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EXECUTIVE SUMMARY

A harvest strategy must balance short-term economic gains from the fishery against risks to the long-term maintenance and productivity of the stock. An important consideration of a harvest strategy for Bristol Bay red king crabs is its ability to rebuild the stock to a productive level since its abundance is presently depressed. To evaluate the current harvest strategy against alternative strategies, a new method was developed to estimate the population abundance based on the best available information, and two models were constructed to simulate the population over time. Performance of the current harvest strategy, a suite of long-term harvest strategies and a rebuilding strategy were evaluated relative to their effectiveness in meeting the constraints and achieving the benefits that serve as guidelines in the Board of Fisheries policy on king and Tanner crab resource management. Results of the modeling efforts indicate: 1) the current threshold should be maintained at 8.4 million mature females which equates to an effective spawning biomass of 14.5 million pounds with the additional constraint that both number of mature female crabs and weight of effective spawners define threshold; 2) the mature male harvest rate should be lowered from 20% to 10% when the population is above threshold and when effective spawning biomass is below 55 million pounds and to 15% when the population is above threshold and the effective spawning biomass is at or above 55 million pounds; and 3) the maximum harvest rate on legal-sized male crabs should be lowered from 60% to 50%. The threshold minimizes the risks of irreversible effects on reproductive potential. Reducing the mature male harvest rate to 10% at low stock sizes provides for fishing opportunity while promoting stock rebuilding. Once the stock is rebuilt reducing the mature harvest rate to 15% and reducing the maximum legal harvest rate to 50% provides for relatively high yield, greater stability in yield, fewer fishery closures, and healthier stocks over the long-term.

INTRODUCTION

Numerous Alaskan king and Tanner crab fisheries closed to commercial harvest in the 1980s due to low stock size and still remain closed due to continued depressed abundance. Poor success in maintaining productive fisheries over the years prompted planning of long-term research by state and federal researchers to better understand the reasons (Murphy et al. 1994, Kruse MS). Researchers agreed that initial studies should focus on Bristol Bay red king crabs *(Paralithodes camtschaticus)* because of the excellent data available and the economic importance of the fishery. The goals of this effort were to reconstruct past stock abundance, to gain insight into stock dynamics, identify probable causes of stock decline, and attempt to avoid future repeats of stock and fishery collapses by affecting changes in fisheries management as supported by research findings. The need to rebuild the Bristol Bay red king crab stock has become more critical in recent years as the stock has become depressed and the fishery was closed in 1994 and 1995.

The purpose of this report is to provide a non-technical summary of our recommended harvest strategy for red king crabs in Bristol Bay given our research findings on stock abundance, population dynamics, and analysis of harvest strategies. Specifically, we describe (1) the length-based analysis (LBA) for calculation of historical population size, (2) the stock-recruitment relationship used to simulate future abundances, (3) an analysis of long-term harvest strategies that are optimal with respect to a suite of biological and economic considerations and which are robust to uncertainties, and (4) a strategy to rebuild the stock in the near term. This report updates Regional Information Report 5J95-21 of the Alaska Department of Fish and Game: *Overview of population estimation methods and robust long-term harvest strategy for red king crabs in Bristol Bay* by Zheng et al. (1995a). For technical details on this research, readers are referred to several scientific papers. Zheng et al. (1995b) described the development of the LBA and estimation of stock-recruitment relationships for the Bristol Bay red king crab population. Zheng et al. (MSa) reported on a slightly revised version of the LBA and stock-recruitment relationships that included updated data through 1994. Zheng et al. (MSb) analyzed long-term harvest strategies and Zheng et al. (MSc) evaluated rebuilding strategies for this stock . Copies of the four technical papers are available from the authors.

The relationship Between Management Goals and Harvest Strategy

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. The goal of the policy is to maintain and improve these crab resources for the greatest 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 and 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:

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

The Board recognized that these policies may not result in maximization of physical or economic yield. The Board also directed the Alaska Department of Fish and Game (ADF&G) to establish harvest strategies consistent with the Board policy (5 AAC 34.080).

The Board's management goal and policies provide very specific criteria with which the current and alternative harvest strategies for Bristol Bay red king crabs can be evaluated. The following three Board policies imply that harvest rates should be constrained to low or moderate levels: maintain multiple ages and sizes of mature crabs in the population, reduce the variation in yield, and minimize chance of fishery closure due to low abundance. Three other Board policies lead toward the use of a fishery threshold: maintain minimum levels of spawning stock which improve long-term yield, safeguard against population collapse, and provide managers some flexibility when spawning stock is depressed and recruitment uncertain.

A rebuilding strategy will need to patiently accumulate stock by assuring that additions to the stock through recruitment and growth exceed deletions from the stock from directed harvest, handling, bycatch and natural mortality. A rebuilding strategy must balance more immediate loss of harvest against future gains in stock productivity and yields. So harvest strategy depends not only on the management goal and policies but also the planning horizon (or time frame) to realize the desired outcome. Red king crabs take about 7 years to mature and can live more than 20 years. Because of management actions that affect the current spawning stock will take 7 or more years to be manifested as recruitment, the process of rebuilding the population is very slow. Therefore, a planning horizon of several decades is needed to offset the more immediate cost of rebuilding. We must also recognize that uncertainties about mortality from handling or other sources and uncertainty about the degree of density-dependence in the stock-recruit relationship lead us toward selection of a long-term optimal harvest strategy that is robust to differing assumptions.

Abundance Estimation

The National Marine Fisheries Service (NMFS) has estimated the abundance of red king crabs in Bristol Bay by assessment surveys conducted annually since 1968 (e.g., Stevens et al. 1994). This multispecies survey employs a systematic design in which a 20 X 20 nautical mile grid is overlaid on the eastern Bering Sea, and one trawl tow is made per 400 square nautical miles. Population size has been calculated by NMFS using an area-swept method from the number of crabs caught, the width of the trawl opening, and the distance towed.

Over the years, questions have been raised about the accuracy of the survey and the area-swept estimation method due to the coarse spacing of stations, uncertainties about trawl catchability, and occasional unexpected changes in estimated stock size from year to year. Additionally, Increased fishing power in recent years in Bristol Bay coupled with the contracting geographic distribution of red king crabs has led to much shorter seasons. Short seasons yield very few days to accumulate data and therefore few data points for managers to draw conclusions on stock status.

Given the uncertainty in area-swept methods of population estimation and extremely short time series of inseason data for Bristol Bay red king crabs, ADF&G sought to develop methods to estimate crab abundance more accurately. The department wanted to greatly improve the preseason estimates by reconciling the current year's survey results with prior expectations about the stock from previous surveys and harvests. To do so we made objective use of all available survey and fishery data coupled with our knowledge of crab growth and mortality. Such a method would allow fishery biologists and managers to better distinguish true population changes from survey measurement errors. This is because methods that use multiple years and types of data to track trends in stock status smooth out the measurement errors -- year's when the area-swept estimate of abundance was unrealistically high or unrealistically low. Thus, armed with a higher level of confidence about the population estimates, ADF&G managers can focus on timing fishery closures to meet the preseason guideline harvest level (GHL). Additional benefits of more accurate methods are that preseason GHLs and preseason prices should more accurately reflect actual harvests, and as a result fishers should be better prepared to plan their fishing operations for the season.

The Need to Re-evaluate Harvest Strategy

The Board endorsed the current harvest strategy for Bristol Bay red king crabs in 1990 (Pengilly and Schmidt 1995). The current strategy sets GHL as a fixed percentage of mature male abundance and by placing a cap on the overall percentage of legal males that could be harvested. The fishery is to be closed if the abundance is at or below an established threshold. Based on the best available information for Bristol Bay red king crabs at that time, ADF&G established, a mature male harvest rate of 20%, and a harvest cap of 60% of legal abundance. The mature male harvest rate and maximum legal harvest rate were inferred from a simulation study of the red king crab population off Kodiak Island (Schmidt and Pengilly 1990). The North Pacific Fisheries Management Council, Crab Plan Team estimated a threshold level of 8.4 million mature female crabs and that value was incorporated into the harvest strategy. The threshold was estimated using a method that assumed a different stock-recruit model than was actually fitted at the time. Additionally, the spawning stock used in the stock-recruit model was fertilized female crabs and did not include the contribution of mature male crabs to reproduction. Further, the harvest rate and threshold calculations did not take into account the uncertainties on handling mortality and population estimation. Handling mortality is the death of crabs that are caught and discarded back to the sea.

A rational harvest strategy should prescribe a harvest rate that reflects underlying stock productivity. Because fluctuations in the numbers of young entering the population (recruits) can cause huge swings in crab abundance, it is very important to have some understanding about how recruitment of young crabs relates to the abundance of their parental spawning stock. Additionally, it is important to try to account for the effects of environmental changes and fisheries. Our success in developing a LBA for Bristol Bay red king crabs allowed us to more accurately estimate population abundances, redefine the spawning stock from the number of fertilized female crabs to the effective spawning biomass, and reconstruct stock-recruitment relationships from the improved estimates.

Optimal harvest strategy should be based on the best scientific findings. Therefore, we used the LBA and updated stock-recruit curve to construct simulation models specifically designed to evaluate long-term harvest rates and threshold levels, and a rebuilding strategy for Bristol Bay red king crabs. We recommend changing the current harvest strategy based on our new findings.

POPULATION ESTIMATION USING THE LENGTH-BASED ANALYSIS

We assembled all relevant information on red king crabs in Bristol Bay to construct the LBA. This included: (1) individual station data available from each NMFS trawl survey since 1968, (2) commercial catches from ADF&G fish ticket records; (3) shell age and size composition data from NMFS surveys and ADF&G dockside and observer catch samples, and (4) growth increment data for males from Weber and Miyahara (1962) and for females from Gray (1963). There are some features of red king crab biology that are not well known, so we considered them as parameters to be estimated. These are natural mortality, molting probability, and the number of recruits entering the modeled population. The term "natural" mortality is problematic because it is a catchall for deaths due to a variety of causes. A number of factors could give rise to "natural" mortality including environmental change, disease, predation, ghost fishing, bycatch and handling mortality. Currently, it is not possible to separate these factors in the LBA estimation of "natural" mortality. One parameter that we chose not to estimate is trawl gear catchability. Instead, we assumed that the catchability of the survey trawl gear for the size classes considered by the LBA model (female crabs >90 mm and male crabs > 95 mm)is 100%. In other words, all red king crabs of the modeled size classes in the path of the trawl are caught by the trawl. Another study (Kruse and Collie 1991; Collie and Kruse MS) showed that this assumption is reasonable.

To analyze the stock, we kept track of the abundances of male and female crabs separately. In overview, the model works as follows. In any one year the summer trawl survey data provide a tentative estimate based on the area-swept method of the abundance of males and females, their sizes, and shell conditions (e.g., newshells that molted within the past year and oldshells that have not). These abundances are decreased by the number of crabs harvested during each year's fall fishery according to the size and shell-age distributions of the catch. We have good information about crab growth from previous tagging studies and use this to increase the size of crabs in the spring. Young crabs, the recruits, are added to the abundance. Crabs that have died of natural causes are subtracted from the population according to the estimated natural mortality rate. This approach is repeated yearly over the entire record of surveys and commercial catches. The LBA estimates of abundances are then compared to the area-swept estimates of abundance to refine the uncertain parameters and reduce survey measurement errors. The product is a revised time series of crab abundances that provide our best estimates of true abundances given all the information available to us.

The LBA allowed us to estimate natural mortality, molting probability, and recruitment. Typically, scientists report natural mortality as an instantaneous rate, but here we report it as an annual percentage so that it is easier to understand. Natural mortality was low in the

1970s (20% for males and 38% for females) then shifted to high levels in the early 1980s (65% for males and 82% for females) and then returned to low levels in the mid-1980s (20% for males and 27% for females). The higher natural mortality for female crabs compared to male crabs may in part reflect handling mortality. Molting probabilities depend on the size of crabs. Generally, molting probabilities were very high while the population increased from 1972-1979, low during population declines in 1980-1984 and 1992-1993 and intermediate from 1985-1991 when the population showed signs of improvement.

The LBA estimates of abundance fitted well with the NMFS survey estimates of abundance (Figure 1). The legal crab (males ≥135 mm carapace length, CL) abundance increased dramatically in the middle and late 1970s then decreased precipitously in the early 1980s (Figure 1). A moderate increase followed in the mid-1980s then legal crab abundance resumed a decline in recent years. Large female crab (≥90 mm CL) abundance also peaked in the late 1970s, decreased suddenly in the early 1980s and has remained low since the early 1980s (Figure 1). The dramatic declines in abundance coincided with the highest catches and the highest harvest rates on record in 1980 and 1981 (Figure 2). Harvest peaked at 21 million crabs (130 million pounds) in 1980, and legal male harvest rate peaked at an estimated 55% in 1981.

One benefit of the LBA is that it smoothes out measurement errors in the survey. Note for example that the survey appeared to underestimate legal male crab abundances in 1988, 1990, and 1992. For large female crabs, survey abundance was highly variable during 1972 to 1980, but has been more consistent since then. Survey and LBA estimates of male and female crab abundances have been similar in recent years.

STOCK-RECRUITMENT RELATIONSHIP

The LBA provides estimates of the abundances of mature male and female crabs that are used to define the effective spawning biomass (parents) and abundances of resulting progeny (recruits). These abundances are used to calculate stock-recruitment relationships. We estimated effective spawning biomass as the number of mature female crabs that the population of mature male crabs could successfully mate in a given year. The size of maturity of males and females is known fairly accurately. But, there remain questions about exactly how many females a male of given size can mate. For example, in a confined environment, large males can mate with 7-9 females (Powell et al. 1974) and small males can mate with only 2-3 females (Paul and Paul 1990). Breeding pair data indicate that oldshell males play an important role in mating (Schmidt and Pengilly 1990). Also, we know that egg extrusion is incomplete if a female does not mate within one day of molting, and no egg extrusion occurs if the female is not mated within 9 days of molting (FAJ 1963). In the real world, it takes time for males to locate a premolt female, grasp and hold her for 3-7 days (Powell and Nickerson 1965) while she molts, and then mate with her. Thus, controlled experiments in which males are offered unlimited females for mating may yield overly optimistic estimates of their actual mating success. We assumed that males on average can mate with one to three females depending on male size. We estimated the size of the effective spawning stock using this simple linear relationship and the abundance of mature males by size. If there were not enough females for the males to mate, then we set the size of the effective spawning stock equal to the number of mature females. To estimate resultant recruitment, we used the LBA estimate of the number of recruits entering our modeled population 7 years later. Then, using standard statistical methods we fit a curved line through a plot of recruits (vertical axis) against effective spawning stock in biomass (horizontal axis) to estimate the stock-recruitment relationship (Figure 3). This relationship for Bristol Bay red king crabs can be interpreted in several ways. One explanation is that changes in recruitment are a function of the size of the effective spawning biomass. Another explanation is that recruitment changes are due mostly to decadal shifts in environmental conditions. Because both explanations are potentially valid, we fitted an intermediate stock-recruit curve that includes the influence of both stock and environmental causes on recruitment variations.

Development of a stock-recruitment relationship is an important result from the LBA. From our analysis it appears that a shortage of mature males to mate all mature females occurred in 4 of the 23 years studied: 1972, 1973, 1981, and 1982. During these years the effective spawning stock was calculated from the estimated number of females the available males could mate. The greatest shortfall of males occurred in 1982 after several years of heavy fishing and high natural mortality.

The stock-recruit curve (Figure 3) fitted the data well (r^2 = 0.62, df = 15). The curve combines the effects of stock size with environmental changes. Stock size effects are supported by strong recruitment at intermediate levels of effective spawning biomass, moderate recruitment at high stock size, and very low recruitment associated with low spawning biomass. The influence of environmental shifts are suggested by the fact that good years tend to follow good years and bad years tend to follow bad years. Regardless of the relative roles of stock size and environment, it is clear that recruitment is jeopardized when the effective spawning biomass is low.

BRISTOL BAY RED KING CRAB STOCK STATUS

The Bristol Bay red king crab stock is currently depressed. In 1994, the stock reached it's lowest abundance since standard survey assessment began in 1972 (Table 1). The abundance of pre-recruit male crabs (110-134 mm) in 1995 was at the lowest level on record. Mature male (>119 mm) and female (>89 mm) crab abundances have declined steadily since 1989. However, recruitment and legal male abundance increased slightly from 1994 to 1995. Recall there is a 7 year lag between spawners and recruitment of resultant progeny so recruits in 1995 result from the effective spawning biomass in the 1988 brood year. The effective spawning biomass increased from the 1988 brood year to the 1989 brood year (Table 1) which will produce the recruits we should see in 1996. Despite some hope for modest improvements in recruit abundances, it is evident from the 1988 brood year data point on the stock-recruit curve (Figure 3) that spawning biomass and recruitment are still perilously low. Note that the effective spawning biomass has experienced an overall reduction of 42% since it began a steady decline in 1990 (Table 1). Effective spawning biomass is now at it's second lowest point of record, the lowest point occurred 10 years ago in 1985. As a result we do not anticipate significant improvements in the stock unless exceptionally favorable environmental conditions over the past years lead to an unexpectedly strong year class.

Average weight of mature female crabs has increased in the past 3 years from an average of 1.7 lbs to 2.2 lbs. This rise is characteristic of an aging breeding population after a period of poor recruitment. The population benefits in that these larger females produce more viable eggs than smaller females. However, the population is at risk of losing these older crabs to senescence. Therefore, it is imperative to protect the remaining spawning stock to promote rebuilding of the population from this fragile state.

LONG-TERM HARVEST STRATEGIES

To analyze a robust long-term harvest strategies, the population of Bristol Bay red king crabs has to be simulated over many centuries. This necessitates projection of future abundances. The stock-recruit curve provides the foundation for the simulation model by projecting the number of future recruits to the population based on the corresponding effective spawning biomass and assumed environmental conditions. The simulation model consists of a population submodel and a harvest submodel.

The population submodel is based on the LBA and it keeps track of population increases from recruitment and growth, and population decreases due to natural and handling mortality. Natural mortality is simulated to shift between high and low levels to mimic changes that have been observed over the last three decades. In the simulation, high levels were much less frequent than low levels so that handling mortality could also be added to the model without compounding its effects. Handling mortalities were included in the simulation to study the effect of this potentially important factor on harvest strategy. Actual handling mortality rates in the fishery are unknown. Handling mortality of sublegal male and female crabs was set to a 0%, 10%, 20% or a 50% rate in different simulation scenarios to cover as yet undocumented handling mortality and the likely range of values experienced over the history of the fishery. Our calculation of handling mortality assumed that catchability of sublegal male and female crabs is 50% of that for legal size male crabs. The number of female deaths (D) due to handling equals the total female population abundance (F) multiplied by the catchability (0.5), legal male harvest (H, which averages about 40%), and specified handling mortality rate (HM): $D = F*0.5*H*HM$. Deaths from handling for sublegal males are obtained by replacing female abundance in the equation with sublegal male abundance. For example, if we assume a legal male harvest rate of 40%, then a 20% handling mortality rate on a population of 100 female crabs would result in the death of 4 crabs.

The harvest submodel is a set of rules that specifies combinations of mature male harvest rate, maximum legal harvest rate and threshold in millions of pounds of effective spawning biomass used to determine the harvest to be deducted from legal abundance. For example, our current harvest strategy is a 20% harvest rate applied to the abundance of mature male crabs, a maximum rate of 60% on legal male crabs, and a threshold of 8.4 million mature female crabs which equals 14.5 million pounds of effective spawning biomass. The simulation was run for many years so that the response of the population and fishery could be evaluated over the long-term. Statistics on yield, variation in yield, percent of years the fishery is closed and variation in effective spawning biomass were recorded over time. These simulations attempt to reproduce changes in the crab population that would be likely to occur under the current harvest strategy and different test harvest strategies if we applied them to the real stock of Bristol Bay red king crabs.

We considered two performance measures in our analysis of long-term harvest strategies. One measure is optimum yield which incorporates multiple objectives of the Board management policy by equally weighting the benefits of maximum yield with the benefits of stable yield over the long-term. Essentially, this means that some short-term yield and fishing opportunities may be sacrificed if over the long-term it leads to more consistent GHLs, shorter closure periods, and longer open periods. The other performance measure we considered is mean yield which is the average yield expected over the long-term. If the primary management objective is to maximize the catch, then it would be desirable to find the combination of harvest rate and threshold that produce the maximum mean yield. By way of example, a pulse fishery -- a fishery with a few years of extremely high catches followed by many years of no fishing -- may be a reasonable strategy if the only management objective was to maximize yield, but it would be a very poor strategy with respect to the Board policy on king crab management that includes objectives to produce high and stable yields and to minimize the risk of irreversible adverse effects on reproductive potential.

We sought to identify a harvest strategy that is robust to different assumptions about the unknown model parameters. We use the term robust to indicate a harvest strategy that produces high and relatively stable yields while also avoiding combinations of threshold and harvest rate that could pose risk of population collapse. Handling mortality exerts a strong influence on our results. However, few potential factors that contribute to unobserved handling mortality have been studied so the appropriate level of handling mortality to apply to analysis of harvest strategies is not clearly understood. Therefore the effects of a range of handling mortalities on long-term management goals are presented to include the possible handling effects that research has yet to corroborate. There is uncertainty in the interpretation of stock-recruitment data. Additionally, a shift in the level of natural mortality cannot be predicted in advance and it can take several years after a shift to identify that it has occurred. Similarly, measurement errors in the trawl survey data can take several years to smooth out with the LBA. Both of these errors are projected into the annual LBA estimates of population abundance and in turn affect the abundance used to evaluate whether the stock is above or below threshold and the resultant harvest rate.

Results can be evaluated by comparing the optimum yield and mean yield for the current harvest strategy to those for robust harvest strategies. Table 2 shows how mature harvest rates and threshold levels affect the level of optimum yield that could be realized in the long-term given the current 60% maximum legal harvest rate and either a 0%, 10%, 20% or 50% handling mortality rate. Because increased handling mortality reduces yield, optimum yields are scaled between 0% and 100% of the maximum optimum yield for each of the four panels. Threshold is expressed in millions of pounds of effective spawning biomass. Threshold for the current harvest strategy is 8.4 million mature females which on average equates to 14.5 million pounds of effective spawning biomass.

The first panel of Table 2 shows that, if we assume a 0% handling mortality rate, then the optimum yield for the current harvest strategy (60% maximum legal harvest rate, 20% mature harvest rate, and threshold of 14.5 million pounds) is 99.4% of the highest value possible. Optimum yield is actually maximized at a mature harvest rate of 20% and a threshold of 4.8 to 9.7 million pounds. If we assume the level of handling mortality is 10% (panel 2), then optimum yield is maximized at the current harvest strategy. Although we don't know, it may be that handling mortality occurs at rates in excess of 10% and could be as high 20% or conceivably higher on occasion. If handling mortality is greater than 10% (panels 3 and 4) then neither the current strategy nor the strategy that produces the highest optimum yield offer much buffer against population collapse because adjacent combinations of threshold and harvest rate produce yields that fall to zero. Furthermore, the number of scenarios where the population cannot be sustained is strikingly higher for the 50% handling mortality rate compared to the 20% handling mortality rate. If we assume a 20% handling mortality rate (panel 3) with our current harvest strategy of a 60% maximum legal harvest rate, 20% mature harvest rate, and a threshold of 14.5 million pounds then 96.8% of the maximum optimum yield is realized. A reduction in the mature harvest rate to 15% and retention of the current threshold of 14.5 million pounds would essentially maximize optimum yield and be fairly safe from risk of stock collapse given our limited knowledge of handling mortality. If handling mortality is greater than 20% or as high as 50% (panel 4) then our current harvest strategy results in zero optimum yield indicating the population will not be sustained. In this case a mature harvest rate of 15% and a threshold of 24.2 million pounds would be necessary to maximize optimum yield and protect the stock from deficient harvest strategies that lead to population collapse

Table 3 shows comparable results in terms of mean yield rather than optimal yield. Mean yield in Table 3 is expressed as a percentage of the maximum mean yield possible over the long-term for a 60% maximum legal harvest rate and a given combination of mature harvest rate, threshold and handling mortality. The current harvest strategy (20% mature harvest rate and 14.5 million pound threshold) results in 89.8 percent of the maximum yield possible with a 0% handling mortality rate (panel 1). To maximize yield assuming a 0% handling mortality rate we would need a 35% mature harvest rate and a threshold of 48.4 million pounds. As the assumed handling mortality rate is increased (panels 2 and 3), the mean yield achieved with the current harvest strategy remains at 90% of the maximum possible for each scenario. But to maximize yield requires lowering the mature harvest rate to 25% while retaining a threshold of 48.4 million pounds. If we assume a handling mortality as high as 50% (panel 4), then the current harvest strategy results in essentially no yield, i.e., stock collapse.

A harvest strategy that maximizes yield has drawbacks for obvious reasons. Comparing the panels of Tables 2 and 3, we see that the optimum yield and mean yield are maximized at quite different combinations of harvest rates and threshold levels for all scenarios of handling mortality. Optimum yields are maximized for a 60% maximum legal harvest rate at mature harvest rates of 15%-20% and threshold levels at or below 29 million pounds. Mean yields are maximized at mature harvest rates of 20%-40% and at threshold levels at or above 33.9 million pounds. These differences occur because optimum yield balances maximum yield with stability in yield whereas mean yield ignores the adverse effects of fishery closures provided yields are high over the long term.

Next we examined our two performance measures at a lowered maximum legal harvest rate of 50% (Tables 4 and 5). Optimum yields for a 50% maximum legal harvest rate and ranges of mature harvest rates and thresholds are presented in Table 4 for 0%, 10%, 20% and 50% handling mortality rates. At a 0% handling mortality rate our current mature harvest rate of 20% and threshold of 14.5 million pounds result in an optimum yield of 99.5% (Table 4, panel 1) and a mean yield of 92.7% (Table 5, panel 1) of the maximum possible for this scenario. Under a scenario of a 10% handling mortality rate, optimum yield (Table 4, panel 2) is maximized with our current mature harvest rate and threshold but mean yield (Table 5, panel 2) maintains only 92.7% of the maximum possible. For a 20% handling mortality rate, a 15% mature male harvest rate results in higher optimum yields (Table 4, panel 3) than the current 20% rate but lowers mean yields (Table 5, panel 3). If handling mortality is as high as 50% the stock will likely collapse unless mature harvest rate is lowered to 15% and the threshold increased to 24.2 million pounds (Tables 4 and 5, panel 4). Mean yields increase slightly for all scenarios of handling mortality, mature harvest rate and threshold when the maximum legal harvest rate is decreased from 60% to 50% (Tables 3 and 5). A 50% maximum legal harvest rate also provides more buffer from risk of population collapse compared to a 60% maximum legal harvest rate if handling mortality is above 10%, if threshold levels are below 24.2 million pounds and if the mature harvest rate is inadvertently higher than 15% (Tables 2 and 4, panels 3 and 4; Tables 3 and 5, panels 3 and 4). This final point may seem of no consequence under the Board policy of a fixed mature male harvest rate. However, if natural mortality switched to a high level or the trawl survey was subject to measurement error or changes in catchability that falsely inflated abundance estimates for several years in a row then our LBA estimates of abundance would also be high. Unknowingly, managers would be applying a higher harvest rate on the actual stock than intended and this would cause overharvest.

To sum up thus far, If we assume a handling mortality of 10% then the current harvest strategy with a 20% mature harvest rate and a 14.5 million pound threshold would be robust for either a 60% or 50% maximum legal harvest rate. However, if handling mortality is closer to 20%, then a mature harvest rate of 15%, a decrease in the maximum legal harvest rate to 50% and maintenance of the current threshold level of 14.5 million pounds resulted in the highest optimum yield while providing protection from risk of population collapse. Decreasing the current mature harvest rate from 20% to 15% is a robust long-term harvest strategy for both maximizing and stabilizing long-term yield given the extent of our knowledge of stock-recruit relationships and uncertainties about handling mortality and other sources of mortality. Reducing the maximum legal harvest rate from 60% to 50% is part of our robust long-term harvest strategy for Bristol Bay red king crabs because it decreases the risk of population collapse in the event of a potential error in the survey or dramatic shift in natural mortality. Lastly, if concern exists that handling mortality could reach as high as 50% on occasion, then a long-term harvest strategy would include a mature harvest rate of 15%, a maximum legal harvest rate of 50%, and would increase the threshold from the current level of 14.5 million pounds to 24.2 million pounds to protect against high vulnerability to population collapse at lower thresholds.

It is important to compare the current harvest strategy to the robust long-term harvest strategy for several measures of performance relevant to the Board policy on red king crabs in Bristol Bay. So far we have discussed the yield and variation in yield. Also, we kept track of two other important considerations: the variation in effective spawning biomass and the number of years that the fishery would be closed if abundance drops below threshold. The amount of variation in the effective spawning biomass indicates the degree of instability in future recruitment and frequency of fishery closures. Keeping track of the number of years that the fishery would be closed can be considered as an indicator of lost benefits due to foregone harvests.

We compared mean yield, standard deviation of yield, the coefficient of variation (CV) of the effective spawning biomass, percentage of years without a fishery, and ranges of the duration of years the fishery was closed and open for the current and robust strategies at 0%, 10%, 20%, and 50% handling mortalities (Table 6). Mean yield was higher for the current harvest strategy than the robust long-term harvest strategy at 0%, 10% and 20% handling mortality rates but the fishery was closed a slightly greater percentage of the time. The current harvest strategy does not sustain the red king crab population in Bristol Bay at a 50% handling mortality rate. The robust long-term harvest strategy produced the desirable effect of lowering the standard deviation in yield and CV of effective spawning biomass. Lower values for these factors are indicative of long-term stability.

Comparison of historical yield and standard deviations for three different but overlapping series of years to the yield and standard deviation for the current and robust long-term harvest strategies demonstrates a slightly larger decrease in yield under the robust long-term harvest strategy than the current harvest strategy (Table 6, panel 2). Both strategies have lower standard deviations in yield than observed historically but the robust long-term harvest strategy results in a greater reduction in standard deviation in yield than the current harvest strategy.

REBUILDING STRATEGY

An important consideration for any harvest strategy is its effectiveness in rebuilding a depressed stock to a productive level. The Board specifically directs management in it's policy statement to maintain an adequate brood stock to rebuild king crab populations when they are depressed. They also specify that maintenance of brood stock takes precedence over short term economic considerations. Towards that end, the Board directed ADF&G to establish thresholds when adequate data were available and to close fisheries when the population is at or below threshold.

We must recognize that Bristol Bay red king crabs are at an all-time low abundance and increased recruitment is essential for rebuilding the stock. Two factors influence recruitment: the effective spawning biomass and environmental conditions. The latter is not controllable through management action but we can change fishing activities to increase the likelihood of strong recruitment by rebuilding of the spawning biomass. The Bristol Bay red king crab stock is depressed and the fishery has been closed for two years. It will likely take a number of years to rebuild the effective spawning biomass to maintain a productive brood stock unless extremely favorable environmental conditions prevail. This is evident by following the trajectory of recent years on the stock recruitment curve (Figure 3). Effective spawning biomass has declined steadily since 1989 (Table 1) which bodes very poorly for recruitment in the future given the stock-recruit curve.

To enhance our chances of rebuilding the stock in the most efficient manner we analyzed a suite of rebuilding strategies using the LBA model and computer simulations to select a strategy based on performance criteria. As with the long-term harvest strategies analysis described previously in this report, the population of Bristol Bay red king crabs is simulated over time using the stock-recruit curve to project future abundances under variable environmental conditions. The main difference between the rebuilding strategies simulation and the long-term harvest strategy simulation is that we examine a rebuilding schedule over a short time span compared to the long-term averages we examined in our analysis of optimal harvest policy. The rebuilding simulation model, like the long-term harvest strategies model, consists of a population submodel and a harvest submodel. The population submodel increases and decreases the population through growth and recruitment and commercial catch, natural, handling, and bycatch mortality. This submodel differs in two ways from that used to simulate the population over the long-term. First, a mean annual natural mortality was computed for male and female crabs rather than a variable natural mortality over time (Zheng et. al. MSc). This is because a short time horizon of a few decades was used to rebuild the stock compared to many centuries used to simulate the population for the long-term harvest strategies analysis. Second, for basis of comparison we assumed a 20% handling mortality rate for large female and sublegal male crabs caught in the directed fishery and we deducted 200,000 crabs from the model each year based on the Zone 1 prohibited species cap of 200,000 red king crabs in groundfish fisheries in the eastern Bering Sea. In fact, we don't know what handling mortality rate occurs in the directed fishery and we don't know how many crabs are killed by trawls. But these numbers seemed reasonable to evaluate alternative rebuilding strategies until better information becomes available. The harvest submodel specifies alternative rebuilding schedules by varying the mature male harvest rate and threshold used to deduct harvest from the legal abundance.

We selected from rebuilding strategies that ranged from no harvest until the stock is rebuilt (most aggressive) to the status quo (least aggressive). Intermediate between these two extremes we evaluated rebuilding strategies that become progressively more aggressive by increasing the threshold level and decreasing the mature harvest rate when the stock is above threshold but below the target level (Table 7, panel 1). A rebuilding strategy culminates when a target biomass is reached where the stock is considered rebuilt to a productive level. We set the target rebuilding biomass equal to an effective spawning biomass of 55 million pounds (Figure 3). This level is intermediate to historical levels, effective spawning biomasses above this point have produced strong recruitment with high probability in the past. Once the population reached this target level in a simulation, we used the current mature male harvest rate (20%) for the remaining years. Although we recommend a 15% harvest rate of mature males over the long-term, we thought it prudent to analyze the 20% rate corresponding to the current strategy. Each strategy was simulated over 50 years, a realistic period to promote rebuilding given the long life span of these crabs.

A number of performance measures were used to evaluate rebuilding strategy alternatives compared to the current harvest strategy. Statistics on effective spawning biomass, catch, probability of fishery closure, and probability of rebuilding were collected. An example best illustrates how these probabilities are estimated. To estimate the probability of a fishery being rebuilt in year 10 of the 50 year planning horizon the rebuilding simulation model was run 500 times with harvest deducted from the legal abundance according to the specific rebuilding strategy. The 500 replicates introduce different environmental conditions and measurement error into the estimate of probability. A tally is kept of the number of times the effective spawning biomass is above and below the 55 million pound rebuilding target during the 500 simulations. The tally of effective spawning biomass above 55 million pounds is divided by the total number of simulations (500) to estimate the proportion of times the fishery was rebuilt, and this equals the rebuilding probability for that one year. The probability of fishery closure is estimated the same way and is the proportion of the 500 replicate simulations with an effective spawning biomass below threshold which triggers a closure.

We sought a rebuilding strategy that is consistent with the objectives of the Board policy to provide for sustained and reliable fisheries and opportunity for stock rebuilding. To do so we chose a strategy that minimized the probability of fishery closure by maintaining the current threshold of 14.5 million pounds of effective spawning biomass (rather than increasing the threshold) but which reduces the mature harvest rate by half to a 10% rate. Comparison of the current harvest strategy to the selected rebuilding strategy shows both had over a 30% probability of fishery closure the first year of the simulation but declined rapidly to low probabilities of fishery closure by the fifth year (Figure 4). The current harvest strategy maintained approximately an 8% probability of closure in any given year over the 50 year planning horizon. This is about 5% higher than for the selected rebuilding strategy where the probabilities of fishery closure averaged about 3% and declined over the 50 year planning horizon. The selected rebuilding strategy has a higher probability of achieving the stock to the target level of effective spawning biomass at a given point in the 50 year planning horizon and does so more rapidly than the current harvest strategy (Figure 5). The rebuilding strategy has a 50% probability of achieving the target level of effective spawning biomass in 15 years, 10 years earlier than with the current harvest strategy. Under the rebuilding strategy you would have a 95% probability of reaching the target level over a 50 year planning horizon but only a 75% probability using the current strategy.

Performance of all rebuilding strategies we considered is summarized in Table 7. Strategy 4 is our recommended rebuilding strategy. Strategy 3 (Table 7, panel 2) outperformed the recommended strategy with respect to rebuilding the stock but closed the fishery until the target level of effective spawning biomass, 55 million pounds, was reached. Strategy 7 also provided swifter rebuilding to the target level of effective spawning biomass than strategy 4. That strategy had a smaller reduction in mature harvest to 15% but the fishery had fewer openings because of an increase in threshold to 24.2 million pounds.

A desirable rebuilding strategy needs to balance immediate loss and future gain. Comparison of our current harvest strategy to the rebuilding strategy we chose demonstrates that the status quo harvest strategy sacrifices stock productivity after 10 to 50 years to maximize yield in the next 20 years. First, lets look at the future stock productivity as measured by the biomass of effective spawners. The probabilities of reaching an effective spawning biomass using the current harvest strategy and the rebuilding strategy over 10, 30 and 50 year planning horizons are compared in Figure 6. The current harvest strategy has a higher probability of smaller average effective spawning biomass (mean of 27.7 million pounds) over a 10 year period than the proposed rebuilding strategy (mean of 33.9 million pounds). Neither strategy comes close to producing the target level of 55 million pounds of effective spawning biomass using this short planning horizon. Increasing the planning horizon to 30 years results in greater probabilities of achieving larger effective spawning biomass for both strategies. However using the rebuilding strategy, the probability of the effective spawning biomass being below 25 million pounds is low and the probability of a mean effective spawning biomass of 50 million pounds is in excess of 50%. The current harvest strategy by comparison still results in a high probability of a low effective spawning biomass with a mean near 25 million pounds. The rebuilding strategy over a 50 year planning horizon produces a high probability of an effective spawning biomass greater than the target level of 55 million pounds. The current strategy even over a 50 year period has a high probability that effective spawning biomass will be lower than the target level.

Annual catch for the current strategy and rebuilding strategy over a 50 year planning horizon are presented in Figure 7. In the first 10 years of our simulations the catch is greater under the current harvest strategy but thereafter catches average about 5 million pounds higher annually with the rebuilding strategy. The current harvest strategy produces immediate benefits through higher catches in the near future than the rebuilding strategy. However, these benefits are short lived because it reduces the effective spawning biomass and subsequently lowers recruitment. As a result the current strategy is expected to produce lower long-term effective spawning biomass and catches than the rebuilding strategy. Clearly, careful consideration must be given to the planning horizon intended by the policies used to achieve the Boards management goal and benefits available from this resource.

DISCUSSION

The LBA estimates of abundance of red king crabs in Bristol Bay uses the best scientific information available: knowledge of crab biology, numbers of crab by size, shell condition, and sex from the NMFS area-swept method, commercial catch and the catch composition from observers and dockside samplers during the commercial fishery. The LBA allows us to estimate historical shifts in natural mortality and proportion of crab molting rather than assuming constant values that are known to be in error. When we compare the LBA estimates of abundance to the annual area-swept estimates we generally find close correspondence in the long-term trend. Thus, the LBA helps validate the NMFS survey to estimate red king crab abundance in Bristol Bay. However, the LBA smoothes out the measurement errors of the survey. Because of these adjustments for survey measurement errors, the LBA provides abundance estimates that are likely to be most representative of the true population.

Beginning in 1995, the LBA was used to analyze survey and fishery data to set the annual GHL for the Bristol Bay red king crab stock. Our principle reasons are that the LBA provides a logical interpretation of survey results and it also provides estimates that are more consistent with data on size frequency and shell composition from the survey. It is important to keep in mind when comparing the two estimates that the area-swept estimator implicitly assumes that the current year's crab population is totally independent of last year's. In contrast, the LBA makes use of information from previous year's population abundances to estimate the current year's stock size.

The LBA can project next year's summer abundance in advance by taking the abundance estimate from this year's summer survey, removing commercially-caught crabs and accounting for annual mortality, crab growth and recruitment the following spring. The LBA is designed to be updated annually with new survey and fishery data. It is flexible in that we can make modifications as new information becomes available. In fact, it was already modified once (Zheng et al. 1995b) from the original version (Zheng et al. 1995a). Results from new research on handling mortality, breeding success of male crabs, and environmental effects can be incorporated in the LBA and future analyses of harvest strategy.

The stock-recruitment relationship for red king crabs in Bristol Bay demonstrates how current and historical stock sizes are associated with stock productivity. The stock-recruitment relationship helps us reconstruct the roller coaster history of the Bristol Bay stock. Intermediate stock sizes of the late 1960s and early 1970s was associated with outstanding recruitment. Seven years later in the late 1970s (Figure 3) this strong recruitment pushed the spawning stock to record levels. As the stock increased, a huge domestic fishery developed. Catches climbed dramatically, harvest rates increased to high levels, and natural mortality increased 4 to 5 fold (Figure 2). These factors combined to cause a very rapid shift from a high stock and moderately-low recruitment to a depressed stock and low recruitment during 1980 to 1982. Moderate recruitment from the high stock levels of the late 1970s was cropped off by fairly high harvest rates in the mid 1980s. Since that time, the depressed stock has continued to produce low recruitment even though natural mortality has long since returned to more normal, lower levels. "Natural" mortality is probably a somewhat misleading term. Old age and ecological processes such as predation and disease typically are associated with natural mortality but handling mortality in crab fisheries and bycatch mortality in the groundfish fisheries are potential major contributors. Also uncertain are effects of trawling on crab habitat or crabs not retained by trawls and effects of ghost fishing by lost pots especially prior to biodegradable escape requirements for pots established in 1977.

Clearly, the current depressed spawning stock has a very low chance of producing a strong year class. The stock-recruit curve suggests that improvement in the stock will depend on a rebuilding plan that patiently accumulates spawning stock by insuring additions through growth and recruitment are greater than losses from natural mortality, bycatch, and handling mortality. The only other hope is for a chance environmental event that yields exceptionally strong recruitment. However, good recruitment has yet to be documented for Bristol Bay red king crabs in a depressed stock condition.

Red king crabs have life history traits that make them exceptionally vulnerable to overfishing (Kruse 1993). Once the population collapses, it will take a long time to recover. For the two largest red king crab populations in Alaska, a decade after crashing in the early 1980s, the abundance of Bristol Bay red king crabs is still low and Kodiak red king crabs are extremely depressed. Similar histories occurred for red king crab stocks along the south side of the Alaska Peninsula and off Dutch Harbor. The red king crab stock in Norton Sound has never been closed due to low abundance, which may be attributed in part to a harvest strategy for Norton Sound that specifies an exploitation rate of half that used in other Bering Sea commercial king crab fisheries (ADF&G 1994). Our analysis of the Bristol Bay stock shows that high harvest rates contributed to the crash of this stock in the early 1980s. Harvest controls may not always be able to prevent population collapse, but they will certainly help minimize the chance of collapse by preventing overfishing. Similarly, there is no guarantee that any management strategy will rebuild Bristol Bay red king crabs within a certain time horizon due to unpredictable environmental conditions. However a strategy with a reduced harvest rate would enhance the chance of rebuilding and reduce the risk of further stock decline.

Optimal harvest strategy depends on management goals. One strategy may be appropriate to maximize yield, whereas a totally different strategy is best to stabilize yield and employment. The Board has set a management policy that considers yield, stability of yield, risks of irreversible adverse effects on reproductive potential, and maintenance of multiple ages and sizes of mature crabs. Harvest rates and threshold are integral parts of the management strategy needed to meet the Board policy. Moderate harvest rates reduce the variation in yield, help to maintain multiple ages and sizes of mature crabs in the population, and reduce the chances that the fishery is closed due to abundances below threshold. The threshold serves as a safeguard to protect the population from total collapse. Because the threshold helps maintain minimum levels of spawning stock, it improves the long-term yield, and it provides managers with flexibility in the face of uncertainty about stock productivity at unprecedented low levels of spawning biomass.

All sources of fishing-related mortality may have an important effect on red king crab harvest strategy. Besides commercial catch, other sources include handling mortality in the directed fishery, bycatch in other pot and trawl fisheries, lethal interactions between crabs and trawls on the sea floor, and ghost fishing by lost gear. Because our purpose was to evaluate harvest strategies for the directed crab red king crab fishery, we attempted to explicitly incorporate a wide range of possible handling mortality rates in our analysis. However, we wish to point out that mortality from other sources can also pose risks to recovery of the stock.

Our model shows that increases in handling mortality cause reductions in recruitment to the fishery and subsequent reductions in spawning stock and yield. However, the appropriate level of handling mortality to apply in our model of red king crabs is uncertain. Murphy and Kruse (1995) compiled a bibliography of capture and handling effects on crabs and lobsters, and Kruse (1993) summarized some of this literature in his review of implications of crab biology on fishery management. Lethal and sublethal effects of handling have been well documented in crustaceans. Effects include immediate death, increased vulnerability to predation, reduced vigor, lost limbs, and reduced feeding and growth. However, these studies show that such effects are species specific.

Zhou and Shirley (1995, MS) attempted to simulate the effects of capture, pot retrieval, pot unloading, and water impact of discarded red king crabs. Crabs were distributed into one of five treatments: controls (unhandled), handled once, handled twice, handled three times, and modified handling (no deck impact and return to water via ramp). Crabs were held for 4 months in the laboratory. Although injuries to spines and rostrum increased with number of handlings, they did not affect survival. Zhou and Shirley found no significant effects of handling on mortality, feeding rates, righting response (a measure of vigor), and bacterial infections. In a field study, Watson and Pengilly (1994) studied the effects of water impact on the recovery of tagged red king crabs during the commercial fishery and found no effect.

In contrast, Carls and O'Clair (1990) conducted experiments on cold air exposure (measured as degree-hours) and found effects on limb loss, righting response, growth rates, and mortality. Generally, the significant effects were limited to the extreme exposures. For instance, mortality increased significantly below -4.6° C-hours (e.g., -4.6° C for 1 hour is treated the same as -9.2° C for 0.5 hours) and death was delayed weeks later often during molting. Likewise, right times were not affected until exposures below -4.6° C-hours, and limb loss occurred during molting for crabs exposed below -6° C-hours. Exposure did not affect percent egg hatching, timing of larval release, nor larval swimming ability unless the female died.

In the 1994 red king crab fishery in Bristol Bay, Zhou and Shirley (MS) estimated that, on average, the maximum time of crabs in air was related to total number of crabs in the pot, ranging from 1.5 minutes for 20 crabs per pot to 3.5 minutes for 150 crabs per pot. Given that air temperature varied between 0.5 to 6.6° C, red king crabs were not exposed to air for degree-hour combinations that caused effect in Carls and O'Clair's (1990) study.

Notwithstanding the studies to date, uncertainties lead us to make assumptions about the level of handling mortality in the red king crab fishery. For instance, effects of handling on subsequent predation are unknown. Also, despite management actions (e.g., gear modifications, concurrent Tanner and king crab fisheries) and improved fishing practices (e.g., sorting tables, discard chutes) taken to reduce handling, some crabs receive abnormal treatment (e.g., dropped from height on deck, stepped on, left on deck). Given these unknowns, we believe that handling mortality of 10-20% may be reasonable for contemporary crab fisheries for purposes of our analysis. We have considered handling mortality as high as 50% in our analysis to gauge potential handling effects that may have occurred historically in some years. In any case, we feel it is prudent to err on the side of conservation in the face of uncertainties until additional research provides a higher degree of confidence about these unknowns.

RECOMMENDATIONS

Our analysis of the Bristol Bay red king crab stock leads us to recommend adjustments to the current harvest strategy to rebuild and maintain the population at productive levels while guarding against effects of handling mortality that were not addressed previously. The current strategy would be adequate if the population was not depressed and if there was no handling mortality. However, this is not the case and a change in harvest strategy is warranted. We recommend changing the mature harvest rate, maximum legal harvest rate and threshold in support of the Board policy on management of crab resources. We addressed this policy by balancing yield and stability of yield while promoting rebuilding of the stock to historically productive levels.

Our first recommendation is in support of the Board policies to maintain reproductive viability and adequate stock to rebuild the population when it is depressed. We recommend using a fishery threshold and redefining it to 8.4 million mature females and an effective spawning biomass of 14.5 million pounds. If preseason survey data indicates that the population is at or below either of these two indices of stock reproductive potential, the fishery will remain closed for the season. A threshold minimizes the risk to future stock productivity by preventing irreversible stock collapse. A threshold is most important when future recruitment is influenced by stock size (versus the environment) because decline of the population below some critical size needed for rebuilding puts it at high risk to irreversible collapse (Zheng et al. MSb). Dual measures of threshold are needed because neither number nor weight of crabs is sufficient by itself to protect red king crab reproductive potential. When recruitment is poor, the majority of spawners are older, larger crabs that weigh more. These heavier spawners equate to fewer individuals so a threshold based on weight alone is deficient in number of spawners. When a strong year class of young crabs coincides with disease and senescence of older crabs, a recruit-based fishery results and spawners are smaller than average. Small male spawners mate with fewer female crabs that produce fewer viable eggs (Paul and Paul, 1990) so a threshold based on numbers alone may not realize the desired production of future effective spawning biomass. Further protection for the stock can be afforded by increasing the threshold above the current 8.4 million mature females (14.5 million pounds effective spawning biomass). If concerns exist that handling mortality is higher than 20%, then it is wise to increase the threshold to guard against severe depletion of the crab stock.

If, in fact, environment is dominating recruitment, then a threshold is less important. However, lower harvest rates are more appropriate for environmentally driven stocks due to the lower productivity of the stock. In such case, mean yields are much lower than those when recruitment is driven by stock size effects (Zheng et al. MSb). Since we don't know yet whether stock size, environment or some combination of both is controlling recruitment, appropriate harvest rates should hedge that both affect recruitment. Our second recommendation to lower harvest rates realizes the benefits in the Boards policy of sustained and reliable supply of product while rebuilding the stock. A reduction in harvest rate also supports the Boards policy to maintain an adequate brood stock to rebuild the red king crab population from it's depressed state. Specifically, we recommend a mature harvest rate of 10% when the population is above threshold but the effective spawning biomass is less than 55 million pounds. When effective spawning biomass is above 55 million we recommend decreasing the mature male harvest rate from 20% to 15% and the maximum legal harvest rate from 60% to 50%. This is a robust harvest strategy if handling mortality is at lower moderate levels (10-20%). If handling mortality is higher, the optimal strategy as noted above, is to increase the threshold.

Our recommendations try to achieve a balance between short-term gains in yield and fishing opportunity and long-term stability in yield and reproductive potential. We have evaluated a rebuilding strategy to address conservation concerns for this depressed stock and coupled it to a long-term harvest strategy designed to keep the stock as healthy as possible once it is rebuilt. Both analyses address concerns about handling mortality for Bristol Bay red king crabs. Obviously, a decision on a specific harvest strategy falls within the purview of the Board.

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Table 1. LBA estimation of pre-recruit, mature, and legal male abundances and mature female abundances (millions of crabs) and effective spawning biomass(millions of pounds) for red king crab in Bristol Bay from 1972 to 1995. Abundances of small male and female crabs (millions of crabs) are from the NMFS.

	Males				Females		
Year	Small <110mm	Pre-rec 110-134mm	Mature >119mm	Legal >134mm	Small <89mm	Mature >89mm	Effective Spawning Biomass
1972		15.315	18.831	10.176		59.845	56.319
1973		28.900	24.020	10.661		69.545	66.181
1974		37.007	36.262	15.393		71.418	98.120
1975	84.9	38.033	43.461	21.423	70.8	66.030	116.182
1976	70.2	49.215	52.031	26.252	35.9	75.490	129.055
1977	80.2	65.383	66.623	31.508	33.5	118.791	174.517
1978	62.9	61.964	79.476	41.619	38.2	119.528	198.756
1979	48.1	38.689	76.172	48.865	45.1	93.001	166.382
1980	56.8	27.210	61.185	44.665	44.8	93.470	165.640
1981	56.6	17.836	18.874	9.505	36.3	71.286	60.318
1982	107.2	17.184	10.935	2.889	77.2	29.837	25.338
1983	43.3	13.936	9.316	2.460	24.3	10.144	16.870
1984	81.8	13.463	8.609	2.287	57.6	13.878	17.124
1985	13.7	11.273	7.252	1.766	6.9	7.459	11.109
1986	11.8	13.476	12.216	4.376	4.5	9.394	14.873
1987	20.1	12.058	14.371	6.734	16.8	15.805	24.859
1988	8.5	10.965	15.063	8.352	2.7	17.173	28.620
1989	8.6	9.971	16.012	9.832	4.4	17.975	31.253
1990	8.2	7.381	15.316	10.293	7.2	13.881	26.741
1991	8.1	5.235	12.141	8.617	4.7	13.718	26.590
1992	7.0	6.325	10.155	6.774	2.2	13.269	25.973
1993	5.7	7.150	10.078	5.892	2.5	11.561	23.520
1994	5.9	5.625	8.539	4.625	3.4	8.746	19.250
1995	9.2	4.660	8.484	5.337	4.7	8.451	18.081

Table 2. Optimum yields expressed as percentages of the highest value possible for optimal combinations of mature male harvest rate (HR) and threshold for four levels of handling mortality and a 60% maximum legal harvest rate. Yields corresponding to current mature male harvest rate and threshold are underlined, and maximum values (>99.0%) of optimum yield are shown in bold.

Mature	Threshold (Millions of Pounds of Effective Spawning Biomass)										
Male	0.0	4.8	9.7	14.5	19.4	24.2	29.0	33.9	38.7	43.6	48.4
HR	0% Handling Mortality and 60% Maximum Legal harvest Rate										
0.40	66.2	66.2	67.5	69.0	69.0	67.9	65.9	62.2	58.1	51.4	43.4
0.35	69.9	69.9	70.5	71.5	71.4	70.0	67.9	64.2	59.9	54.0	46.0
0.30	79.2	79.2	79.4	79.7	79.3	77.5	74.9	71.3	66.6	61.4	54.0
0.25	93.4	93.5	93.5	93.5	92.6	90.3	87.1	82.7	78.0	72.4	64.9
0.20	**99.9**	**100.0**	**100.0**	**<u>99.4</u>**	97.9	95.1	90.8	85.8	80.1	74.3	67.0
0.15	92.7	92.7	92.6	91.6	89.8	86.8	82.5	77.2	71.6	66.5	59.8
0.10	73.5	73.5	73.4	72.7	71.0	68.3	64.8	60.4	56.4	51.5	45.9
	10% Handling Mortality and 60% Maximum Legal Harvest Rate										
0.40	0.0	0.0	0.0	44.0	55.6	57.5	57.6	55.6	51.6	45.6	37.4
0.35	0.0	0.0	0.0	52.5	58.3	60.6	60.5	58.3	53.9	48.5	39.8
0.30	0.0	0.0	41.1	64.7	68.2	68.9	68.1	65.7	61.9	56.3	48.7
0.25	83.4	83.4	84.4	86.0	86.7	86.1	84.3	80.9	76.8	71.4	64.4
0.20	**99.1**	**99.1**	**99.5**	**<u>100.0</u>**	**99.6**	97.6	94.6	89.6	84.5	78.0	71.3
0.15	97.2	97.2	97.3	96.5	95.1	92.5	88.1	83.2	77.5	71.8	64.8
0.10	78.9	78.9	78.7	78.0	76.5	73.7	70.0	65.5	61.1	55.9	50.4
	20% Handling Mortality and 60% Maximum Legal Harvest Rate										
0.40	0.0	0.0	0.0	0.0	49.9	58.0	60.1	60.5	59.2	55.2	50.0
0.35	0.0	0.0	0.0	0.0	53.5	60.3	62.3	62.4	60.8	56.9	52.0
0.30	0.0	0.0	0.0	0.0	62.8	67.3	69.1	68.6	66.8	63.3	58.4
0.25	0.0	0.0	0.0	75.4	81.3	83.0	83.6	82.2	80.4	76.5	72.3
0.20	93.9	94.0	95.1	<u>96.8</u>	97.9	97.7	95.9	93.7	90.4	86.2	81.1
0.15	**99.8**	**99.8**	**100.0**	**99.9**	**99.4**	97.8	95.1	92.0	88.0	83.6	78.4
0.10	88.9	88.9	88.8	88.3	87.2	85.4	82.9	79.6	76.3	72.4	68.3
	50% Handling Mortality and 60% Maximum Legal Harvest Rate										
0.40	0.0	0.0	0.0	0.0	0.0	0.0	12.8	16.5	17.2	15.0	10.1
0.35	0.0	0.0	0.0	0.0	0.0	0.0	15.3	19.0	20.0	17.9	14.4
0.30	0.0	0.0	0.0	0.0	0.0	0.0	21.8	26.0	27.6	26.3	22.2
0.25	0.0	0.0	0.0	0.0	0.0	29.5	39.1	44.6	46.5	46.4	43.4
0.20	0.0	0.0	0.0	<u>0.0</u>	48.3	66.4	74.9	78.0	77.6	75.6	72.3
0.15	0.0	0.0	1.6	93.9	98.3	**100.0**	**99.0**	97.2	93.7	89.6	84.7
0.10	97.9	97.9	98.1	98.0	97.5	96.2	93.4	90.4	86.2	81.3	76.6

Table 3. Mean yields expressed as percentages of the maximum mean yield possible for combinations of mature male harvest rate (HR) and threshold for four levels of handling mortality and a 60% maximum legal harvest rate. Yields corresponding to current mature male harvest rate and threshold are underlined, and maximum values (>99.0%) of mean yield are shown in bold.

Mature	Threshold (Millions of Pounds of Effective Spawning Biomass)										
Male	0.0	4.8	9.7	14.5	19.4	24.2	29.0	33.9	38.7	43.6	48.4
HR	0% Handling Mortality and 60% Maximum Legal Harvest Rate										
0.40	94.0	94.0	94.5	95.5	96.4	97.4	98.2	99.0	**99.5**	**99.8**	**99.9**
0.35	94.8	94.8	95.1	95.9	96.8	97.6	98.4	**99.1**	**99.7**	**99.9**	**100.0**
0.30	96.0	96.0	96.2	96.7	97.4	98.0	98.8	**99.2**	**99.7**	**99.8**	**99.7**
0.25	95.6	95.6	95.7	96.1	96.5	96.9	97.2	97.3	97.3	97.3	96.8
0.20	89.5	89.5	89.6	<u>89.8</u>	90.0	90.0	89.9	89.7	89.3	88.9	88.2
0.15	77.5	77.5	77.5	77.6	77.5	77.4	77.1	76.6	76.1	75.6	74.7
0.10	59.9	59.9	59.9	59.8	59.7	59.5	59.1	58.6	58.1	57.5	56.8
	10% Handling Mortality and 60% Maximum Legal Harvest Rate										
0.40	7.3	7.3	16.2	83.8	89.1	92.0	94.3	96.1	97.6	99.0	**99.6**
0.35	15.9	15.9	16.7	86.3	89.8	92.6	94.7	96.4	97.8	**99.1**	**99.9**
0.30	17.5	17.5	82.0	89.3	91.8	94.0	95.7	97.2	98.4	**99.4**	**100.0**
0.25	91.4	91.4	91.8	92.9	94.2	95.4	96.7	97.4	98.1	98.6	98.7
0.20	89.9	89.9	90.1	<u>90.6</u>	91.4	91.9	92.3	92.5	92.5	92.3	91.9
0.15	80.4	80.4	80.4	80.6	80.8	80.9	80.8	80.5	80.2	79.7	79.0
0.10	63.2	63.2	63.2	63.2	63.2	63.0	62.7	62.3	61.8	61.2	60.5
	20% Handling Mortality and 60% Maximum Legal Harvest Rate										
0.40	0.0	0.0	0.3	4.9	74.3	82.2	87.3	91.5	94.8	97.1	99.0
0.35	0.2	0.2	3.0	5.2	75.8	83.3	87.8	92.1	95.1	97.3	99.2
0.30	4.5	4.5	5.1	6.2	80.4	85.9	89.9	93.3	96.1	98.0	**99.7**
0.25	6.9	6.9	12.4	83.7	88.3	91.3	94.1	96.1	97.8	98.9	**100.0**
0.20	87.8	87.8	88.5	<u>89.9</u>	91.6	92.9	94.1	94.9	95.4	95.7	95.6
0.15	83.0	83.1	83.2	83.7	84.3	84.6	84.8	84.8	84.7	84.3	83.7
0.10	67.0	67.0	67.1	67.1	67.1	67.1	66.9	66.5	66.1	65.5	64.8
	50% Handling Mortality and 60% Maximum Legal Harvest Rate										
0.40	0.0	0.0	0.0	0.0	1.1	3.4	55.2	66.4	75.1	82.7	88.6
0.35	0.0	0.0	0.0	0.0	1.3	39.9	55.7	67.6	76.3	83.4	89.1
0.30	0.0	0.0	0.0	0.0	1.8	3.9	58.5	69.5	78.2	84.8	90.7
0.25	0.0	0.0	0.0	0.1	2.7	50.0	64.5	74.8	83.3	89.0	93.9
0.20	0.0	0.0	0.3	<u>1.8</u>	58.5	73.9	83.2	89.1	93.5	97.0	**99.4**
0.15	7.3	7.3	41.3	83.4	87.4	90.4	92.3	94.1	95.0	95.8	96.0
0.10	77.5	77.5	77.7	78.1	78.6	79.1	79.3	79.4	79.2	78.8	78.2

Table 4. Optimum yields expressed as percentages of the highest value possible for optimal combinations of mature male harvest rate (HR) and threshold for four levels of handling mortality and a 50% maximum legal harvest rate. Maximum values (>99.0%) of optimum yield are shown in bold.

Mature	Threshold (Millions of Pounds of Effective Spawning Biomass)										
Male	0.0	4.8	9.7	14.5	19.4	24.2	29.0	33.9	38.7	43.6	48.4
HR	0% Handling Mortality and 50% Maximum Legal harvest Rate										
0.40	78.4	78.4	78.5	78.5	77.8	75.8	73.0	69.4	64.4	58.7	52.3
0.35	78.9	78.9	79.1	79.0	78.3	76.3	73.4	69.7	64.8	59.1	52.6
0.30	81.9	82.0	82.1	81.9	71.2	79.0	76.0	72.1	67.7	61.6	55.0
0.25	90.7	90.8	90.8	90.6	89.6	87.3	84.0	79.7	75.6	69.5	62.0
0.20	**100.0**	**100.0**	**100.0**	**99.5**	98.0	95.5	91.4	86.5	81.1	75.1	68.2
0.15	95.5	95.5	95.4	94.5	92.7	89.7	85.5	80.1	74.2	69.0	62.0
0.10	76.5	76.5	76.3	75.6	73.8	71.1	67.4	62.8	58.7	53.5	47.8
	10% Handling Mortality and 50% Maximum Legal Harvest Rate										
0.40	54.5	54.5	67.7	70.9	72.5	71.8	70.4	67.4	62.5	58.0	50.0
0.35	55.5	55.5	68.9	71.7	73.1	72.3	70.8	67.7	62.8	58.5	50.7
0.30	71.6	71.6	73.0	75.1	75.8	75.2	73.4	70.3	65.3	61.2	53.5
0.25	84.8	84.8	85.3	86.1	86.1	84.8	82.6	79.3	74.8	69.7	62.0
0.20	**99.4**	**99.5**	**99.7**	**100.0**	**99.5**	97.6	94.6	89.8	85.1	78.6	72.0
0.15	**99.7**	**99.7**	**99.8**	**99.0**	97.7	95.1	90.8	85.7	80.0	74.1	66.9
0.10	81.6	81.6	81.5	80.7	79.2	76.3	72.5	67.8	63.3	57.9	52.2
	20% Handling Mortality and 50% Maximum Legal Harvest Rate										
0.40	0.0	0.0	0.0	62.0	70.5	72.8	73.3	72.1	69.5	66.1	61.3
0.35	0.0	0.0	0.0	65.5	71.1	73.3	73.6	72.4	69.8	66.5	61.5
0.30	0.0	0.0	0.0	69.1	73.5	75.2	75.6	74.2	71.8	68.6	63.5
0.25	0.0	0.3	68.6	80.5	82.7	83.5	83.0	81.1	78.6	75.2	70.7
0.20	93.5	93.6	94.3	95.3	96.0	95.5	93.9	91.6	88.6	84.6	79.9
0.15	**99.2**	**99.2**	**99.4**	**99.3**	98.7	97.3	94.7	91.6	87.7	83.4	78.2
0.10	88.8	88.8	88.7	88.3	87.2	85.4	82.8	79.6	76.3	72.4	68.3
	50% Handling Mortality and 50% Maximum Legal Harvest Rate										
0.40	0.0	0.0	0.0	0.0	0.0	26.5	36.8	41.6	42.6	40.5	36.7
0.35	0.0	0.0	0.0	0.0	0.0	27.3	37.8	42.2	43.0	41.7	37.3
0.30	0.0	0.0	0.0	0.0	0.0	30.4	40.0	44.9	45.8	44.3	40.1
0.25	0.0	0.0	0.0	0.0	0.0	40.4	50.2	54.5	55.2	53.7	50.0
0.20	0.0	0.0	0.0	0.0	55.7	69.5	76.4	78.3	78.1	75.5	71.7
0.15	0.0	0.0	1.3	94.5	98.0	**99.4**	98.7	96.7	93.4	89.2	84.5
0.10	97.9	97.9	98.1	98.0	97.5	96.1	93.4	90.4	86.2	81.3	76.6

Table 5. Mean yields expressed as percentages of the maximum mean yield possible for combinations of mature male harvest rate (HR) and threshold for four levels of handling mortality and a 50% maximum legal harvest rate. Maximum values (>99.0%) of mean yield are shown in bold.

Mature Male	Threshold (Millions of Pounds of Effective Spawning Biomass)										
	0.0	4.8	9.7	14.5	19.4	24.2	29.0	33.9	38.7	43.6	48.4
HR	0% Handling Mortality and 50% Maximum Legal Harvest Rate										
0.40	97.8	97.8	97.9	98.3	98.7	**99.2**	**99.6**	**99.8**	**99.9**	**99.9**	**99.7**
0.35	97.9	97.9	98.0	98.4	98.8	**99.2**	**99.6**	**99.8**	**100.0**	**99.9**	**99.8**
0.30	98.1	98.1	98.2	98.6	**99.0**	**99.3**	**99.8**	**99.9**	**100.0**	**99.9**	**99.7**
0.25	97.7	7.7	97.8	98.0	98.3	98.6	98.7	98.8	98.8	98.6	98.1
0.20	92.6	92.6	92.7	92.9	93.0	93.1	93.0	92.8	92.4	92.0	91.4
0.15	80.7	80.7	80.7	80.8	80.7	80.6	80.3	79.8	79.3	78.7	77.9
0.10	62.4	62.4	62.4	62.4	62.2	62.0	61.6	61.1	60.6	60.0	59.2
	10% Handling Mortality and 50% Maximum Legal Harvest Rate										
0.40	89.0	89.0	92.2	93.8	95.3	96.5	97.7	98.6	**99.3**	**99.8**	**99.9**
0.35	89.2	89.2	92.5	94.0	95.4	96.6	97.7	98.7	**99.3**	**99.8**	**100.0**
0.30	92.7	92.7	93.3	94.5	95.7	96.9	98.0	98.8	**99.3**	**99.9**	**100.0**
0.25	94.4	94.4	94.7	95.4	96.2	97.1	98.0	98.6	**99.0**	**99.3**	**99.2**
0.20	92.3	92.3	92.4	92.9	93.5	94.0	94.3	94.4	94.4	94.2	93.9
0.15	82.5	82.5	82.6	82.7	83.0	83.0	82.9	82.7	82.3	81.8	81.1
0.10	64.9	64.9	64.9	65.0	64.9	64.7	64.4	64.0	63.5	62.9	62.2
	20% Handling Mortality and 50% Maximum Legal Harvest Rate										
0.40	6.5	6.5	15.3	81.9	87.7	90.9	93.4	95.2	96.7	98.0	**99.0**
0.35	6.8	6.8	15.5	83.4	87.9	91.0	93.5	95.3	96.7	98.0	**99.0**
0.30	7.4	7.5	16.2	84.8	88.7	91.5	93.8	95.6	97.0	98.2	**99.0**
0.25	49.4	49.6	83.5	88.7	91.1	93.1	94.8	96.3	97.4	98.2	98.8
0.20	89.1	89.1	89.5	90.6	91.9	93.0	94.0	94.6	95.0	95.3	95.2
0.15	83.2	83.2	83.3	83.7	84.3	84.6	84.8	84.8	84.7	84.3	83.7
0.10	67.0	67.0	67.1	67.1	67.1	67.1	66.9	66.5	66.1	65.5	64.8
	50% Handling Mortality and 50% Maximum Legal Harvest Rate										
0.40	0.0	0.0	0.0	0.1	3.2	55.3	69.1	79.1	86.1	91.7	95.8
0.35	0.0	0.0	0.0	0.0	3.1	56.0	69.3	79.6	86.2	91.8	95.8
0.30	0.0	0.0	0.0	0.0	3.4	57.0	70.4	80.1	86.7	92.2	96.1
0.25	0.0	0.0	0.0	0.1	3.8	62.7	74.8	82.6	88.8	93.9	97.5
0.20	0.3	0.3	0.6	3.4	66.3	78.6	86.4	91.2	95.0	98.0	**100.0**
0.15	7.6	40.8	42.6	84.6	88.0	90.7	92.6	94.3	95.1	95.9	96.1
0.10	77.6	77.6	77.7	78.1	78.7	79.1	79.3	79.4	79.2	78.8	78.2

Table 6. Comparisons of mean yield, standard deviation of yield (SD), coefficient of variation (CV) of effective spawning biomass (CV SP%), percentage of years without fishing (Close%), and the number of consecutive years that the fishery was closed (Close Duration) and open (Open Duration) for the current harvest strategy (a 20% mature male harvest rate, a 60% maximum legal male harvest rate and a threshold of 14.5 million pounds of effective spawning biomass) and the robust strategy (a 15% mature male harvest rate, a 50% maximum legal male harvest rate and a threshold of 14.5 million pounds of effective spawning biomass) for Bristol Bay red king crab. Historical mean yield and its standard deviation were included for comparison. Yield and standard deviation are in millions of pounds.

HM%	Yield	SD	CV SP%	Close%	Close Duration	Open Duration
Current Strategy						
0	32.993	20.660	58.1	2.8	1-3	1-189
10	30.951	19.527	58.2	3.1	1-3	1-238
20	28.245	18.194	58.9	4.0	1-4	1-238
50*	6.816	6.492	79.8	38.6	1-9	1- 16
Robust Strategy						
0	28.474	17.218	57.0	2.3	1-3	1-237
10	27.505	16.581	56.7	2.4	1-3	1-238
20	26.362	15.919	56.7	2.6	1-4	1-294
50	21.148	13.458	58.9	4.6	1-4	1-238

Historical Yield		
Period	Mean Yield	SD
1953-94	30.595	28.972
1960-94	34.621	30.151
1972-94	33.068	34.734

Notation:

HM%: % handling mortality rate.

*The population was not sustainable for this scenario. The statistics were computed using the results before the population collapsed to zero abundance (493 years).

Table 7. Alternative rebuilding strategies examined and their outcomes over a 30 year planning horizon. The term HR refers to the mature male harvest rate, threshold is in millions of pounds of effective spawning biomass (ESB), and target is the target rebuilding level of 55 million pounds of ESB.

	Alternative Strategies						
Feature	1	2	3	4	5	6	7
Threshold	14.5	24.2	55.0	14.5	14.5	24.2	24.2
HR if ESB≤Threshold	0	0	0	0	0	0	0
HR if Threshold <ESB≤Target (%)	20.0	20.0	0	10.0	15.0	10.0	15.0
HR if ESB>Target (%)	20.0	20.0	20.0	20.0	20.0	20.0	20.0

Outcomes Over a 30 Year Planning Horizon							
Feature	1	2	3	4	5	6	7
ESB	50.4	59.1	69.6	64.9	60.1	66.8	64.1
Mean Catch	16.6	17.6	17.3	18.1	17.7	18.1	18.1
Probability of Fishery Closure (%)	6.4	7.4	8.4	2.0	3.4	3.6	5.0
Probability of Rebuilding (%)	60.8	72.8	93.0	84.4	76.2	86.6	82.0

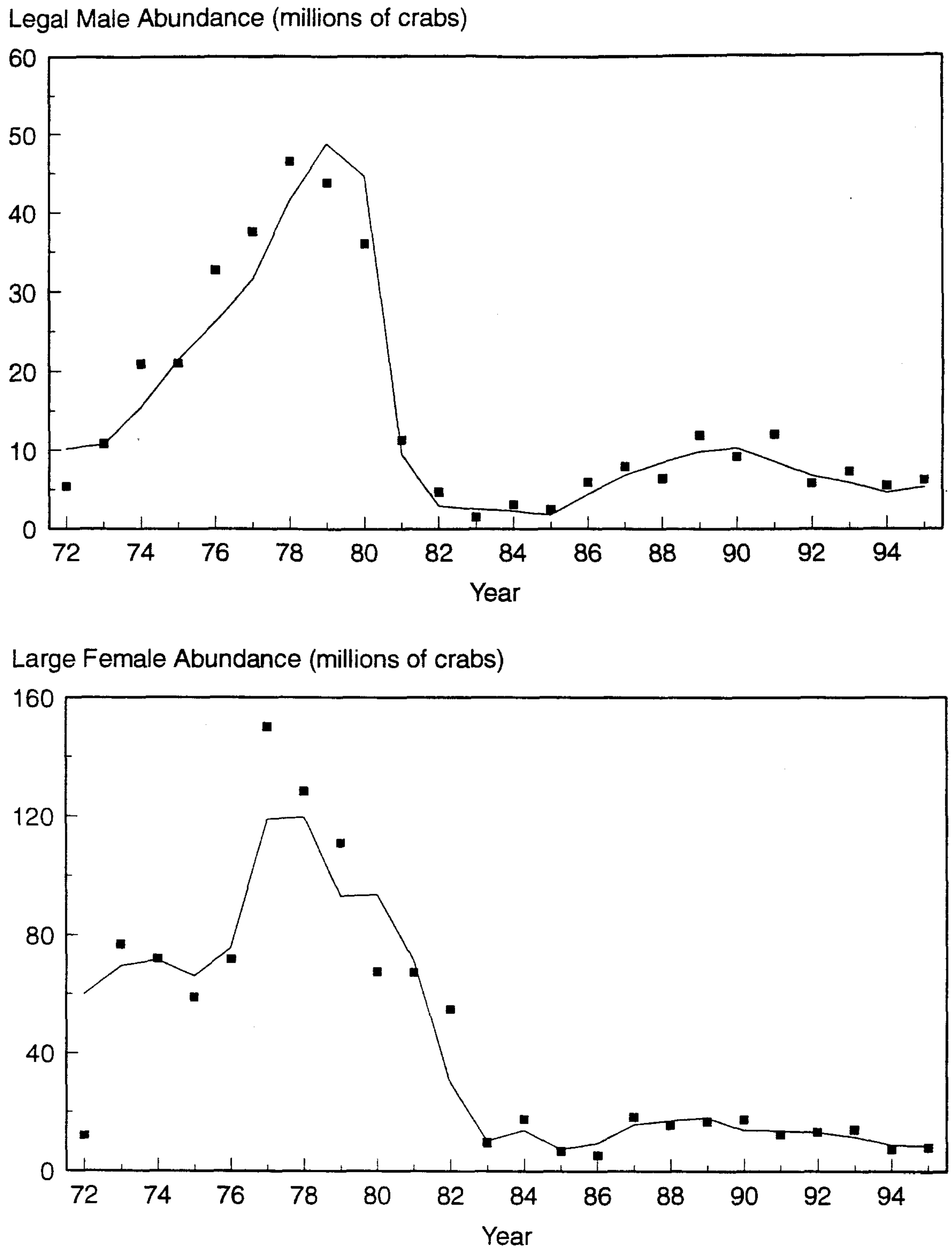

Figure 1. Comparison of NMFS survey (dots) and LBA (solid line) estimates of legal male (top panel) and large female (lower panel) red king crab abundances in Bristol Bay.

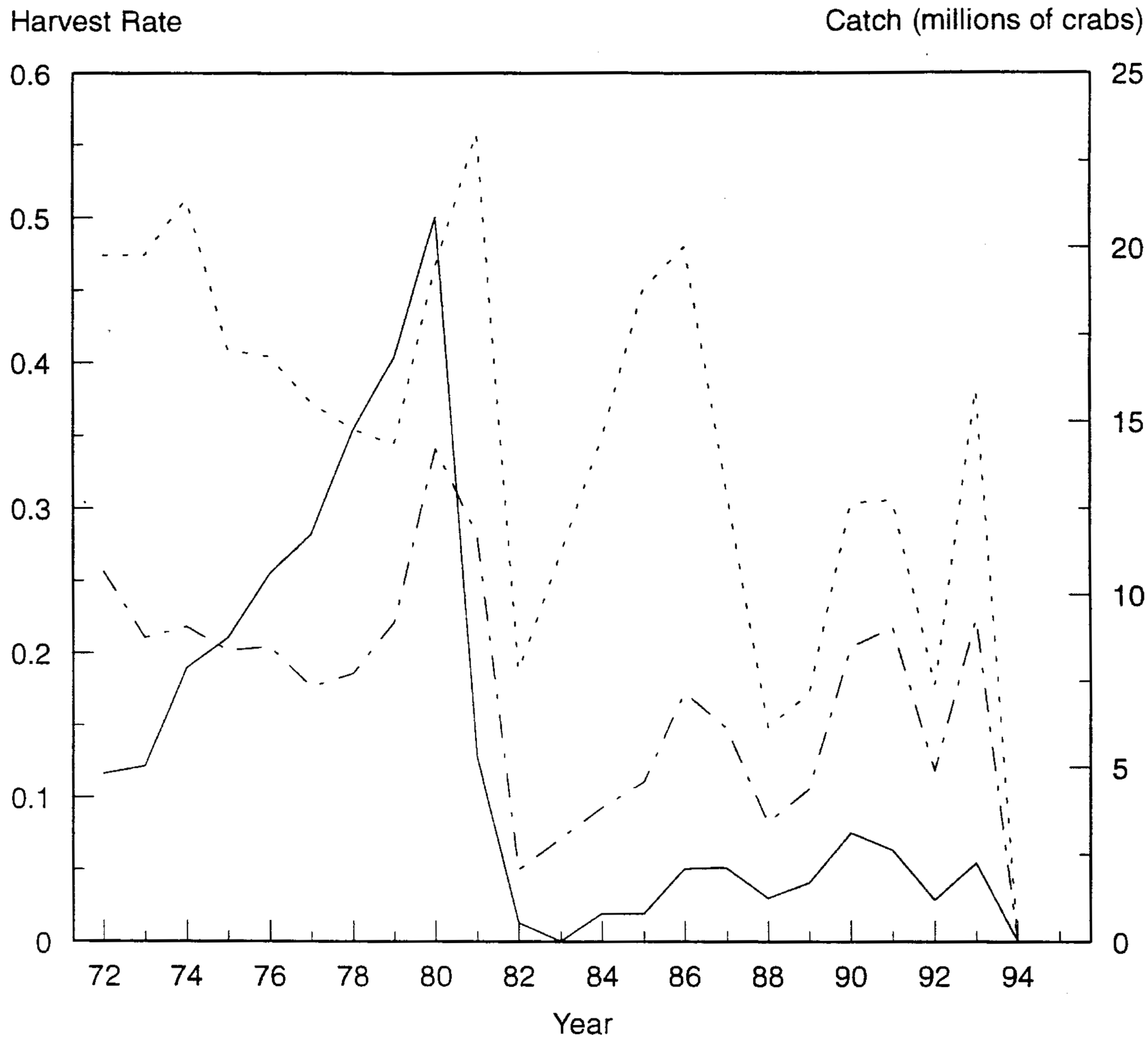

Figure 2. Catch (solid line), mature (dashed line), and legal (dotted line) male crab harvest rates of red king crabs in Bristol Bay.

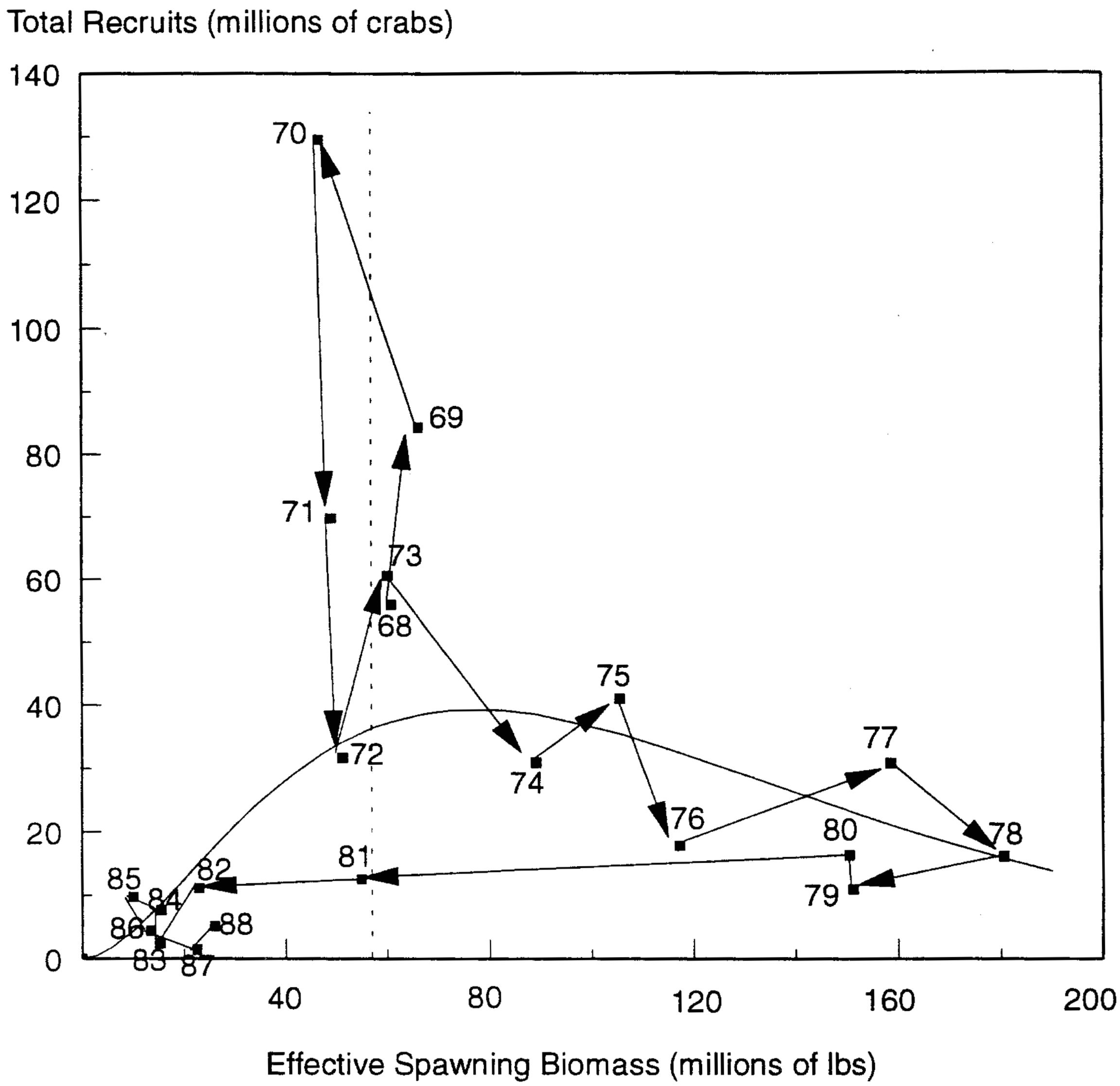

Figure 3. The relationship between total recruits at age 6.2 (i.e., 7-year time lag) and effective spawning biomass for Bristol Bay red king crabs. Numbers refer to brood year. The vertical dotted line indicates the rebuilding target level of 55 million pounds.

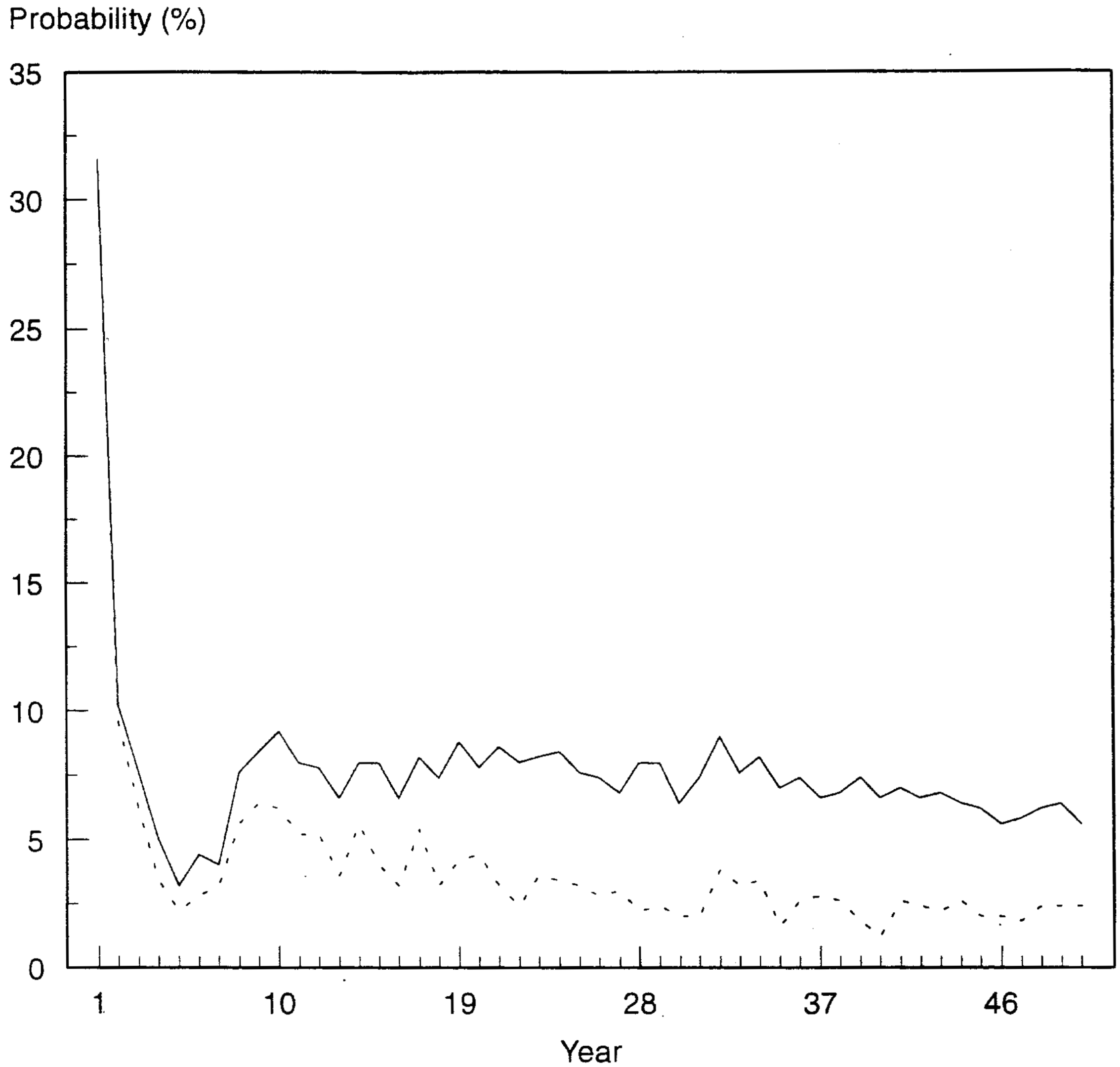

Figure 4. Probability of Bristol Bay red king crab fishery closure over a 50 year planning horizon for the current harvest strategy (solid line) and the rebuilding strategy (dotted line).

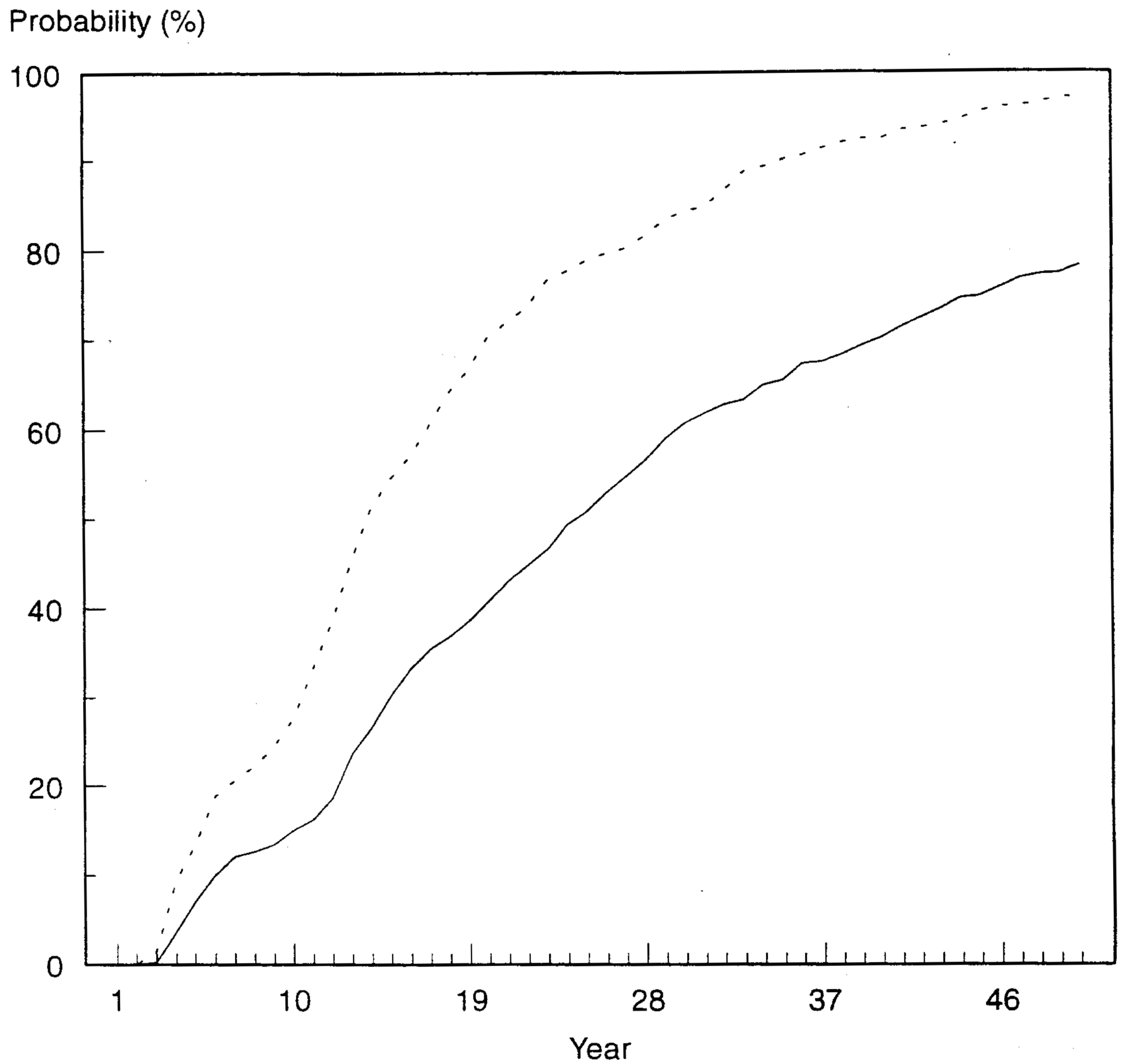

Figure 5. Probability of rebuilding Bristol Bay red king crab to the effective spawning biomass of 55 million pounds over a 50 year planning horizon for the current harvest strategy (solid line) and the rebuilding strategy (dotted line).

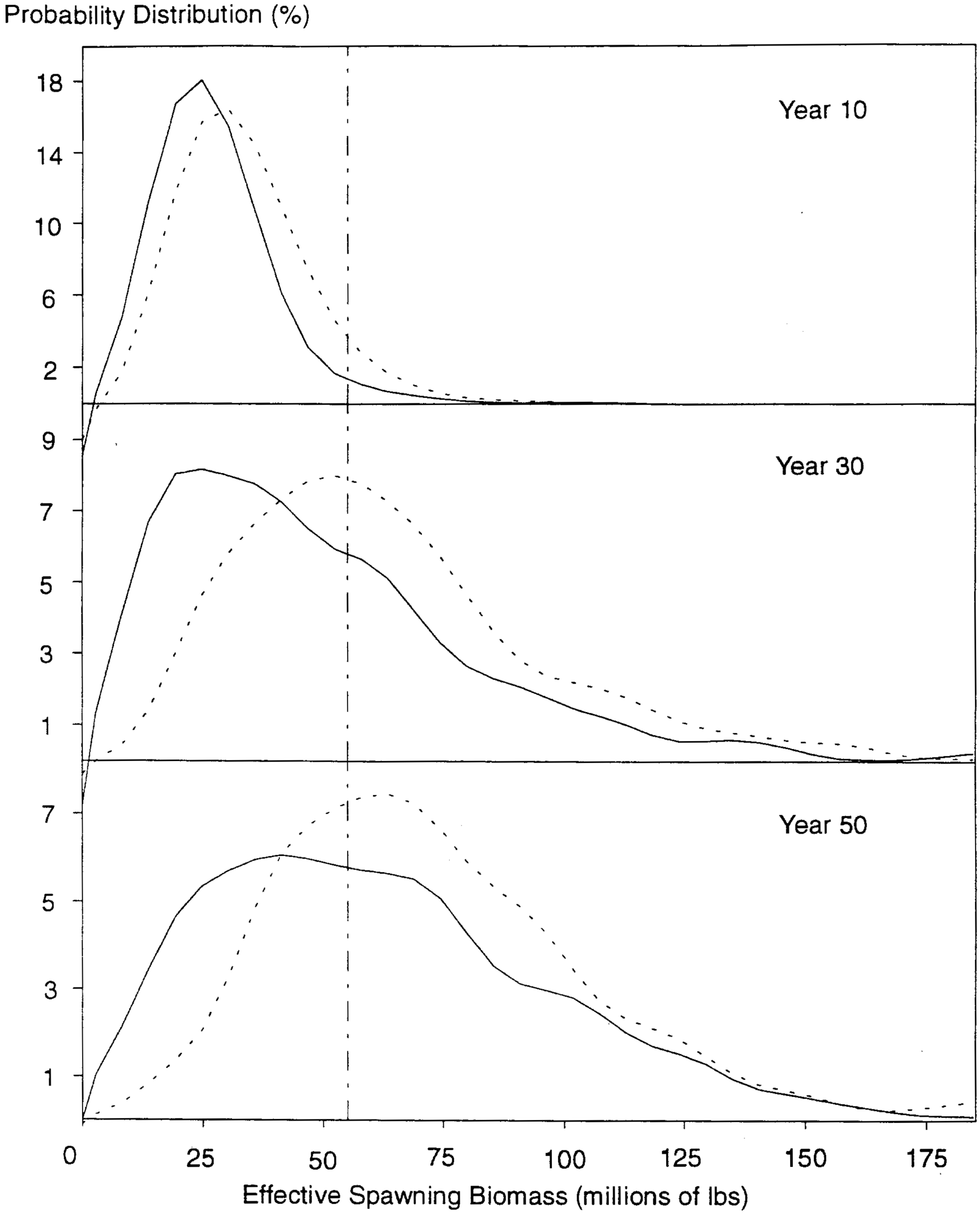

Figure 6. Probability of Bristol Bay red king crabs reaching an effective spawning biomass over 10, 30, and 50 year planning horizons for the current harvest strategy (solid line) and the rebuilding strategy (dotted line).

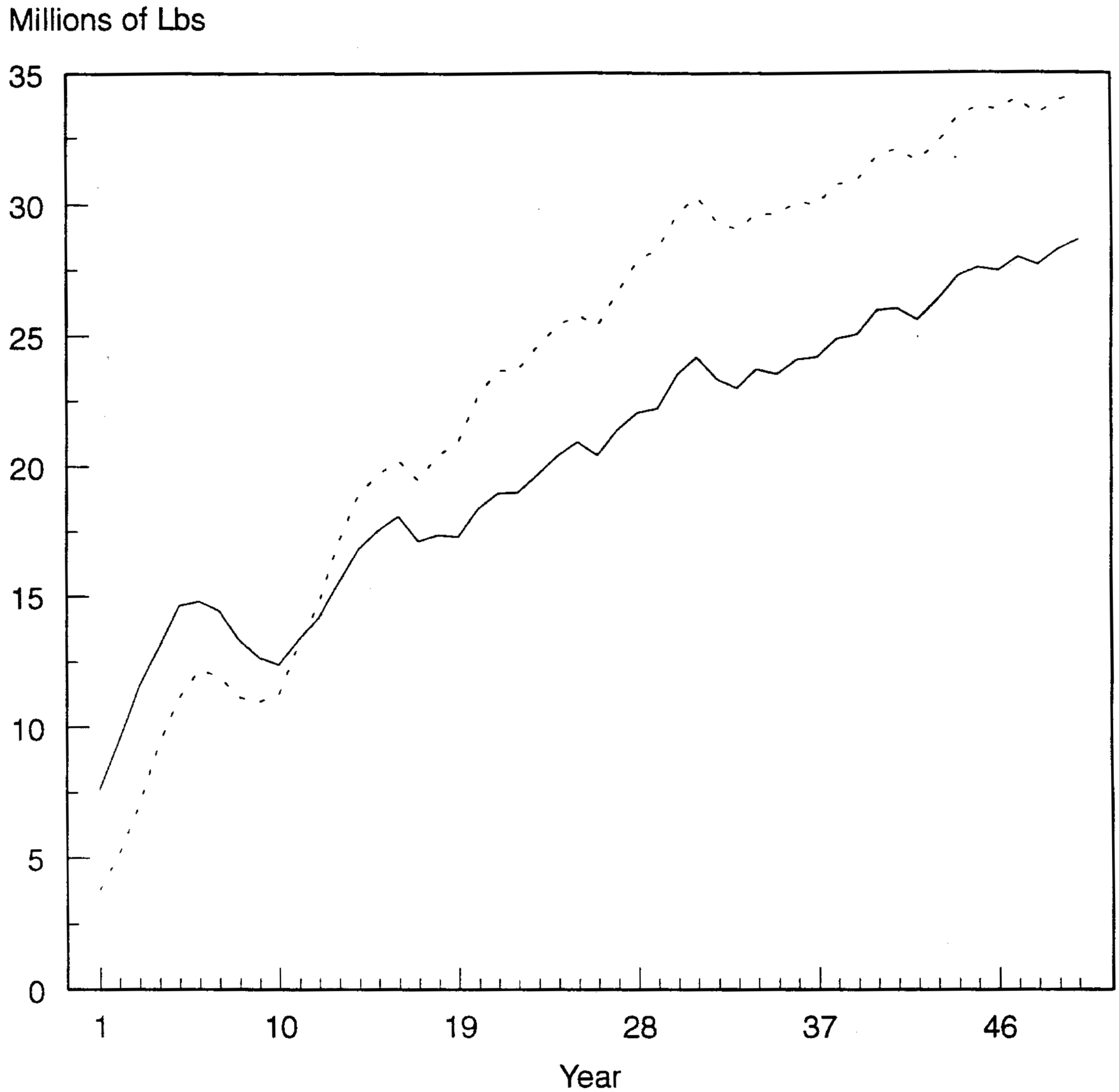

Figure 7. Annual catch of Bristol Bay red king crabs over a 50 year planning horizon for the current harvest strategy (solid line) and the rebuilding strategy (dotted line).