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Management of Multipurpose Heterogeneous Fishing Fleets Under Uncertainty

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Abstract *This paper describes an approach to modeling fisheries that can be useful in policy analysis when the population dynamics are not well known and the fleet is composed of a variety of multipurpose vessels. An empirical application of the methodology to the northern California Dungeness crab fishery is discussed. A multivariate time-series model provides the intertemporal (year-to-year) relationships for a simulation model describing both within season and year-to-year fleet behavior. Appropriate modifications of the simulation model parameters reflect alternative policy scenarios. The analysis of the simulation outcomes provide insight into fleet response to several management alternatives that have been considered for the crab fishery.*

Introduction

Although the study of fisheries economics has been built upon the application of the canonical model of a renewable resource with suitable bioeconomic growth relations assumed known or estimable (e.g., Clark), the necessary growth relationships have yet to be quantified for many species of interest, and the data necessary to do so do not appear available today. Additionally, most models refer to a single species harvested by a homogeneous fleet while commercial fishing fleets are often composed of a variety of vessels. Their operations are better described as multispecies (harvesting a number of species simultaneously), multipurpose (harvesting different species at different times of the year), or both.

Limitations of the traditional approach do not alter the necessity of formulating management policies for fisheries as mandated by the Fisheries Conservation and Management Act of 1976 (FCMA) and similar legislation, nor do they diminish the need for economic input into selecting management alternatives. What is necessary is a recognition by economists of both the limitations of the traditional approach and the need to develop alternative approaches that are applicable using the data now available.

The objective of this paper is to present an approach to quantitative economic analysis of commercial fisheries useful for policy modeling given current data and model limitations. The behavior of a commercial fishing fleet in an open-access fishery under the broader set of assumptions is explained and the effects of alternative management policies are considered. Both the short-run and long-run decisions of fishermen are studied and the dynamic evolution of the fleet analyzed. To maintain relevance to fishery managers and others interested in applications of the methodology developed in this study, all economic and physical variables used may be obtained from current data sources. In the absence of adequate bioeconomic models, a multivariate, linear, time-series model of the Box-Jenkins type provides adequate intertemporal relationships for certain policy evaluations. Current regulations are assumed to continue unless otherwise specified. The empirical methodology is developed in an application to the Dungeness crab fleet on the northern California coast (Eureka is the major port involved.)

An intraseasonal model shows that heterogeneous capital in an open-access fishery results in inefficient allocation of existing effort in addition to the usual excess investment associated with common property resources. The intraseasonal behavioral model and the interseasonal time-series model are combined in a Monte Carlo simulation of the Dungeness crab fleet. The simulation model is used to analyze the effects of catch limitations, license restrictions, and season changes in the crab fishery as well as the indirect effects of the closure of the salmon fishery on the crab fleet.

Background

The Dungeness crab, *Cancer magister*, is a prime commercial species found off the Pacific Coast of North America from mid-California north to the Alaska Peninsula.[1] For over thirty years crab stocks have been commercially harvested, subject to regulation, and studied intensively. From a biological perspective, current regulations are considered sufficient to maintain the harvest of the resource for the benefit of society. These regulations fall primarily into four categories: fishing seasons, male only harvest, minimum size at capture, and escape ports to reduce incidental fishing mortality on non-legal crab (Pacific Marine Fisheries Commission).

Vessels participating in the Eureka Dungeness crab fishery are multipurpose in that they can operate in two or more fisheries each year. The efficiency of a given vessel in alternative fisheries depends on its capacity and configuration. The activity of the fleet can be approximated by the activities of the dominant crabber-troller vessels. The crabber-troller fleet consists of "small" (under 40 feet) vessels that concentrate on crab and salmon and "large" (40 feet or over) vessels that also fish for albacore. Information on the production patterns, revenues, and associated costs for the crabber-troller vessels are given in Fletcher and Johnston (1984).

Salmon is a common alternative for crab vessels, offering a choice of activities when the two open seasons overlap. As there is little simultaneity between crab and albacore fishing, the salmon fishery is modeled as the primary alternative activity of the multipurpose crab fleet. Under current conditions, there is little potential for actual fishing overlap since excess capacity has shortened the effective crab season substantially.

The crab and salmon fisheries and the commercial crab fishing fleet have experienced a great deal of volatility during the post-war period. Crab landings, for example, went from a low of less than 100 tons in 1974 to 5,500 tons in 1977. Crab fleet size and revenues for the crab and salmon fisheries are presented in Figure 1.

An acceptable biological model is not yet available to explain either the causes of the cycles in the northern California Dungeness crab catch record, nor an apparent correlation between salmon and crab landings (Botsford, Methot, and Wilen 1982; Botsford, Methot, and Johnston 1983). Given the present lack of knowledge of the causal dynamic relationships in the crab and salmon fisheries, one is unable to develop the empirical relationships usually assumed in fisheries models. An alternative means to depict these relationships must be adopted until sufficient knowledge to specify causal relationships is acquired.

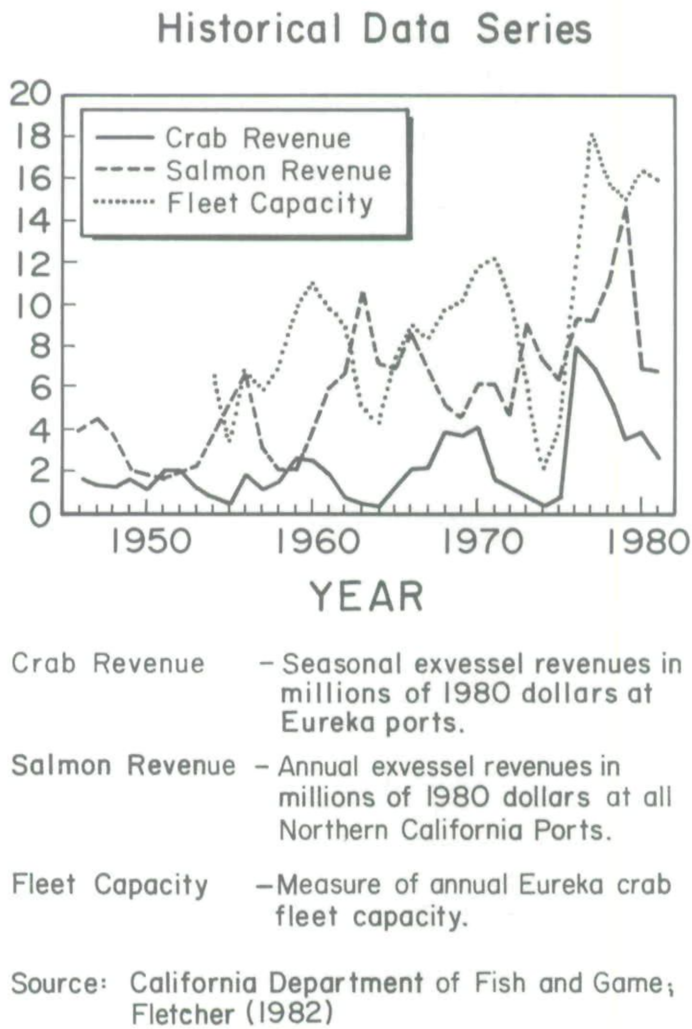

Figure 1. Historical Data Series.

Dynamic Fleet Behavior for the Open-Access Eureka Crab Fishery

During any given year, a fishing fleet can be defined by the vessels participating in a particular fishery. In a dynamic context, however, the appropriate definition is unclear. Consider the Eureka crab fleet. Over 120 vessels were active during the 1971 season. By 1974, when landings were at record low levels, the active fleet had been reduced to 20 vessels. As landings improved, fleet size also increased. By the 1977 season, over 180 vessels were operating including new entrants and many of the vessels active in 1971 that had dropped out of the fishery during the intervening years. Such examples imply that the fleet size in a given year cannot appropriately be modeled as decisions to invest or disinvest. Conversely, fishing vessels do not have the ability to move instantly between alternatives at zero cost. Vessels can participate in a variety of fishing activities but only with some discrete switching cost.

The entry decision for individual vessels depends on a number of variables including physical vessel characteristics, the personal preference of the skipper, and opportunity costs as determined by the net revenue available from other alternatives. A major determining factor is expected returns to participation in the fishery as a function of price, abundance, variable costs, and the total number of other participants. Entry or switching costs including any necessary vessel and gear modification, travel costs, and additional licensing expense are also important. Fleet behavior reflects the aggregate decisions of all individual participants.

The problem of modeling the dynamics of fleet entry and exit is central to the problem of modeling open-access fisheries. One approach is to consider fleet behavior directly. Assume fishermen form they expectations of fleet size rationally in the sense of Muth. In the aggregate, expected fleet size, N_t^e, can be assumed to adjust as a function of the present value of expected returns per vessel, Y_t^e. When the cost of switching is small and the decision can be revised annually, a fisherman need only be concerned with the expected profitability each season. That is:

$$N_t^e = N_{t-1} + f(Y_t^e) \approx N_{t-1} + h(R_t^e, N_t^e, C_t^e) \tag{1}$$

where R_t^e is expected total revenue generated by the fishery during the season and C_t^e is expected production costs. Revenues depend on the expected fleet size, expected abundance of the resource, A_t^e, and expected price, P_t^e:

$$R_t^e = g(N_t^e, A_t^e, P_t^e) \tag{2}$$

Relations 1 and 2 define a pair of implicit simultaneous equations in fleet size, revenue, and a set of exogenous variables. The economically rational expectations of Feige and Pearce provide a plausible approach for an empirical implementation of these relations. Assuming costs for information on past fishing revenues and fleet size are relatively small, such data should be utilized intensively in expectation formulation. An appropriate estimation procedure that utilizes this information efficiently is a multivariate time-series model.

Time-Series Model of the Eureka Crab Fishery and Related Series

Previous crab demand studies indicate that the price of King crab and personal income in California are significant variables in explaining the exvessel price of Dungeness crab, but a dynamic model providing long term estimates for these variables is not available (Erickson 1975; Youde and Wix 1967). However, since entry and exit decisions by fishermen are assumed to depend on the net revenue available from alternative activities, behavioral relations describing fleet dynamics must reflect the economic criteria, not just the biological influence reflected in catch. If costs are relatively constant over time, the primary dynamic influences due to fluctuating net revenues are captured in the data on harvest revenue.

Various approaches to time-series modeling are possible. Prices and landings could have been modeled as separate series and revenue forecasts calculated for use in modeling fleet dynamics. The approach chosen for this analysis was to model fleet revenues directly. The advantage of this approach is a reduction in model size, an important consideration in multivariate estimation procedures used for this study, especially given the paucity of data. The analysis is based on the simultaneous modeling of three data series: crab revenues, salmon revenues, and crab fleet capacity. The final result is an explicit relationship between fleet capacity and the driving forces, fleet revenues from alternative fishing activities.

The data series on fleet capacity developed for this study corresponds to fleet capacity each year in terms of a standard measure of fishing effort (Hannesson). Let S_t, Y_{St} and L_t, Y_{Lt} be, respectively, the number of vessels and the total landings for the subfleets of small and large vessels each year. Defining the catch-per-unit-effort (CPUE) as the average annual crab catch per vessel, the ratio of the CPUE of large boats to that of small boats defines the relative efficiency of large to small boats, RE_t.[2] That is, the fleet capacity in small boat units each year, F_t, is given by:

$$F_t = L_t(Y_{Lt}/L_t)/(Y_{St}/S_t) + S_t = S_t(Y_{Lt}/Y_{St} + 1) \tag{3}$$

The average measure of relative efficiency over the 1954–1977 period was 1.25[3] and was used to calculate the effective fleet capacity in small boat units from aggregate data on the small and large subfleets.

Development of a time-series model is an iterative process of model fitting and forecast evaluation referred to as identification and verification procedures. Detailed descriptions of all procedures used in this analysis is not possible in the limited space available. Hopefully the following outline contains the essence of the results. The interested reader is referred to Fletcher (1982) for additional information.

The general form of the vector, autoregressive, moving average (ARMA) model of k series $\{z_t\}$ takes the form:

$$\phi(B)z_t = \theta(B)a_t \tag{4}$$

where B is the backshift operator such that $z_t(B^k) = z_{t-k}$, $\phi(B)$ and $\theta(B)$ are p^{th}

and q^{th} order, respectively, polynomials in B, $\{z_t\} = \{Z_t\text{-}n\}$ is a series of vectors of deviations of the series Z_t from the origin n, and $\{a_t\}$ is a sequence of vectors of random shocks (innovations) independently, identically, and multivariate normally distributed with mean 0 and covariance matrix $\sum$. The series z_t is assumed to be stationary and invertible. The identification procedures used in the analysis follow that of Tiao et al. and is a generalization of the univariate approach presented by Box and Jenkins.

The series chosen for analysis were the Eureka Crab Fleet Capacity, F_t, Eureka Crab Revenue, C_t, and the Northern California Salmon Revenue, S_t. The salmon revenue series was included since salmon is the primary fishing alternative for most of the crab fleet and is therefore potentially important in predicting fleet behavior. In addition, crab and salmon catch data exhibit biologically unexplained correlations (Botsford, Methot, and Wilen 1982).

Initial models of the three series failed to provide sufficiently accurate one-step-ahead forecasts for use in further model development. The difficulty was traced to an extreme jump in the crab revenue series between 1975 and 1976. Given that this change was an anomaly independent of the usual structure,[4] intervention analysis (a dummy variable technique) was used (Jenkins 1979). A pulse variable, I_t, equal to one in 1975 and zero elsewhere was introduced into the model and improved the forecasts significantly.

The logs of the actual values of the data series were used in model development. Although a multivariate ARIMA procedure was used in the analysis, the final model was identified as an AR with a 10-year cycle. Properly ordered, the matrix of coefficients of the final AR polynomial is lower triangular, a generalization of a transfer function model, but obtained without prior restrictions. Mathematically, the final model in matrix AR form is presented as:

$$\underbrace{\begin{bmatrix} \underset{(.20)}{1 + .27B} & & & \\ & \underset{(.14)}{1 - .43B} & & \\ \underset{(1600)}{-11000B} & \underset{(.09)}{-.27B^4} & \underset{(.12)(.10)}{(1 - .78B + .23B^2)}\ \underset{(.12)}{(1 - .27B^{10})} & \\ & & \underset{(.09)(.09)}{(-.26B + .16B^2)}\ \underset{(.12)}{(1 - .27B^{10})} & \underset{(.22)}{1 - .72B} \end{bmatrix}}_{\phi(B)} \underbrace{\begin{bmatrix} I_t \\ S_t \\ C_t \\ F_t \end{bmatrix}}_{Z_t}$$

$$= \underbrace{\begin{bmatrix} 5.8 \times 10^{-6} \\ (4.6 \times 10^{-6}) \\ 1.13 \\ (.27) \\ -.13 \\ (.15) \\ .13 \\ (.10) \end{bmatrix}}_{n} + \underbrace{\begin{bmatrix} e_{1i} \\ e_{2t} \\ e_{3t} \\ e_{4t} \end{bmatrix}}_{a_t} \qquad (5)$$

The standard errors of the coefficients are given in parentheses. All of the AR coefficients are significant expect for the intervention variable on its own past, which is necessary for internal program computations. The estimated constant terms for the terms for the crab revenues and crab fleet capacity are not significant but were retained for symmetry of the final form and because the model was not differenced.

Consider the individual rows of $\phi(B)$ in Equation 5. The first row represents the dummy variable. The second row gives the salmon revenue (S_t) as a simple first order AR process. The third row indicates that crab revenues (C_t) are best estimated as a process that depends on salmon revenues the four years prior, a complex second order AR process with a ten-year cycle in past crab revenues, and the intervention variable. The fourth row gives fleet capacity as a function of past crab revenues and a first order AR component of the previous year's capacity.

Intraseasonal Behavior of Heterogeneous, Multipurpose Fleets

Particular problems associated with multipurpose, heterogeneous fishing fleets have only recently been treated in the literature (Huppert 1979; Holt 1981; and McKelvey 1983). The model presented here has similarities to those of Holt and McKelvey. An implication that follows from the model is that, in addition to the usual economic inefficiencies that arise under open access, there are efficiency losses due to the heterogeneous composition of the fleet.

To model intraseasonal fleet behavior for fisheries such as the Dungeness crab where growth and reproduction occur primarily during the season closures, one can abstract from the biological dynamics and concentrate on recruitment, R_j, and escapement, S_j, for each species, j. Escapement differs from recruitment only through total fleet harvest, H_j; other interactions are relegated to the interseasonal model.

Ignoring natural mortality, the stock of fish for each species, $x_j(t)$, decreases over the season as fish are harvested. The fishing season for each species has maximum length, T_j, either through regulation or natural availability. To avoid confusion, each fishing unit is referred to as a vessel. The catch rate per vessel, $h_j(t)$, is assumed proportional to the total stock by the catchability coefficient, q_j, so that $h_j(t) = q_j x_j(t)$.

Let N_i be the number of homogeneous vessels in subfleet i. All N_i vessels fish for species j until switching time t_{ij}, $t_{ij} \leq T_j$. The number of vessels active in fishery j at time t, $N_t(t)$, is represented by the step function:

$$N_j(t) = \sum_i N_{ij}(t) \qquad \begin{array}{ll} N_{ij}(t) = N_i & t \leq t_{ij} \\ N_{ij}(t) = 0 & t > t_{ij} \end{array} \tag{6}$$

$N_{ij}(t)$ represents the number of vessels in subfleet i fishing for species j at time t. The stock level decreases by the total fleet catch each day:

$$\dot{x}_j(t) = -q_j N_j(t) x_j(t) \qquad x_j(0) = R_j \qquad 0 < t < T_j \tag{7}$$

Total fleet fishing effort for any species up to time t, $F_j(t)$, is the total number of vessel days fished to that point composed of those boats still fishing and the contribution of those that have stopped prior to time t.

$$F_j(t) = N_j(t)t + \sum_{\{k|t_{kj}<t\}} N_k t_{kj} \tag{8}$$

Solving Equation 6 for $x_j(t)$, the fish stock during the season and the escapement can be represented by:

$$x_j(t) = R_j e^{-q_j F_j(t)} \qquad 0 < t < T_j \tag{9a}$$

$$x_j(T_j) \overset{\Delta}{=} S_j \tag{9b}$$

This function is continuous, bounded, and differentiable at all but a finite number of points and therefore integrable on [0,T]. The exvessel price for each species, P_j, is assumed constant over the season. Each vessel from fleet i has annual fixed costs, I_i, and constant operating costs per day in fishery j, c_{ij}, which can include opportunity costs associated with alternative fisheries. Annual profit for a class i vessel is represented by:

$$\prod_i = \sum_j \left[\int_0^{t_{ij}} P_j q_j R_j e^{-q_j F_j(s)}\, ds - c_{ij} t_{ij} - I_j \right] \tag{10}$$

Under open access, each fisherman seeks to maximize profits by choosing effort levels in each fishery, t_{ij}, given seasonal constraints, T_j, and the number of vessels in each subfleet, N_i. As the second order conditions are guaranteed by the functional forms, the first order Kuhn-Tucker conditions (FOC) represent conditions for a maximum:

$$P_j q_j R_j e^{-q_j F_j(t_{ij})} - c_{ij} - \mu_{ij} \leq 0 \tag{11a}$$

$$(T_j - t_{ij}) \geq 0 \tag{11b}$$

$$(\partial L/\partial t_{ij})t_{ij} = (\partial L/\partial \mu_{ij})\mu_{ij} = 0 \tag{11c}$$

$$t_{ij} \geq 0,\ \mu_{ij} \geq 0 \tag{11d}$$

Assuming a vessel participates in a given fishery Equation 11a emphasizes that each vessel fishes until daily revenue is reduced to daily costs or the season ends. If the season ends first, μ_{ij} represents the profit rate at the end of the season for species j for a type i vessel, or equivalently, the amount a fisherman would pay to fish an additional day.

To this point, the number of vessel classes and species has not been specified and the FOC are applicable to any number of species and vessel types. Considering the diverse nature of the fleet active in fisheries such as the Dungeness crab, daily costs may be expected to vary substantially among participants. If daily costs include opportunity costs for both the vessel and the captain, the variation across the fleet increases. Considering the necessary conditions for profit maximization, the decrease in effort observed as the season progresses is seen as a reflection of rational decisions by participants to maximize profits. Vessels with high costs may fish for a given species for only a short time while those with low costs may continue to fish throughout the season.

The necessary conditions can also be used to show the relationships among daily cost, price, and escapement. Choose i to represent the vessel class with minimum daily costs in fishery j, say c'_{ij}. Solving the revenue for the last fishing day of a type i vessel on species j using Equations 9a, 9b and 11a and the complementary slackness conditions (11c), one gets:

$$S_j = \frac{c'_{ij} + \mu_{ij}}{P_j q_j} \geq \frac{c'_{ij}}{P_j q_j} \tag{12}$$

Escapement for any stock is then inversely related to price and fishing effectiveness (technological inputs) and directly related to daily variable costs of the most efficient vessel. If μ_{ij} is zero so the season constraint is not binding (the usual case for many open-access fisheries), equality holds in Equation 12 and escapement is determined by marginal profitability conditions. If the season constraint is binding, these conditions set a lower bound on escapement. If annual economic profits are zero for all vessels, the number in each subfleet is in equilibrium in the sense that there is no incentive for additional boats to enter or for any participant to either leave or invest in changing vessel characteristics.

Note that an equilibrium under open-access for a heterogeneous fleet implies an additional kind of inefficiency. Whereas loss of efficiency by a homogeneous fleet results from the operation of an excess number of vessels, an additional loss results from excess use of relatively inefficient vessels over at least a portion of the season. This can be easily seen by assuming that Equation 12 is an equality so that the most efficient vessel stops fishing before the season is finished. Less efficient vessels with higher variable costs would have quit earlier in the season, but would have still fished too long for social optimality. This follows because social costs could be reduced by restraining less efficient vessels so that the more efficient vessels could fish throughout the season. Consequently, costs could be reduced without a reduction in fleet size.

The Simulation Model

The simulation model reflects the dynamic behavior of the Dungeness crab fleet, combining insights gained from the theoretical model of intraseasonal behavior with the time series approach to modeling year-to-year relationships. The model simulates fleet capacity, costs, and revenues on a monthly basis for a specified number of years reflecting the dynamic evolution of the various measures both within a given season and from season to season.

The simulation model can be divided into five components: (1) an initialization sequence, (2) a Monte Carlo simulation driver and controller, (3) a model of interseasonal dynamics, (4) a model of intraseasonal behavior, and (5) a finalization sequence (Fig. 2). The initialization and finalization sequences provide the interface between the user and the computer model—parameters are set and results reported. The Monte Carlo simulation controller provides values for the stochastic variables needed by the inter- and intraseasonal components of the

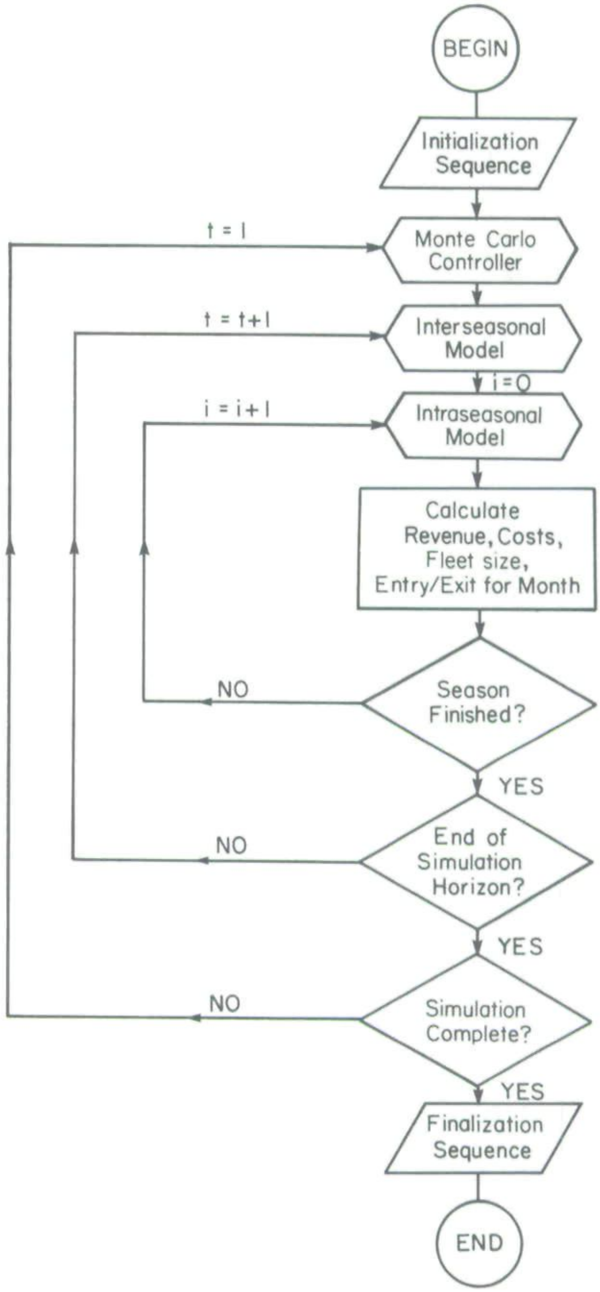

Figure 2. Overview of the Simulation Model Structure.

simulation model and provides for the transfer of variable values within the simulation framework. The controller can be considered a controlling loop for the simulations as indicated by the outer loop in Figure 2. While these components are important in the actual model workings, they are common to any such simulation program.[5] The remaining two components reflect the intertemporal and behavioral relationships discussed in previous sections and are considered in detail.

The interseasonal model (the middle loop in Fig. 2) is a direct implementation of the final form of the multiple time-series model reported as difference Equation 5 and provides the seasonal values for potential crab revenues, the capacity of the crab fleet at the beginning of each season, and the level of expected salmon revenues that reflect the opportunity cost of salmon fishing. Initial values are given by historical observations and the equations evaluated to give the forecasts (expected values) for each of the series. The outcomes are made stochastic by adding a random normal element to these expectations. The inverse of the transformations used in the development of the time-series model results in stochastic realizations for the revenue and capacity variables with appropriate units for use in simulations. As the model iterates over the planning horizon, the simulated realizations replace historical values in the estimation process.

The intraseasonal model is represented by the middle loop in Figure 2 and has as a basis the theoretical intraseasonal model developed above. The decisions of individual fishermen are assumed to be determined primarily by net revenues from fishing activities that depend on catch, price, and cost. The approach taken in the simulation development is to model revenue relationships directly rather than consider catch and price separately. While a more complete model of fishing activities could have directly captured some of the additional effects of price competition and, if available, direct biological relationships, the time-series approach indirectly incorporates all past effects reflected in the revenue streams in the estimates of potential revenues. Given the ability of the time-series approach to include all effects in past data in the development of future estimates, the reliance on revenue relationships seems adequate for exploring the possibilities of this approach in the analysis of fisheries management policies. This approach also reflects current knowledge of the forces important in the crab fishery.

The intraseasonal model concentrates on monthly values for the crab fleet capacity, the composition of the fleet in terms of large and small vessels, revenues from crab fishing activities, and costs (including the opportunity cost of potential salmon fishing, if applicable). In addition to the primary forces based on the theoretical model, adjustments are added to reflect characteristics peculiar to the Dungeness crab fishery and fleet, a "fine-tuning" process necessary to provide a model adequate for policy analysis. The individual details are discussed in the following outline of the primary factors.

The simulation during a given year begins with the initial fleet capacity, potential crab revenues for the season, and the level of opportunity costs of salmon fishing provided by the interseasonal model. The first consideration is the effective starting date of the fishing season to reflect the possibility of bargaining delays. To simulate the effects of such delays, the probability of delay specified for a particular run is compared to a draw from a uniform distribution. If a delay is indicated, the effective start of the season is put off, the potential season length is shortened, and the simulation begins at a later date. For the historical simulations, the probability of delay is given by the proportion of seasons when such delays occurred.

The proportion of the fleet made up of small and large vessels is also input. For the historical simulations, the actual compositions are used. For future scenarios, the usual procedure is to assume half of the capacity comes from small vessels. Given fleet capacity and potential seasonal revenues, realized crab revenues for the first month are calculated as the minimum of (i) the remaining revenues not yet captured, (ii) an upper bound that can be specified to reflect either vessel capacity or landing restrictions (a possibility added to include institutional barriers that have arisen due to excess capacity during the early part of the season), or, most commonly, (iii) an amount calculated using a logistic relationship (see Equation 8) plus a linear term that reflects the usual characteristics of the fishery.

After the first month, the evolution of the subfleets are considered separately but with total fleet revenues a function of total capacity. Each vessel considers costs,[6] remaining potential revenues, and an updated expectation of total fleet capacity during the next month in the decision to remain active in the crab fishery during the next month or exit. Subfleet capacity is assumed to change as a function of expected profit per vessel. Due to the inability of two vessel classes to reflect adequately the diverse nature of the fishing fleet, a partial adjustment process is used. If expected profits are sufficiently high, entry can be induced; if profits are sufficiently negative, exit can be quite rapid. Once the capacity for the next month is determined, realized revenues are calculated for the active fleet and the simulation continues. Since larger vessels generally have higher variable and opportunity costs, the proportion of small vessels in the fleet tends to increase as CPUE declines over the season.

After the salmon fishery becomes a viable alternative during the fifth month of the crab season, the model considers not only revenues and costs from crab fishing but the alternative profitability of fishing for salmon. If expected salmon profits are sufficiently high, some vessels switch from crab to salmon.

The iterative process of determining capacity, revenues, costs, and net revenues for individual vessels, subfleets, and the entire active fleet continues until the end of the crab season. To adequately include the effect of limited entry policies in years when the potential revenues exceed the capacity of the fleet to harvest the available catch, partial carry over is allowed for remaining revenues assuming a natural mortality of 50% between seasons.[7]

Given the relationships discussed, the model was calibrated and modified through several iterations until model performance was deemed satisfactory. The results and interpretations of various simulations are discussed in the remainder of the paper.

Simulation of the Eureka Crab Fishery Under Open Access

To assess simulation model performance, simulations were run assuming a constant institutional structure. A simulation was performed over the 1968–1977 period using historical annual values for crab revenues, salmon revenues, and crab fleet capacity for the interseasonal model estimates, and historical relative efficiency and fleet composition measures for each year. A random simulation was also performed for the future period, 1982–1991 assuming a relative efficiency of large to small boats to be 1.25 (the historical average), and an opening season fleet equally divided into small and large vessels. The period 1968–1977 coincides with the primary data base period and allows for simulation of a complete cycle

Table 1
Composite Economic Summaries of the Simulation Results 1968–1977 and 1982–1991

Description of the Statistics (all economic values are in real 1980 dollars)	Simulation Results for the Historical Period 1968–1977*	Simulation Results for the Future Period 1982–1991*
Annual fixed costs for all small boats (00,000)	4.05 (.44)	4.97 (3.6)
Annual fixed costs for all large boats (00,000)	6.57 (.46)	7.18 (.36)
Months fishing by all small boats per season (00)	1.73 (.61)	1.77 (.26)
Months fishing by all large boats per season (00)	1.78 (.71)	1.75 (.26)
Seasonal variable costs for all small boats (00,000)	4.32 (.61)	4.41 (.26)
Seasonal variable costs for all large boats (00,000)	6.22 (.71)	6.12 (.26)
Seasonal crab revenues for all small boats (000,000)	1.14 (.87)	1.11 (.39)
Seasonal crab revenues for all large boats (000,000)	1.75 (.96)	1.67 (.39)
Seasonal crab revenues for the crab fleet (000,000)	2.89 (.92)	2.78 (.39)
Revenue per small boat per month less variable costs (000)	2.80 (.53)	2.52 (.30)
Revenue per large boat per month less variable costs (000)	3.40 (.76)	3.18 (.31)
Seasonal revenue for the fleet less variable costs (000,000)	1.09 (1.16)	1.00 (.54)
Revenue per small boat per month less variable and fixed costs (000)	.45 (5.04)	−.29 (5.92)
Revenue per large boat per month less variable and fixed costs	−.30 (16.1)	−.93 (2.65)
Seasonal fleet revenue less variable and fixed costs (000,000)	.02 (40.7)	−.21 (2.97)

* Mean results reported, coefficient of variation in parentheses.

under the same institutional structure. The composite results can be interpreted as averages over the cycle. Each pass through the middle loop of the model corresponds to a single realization of a stochastic process for a specified period. The future simulation results reported are the average of 100 iterations over a ten-year period and approximate the mean of the process. Given that the stochastic process is stable, the averages obtained from the future simulations are likely to possess less variability than the actual realization from the past cycle.

Consider the average expectations and realizations of the Eureka crab revenue and Eureka crab fleet capacity for each simulation run. For the historical run 1968–1977, the expectations are the average of the one-step-ahead forecasts ($2.88 million and 108 vessels) for the ten years from the difference equations, while the realizations are the average historical values ($2.98 million and 109 vessels). For the future period (1982–1991), the realizations ($2.74 million and 136 vessels) are calculated by adding a random draw from a normal distribution determined by the mean and variance of the calculated forecast errors. Future expectations ($.82 million and 138 vessels) are updated based on past realizations.

The average initial expectations for annual crab revenue are similar for both periods, but the expectation of fleet capacity for the future period is much higher. This reflects the substantial entry into the Eureka crab fleet during the 1977–1981 period. The close agreement between the seasonal crab revenue series for the two periods indicates that the average over the cycle is relatively stable. The coefficient of variation for the crab revenue realizations is higher for the historical period (.89) than for the simulated period (.39). This indicates that the data for the 1968–1977 period are unusually noisy (a fact well known by fishermen). The variability in the simulation results are reasonable, at least from a historical perspective.

The economic summaries reported in Table 1 reflect the change in the fleet capacity. Since revenues are similar and costs constant, the total number of boat-months fishing is also similar for both periods. The average revenues net of variable costs for the fleet are also close, decreasing from $1.09 million for the past period to $1.00 million for the future. The decrease in the associated coefficient of variation follows from the decrease in the variability of the crab revenue series. The difference in fleet capacity is reflected in the increased fixed costs for the future period and a corresponding decline in net revenues. Revenue adjusted for fixed costs as well as variable costs fell from an average of $25,000 for 1968–1977 to an average of −$214,00 for the future period reflecting additional entry in the late 1970s that pushed fleet capacity above the open-access equilibrium.

Analysis of Fishery Management Policies

The simulation model is used to assess the effects of landing restrictions and potential management policies on the fleet and the social benefits attributed to the Eureka crab fishery. Random simulations over the 1982–1991 cycle of the fishery are computed assuming alternative policy scenarios and compared to those of a run made under the current institutional structure. The implications are discussed for the alternative scenarios considered: (1) the effects of uniform landing quotas for all vessels, (2) limited entry programs for the Eureka crab fishery, (3) a uniform, coast-wide, January first season opening, and (4) the effects of single species management policies on a multipurpose fleet.

The criteria used in evaluating the various options discussed in this paper as well as some of the critical assumptions embedded in the analysis deserve consideration. It is assumed that the management schemes can be implemented with similar transactions costs. The simulation model incorporates the number of boats as a measure of capital investment in the fishery. This assumes that technology is invariant for all levels of capitalization and does not adjust to changes in profitability. Capital investment within the scope of the model is, therefore, easily controlled by placing a limit on fleet capacity. Although this is referred to as a license limitation policy, the effect on the capital stock is equivalent to much stronger action.

Maximum dynamic economic yield is the assumed goal of economically rational fishery management, but present understanding of the bioeconomic relationships in the Eureka crab fishery is not sufficient for the development of complete biological control policies. Two alternative criteria used to measure the resource value are average annual exvessel value of the catch (fleet revenues) and average fleet quasi-rents. While revenues do not correspond directly to an explicit management objective from the fleet perspective, the measure is of importance to policymakers interested in the implications of management for all aspects of the fishing sector including processing, employment, and other related activities. Since this study does not consider these related issues, any change in fleet revenues serves to reflect some effects of management on the sector.

The values reported are simple averages; future periods are not discounted. The results thus represent the average yearly effects of imposing management. The value of a specific management plan at any given time would be the present value of the stream of benefits to be gained. Such a calculation would depend not only on the discount rate, but the point in the cycle where the plan is implemented.

Crew share (hired labor costs) and the cost of variable inputs are known. However, the allocation of fixed costs to a single production process in a multiple output framework is arbitrary. One-half of the annual fixed costs per vessel is allocated to the crab fishing activity, reflecting the average proportion of total fishing time spent fishing for crab. While fixed costs directly affect the level of rents calculated, the qualitative difference in policy alternatives are robust to changes in the proportion of fixed costs allocated to the crab fishing activity.

Returns to capital and to the entrepreneur are included in the quasi-rents. The opportunity value of an entrepreneur's time must be individually valued. The opportunity value of *in situ* capital in fishing vessels is also difficult to estimate. However, since the qualitative properties of the model are robust to the assignment of fixed costs, any inaccuracy does not have a significant impact on policy implications.

Impacts of Marketing Restrictions

By the 1970s, increased effort on the Eureka crab stock resulted in large landings during the first few weeks of most seasons. Consequently, the harvest capacity of the fleet surpassed the capacity of buyers to process and market the catch. Also, the fishermen had organized an effective bargaining unit, the Humbolt Fisherman's Marketing Association, to negotiate crab and salmon prices with local processors. Agreements on crab price included a provision that processors buy from all members of the Association, which was open to all who wished to join.

Such an agreement tended to exacerbate the problem of redundant capital by providing a ready market for all new entrants.

As fleet capacity increased, so did total landings during the first part of the season. Processors reacted by limiting the amount of crab they would buy from each fisherman each day. The limits were primarily implemented as daily quotas per boat and were independent of boat capacity. The effects of such restrictions can be considered by comparing simulation results under alternative relative efficiency assumptions of large vessels. The average efficiency ratio over the historical period was estimated to be 1.25, but observations on years of average landings when fewer restrictions were imposed indicated a value of 1.5.

Simulations based on the continuation of the historical, open-access fleet behavior were performed assuming a relative efficiency of 1.25 and 1.5. The results of these simulations are presented in Table 2. Results are included for the 1982 season as well as the average over the ten-year cycle to highlight the effects of the cycle on the variability in the results. The means are reported and the sample standard deviations included in parentheses. Effects of changing the assumed relative efficiency from 1.25 to 1.50 are significant. Net revenue per large boat per month increases by more than $1,200 per month over the ten-year cycle and provides an estimate of the costs of restricting the productivity of large vessels. Note that the 1982 results reflect the over capacity in the fishery following excess entry in the late 1970s in response to abnormally high revenues. Although these figures are lower for the average over the ten-year period reflecting some exit, the negative values still indicate average over capitalization.

The simulation results imply that uniform landing restrictions on all vessels

Table 2

Summary of Simulation Results Under Alternative Efficiency and Limit Assumptions (Open-Access Scenario 1982–1991)

Relative Efficiency (RE) (Large to Small Boats)	Total Fleet Revenue* (000)	Net Revenue* per Month per Small Boat	Net Revenue* per Month per Large Boat	Total Net Revenue* Fleet (000)
Average Simulation Results for the Crab Season 1982 Only** Average Fleet Capacity in Small-Boat Units = 161 (36)				
1.25	$2510	$−1190	$−2533	$−808
	(549)	(1097)	(1658)	(434)
1.50	2521	−1269	−2349	−563
	(553)	(1133)	(1655)	(411)
Average Simulation Results Over the Crab Cycle—1982–1991** Average Fleet Capacity in Small-Boat Units = 138 (50)				
1.25	$2745	$−248	$−2134	$−434
	(1082)	(1697)	(2436)	(657)
1.50	2776	−291	−929	−214
	(1089)	(1723)	(2459)	(636)

* All revenue values are in 1980 dollars.

** The mean results are reported with sample standard deviations in parentheses.

as imposed by processors in the past have a disproportionate effect on larger vessels with higher costs and larger capacities. The varying effects on vessel types of the quotas used by processors to limit production causes distortions in the production patterns of heterogeneous fleets. A government imposed policy of this type would have substantial equity problems among participants. Any management plan should recognize possible asymmetric effects of policies among participants in a heterogeneous fleet.

During the past few years, some of the boats have been able to establish new markets and can now fish without landing restrictions. The effects of landing limits have thus been reduced during the 1980s as effective processing capacity increased. To reflect the ability of larger boats to now fish more productively, the relative efficiency value of 1.5 is used for the remainder of the policy simulations.

Capital Limiting Policies

To approximate the effects of a capital limiting program, the simulation was repeated under various levels of maximum fleet capacity. The results of the simulations are reported in Table 3. The management-imposed limit on fleet capacity is in the first column. The second column contains the average effective fleet capacity. Column three is an average of the season lengths for the small and large subfleets and is indicative of the level of capital utilization in the crab fishery.

Note that under the fixed-cost allocation assumption, net revenues for both boat classes are negative indicating entry in excess of the open-access equilibrium. Fishermen may not experience negative cash flows, but revenues do not appear to be sufficient to cover all of the long-run costs.

The effect of lowering the capacity constraint is not large until the level of 100 units of capacity is reached. As the capital constraint is tightened further, the average fleet capacity over the cycle quickly approaches the upper limit. As the capacity constraint is lowered, the remaining vessels fish longer. The average season length approaches the legal limit of eight months, showing greater capital utilization. For limits of 60 units or less, the average fleet size is the same as the limit, indicating the constraint is binding throughout the crab cycle.

As the fleet size is reduced the average total fleet revenue also decreases since fewer boats cannot catch all crab in exceptionally good years and thus, on average, catch slightly fewer crab. Net revenues for the fleet increase until the capacity reduction effect exceeds the cost savings. At first, the loss in revenues to the sector is smaller than the gain in net revenue. The decrease in revenues is more than offset by the cost savings, so the increase in producers' surplus must exceed any loss to the sector as a whole indicating an increase in social welfare from management. The gain exceeds the loss until the fleet size is reduced to 50 units. The model indicates a gain in net revenue of over $850,000 per year from a policy limiting capital to 50 units compared to the open-access fishery. Since total revenues decrease by only $187,000, the fleet size of 50 units must be socially preferred to less restrictive alternatives. While additional limitations would increase net revenue and thus producers' surplus, the gains would be exceeded by the loss in total value of the catch. While the results indicate that the quasi-rents increase until the fleet is reduced to about 30 units, the approach used does not provide a method of directly comparing gains to the fleet with decreases in sector size.

Table 3
Effects of Alternative Levels of Capital Restrictions Average Simulation Model Results, 1982–1991*

Upper Bound on Fleet Capacity (Small-Boat Units)	Effective Average Fleet Capacity** (Small-Boat Units)	Average Season Length** (Months)	Average Total Fleet Revenue**	Restriction Effects on Change in Total Fleet Revenue	Total Net Fleet Revenue**	Restriction Effects on Change in Total Net Fleet Revenue
None	138	3.2	$2776		$ −214	
				$4		$397
100	95	4.6	2780		183	
				−61		256
70	69	5.8	2719		439	
				−47		100
60	60	6.4	2672		539	
				−83		99
50	50	7.0	2589		638	
				−154		89
40	40	7.5	2435		727	
				−280		37
30	30	7.9	2155		764	
				−480		−83
20	20	8.0	1675		681	

* All values are in thousands of 1980 dollars.
** Means of the simulation results reported.

This analysis of the historical profit structure of the Eureka crab fleet indicates that entry in the Eureka crab fishery has been in excess of the open-access equilibrium. Assuming the open-access framework continues, the simulation results for the next ten years indicate the problem of excess capacity will remain but that total fleet capacity will decrease moderately from current levels. Substantial benefits can be obtained by limiting (and reversing) capital investment in the fishery. The results indicate a fleet reduction to 25% of peak historical capacity is warranted and even further reductions may be desirable.

Uniform Coastwide Crab Season Opening

The possibility of changing the opening date of the crab season to provide a uniform coastwide opening date is discussed and the consequences analyzed in the 1978 report of the Pacific Marine Fisheries Commissions. The conclusion reached is that the net benefit to California from implementing such a policy would be a loss of $38,500.

The effects of changing the opening date can be simulated within the model by assigning a probability of one for a January 1 season opening. This policy is considered for the traditional open-access fishery and in conjunction with the policy of constraining the fleet to 50 units. In both cases, the reduction in total revenue exceeds the increase in net revenues. The increase in net revenue is approximately $4,000 under open-access and $7,000 with a capital limiting policy. This implies that the fishermen are not adversely affected by such a change. The decrease in total revenue is far larger when capital is limited ($81,000 vs $14,000). As the season length is shortened, there is a trade-off between sector revenue and producers' welfare. To maintain the same annual landings for a shorter season, a larger fleet is required, and net revenues must correspondingly decline. A coastwide January 1 uniform season opening for the Dungeness crab fishery would have little impact under open-access. Under restricted entry, a shorter season would require a larger fleet to maintain the same harvest levels. When capacity is limited, an additional cost must be added to the impact of changing season lengths in the analysis. Interactive effects of the two policies cannot be ignored. There are real costs to changing the starting time of the season given that fleet capacity is approximately optimal.

Cross Effects of Salmon Management on the Crab Fishery

It is hypothesized that economically important interaction effects occur when simultaneously available species are harvested by a multipurpose fishing fleet. For the Eureka Dungeness crab fleet, the most common alternative species harvested is salmon. Some of the possible cross effects of implementing single species management policies on complementary fisheries harvested by a multipurpose fleet are considered in the salmon-crab examples. The legal seasons for crab and salmon have historically overlapped from the April 15 start of the salmon season until the end of the crab season. However, few of the crab vessels were normally active in the salmon fishery prior to May 1, the date used in the simulations as the effective start of the salmon season.

The initial hypothesis that interactions are important is not substantiated by the simulation results, but this is not surprising given the lack of substantial simultaneous fishing for crab and salmon. Under open-access, the crab season is over before the salmon season begins. When a capital limiting policy is imposed on the crab fishery but the salmon fishery remains open-access, crab are so profitable that the salmon are ignored.

Since the opening of the salmon season was often delayed by fishery managers over the past few years, an obvious test is to consider the impact of such closures on the Eureka crab fleet. To find the greatest impact of changing the salmon season, the traditional salmon season represented within the model as a May 1 opening is compared with the alternative of not allowing the crab and salmon fisheries to overlap. In this case, the results for the limited entry scenario are identical.

Summary of Policy Analysis

The analysis of the effects of landings restrictions imposed by processors on the Eureka crab fleet indicates that the productivity of larger vessels are affected substantially more than that of smaller vessels. Correspondingly, the costs of efficiency declines due to the restrictions were much higher for larger vessels. The implications apply to fisheries management policies generally. Naive policies that place uniform restrictions on all participants in a heterogeneous fleet can impose costs that vary substantially between different subsets of the fleet. An analysis of proposed policies should consider possible asymmetric effects on vessel net income.

Under the open-access assumption, economic analysis shows that excess capital investment occurs in the production capacity for natural resources. The possibly surprising result of this study is the magnitude of the over-capitalization phenomenon in the Eureka crab fleet. Simulation results indicate that a reduction to no more than 25% of peak capacity is desired. But, since the analysis does not allow for technical change under restricted entry, the 25% figure may be overly conservative (i.e., the true optimal capacity may be lower.)

The simulation results indicate that unless fleet capacity were restricted substantially, a change in the opening of the crab season would have little effect on the net revenue obtained by the crab fleet. There are other factors which may be affected by changes in the season opening date, however, and the results should be interpreted cautiously.

The final point deals with the economic interaction of the crab and salmon fisheries due to the multipurpose nature of the fleet. An initial hypothesis was that such interactions would be significant, but the analysis does not indicate significant interactions. There are three possible explanations for the results obtained. There may be no significant interactions, the simulations performed may not have tested the interactions adequately or since the simulation model was calibrated primarily over data for the 1968–1977 period prior to the imposition of management policies, more current data may lead to different conclusions.

Conclusions

The model of fleet dynamics developed for this study was based on the fishermen's expectations using the "economically rational" approach to expectations formulation. Assuming that the information available to fishermen is reflected in a relatively small number of variables, multiple time-series techniques can model expectations efficiently. Further research into the way fishermen form expectations may provide a better understanding of fleet behavior. If the information set that fishermen use in forming their expectations can be more closely identified, predictions of future behavior can be more precisely estimated.

The economic interactions between species was not found to be significant in this study, but the results cannot be generalized. Policies that entail uniform restrictions on all vessels in a heterogeneous fleet can have significant equity effects. Thus, economic analyses of various fisheries management policies that ignore the multipurpose and heterogeneous aspects of many commercial fleets may be misspecified.

Given recent legislation, fisheries management will intensify. For many such fisheries, biological models of the population dynamics of sufficient precision are not yet available to provide the basis for a bioeconomic model of the fishery. In such cases, statistical time-series techniques provide statistically reliable information which can be used for short to medium range planning decisions. The multiple time-series approach can be considered the "positive economic" analog to the usual bioeconomic approach.

The time-series estimates can be replaced by estimates from traditional bioeconomic models if and when such models become available. Until then, all available information should be made available to fishery managers to provide the basis for economically sound fisheries policy. Future research in the analysis of fisheries management policies should, when appropriate, incorporate time-series techniques.

The simulation approach can combine knowledge of intraseasonal fleet behavior with estimates of interseasonal dynamics and use all available information to analyze alternative policies. Given the paucity of data available to fishery managers, techniques that use available information efficiently and completely are essential.

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Notes

1. See Browning (1974) for a detailed description of the Dungeness crab and other North Pacific fisheries.
2. The Eureka crab fleet each year was defined to include only vessels landing at least 1,000 pounds of crab at the Eureka ports over the season. The lengths of individual vessels were obtained from license records maintained by the California Department of Fish and Game, Long Beach.
3. A one-tailed test of equal average efficiencies was rejected at the 1% level. A regression of the natural log of the relative efficiency measure against time indicated no bias in technical efficiency gains.
4. Crab revenues increased from a historically low value of $.77 million in 1975 to a record high $7.93 million for the 1976 season. This increase can be traced to two distinct causes, one biological and the other economic. The surge in the quantity of crab landed was due to an abnormally large 1972 year class that reached commercial harvest size for

the 1976 season (Ron Warner, CDFG, Eureka, personal communication). In addition, the preseason price was set relatively high reflecting the expectations of the industry. The marketing association was able to maintain the high price with processes for a significant portion of the season before the market forced drastic price reductions.

5. A detailed description of all components of the simulation model including the source code listing is included in Fletcher (1982).
6. See Fletcher and Johnston (1984) for an analysis of costs of crab fishing.
7. There is little scientific basis for exact mortality estimates. Rather, the 50% figure represents an informal consensus of a reasonable rate indicated by biologists and management specialists familiar with the crab fishery.

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