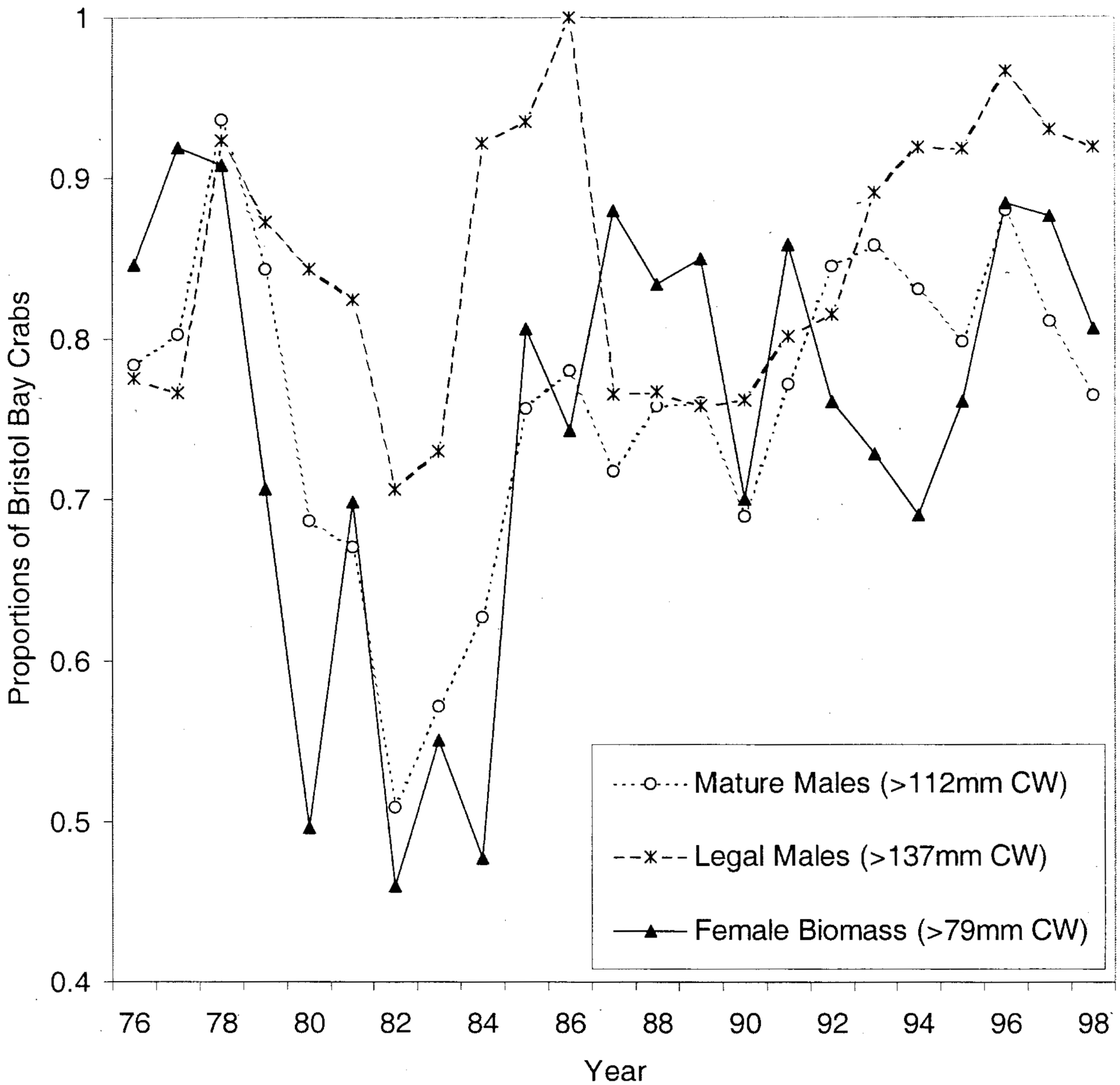
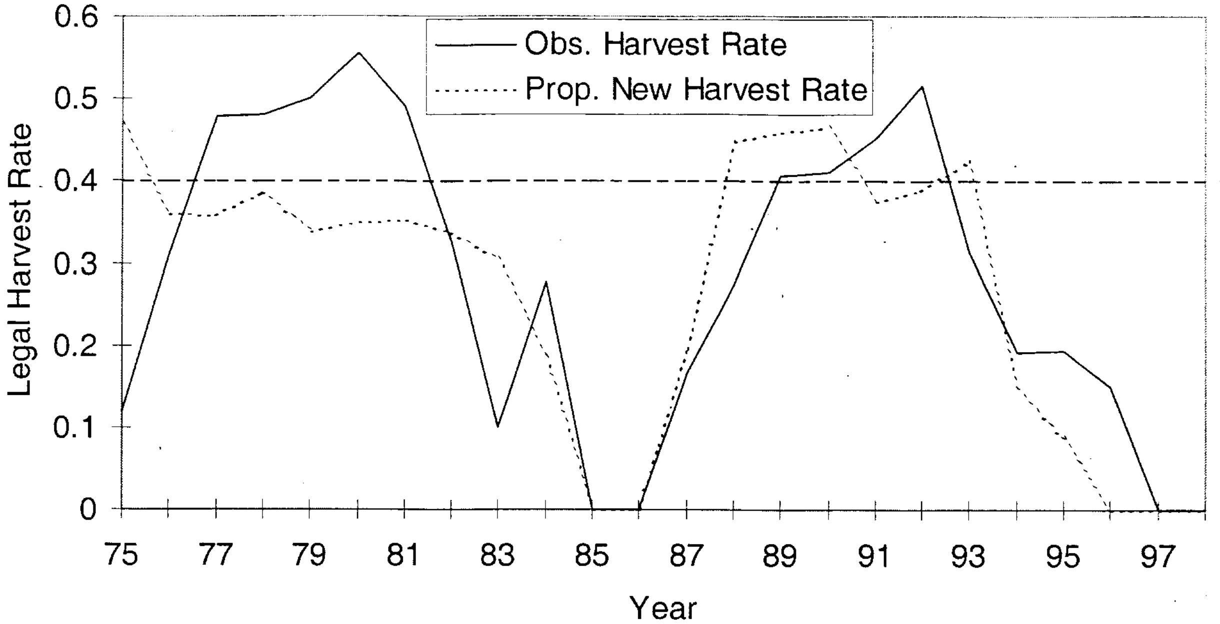


Figure 5. Proportions of Bristol Bay mature female, mature male, and legal Tanner crabs in the Eastern Subdistrict (east of 173° W in the eastern Bering Sea), estimated by the area-swept approach from NMFS survey trawl survey data.



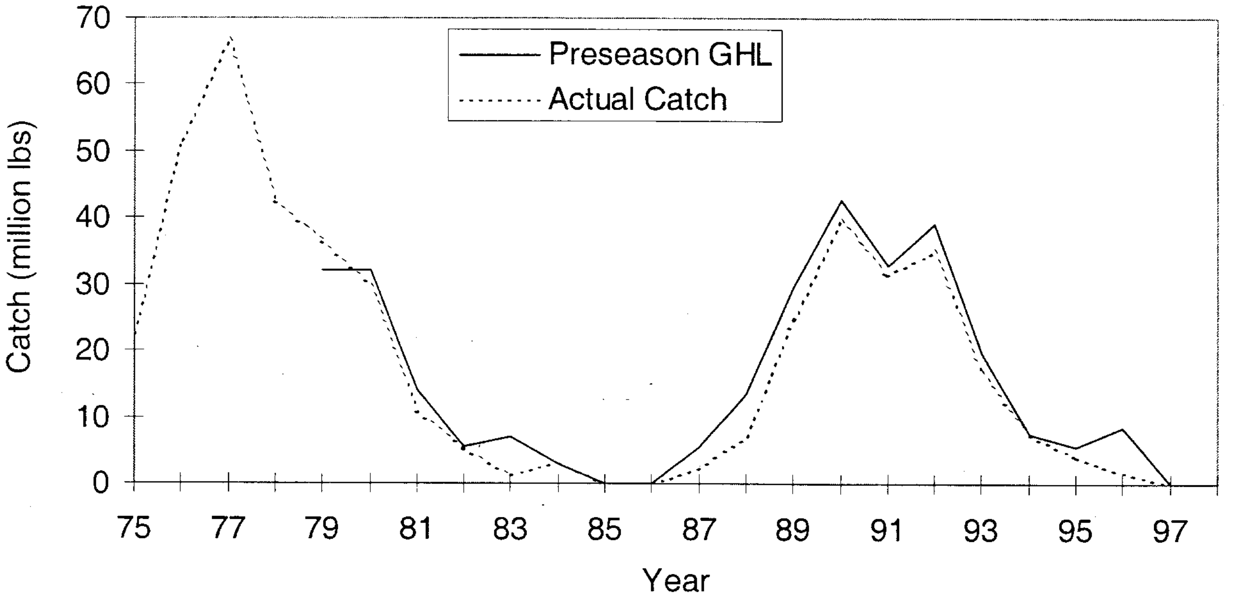


Figure 6. Comparison of the estimated harvest rates (solid line) and the harvest rates derived from the proposed new strategy (dotted line) as a proportion of total legal crab abundance (upper plot) and comparison of preseason guideline harvest levels and actual catches for eastern Bering Sea Tanner crabs (lower plot) from 1975 to 1998. Tanner crab abundances were estimated by the LBA for the Bristol Bay area and by the area-swept method for the Pribilof Islands area.