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An Evaluation of Alternative Management Options for the Southeastern Bering Sea King Crab Fishery

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NOTICE

AN EVALUATION OF ALTERNATE MANAGEMENT OPTIONS FOR THE SOUTHEASTERN BERING SEA KING CRAB FISHERY

by

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SUMMARY

1. Management options of: (1) relaxed quotas, (2) lowered size limits, and (3) extended seasons were compared with multiple age group management currently employed to reduce dependency on a stock dominated by new recruits.

2. The management options were compared to actual management policy by modeling the major features of the southeastern Bering Sea fishery for the 1970-79 period, and then altering the model to reflect the new management options.

3. For management option one, relaxed quotas, economic analysis of catch and effort indicated that annual returns to the fleet were maximized when effort was increased moderately to double the historical level. However, if price goes down with the size of crabs in the catch, the gain is reduced.

4. For management option two, lowered size limits, a 5.25-inch minimum size limit produced higher annual returns to the fleet than either a 6-inch limit or the limit actually in force, 6.5 inches. Gains under the lowest size limit were further increased when effort was doubled. Gains were rapidly reduced, however, if price is related to size of crab in the catch.

5. Management option three, the extended season, produced higher annual returns than the actual policy, especially if late season effort is doubled rather than some lesser increase. Gains increased slightly when price was related to size.

6. If price is not related to size, average annual returns for years 1978-79 were increased most by the doubling effort with a 5.25-inch minimum size limit, followed by, 5.25-inch size limit, the relaxed quota option with doubled effort, and then the extended season. Excepting this last option, when price is related to size, average annual returns generated by the options decreased compared to average actual returns.

7. When compared to actual management policy, none of the options examined impaired the reproductive capacity of the simulated stocks. Actual stock levels have been high in recent years, and the available research survey data indicate that strong recruitment may result even from relatively low stock levels.

INTRODUCTION

The history of the Alaskan king crab fisheries has been marked by fluctuations. The southeastern Bering Sea fishery, which currently produces most of the catch from Alaska, increased seven-fold to 64 million pounds during the early sixties. It declined to 19 million pounds in 1971, and recovered subsequently to a high of 108 million pounds in 1979. Likewise, the Kodiak fishery exhibited a five-fold harvest increase during the early 1960's, to a peak of 96 million pounds. This was followed by a nine-fold decrease due to a low stock level during the late 1960's which has persisted to the present.

To avoid the adverse impacts of fluctuating catches, current resource management policy attempts to maintain fishable crab stocks that are comprised of a broad base of age groups. This is attempted to avoid dependency on a recruits-only fishery and to ensure maintenance of a viable brood stock under the assumption that large males are required for breeding. Thus, in the eastern Bering Sea under conditions of good recruitment the goal of management policy is to annually harvest so that fishing mortality on any particular recruit group is in the range of 35-40 per cent. This rate of exploitation allows escapement of recruits and maintenance of "holdover" crab, forming a multiple-age stock in following years. While such a policy may lessen the impact of fluctuations, the question arises as to whether other management policies might be desirable from the standpoint of producing increased catches and revenue. For example, harvesting 40 per cent of a given recruitment leaves more to be caught in subsequent years but also leaves more to die naturally. A higher rate of fishing or harvesting at a lower age would presumably transfer some of this natural mortality loss to the catch. On the other hand, higher rates of exploitation or lower size limits may lead to greater instability of population, as well as catch, by affecting reproductive potential and future recruitment.

The purpose of this study is to compare, both in terms of population impacts and economic benefits, the multiple age group management strategy with three other options involving higher levels of fishing and different size limits. The three options considered have their biological basis in the yield-per-recruit theory of fish stock management (Beverton and Holt, 1957; Ricker 1975). Under this theory of management, the size (or age) of entry into the fishery and effort (or fishing mortality) are adjusted to achieve the greatest yield for a given recruitment. For the red king crab fishery in the eastern Bering Sea, the maximum yield for various combinations of age-at-entry and fishing mortality is shown by the line in Figure 1. The "X" marks

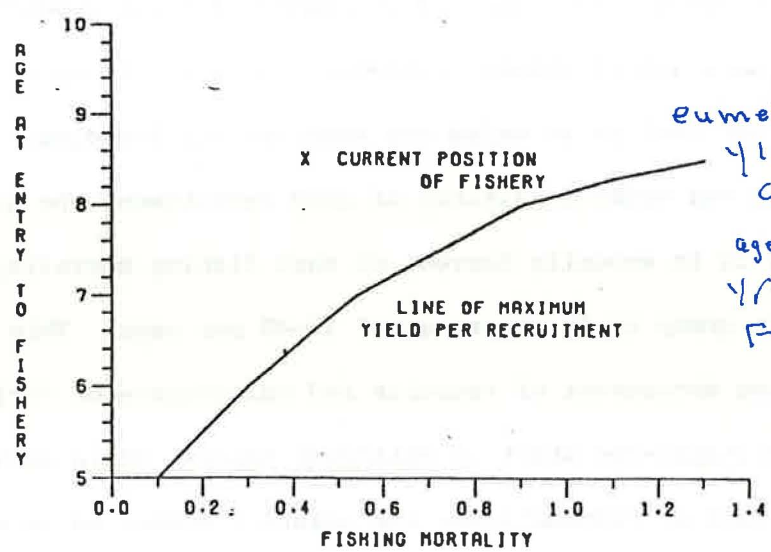

Figure 1.--Yield per recruitment for male red king crabs in the southeastern Bering Sea.

the current postion of the fishery. It appears, therefore, that some gain in yield can be obtained by changing the fishing mortality or size limit or both. Accordingly, management options were developed around this premise, with an examination of a range of increases in fishing mortalities, and decreases in size.

The relaxation of quotas, or management option one, was effected by allowing three higher than actual levels of effort to operate on the stock without regard to limitation of the catch. These higher levels of effort are depicted in Figure 2, and amount to doubling, tripling and quadrupling the actual potlifts per season during the 1975-79 period, a period of increasing stock abundance. Increased effort patterns are given on a monthly basis in Appendix 2.

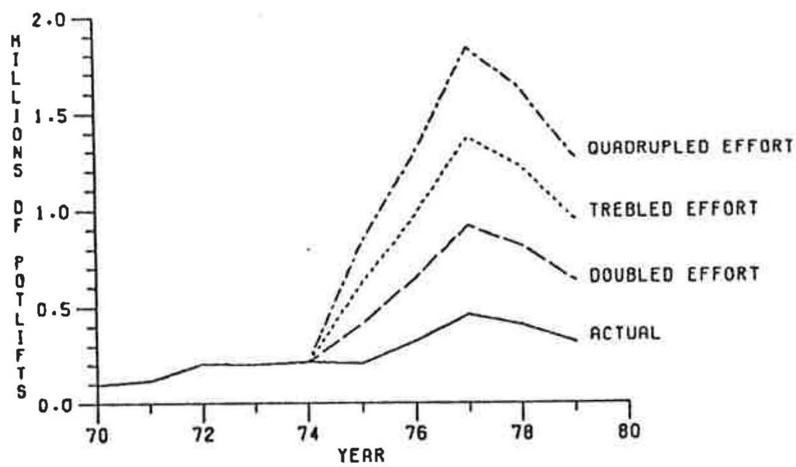

Figure 2.--Comparison of simulated effort patterns under the relaxed quota option.

The lowering of the size limit, or option two, was simulated by shifting the estimated selection curve toward the younger age groups (Figure 3). Thus, the curve whereby crabs are fully available at age 8 corresponds to a minimum size limit of about 6 inch carapace width. Similarly, age 7 full availability is equivalent to about 5.25 inch minimum size limit. During simulations, these variations were compared to the current 6.5 inch size limit.

Is this the correct way to do it?

The extended season option, or management option three, was carried out to examine the applicability to the Bering Sea stock of a strategy already in effect around Kodiak. This option is a compromise between the strict yield-per-recruit approach and multiple age group management. Fishing mortality is

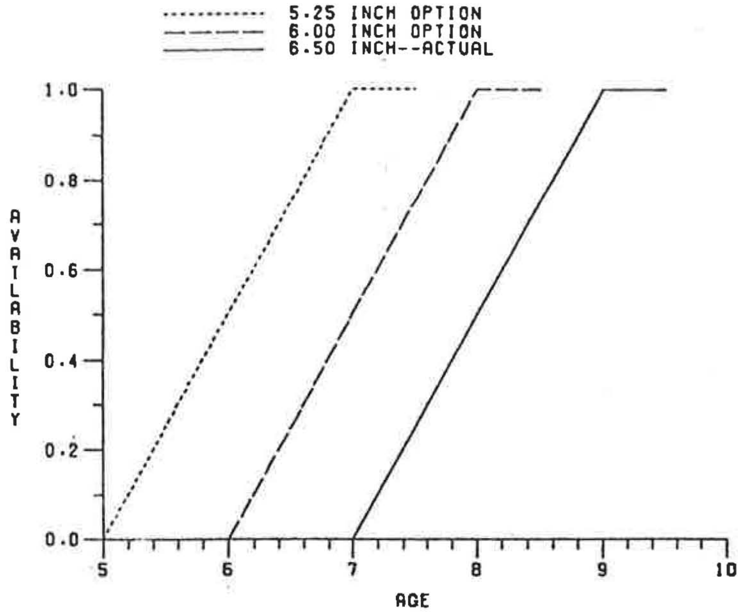

Figure 3.—Comparison of selection curves used under the lowered size limit option.

increased on older crabs that would otherwise soon die naturally, while exploitation of recruits is controlled to allow carry-over to the next year. The extended season option was simulated by extending the fishing period beyond the initial quota for an additional month during 1978 and 1979, years of short seasons and high stock abundance. During the extended period, effort was increased to 40% and 100% of the original season levels. The selection curve was shifted to older ages to approximate a 7 inch minimum size during the extended season. The data used for examining this option are given in Appendix 2.

THE SIMULATION MODEL

The comparison of management options was made using a computer simulation model of the crab stock and fishery. This approach greatly facilitated the bookkeeping necessary to keep track of the various age groups in a population which is simultaneously increasing due to growth and recruitment and decreasing due to natural and fishing deaths over a number of years. The effort inputs and catch outputs from simulation runs are then used to examine economic benefits of alternate strategies.

The Exploited Population Model

The model employed for this study is a modified version of a crab population simulator described by Newell and Paulik (1972), and modified by Balsiger (1974). The model simulates a life history pattern of growth, natural mortality and reproduction, and also provides for analysis of fishing management policies and their impact upon the population.

The general life history pattern of the king crab, as represented in the model, is shown in Appendix Figure 1-1. Starting with a given spawning population, crabs are recruited into the population where they grow according to sex-specific rates. Natural mortality is applied to both sexes, and fishing mortality, which is specified in terms of effort, catchability, and availability, is applied only to male crabs. Copulation is dependent upon sex and size ratios during the mating season, and recruitment production is dependent upon copulated female abundance.

Annual recruitment is specified by a spawner-recruit function which may be over-riden by user-specified recruitment values. Fishing effort may be controlled by annual quota, and initial and late season age limits (corresponding to size) may also be specified for the fishery. Model computations are performed monthly and are summed or averaged annually. The unit length of time is one year and begins at spawning time. Details of computation of the processes in the model, as well as a listing of the computer program, are given in Appendix 1.

Data on stock structure and abundance, abundance of recruits, natural mortality, growth, catchability, availability and fishing effort have been incorporated into the simulation model. Natural mortality of the exploitable stock has been estimated from both current fishery and research survey data using methods of Beverton and Holt (1957). This analysis, presented in Appendix 3, indicates that natural mortality is about 25% lower than when estimated by Balsiger (1974). Re-estimated rates are represented in Table 1.

Table 1.--Estimates of instantaneous natural mortality, M, for the exploited stock of red king crab in the eastern Bering Sea (see Appendix 3 for analysis).

Age	Annual M
9	.11
10	.23
11	.50
12	.57
13	.61
14	.76

A first estimate of female natural mortality, based on analysis of research survey data, is also presented in Appendix 3. This analysis indicates the female annual instantaneous rate of mortality, estimated at 0.58, is substantially higher than the male rate, at least for the 3 or 4 years following maturation, which occurs at about age five.

Annual catchability of the exploitable stock was estimated from research survey and fishery information. This analysis, given in detail in Appendix 4, indicates a decline in catchability in recent years (Table 2).

Table 2.—Estimates of annual catchability, q, for red king crab in the eastern Bering Sea (see Appendix 5 for analysis).

Year	q
1970	$.326 \times 10^{-5}$
1971	--
1972	$.336 \times 10^{-5}$
1973	$.212 \times 10^{-5}$
1974	$.170 \times 10^{-5}$
1975	$.170 \times 10^{-5}$
1976	$.100 \times 10^{-5}$
1977	$.070 \times 10^{-5}$
1978	$.082 \times 10^{-5}$

Availability of the male stock to the fishery was also estimated from survey and fishery data, and indicates that age 8 males have been, on the average, 50 per cent recruited to the pot fishery.

Stock abundance and age structure used for initiating the simulations were obtained from survey data. Abundance estimates for each age from five to fourteen for both sexes were averaged over the survey years 1968-72 (Appendix 2). Growth rates for both males and females were derived from information given by Balsiger (1974), and are illustrated in Appendix A, Figure 2-1. Fishing effort used in the simulations is the actual reported effort in the eastern Bering Sea for the 1970-79 period, in terms of pot-lifts (Appendix 2).

For the purpose of comparing management options in terms of their effects on reproductive potential, recruitment of 5-year-old males was related to abundance of spawning females. Research survey data for the Bering Sea was used in an attempt to describe this relationship, which is portrayed graphically in Figure 4a. The limited amount of data available made it difficult to determine a relationship. However, Beverton and Holt and Ricker curves were fitted to the data, and these relationships used to assess the relative effects of the management options on future recruitment.

The major link between exploitation of the stock and spawning females (and thereby, recruitment) is provided by the relationship shown in Figure 4b. Here, the percentage of the mature female stock copulated in any year is related to the size of mating males in relation to the size of mating females. This relationship provides for full copulation when males are at least 1.7 times larger by weight than females. Below that value, copulation drops off rapidly. Copulation is also a function of the sex ratio during mating which was not important to copulation in this study (see Appendix 1).

Economic Framework

Minimizing fluctuations in king crab harvest levels by maintenance of a multiple-age-group fishery affects participants at all levels of the marketing chain. Quantity variations which stem from a multiple-age-group management policy result ultimately in price and earnings changes of both harvesting and processing sectors of the industry. Final consumers are also affected. While participants at each level of the market feel the impact of changes in management policies, a decision was made to focus only on the harvesting segment. To explore the impact of different management alternatives on this sector of the industry, gross revenue was

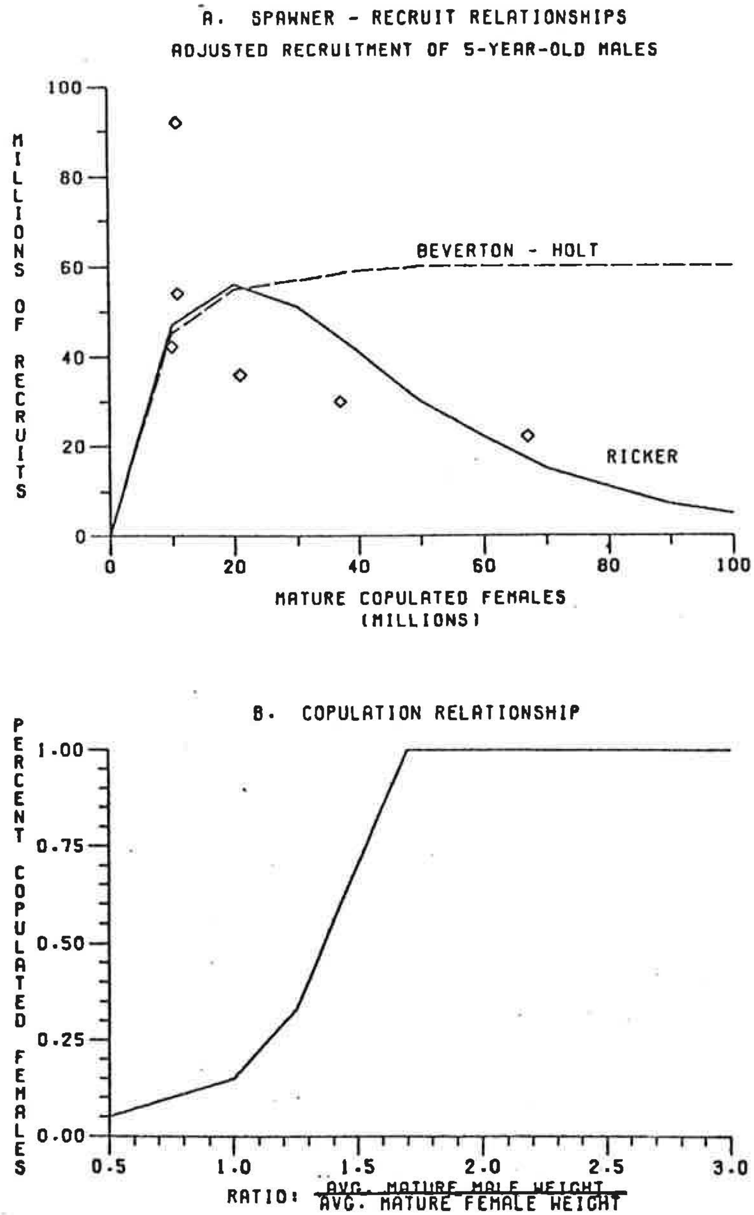

Figure 4.--Reproduction relationships used during simulations.

calculated for each option[1]. Annual returns, gross revenue less operating costs, were also calculated[2].

SIMULATION RESULTS

Assessment of the biological and economic impact of the three management options was accomplished by first calibrating the model to reproduce the evolution of the southeastern Bering Sea king crab fishery from 1970 through 1979. Once the calibration was completed, the simulated management options were compared with the simulation of the actual fishery to evaluate the effects of variation in quotas, size limits and season length on the crab stock and the harvestors who participated in the fishery. Exploitable stock, catch-per-unit-of-effort (CPUE), average size of crabs in the catch, per cent copulated females and future recruitment to the exploited stock were examined to determine the impact of the various management options on the crab stock. Gross revenues and annual returns were examined to determine how the harvesting segment is affected by different approaches to management.

Parameters chosen to evaluate success in simulating the fishery and stock were abundance of exploitable stock, catch, catch rates and average size of crabs in the catch. Comparisons of actual with simulated data are shown in Figure 5. Good agreement has been obtained for abundance of the exploited stock, catch, CPUE and average size in the catch. The close

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1/ Price flexibiliities with respect to quantity and income of -0.31 and 2.12 were assumed for forecasting pruposes.

2/ Cost data reported by Katz and Lee (1976) were used to calculate annual returns.

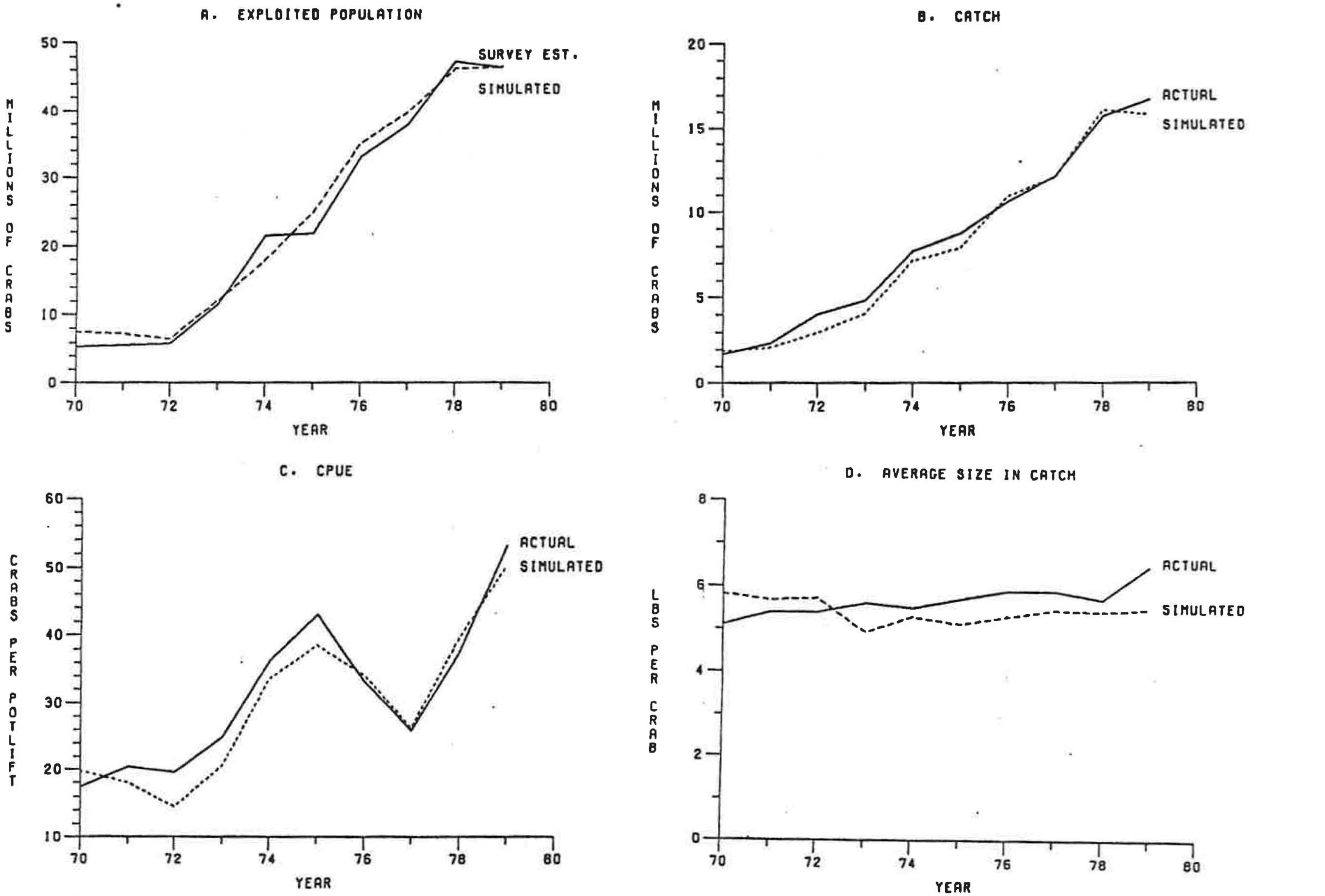

Figure 5.--Comparisons of actual and simulated data.

correspondence between the actual exploited population, estimated by annual research surveys, and its simulated counterpart was obtained by increasing observed abundances of five-year-old males. The discrepancy between observed and simulated abundance of five-year-olds, the earliest age group modeled, is shown in Figure 6a. On the average, observed abundances of five-year-olds were approximately doubled to achieve the agreement depicted in Figure 5. This suggests that five-year-old crabs are not fully available to the survey sampling gear, which is also indicated by stock age compositions obtained from the surveys (Figure 6b).

Beyond the abundance of five-year-old recruits, the greatest discrepancy between actual and simulated data occurs for the average size of crabs in the catch. This can be explained in various ways (growth or fishery selectivity changes, for example) but does not appear to impact substantially on the major results.

In reporting the outcome of the various simulation runs, the results obtained during calibration are defined as "actual" values, even though exact duplication of the history of the fishery was not achieved. Thus, outcomes of the simulation runs for quota relaxation, size limit reduction, and season extension are compared with simulated "actual" values. Finally, results obtained for the three management options are compared.

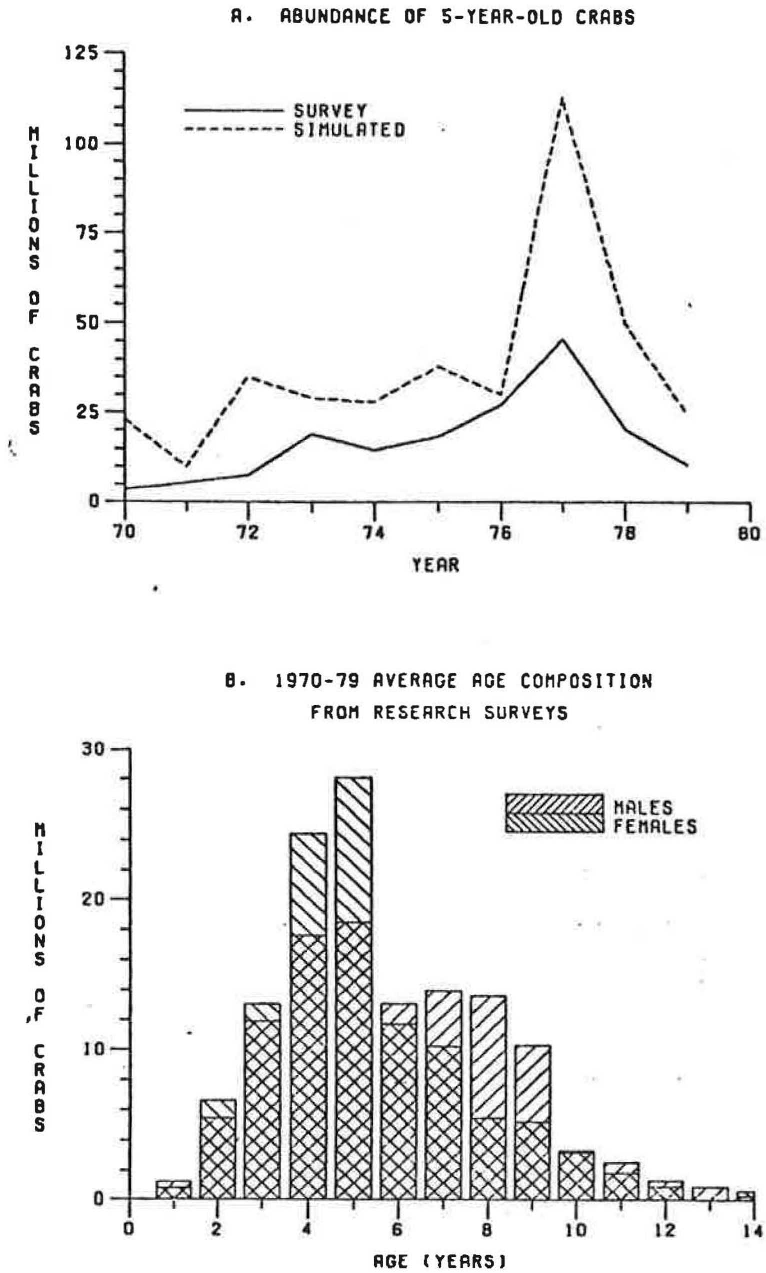

Figure 6.--a) Comparison of actual and simulated recruitment, and, b) average stock composition from research surveys by sex.

Quota Relaxation

The analysis of the impact of a quota relaxation was accomplished by increasing the level of effort exerted in years 1975 through 1979 without restricting the catch. The effects of a doubling, tripling and quadrupling of effort over actual historical levels were explored. Since the increased effort levels affect the size of crab in the catch, major findings are presented below for two alternative assumptions concerning the response of the ex-vessel price to changes in the average size of crabs caught. Initially, price was assumed to be independent of size. This assumption was then relaxed and price was made to increase (or decrease) by 2 percent for each percentage increase (or decrease) in average size (Note 1, Appendix 7). It must be emphasized that this price/size response should not be interpreted as the actual relationship that exists between price and size. It was selected to illustrate how different sizes might affect annual returns.

Gross revenues and annual returns associated with the doubling, tripling, and quadrupling of effort are shown in Figure 7, and indicate that a quadrupling of effort produces the largest gross revenues in four of the five simulated years. A doubling of effort is the most desirable strategy when harvesting costs are taken into account. Doubling the level of effort increased average annual returns by $8.4, $1.1, and $6.6 million over actual, triple and quadruple effort levels. In percentage terms, a doubling in the level of effort increases average annual returns by 15 percent over the actual level. The relationship between annual returns for effort levels considered is shown in Figure 8 for 1979. The difference between the lines labeled gross revenue and total cost indicates the magnitude of annual returns. A comparison of the differences indicates that annual returns are maximized by doubling effort relative to the actual level.

Simulated exploitation rates, catches, CPUE and average size in the catch are shown in Figure 9. The exploitation rates reflect the increased effort levels, with a doubling of fishing effort producing exploitation rates of around .5-.6. Since catch does not increase in proportion to effort, CPUE drops off as effort is increased. Average size in the catch declines slightly due to increased fishing mortality on the stock.

Results obtained, given the assumption that the ex-vessel price is affected by changes in the size of crabs in the catch, are shown in Figure 10. Here it is seen that the advantage of a doubling of effort over actual levels is diminished, indicating that the downward pressure on prices due to the smaller average size of crabs caught approximately offsets the increase in gross revenue which results from the larger catches associated with higher effort levels. Figure 11 shows that the lower average size of crabs caught decreases annual returns associated with increased effort levels. Upon comparing average annual returns for years 1975-79, the increase in average annual return derived from doubling effort over actual levels was determined to be approximately $3.2 million. This is compared to $8.4 million which was obtained when price was assumed independent of size. Figure 12 indicates that for 1978 and 1979 the dominance of average annual returns accruing from a management strategy which allows a doubling of effort increases as the responsiveness of price to size changes approaches zero (from 2.0 approximately). Conversely, annual returns derived from maintaining actual effort levels dominate as the price/size response increases beyond approximately 2.0.

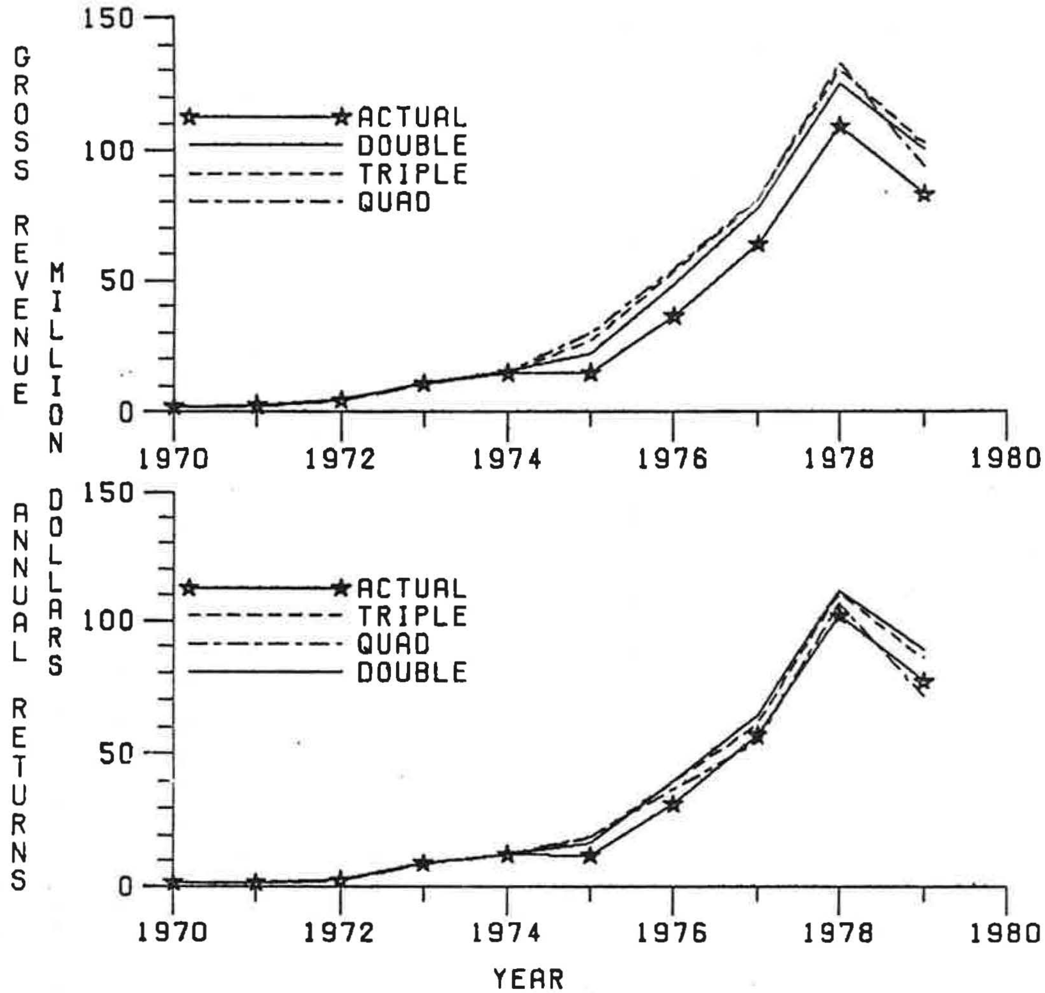

Figure 7.--Comparisons of gross revenues and annual returns under increasing effort with price independent of crab size.

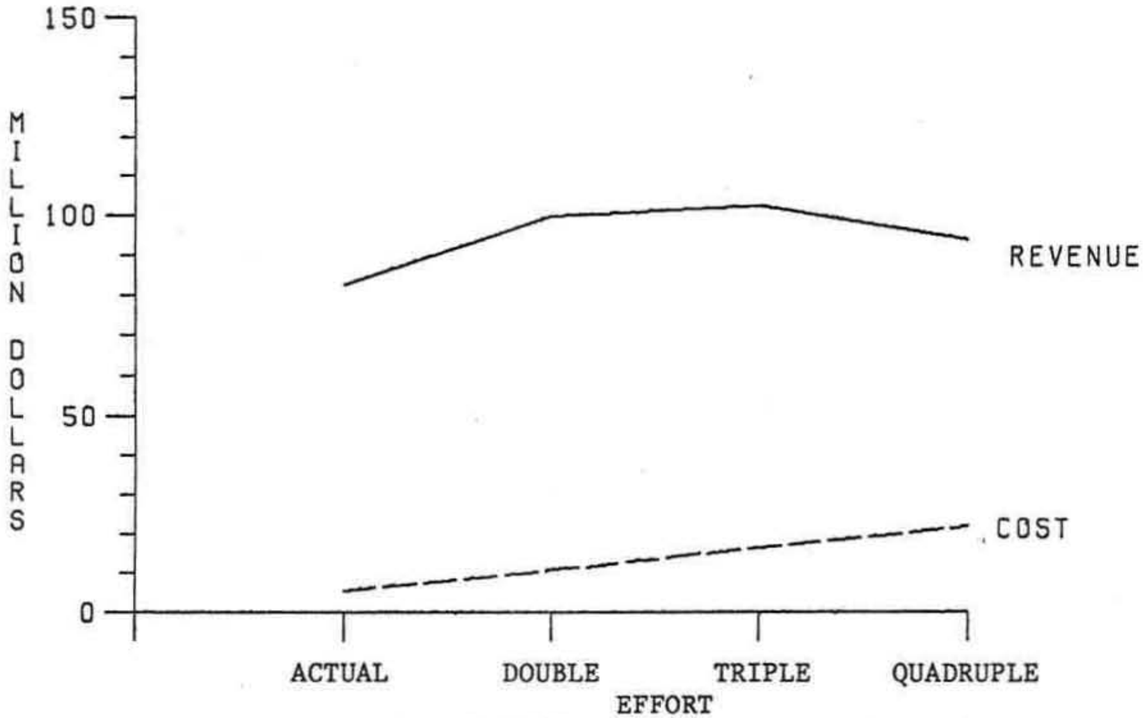

Figure 8.--Comparisons of 1979 gross revenues and total costs with price independent of crab size.

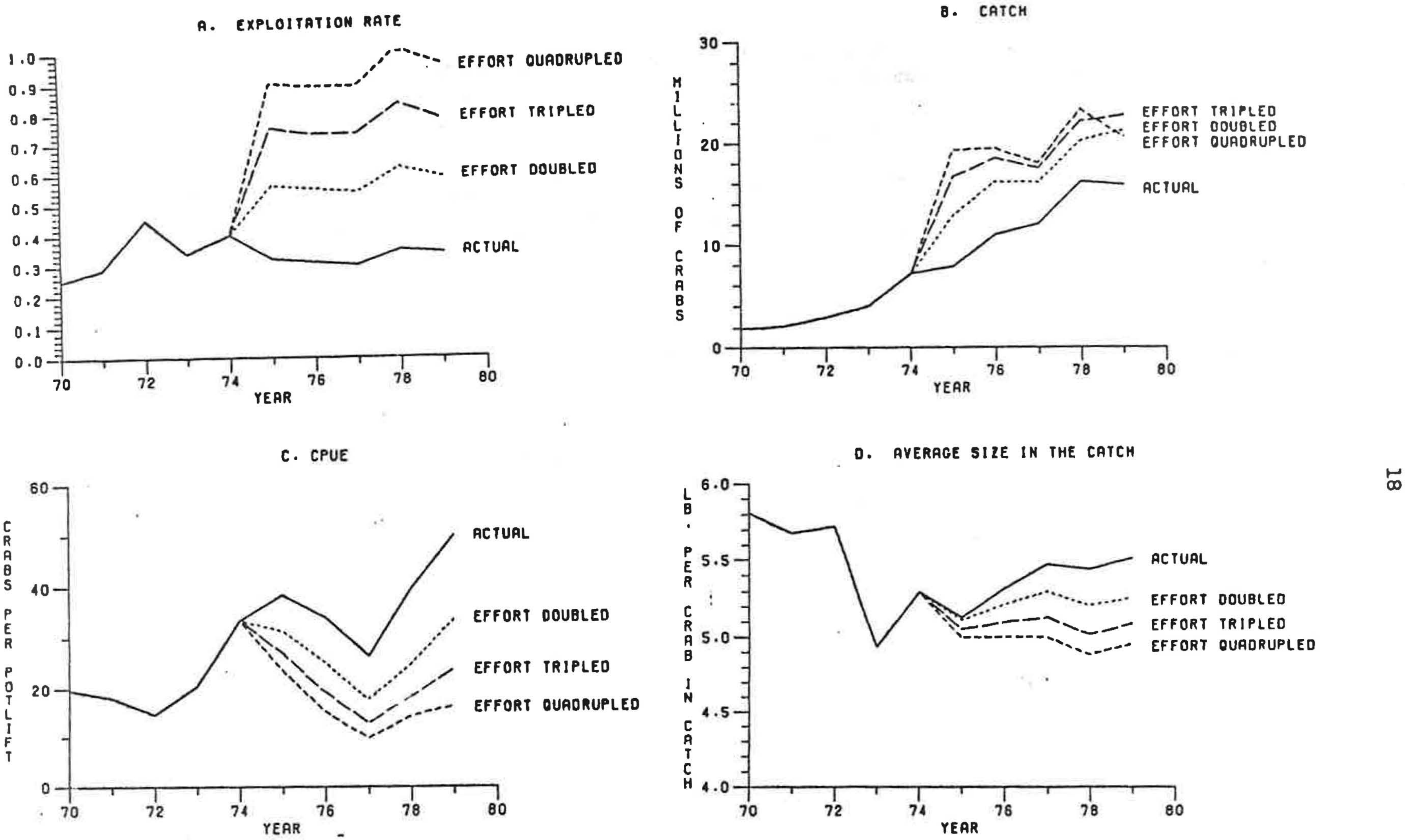

Figure 9.--Comparison of simulated exploitation rate, catch, CPUE, and average size under increasing effort.

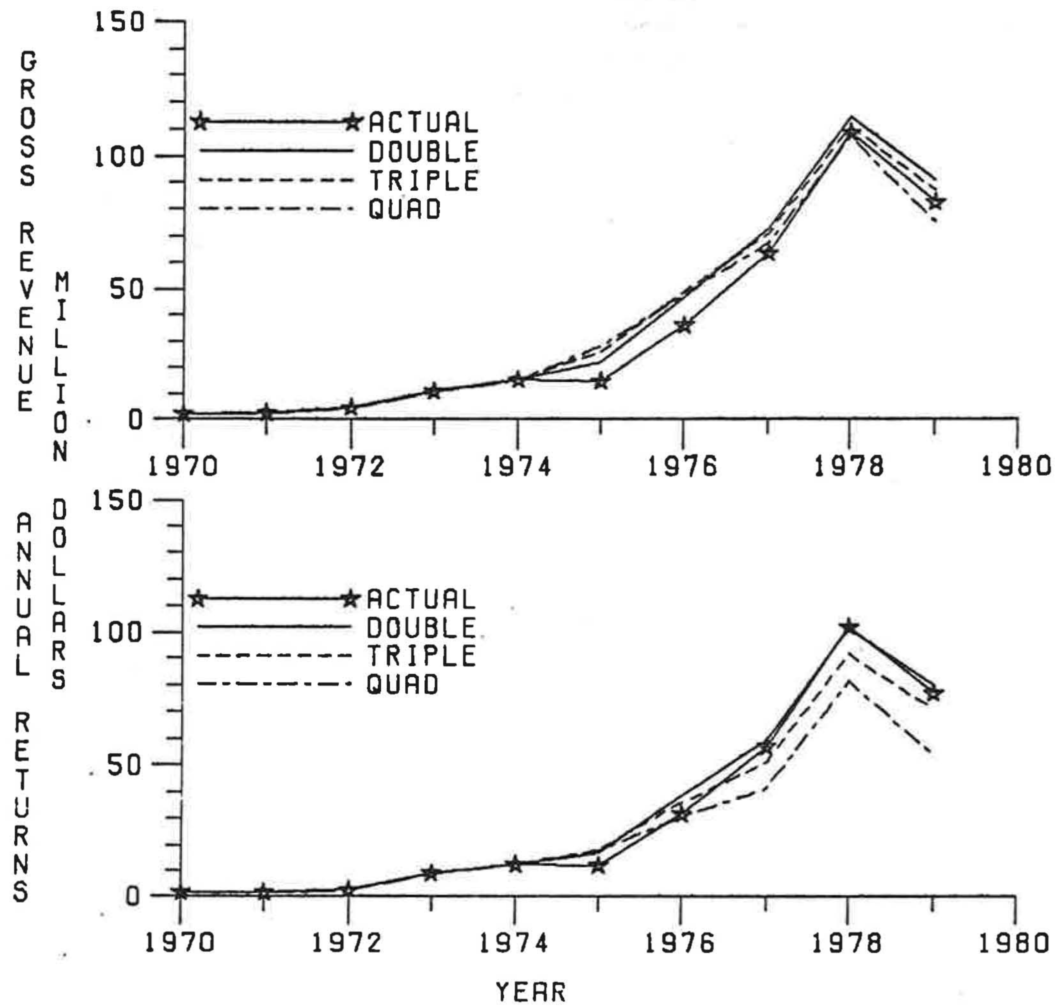

Figure 10.--Comparisons of gross revenues and annual returns under increasing effort with price dependent on crab size.

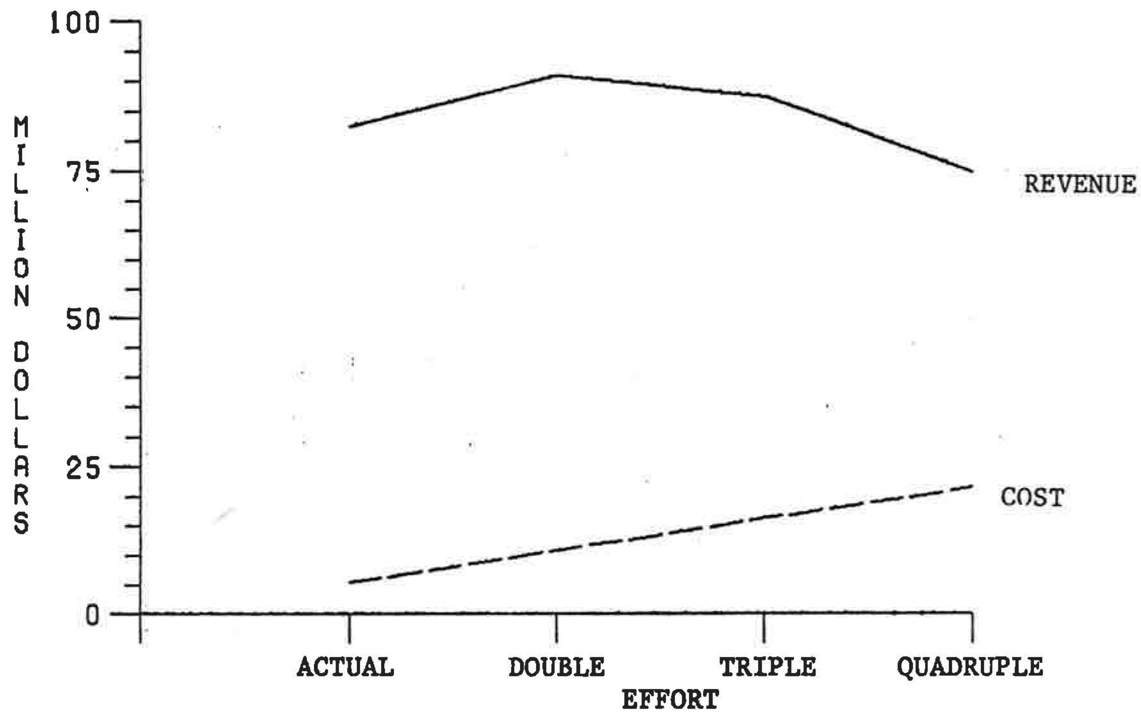

Figure 11.--Comparisons of 1979 gross revenues and total costs with price dependent on crab size.

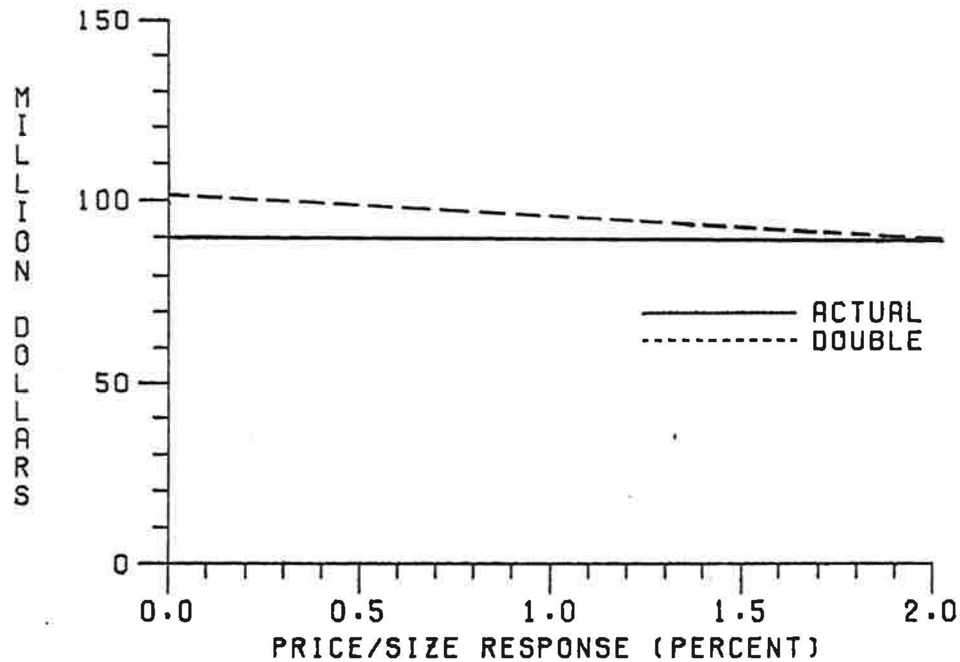

Figure 12.--Relationship between price/size response and average 1978-79 annual returns for actual and double effort levels.

Lower Size Limits

A decision was made to examine the effect of two alternatives to the present minimum size limit of 6.5 inches in carapace width on gross revenue and annual returns. The first option examined established a size limit of 5.25 inches while the second used a 6-inch minimum size. Gross revenues and annual returns for each simulated year are presented in Figure 13, given the assumption that price is independent of the average size of crabs caught. Results indicate that a 5.25-inch size limit produces the highest gross revenues and annual returns. The reason for this is that catches and CPUEs increase substantially over actual levels when size limits are lowered (Figure 14). Catches increase because more of the stock is available to the fleet. CPUEs increase because the effort is not increased, but remains at historic levels. Results shown in Figure 15 indicate, however, that when price is assumed to be dependent upon the average size of crabs in the catch, higher size limits yield larger gross revenues and annual returns, since the average size in the catch drops off substantially for lower size limits (Figure 14C). It can be concluded from this analysis that, when a one percent change in the average size of crabs caught causes a two percent price change, higher size limits are preferred to smaller ones, if maximizing either gross revenues or annual returns is the relevant objective. This outcome can be attributed to the downward pressure exerted on price by the increased number of smaller crabs in the catch overpowering the increased gross revenues stemming from larger catches. Figure 16 indicates that average annual returns for 1978 and 1979 for the 6.5-inch size limit dominate those associated with 5.25- and 6-inch size limits when the price/size response is larger than approximately 1.2 and

1.1 percent. The lower size limits yield higher annual returns when the price/size response falls below this value.

Actual effort for years 1975 through 1979 was doubled to further explore the effects of lower size limits. Given a 5.25 inch size limit and price/size independence, higher effort levels increased average annual return for years 1975-79 by $30.9 and $10.7 million, respectively, over those associated with size limits of 6.5 and 5.25 inches with effort held constant at actual levels. These gains are caused by heavier fishing on the larger available stock created by the lowered size limit, which produces a larger catch (Figure 14 A). Since effort was increased to a moderate level, CPUE declined only slightly. When average annual returns for the specified time period were compared given the assumption that prices are affected by the size of crab caught, the 6.5 inch size limit with effort held at actual levels was found to produce average annual returns that exceeded those associated with a 5.25 inch size limit with effort doubled provided that the price/size response exceeded approximately 1.25 percent (Figure 16). The converse was true for price/size responses less than 1.25 percent.

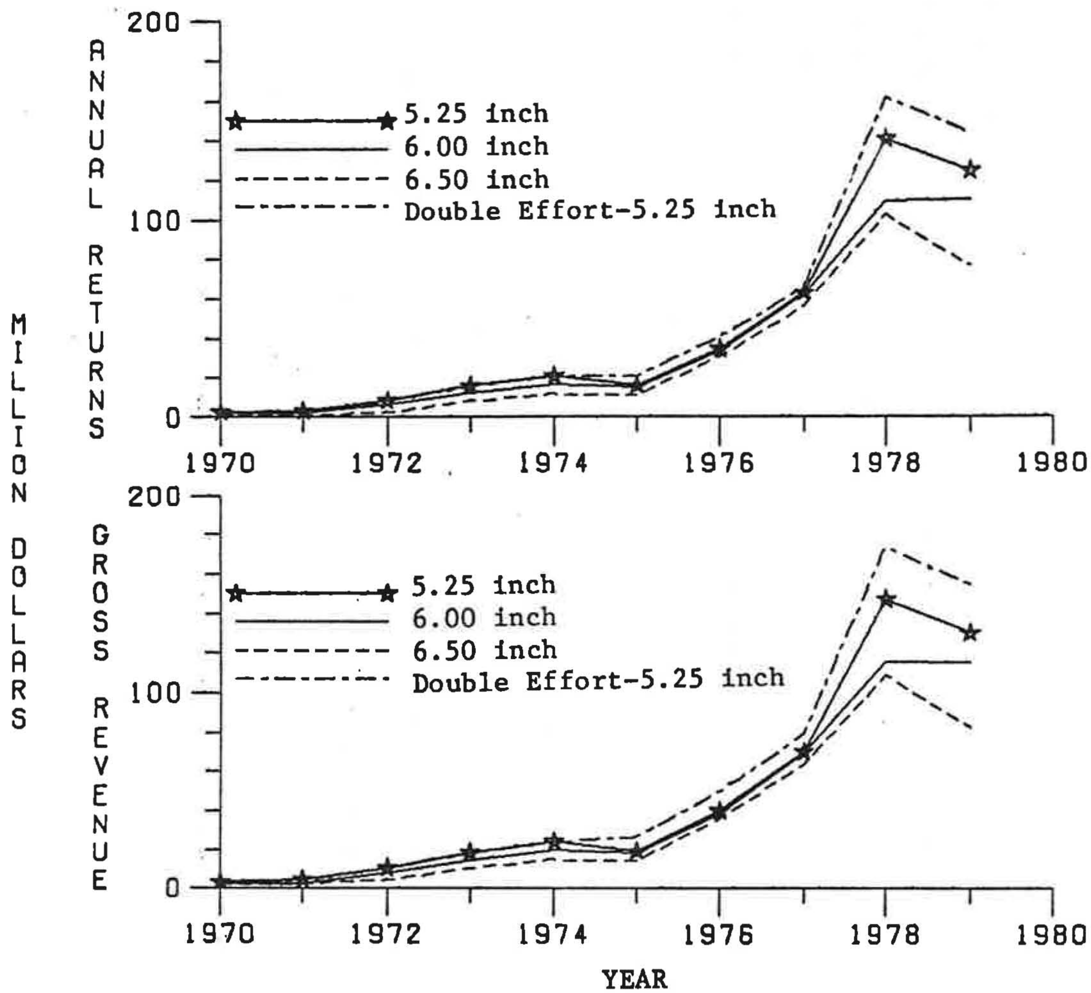

Figure 13.--Comparisons of gross revenues and annual returns under several size limits with price independent of crab size.

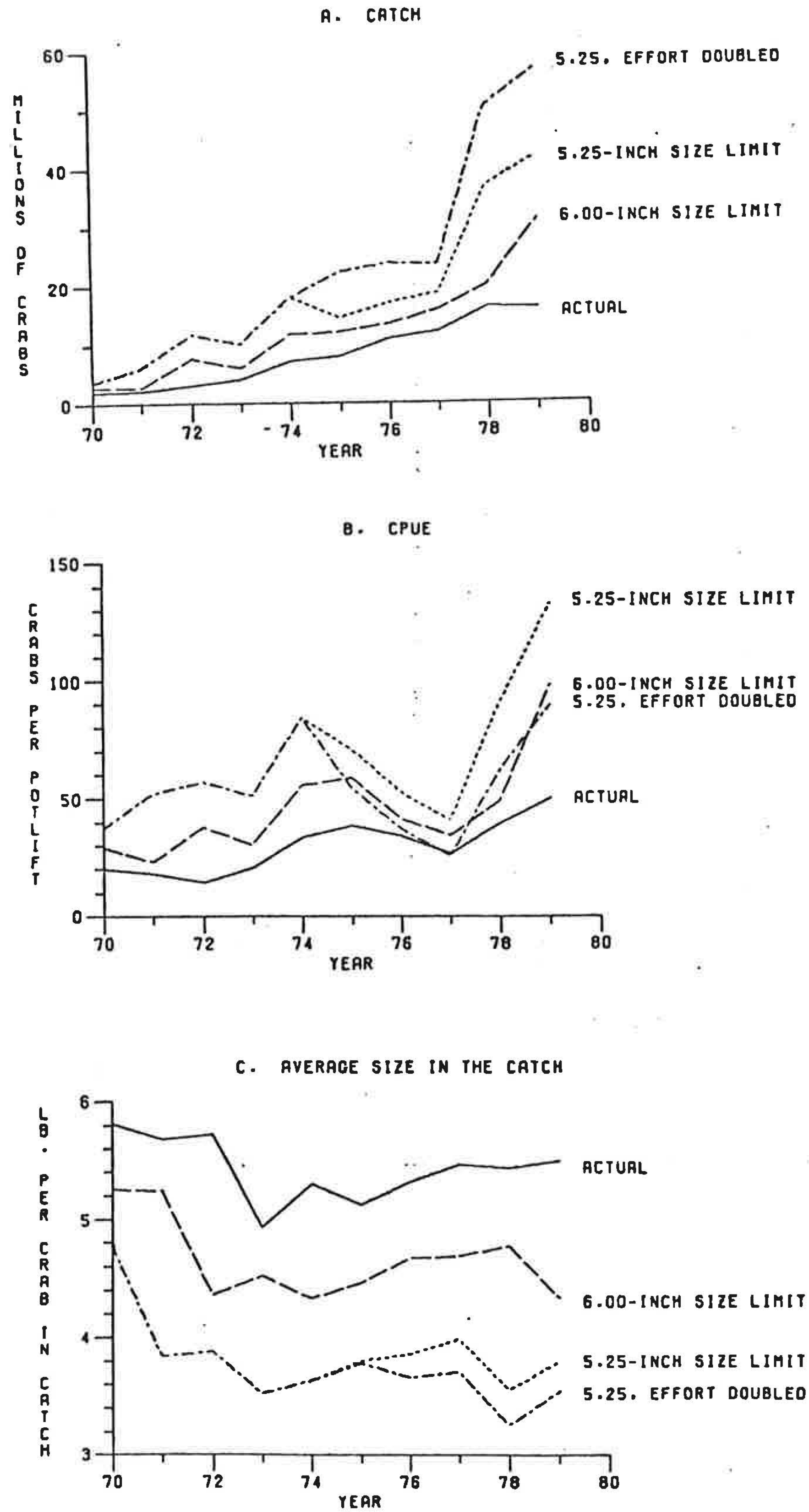

Figure 14.--Comparisons of simulated catch, CPUE and average size in the catch under two lower minimum size limits.

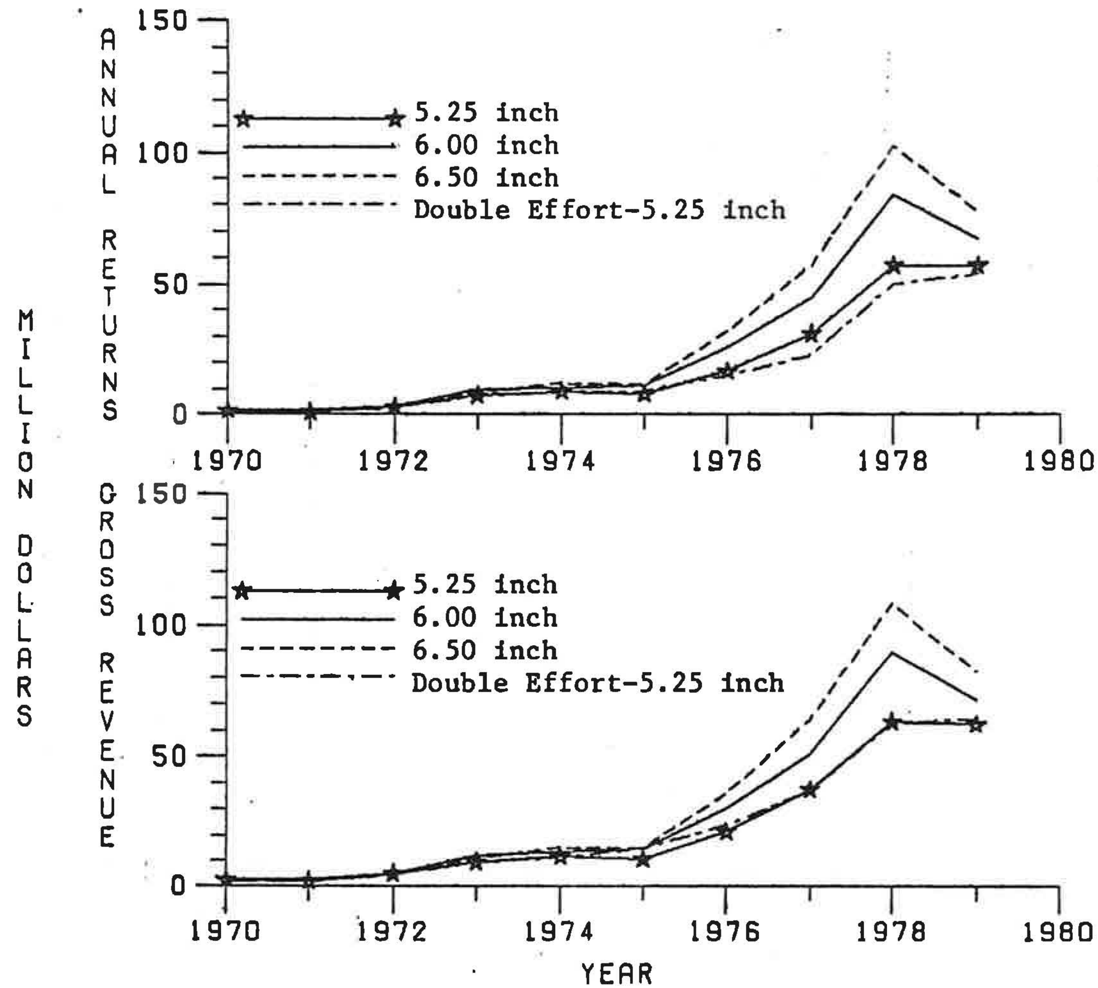

Figure 15.--Comparisons of gross revenues and annual returns under several size limits with price dependent on crab size.

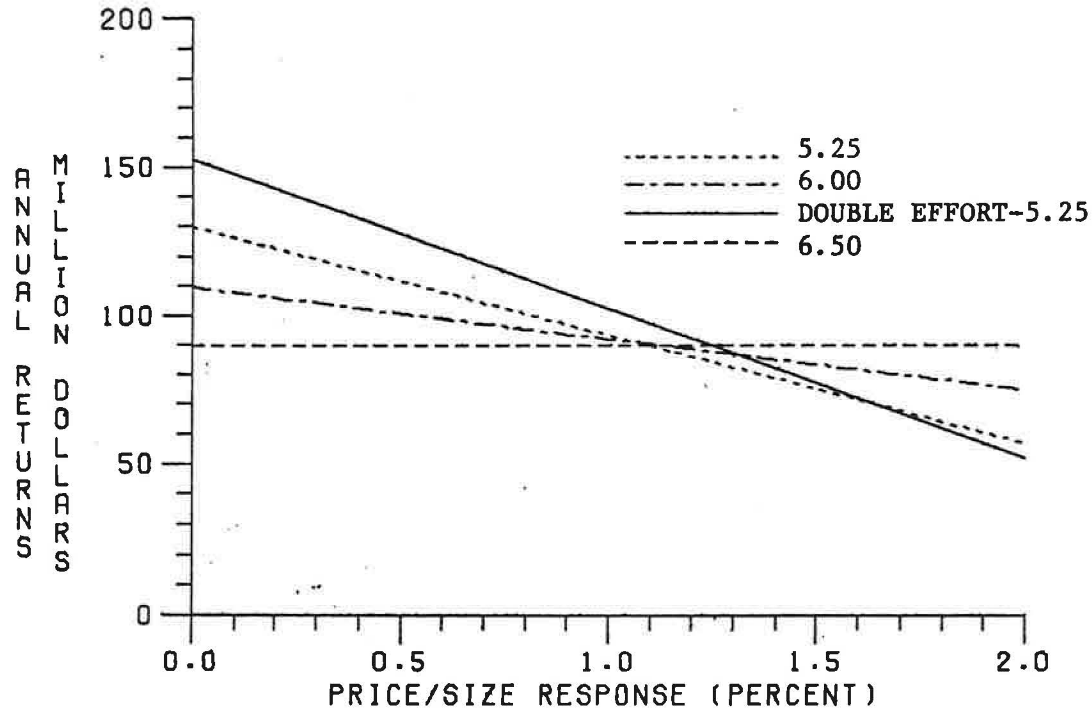

Figure 16.--Relationship between price/size response and average 1978-79 annual returns for 5.25-, 6.00- and 6.50-inch size limits.

Extended Season

The Alaska Department of Fish and Game has adopted the practice of increasing the size limit and allowing crabbing to continue after the regular season quota is reached. The rationale for this approach is that the extended season makes it possible to harvest larger crabs which would otherwise die from natural causes. Because of the current use of an extended season at Kodiak, a decision was made to examine how its implementation would affect the eastern Bering Sea fishery.

Several assumptions were required prior to this examination. First, it was necessary to assume that historical catch and season lengths remain constant from 1970 through 1977. Second, during 1978 and 1979 the extended season was assumed to run one month beyond the length of the regular season, with a 7-inch minimum size limit in effect. Lastly, effort levels during the extended season were chosen so that total annual effort increased by two arbitrary rates, 40 and 100 percent, over historical levels. The average results of the simulation runs for 1978 and 1979 for each of these effort levels are shown in Figure 17. The effect of an extended season, coupled with larger quantities of effort, is an increase in both gross revenues and annual returns over actual levels. This result was found to hold for price/size response relationships ranging in size from 0 to 2. Figure 18 indicates that difference between average annual returns associated with the different strategies increases as price becomes more responsive to size. This indicates that the attractiveness of an extended season which allows harvesting of larger crabs increases as the responsiveness of price to the average size of crabs in the catch increases. The two factors which are responsible for the dominance of the extended season/higher effort level strategies over the actual case are larger catches, and larger average sizes of crabs in the catch (Figure 19).

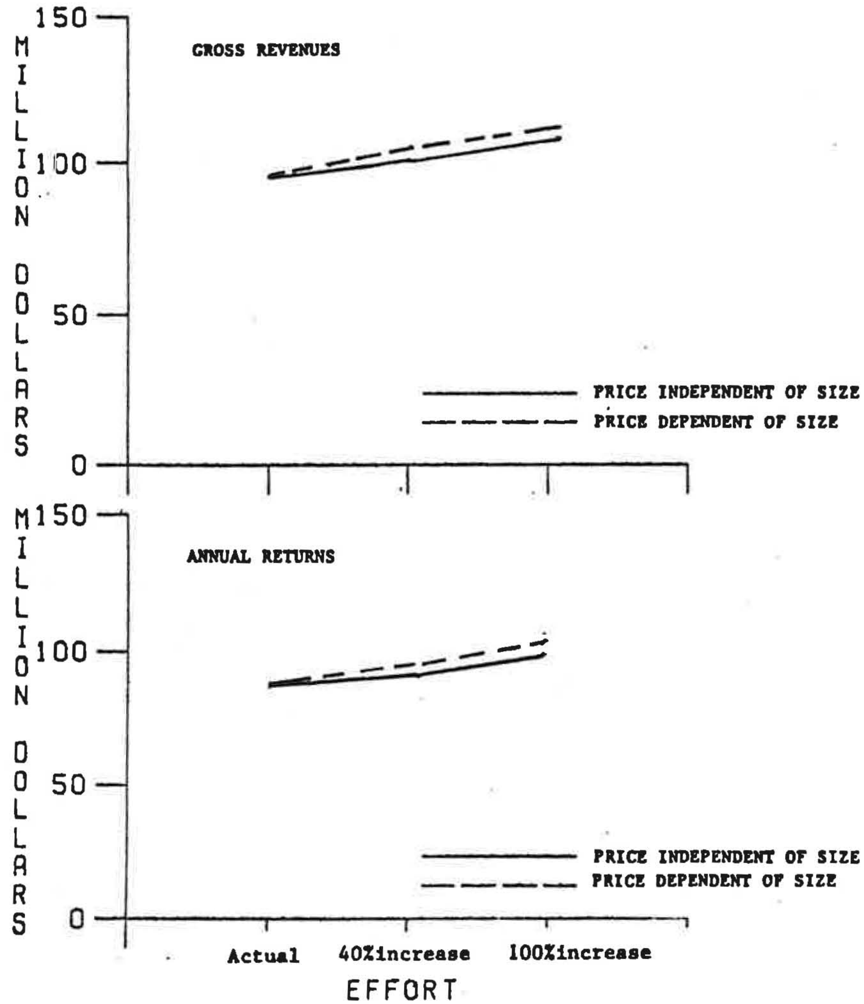

Figure 17.--Average 1978-79 gross revenues and annual returns under extended seasons with increasing effort.

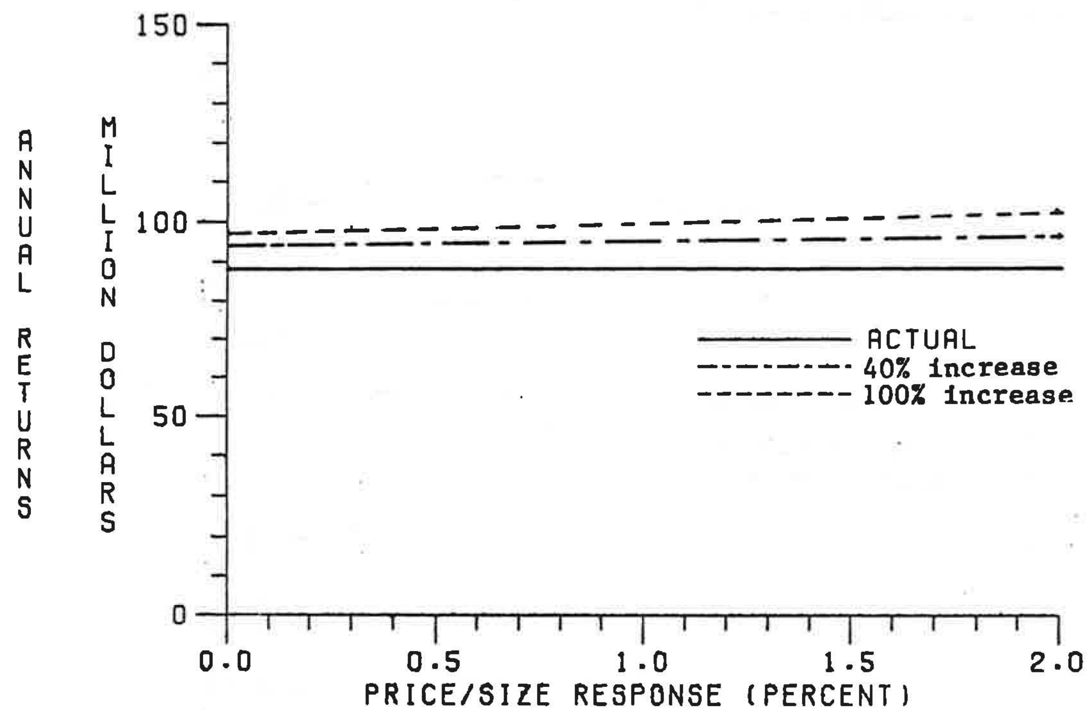

Figure 18.--Relationship between price/size response and average 1978-79 annual returns under extended seasons with increasing effort.

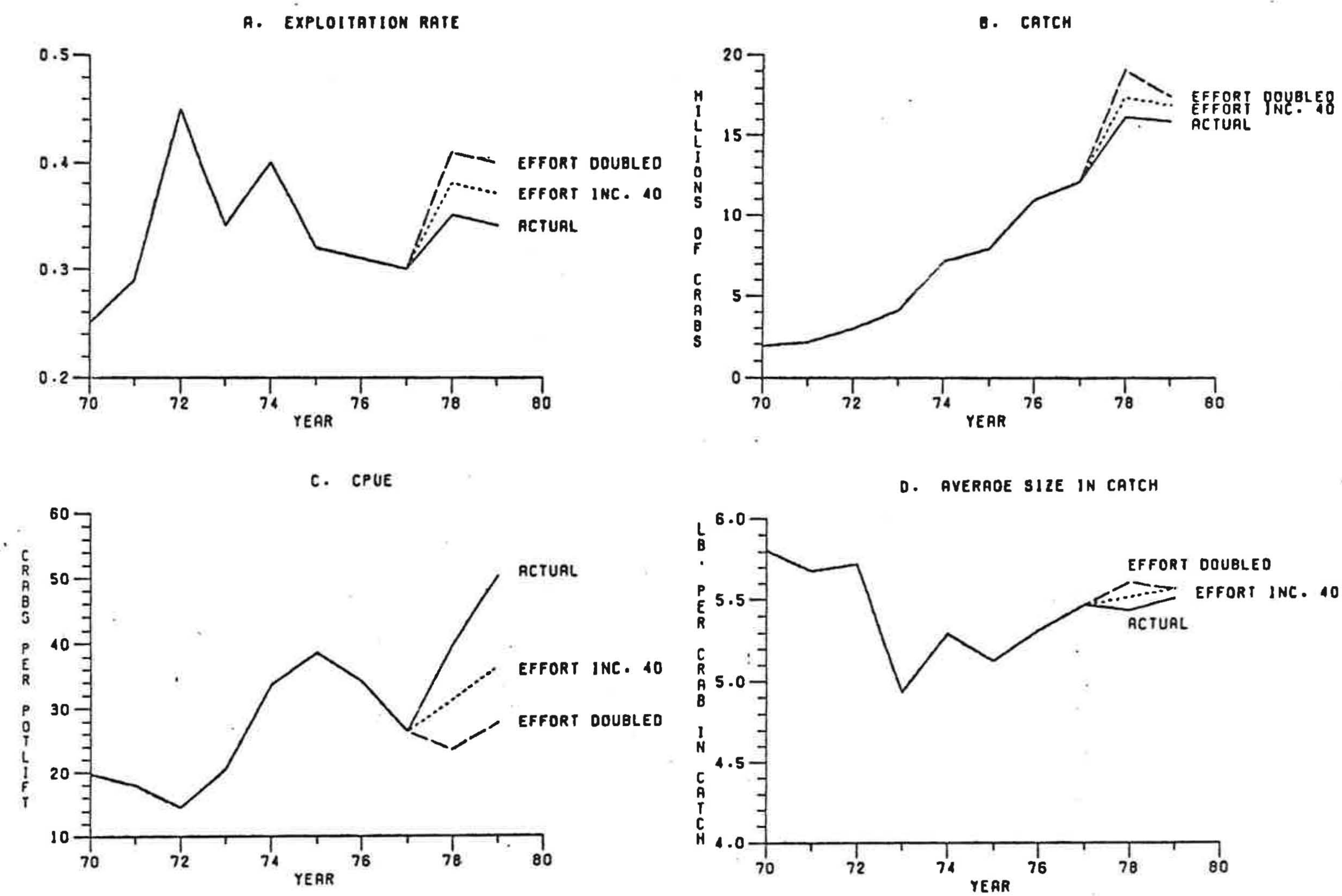

Figure 19.--Comparisons of simulated exploitation rate, catch, CPUE and average size under extended seasons with increasing effort.

Quota Relaxation, Lower Size Limits, and Extended Season: A Comparison

The preceding discussions have focused on comparing gross revenues and annual returns associated with management strategies which involved either a quota relaxation, lowering of the size limit or an extension in season length with actual simulated values. In this section, comparisons will be made of annual returns associated with a doubling of effort over actual levels, a 5.25-inch size limit, a 5.25-inch size limit with double effort, and a doubling of effort relative to actual levels during an extended season with a 7-inch size limit. Comparisons made will be limited to results obtained for 1978 and 1979, since annual returns for the extended season option were derived for just these two years. The effect of these management approaches on the reproductive potential of the stock will also be discussed.

Average annual returns for 1978 and 1979 for each management option and actual average returns are presented in Table 3. Findings presented in

Table 3.--Comparison of average annual returns for simulated years 78 and 79 for three management options (million $).

Management Option	Price Unresponsive to Size	Price Responsive to Size*
Actual	89.6	89.6
Double effort with second season on crabs 7 inches and larger	96.3	101.4
Double effort	100.4	90.8
5.25-inch size limit	132.79	56.82
Double effort--5.25" size limit	152.71	51.86

*1 percent change in the average size of crabs caught assumed to change price by 2 percent.

this table indicate that a lowering of the size limit to 5.25 inches coupled with a doubling of effort yields the highest average annual return when price is independent of the size of crabs in the catch. When the price/size independence assumption is replaced with the assumption that a one percent change in average size causes a two per cent change in price, an extended season with a 7-inch size limit and a doubling in the actual amount of effort because of the extended period produces the largest average annual returns. Figure 20 indicates that average annual returns for 1978 and 1979 produced by a lowering of the size limit to 5.25 inches with a doubling of effort dominates returns associated with the other options until the price/size response approaches one. A strategy of doubling actual effort levels during an extended season with a 7-inch size limit yields the highest average annual return when the price/size response exceeds one. It should also be noted that average annual returns which accrued from actual effort levels dominate those produced by doubling effort as long as the price/size response exceeds two approximately.

Some industry sources suggest that variations in the average size of crabs caught above a 5-inch threshhold would not affect price. Further, it was suggested that if the size of crabs dropped below 5 inches, price might be adversely affected. If so, results of the analysis suggest that average annual returns for the 1978 and 1979 seasons could have been increased by following any one of the four alternative management options listed in Table 3. Doubling actual effort coupled with a 5.25" size limit produced the largest 1978-79 average annual return.

There is little impact on the reproductive capacity of the simulated stock under any of three management options. The percentage of females copulated drops to its lowest level of around 60 per cent with the 5.25-inch size limit and a doubling of effort in effect (Figure 21). This owes to the fact that even at the lowest size limit, as well as the highest effort levels, there remain substantial numbers of younger males that are, on the average, larger in size than the mature females (Figure 22 and Appendix Figure 2-1).

The effect of reduced copulation on later recruitment is minimal. Simulated recruitment of five-year-old males under two different assumed spawner-recruit relationships is given in Figure 23. There is little or no difference between management options in projected recruitment for years 1980-85. This is explained by the high population of mature females during the 1975-79 period, which overshadows reduction in copulation. It should be pointed out that the simulated recruitment projections can be used only for comparisons between management options, and cannot be used for forecasting actual trends in recruitment.

At high population levels, maintaining full female fertilization infers a proportional spawner-recruit relationship (Figure 24). Such a relationship dictates that populations either increase without bounds or progress to zero. These two situations are clearly improbable. Thus, a proportional relationship can be dismissed.

The available data do not permit discrimination of either one of the assumed spawner-recruit relationships from randomly-occurring recruitment. However, it is evident from the data presented in Figure 4a that the current high levels of recruitment resulted from relatively low levels of female abundance which occurred in the early 1970's. This suggests that the current high level of females in the southeastern Bering Sea (estimated at greater than 100 million crabs) is superfluous to maximizing recruitment, and that full female copulation is not required at high population levels, thereby minimizing the effect of exploitation on reproductive capacity.

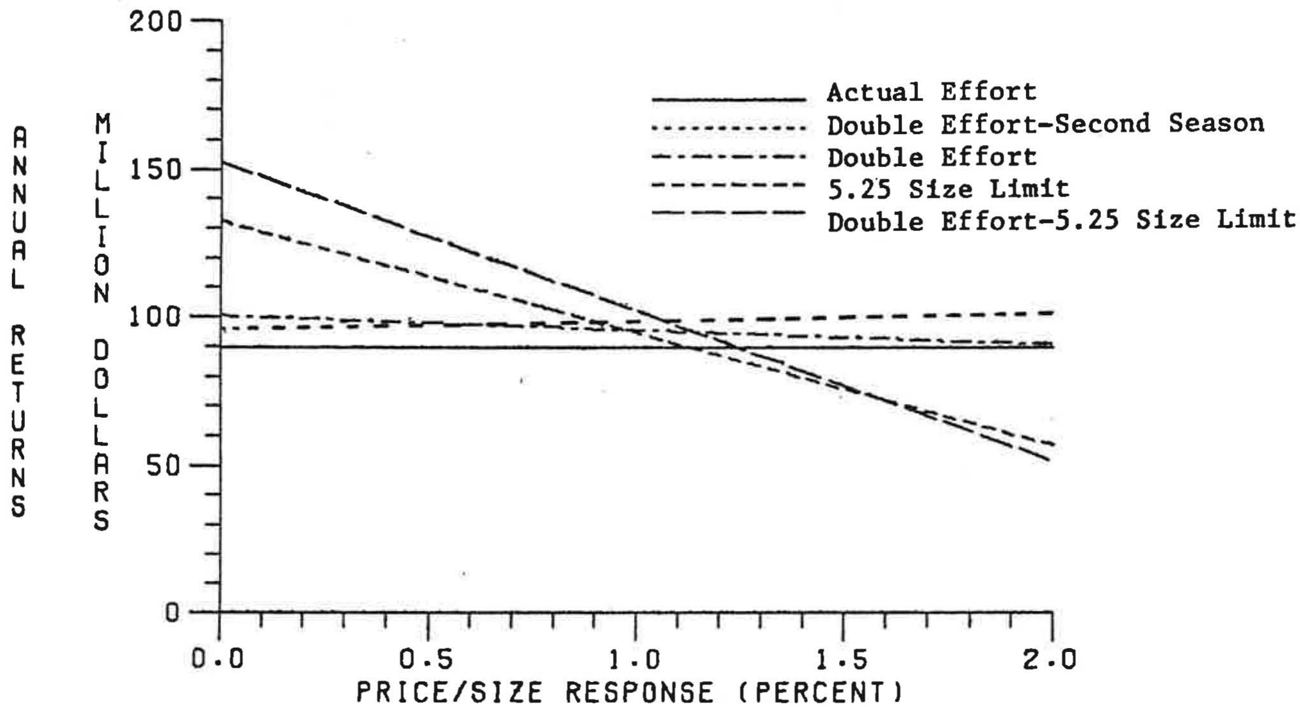

Figure 20.--Comparison of average 1978-79 annual returns for selected management strategies.

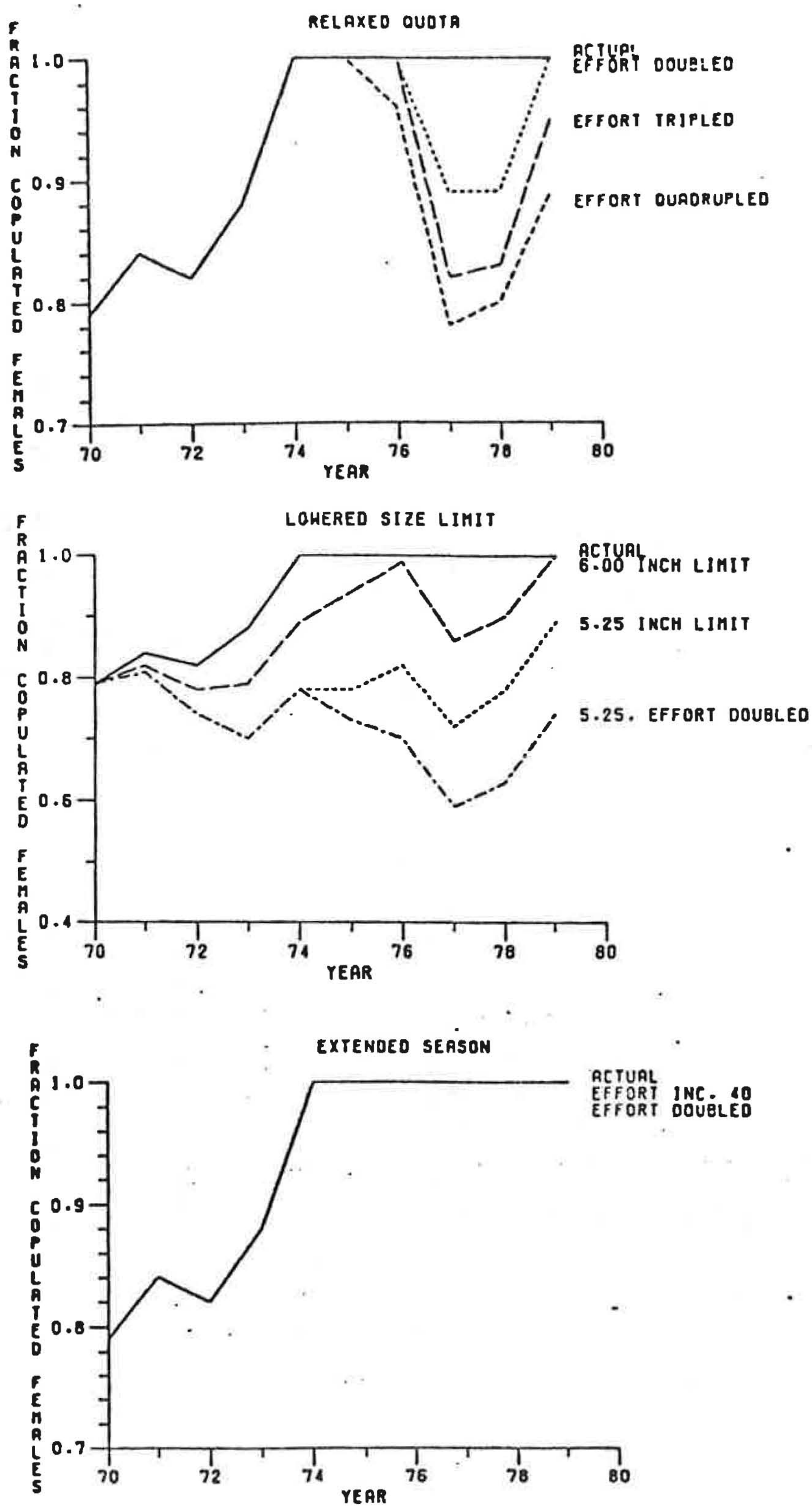

Figure 21.--Comparisons of simulated proportion of females copulated for various management options.

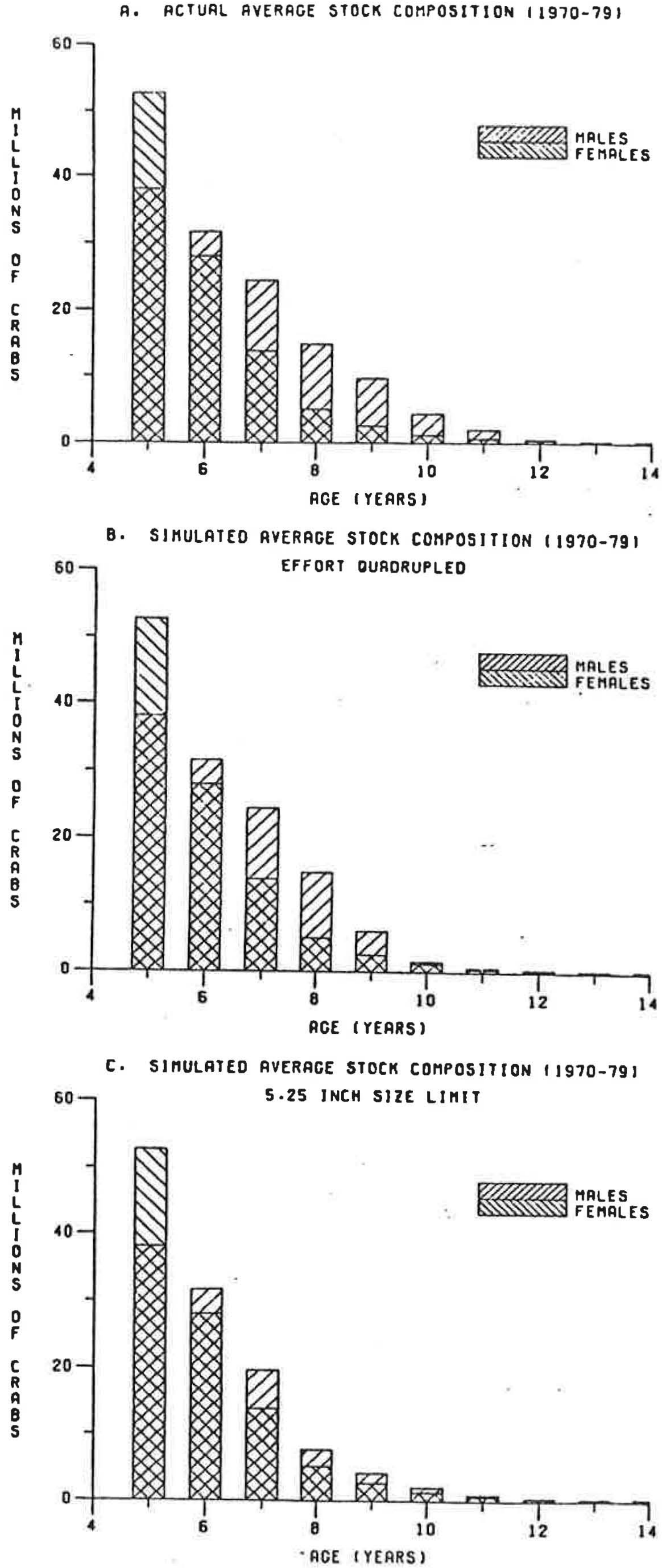

Figure 22.--Comparisons of actual stock age and sex composition with relaxed quota and lowered size limit management options.

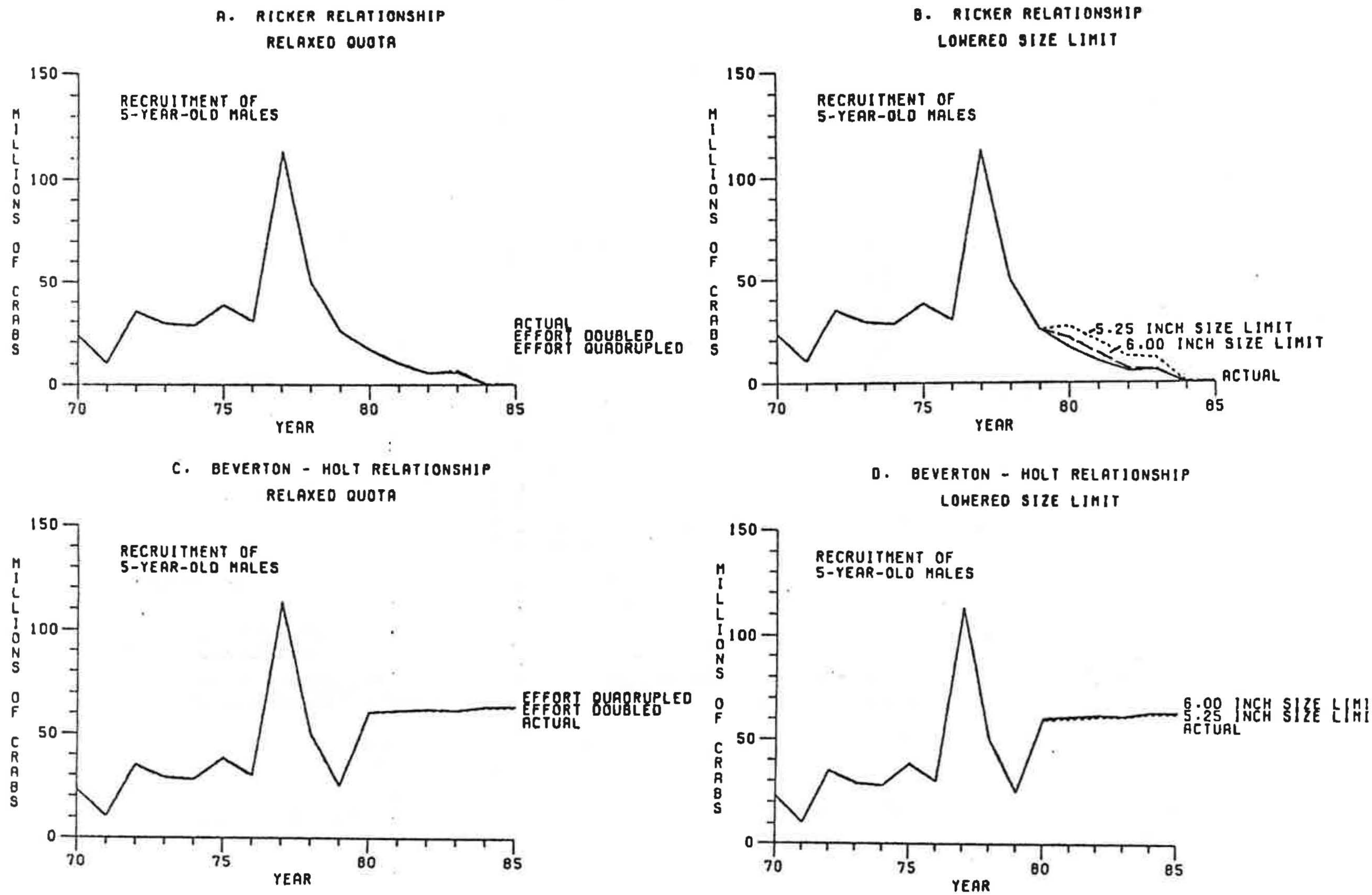

Figure 23.--Comparisons of recruitment trends for two spawner-recruit relationships and two management options, relaxed quotas and lowered size limits.

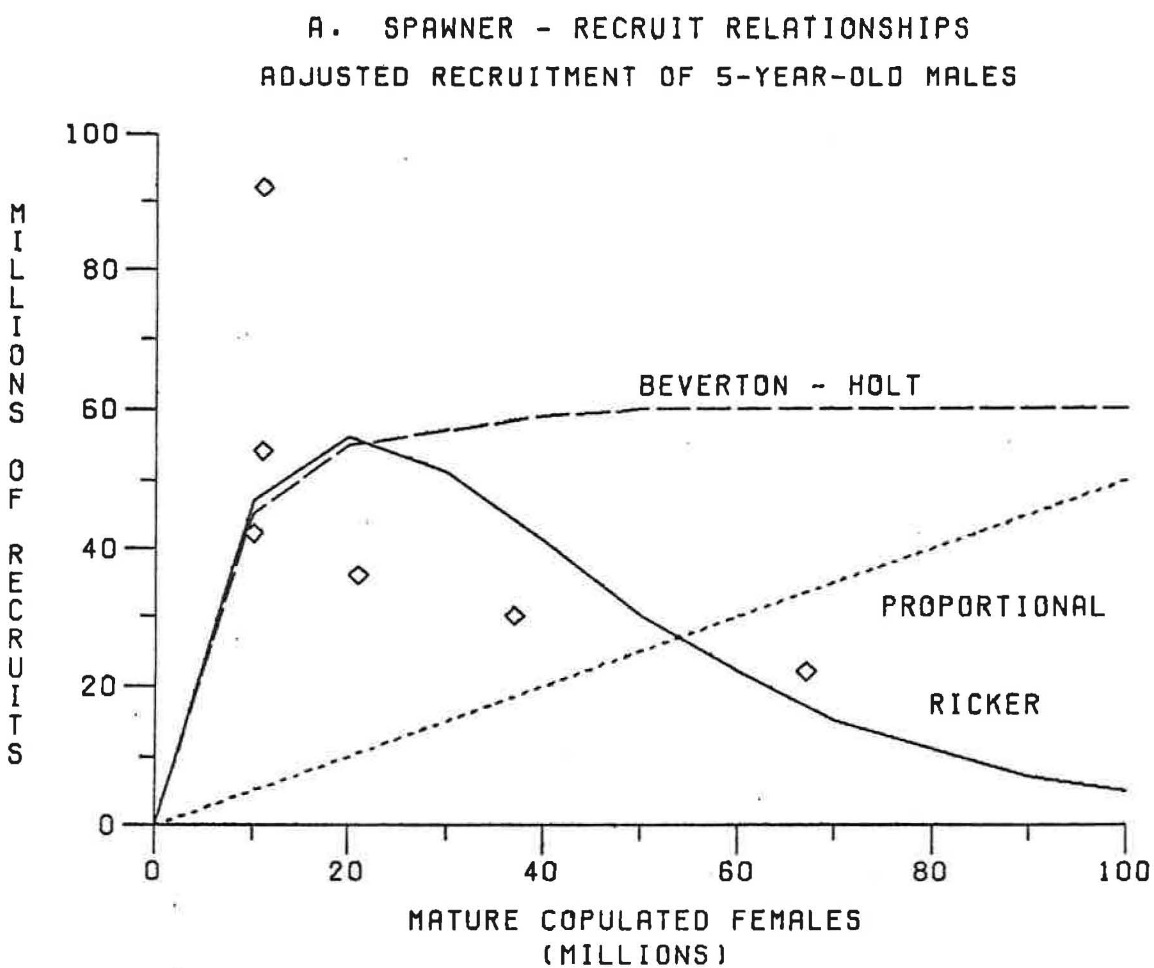

Figure 24. Comparison of general spawner-recruit relationships.

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LIST OF APPENDICES

APPENDIX 1

Model Description and Program Listing

Model Computations

The basic model components of mortality, growth, yield, reproduction and recruitment are described below in detail and are modified from Newell and Paulik (1972).

Mortality

Mortality, which is the sum of natural and fishing mortalities, may be age and month specific and is represented by an exponential decline giving

$$P_{i,\ j+1} = P_{ij}\ e^{-Z_{ij}}$$

where P_{ij} is the number of male or female crabs belonging to the i^{th} age group at the beginning of month j, Z_{ij} is the total instantaneous mortality acting on age group i during month j, and e = 2.71828...

Total instantaneous mortality is the sum of instantaneous natural and fishing mortalities. Fishing mortality is the product of four factors: (1) availability, which represents the fraction of an age group that is available to the fishery in a given month and may be the resultant of fishery regulation or gear selectivity; (2) catchability, which represents the fraction of the available population that is caught by a single unit of effort, may be year and month specific, and may result from immigration, emigration or other behavioral characteristics; (3) fishing effort, which may be year and month specific and is in this case expressed in pot-lifts; and (4) a fishing mortality multiplier which is used to readily change fishing effort between simulation runs. The mortality function is

$$Z_{ij} = XM_{ij} + A_{ij}Q_{ij}EF_{kj}FMULT_{ij}$$

where XM_{ij} is the coefficient of instantaneous natural mortality of the i^{th} age group in month j, A_{ij} is the fraction of the i^{th} age group available to the fishery is month j, Q_{ij} is the year and month specific catchability coefficient, EF_{kj} is the number of units of effort during month j of year k, and $FMULT_{ij}$ is the age and month specific fishing mortality multiplier.

The average population of males or females is given by

$$AN_{ij} = P_{ij} (1 - e^{-Z_{ij}}) / Z_{ij}$$

where AN_{ij} is the average population of age group i during month j.

Growth

Growth in the model is represented by a linear segmental growth curve. Using this function, average individual weight is

$$W_{ij} = W_{i,\ j-1} + (W_{ij} - W_{i,\ j-1})\ DT$$

where W_{ij} is the average individual weight of age group i at the beginning of month j, and DT = 1. With this type of function, any shape of growth curve may be approximated, including the stepwise growth of crabs. W_{ij} values are specified on input.

Yield

Yield in both numbers and weight is calculated monthly for each age group. Yield in numbers is

$$YN_{ij} = A_{ij}F_{ij}AN_{ij}$$

where $F_{ij} = Q_{ij}EF_{kj}$ and AN_{ij} is the average male crab population of age group i during month j.

Yield in weight is

$$YW_{ij} = YN_{ij} \left\{ W_{ij} + (W_{i,j+1} - W_{ij}) \left[1/Z_{ij} - 1/(e^{Z_{ij}} - 1) \right] \right\}$$

and may be controlled by input of annual quota values which, when reached or exceeded during any month of a given year, terminate fishing effort in succeeding months for male crabs between the age of first availability, specified in the availability matrix, and some higher specified age. If this age is not specified, fishing is terminated for all age groups of males when the quota is reached or exceeded.

Reproduction

This sector of the model is comprised of two major components: production of recruits and copulation. The production of recruits in a given year may be specified by one of two spawner-recruit functions: the Beverton and Holt formulation and the Ricker model. For the Beverton and Holt function, the number of recruits entering the population is

$$R_{i,j} = \frac{1}{A_1 + \frac{A_2}{L}}$$

where $R_{i,j}$ is the number of recruits entering the population at age i in month j, L is the number of mating females i+1 years previous, and A_1 and A_2 are estimated parameters of this formulation. The Ricker model has the formulation

$$R_j = A1'Le^{-A2'L}.$$

In lieu of spawner-recruit functions, input values for annual numbers may be specified.

The second major component of the reproductive sector concerns the computation of the proportion of females copulated (PCF). The mating behavior of king crabs appears to be influenced both by the abundance and size of males in relation to females. In the model, these influences are included by computing PCF as a function of the ratio of mature males to mature females and also as a function of the ratio of the average weight of mature males to average weight of mature females. These relationships are specified by

$$\begin{aligned} PCF &= 4SXR \quad , SXR < .25 \\ &= 1 \quad , SXR > .25 \end{aligned}$$

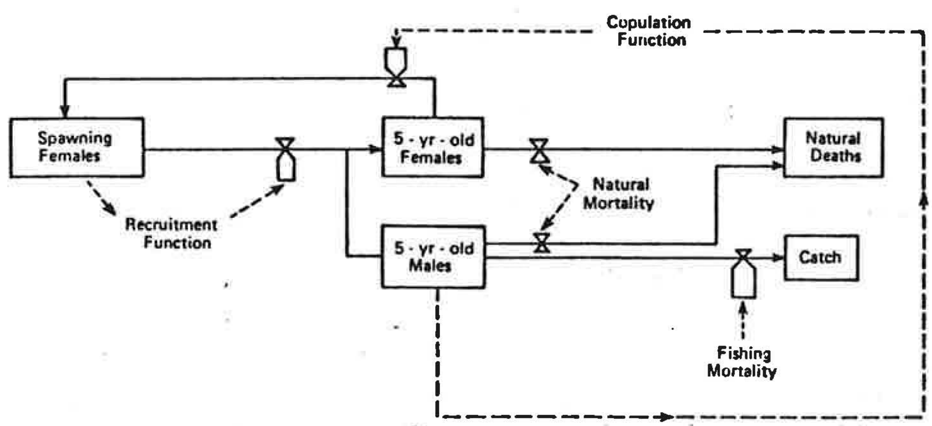
where SXR is the ratio of mature males to mature females during the breeding season (April and May, model months 2 and 3) and

$$PCF = .5SZR \text{ or}$$

$$PCF = .065e^{1.7SZR} \quad , SZR<1.70$$

$$PCF = 1 \quad , SZR \geq 1.70$$

where SZR is the ratio of average mature male weight to average mature female weight during the breeding season and either the linear or exponential form is specified by the user. PCF is computed as a function of both breeding sex and size ratio, and the lesser-valued of the two computations is used in determining mating female abundance in any year of simulations.



Appendix Figure 1-1.--King crab life history pattern (modified from Newell and Paulik, 1972).

```
      PROGRAM CRABEX(INPUT,OUTPUT,CRBOUT,ECINEBS,POPCOMM,POPCOMF
     1,CATCOMM,EXPLCIT,CRBOUTD,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7=
     2CRBOUT,TAPE8=ECINEBS,TAPE9=POPCOMM,TAPE10=POPCOMF
     3,TAPE11=CATCOMM,TAPE12=EXPLOIT,TAPE13=CRBOUTD)
C     HIGHEST STATEMENT NUMBER IS   142
      DIMENSION TEM(15), STLAR(6), PT(15,12), PFT(15,12), WMT(12), AFN
     $(15,12),EGGS(15),FMORTT(15),POM(15),POF(15),CAT(15)
      DIMENSION P(15,12), XM(15,12), A(15,12),EF( 50,12), AN(15,12), YN
     $(15,12), YW(15,12), W(200), WF(200), FM(15,12), XNMJ(12), FMJ(12),
     $ YWJ(12), YNJ(12), PJ(12), ANJ(12), FPJ(12), FANJ(12), YWI(15),
     $ YNI(15), ANI(15), FANI(15), TITLE(13), FMULT(180), FT(15,12), ZLY
     $(15), XNMI(15), FMI(15), PF(15,12), COP(15), SMM(15), SMF(15), FMT
     $(15,12),R( 50),Q(50,12),QUOTA( 50),F(15,12),TEF( 50),U(15),WFT(12)
     $,RECRUIT( 50),XNAT(15),TXM(15),FMORT(15,12),AA(15,12),KR(5),
     $PM(15,12),ACCP( 50,15),ACCF( 50,15),ACCM( 50,15),SACCP( 50),
     $SACCF( 50),SACCM( 50),NCODE(15),XMF(15,12),TXMF(15)
      REAL LARVAE, LENGQ
      INTEGER,ABREV
      EGG(LENGQ) = (-170.+1.93*LENGQ)*1000.
      FLENGT(WEIGHT) = (WEIGHT/3.614E-07)**(1./3.16)
C
C
C         KING CRAB POPULATION SIMULATOR,  ADAPTED FROM CRABS BY BALSIGER
C                                        MODIFIED BY REEVES
C
C     READ INPUT DATA
C
      READ (5,47) TITLE
      WRITE (6,55) TITLE
C     CONTROL CARD
      READ (5,46) NY,ABREV,NRE,NXM,NFMT,XMMULT,N1,N2,N3,N4,N5,N6,L2
C     PARAMETER CARDS
      READ (5,48) NYC,MFR,MSB,MSE,THRESH,(KR(I),I=1,5),A1,A2,MY,PCF
      WRITE (6,56) NYC,MFR,MY,MSB,MSE,NRE,A1,A2,THRESH,PCF
      CALL INPT(NYC,NXM,XMU,PT,PFT,XM,AA,EF,Q,FMULT,FMT,W,WF,NFMT,R,NY,
     $QUOTA,TXM,XMF,TXMF)
      DO 1 I=1,NYC
      NCODE(I)=I+3
      TEM(I)=0.
      TXM(I)=TXM(I)*XMMULT
        DO 1 J=1,12
      YN(I,J)=0.0
      YW(I,J)=0.0
      FMORT(I,J)=0.
    1 XM(I,J)=XM(I,J)*XMMULT
      SSACCF=0.
      SSACCM=0.
      DO 97 K=1,NY
      SACCP(K)=0.
      SACCF(K)=0.
      SACCM(K)=0.
      TEF(K)=0.
      DO 97 I=1,NYC
      ACCP(K,I)=0.
      ACCF(K,I)=0.
   97 ACCM(K,I)=0.
C
C     FISHING MORTALITY MULTIPLIER LOOP
C
      DO 125 NF=1,NFMT
      CHK=0.
      TYNA=0.
      TYWA=0.
      TTEF=0.
      YNASQ=0.
        DO 2 I=1,6
    2   STLAR(I) = 2.E12
        DO 3 I=1,NYC
          DO 3 J=1,12
            PM(I,J) = FMT(I,J)
            P(I,J) = PT(I,J)
    3 PF(I,J)=PFT(I,J)
        DO 4 I=1,NYC
    4   COP(I) = PF(I,12)
C
C     MAIN  TIMING  LOOP -- K = YEARS
C
      DO 45 K=1,NY
       IF (NF-1) 7,7,5
    5   DO 6 I=1,NYC
    6   ZLY(I) = XM(I,12)+A(I,12)*FT(I,12)*EF(K,12)*FMULT(NF-1)*PM(I,12)
    7 DO 91 I=1,NYC
      U(I)=0.
      DO 91 J=1,12
      A(I,J)=AA(I,J)
   91 F(I,J)=Q(K,J)*EF(K,J)*FMULT(NF)
```

```
C     LARVAE
          DO 8 IL=2,NYC
          TEM(IL) = XMF(IL,5)/2.
          DO 8 IK=6,12
    8     TEM(IL) = TEM(IL)+XMF(IL-1,IK)
          DO 9 IL=1,NYC
          DO 9 IK=1,3
    9     TEM(IL) = TEM(IL)+XMF(IL,IK)
          LARVAE = 0.
          DO 10 IL=1,NYC
          JW = 12*(IL-1)+1
      E=EGG(FLENGT(WF(JW)))
      IF(E.LE.O.) E=0.
      EGGS(IL)=COP(IL)*EXP(-TEM(IL))*E
      LARVAE=LARVAE+PF(IL,1)*EXP(-XMF(IL,1)/2.)*PCF
   10     CONTINUE
      IF(K.EQ.1) LARVAE=LARVAE+R(K)/FMT(1)*(1.-FMT(1))
C
C     RECRUITMENT
C
          J = MFR
          I = (J-1)/12+1
          JJ = J+12-12*I
C     BEVERTON-HOLT FUNCTION
   11     IF (NRE.NE.2.AND.STLAR(6).LT.1.) GO TO 13
      IF(K.LE.10) GO TO 89
      IF(NRE-1) 87,88,89
   87 P(I,JJ)=1./(A1+A2/(STLAR(6)))
      GO TO 90
   88 P(I,JJ)=A1*(STLAR(6))*EXP(-A2*STLAR(6))
      GO TO 90
   89 P(I,JJ)=R(K)
      DO 133 KK=1,5
  133 IF(K.EQ.KR(KK)) GO TO 90
      IF(NRE.LT.2.AND.STLAR(6).LT.THRESH) GO TO 87
   90 PF(I,JJ)=P(I,JJ)*(1./PM(I,J)-1.)
      RECRUIT(K)=P(I,JJ)
          WRITE (6,57) K,P(I,JJ),STLAR(6)
          GO TO 14
   13     WRITE (6,50)
      P(I,JJ)=0.
      PF(I,JJ)=0.
   14     CONTINUE
          DO 15 IBACK=1,5
          I=6-IBACK
   15     STLAR(I+1) = STLAR(I)
          STLAR(1) = LARVAE
          DO 16 III=1,NYC
      EGGS(III)=0.
   16     COP(III) = 0.
      HARVEST=0.
C
C     MONTHLY CALCULATION LOOP -- J = MONTH
C
          DO 29 J=1,12
            WMT(J) = 0.
      WFT(J)=0.
      XNFT=0.
            XNMT = 0.
C
C     YEAR-CLASS CALCULATION LOOP -- I = YEAR-CLASS
C
          DO 26 I=1,NYC
      F(I,J)=Q(K,J)*EF(K,J)*FMULT(NF)
              IF (J-1) 17,17,18
   17         IP = I-1
              JP = 12
              GO TO 19
C
   18         IP = I
              JP = J-1
C     INDEX LOOP TO MONTH OF RECRUITMENT
   19         IF (12*(I-1)+J-MFR) 26,25,20
   20         IF (J-1) 21,21,24
   21         IF (K-1) 22,22,24
   22         IF (NF-1) 24,24,23
C     POPULATION YEAR I MONTH 1
   23         P(I,1) = P(IP,12)*EXP(-ZLY(IP))
      IF(P(I,1).LT.1.) P(I,1)=0.
              PF(I,1) = PF(IP,12)*(EXP(-XMF(IP,JP)))
      IF(PF(I,1).LT.1.) PF(I,1)=0.
      IF(PM(I,J).EQ.1.) PF(I,J)=0.
              GO TO 25
C     POPULATION AT BEGINNING OF MONTH
   24         P(I,J) = P(IP,JP)*EXP(-(XM(IP,JP)+A(IP,JP)*F(IP,JP)))
      IF(P(I,J).LT.1.) P(I,J)=0.
              PF(I,J) = PF(IP,JP)*(EXP(-XMF(IP,JP)))
      IF(PF(I,J).LT.1.) PF(I,J)=0.
      IF(PM(I,J).EQ.1.) PF(I,J)=0.
C     MORTALITY
   25         Z = XM(I,J)+A(I,J)*F(I,J)
C     AVERAGE POPULATION FOR THE MONTH
      AFN(I,J)=PF(I,J)*(1-EXP(-XMF(I,J)))/XMF(I,J)
      AN(I,J)=P(I,J)*(1.-EXP(-Z))/Z
```

```
C     YIELD IN NUMBERS
               YN(I,J) = A(I,J)*F(I,J)*AN(I,J)
      FMORT(I,J)=A(I,J)*F(I,J)
C     FRACTION MALES AT END OF MONTH
  111 FM(I,J)=P(I,J)/(P(I,J)+PF(I,J))
               JW = 12*(I-1)+J
C     YIELD IN WEIGHT
               YW(I,J) = YN(I,J)*(W(JW)+(W(JW+1)-W(JW))*(1./Z-1./(EXP(Z)-
     $         1.)))*2.2
      HARVEST=HARVEST+YW(I,J)
C     WEIGHT OF MALES TOTAL
               WMT(J) = WMT(J)+AN(I,J)*W(JW)
      WFT(J)=WFT(J)+AFN(I,J)*WF(JW)
C     NUMBER OF MALES TOTAL
               XNMT = XNMT+AN(I,J)
      XNFT=XNFT+AFN(I,J)
   26          CONTINUE
C
C
C        QUOTA CHECK
C
      IF(HARVEST.LT.QUOTA(K).OR.J.EQ.12) GO TO 94
      IF(L2.GT.0) GO TO 119
      EF(K,J+1)=0.
      CHK=1.
      GO TO 94
  119 DO 118 ISL=1,L2-1
      CHK=2.
  118 A(ISL,J+1)=0.
C
C     SPAWNING
C
   94          IF (J-MSB) 29,27,27
   27          IF (J-MSE) 73,73,29
   28          CONTINUE
   73 IF(J.EQ.MSB) PCF=0.
      ANM=0.
      ANF=0.
      WMATM=0.
      WMATF=0.
C     COPULATION
   74 DO 77 IC=MY,NYC
C     AVERAGE NUMBER MATURE MALES AND FEMALES
      JW=12*(IC-1)+J
      WMATM=WMATM+AN(IC,J)*W(JW)
      WMATF=WMATF+AFN(IC,J)*WF(JW)
      ANF=ANF+AFN(IC,J)
      ANM=ANM+AN(IC,J)
   77 CONTINUE
C     AVERAGE WEIGHT OF MALES
      IF(ANM.LE.0.) GO TO 85
      AWM=WMATM/ANM
      GO TO 86
   85 AWM=0.
C     AVERAGE WEIGHT OF FEMALES
   86 IF(ANF.LE.0.) GO TO 102
      AWF=WMATF/ANF
      GO TO 103
  102 AWF=0.
  103 IF(AWF.LE.0.) GO TO 104

C          BREEDING SIZE RATIO
      SZR=AWM/AWF
      GO TO 106
  104 SZR=0.
  106 IF(ANF.LE.0.) GO TO 105
C        BREEDING SEX RATIO
      SXR=ANM/ANF
      GO TO 107
  105 SXR=0.
C       COPULATION COEFFICIENTS
  107 PCF=4.*SXR
      PCFSZ=.065*EXP(1.70*SZR)
      IF(PCFSZ.LT.PCF) PCF=PCFSZ
      IF(PCF.GT.1.) PCF=1.
C     SPAWNING SUCCESS PERCENT
   76 SSP=PCF*100.
C
C
   29        CONTINUE
   92 DO 93 LL=1,NYC
      XMAT(LL)=0.
   93 COP(LL)=PF(LL,12)
      DO 30 J=1,12
               YWJ(J) = 0.
               YNJ(J) = 0.
               PJ(J) = 0.
               FPJ(J) = 0.
               ANJ(J) = 0.
               XNMJ(J) = 0.
               FMJ(J) = 0.
   30          FANJ(J) = 0.
```

```
          DO 31 I=1,NYC
            YWI(I) = 0.
            YNI(I) = 0.
            ANI(I) = 0.
            XNMI(I) = 0.
            FMI(I) = 0.
   31     FANI(I) = 0.
          TWMT = 0.
          YWA = 0.
          BPJ = 0.
          YNA = 0.
          ANA = 0.
          FANA = 0.
          ANMA = 0.
      POPT=0.
      SXNAT=0.
      SYNI=0.
      WSYNI=0.
      IAGES=0
      SCALE=1000000.
C
C     SUMMARY TOTALS
C
          DO 33 J=1,12
      TEF(K)=TEF(K)+EF(K,J)*FMULT(NF)
            DO 32 I=1,NYC
C     YIELD IN WEIGHT FOR MONTH
              YWJ(J) = YWJ(J)+YW(I,J)
C     YIELD IN NUMBERS FOR MONTH
              YNJ(J) = YNJ(J)+YN(I,J)
C     TOTAL POPULATION FOR MONTH
              PJ(J) = PJ(J)+P(I,J)
C     TOTAL FISHABLE POPULATION
              FPJ(J) = FPJ(J)+P(I,J)*A(I,J)
C     TOTAL AVERAGE POPULATION FOR MONTH
              ANJ(J) = ANJ(J)+AN(I,J)
C     TOTAL AVERAGE MALE POPULATION FOR THE MONTH
              FANJ(J) = FANJ(J)+AN(I,J)*A(I,J)
C     TOTAL NUMBER OF FEMALES FOR THE MONTH
              XNMJ(J) = XNMJ(J)+AFN(I,J)
C     TOTAL NUMBER OF MALES FOR YEAR-CLASS
              XNMI(I) = XNMI(I)+AN(I,J)/12.
C     TOTAL YIELD IN WEIGHT FOR YEAR-CLASS
              YWI(I) = YWI(I)+YW(I,J)
C     TOTAL YIELD IN NUMBERS FOR YEAR-CLASS
              YNI(I) = YNI(I)+YN(I,J)
C     AVERAGE MONTHLY POPULATION FOR YEAR-CLASS
              ANI(I) = ANI(I)+AN(I,J)/12.
C     AVERAGE FISHABLE MONTHLY POPULATION FOR YEAR-CLASS
   32       FANI(I) = FANI(I)+AN(I,J)*A(I,J)/12.
C     TOTAL ANNUAL YIELD IN WEIGHT
          YWA = YWA+YWJ(J)
C     TOTAL ANNUAL YIELD IN NUMBERS
          YNA = YNA+YNJ(J)
C     TOTAL ANNUAL AVERAGE MALE POPULATION
          ANA = ANA+ANJ(J)/12.
C     TOTAL ANNUAL AVERAGE FEMALE POPULATION
          ANMA = ANMA+XNMJ(J)/12.
C     TOTAL AVERAGE ANNUAL BIOMASS
          TWMT = TWMT+WMT(J)/12.
C     TOTAL ANNUAL AVERAGE FISHABLE POPULATION
   33     FANA = FANA+FANJ(J)/12.
C         CALCULATE EXPLOITATION RATE ,YR CLASS AND TOTAL
      TYNA=TYNA+YNA
      YNASQ=YNASQ+YNA**2.
      TYWA=TYWA+YWA
      TTEF=TTEF+TEF(K)
      DO 113 I=1,NYC
      IF(YNI(I).EQ.0.) GO TO 113
      IF(P(I,1).EQ.0.) GO TO 113
      U(I)=YNI(I)/P(I,1)
      POPT=POPT+P(I,1)*A(I,1)
      SYNI=SYNI+YNI(I)
      WSYNI=WSYNI+YNI(I)*I
      IAGES=IAGES+1
  113 CONTINUE
      EXPL=YNA/POPT
      AVAGE=WSYNI/SYNI
      DO 127 I=1,NYC
      IF(YNI(I).EQ.0.) GO TO 127
      PLEFT=P(I,12)*EXP(-XM(I,12)+A(I,12)*F(I,12))
      XNAT(I)=P(I,1)-PLEFT-YNI(I)
      SXNAT=SXNAT+XNAT(I)
      ACCP(K,I)=P(I,1)/SCALE
      ACCF(K,I)=YNI(I)/SCALE
      ACCM(K,I)=XNAT(I)/SCALE
  127 CONTINUE
          DO 35 J=1,12
C     FRACTION OF MALES FOR MONTH
```

```
          IF (ANJ(J).LT..0000001) GO TO 34
          FMJ(J) = XNMJ(J)/ANJ(J)
          GO TO 35
C
   34     FMJ(J) = 0.
   35   CONTINUE
      DO 37 I=1,NYC
      FMORTT(I)=0.
  109 BPJ=BPJ+PF(I,1)
C     FRACTION OF MALES FOR YEAR-CLASS
          IF (ANI(I).LT..0000001) GO TO 36
          FMI(I) = XNMI(I)/ANI(I)
          GO TO 37
C
   36     FMI(I) = 0.
   37   CONTINUE
C     AVERAGE FRACTION OF MALES FOR THE YEAR
C     AVERAGE YIELD IN WEIGHT PER CRAB
        IF (YNA.LT..0000001) GO TO 38
        AYW = YWA/YNA
        GO TO 39
C
   38   AYW = 0
   39   CONTINUE
      CPUE=YNA/TEF(K)
      TEFMULT=TEF(K)*10.
      AVAGE=AVAGE+4.
      DO 142  I=1,NYC
      DO 142  J=1,12
  142 FMORTT(I)=FMORTT(I)+FMORT(I,J)
      SUMW=0.
      SUMF=0.
      DO 141  I=1,NYC
      IF(YNI(I).LE.0.) GO TO 141
      SUMW=SUMW+P(I,12)
      SUMF=SUMF+FMORTT(I)*P(I,12)
  141 CONTINUE
      WTDF=SUMF/SUMW
      WRITE(7,110) K,RECRUIT(K),POPT,SXNAT,YNA,TEFMULT,LARVAF,CPUE,
     $EXPL,PCF,SXR,SZR,AYW,U(6),U(7),U(8),AVAGE,WTDF
      WRITE(13,110)K,RECRUIT(K),POPT,SXNAT,YNA,TEFMULT,LARVAF,CPUE,
     1EXPL,PCF,SXR,SZR,AYW,U(6),U(7),U(8),AVAGE,WTDF
  110 FORMAT(I3,5F11.0,F16.0,F6.2,8F5.2,F5.1,F4.2)
      REC=RECRUIT(K)/1000000.
      WRITE(8,126) K,YWA,TEF(K),(YNI(I),I=5,NYC),(YWI(I),I=5,NYC)
     $,REC,XMMULT,AYW
  126 FORMAT(I3,F11.0,F9.0,6F10.0/6F10,2F5.1,F6.2)
C
C     OUTPUT SECTOR
C
      IF (ABREV-1) 43,40,40
   40      IF (ABREV-2) 42,41,41
C
C     OUTPUT OPTION 2 -- ANNUAL SUMMARIES ONLY
   41   WRITE (6,51) K
        WRITE (6,58) BPJ,ANMA
      WRITE(6,49) PJ(1),ANA,FANA,YNA,YWA,TEF(K),CPUE,
     $EXPL,(P(I,1),I=1,NYC)
        WRITE (6,59) (PF(I,1),I=1,NYC)
      WRITE(6,100) (U(I),I=1,NYC)
  100 FORMAT(1H0,*YEAR CLASS EXPLOITATION RATES*/(10F12.5))
      WRITE(6,131) (YNI(I),I=1,NYC)
  131 FORMAT(1H0,*YEAR CLASS CATCHES (NOS)*/(10E12.5))
        WRITE (6,67) AYW,IAGES
        WRITE (6,68) TWMT*2.2,AVAGE
      WRITE(6,101) PCF,SZR,SXR
      WRITE(6,130) ((FMORT(I,J),J=1,12),I=1,NYC)
  130 FORMAT(1H0,*FISHING MORTALITY MATRIX(INCLUDES AVAILABILITY)*
     $//(12F10.5))
      DO 140  I=1,NYC
      DIV=1000000.
      POM(I)=P(I,1)/DIV
      POF(I)=PF(I,1)/DIV
  140 CAT(I)=YNI(I)/DIV
      WRITE(9,139) K,(POM(I),I=1,NYC)
      WRITE(10,139) K,(POF(I),I=1,NYC)
      WRITE(11,139) K,(CAT(I),I=1,NYC)
      WRITE(12,139) K,(U(I),I=1,NYC)
  139 FORMAT(I3,2F7.2,8F6.2)
      IF(CHK.EQ.2.) WRITE(6,121)
        GO TO 45
C
C     OUTPUT OPTION 1 -- MONTHLY AND ANNUAL SUMMARIES
   42   WRITE (6,51) K
        WRITE (6,52) (J,PJ(J),ANJ(J),FANJ(J),YNJ(J),YWJ(J),J=1,12)
        WRITE (6,53) (ANA,FANA,YNA,YWA,(P(I,1),I=1,NYC))
        WRITE (6,67) AYW
        GO TO 45
```

```
C
C     OUTPUT OPTION 0 -- ALL CALCULATIONS BY MONTH AND AGE CLASS
   43     WRITE (6,54) (K,N1,N2,N3,N4,N5,N6)
          DO 44 J=1,12
            WRITE (6,60) (J,AN(N1,J),AN(N2,J),AN(N3,J),AN(N4,J),AN(N5,J)
     $      ,AN(N6,J),ANJ(J),FANJ(J),FMJ(J))
            WRITE (6,61) (YN(N1,J),YN(N2,J),YN(N3,J),YN(N4,J),YN(N5,J),
     $      YN(N6,J),YNJ(J))
            WRITE (6,62) (YW(N1,J),YW(N2,J),YW(N3,J),YW(N4,J),YW(N5,J),
     $      YW(N6,J),YWJ(J))
   44     CONTINUE
          WRITE (6,63) (P(N1,1),P(N2,1),P(N3,1),P(N4,1),P(N5,1),P(N6,1),
     $    PJ(1),FPJ(1))
          WRITE (6,64) (ANI(N1),ANI(N2),ANI(N3),ANI(N4),ANI(N5),ANI(N6),
     $    ANA)
          WRITE (6,65) (FMI(N1),FMI(N2),FMI(N3),FMI(N4),FMI(N5),FMI(N6))
          WRITE (6,66) (FANI(N1),FANI(N2),FANI(N3),FANI(N4),FANI(N5),
     $    FANI(N6),FANA)
          WRITE (6,61) (YNI(N1),YNI(N2),YNI(N3),YNI(N4),YNI(N5),YNI(N6),
     $    YNA)
          WRITE (6,62) (YWI(N1),YWI(N2),YWI(N3),YWI(N4),YWI(N5),YWI(N6),
     $    YWA)
          WRITE (6,67) AYW
          WRITE (6,68) TWMT
   45 CONTINUE
      TCPUE=TYNA/TTEF
      VARYNA=(YNASQ-TYNA**2./NY)/(NY-1)
      WRITE(6,117) TYWA,TYNA,TTEF,TCPUE,VARYNA
  117 FORMAT(2(50(1H*)/)* SIMULATION RUN TOTALS*/1H ,*YIELD(LBS) = *,F15
     $.0,*  YIELD(NOS) = *,F15.0,*  EFFORT(POT-LIFTS) = *,F15.0,
     $*  CRABS/POT = *,F15.0/24X,*VAR(YIELD IN NOS) = *,E15.6)
  125 CONTINUE
      IF(CHK.NE.1.) GO TO 120
      WRITE(6,98) ((EF(I,J),J=1,12),I=1,NY)
   98 FORMAT(1H0,*ACTUAL FISHING EFFORT MATRIX (ROWS = YEARS,
     $ COLUMNS = MONTHS)*/(12F10.0))
  121 FORMAT(1H0,*ORIGINAL AVAILABILITY MATRIX ALTERED*,
     $*  -- 2ND SIZE LIMIT IN EFFECT*)
  120 IF(XMMULT.EQ.1.) GO TO 122
      WRITE(6,123) XMMULT
  123 FORMAT(1H0,*NATURAL MORTALITY MULTIPLIER = *,F5.2,
     $*  M ALTERED AS FOLLOWS:*,65X,*TOTAL M*/)
      DO 129 I=1,NYC
  129 WRITE(6,132) (XM(I,J),J=1,12),TXM(I)
  132 FORMAT(1H ,(13F10.6))
  122 WRITE(6,137) (NCODE(I),I=5,15)
  137 FORMAT(1H0,*YEAR                 AGE GROUPS*/4X,11I6)
      DO 134 K=1,NY
      DO 134 I=5,15
      SACCP(K)=SACCP(K)+ACCP(K,I)
      SACCF(K)=SACCF(K)+ACCF(K,I)
      SACCM(K)=SACCM(K)+ACCM(K,I)
  134 CONTINUE
      DO 135 K=1,NY
      SSACCF=SSACCF+SACCF(K)
      SSACCM=SSACCM+SACCM(K)
  135 WRITE(6,136) K,(ACCP(K,I),I=5,15),SACCP(K),
     $(ACCF(K,I),I=5,15),SACCF(K),(ACCM(K,I),I=5,15),SACCM(K)
  136 FORMAT(1H ,I3,11F6.2,F10.2/2(4X,11F6.2,F10.2/))
      WRITE(6,138) SSACCF,SSACCM
  138 FORMAT(1H0,*TOTAL CATCH = *,F15.2,* TOTAL M LOSS = *,F15.2)
      WRITE(6,124)
  124 FORMAT(1H1,*YEAR*,2X,*RECRUITS*,3X,* FISH. POP.*,3X,*NAT LOSS*,3X,
     $*   YIELD*,7X,*EFFORT*,4X,*  LARVAE*,6X,*CPUE*,3X,* U*,2X,*PCF*,
     $2X,*SXR*,1X,* SZR*,1X,*AWT*,3X,*U9*,3X,*U10*,3X,*U11*//)
C
   46 FORMAT(5I3,F3.1,7I3)
   47 FORMAT (13A6)
   48 FORMAT(4I2,E13.0,5I3,1X,2E13.0,I3,F10.0)
   49 FORMAT(1H0,*MALE*,*F17.6,F11.0,2F11.3/1H ,
     $*YEAR CLASSES AT START OF YEAR*/* MALES*,(10E12.5/))
   50 FORMAT (*  NO RECRUITMENT IN THIS YEAR*)
   51 FORMAT (1H0,4HYR =,I3,4X,7HINITIAL, 9X,7HAVERAGE, 9X,7HAVERAGE,10X
     $,5HYIELD,11X,5HYIELD,11X,5HEFFORT,10X,*CPUE*,10X,*AVERAGE*/
     $1H ,12X,5HTOTAL,12X,5HTOTAL,10X,8HFISHABLE,11X,2HIN,13X,2HIN,
     $13X,2HIN,12X,*CRABS PER*,6X,*EXPLOITATION*/1H , 9X,10HPOPULATION,
     $7X,10HPOPULATION,,7X,10HPOPULATION, 8X,7HNUMBERS, 9X,6HWEIGHT,
     $ 9X,9HPOT-LIFTS, 9X,*POT-LIFTS*,7X,*RATE*/)
   52 FORMAT (1H ,2X,I2,5E18.6)
   53 FORMAT (1H ,4HYEAR,18X,4E18.6/1H0,30HYEAR-CLASSES AT START OF YEAR
     $ /1H ,10E12.5/1H ,10E12.5/)
   54 FORMAT (1H1,6HYEAR =,I3,39X,12HYEAR-CLASSES,48X,8HFISHABLE,4X,
     $8HFRACTION/1H ,3HMO.,4X,6HENTITY,12X,I1,5I12,10X,5HTOTAL,6X,
     $5HTOTAL,8X,5HMALES)
   55 FORMAT (1H1,20X,13A6//1H ,31X,*  PRODUCED BY CRABEX, A MODIFIED VE
     $RSION OF CRABS.  CRABEX WAS WRITTEN IN 1973.*//)
   56 FORMAT (1H0,*NUMBER OF YEAR-CLASSES =*,I3/1H ,*AGE (MO.) AT FIRST
     $RECRUITMENT =*,I4/1H ,*AGE AT MATURITY = *,I5/1H ,
     $*MONTH SPAWNING BEGINS = *,I3/1H ,*MONTH SPAWNING ENDS = *,I3/
     $1H ,*RECRUITMENT REGULATION OPTION = *,I2/1H ,
     $*RECRUITMENT REGULATION PARAMETERS   A1  = *,E14.6/1H ,36X,*A2 =*,
     $,E14.6/1H ,*THRESHOLD FOR LARVAE = *,E14.6/1H ,
```

```
     $*INITIAL PERCENT COPULATED FEMALES = *,F10.5)
   57 FORMAT (50(1H*)/* RECRUITMENT IN YEAR *I4,* IS*E14.6,* FROM*,
     $E14.6,* LARVAE*)
   58 FORMAT (* FEMALE*2E18.6)
   59 FORMAT (8H FEMALES,(10F12.5))
   60 FORMAT (1H0,I3,3X,10HAVG. POPL.,4X,8E12.5,F6.3)
   61 FORMAT (1H ,6X,11HYIELD (NO.),3X,6E12.5,12X,E12.5)
   62 FORMAT (1H ,6X,11HYIELD (WT.),3X,6E12.5,12X,E12.5)
   63 FORMAT (1H0,3H YR,3X,11HINIT. POPL.,3X,9E12.5)
   64 FORMAT (1H ,6X,10HAVG. POPL.,4X,7E12.5)
   65 FORMAT (1H ,6X,14HFRACTION MALES,6(F6.3,6X),24X,F6.3)
   66 FORMAT (1H ,6X,14HFISH. AV. POP.,6E12.5,12X,E12.5)
   67 FORMAT (1H ,*AVERAGE WEIGHT OF CATCH PER CRAB(LBS.) =*,F8.4,5X,
     $* NO. OF YEAR CLASSES IN CATCH = *,I4)
   68 FORMAT (* AVERAGE ANNUAL BIOMASS(LBS.) = *E14.6,10X,
     $* WEIGHTED AVERAGE AGE IN CATCH = *,F6.1)
  101 FORMAT(1H ,*FRACTION FEMALES COPULATED = *,F8.3,5X,
     $*BREEDING SIZE RATIO = *,F8.3/
     $1H ,42X,*BREEDING SEX RATIO = *,F8.3)
      END
      SUBROUTINE INPT(NYC,NXM,XMU,P,PF,XM,A,EF,Q,FMULT,FM,W,WF,NFMT,R
     $,NY,QUOTA,TXM,XMF,TXMF)
C          HIGHEST STATEMENT NUMBER IS 43
      DIMENSION P(15,12), PF(15,12), XM(15,12), A(15,12),EF( 50,12),
     $ FMULT(100), FM(15,12), W(200), WF(200),R( 50),Q(50,12),QUOTA( 50)
     $,F(15,12),TXM(15),XMF(15,12),TXMF(15)
    1 READ (5,17) ITYPE
      IF (ITYPE) 16,16,2
    2 GO TO (3,4,6,9,10,11,14,15,33,38), ITYPE
    3 CONTINUE
C     INITIAL POPULATION
      READ (5,18) (P(I,12),I=1,NYC)
      GO TO 1
C     MORTALITY OPTION--0  MONTHLY VALUES; 1  UNIFORM VALUE
    4 CONTINUE
      IF (NXM-1) 5,6,6
C     INSTANTANEOUS MONTHLY NATURAL MORTALITY
    5 READ (5,19) ((XM(I,J),J=1,12),I=1,NYC)
      READ(5,19) ((XMF(I,J),J=1,12),I=1,NYC)
      WRITE (6,22)
      DO 42 I=1,NYC
      TXM(I)=0.
      DO 41 J=1,12
   41 TXM(I)=TXM(I)+XM(I,J)
   42 WRITE (6,43) (XM(I,J),J=1,12),TXM(I)
      WRITE(6,44)
      DO 45 I=1,NYC
      TXMF(I)=0.
      DO 46 J=1,12
   46 TXMF(I)=TXMF(I)+XMF(I,J)
   45 WRITE(6,43) (XMF(I,J),J=1,12),TXMF(I)
      GO TO 1
C     UNIFORM NATURAL MORTALITY
    6 READ (5,19) XMU
      WRITE (6,30) XMU
      DO 7 I=1,NYC
        DO 7 J=1,12
    7 XM(I,J) = XMU
      GO TO 1
C     FRACTION OF POPULATION AVAILABLE TO FISHERY
    8 READ (5,19) ((A(I,J),J=1,12),I=1,NYC)
      WRITE (6,23)
      WRITE (6,29) ((A(I,J),J=1,12),I=1,NYC)
      GO TO 1
C
    9 CONTINUE
C     FISHING MORTALITY
      READ (5,19) ((EF(I,J),J=1,12),I=1,NY)
      WRITE (6,24)
      WRITE (6,40) ((EF(I,J),J=1,12),I=1,NY)
      READ(5,37) ((Q(I,J),J=1,12),I=1,NY)
      WRITE(6,35)
      WRITE(6,36) ((Q(I,J),J=1,12),I=1,NY)
      GO TO 1
C
   10 CONTINUE
C     FISHING MORTALITY MULTIPLIER
      READ (5,20) (FMULT(I),I=1,NFMT)
      WRITE (6,25)
      WRITE (6,29) (FMULT(I),I=1,NFMT)
      GO TO 1
C
   11 CONTINUE
C     INITIAL FRACTION MALES
      READ (5,20) (FM(I,12),I=1,NYC)
      WRITE (6,26)
      WRITE (6,29) (FM(I,12),I=1,NYC)
      DO 12 I=1,NYC
        DO 12 J=1,12
   12 FM(I,J) = FM(I,12)
```

```
C         ESTABLISH MALE AND FEMALE POPULATIONS FROM FRACTION AND TOTAL
      DO 13 I=1,NYC
        PF(I,12) = P(I,12)*(1-FM(I,12))
        P(I,12) = P(I,12)*FM(I,12)
   13 CONTINUE
      GO TO 1
C     WEIGHT
   14 NWT = 12*NYC+1
      READ (5,19) (W(I),I=1,NWT)
      GO TO 1
C
   15 CONTINUE
      READ (5,19) (WF(I),I=1,NWT)
      WRITE (6,27)
      WRITE (6,29) (W(I),I=1,NWT)
      WRITE (6,32)
      WRITE (6,29) (WF(I),I=1,NWT)
      WRITE (6,21)
      WRITE (6,28) (P(I,12),I=1,NYC)
      WRITE (6,31)
      WRITE (6,28) (PF(I,12),I=1,NYC)
      GO TO 1
   33 READ(5,18) (R(I),I=1,NY)
      WRITE(6,34)
      WRITE(6,28) (R(I),I=1,NY)
      GO TO 1
   38 READ(5,18) (QUOTA(I),I=1,NY)
      WRITE(6,39)
      WRITE(6,28) (QUOTA(I),I=1,NY)
C
   16 RETURN
C
   17 FORMAT (I2)
   18 FORMAT (6E13.6)
   19 FORMAT (12F6.0)
   20 FORMAT (10F8.0)
   21 FORMAT (1H0,*INITIAL POPULATION STRUCTURE OF MALE CRABS*/)
   22 FORMAT (1H0,59HNATURAL MORTALITY MATRIX (ROWS = YEAR-CLASSES, COLS
     $. =MO.),62X,*TOTAL M*/)
   23 FORMAT (1H0,54HAVAILABILITY MATRIX (ROWS = YEAR-CLASSES, COLS. = M
     $O.)/)
   24 FORMAT (1H0,59HFISHING EFFORT MATRIX (ROWS = YEARS, COLS
     $. = MO.)/)
   25 FORMAT (1H0,29HFISHING MORTALITY MULTIPLIERS/)
   26 FORMAT (1H0,36HINITIAL FRACTION MALES IN POPULATION/)
   27 FORMAT (1H0,37HWEIGHT OF MALES AT BEGINNING OF MONTH/)
   28 FORMAT (1H ,9F14.6)
   29 FORMAT (1H ,12F10.6)
   30 FORMAT (1H0,49HNATURAL MORTALITY FOR EACH YEAR-CLASS AND MONTH =,
     $F10.6)
   31 FORMAT (1H0,*INITIAL POPULATION STRUCTURE OF FEMALE CRABS*/)
   32 FORMAT (1H0,*WEIGHT OF FEMALES AT BEGINNING OF MONTH*/)
   34 FORMAT(1H0,*ANNUAL INPUT RECRUITMENTS*/)
   35 FORMAT(1H0,*CATCHABILITY MATRIX (ROWS = YEAR-CLASSES, COLS.
     $ = MONTHS)*)
   36 FORMAT(1H ,12E10.2)
   37 FORMAT(12F6.0)
   39 FORMAT(1H0,*ANNUAL QUOTAS*)
   40 FORMAT(1H ,12F10.0)
   43 FORMAT(1H ,13F10.6)
   44 FORMAT(1H ,60X,*FEMALES*)
      END
```

Appendix 2

Data for the Model

Appendix Table 2-1.--Age-specific population parameters used in simulations.

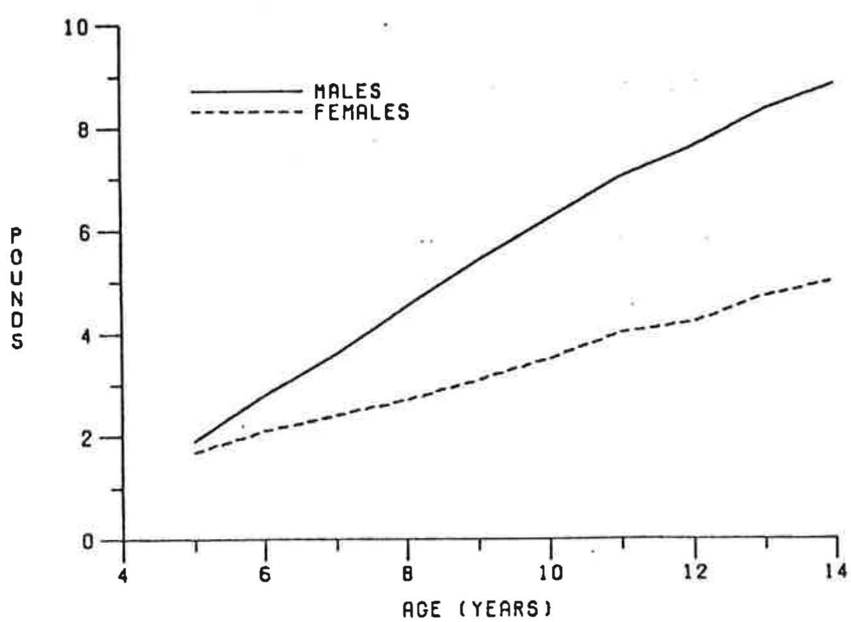
AGE	NATURAL MORTALITY (annual M)		AVERAGE WEIGHT (kg)		AVAILABILITY BY MINIMUM SIZE LIMIT (%)			ORIGINAL POPULATION STRUCTURE		
	Male	Female	Male	Female	5.25"	6.00"	6.50"	MALES* (millions)	FEMALES (millions)	PROPORTION OF MALES
5	.13	.58	.87	.76	0.0	0.0	0.0	4.7	6.5	.42
6	.12	.58	1.25	.94	.5	0.0	0.0	4.2	3.2	.57
7	.08	.58	1.65	1.08	1.0	0.5	0.0	3.7	1.9	.66
8	.08	.58	2.05	1.24	1.0	1.0	0.5	3.4	1.7	.67
9	.11	.58	2.44	1.42	1.0	1.0	1.0	2.7	1.6	.63
10	.23	.58	2.81	1.61	1.0	1.0	1.0	1.0	1.4	.42
11	.50	.58	3.16	1.82	1.0	1.0	1.0	1.2	1.2	.50
12	.57	.58	3.47	1.90	1.0	1.0	1.0	0.3	0.4	.43
13	.61	.58	3.76	2.14	1.0	1.0	1.0	0.2	0.4	.33
14	.76	.58	4.02	2.29	1.0	1.0	1.0	0.3	0.4	.43

* Ages 5-7 estimated by back-calculation using the natural mortality schedule.

Appendix Table 2-2.--Year-specific data used in simulations.

YEAR	CATCHABILITY * (q)	RECRUITMENT (millions of 5-year olds)	FISHING EFFORT pot-lifts
1970	$.33 \times 10^{-5}$	23	96,500
1971	$.33 \times 10^{-5}$	10	118,400
1972	$.33 \times 10^{-5}$	35	205,000
1973	$.21 \times 10^{-5}$	29	198,300
1974	$.26 \times 10^{-5}$	28	213,000
1975	$.20 \times 10^{-5}$	38	205,000
1976	$.13 \times 10^{-5}$	30	321,000
1977	$.09 \times 10^{-5}$	113	458,900
1978	$.12 \times 10^{-5}$	50	407,900
1979	$.12 \times 10^{-5}$	25	316,300

* 1979 values extended for future projections of recruitment.



Appendix Figure 2-1.--Growth curves used in simulations for male and female red king crabs.

Appendix Table 2-3.--Monthly pot-lift data used for simulation of the actual fishery.

YEAR	TOTAL POTLIFTS	J	F	M	A	M	J	J	A	S	O	N	D
1970	96,500	2,200	4,300	15,700	13,000	3,800	10,800	18,200	23,500	4,700	300	0	0
1971	118,400	600	1,100	2,300	4,400	1,300	3,100	25,000	36,600	28,400	12,200	2,300	1,100
1972	205,000	5,700	11,800	8,300	0	0	24,100	52,800	48,500	38,200	11,700	2,100	1,800
1973	198,300	1,900	4,400	6,300	6,100	0	13,700	70,000	64,100	31,800	0	0	0
1974	213,000	0	0	0	0	0	0	0	83,200	74,700	55,100	0	0
1975	205,000	0	0	0	0	0	0	0	4,200	44,200	122,200	34,500	0
1976	321,000	0	0	0	0	0	0	0	1,700	20,000	135,300	116,300	47,700
1977	458,900	0	0	0	0	0	0	0	0	62,300	185,200	157,500	53,900
1978	407,900	0	0	0	0	0	0	0	0	114,200	293,700	0	0
1979	316,300	0	0	0	0	0	0	0	0	316,300	0	0	0

Appendix Table 2-4.--Increased effort levels used for simulating: A. Relaxed quota, and B. Extended season.

YEAR	EFFORT LEVEL	SEPT.	OCT.	NOV.	DEC.	TOTAL
A.						
	2X	102,500	102,500	102,500	102,500	410,000
1975	3X	153,800	153,800	153,800	153,800	615,200
	4X	205,1001	205,100	205,100	205,100	820,400
	2X	160,500	160,500	160,500	160,500	642,000
1976	3X	240,800	240,800	240,800	240,800	963,200
	4X	321,000	321,000	321,000	321,000	1,284,000
	2X	229,500	229,500	229,500	229,500	918,000
1977	3X	344,200	344,200	344,200	344,200	1,376,800
	4X	458,900	458,900	458,900	458,900	1,835,600
	2X	204,000	204,000	204,000	204,000	816,000
1978	3X	305,900	305,900	305,900	305,900	1,223,600
	4X	407,900	407,900	407,900	407,900	1,631,600
	2X	316,300	316,300	0	0	632,600
1979	3X	316,300	316,300	316,300	0	948,900
	4X	316,300	316,300	316,300	316,300	1,265,200
B.						
1978	1.4X	114,200	293,700	150,000	0	557,900
	2X	114,200	293,700	407,900	0	815,800
1979	1.4X	316,300	150,000	0	0	466,300
	2X	316,300	316,300	0	0	632,600

APPENDIX 3

Natural Mortality Analysis

Natural Mortality Analysis

Estimates of natural mortality for male and female red king crab are based on survey estimates of abundance by age. For males, regression estimates of total mortality were obtained using

$$\ln(n_i) = a - Zi \quad \text{where} \qquad (1)$$

n_i = number of crabs at age i, i = 9,...14

Z = estimate of annual instantaneous total mortality.

Estimates of Z were obtained for each survey year and were considered applicable to that and the preceding two years. For these three year periods, average fishing effort and estimated catchability were calculated. Annual instantaneous natural mortality was estimated from

$$M_p = Z_p - q_p f_p \quad \text{where} \qquad (2)$$

Z_p = estimated annual instantaneous total mortality for period p

q_p = estimated average catchability for period p and

$\bar{f}_p$ = average annual pot-lifts for period p.

An overall estimate of M was obtained by averaging over periods. This average M, .26, was determined to be 24% lower than the weighted average M of .34 calculated from Balsiger's (1974) M schedule. Age specific values of M for ages 9-14 were adjusted accordingly (App. Table 3-2). Estimates for ages 5-8 were left unchanged.

For females, an overall estimate of annual instantaneous natural mortality was calculated from average stock abundance estimates by equation one, except that i = 8, ..., 14 . The estimate obtained for this age range was expropolated to ages 5-7, since abundance estimates for younger crabs are considered less reliable.

Appendix Table 3-1.--Estimate of average annual instantaneous natural mortality for exploited male red king crabs.

	MILLIONS OF MALE CRABS											
AGE	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	MEAN
9	2.7	3.1	2.5	--	2.3	4.7	8.5	9.5	13.4	14.2	20.2	17.7	
10	1.2	1.0	0.6	--	1.0	1.3	2.1	2.5	4.5	4.7	6.2	7.1	
11	0.9	0.5	0.3	--	0.3	0.9	3.5	2.0	2.9	3.3	4.6	4.5	
12	0.6	0.3	0.1	--	0.3	0.5	0.7	1.3	1.5	2.0	2.1	3.5	
13	0.3	0.2	0.0	--	0.1	0.2	0.2	0.5	0.7	0.7	1.4	2.3	
14	0.5	0.3	0.1	--	0.2	0.1	0.1	0.3	0.3	1.5	0.5	1.3	
$\hat{Z}_p$	.37	.49	.65	--	.55	.73	.88	.64	.72	.50	.68	.48	
Period p	66-68	67-69	68-70	69-71	70-72	71-73	72-74	73-75	74-76	75-77	76-78	77-79	
$\bar{f}_p$	20,279	52,181	80,860	104,535	140,075	173,950	205,414	205,431	246,347	328,351	395,950	433,410	
$\hat{q}_p$ (x10^{-5})	--	--	.326	.326	.331	.247	.239	.193	.155	.122	.084	.076	
$\hat{M}_p$			.39	--	.09	.25	.39	.24	.34	.10	.35	.15	.26

Appendix Table 3-2.--Adjusted natural mortality schedule used in simulations for male red king crabs.

AGE	BALSIGER M ESTIMATES	1970-1979 AVERAGE STOCK	ADJUSTED M ESTIMATES
9	.15	10.0	.11
10	.30	3.3	.23
11	.66	2.5	.50
12	.75	1.3	.57
13	.80	.7	.61
14	1.00	.5	.76
Weighted Average	.34		

Appendix Table 3-3.--Estimate of average annual instantaneous natural mortality for female red king crabs.

			MILLIONS OF FEMALE CRABS								
AGE	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	MEAN
8	1.0	--	0.7	5.6	4.1	4.1	8.2	16.1	6.7	13.9	6.7
9	0.7	--	0.3	5.3	4.7	3.6	6.8	12.3	5.2	7.5	5.2
10	0.8	--	0.3	3.4	2.3	2.7	3.2	5.9	3.6	6.3	3.2
11	0.5	--	0.2	2.5	1.7	1.0	1.6	3.8	2.4	2.5	1.8
12	0.3	--	0.1	1.0	0.7	0.4	0.3	0.7	0.4	0.6	0.5
13	0.2	--	0.1	0.9	0.6	0.3	0.2	0.6	0.3	0.6	0.4
14	0.2	--	0.1	0.4	0.4	0.1	0.3	0.6	0.5	0.4	0.3
$\hat{Z}$											.58

APPENDIX 4

Catchability and Availability Analysis

Catchability and Availability Analysis

Annual catchability of male red king crabs was estimated from research survey and fishery information according to the formula

$$q_i = [c/f]_i \div N_i \quad \text{where}$$

c_i = catch in numbers in year i

f_i = effort in pot-lifts in year i

N_i = estimated exploitable stock in year i.

Data used for the estimates are given in Appendix Table 4-1.

Availability of eight-year-old male crabs was estimated by first assuming age nine crabs to be fully available to fishery and then comparing the average age eight to the average age nine exploitation rate:

$$a_8 = U_8/U_9 \quad .$$

Exploitation rates were determined from the data in Appendix Table 4-2 and are calculated to be $U_8 = 2.3/13.6 = .17$ and

$$U_9 = 3.4/10.3 = .33 \; .$$

Appendix Table 4-1.--Estimates of annual catchability, q, from survey and fishery data.

YEAR	EXPLOITABLE STOCK (millions of crabs)	CATCH (millions of crabs)	POT LIFTS	$\hat{q}$
1970	5.4	1.7	96,500	$.326 \times 10^{-5}$
1971	--	2.4	118,400	--
1972	5.8	4.0	205,000	$.336 \times 10^{-5}$
1973	11.4	4.8	198,300	$.212 \times 10^{-5}$
1974	21.3	7.7	213,000	$.170 \times 10^{-5}$
1975	21.6	8.7	205,100	$.196 \times 10^{-5}$
1976	33.0	10.6	321,000	$.100 \times 10^{-5}$
1977	37.7	12.1	458,900	$.070 \times 10^{-5}$
1978	47.1	15.7	407,891	$.082 \times 10^{-5}$
1979	46.3	16.8	316,300	$.115 \times 10^{-5}$

Appendix Table 4-2.--Data used to estimate availability of eight-year-old males to the fishery.

YEAR	STOCK ESTIMATE (millions of crabs) AGE 8	AGE 9	CATCH COMPOSITION (per cent) AGE 8	AGE 9	TOTAL CATCH
1970	3.5	2.5	29	29	1.7
1971	--	--	32	41	2.4
1972	3.2	2.3	31	39	4.0
1973	7.3	4.7	32	37	4.8
1974	12.3	8.5	33	39	7.7
1975	10.9	9.5	24	43	8.7
1976	19.3	13.4	16	43	10.6
1977	22.5	14.2	18	50	12.1
1978	24.1	20.2	--	--	15.7
1979	19.7	17.7	--	--	16.8
MEAN	13.6	10.3	27	40	8.5

APPENDIX 5

Spawner-Recruit Analysis

Spawner-Recruit Analysis

Research survey estimates of mature female mating stock and age five males have been used to fit spawner-recruit curves for simulations. These data are shown in Appendix Table 5-1. Estimates of annual recruitment have been adjusted by a raising factor in order to calibrate the simulation model.

Appendix Table 5-1.--Survey data used for estimating the spawner-recruit relationship for southeastern Bering Sea red king crabs.

YEAR	ESTIMATED STOCK (millions of crabs) MATURE Males	Females	AGE 5 MALES	SIMULATED STOCK AGE 5 MALES	ADJUSTMENT FACTOR	ADJUSTED RECRUITMENT
1968	26	37				
1969	40	21				
1970	17	11				
1971	--	--				
1972	22	11				
1973	56	67				
1974	67	61	15	28	1.87	30
1975	71	49	18	38	2.11	36
1976	109	61	27	30	1.11	54
1977	147	126	46	113	2.47	92
1978	115	117	21	50	2.38	42
1979	95	122	11	25	2.27	22
MEAN					2.02	

Two spawner-recruit functions were fitted to the data: The Ricker formulation

$R = A1Se^{-A2s}$ and the

Beverton and Holt model

$$R = \frac{1}{A1 + A2/S}$$

Regression estimates of the parameters A1 and A2 are given in Appendix Table 5-2. Estimates for the Beverton-Holt model were derived from an eye-fitted curve (Figure 4b) rather than the actual data points because of a lack of fit of the model to the data. Correction for possible reduced availability to the survey gear of age 5-7 females did not significantly change the parameter estimates for the Ricker curve.

Appendix Table 5-2. Parameter estimates for spawner recruit models used in simulations.

PARAMETER	RICKER	BEVERTON-HOLT
A1	7.8303	$.15507 \times 10^{-7}$
A2	$.51135 \times 10^{-7}$	.0734

APPENDIX 6

Gross Revenue and Annual Return Tables

Table 6-1.--Gross revenue accruing from four different effort patterns with ex-vessel price assumed independent of the average size of crabs caught (million $).

Year	Actual Effort	Effort Pattern*		
		Double	Triple	Quadruple
1970	2.18	2.18	2.18	2.18
1971	2.42	2.42	2.42	2.42
1972	4.33	4.33	4.33	4.33
1973	10.75	10.75	10.75	10.75
1974	14.96	14.96	14.96	14.96
1975	14.57	21.97	26.81	29.98
1976	35.92	48.59	53.02	54.41
1977	63.58	77.55	80.62	80.90
1978	108.50	124.69	130.00	132.19
1979	82.50	99.60	102.17	93.12

*Actual effort levels were assumed for years 1970-74.

Table 6-2.--Annual returns accruing from four different effort patterns with ex-vessel price assumed independent of the size of crabs caught (million $).

Year	Actual Effort	Effort Pattern*		
		Double	Triple	Quadruple
1970	1.39	1.39	1.39	1.39
1971	1.42	1.42	1.42	1.42
1972	2.51	2.51	2.51	2.51
1973	8.75	8.75	8.75	8.75
1974	12.41	12.41	12.41	12.41
1975	11.89	16.61	18.77	19.25
1976	31.53	39.81	39.85	36.86
1977	56.92	64.24	60.65	54.27
1978	102.12	111.93	110.87	106.69
1979	77.09	88.79	85.95	71.49

*Actual effort levels were assumed for years 1970 through 1974.

Table 6-3.--Gross revenue accruing from four different effort patterns with ex-vessel price assumed to be dependent upon average size of crabs caught (million $)*.

Year	Actual Effort	Effort Pattern** Double	Triple	Quadruple
1970	2.18	2.18	2.18	2.18
1971	2.42	2.42	2.42	2.42
1972	4.33	4.33	4.33	4.33
1973	10.75	10.75	10.75	10.75
1974	14.96	14.96	14.96	14.96
1975	14.57	21.89	26.08	28.48
1976	35.92	46.77	48.72	48.05
1977	63.58	72.80	70.89	67.57
1978	108.50	114.35	110.67	106.77
1979	82.50	90.75	87.16	75.43

*One percent change in weight assumed to cause a two percent price change.

**Actual effort levels were assumed for years 1970 through 1974.

Table 6-4.--Annual returns accruing from four different effort patterns with ex-vessel price assumed to be dependent upon average size of crabs caught (million $)*.

Year	Actual Effort	Effort Pattern**		
		Double	Triple	Quadruple
1970	1.39	1.39	1.39	1.39
1971	1.42	1.42	1.42	1.42
1972	2.51	2.51	2.52	2.51
1973	8.75	8.75	8.75	8.75
1974	12.41	12.41	12.41	12.41
1975	11.89	16.53	18.04	17.75
1976	31.53	38.00	35.55	30.49
1977	56.92	59.48	50.92	40.94
1978	102.12	101.60	91.54	81.27
1979	77.09	79.94	70.94	53.80

*One percent change in weight assumed to cause a two percent price change.

**Actual effort levels were assumed for years 1970 through 1974.

Table 6-5.--Gross revenues associated with 5.25-, 6.0-, and 6.5-inch size limits (million $)*.

	Price Independent of Size			Price Dependent on Size**		
	Size Limit			Size Limit		
Year	5.25"	6.0"	6.5"	5.25"	6.0"	6.5"
1970	3.29	2.83	2.18	2.22	2.31	2.18
1971	4.56	2.85	2.42	2.10	2.43	2.42
1972	10.46	8.04	4.33	4.84	4.67	4.33
1973	17.98	14.15	10.75	9.22	11.90	10.75
1974	23.86	19.46	14.96	11.30	13.04	14.96
1975	19.01	18.61	14.57	10.47	14.12	14.57
1976	39.73	38.35	35.92	20.99	29.66	35.92
1977	70.05	69.43	63.58	37.41	51.22	63.58
1978	147.07	115.86	108.50	63.22	89.78	108.50
1979	130.29	115.22	82.50	62.19	71.74	82.50

*Effort was set at actual levels for all size limits.

**One percent change in average size of crabs caught was assumed to cause a two percent price change.

Table 6-6.--Annual returns associated with 5.25-, 6.0-, and 6.5-inch size limits (million $)*.

	Price Independent of Size			Price Dependent on Size**		
	Size Limit			Size Limit		
Year	5.25"	6.0"	6.5"	5.25"	6.0"	6.5"
1970	2.49	2.03	1.39	1.43	1.51	1.39
1971	3.56	1.85	1.42	1.09	1.42	1.42
1972	8.63	6.21	2.51	3.01	2.84	2.51
1973	15.99	12.15	8.75	7.22	9.90	8.75
1974	21.31	16.92	12.41	8.75	10.49	12.41
1975	16.33	15.93	11.89	7.79	11.44	11.89
1976	35.34	33.96	31.53	16.61	25.27	31.53
1977	63.39	62.77	56.92	30.75	44.57	56.92
1978	140.70	109.48	102.12	56.84	83.41	102.12
1979	124.88	109.81	77.09	56.79	66.34	77.09

*Effort was set at actual levels for all size limits.

**One percent change in average size of crabs caught was assumed to cause a two percent price change.

Table 6-7.--Gross revenues and annual returns for 1978 and 1979 for actual effort levels, a doubling of effort and a 40 percent increase in effort during a second season with a 7-inch minimum size.

Level of Effort During Second Season with 7" Minimum Size	Year	Price Independent of Size Size Limit		Price Dependent on Size* Size Limit	
		Gross Revenue	Annual Returns	Gross Revenue	Annual Return
Double effort over aactual levels	1978	126.56	113.81	134.61	121.86
	1979	89.68	78.87	91.65	80.83
Increase effort 40 percent over actual levels	1978	116.32	107.60	119.77	111.05
	1979	87.47	79.50	89.39	81.42
Actal levels	1978	108.50	102.12	108.50	102.12
	1979	82.50	77.09	82.50	77.09

*One percent change in the average size of crabs caught was assumed to cause a two percent price change.

Table 6-8.--Biological and economic effects of a doubling of the actual level of effort with 5.25 and 6.00 inch size limits.*

Year	Exploitation Rate	Catch (million crabs)	CPUE	Average size in catch (lbs)	Fraction copulated females	Price independent on size: Gross revenues (million $)	Price independent on size: Annual returns (million $)	Price dependent on size: Gross revenues (million $)	Price dependent on size: Annual returns (million $)
EFFORT DOUBLED, 5.25 INCH MINIMUM SIZE									
1970	.26	3.6	37	4.8	.79	3.29	2.49	2.22	1.43
1971	.31	6.2	52	3.9	.81	4.56	3.56	2.10	1.09
1972	.48	11.7	57	4.0	.74	10.46	8.63	4.84	3.01
1973	.34	10.1	51	3.5	.70	17.98	15.99	9.22	7.22
1974	.41	18.0	84	3.6	.78	23.86	21.31	11.30	8.75
1975	.55	22.3	54	3.8	.73	26.93	11.57	14.68	9.32
1976	.56	23.8	37	3.7	.70	49.96	41.18	23.73	14.96
1977	.55	23.6	26	3.7	.59	79.10	65.79	36.52	23.20
1978	.66	50.2	61	3.3	.63	174.04	161.29	62.73	49.98
1979	.60	56.9	90	3.6	.74	154.94	144.12	64.55	53.74
EFFORT DOUBLED, 6.00 INCH MINIMUM SIZE									
1970	.26	2.8	29	5.3	.79	2.83	2.03	2.31	1.51
1971	.29	2.7	23	5.2	.82	2.85	1.85	2.43	1.42
1972	.50	7.7	38	4.4	.78	8.04	6.21	4.67	2.84
1973	.33	6.0	30	4.5	.79	14.15	12.15	11.90	9.90
1974	.42	11.8	56	4.3	.89	19.46	16.92	13.04	10.49
1975	.55	19.0	46	4.5	.90	27.01	21.65	20.50	15.14
1976	.56	18.8	29	4.5	.87	48.92	40.14	35.60	26.82
1977	.56	20.7	23	4.4	.73	82.24	68.92	54.38	41.06
1978	.62	23.3	29	4.5	.75	124.51	111.75	85.51	72.76
1979	.66	46.0	73	4.1	.88	146.34	135.52	79.74	68.93

*Actual effort was held constant for years 1970-74.

APPENDIX 7

KING CRAB PRICES

Note 1: Interpretation of the price size response relation

Given that the price/size response is 2, the ex-vessel price is $1.00 per pound, and the average weight is 5.00 pounds, a 1% reduction in average wiehgt (0.05 lbs) would decrease price by 2 cents. Further, a pound decrease in average weight would decrease price by 40 cents per pound.

Note 2: Price response coefficients use in the analysis

Two price response relationships were estimated. In one equation the Kodiak king crab price was specified as the dependent variable; while, the Bering Sea king crab price was selected as the dependent variable in a second equation. Results of the analysis are reported below:

1 ...... $KP = 9.19712 - 0.311061Q + 2.12009I$
$\quad\quad (0.8039) \quad (0.1292) \quad (0.1301) \qquad R^2 = 0.95$

2 ...... $BSP = -12.3013 - 1.21167Q + 3.11236I$
$\quad\quad (2.9391) \quad (0.9043) \quad (0.9138) \qquad R^2 = 0.86$

where:

KP = Kodiak king crab price

BSP = Bering Sea King crab price

Q = Total quantity of King crab caught in Alaska

I - Total disposable income

Standard errors are given below each coefficient. All variables were transformed into log form. Equation 1 coefficients associate with quantity and income were used in the analysis. These coefficients were selected because they were considered to be more realistic. Price data available for the Bering Sea was reflective of only the developing phase of the fishery. Kodiak price data on the other hand were reflective of all phases of the fisheries evolution.

Table 7-1.--Kodiak and Bering Sea King Crab Prices: 1960-1979

Year	Kodiak King crab price ¢/lb	Bering Sea King Crab Price ¢/lb
1960	7.5	
1961	8.5	
1962	9.5	
1963	10.0	
1964	10.0	
1965	9.9	
1966	12.8	
1967	11.0	
1968	26.0	
1969	26.9	22.0
1970	28.0	20.0
1971	30.0	20.0
1972	38.0	25.0
1973	66.0	52.0
1974	44.0	39.0
1975	45.0	35.0
1976	72.0	61.0
1977	138.0	95.0
1978	140.0	123.0
1979	93.0	90.0

Sources - Data for 1960 through 1977 were obtained from State of Alaska, Commercial Fisheries Entry Commission. Industry sources were contacted to obatin data for 1978 and 1979.

Table 7-2.--Price and average weight of crabs caught given four different effort patterns.

YEAR	EFFORT** ACTUAL Price ¢/lbs	ACTUAL Weight lbs/crab	DOUBLE Price ¢/lbs Size indep	DOUBLE Price ¢/lbs Size dep*	DOUBLE Weight lbs/crab	TRIPLE Price ¢/lbs Size indep	TRIPLE Price ¢/lbs Size dep*	TRIPLE Weight lbs/crab	QUADRUPLE Price ¢/lbs Size indep	QUADRUPLE Price ¢/lbs Size dep*	QUADRUPLE Weight lbs/crab
1970	19.71	5.81	19.71	19.71	5.81	19.71	19.71	5.81	19.71	19.71	5.81
1971	20.08	5.68	20.08	20.08	5.68	20.08	20.08	5.68	20.08	20.08	5.68
1972	25.52	5.72	25.52	25.52	5.72	25.52	25.52	5.72	25.52	25.52	5.72
1973	53.53	4.93	53.53	53.53	4.93	53.53	53.53	4.93	53.53	53.53	4.93
1974	39.59	5.29	39.59	39.59	5.29	39.59	39.59	5.29	39.59	39.59	5.29
1975	36.08	5.12	33.42	33.30	5.11	31.95	31.08	5.05	31.07	29.52	4.99
1976	61.92	5.31	57.62	55.47	5.21	56.30	51.73	5.09	55.90	49.36	4.99
1977	96.41	5.46	90.96	85.38	5.29	89.88	79.03	5.12	89.78	74.98	4.99
1978	123.98	5.43	118.61	108.78	5.20	117.08	99.67	5.01	116.46	94.06	4.88
1979	94.62	5.50	89.31	81.37	5.25	88.58	75.57	5.08	91.22	73.89	4.95

* It was assumed that a one per cent charge in weight causes a two per cent price change.

** Actual effort levels were assumed for years 1970-1974.

Table 7-3.--Price and average weight of crabs caught given size limits of 5.25, 6.00 and 6.5 inches.

	SIZE LIMIT							
	5.25"			6.00"			6.50"	
	Price ¢/lbs		Weight lbs/crab	Price ¢/lbs		Weight lbs/crab	Price ¢/lbs	Weight lbs/crab
	Size			Size				
YEAR	indep	dep*		indep	dep*			
1970	19.07	12.90	4.78	19.33	15.78	5.25	19.71	5.81
1971	19.13	8.79	3.85	19.88	16.92	5.24	20.08	5.68
1972	22.91	10.60	3.89	23.86	13.86	4.36	25.52	5.72
1973	50.26	25.77	3.53	51.93	43.65	4.52	53.53	4.93
1974	36.48	17.28	3.64	37.93	25.42	4.33	39.59	5.29
1975	34.42	18.96	3.80	34.56	26.23	4.46	36.08	5.12
1976	60.54	31.99	3.86	61.03	47.20	4.67	61.92	5.31
1977	93.77	50.08	3.99	94.02	69.37	4.69	96.41	5.46
1978	112.50	48.36	3.56	121.30	94.00	4.78	123.98	5.43
1979	81.63	38.97	3.80	85.15	53.02	4.34	94.62	5.50

* It was assumed that a one per cent change in weight causes a two percent price change

Table 7-4.--Price and average weight of crab caught given a 6.5" size limit with the actual level of effort, a 5.25" size limit with double the level of effort, and a 6.5" size limit with double the level of effort.**

YEAR	Actual effort 6.5" size limit Price ¢/lbs	Actual effort 6.5" size limit Weight lbs/crab	Double effort 5.25" size limit Price ¢/lbs size indep	Double effort 5.25" size limit Price ¢/lbs size dep*	Double effort 5.25" size limit Weight lbs/crab	Double effort 6.0" size limit Price ¢/lbs size indep	Double effort 6.0" size limit Price ¢/lbs size dep*	Double effort 6.0" size limit Weight lbs/crab
1970	19.71	5.81	19.07	12.90	4.78	19.33	15.78	5.25
1971	20.08	5.68	19.13	8.79	3.85	19.88	16.92	5.24
1972	25.52	5.72	22.91	10.60	3.89	23.86	13.86	4.36
1973	53.53	4.93	50.26	25.77	3.53	51.93	43.65	4.52
1974	39.59	5.29	36.48	17.28	3.64	37.93	25.42	4.33
1975	36.08	5.12	31.91	17.40	3.78	31.89	24.20	4.46
1976	61.92	5.31	57.20	27.17	3.66	57.52	41.86	4.53
1977	96.41	5.46	90.41	41.74	3.71	89.32	59.06	4.44
1978	123.98	5.43	106.24	38.29	3.26	118.67	81.50	4.50
1979	94.62	5.50	76.71	31.96	3.55	78.33	42.68	4.06

* It was assumed that a one percent change in weight causes a two percent price change.

** Actual effort was held constant in all cases for years 1970-1974.

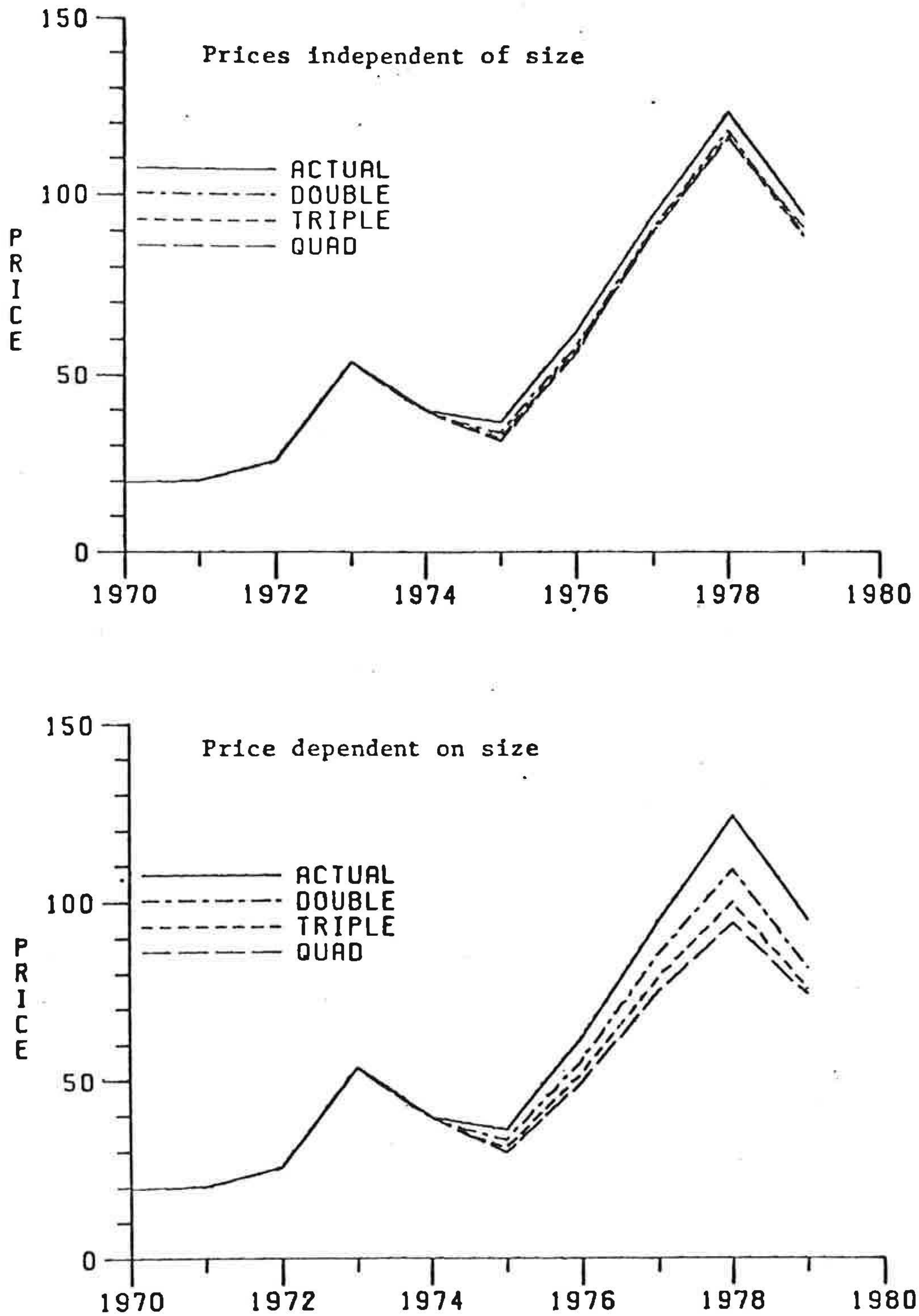


Figure 7-1.--Bering Sea king prices associated with a quota relaxation and double, triple, and quadruple actual effort levels.

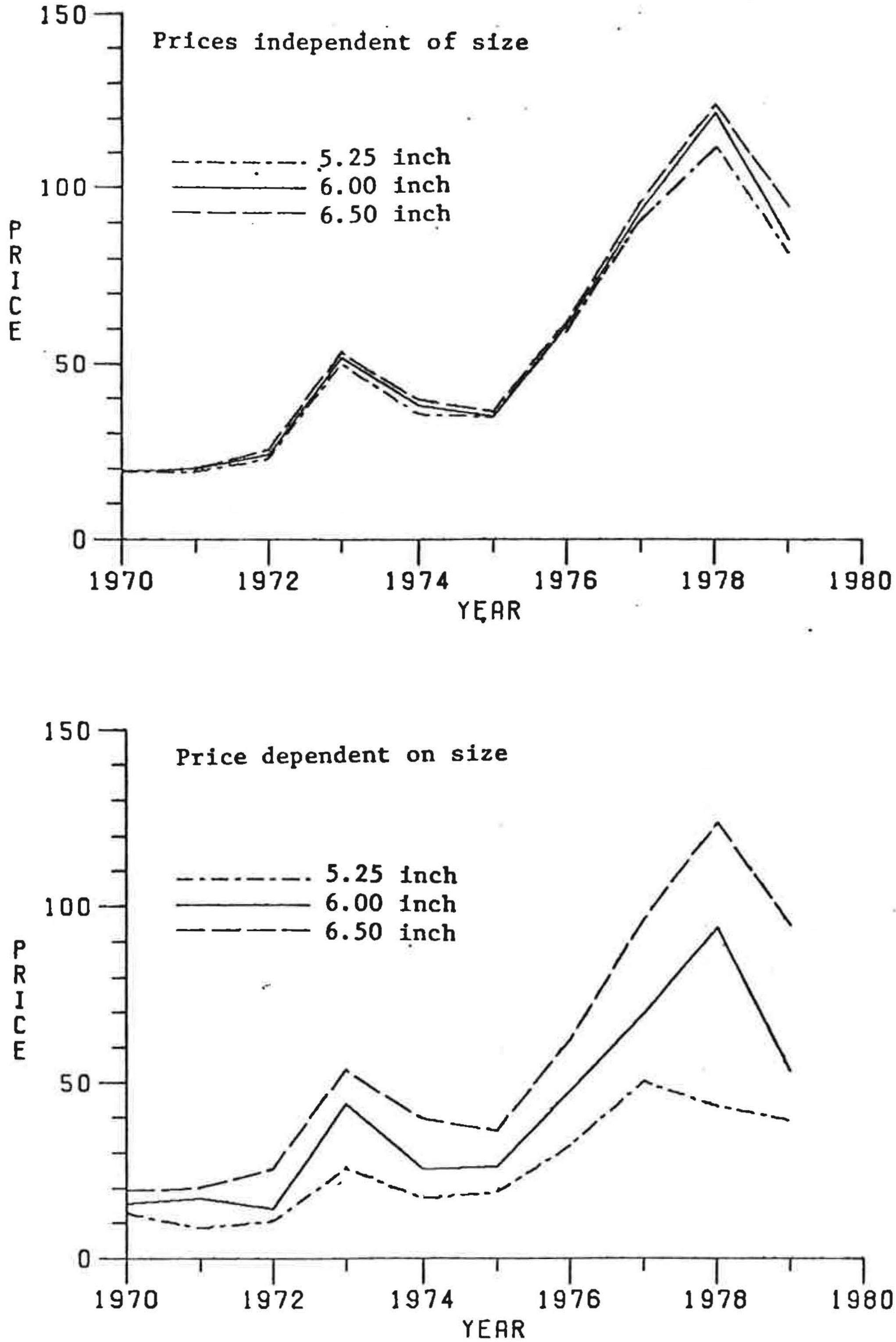


Figure 7-2.--Bering Sea king crab prices associated with size limits of 5.25, 6.00, and 6.50 inches with actual effort levels maintained.

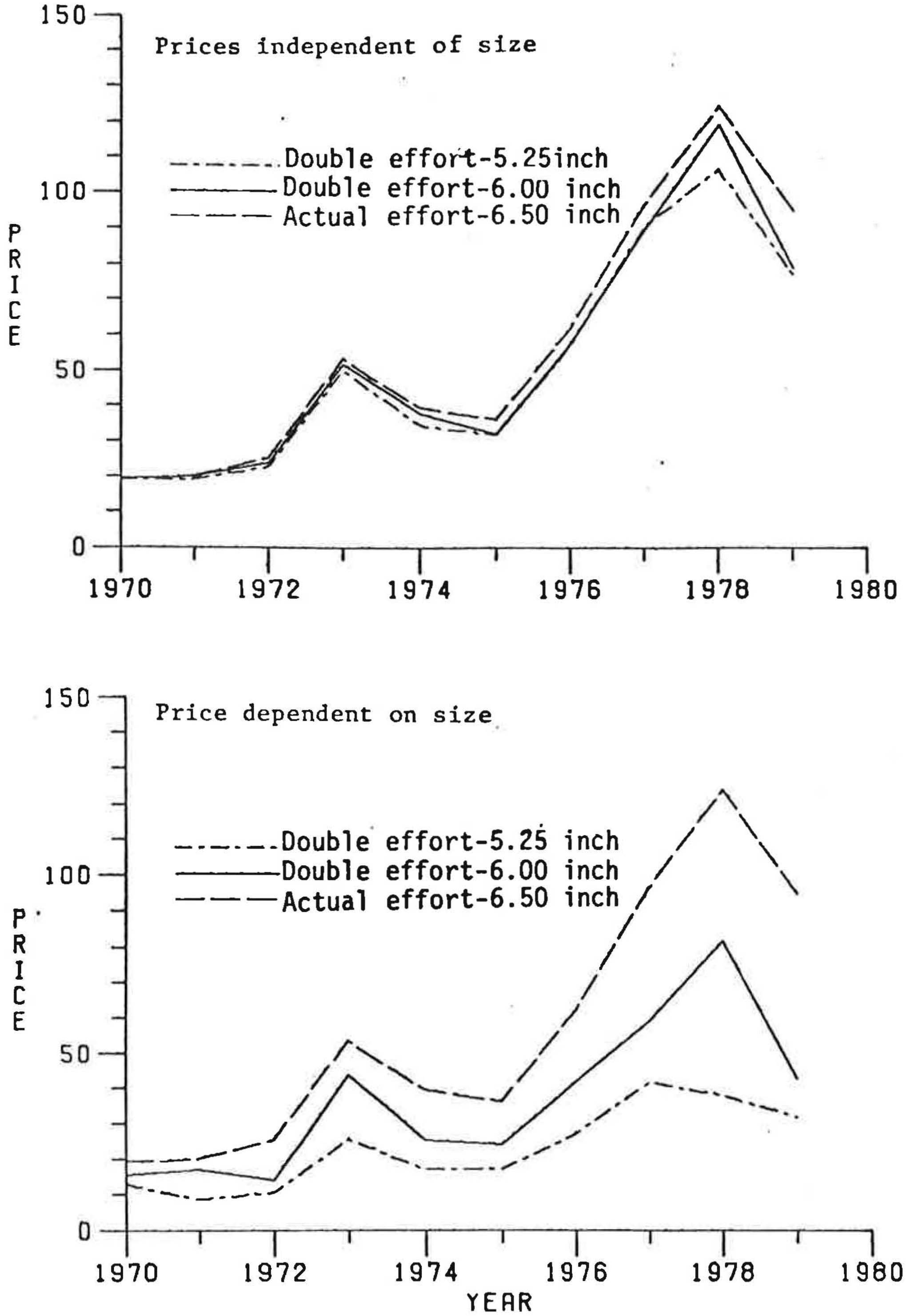


Figure 7-3.--Bering Sea king crab prices for a 6.50 inch size limit, with actual effort maintained, compared with those for a 5.25 and 6.00 inch size limits with effort doubled for years 1975-79.