OVERVIEW OF POPULATION ESTIMATION METHODS AND ROBUST LONG-TERM HARVEST STRATEGY FOR RED KING CRABS IN BRISTOL BAY

By

Jie Zheng, Margaret C. Murphy, and Gordon H. Kruse

Regional Information Report No. 5J95-21
Alaska Department of Fish & Game
Commercial Fisheries Management and Development Division
P.O. Box 25526
Juneau, Alaska 99802-5526

September 14, 1995

OVERVIEW OF POPULATION ESTIMATION METHODS AND ROBUST LONG-TERM HARVEST STRATEGY FOR RED KING CRABS IN BRISTOL BAY

By

Jie Zheng, Margaret C. Murphy and Gordon H. Kruse

Regional Information Report No. 5J95-21[1]
Alaska Department of Fish & Game
Commercial Fisheries Management and Development Division
P.O. Box 25526
Juneau, Alaska 99802-5526

September 14, 1995

---

[1]The Regional Information Report Series was established in 1987 to provide an information access system for all unpublished divisional reports. These reports frequently serve diverse ad hoc informational purposes or archive basic uninterpreted data. To accommodate timely reporting of recently collected information, reports in this series undergo only limited internal review and may contain preliminary data; this information may be subsequently finalized and published in the formal literature. Consequently, these reports should not be cited without prior approval of the author or the Commercial Fisheries Management and Development Division.

PURPOSE

Our purpose is to provide a non-technical summary of the methods used to estimate the abundance of red king crabs *(Paralithodes camtschaticus)* in Bristol Bay and review a new harvest strategy that we consider robust over the long-term. In particular, we describe (1) the length-based analysis (LBA) for calculation of population size, (2) the stock-recruitment relationship used to project the abundance for simulation, and (3) an evaluation of optimal and robust harvest strategies from simulation of the population over many years. For technical details on this research, readers are referred to several scientific papers. Zheng et al. (1995) 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 this LBA and stock-recruitment relationships that included updated data through 1994. Zheng et al. (MSb) analyzed harvest strategies for this stock. Copies of these three papers are available from the authors.

INTRODUCTION

Background

Numerous Alaskan king and Tanner crab fisheries closed to commercial fishing in the 1980s due to low stock size and many of these fisheries 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 1995). Improved abundance estimates and a re-evaluation of current harvest strategies are important components of this effort. Because of the excellent data available and the economic importance of the red king crab fishery in Bristol Bay, we focused our initial studies on this stock.

How Abundant is the Stock?

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 given the coarse spacing of stations, uncertainties about trawl catchability, and occasional unexpected changes in estimated stock size from year to year. Given these uncertainties, the Alaska Department of Fish and Game (ADF&G) typically calculated a guideline harvest range (GHR) by multiplying the established harvest rate times the upper and lower confidence intervals of the abundance estimated from the area-swept method. Inseason fishery performance (e.g., catch per unit effort, CPUE) was then used to judge the survey accuracy during the fishing season and, if necessary, to adjust the final harvest. However, inseason fishery performance data has become more difficult to use. 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. 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 would focus on timing fishery closures to meet the preseason guideline harvest level (GHL) rather than attempting to use current year's inseason fishery performance data to resolve uncertainties about survey errors. 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.

How Should the Stock Best be Managed?

In March 1990 the Alaska Board of Fisheries (BOF) adopted a fishery management policy that strives to provide for a sustained and reliable supply of high quality product, substantial and stable employment, minimum risks of stock collapse, and maintenance of fisheries on multiple ages and sizes of crabs (ADF&G 1994). The BOF recognized that this policy "may not result in maximization of physical or economic yield" (ADF&G 1994). For a number of king crab stocks, the BOF adopted an exploitation rate strategy in which the GHL is set as a fixed percentage of mature male abundance placing a cap on the overall percentage of legal males that could be harvested, and 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 estimated a threshold of 8.4 million mature females, a mature male harvest rate of 20%, and a harvest cap of 60% of legal abundance (Pengilly and Schmidt 1995). 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 threshold was estimated from an assumed stock-recruit model that differed from the one that was actually fitted at the time and the spawning stock used in the stock-recruit model was fertilized female crabs excluding the contribution of mature male crabs to reproduction. Further, the threshold and harvest rate calculations did not take handling mortality into account.

A rational harvest rate strategy should prescribe an exploitation 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 these improved estimates and population changes that occurred over the past three decades.

Harvest rate strategy and threshold should be based on the best scientific findings. Therefore, we used the LBA and updated stock-recruit curve to construct a simulation model specifically designed to evaluate optimal long-term harvest strategies and threshold levels for Bristol Bay red king crabs. Because of the multiple objectives of the BOF management policy, we defined optimal scenarios by equally weighting the benefits of maximum yield with stability of 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.

METHODS

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 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 is 100%, that is, that all red king crabs above a certain size in the path of the trawl are caught. 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 distribution of the catch, and their shell ages. 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 and crabs that have died of natural causes are subtracted. 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.

Stock-Recruitment Relationships

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. To estimate effective spawning biomass, we need to estimate the number of mature female crabs that 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 normal 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. 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.

Analysis of Harvest Strategies

To figure out optimal and robust harvest strategies, the population of Bristol Bay red king crabs has to be simulated over time. This necessitates projection of future abundances which is what the stock-recruit curve allows us to do. It provides the foundation for the simulation model by projecting the number of future recruits to the population based on the corresponding effective spawning biomass. The simulation model is constructed of a population submodel and a harvest submodel. The population submodel is based on the LBA and it keeps track of population increases that depend on the stock-recruitment relationship 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 it's effects. Handling mortalities were included in the simulation to study the effect of this potentially important factor on harvest strategy. Under different simulation scenarios, handling mortality of sublegal male and female crabs was set to a 0%, 20% or a 50% rate to cover the likely range of values experienced in the fishery. The harvest submodel is a set of rules that specifies combinations of mature male harvest rate, maximum legal harvest rate and threshold used to determine the harvest to be deducted from legal abundance. 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 different test harvest strategies if we applied them to the real stock of Bristol Bay red king crabs.

RESULTS

Length-Based Analysis

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). We feel that years when natural mortality is highest most likely correspond to years when handling mortality was significant. Additionally, the higher natural mortality for female crabs compared to male crabs probably in part reflects 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 (Fig. 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 (Fig. 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 (Fig. 1). The dramatic declines in abundance coincided with the highest catches and the highest harvest rates on record in 1980 and 1981 (Fig. 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 smooths 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 very similar in recent years.

Stock-Recruitment Relationships

One important result from the LBA is development of a stock-recruitment relationship. From our analysis it appears that a shortage of mature males 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 (Fig. 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.

Analysis of Harvest Strategies

We considered two performance measures in our analysis of harvest strategies. One measure is optimum yield in which the benefits of high yield are balanced against 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 policy was to maximize yield, but it would be a very poor strategy with respect to the BOF policy on king crab management that includes objectives to produce high and stable yields.

We recognize that there are uncertainties in our analysis. Handling mortality is important, but we don't have good estimates of handling mortality rates. Natural mortality shifts are difficult to predict, and survey errors can lead to errors in estimates of population estimates, harvest rates, and thresholds. To acknowledge these features, we sought to identify a robust harvest strategy. 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 pose risk of population collapse. Results can be evaluated by comparing the optimum yield and mean yield for the current harvest strategy to those for robust harvest strategies.

Table 1 is used to show how threshold levels and mature harvest rates effect the level of maximum stable yield that will be realized in the long-term given the specific combinations of maximum legal harvest rates (60% and 50%) and handling mortality rates (20% and 50%). Maximum stable yields are scaled between 0 and 100. Threshold is expressed in millions of pounds of effective spawning biomass. Threshold for the current harvest strategy is 8.4 million mature females which equates to 14.5 million pounds of effective spawning biomass.

The first panel of Table 1 shows that, if we assume a 20% 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 96.8% of the highest value possible. Optimum yield is actually maximized at a mature harvest rate of 15% with a threshold of 9.7 million pounds. However, 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. That is, these scenarios provide little safeguard against errors in estimates of threshold or harvest rate. Instead, a mature harvest rate of 15% and thresholds ranging from 14.5 million pounds to 24.2 million pounds would be fairly safe from risk of stock collapse.

Table 2 shows comparable results in terms of mean yield rather than optimal. Mean yield in Table 2 is expressed as a percentage of the maximum mean yield possible over the long-term for a given combination of harvest rate, threshold and handling mortality. The current harvest strategy results in 89.9 percent of the maximum yield possible with a 20% handling mortality rate (Table 2, panel 1). To maximize yield for a 60% maximum legal harvest rate and a 20% handling mortality rate we would need a threshold of 48.4 million pounds and a 25% mature harvest rate. This strategy which maximizes yield has drawbacks for obvious reasons. Comparing the top panels of Tables 1 and 2, we see that the optimum yield and mean yield are not maximized at the same combinations of harvest rates and threshold. This is because the optimum yield balances maximum yield with stability in yield.

Assuming a 20% handling mortality but instead lowering the maximum legal harvest rate from 60% (Table 1, panel 1) to 50% (Table 1, panel 2) decreases the optimum yield for our current mature harvest rate of 20% to 95.3%. However, a 50% maximum legal harvest rate further buffers the harvest strategy from the risk of population collapse and results in higher mean yield (Table 2, panel 1 and 2). Under this scenario of 20% handling mortality and 50% maximum legal harvest rate optimum yields are highest at a mature harvest rate of 15% for thresholds ranging from 0 to 19.4 million pounds. A threshold of 9.7 million pounds or greater provides sufficient protection against population collapse due to errors in harvest rate estimates. Note that decreasing the maximum legal harvest rate from 60% to 50% causes no change in yield at a 15% mature harvest rate and 20% handling mortality rate for any choice of threshold.

For a 20% handling mortality rate, a 15% mature male harvest rate results in higher optimum yields than the current 20% rate. Decreasing the maximum legal harvest rate from 60% to 50% and retaining a threshold at or above the current value of 14.5 million pounds provides a sufficient margin of error to protect the stock from deficient harvest strategies that lead to population collapse. Lesser values of threshold could put the stock at risk of collapse should mature harvest rates be inadvertently higher than 15%.

Handling mortality could occur at rates in excess of 20% and conceivably could be as high as 50% on occasion. Optimum yields and mean yields are quite different between scenarios with 20% and 50% handling rates (Table 1, Table 2). 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. At a 50% handling mortality rate our current harvest strategy with a 60% maximum legal harvest rate, 20% mature harvest rate, and a threshold of 14.5 million pounds leads to an optimum yield of zero indicating the population will not be sustained (Table 1, panel 3). The optimum yield under this scenario is maximized for a mature harvest rate of 15% and a threshold of 24.2 million pounds. Mean yield is maximized as threshold increases above 24.2 million pounds and the mature harvest rate is increased to the current 20% level (Table 2, panel 3).

For a 50% handling mortality rate, reducing the maximum legal harvest rate from 60% to 50% has no effect on the mature harvest rate that maximizes the optimum yield (15%) or mean yield (20%) (Table 1 and 2, panels 3 and 4). Decreasing the maximum legal harvest rate from 60% to 50% under a handling mortality rate of 50% does provide greater safeguards against population collapse for higher mature harvest rates. This may seem of no consequence under the BOF policy of a fixed mature male harvest rate. However, if the trawl survey was subject to measurement error that falsely inflated abundance estimates for multiple years in a row then our LBA estimates of abundance would also be high. Unknowingly, managers would be applying a mature harvest rate that was higher than intended and that could result in over harvest.

To sum up thus far, a mature harvest rate of 15% resulted in higher optimum yields for all scenarios of handling mortality and maximum legal harvest rate. Decreasing the current mature harvest rate from 20% to 15% is a robust harvest strategy for both maximizing and stabilizing long-term yield. The harvest strategy for Bristol Bay red king crabs can be made even more robust by decreasing the risk of population collapse in the event of a potential error in the survey or dramatic shift in natural mortality, by reducing the maximum legal harvest rate from 60% to 50%. Lastly, if concern exists that handling mortality could reach 50%, then a robust 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 harvest strategy for several measures of performance relevant to the BOF policy on red king crabs in Bristol Bay. So far we have discussed the yield and variation in yield. We compare these factors and 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 both strategies in Table 3. Mean yield and number of years the fishery was open are higher for the current harvest strategy than the robust harvest strategy at a 20% handling mortality rate. On the other hand, the standard deviation in yield and CV of effective spawning biomass were lower for the robust strategy. Lower values for these factors are indicative of long-term stability. The current harvest strategy does not sustain the red king crab population in Bristol Bay at a 50% handling mortality rate. The robust harvest strategy under both a 20% and 50% handling mortality results in a 25% reduction in mean yield compared to average historic yield but also results in a 50% reduction in the standard deviation in yield.

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 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. Thus the LBA helps validate use of the NMFS survey data to accurately estimate red king crab abundance in Bristol Bay. However, the LBA smooths 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. Therefore, beginning in 1995, the LBA is used to analyze survey and fishery data to set annual GHLs 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 on the previous year's population 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 stock-recruitment relationship for red king crabs in Bristol Bay helps us assess stock productivity with respect to current and historical stock sizes. Clearly, the current depressed spawning stock has a very low chance of producing a strong year class (Fig. 3). The curve suggests that improvement in the stock will depend on a rebuilding plan that patiently accumulates stock by harvesting at levels below recruitment. 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. The stock-recruitment relationship also helps us reconstruct the roller coaster history of the Bristol Bay stock. Intermediate stock sizes of the late 1960s and early 1970s led to outstanding recruitment. Seven years later in the late 1970s (Fig. 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 (Fig. 2), and natural mortality increased 4 to 5 fold. 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 (Fig. 3). 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 all crab fisheries and bycatch mortality in the groundfish fisheries are potential major contributors.

It is important to understand that the stock-recruit curve is not used to estimate population abundances for setting guideline harvest levels. However, it can be used to project future stock changes, and it can provide some indications whether the population will be above or below threshold in the coming year. Perhaps the most powerful application of the stock-recruit curve is in simulations to evaluate harvest strategies.

Optimal harvest strategy depends on management goals. One strategy may be appropriate to maximize physical yield, whereas a totally different strategy is best to stabilize yield and employment. The BOF 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. We addressed this policy by balancing yield and stability of yield while keeping track of other relevant considerations.

Harvest rates and thresholds are integral parts of the management strategy needed to meet the BOF 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.

We chose to represent the stock-recruitment relationship for Bristol Bay red king crabs with a curve that includes both stock and environmental effects. However, in another analysis (Zheng et al. MSb) we examined the results if one assumes that stock effects are dominant versus results if one assumes that environmental effects are dominant. We can use these two extremes as side boards for what can potentially occur. The mean yields for the environmentally-based curve were much lower than those for the curve based on stock size effects. Generally, a threshold is most important when stock effects are dominant because the population is at higher risk of irreversible collapse. If environmental effects are dominant, then a threshold is less important but lower harvest rates are appropriate due to the lower productivity of the stock. Overall, there are many similarities among the optimal harvest strategies for these two curves. The curve we have applied with stock and environmental effects combined gave intermediate results.

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. In conjunction with the king and Tanner crab management policy adopted by the BOF in 1990, the current harvest strategy was implemented for Bristol Bay (Schmidt and Pengilly 1990; Pengilly and Schmidt 1995). We found that a harvest rate strategy combined with a threshold is consistent with the BOF policy in that it enhances long-term yield, promotes stability and addresses many conservation concerns.

Handling mortality has a very important effect on the red king crab harvest strategy. From our simulations we know an increase in the handling mortality rate reduces future recruitment to the fishery, parent spawning stock and long-term yield. The appropriate level of handling mortality to apply to evaluate harvest strategies for Bristol Bay red king crabs is not clearly understood because not all potential factors contributing to later unobserved mortalities have been studied. Red king crabs exposed to cold air have reduced vigor, lowered growth and increased mortality during molting in severe situations (Carls and O'Clair 1990). These effects could be exacerbated by unusually cold weather during the November fishery in Bristol Bay. Simulations of repeated deck and water impacts of red king crabs resulted in a significant increase in body damage with increased handling but no significant difference in mortalities for 4 months after the experiments. Injury to crabs can reduce growth, lower predator defenses, and inhibit molting (Kruse 1993, Murphy and

Kruse 1995). We contend handling mortality rates in the range of 20% to 50% are realistic given our knowledge.

Our analysis of the Bristol Bay stock leads us to recommend adjustments to the current harvest strategy to guard against effects of handling mortality that were not addressed previously. The current strategy would be good if there were no handling mortality. However, if handling mortality is actually at low or moderate levels (10% to 30%), a robust harvest strategy would be to decrease the mature male harvest rate from 20% to 15% and the maximum legal harvest rate from 60% to 50%. Further protection for the stock can be afforded by increasing the threshold above the current 14.5 million pounds effective spawning biomass. If concerns exist that handling mortality is greater (40% to 50%), then it becomes mandatory to increase the threshold to guard against severe depletion of the crab stock.

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 the most robust options for a harvest strategy given the BOF policy and likely range in handling mortality for Bristol Bay red king crabs. Obviously, a decision on a specific harvest strategy falls within the purview of the BOF. For example, the BOF could choose to maximize mean yield by increasing the harvest rate, but the tradeoff is the threshold needs to be substantially increased. In so doing, a pulse fishery would be created. As another example, the BOF could choose to maximize optimum yield when the stock is healthy, but they may opt for a more conservative, risk-averse strategy (i.e. rebuilding strategy) when the stock is depressed.

The LBA is designed to be updated annually with new survey and fishery data. The LBA is flexible in that we can modify it as new information becomes available. New research providing answers to questions about handling mortality, breeding success of male crabs, and environmental effects, can be incorporated in our simulation model and the harvest strategy can be reanalyzed and modified accordingly. In the research that we reported here, we analyzed robust long-term harvest strategies. We have also used the LBA to analyze rebuilding schedules for Bristol Bay red king crabs. This work will provide the BOF with additional guidance on short-term remedial management options that they may wish to consider to promote the more rapid recovery of this stock. Results of this rebuilding strategies analysis and specific ADF&G management recommendations will become available to the public prior to the March 1996 BOF meeting.

ACKNOWLEDGMENTS

We thank Doug Pengilly, Ivan Vining, Paul Larson, Ken Griffin and Pete Probasco for their review comments. This paper is funded in part by cooperative agreement NA37FL0333 from the National Oceanic and Atmospheric Administration. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies.

LITERATURE CITED

ADF&G (Alaska Department of Fish and Game). 1994. Commercial shellfish fishing regulations, 1994-1995 edition. Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Juneau.

Carls, M.G., and C.E. O'Clair. 1990. Influence of cold air exposures on ovigerous red king crabs (*Paralithodes camtschatica*) and Tanner crabs (*Chionoecetes bairdi*) and their offspring, p. 329-343. *In* Proc. Int. Symp. King & Tanner Crabs, Alaska Sea Grant Rep. 90-04.

Collie, J.S., and G.H. Kruse. MS. Estimating king crab abundance from commercial catch and research survey data. Submitted to the Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. Canadian Special Publication of Fisheries and Aquatic Sciences.

FAJ (Fisheries Agency of Japan). 1963. Report on research by Japan for the International North Pacific Fisheries Commission during the year 1961. International North Pacific Fisheries Commission Annual Report 1961:48-82.

Gray, G.W. 1963. Growth of mature female king crab *Paralithodes camtschatica* (Tilesius). Alaska Department of Fish and Game, Division of Commercial Fisheries, Informational Leaflet 26.

Kruse, G.H. 1993. Biological perspectives on crab management in Alaska. Pages 355-384 *in* G.H. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn II, editors. Proceedings of the international symposium of management strategies for exploited fish populations. University of Alaska Fairbanks, Alaska Sea Grant Report 93-02, Fairbanks.

Kruse, G.H. 1995. Long-term research strategy for king and Tanner crabs in Alaska. Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Regional Information Report 5J95-??, Juneau.

Kruse, G.H., and J.S. Collie. 1991. Preliminary application of a population size estimation model to the Bristol Bay stock of red king crabs. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 5J91-09, Juneau.

Murphy, M.C., W.E. Donaldson, and J. Zheng. 1994. Results of a questionnaire on research and management priorities for commercial crab species in Alaska. Alaska Fishery Research Bulletin 1:81-96.

Murphy, M.C., and G.H. Kruse. 1995. An annotated bibliography of capture and handling effects on crabs and lobsters. Alaska Fishery Research Bulletin 2(1):23-75.

Paul, J.M., and A.J. Paul. 1990. Breeding success of sublegal size male red king crab *Paralithodes camtschatica* (Tilesius, 1815) (Decapoda, Lithodidae). Journal of Shellfish Research 9:29-32.

Pengilly, D., and D. Schmidt. 1995. Harvest strategy for Kodiak and Bristol Bay red king crab and St. Matthew Island and Pribilof blue king crab. Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Special Publication 7, Juneau.

Powell, G.C., K.E. James, and C.,L. Hurd. 1974. Ability of male king crab, *Paralithodes camtschatica*, to mate repeatedly, Kodiak, Alaska. Fishery Bulletin 72:171-179.

Powell, G.C., and R.B. Nickerson. 1965. Reproduction of king crabs, *Paralithodes camtschatica* (Tilesius). Journal of the Fisheries Research Board of Canada 22:101-111.

Schmidt, D., and D. Pengilly. 1990. Alternative red king crab fishery management practices: modeling the effects of varying size-sex restrictions and harvest rates. Pages 551-566 *in* Proceedings of the international symposium on king and Tanner crabs. University of Alaska Fairbanks, Alaska Sea Grant College Program Report 90-04.

Stevens, B.G., J.A. Haaga, and R.A. MacIntosh. 1994. Report to industry on the 1994 eastern Bering Sea crab survey. National Marine Fisheries Service, Alaska Fisheries Science Center Report 94-07, Kodiak.

Weber, D.D., and T. Miyahara. 1962. Growth of the adult male king crab, *Paralithodes camtschaticus* (Tilesius). Fishery Bulletin 62:53-75,

Zheng, J., M.C. Murphy, and G. H. Kruse. 1995. A length-based population model and stock-recruitment relationships for red king crabs, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Canadian Journal of Fisheries and Aquatic Sciences, *In press.*

Zheng, J., M.C. Murphy, and G.H. Kruse. MSa. An update of the length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Submitted to the Alaska Fishery Research Bulletin (manuscript draft 95-5012).

Zheng, J., G.H. Kruse, and M.C. Murphy. MSb. Analysis of harvest strategies for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Contribution PP-104 of the Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Juneau.

Zhou, S., and T.C. Shirley. 1995. Effects of handling on feeding, activity and survival of red king crabs, *Paralithodes camtschaticus* (Tilesius, 1815). Journal of Shellfish Research 14:173-177.

Table 1. Optimum yields expressed as percentages of the highest value possible for optimal combinations of mature male harvest rate (HR) and threshold under two levels of handling mortality and two levels of maximum legal harvest rate. Yields corresponding to current mature male harvest rate and threshold are underlined, and maximum values (>99.0%) of yield are shown in bold.

Mature Male HR	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
	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	96.8	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
	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 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	0.0	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
	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 2. Mean yields expressed as percentages of the maximum mean yield possible for combinations of mature male harvest rate (HR) and threshold under two levels of handling mortality and two levels of maximum legal harvest rate. Yields corresponding to current mature male harvest rate and threshold are underlined, and maximum values (>99.0%) of yield are shown in bold.

Mature Male HR	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
	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
	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 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
	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 3. Comparisons of mean yield, standard deviation of yield (SD), coefficient of variations (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 24.2 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						
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						
20	26.576	16.452	55.1	8.1	1-6	1-173
50	22.616	14.362	54.5	10.3	1-5	1-101

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).

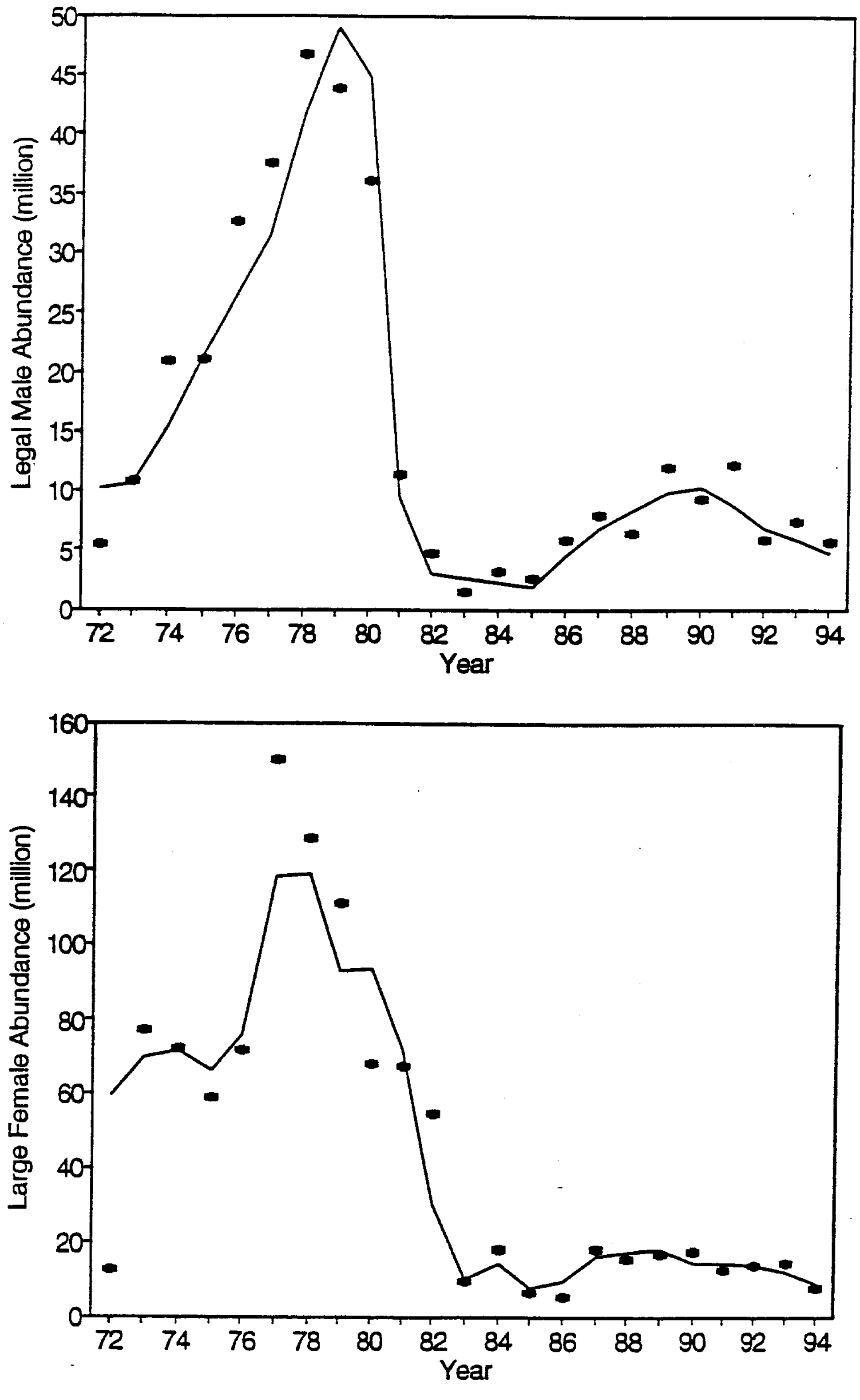

Figure 1. Comparison of NMFS survey (dots) and LBA (solid line) estimates of legal male (top panel) and large female (lower panel) red king crab abundances in Bristol Bay.

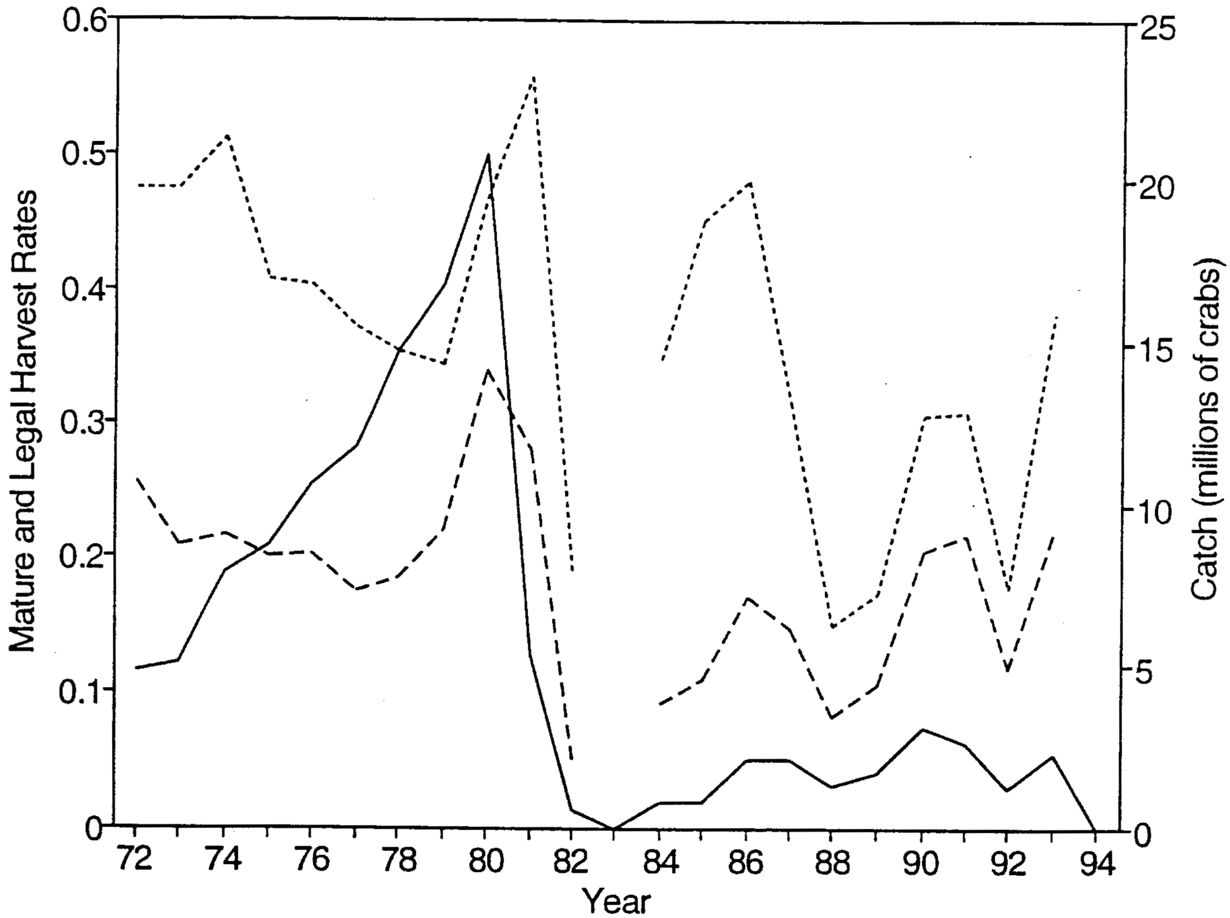

Figure 2. Catch (solid line), mature (dashed line) and legal (dotted line) male crab harvest rates of red king crabs in Bristol Bay .

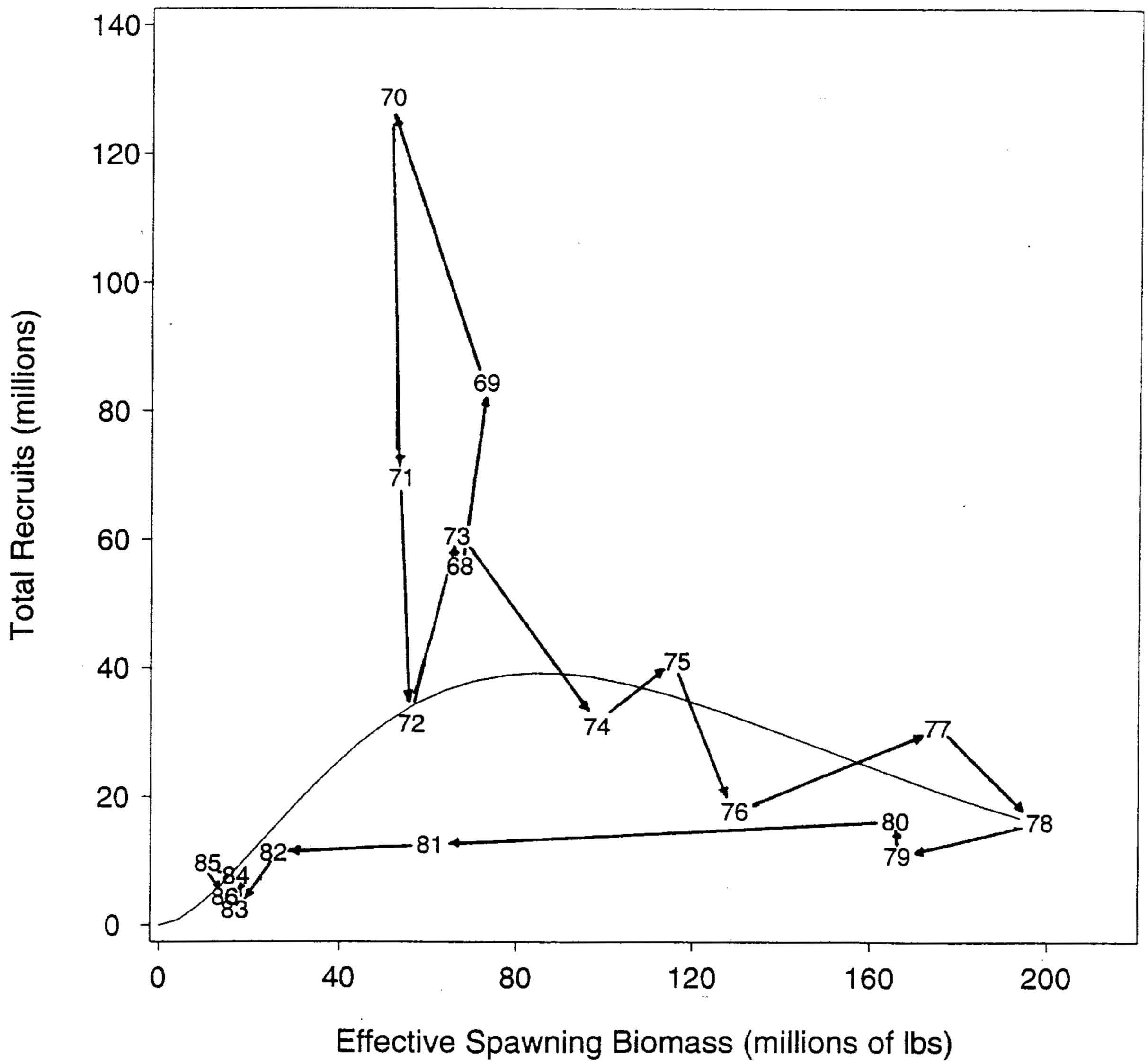

Figure 3. Relationship between effective spawning biomass and total recruits at age 6.2 (i.e., 7-year time lag) for red king crabs in Bristol Bay. Numerical label is the brood year, and the line represents the Ricker stock-recruit curve.