AN APPLICATION OF YIELD MODELS TO A CALIFORNIA OCEAN SHRIMP POPULATION

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ABSTRACT

Two types of yield models were utilized to analyze fishery data from California’s northernmost bed of ocean shrimp, *Pandalus jordani*. The Schaefer form of stock production model was applied to catch and effort data for the years 1954 through 1969. Age-structured catch data for 1955 through 1968 were analyzed by the Murphy method to obtain mortality rates and biomass estimates. Catchability coefficients and a growth curve were also estimated. Attempts to fit spawner-recruit models to estimates obtained from the age-structured catch data were inconclusive; so, age specific mortality and growth estimates were only used to fit a yield-per-recruit model.

After comparing the results from the two models, the Schaefer model was deemed most suitable for managing this fishery. The model estimated the maximum sustainable yield at 2.46 million pounds. A strategy for managing the fishery under a quota system was proposed.

The fishery for ocean shrimp, *Pandalus jordani*, in California has a unique importance despite the fact that it does not rank high among the State’s fisheries in terms of pounds landed or value of the landings. This unique importance exists since the fishery developed after discovery of the shrimp beds by the California Department of Fish and Game’s exploratory fishing and because it has been under continuous quota control by the California Fish and Game Commission since the fishery’s inception in 1952 (Dahlstrom 1961, 1970). It is also the only California commercial fishery whose catch is fully regulated under a quota system.

This paper is limited to a discussion of the population and fishery which range along the coast from the mouth of the Mad River in California to the Rogue River in Oregon. This fishery consists primarily of regulated California vessels, but there is a small Oregon fleet not covered by California’s regulations while fishing north of the California border. Three smaller populations which occur farther south in California are not considered here.

Initially, quotas were set arbitrarily at one-fourth the estimated biomass on the bed. Biomass was originally estimated from an examination of commercial catch data and later from research vessel cruise data. In later years, quota recommendations were at least partially directed toward allowing what was deemed an appropriate spawning stock to remain at the end of the season. Spawning stock values were based on estimated preseason year class abundance and estimated survival over the fishing season.

Estimating procedures which assume commercial or research fishing gear catches all shrimp in the water column above the swept path must inherently be negatively biased since escape ment over, around, and through the gear occurs. The methods just discussed are of this type. A more complete account of the basis for quota recommendations prior to 1969 is found in Dahlstrom (1961, 1970), Dahlstrom and Gotshall (1969), and Gotshall (in press).

Over the history of this fishery substantial amounts of data have been collected. Of relevance to this paper are catch and effort data, estimated age and sex composition of landings,
and research vessel biomass estimates for 1965 through 1968. These data were used in applying a stock production model and a dynamic pool model. The general characteristics of these two models were discussed by Schaefer and Beverton (1963) under the designations of "Schaefer Approach" and "Beverton-Holt Approach," respectively.

**STOCK PRODUCTION MODEL**

From an operational viewpoint stock production models possess the advantage of requiring only catch and effort data, which are usually available at relatively little expense, for their fitting. Another desirable characteristic is the inclusion of density dependent effects, even though they are treated grossly and population response to density is assumed to be instantaneous. Pella and Tomlinson (1969) discuss the assumptions implicit in the model. The most notable fisheries application of this type model was to yellowfin tuna of the eastern Pacific by Schaefer (1954, 1957), who developed a method for fitting the model to a population in a non-equilibrium state.

Pella (1967) examined a number of methods for estimating parameters of the Schaefer model and concluded that a surface searching technique for minimizing the summed, squared deviations between observed catches and catches predicted by an integrated form of the Schaefer model was generally most satisfactory.

Pella and Tomlinson (1969) generalized the Schaefer model to allow asymmetry in the integrated form and gave the population growth rate as

\[
\frac{dP(t)}{dt} = HP^m(t) - KP(t) - qf(t)P(t), \quad (1)
\]

where \( H, K, m, \) and \( q \) are constants. \( P(t) \) represents the population size at time \( t \), \( f(t) \) is the fishing intensity at \( t \), \( q \) is the catchability coefficient, and \( m \) determines the amount of asymmetry in the equilibrium yield curve. In the Schaefer model, \( m = 2 \) and the equilibrium curve is a parabola. The integral of (1) from time 0 to \( t \) with \( f \) constant is

\[
P(t) = \left[ \frac{H}{K+qf} - \left( \frac{H}{K+qf} - P(0)^{1-m} \right) \times e^{-(K+qf)(1-m)t} \right]^{1/(1-m)}, \quad (2)
\]

and Pella and Tomlinson (1969) used a numerical approximation of

\[
C(t) = \int_0^t qf(t)P(t)\,dt \quad (3)
\]

for computer calculation of expected catch over the interval. Pella (1967) gives the integrated form of (3) for the Schaefer model.

A computer program, GENPROD, (Pella and Tomlinson, 1969) for fitting the generalized model to catch and effort data uses the criterion of least squares between observed and predicted catches. Fox (1971) discusses least squares for estimating parameters in (2) and suggests alternatives which may be preferable to that used by GENPROD.

**CATCH AND EFFORT DATA**

Catch and effort data have been collected since the beginning of the fishery in 1952, but data from the first 2 years of the fishery are not used in this study because there was little effort and low catch-per-effort values indicated that fishermen had not fully acquired the skills needed for successfully catching shrimp. California landings were obtained from market receipts, and effort by California vessels was obtained from compulsory logbooks carried by all California trawlers. Oregon landings and effort were supplied by the Oregon Fish Commission (Jack Robinson, Oregon Fish Commission, personal communication).

California vessels were restricted to use of beam trawls until otter trawls became legal in 1963. Oregon vessels have used otter trawls since their entry into the fishery in 1960. A correction factor was used to convert California beam trawl effort to otter trawl effort for 1954 to 1962.

Fishing power of beam trawls relative to otter trawls was estimated from 40 pairs of catch-per-hour statistics. These paired statistics consisted of the average weekly catch-per-hour for
each gear within a 10-fm depth interval bounded by a 10-min by 10-min block area. The data were collected during 1960 through 1962 when Oregon vessels were using otter trawls and California vessels were still restricted to beam trawls. California Department of Fish and Game trawler logbooks and information supplied by the Oregon Fish Commission were the sources of the records (Tom Jow, California Department of Fish and Game, personal communication).

With otter trawl taken as the standard gear, the relative log fishing power of beam trawls was computed by Robson's (1966) method except the two gear types were used in a manner analogous to his treatment of individual vessels. If the logarithm of catch-per-hour is normally distributed and the other assumptions of Robson's model hold, then his method produces $B_i$, an unbiased estimate of relative log fishing power, $\beta_i$ for the $i$th gear. However, $\exp(B_i)$ is a biased estimate of $\exp(\beta_i)$. An unbiased estimator for $\exp(\beta_i)$ is given by Laurent (1963) as

$$
\exp(\beta_i) = \left[ \exp(B_i) \right] \left[ 1 + \sum_{j=1}^{\infty} \frac{(-1)^j}{j! 2^j} \right] \left[ \frac{(n-k-1)^j}{(n-k-1)(n-k+1) \ldots (n-k+2j-3)} \right],
$$

where $v(B_i)$ is an unbiased estimate of the variance of $B_i$ with $n-k-1$ degrees of freedom. Robson's method provides $v(B_i)$ and our computer program for calculating fishing power carries the series expansion in (4) to 15 terms. This computer program is described by Berude and Abramson (1972) and a FORTRAN listing is contained in Abramson (1971).

The estimated fishing power of beam trawls relative to otter trawls in the shrimp fishery was 0.71; all beam trawl effort used in this study was adjusted by that factor.

**Fitting the Production Model**

Usable catch and effort data covered a period of 16 years, each divided into open and closed seasons. Each season was treated as a separate interval in the fitting procedure and thus population estimates were obtained at 32 points in time. Table 1 shows catch, adjusted effort, and time for the series of seasons used to fit the generalized production model.

When initially fitting GENPROD to the data the parameters representing optimum effort ($F_{opt}$), catchability coefficient ($q$), maximum catch-per-effort ($U_{max}$), and the ratio of initial population to maximum population ($r$) were unrestricted. Pella and Tomlinson (1969) give these parameters as transformations of those in (2). The equation was fitted with the parameter $m$ taking values from 1.4 to 2.6 by increments of 0.2. Results showed that number or distribution of data points was not sufficient to determine the value of $m$ with any degree of precision and that very small population estimates accompanied by excessively large $q$ values were being obtained.

The first problem was handled by setting $m = 2$, since the symmetric or Schaefer model seemed best in face of the uncertainty. The catchability coefficient was fixed at a value which minimized the sum of the squared deviations between GENPROD's estimates of $P(t)$ and research vessel cruise estimates of population biomass at seven time points when both were available. The research vessel biomass estimates were obtained from surveys conducted in the spring and fall of 1965, 1966, and 1967 and the fall of 1968 (Gotshall, in press). Gotshall's catch in weight per standard haul was expanded on an areal basis to provide estimates for the entire survey area; as mentioned previously, these are negatively biased. Based on this procedure, $q = 8.5 \times 10^{-5}$ was the best value. The final fit of the Schaefer model was made with GENPROD's computing parameters $KK$ and $N$ set equal to 5 and 10, respectively. $KK$ is related to the fineness of the surface searching procedure, and $N$ involves the accuracy of the numerical integration used to estimate expected catch. These computing parameters are explained fully in Pella and Tomlinson (1969).

GENPROD estimated a maximum equilibrium catch ($C_{max}$) of 2.46 million pounds, an effort level required to obtain this catch under equilibrium conditions ($F_{opt}$) of 6,049 otter trawl
TABLE 1.—Estimates of Schaefer model parameters, observed catch and effort, predicted population size and catch, population and catch in millions of pounds, effort in thousands of hours.

<table>
<thead>
<tr>
<th>Time interval</th>
<th>Begin</th>
<th>End</th>
<th>Population size</th>
<th>Applied effort</th>
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<td></td>
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<td></td>
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<td></td>
<td></td>
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Parameter estimates

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<td>$P_{\text{opt}}$</td>
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<td>$U_{\text{opt}}$</td>
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<tr>
<td>$K$</td>
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hours, and an optimum population size ($P_{\text{opt}}$) of 4.79 million pounds. Other parameter estimates, as defined by Pella and Tomlinson, and the complete output from the program are shown in Table 1.

Figure 1 shows both the expected catch as predicted by the model and the observed catch plotted against time. The fit appears to be generally quite good, although it has worsened during the most recent 5 years. The statistic $R$, derived by Pella and Tomlinson to measure the improvement in estimating catch from this model rather than from the mean catch, was 0.91. However, a somewhat spurious $R$ is obtained when intervals with no catch are included in the data. This occurs because the model always predicts a zero catch from zero effort and the arithmetic mean cannot make such a prediction. Recalculating $R$ from only periods when effort was applied yielded 0.75.

Figure 2 shows the fitted line ($m = 2$) for catch per unit effort versus effort in the equilibrium state and the observed catches per hour by year. However, the population should not
have been in equilibrium during the period studied since the level of effort fluctuated from year to year.

The actual catch exceeded the estimated maximum equilibrium yield (2.46 million pounds) during the period 1954 through 1969 only three times (Table 1): 1962, 1968, and 1969. Effort has always been substantially below the estimated level which would produce the maximum sustainable yield. A literal interpretation of these results would indicate the population has been underexploited until recently.

It is a problem in actual management situations to deduce how well a model such as this represents a population. In years when the observed catch-per-unit effort deviates substantially from the corresponding expected value, it cannot be determined whether deviations are due to an actual departure from the expected population size or due to a temporary change in the catchability. In the management strategy which we will discuss later, we are assuming the population size is being predicted correctly by the model and we are essentially ignoring deviations between the observed and expected catch insofar as they may represent actual population deviations.

**Dynamic Pool Model**

Catch data by age categories, both in weight and numbers, were utilized to estimate mortality, growth, and recruitment parameters necessary in a dynamic pool model.

**Age-Structured Catch Data**

Catches from the population were landed at Eureka and Crescent City, Calif., and Brookings, Oreg. Landings data were obtained mainly from the Pacific Marine Fisheries Commission Data Series (1965-1969). Catches south of the California-Oregon border were recorded in that publication in tables for PMFC Area 96, but those from north of the border were included in, but did not comprise all of, the catch reported from PMFC Area 88. Catches within PMFC Area 88 south of the Rogue River were obtained from the Oregon Fish Commission (Jack Robinson, Oregon Fish Commission, personal communication). Catches made in the more recent years were obtained from the California Department of Fish and Game Shellfish Program (Daniel Gotshall and Walter Dahlstrom, California
Department of Fish and Game, personal communication). Virtually all catches were made during single day trips.

Landings were stratified into port-months, with Eureka-Crescent City as "California" and Brookings as "Oregon." Relative age frequency and weight at age were determined from samples of most port-month catches. Values used for California strata not sampled were either the average of preceding and following strata or the nearest sampled strata of the same season. The Oregon Fish Commission provided values for all Oregon strata.

Several methods of drawing samples from within strata were used by California. For all but very recent years, the methods were equivalent to assuming a simple random sample of shrimp from within strata. These sampled shrimp were aged by carapace length measurements, and the fraction falling into a specific age group determined its relative frequency. In recent years a simple random sample of boatloads was assumed drawn, and the length composition of a subsample from each boatload was weighted by the estimated number of shrimp in the load. Estimates by strata, done separately for Oregon and California, were combined to obtain the values in Table 2.

The average weight at age was determined by two methods: (1) the aged shrimp were placed into length frequency groups, a length-weight key was used to convert length to weight, and average weight for each age group was calculated; (2) the aged shrimp were weighed and an average weight computed directly for each age group. The study of aged catch data was performed for the 1955 through 1968 seasons. All aged shrimp fell into age groups 0, I, II, or III, but the 0 group was rare and omitted from the study.

Catch by age category for 2,598 million shrimp (22.88 million pounds) harvested during 1955 through 1968 are listed by month in Table 2. During the first 7 of these years, the fishery was active during 39 months and captured an estimated 954 million shrimp, excluding age 0, yielding a monthly average of 24.5 million. These shrimp weighed about 8.25 million pounds, averaging 212,000 lb. per month of fishing and 0.0086 lb. per shrimp. The fishery was active during 46 months of the second 7 years and caught an estimated 1,644 million shrimp, excluding age 0, for a monthly average of 35.7 million. These weighed about 14.63 million pounds, averaging 318,000 lb. per month and 0.0089 lb. per shrimp. The relative frequencies in numbers during the first 7 years were: 0.559 for age I, 0.422 for age II, and 0.019 for age III. During the second 7 years the frequencies were 0.495 for age I, 0.463 for age II, and 0.042 for age III. The reliability of the age frequency values is uncertain due to the aging method.

**GROWTH CURVE**

A growth in weight curve was obtained empirically by plotting average weights of shrimp by month and age for all seasons 1955 through 1968 (Tables 2 and 3, Figure 3). Dahlstrom (1970) and Gotshall (California Department of
<table>
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<tr>
<th>Season</th>
<th>Month</th>
<th>Age group</th>
<th>Relative frequency</th>
<th>Average weight (lb.)</th>
<th>C.P.E. numbers</th>
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<td></td>
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<td></td>
<td></td>
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<th>Average weight (lb.)</th>
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FISHERY BULLETIN: VOL. 70, NO. 3
Table 2.—Continued.

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<th>Numbers</th>
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<td>0.0175</td>
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</table>

Annual average count per pound for ages I, II, and III combined varied from 94 in 1961 to 142 in 1965 (Figure 4). Monthly values varied from 76 to 155 with an average for all years of 114.

Table 3.—Average weight in pounds by age. From aged catch landed in northern California and southern Oregon, 1955-1968.

<table>
<thead>
<tr>
<th>Month</th>
<th>Age I</th>
<th>Age II</th>
<th>Age III</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>0.0038</td>
<td>0.0092</td>
<td>0.0146</td>
</tr>
<tr>
<td>April</td>
<td>0.0043</td>
<td>0.0098</td>
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</tr>
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<td>May</td>
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<td>June</td>
<td>0.0055</td>
<td>0.0110</td>
<td>0.0164</td>
</tr>
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<td>July</td>
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</tr>
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<td>September</td>
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</tr>
<tr>
<td>January</td>
<td>0.0086</td>
<td>0.0140</td>
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</table>

Fish and Game, personal communication) indicated that shrimp grow faster in the open season than during the closed season. Hence, the empirical curve was drawn to show seasonal differences in the growth rate. A more objective fit of the data could be obtained, but it would not alter the results enough to change the conclusions contained herein.

The curve shows relatively constant (linear) growth in weight during the open season, but slower growth during the closed period. The shrimp apparently do not approach an asymptotic weight prior to reaching maximum age in the fishery, and growth in weight could be described as linear during the exploited phase. Obviously, there was considerable variation, increasing with age.

Because of the variation exhibited by the size at age data, it is possible that significant random or systematic errors are contained in the age composition data and that the subsequent analyses of these data will be correspondingly affected.
PARAMETER ESTIMATION WITH THE MURPHY METHOD

Reference Values

We used the generalized Murphy catch equation (Tomlinson, 1970) to analyze aged catch data. Gotshall (in press) provides estimates of natural mortality and biomass based upon a fishery independent randomized trawling scheme (Abramson, 1968). Since the biomass estimates are inherently negatively biased regardless of the catchability of shrimp and the mortality estimates may deviate from the population parameters in either direction, we decided to choose a natural mortality which would provide Murphy Method biomass estimates of a magnitude similar to those obtained from the randomized trawling scheme.

An annual natural mortality coefficient of $M = 1.44$ applied to all age groups yielded the appropriate biomass estimates. This is within the range of the $M$ values given in Gotshall's (in press) Table 6 and cannot be considered significantly different from those estimates in view of the sizes of the standard errors shown in his Table 9.

Constructing Catch Ratios

Ratios of number caught in month $i + 1$ to number caught in month $i$ were calculated for all age III catches, giving values useful for within-season estimation of fishing mortality. To estimate across the closed seasons, the ratio of catch at age III in the first catch-month of season $i + 1$ to catch at age II in the last catch-month of season $i$ was calculated. For example, with 2 seasons and 3 months in each season, the ratios computed by this scheme would be:

- $R(1) = C_{III}(2)/C_{III}(1)$
- $R(2) = C_{III}(8)/C_{III}(2)$
- $R(3) = C_{III}(4)/C_{II}(3)$
- $R(4) = C_{III}(5)/C_{III}(4)$
- $R(5) = C_{III}(6)/C_{III}(5)$

where the catches used represent monthly catches by age (Table 4) and a closed season exists between months 3 and 4.

An additional assumption is that the exploitation rate ($E$) during the last month of each season is equal for ages II and III. Thus in the example, $E_{II}(3) = E_{III}(3)$. This assumption is necessary to allow estimation across the closed season.

Using these ratios for age III within season and age III to age II between seasons and assuming various exploitation rates for the last month of fishing in 1968, it was possible to make numerous estimates of the exploitation rates at age III during each month of fishing from 1955 to 1968. The Murphy method with backward calculation (Tomlinson, 1970) was used. The technique is similar to one used by Murphy (1965, 1966), except that Murphy used years instead of months, combined some age groups within years, had no years without catches, and did not treat year classes separately.

The data were separated into catches from year classes 1952 through 1967. Using the same hypothetical example as before (Table 4), the catch data can be put in the order $C_1(1), C_1(2), C_1(3), 0, C_{II}(4), C_{II}(5), 0, C_{III}(7), C_{III}(8), C_{III}(9)$. The catch ratios are computed as $C_1(2)/C_1(1), C_1(3)/C_1(2), 0, C_{II}(4)/C_{III}(3), C_{III}(5)/C_{III}(4), C_{III}(6)/C_{II}(5), 0, C_{III}(7)/C_{III}(6), C_{III}(8)/C_{II}(7), C_{III}(9)/C_{III}(8)$. Since these catches all came from the same cohort, the Murphy method can be used to estimate $E_1(1), E_1(2), \ldots, E_{III}(8)$, given that $E_{III}(9)$ is known. The previous analysis of age III data gave estimates of $E$ at age III during the last month of fishing in each season, and these were used as starting values for backward calculation on each year class from 1952 through 1965. It was necessary in estimating $E$ for the 1966 and 1967 year classes to choose values which gave an average population size in 1968 similar to the results obtained from fitting the Schaefer model.

Additional Modifications and Assumptions

Two additional assumptions fundamental to the results are: (1) ages II and III were exploited at the same rate, on the average, over the entire time period; (2) the catchability coefficient ($q$), computed as monthly catch-per-effort in weight divided by estimated average population weight for the combined age groups during the month, was reasonably constant over the entire time period. In order to satisfy these two assumptions, it was necessary to alter some
Table 4.—Hypothetical structure of age-structured shrimp catches and exploitation rates as arranged for analysis by the Murphy method.

<table>
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<th>Catch-month</th>
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<th>Exploitation rates by ages</th>
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<td>$C_1^{(2)}$</td>
<td>$C_1^{(2)}$</td>
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<tr>
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<td>$C_1^{(3)}$</td>
<td>$C_{II}^{(3)}$</td>
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<td></td>
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<td>6</td>
<td>$C_1^{(6)}$</td>
<td>$C_{II}^{(6)}$</td>
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<tr>
<td></td>
<td></td>
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</tr>
<tr>
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<td>7</td>
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<td>$C_{II}^{(7)}$</td>
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<td>8</td>
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<td>$C_{II}^{(8)}$</td>
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<tr>
<td>3</td>
<td>9</td>
<td>$C_1^{(9)}$</td>
<td>$C_{II}^{(9)}$</td>
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</table>

of the $E$ values from the age III analysis used as starting values for the year class solutions.

An additional problem occurred which resulted in some final changes that were arbitrary and difficult to explain. For some years, especially 1955 through 1959, estimates of population size were quite low and $q$ very high. It was demonstrated that a good transfer from age III to age II across the closed season did not occur for the year classes involved. Therefore, with year classes 1953 through 1958, 1962, 1963, and 1966, the estimation from the last catch-month at age II to the first catch-month at age I disregarded estimates during age III. It is hoped that the final result justifies these arbitrary decisions. It was also noted from the dots on Figure 3 that a growth curve from the sample data (Table 2) for seasons 1955 through 1959 indicates faster growth during the closed season than during the open season. This seems extremely doubtful in light of other contrary evidence and indicates that the problem was caused by inaccurate aging. Since age III shrimp make up such a small fraction of the catch and population biomass, it was not considered to seriously discredit final results.

### Fishing Mortality Estimates

Estimation of monthly instantaneous fishing mortality coefficients, $(F)$, was accomplished for each age group in each month by applying the Murphy method, as described above, to catches in numbers (Table 2). Since $M = 0.12$ was used as monthly instantaneous natural mortality for all months and ages, monthly exploitation rates, $E$, and monthly survival rates, $s$, may be obtained from

$$E = F\left[1 - e^{-(F+0.12)}\right] / (F + 0.12),$$

and

$$s = e^{-(F+0.12)}.$$

The estimates of $F$ (Table 5) varied considerably, but age I was always exploited at a rate lower than ages II and III. During the 7 years, 1955-1961, average estimated $F$ was 0.015 for age I, 0.056 for age II, and 0.057 for age III. In the 7 years, 1962-1968, $F(I) = 0.023$, $F(II) = 0.116$, and $F(III) = 0.159$. Averages for all 14 years were $F(I) = 0.019$, $F(II) = 0.088$, and $F(III) = 0.089$. Thus, as previously stated for a condition of estimation, ages II and III were exploited at about the same rates.

Converting fishing mortality to exploitation (Table 6), it was estimated that the fishery was removing about 5% of ages II and III and 1% of age I each month of fishing. Fishing intensity increased over the years and during 1962-1968 exploitation was nearly double that of 1955-1961 for each age. During the period 1961-1967, July and August were the most important months, followed by May, June, and September, while April and October were of little importance. Average $F$ (Table 10) during these years, for
Table 5.—Monthly instantaneous fishing mortality coefficients.

<table>
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June to September, was 0.16 for age II, 0.21 for age III, and only 0.03 for age I.

**Biomass Estimation**

The Murphy method produces estimates of population size in numbers at the beginning of each catch interval. The present study also required estimates of biomass. Murphy (1966) stated he computed biomass by dividing the catch in weight by the appropriate estimate of \( E \) from his analysis of numbers in the catch. This would result in a positively biased biomass estimate, since it is equivalent to multiplying the number alive at the beginning of a catch interval by the average weight during the interval.

Two ways of computing the correct estimates of biomass utilizing Murphy's method to estimate numbers are possible:

**Table 6.** Monthly exploitation rates.

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<th>Year</th>
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<th>III</th>
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</table>
(1) Multiply the estimated average weight at the beginning of each interval by the number estimated for the population by the Murphy method. That is,
\[ \hat{P}_{*ij} = \hat{C}_{ij} \hat{w}_{*i}/\hat{E}_{ij} = \text{estimated biomass to begin interval } j, \text{ age } i, \]
\[ \hat{w}_{*i} = \text{estimated average weight for age } i \text{ at beginning of interval } j, \]
\[ \hat{C}_{ij} = \text{estimated number of age } i \text{ caught during interval } j. \]

(2) Multiply the average number of age \( i \) alive during interval \( j \) by the average weight of age \( i \) individuals during this interval. That is,
\[ \hat{P}_i = \hat{N}_i \hat{w}_i = \text{estimated average biomass of age } i, \text{ during } j, \]
\[ \hat{w}_i = \text{average weight in the catch of age } i, \text{ during interval } j, \]
\[ \hat{N}_i = \text{average number alive during interval } j \text{ of age } i. \]

For this study, the second method was used with average population numbers, \( \hat{N}_i \), being given by
\[ \hat{N}_i = \hat{N}_i (1-e^{-t_i Z_i}) / (t_i Z_i) \]
\[ \hat{N}_i = \hat{C}_i / \hat{E}_i, \]
\[ t_i = \text{fraction of year elapsed during interval } j; \; t_i = 1/12 \text{ for all intervals.} \]
\[ \hat{Z}_i = \text{total annual instantaneous mortality coefficient during } j. \]

Total population biomass for ages I through III was computed as
\[ \hat{P}_i = \sum_{i=1}^{9} \hat{N}_{ij} \hat{w}_{ij} = \text{average biomass available during interval } j, \text{ and the} \]
catchability coefficient from
\[ \hat{q}_i = \sum_{i=1}^{9} \hat{C}_{ij} \hat{w}_{ij} / (\hat{P}_{ij}); \; f_i \text{ is effort expended during interval } j. \]

Estimates of within-season monthly population biomass varied from a high of 12.0 million pounds in May 1955 to a low of 3.4 million pounds in October 1964 (Table 7). Population changes estimated by the Murphy method follow trends estimated by the Schaefer model (Figure 5), except Schaefer model estimates exhibit considerably less within season change. This difference in range of within season change was caused by the different ways in which the two models treat growth and recruitment. The Schaefer model assumes a continuous process for combined growth and recruitment, whereas the Murphy method treats growth as continuous (Figure 3) and recruitment as instantaneous (Table 7).

Estimates of monthly catchability (\( q \)) (Table 7) had extreme variation and showed an average within season increase (Figure 6). However, the within season changes were inconsistent and obscured by the variation. Monthly estimates of \( q \) varied from \( 21.3 \times 10^{-5} \) in June 1968 to \( 3.8 \times 10^{-5} \) in May 1955. Yearly averages had less variation and appeared to show no long-term trend (Figure 7). Average \( q \) over all months was about \( 9.0 \times 10^{-5} \) which agreed closely with the value \( 8.5 \times 10^{-5} \) used for the Schaefer model.

Spawning Biomass and Recruitment

Female spawning biomass consisted of all ages II and III shrimp plus some fraction of age I shrimp. Some data from commercial catch samples on the fraction of age I shrimp func-

1034
### Table 7.—Ocean shrimp population biomass in thousands of pounds by age and month.

<table>
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<th>Year</th>
<th>Month</th>
<th>Ages</th>
<th>Est.</th>
<th>Year</th>
<th>Month</th>
<th>Ages</th>
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### Discussion

In the context of the table, the number of shrimp biomass in September of season \(i + 1\) is directly proportional to the biomass which will spawn sometime prior to May of season \(i + 1\). Recruitment was defined as the number of age I shrimp alive on May 1 of each year. Thus, the female biomass in September of season \(i\) is proportional to the biomass which will spawn during the spawning season. Recruitment is expressed as females were made available from unpublished sources, but a good method for predicting the fraction of age I shrimp that would function as females was not found. Thus, a simple mean was computed from the data available for years 1957 through 1967 (Table 8). It is assumed that this mean proportion (0.33) predicts the fraction of the biomass of age I shrimp alive in September that will be females and that the sum of the September biomass of ages II and III, plus the fraction of age I functioning as females in September, is directly proportional to spawning biomass during the spawning season.
models for predicting recruitment from population biomass were tried.

Model I:  \[ R_{i+2} = aS_i e^{-bs_i} \]

Model II:  \[ R_{i+2} = cS_i e^{-dP_{i+1}} \]

where

\[ R_{i+2} = \text{number of age I shrimp on May 1, season } i+2. \]

\[ S_i = \text{average biomass of functioning females during September of season } i. \]

\[ P_{i+1} = \text{average total biomass (ages I, II, and III) during September of season } i+1. \]

\[ a, b, c, \text{ and } d \text{ are constants.} \]

Model I assumes the number of eggs produced is proportional to spawning biomass and that survival from egg to recruitment is influenced by this same spawning biomass. Model II assumes the number of eggs is proportional to spawning biomass and that survival from egg to recruit is a function of average biomass competing for the population space. September of season \( i+1 \) was selected for Model II because this seemed likely to be proportional to the average biomass encountered by age 0 shrimp, and data were available for all Septembers. May 1 was selected for recruitment since most seasons opened on this date.

Both models of recruitment were fitted by using transformations and a linear model (Paulik and Gales, 1965). The transformed equations are:

Model I:  \[ \log_e \left( \frac{R_{i+2}}{S_i} \right) = \log_e (a) - bs_i; \]

Model II:  \[ \log_e \left( \frac{R_{i+2}}{S_i} \right) = \log_e (c) - dP_{i+1}. \]

Estimates of recruitment by the Murphy method varied from a high of 1.5 billion shrimp on May 1, 1962, to a low of 0.6 billion on May 1, 1968. Spawning stocks producing recruitment varied from 4.5 million pounds in September 1959 to 1.8 million pounds in September 1963 (Table 9).

The range in recruitment observed at any given spawning stock size was very large relative to the range in size of spawning stock, and the fitting of Model I did not result in a meaningful
Table 9.—Recruits vs. spawners and population biomass.

<table>
<thead>
<tr>
<th>Year (i)</th>
<th>( R_{i+2} )</th>
<th>( S_i )</th>
<th>( P_{i+1} )</th>
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<td>1955</td>
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<td>7,793</td>
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<td>4,061</td>
<td>7,646</td>
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<td>7,234</td>
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<tr>
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<td>1,508.4</td>
<td>3,499</td>
<td>6,744</td>
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<tr>
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<td>4,508</td>
<td>6,508</td>
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<tr>
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<td>3,126</td>
<td>7,475</td>
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<td>1961</td>
<td>899.7</td>
<td>3,623</td>
<td>6,685</td>
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<td>1962</td>
<td>685.3</td>
<td>3,095</td>
<td>3,791</td>
</tr>
<tr>
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<td>1,795</td>
<td>3,633</td>
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<td>1,930</td>
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<tr>
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<td>2,262</td>
<td>4,439</td>
</tr>
<tr>
<td>1966</td>
<td>613.9</td>
<td>1,924</td>
<td>6,641</td>
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</table>

1 \( R_{i+2} \) = Recruits in millions on May 1 of year \( i+2 \).
2 \( S_i \) = Spawners in thousands of pounds during September of year \( i \).
3 \( P_{i+1} \) = Population in thousands of pounds during September of year \( i-1 \).
4 Estimated from June.

Yield per Recruit

Because a well-defined spawner-recruit relationship could not be determined the use of a self-generating model of the dynamic pool type, such as Walters (1969), is not feasible. We can, however, utilize the age-structured catch data to examine this type of model under the assumption that recruitment is constant.

We feel that the greatest confidence can be placed in the estimates of instantaneous fishing mortality \( F_{ij} \) for 1961 through 1967 (Table 5). For this reason, these values were combined to yield average monthly values \( \bar{F}_{ij} \). The averages were computed as simple arithmetic means to give vectors of average fishing mortality by month and age for April through October (Table 10), and allow for computations of yield per recruit. Yield per million recruits was computed by step-wise integration (Ricker, 1958; Paulik and Bayliff, 1967). For a season of \( l \) months, a year class would be exposed to fishing for \( n = 3l \) months and protected for \( 3(12-l) \) months. This would give a total lifetime after recruitment of \( L=36 \) months. The yield can be expressed as

\[
Y = \sum_{k=1}^{L} y_k = \sum_{i=1}^{3} \sum_{j=1}^{12} C_{ij}\bar{w}_{ij}; \quad k = 12(i-1) + j
\]

where

\[
\bar{w}_{ij} = \text{average weight taken from the empirical growth curve},
\]

\[
C_{ij} = L_{ij} E_{ij} = \text{number caught in month } j \text{ of year } i,
\]

\[
E_{ij} = \bar{F}_{ij}(1-e^{-Z_k})/Z_k = \text{monthly exploitation rate in month } j \text{ of year } i
\]

\[
Z_k = (\bar{F}_{ij} + M) = \text{total monthly instantaneous mortality}
\]

(note that \( Z \) was previously used

Table 10.—Mean monthly instantaneous fishing mortality coefficients, \( \bar{F}_{ij} \) by age group.

<table>
<thead>
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<th>Age group</th>
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<td>May</td>
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<td>June</td>
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<td>September</td>
<td>0.019</td>
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<tr>
<td>October</td>
<td>0.009</td>
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to represent the annual mortality coefficient,
\[ L_k = R \exp \left[ - \sum_{h=1}^{k-1} Z_h \right] = \text{number survivors to begin interval } k, \]
\[ Z_h = M \text{ during months closed to fishing.} \]
\[ R = \text{number of recruits} = 1,000,000. \]
\[ M = 0.12. \]

The yields at various levels of fishing intensity were predicted by multiplying all \( F_{ij} \) by a constant equal to the intensity change desired and recalculating catches for all months. Estimates of expected yield in numbers and expected average weight per shrimp were also provided by this procedure. By setting appropriate values of \( F = 0 \), yields for various seasons and entry ages were computed.

If \( M = 0.12 \) is the monthly instantaneous mortality coefficient and if growth in weight at age is taken from the empirical growth curve (Table 3), a year class of shrimp that is not fished will reach its maximum biomass during the period July to August as age I. The biomass will then decline rapidly and by July to August as age II it will be about one-half the maximum.

The estimated yield per recruit for the period 1961 to 1967 was 0.00165 lb. per shrimp. Since the average annual catch during that 7-year period was 1.918 million pounds, it would have required an average of 1.162 billion recruits on April 1 to support the catch. The Murphy method estimates an average recruitment on May 1 of about 1.155 billion. Thus, the analysis of yield per recruit is in good agreement with the Murphy method results.

Given 1.155 billion recruits on April 1, it would require a yield per recruit of 0.00216 lb. per shrimp to obtain a total harvest approximately equal to the maximum sustainable yield estimated from the Schaefer model. To have obtained a yield-per-recruit of 0.00216 during those 7 years would have required an increase in fishing mortality of about 75% (Figure 9). This additional yield could not have been obtained by shortening the season or changing age at recruitment unless a substantial increase in fishing mortality accompanied the changes (Figures 9 and 10). With the distribution of fishing effort observed during 1961-1967, the average total monthly instantaneous fishing mortality \( \left( \sum F_{ij} \right) \) operating against a year class during 3 seasons was estimated to be 2.0176. While maintaining total fishing mortality at 2.0176,

**Figure 9.** Yield in pounds per million recruits as a function of age at entry into the fishery and fishing mortality. Fixed population parameters used were 1961-1967 means.

**Figure 10.** Yield in pounds per million recruits as a function of season opening date and monthly fishing mortality coefficient. October 31 season closing date assumed and fixed population parameters used were 1961-1967 means.
the annual yield could theoretically be increased to about 2.8 million pounds by shifting fishing mortality so that I's and II's suffered equal rates. This would involve a 75% reduction in fishing mortality at ages II and III and assumes that the population with the new age structure would continue to produce 1.155 billion recruits. Such a change would also produce a reduction of 26% in the average size of shrimp in the catch and pose the problem of how the mortality pattern could be so altered.

**INTER-MODEL COMPARISONS**

Because we were unable to determine a spawner-recruit relationship and produce a self-generating form of the dynamic pool model, a realistic comparison of the results from the two types of models is not possible. In addition, the yield-per-recruit model treats natural mortality and growth parameters as constant while in the Schaefer model they are components of density dependent terms.

It is of interest to note that the biomass estimates obtained from the age-structured catch data by the Murphy method are in general agreement with the corresponding estimates of the Schaefer model. Although this does not compare the yield-per-recruit and Schaefer models, we feel it indicates some support of the Schaefer model from a semi-independent source. Another point of agreement between the yield-per-recruit and Schaefer models was that, given the average recruitment over the 1961-67 period, the former required a 75% increase in fishing mortality to produce the Schaefer model's maximum sustainable yield while the average annual effort expended during that period would require a 68% increase to reach the optimum effort level of the Schaefer model. However, as can be seen from Figure 9, maximum yield-per-recruit is predicted to occur at a much higher effort level under the previously mentioned assumption of constant parameters.

It seems clear from the foregoing discussion of results relative to the two models that management procedures should be based on the Schaefer model at the present time.

**PROPOSED MANAGEMENT STRATEGY**

Fitting an equation such as the Schaefer model to a set of actual catch and effort data may be viewed as merely an interesting exercise unless one has to make actual management recommendations based upon the results. Then the situation becomes somewhat sticky. It is obvious that a simple deterministic model such as Schaefer's will not precisely describe the dynamics of a fish population. At best, there will be fluctuation in recruitment, growth, and catchability which will cause some consternation to the manager attempting to use such a model.

In the case of the shrimp fishery, the management strategy we propose treats the Schaefer model estimates as exactly correct, responds to indicated deviations from the optimum population size in a relatively arbitrary but conservative manner, and integrates the Oregon and California fishing. This conservative strategy attempts a gradual reduction in the biomass when the model estimates it to be above $P_{opt}$ and a rapid increase in the stock size when it is estimated to be below $P_{opt}$. To formulate this procedure, let $Q$ be the catch quota (California + Oregon) and $C_p(P) = H P^2 - K P$ be the equilibrium yield obtainable from a population of size $P$. With $P(t)$ the population when the next fishing season commences,

\[
Q = \frac{P(t) - P_{opt}}{2} + C_e \left( \frac{P(t) + P_{opt}}{2} \right);
\]

\[
P(t) > P_{opt},
\]

\[
Q = P(t) - P_{opt} + C_e \left( P(t) \right);
\]

\[
P(t) < P_{opt}.
\]

When the model predicts the stock is in the surplus condition we are, then, proposing to harvest one-half of this surplus plus the predicted sustainable yield at the point midway between $P(t)$ and $P_{opt}$. A predicted stock deficit evokes a procedure which harvests the sustainable yield at $P(t)$ minus the amount by which the stock falls short of $P_{opt}$. For example, the 1970 California shrimp quota of 3.4 million pounds was set by the above method with $P(t) - P_{opt} =$
7.1 - 4.8 = 2.3 and $C_e$ (5.9) = 2.3 for a recommended yield of 3.4 million pounds (Table 1). It was assumed the Oregon fleet's catch from Oregon waters would be negligible.

A more radical strategy such as harvesting all of the surplus stock could be employed, but the attendant risks would be higher. These risks would include a possible disturbance of whatever stability exists in the population, particularly with reference to age structure. It might also be argued that the observed catch-per-effort should be used to adjust $P(t)$ before making the quota calculation described above. Here again, a substantial risk would be involved if the observed catch-per-effort were much higher than the expected since with our methods it could not be determined whether such an anomaly was due to abnormal catchability or to a real increase in the stock size. The quota-setting procedure we recommended above does respond in a limited way to a higher than expected catch. Since the fishery operates under a quota, a catch-per-effort which is higher than expected will result in the quota being filled with a lower than expected amount of effort and usually in a shorter time period. An examination of (2) shows that this will increase $P(t)$ and thus result in a larger quota for the season beginning at time $t$.

This fishery must be carefully followed in the future to observe how well the model based upon current parameters describes the observed catch and effort pattern. An equation such as this which is fitted to data from only 16 years cannot be considered definitive from a statistical estimation viewpoint and, in addition, there is a chance the population parameters will actually be changing. For example, one cannot avoid speculating about the effect of the large Pacific coast hake fishery on the shrimp natural mortality rate. Since hake may be a substantial predator upon shrimp (Gotshall, 1969), a reduction of the hake population due to a large fishery might increase the abundance of ocean shrimp.

Beyond the technical management problems which we have discussed at length, there is the institutional problem of a single state attempting to manage an interstate fishery. While the catch from Oregon waters by Oregon-based vessels has usually been so small that it affects the population negligibly, at times it has been substantial. A sustained change in conditions could nullify the effect of California's quota mechanism.

**ACKNOWLEDGMENTS**

Many biologists of the Department of Fish and Game collected the data used in this paper. Daniel W. Gotshall and Walter A. Dahlstrom were of special help to us in obtaining the data and in freely passing on to us their knowledge of this shrimp fishery and of shrimp life history. We also wish to thank Catherine L. Berude for programming and computing assistance.

**LITERATURE CITED**

**ABRAMSON, N. J.**


**ABRAMSON, N. J. (compiler).**


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