



**Northwest and
Alaska
Fisheries Center**

**National Marine
Fisheries Service**

U.S. DEPARTMENT OF COMMERCE

NWAFRC PROCESSED REPORT 82-06

A Management Analysis of the Pacific Whiting Fishery

April 1982

NOTICE

This document is being made available in .PDF format for the convenience of users; however, the accuracy and correctness of the document can only be certified as was presented in the original hard copy format.

Inaccuracies in the OCR scanning process may influence text searches of the .PDF file. Light or faded ink in the original document may also affect the quality of the scanned document.

A MANAGEMENT ANALYSIS OF THE PACIFIC WHITING FISHERY

by

R.C. Francis^{1/}, G.L. Swartzman^{2/}, W.M. Getz^{3/}, R. Haar^{2/}, and K. Rose^{2/}

Resource Ecology and Fisheries Management Division
Northwest and Alaska Fisheries Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
2725 Montlake Boulevard East
Seattle, WA 98112

April 1982

^{1/} Northwest and Alaska Fisheries Center
Resource Ecology and Fisheries Management Division
2725 Montlake Boulevard East
Seattle, WA 98112

^{2/} Center for Quantitative Science in Forestry, Fisheries,
and Wildlife
University of Washington
Seattle, WA 98195

^{3/} Division of Biological Control and
Departments of Entomological Sciences and Plant Pathology
University of California
Berkeley, CA 94720

ABSTRACT

This paper applies a model developed by Getz and Swartzman (1981) to the Pacific whiting (Merluccius productus) fishery off the North American Pacific continental shelf. Recruitment in this stock is linked both to stock level and water temperature in their spawning area. This link forms the basis of a transition matrix in the model for recruitment which depends both on stock level and spawning grounds temperature. Comparison with historical data on fishery catch and stock estimates shows model output to be realistic.

As an aid to management of the fishery, a policy algorithm was developed which aims to utilize strong year-classes in a practical and efficient manner while at the same time maintaining the productive capacity of the stock. Runs with different quota control criteria in the algorithm were compared with 9-yr and 47-yr runs at constant effort and constant quotas, and the management strategy contained in the algorithm was found to be superior, specifically with regard to prevention of stock collapse and having a higher average catch per unit effort (CPUE). In the policy algorithm, average yield can be increased at the expense of CPUE. The choice of quota control criteria depend on management preference for improving yields versus having highly variable effort and lower average CPUE.

CONTENTS

	<u>Page</u>
Introduction.	1
The Getz-Swartzman Model as Applied to Pacific Whiting.	5
Equilibrium Yield	20
A Management Policy Algorithm	21
Results and Evaluation of Management Policy Algorithm	
Short-term runs.	28
Long-term runs	29
Conclusion.	44
Acknowledgments	46
References.	47

INTRODUCTION

Fisheries today are managed using a variety of quantitative tools, prominent among which is classical Beverton and Holt fisheries analysis. While it does consider the fished population as age structured, this approach is weak in its treatment of recruitment, assuming that recruitment is independent of stock. A number of alternatives have been considered, mostly deterministic, including those of Beverton and Holt (1957), Walters (1969), and Ricker (1975). The stock-recruit hypotheses in these models are often poorly supported by data (e.g., Cushing 1973). It appears that environmental conditions play an important role in determining year class strength, and in many instances stock size appears to play a secondary role (Sissenwine 1977, Van Winkle et al. 1979; Lett and Kohler 1976; Nelson et al. 1977).

Since variability in year class strength appears to be an important and regular feature of most commercially important fish stocks, management must begin to consider the resulting year-to-year variability in stock biomass when setting fishing quotas and general management policy. With this in mind, Getz and Swartzman (1981) developed a model of a fish population and resultant fishery dynamics based on classical Beverton and Holt analysis but featuring a stock-recruit relationship that is a transition matrix giving the probabilities that given recruitment levels can arise from different levels of stock abundance. With this model the population age class distribution is replaced by a probability vector for each age class, giving the probability that the (biomass) level of that age class is in each of m arbitrary biomass categories ranging between zero and some maximum. Instead of computing deterministic yield and stock level the model computes expected values and variances for each of these variables.

Management problems associated with the Pacific whiting (Merluccius productus) offshore stock and fishery appear to lend themselves well to an application of a slightly modified version of the Getz-Swartzman model.

A detailed description of the life history of and fishery for Pacific whiting is given by Bailey et al. (in press). Briefly, the coastal stock of Pacific whiting occupies the continental shelf and slope area of the California Current system, ranging from a feeding area off Vancouver Island in the north to a spawning area as far south as the southern tip of Baja California (Figure 1). In autumn, adult whiting make an annual migration from the summertime feeding grounds off the Pacific Northwest coast to winter spawning grounds off the coasts of southern California and Baja California. In spring and summer large adult fish migrate northwards as far as central Vancouver Island and juveniles remain off central and northern California. Oceanographic conditions at the time of spawning appear to play a major role in the recruitment to the exploitable stock of Pacific whiting. Between 1973 and 1980, estimated recruitment at age 3 varied from a low of .3 billion to a high of 1.7 billion.

Since 1966, Pacific whiting has been the target of a large foreign fishery off the west coast of the U.S. and Canada. Estimated catches have ranged from 91 thousand t to 236 thousand t (Bailey et al., in press). The average annual all-nation reported catch for 1966-1980 was 162 thousand t. A small, rather insignificant domestic fishery for whiting, used in the manufacture of pet food, has existed since at least 1879. In recent years a domestic joint venture for whiting has begun to develop. The U.S. joint venture catch has been estimated at 3, 13, 41, and 45 thousand t in 1978 through 1981.

Prior to implementation of the Magnuson Fishery Conservation and Management Act (MFCMA) in 1977, management of the foreign whiting fishery was by bilateral

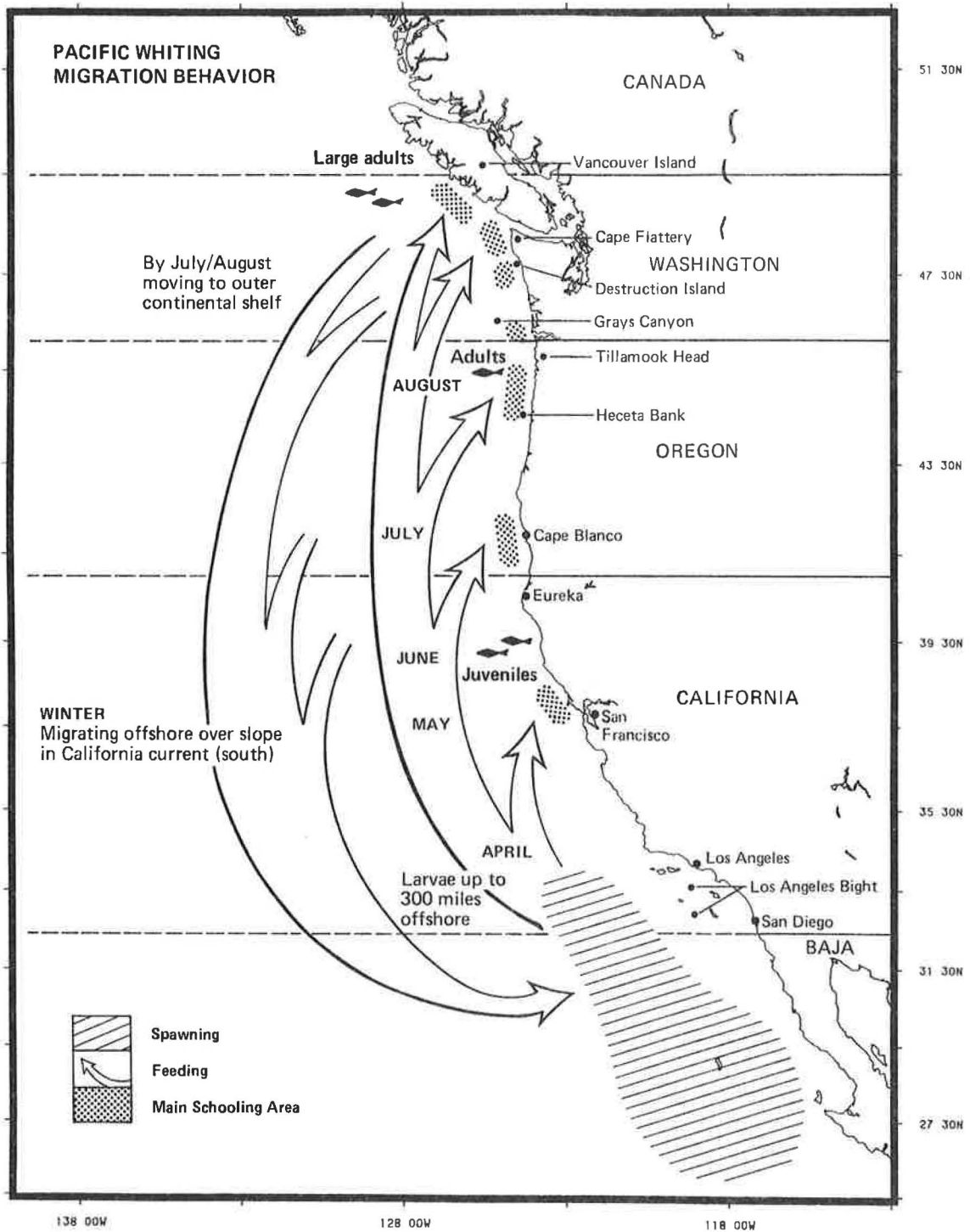


Figure 1.--Migratory patterns of Pacific whiting.

agreement. Since 1977 management in U.S. waters has been directed by a Preliminary Management Plan (PMP) for groundfish. Under the PMP each year a total allowable catch (TAC) for the U.S. portion of the fishery is established. This value is adjusted above or below the estimated maximum sustainable yield (MSY) in the U.S. fishing zone, 175.5 thousand t, depending on the estimated condition of the stock. For example, in 1977 when the stock was estimated to be "at the lowest recorded level of abundance" (Department of Commerce 1977), TAC was set at 130 thousand t in the U.S. zone. In 1979 when the fishery was being supported by two very strong year-classes (1970 and 1973), TAC was set at 198.9 thousand t. A final Fishery Management Plan (FMP) (Pacific Fishery Management Council 1981) for groundfish is currently under review and is projected to be implemented in 1982. The rationale for management of whiting under this plan is stated as follows:

"In the case of Pacific whiting MSY is considered attainable. The estimate of MSY is 175,500 mt, a value midway in the range of MSY estimates. This estimate may be conservative but is justifiable because (1) unexplained signs of population stress were observed when annual catches exceeded 200,000 mt, (2) the substantial variability in biomass estimates has yet to be fully explained, and (3) the inadequacy of past fishery statistics precludes assessment of the effects of fishing. In addition, large increases in catch would adversely impact our efforts to minimize the incidental catch of Pacific ocean perch and other rockfish."

The plan requires that an optimum yield (OY) be set for all species being managed. In the case of whiting $OY = MSY = 175.5$ thousand t. This translates into an MSY for the entire stock of 195 thousand t. The OY can be adjusted at any given time if a "Point of Concern" is reached. This occurs if:

- a) exploitable biomass or spawning biomass is below a level expected to produce MSY;
- b) recruitment is substantially below replacement level;
- c) fishing mortality rate exceeds that required to take the Acceptable Biological Catch for a given calendar year (ABC - the final quota set);

d) catch for a given year is projected to exceed ABC;

e) any other abnormality in the biological characteristics of the stock is discovered.

OY cannot be increased by more than 30% per year without a plan amendment. However, it can be decreased by any amount. Finally, within or between season OY adjustments can be made to allow for "full resource utilization."

The objective of this study is to employ a modified version of the Getz-Swartzman stochastic transition matrix model to explore various management options for the Pacific whiting fishery, a fishery which exhibits considerable recruitment variability. A management algorithm is developed which attempts to take advantage of strong year-classes as they pass through the fishery while at the same time protecting the stock against potentially harmful depletion when under the dominance of weak year-classes.

THE GETZ-SWARTZMAN MODEL AS APPLIED TO PACIFIC WHITING

The analytic framework of the model is described in detail by Getz and Swartzman (1981). Tables 1 and 2 list model parameter values used in this analysis.

The values of n (No. of age classes), m (No. of age-class subdivisions) and m_s (No. of parent stock subdivisions) are limited by computation time. The value of n was increased over those used by Getz and Swartzman (1981) due to the development of a new algorithm (Swartzman et al. in review) which greatly reduces computation time. Specific age-dependent parameters (M_i, q_i, w_i ; $i = 3, \dots, 10$) were derived from the Option 2 (Modified weight-age, Laevastu-Cushing natural mortality) cohort analysis reported by Francis (1982). We felt that since the cohort analysis was performed on 9 age classes (ages 3-11), it was important to retain this structure as closely as possible in the

Table 1.--Parameter values for Pacific whiting data used in the simulation runs.

Parameters		Value for Pacific whiting
n	No. of age classes	8 (age-class 3,4,...,9,10-12)
r	No. of years that recruitment is delayed after spawning	3
m	No. of age class subdivisions	6
m _s	No. of parent stock subdivisions	8
x ₁	Maximum no. of recruits	2.4 x 10 ⁹
S	Maximum fecund stock biomass (kg)	1.5 x 10 ⁹
\bar{t}	Length of fishing season (yr)	0.42

Parameters	Age-classes (i)							
	3	4	5	6	7	8	9	10-12
Natural mortality rates	.278	.210	.195	.257	.357	.457	.557	.657
M _i (yr ⁻¹)								
Catchability coefficient q _i	.0107	.0283	.0338	.0731	.1021	.1695	.1836	.1667
(1000 vessel days effort ⁻¹)								
Fecundity coefficient c _i	.50	.75	1.00	1.00	1.00	1.00	1.00	1.00
(fraction of sexually mature individuals in each age-class)								
Weight coefficients w _i (g)	483	613	717	800	854	906	932	955

Table 2.--Stock-recruitment probability transition matrices. The transition matrix elements t_{ij} represent the probability that a spawning stock biomass in subdivision j (≤ 8) will result in the number of recruits being in subdivision i (≤ 6).

Cold + Intermediate

Average No. recruited (10^9 ind)	Recruitment level								
2.2	6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.8	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.4	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.0	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	2	0.00	0.45	0.60	0.65	0.68	0.68	0.68	0.68
0.2	1	1.00	0.55	0.40	0.35	0.32	0.32	0.32	0.32
Spawning stock levels		1	2	3	4	5	6	7	8
Avg biomass (10^3 t)		0.094	0.281	0.469	0.656	0.844	1.031	1.219	1.406

Warm

Average No. recruited (10^9 ind)	Recruitment level								
2.2	6	0.00	0.00	0.00	0.05	0.10	0.10	0.10	0.10
1.8	5	0.00	0.00	0.05	0.07	0.15	0.15	0.15	0.15
1.4	4	0.00	0.00	0.15	0.15	0.15	0.15	0.15	0.15
1.0	3	0.00	0.20	0.20	0.23	0.20	0.20	0.20	0.20
0.6	2	0.14	0.60	0.45	0.35	0.25	0.25	0.25	0.25
0.2	1	0.86	0.20	0.15	0.15	0.15	0.15	0.15	0.15
Spawning stock levels		1	2	3	4	5	6	7	8
Avg biomass (10^3 t)		0.094	0.281	0.469	0.656	0.844	1.031	1.219	1.406

management analysis. The maximum number of recruits (x_1) and maximum parent (fecund) stock biomass (S) were set to reflect levels in the fishery that would be expected to occur under optimal production conditions. These levels are well above (20-30%) the maximum values estimated during the period (1973-80) over which the parameters were estimated. The age-specific catchability coefficients (q_i ; $i = 3, \dots, 10$) were modified from the annual estimates, produced in the cohort analysis, so that they could be applied to the 5-month fishing season used in the management analysis. Fishing effort is given in units of 1,000 vessel days on the fishing grounds. The fecundity coefficients (c_i) were obtained from Bailey (K.M. Bailey, Univ. of Wash., Seattle, WA 98195, pers. commun.).

The estimates of the elements of the stock-recruitment probability transition matrices are listed in Table 2. These two matrices are constructed under the hypotheses, supported by current data, that:

1) "cold" water temperatures on the spawning grounds result in relatively low average recruitment with less variability than in years of "warm" water temperatures; and

2) "warm" water temperatures on the spawning grounds result in relatively high average recruitment with greater variability than in years of "cold" water temperatures.

The physical data supporting the above hypotheses are the surface water temperatures on the spawning grounds during spawning (Table 3). They are the average sea surface temperature from January-March in the Los Angeles Bight. Bailey (1981) demonstrates that whiting recruitment is inversely correlated to the level of wind-driven Ekman transport on the spawning grounds at the time of spawning. We have assumed that offshore transport is positively correlated with the level of upwelling which, in turn, is negatively correlated with sea surface temperature. Therefore, years of "cold" water temperatures on the

Table 3.--Observed and predicted data on Pacific whiting stock-recruit variables.

Year Class	YCI ⁽¹⁾	$R_3^{(2)}$ (10^9 ind.)	LA (10^{12} ind.)	$\bar{B}_f^{(3)}$ (10^6 t)	Temp. (° C)	Class ⁴
1960	54	(1.015)	2.08	(0.978)	15.85	W
1961	130	(2.221)	2.57	(0.983)	15.91	W
1962	14	(0.379)	-	-	-	
1963	19	(0.459)	4.97	(1.003)	15.46	W
1964	20	(0.475)	3.99	(0.995)	15.98	W
1965	8	(0.284)	8.27	(1.032)	14.89	I
1966	20	(0.475)	19.25	(1.128)	15.19	I
1967	34	(0.697)	-	-	-	
1968	38	(0.602)	13.28	(1.076)	15.79	W
1969	29	(0.618)	3.74	(0.993)	15.31	I
1970	78	1.736	-	-	-	
1971	18	0.673	-	-	-	
1972	14	0.388	1.11	(0.970)	13.69	C
1973	86	1.255	-	0.730	15.71	W
1974	16	0.300	-	0.957	14.20	C
1975	30	0.434	8.23	1.139	14.17	C
1976	-	0.410	-	1.153	14.84	I
1977	-	1.581	-	1.088	15.70	W
1978			14.65	1.060	-	-
1979			5.96	0.933	-	-
1980				1.076	-	-

Predicted data in parentheses.

(1) Year Class Index from Bailey (1981).

(2) Recruitment of year class at age 3.

Predicted values obtained from equation $\bar{R}_3 = .15724 + .01588 \text{ YCI}$.

(3) Fecund stock biomass.

Predicted values obtained from equation $\bar{B}_f = 0.960 + 0.00873 \text{ LA}$.

(4) W = warm, I = intermediate, C = cold.

spawning grounds are assumed to be years of high offshore transport and low larval survival and years of "warm" water temperatures are assumed to be years of low offshore transport and high larval survival.

In order to estimate the elements of the stock-recruitment probability transition matrices, relationships between values of stock biomass, surface water temperature at the time of spawning and subsequent recruitment to the fishery three years later had to be inferred. In order to obtain as many stock-recruit data points as possible, relative and absolute measures of both stock biomass and subsequent recruitment were used. These values are given in Table 3. The relative measures were provided by Bailey (1981). Fecund stock biomass (\bar{B}_f) was assumed to be proportional to the larval abundance (LA) produced by that stock on the spawning grounds (CALCOFI and Soviet cruises) during January after being adjusted for post-January spawning. The adjustment factor was based on the ratios of the observed larval counts in January to those in April. From Francis (in review) one can obtain estimates of fecund stock biomass (\bar{B}_f) at the time of spawning for 1973-1980. \bar{B}_f was regressed on LA for the years both values were available (1975, 1978, 1979). The equation is

$$\bar{B}_f = 0.960 + 0.00873 \text{ LA} \quad (r^2 = 0.14).$$

\bar{B}_f was then estimated (values in parentheses in Table 3) from the regression equation for the years (1960-1972 excepting 1962, 1967, 1970, 1971) where only larval abundance was available. Francis (1982) also provides estimates of recruitment at age 3 (R_3) for the 1970-1977 year classes. Bailey (1981) provides a relative measure of year class strength (YCI) for the 1960-1975 year classes. In order to obtain estimates of absolute recruitment at age 3 for the 1960-1969 year classes, R_3 was regressed on YCI for 1970-1977. The equation is

$$R_3 = 0.15724 + 0.01588 \text{ YCI } (r^2 = 0.91).$$

R_3 was then estimated (values in parentheses in Table 3) from the regression equation for the year classes (1960-1969) where only YCI was available.

Figure 2 gives a frequency histogram of the mean January-March sea surface temperature in the Los Angeles Bight for 1931-79. The distribution was basically trimodal. Therefore, years were subjectively divided into cold (13.40-14.69°C), intermediate (14.70-15.59°C) and warm (15.60-16.90°C) so that each interval roughly contained one of the three modes found in the histogram.

Figure 3 is a plot of fecund stock biomass (\bar{B}_f) against recruitment at age 3 coded by the three temperature intervals (warm, intermediate, cold). This plot provides qualitative evidence in support of the hypotheses proposed at the beginning of this section. This is especially apparent if the values associated with the intermediate temperatures are combined with those associated with cold temperatures.

Finally, defining

t_{kj} = probability that spawning stock biomass in subdivision j
 $(j = 1, \dots, 8)$ results in recruitment numbers in sub-
 division k ($k = 1, \dots, 6$)
 separate sets $\left\{ t_{kj}; j = 1, \dots, 8; k = 1, \dots, 6 \right\}$ were constructed for
cold + intermediate years and warm years.

For the runs reported in this paper, estimates were made based on fecund stock level data in the range of 0.7 to 1.2 million t, and in this range recruitment was assumed to be independent of stock and only dependent on temperature at the time of spawning (see Figure 3). In this range transition probabilities were estimated as described in Getz and Swartzman (1981). In the stock range of 0 to 0.7 million t (values below fecund stock levels actually observed), it was assumed that the expected value of the probability density

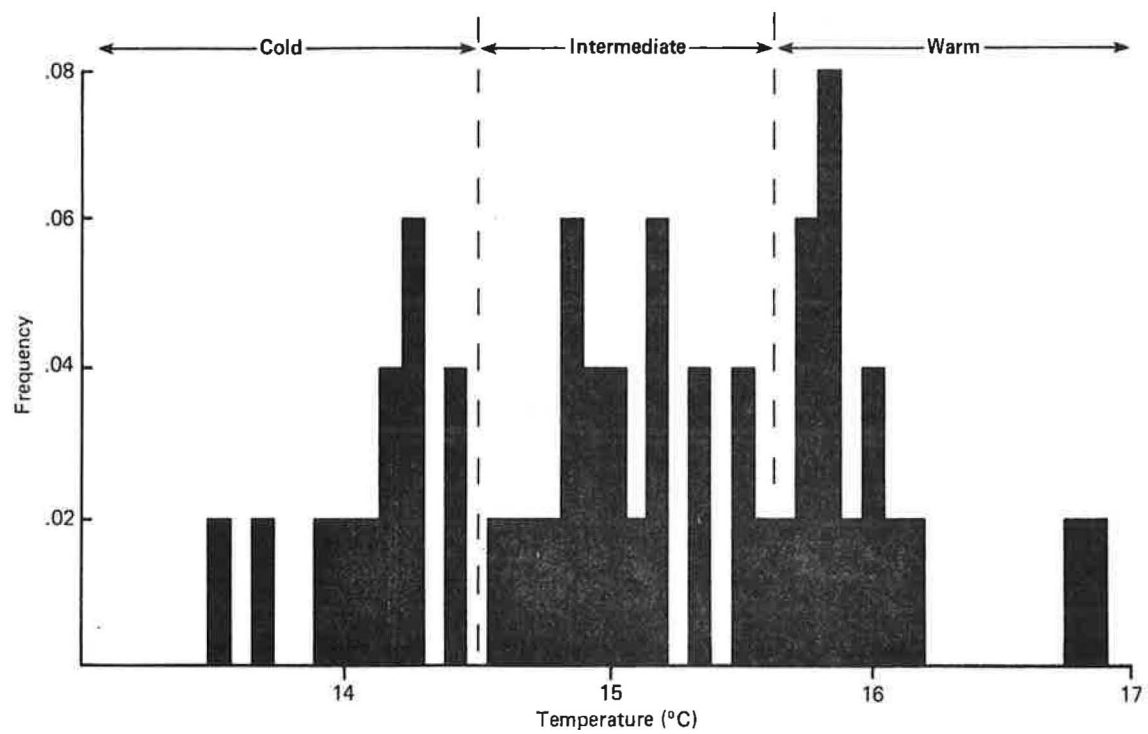


Figure 2.--Frequency histogram of mean January-March sea surface temperatures in Los Angeles Bight: 1931-79.

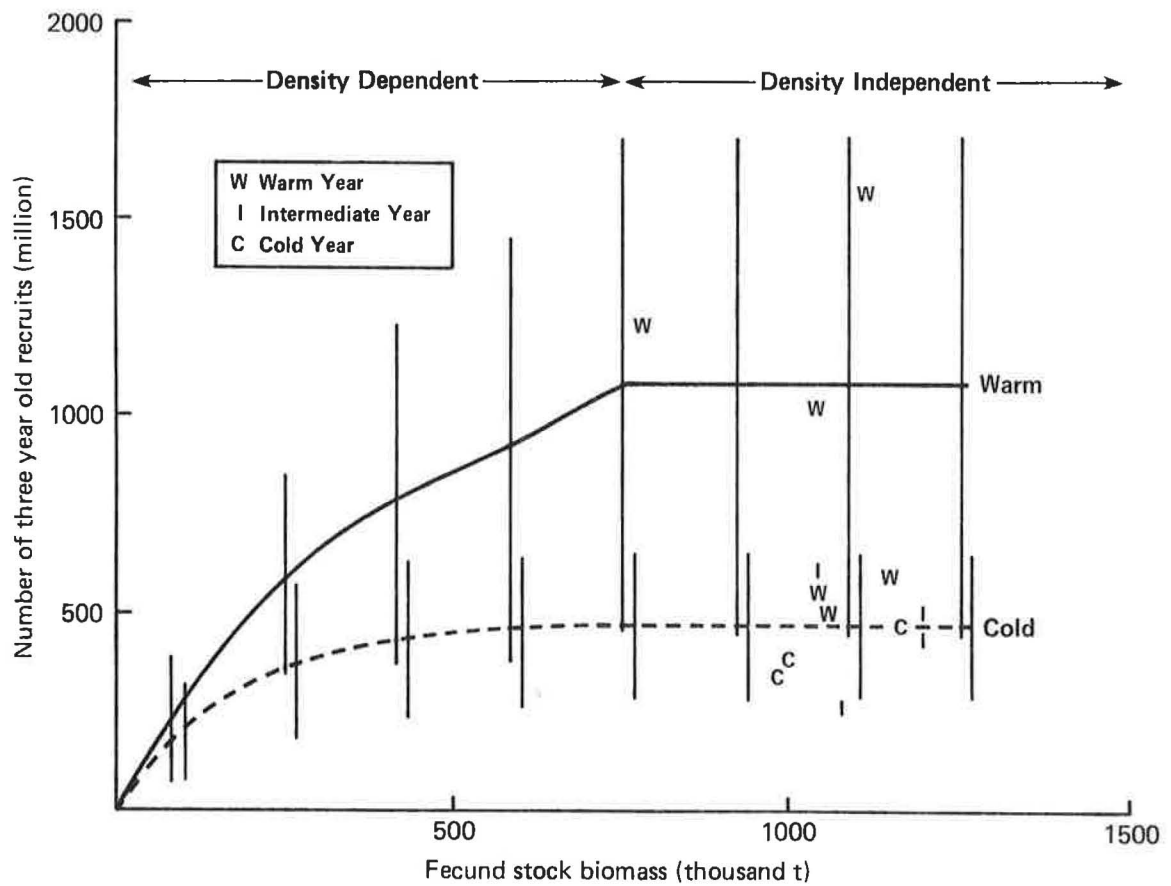


Figure 3.--Stock-recruit relationships of Pacific whiting used in the model (mean ± 1 standard deviation).

function generated by the estimates of t_{kj} would roughly follow an asymptotic stock-recruit curve of the form

$$\bar{R}_3 = \beta (1 - e^{-\alpha \bar{B}_f})$$

where

\bar{R}_3 = average recruitment at age 3.

\bar{B}_f = average spawning (fecund) stock biomass.

The values of α and β for warm and cold years were selected so that the recruitment, R_3 , at $\bar{B}_f = .7 \times 10^6$ t matched the average estimates obtained from the data in Figure 3. For warm years, $\bar{R}_3 = 1087$ million individuals for $\bar{B}_f > 0.7 \times 10^6$ t and for cold + intermediate years, $\bar{R}_3 = 416$ million individuals for $\bar{B}_f > 0.7 \times 10^6$ t. In this lower range transition probability estimates were made iteratively until the assumed (Figure 3) means and variances were obtained. The plots of the recruitment curves are given in Figure 3. The resultant stock-recruitment probability transition matrices for cold + intermediate and warm years are given in Table 2.

Since no data were available for low stock levels (i.e. $\bar{B}_f < 0.7 \times 10^6$ t) two other options (besides the asymptotic model) were considered for estimating the t_{kj} 's in this range. In the first case, recruitment was assumed independent of spawning stock and in the second the decline in recruitment was assumed linear. The first of these options was felt to be unduly optimistic and the second unduly pessimistic. Thus the asymptotic option was considered to be the most realistic. In absence of data over the $0 - 0.7 \times 10^6$ t fecund stock biomass range, it is difficult to determine the most likely behavior of the fishery. Since these levels do affect the MSY estimates (as discussed below) obtained from the Getz-Swartzman model, the idea of probing the fishery by way of management experiments (Walters 1981) is one that has some relevance but is not considered here.

Validation runs of the model were made over a 47-yr period (1933-80) for which surface temperature data at the time of spawning were available. Driving variables for the population and yield model were a) effort levels in thousands of standard vessel days from 1966 to 1980 (Bailey et al., 1982) and b) classification of environmental conditions on the whiting spawning ground into warm or cold (+ intermediate) for 1931-77 based on mean January-March surface temperatures in the LA Bight (Douglas McClain, Natl. Marine Fish. Serv., Southwest Fish. Center, Monterey, CA 93940). These input data, along with the corresponding catches for 1966-1980, are given in Table 4. Figure 4 is a plot of the 47-yr time series of temperature at the time of spawning, Figure 5 a plot of the means and standard deviations of the simulated stock biomass for 1934-80, and Figure 6 a plot of the means and standard deviations of simulated catches along with the observed catches for the history of the fishery (1966-80). One thing that is important to note in Figure 4 is that, whereas the frequency of warm years was 38% between 1931 and 1979, it was 48% between 1956 and 1979, the time span within which the year classes produced could have affected the productivity of the fishery. As will be seen later, this is very important to the estimation of long-term stock production.

It is interesting to observe the cycles in stock biomass predicted by the model (Figure 5). The period between peaks and troughs is around 20 yr, a reflection of the apparently periodic fluctuations in environmental conditions on the spawning grounds. Note that initial conditions for the run (1933-38) were arbitrarily set to large stock levels to represent a virgin stock. So it appears the model reflects the kind of cycles that the stock might be expected to undergo beginning around 1940 or 1941 when the effects of arbitrary initial conditions have been damped out.

Expected fishery yields from the model agree quite well with the observed yields for 1970-80, while for 1966-69 the yields calculated by the model are

Table 4.--Driving variables and observed catches of Pacific whiting for model validation runs.

Year	T°C	Temp. Class.	Year	T°C	Temp. Class.	Effort (1000 Std. days)	Catch (1000 t)
1931	16.03	W	1966	15.19	C	7.14	137.0
1932	14.28	C	1967	15.80	W	6.25	206.1
1933	13.50	C	1968	15.79	W	9.61	103.8
1934	14.97	C	1969	15.31	C	9.04	161.9
1935	14.57	C	1970	15.46	W*	9.18	228.5
1936	15.11	C	1971	14.07	C	7.78	153.2
1937	14.24	C	1972	13.69	C	7.20	151.2
1938	15.67	W	1973	15.71	W	6.31	150.8
1939	14.15	C	1974	14.20	C	8.68	226.5
1940	16.09	W	1975	14.17	C	11.52	217.7
1941	16.16	W	1976	14.84	C	9.21	236.8
1942	15.59	C	1977	15.70	W	4.24	132.4
1943	15.77	W	1978	16.00	W	2.99	104.2
1944	15.29	C	1979	15.00	C	5.27	135.9
1945	15.71	W	1980	-	-	3.20	90.7
1946	14.36	C					
1947	14.93	C					
1948	14.41	C					
1949	14.23	C					
1950	14.01	C					
1951	14.98	C					
1952	15.17	C					
1953	15.20	C					
1954	14.84	C					
1955	14.66	C					
1956	13.93	C					
1957	15.81	W					
1958	16.81	W					
1959	16.72	W					
1960	15.85	W					
1961	15.91	W					
1962	14.80	C					
1963	15.46	C					
1964	15.98	W					
1965	14.89	C					

* 1970 assumed to be a warm year, although it falls outside the necessary range, since it produced a very large year class.

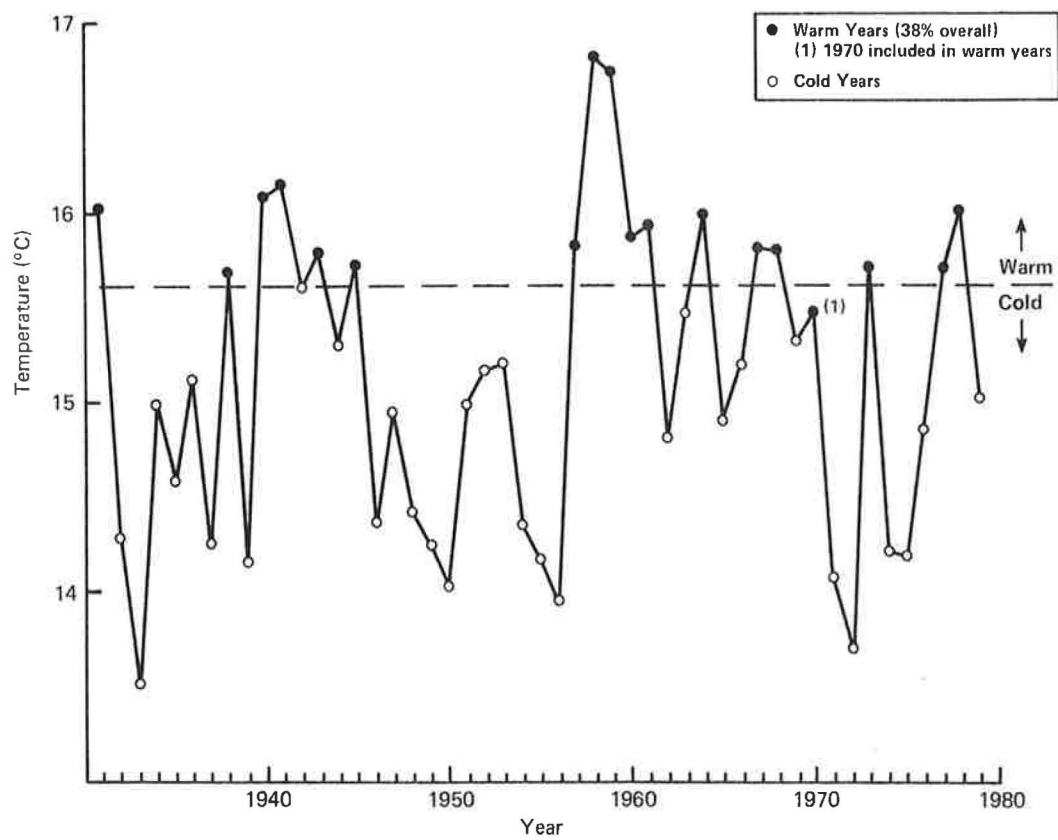


Figure 4.--1931-79 mean January-March sea surface temperature (°C) in Los Angeles Bight.

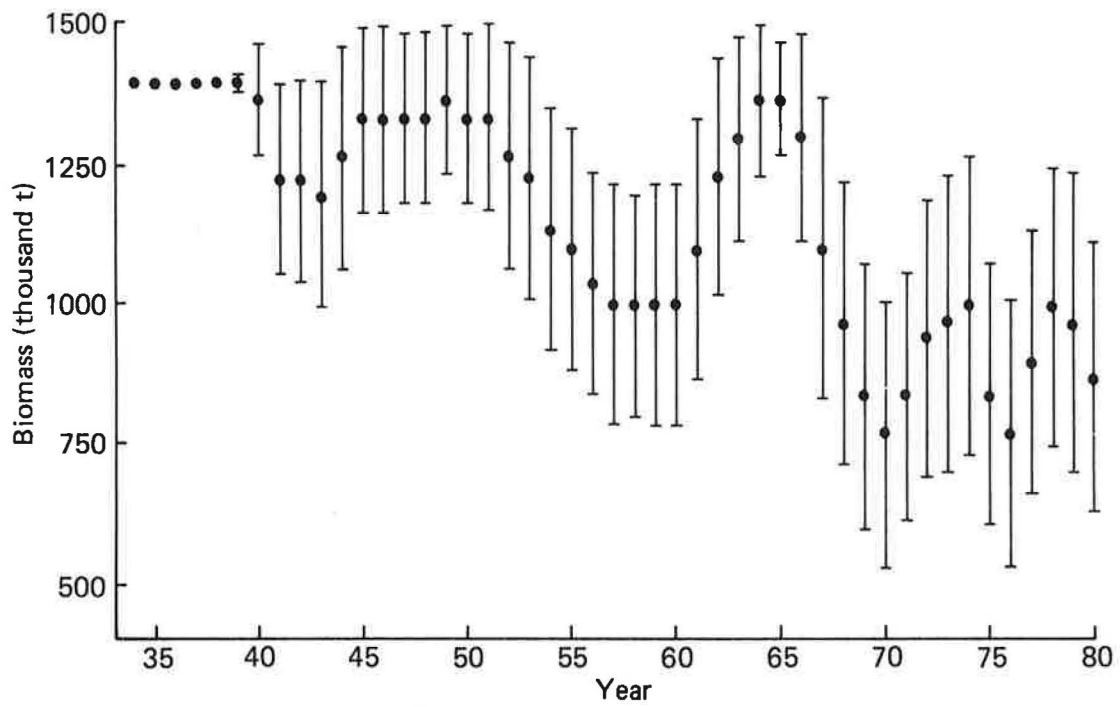


Figure 5.--Expected fecund stock biomass of Pacific whiting (± 1 standard deviation) for 1934-80 historic run.

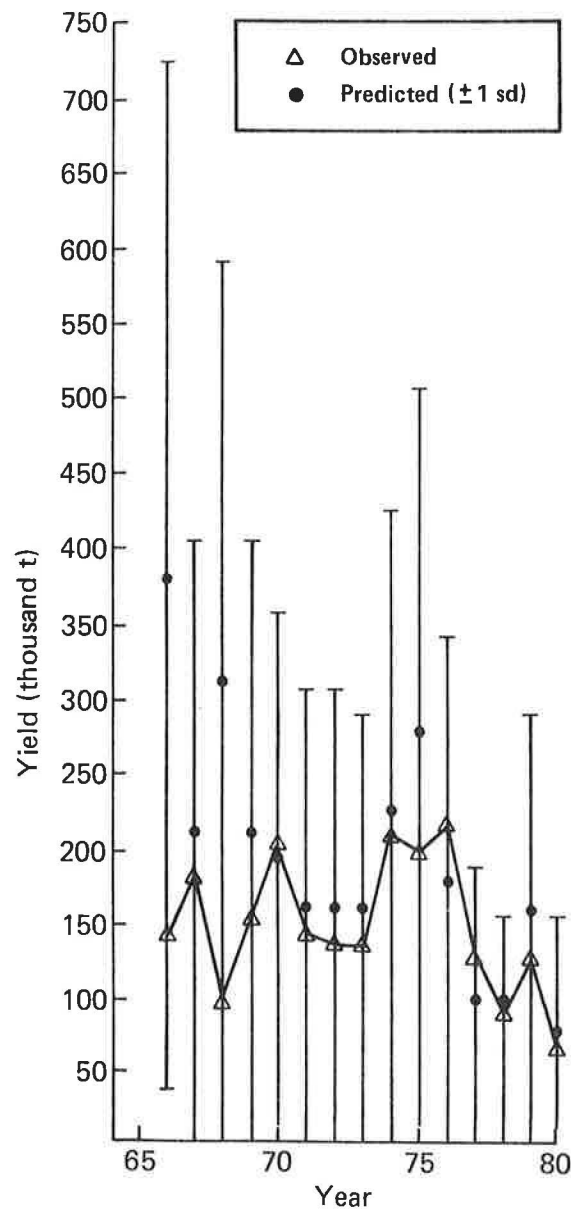


Figure 6.--Observed and predicted (± 1 standard deviation) catches for historic run.

consistently larger than those reported for the fishery. This inconsistency in the early years of the fishery could be due to one or more of the following factors:

- 1) The gear employed by the Soviet fishery changed from predominately side trawlers at the outset to exclusively factory stern trawlers after 1972. A rough attempt was made to standardize effort (Bailey et al., in press) but the fishing power factors may be inaccurate.
- 2) Effort may have been quite inefficient in the early years of the fishery due to a lack of experience in locating the good grounds and deploying the gear to catch the fish.
- 3) There may have been an underreporting of the catch in the early years.
- 4) The model may have overestimated the status of the fishable stock at the time of the initiation of the fishery. Note that the simulated stock is especially high at the time (1966) the fishery started.

One thing that must be kept in mind when interpreting runs of this type is that the 46-yr trend in stock biomass in Figure 5 reflects what might have been expected to occur if there were no major changes in factors affecting stock production from those inferred to occur over the last 20 yr; the time span over which these production parameters were estimated.

EQUILIBRIUM YIELD

For each of the two temperature conditions, as well as a weighted average of the two extremes, the corresponding stock-recruit probability transition matrices were used to run the model from a nominal set of initial conditions until an equilibrium point was reached (30 yr). This was done over a range of fishing effort values. For each value of effort the corresponding mean stock and yield levels and their associated standard deviations were calculated. These results enabled us to plot equilibrium yield-effort curves for the three cases selected:

- 1) Cold year probability transition matrix = T_C ,
- 2) Warm year probability transition matrix = T_W ,
- 3) Composite probability transition matrix

$$T_I = .62 T_C + .38 T_W.$$

Thus we were able to investigate what the equilibrium yield-effort relationship might look like under a long run of cold years (the worst foreseeable conditions), a long run of warm years (the best foreseeable conditions), and a long run of "average" years (the data reflects that around 62% of the years are cold). The results are given in Figure 7 and Table 5. In all three figures, the curves displaying mean yield as a function of effort are bracketed by curves representing one standard deviation on either side of the mean. The results indicate the large variability in productivity of the stock as a function of the environmental conditions. However, one should be careful in applying the results of these runs to infer a value for MSY for whiting. These runs indicate what the levels of sustainable yield might be if environmental conditions on the spawning ground remained constant over a long period of time. However, one can readily see in Figure 4 that this certainly has not been the case over the last 40-50 yr. The longest run of consecutive cold years was 11 (1946-56) and the longest run of consecutive warm years was 5 (1956-61). The MSY level for cold years, however, provides insight into the loss of productivity during a run of cold years and provides an appropriate base stock level for protecting the fishery (i.e., the fished stock should not be allowed to fall below this level), as is discussed more fully below.

A MANAGEMENT POLICY ALGORITHM

In this section, a management policy for setting catch quotas for Pacific whiting is developed, implemented on our model, and compared with the simulated

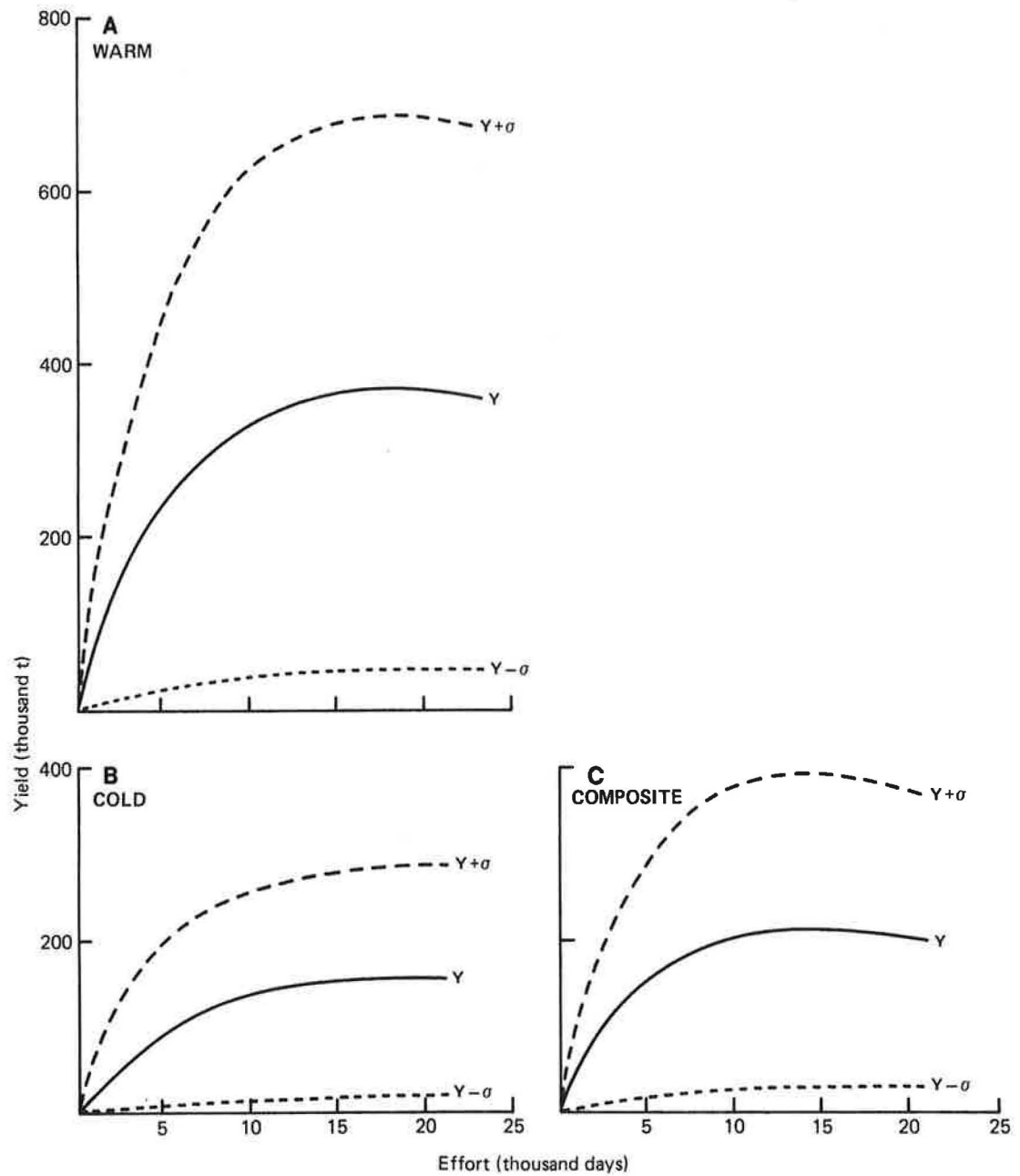


Figure 7.--Sustainable yield of Pacific whiting (\pm standard deviation) for warm, cold, and composite years.

Table 5.--Results of equilibrium yield analysis for Pacific whiting.

Environmental conditions	MSY (1000 t)	Standard dev. (1000 t)	CV	Corresponding effort (1000 days)
Cold	151	132	0.87	19.3
Warm	368	317	0.86	18.9
Composite	209	180	0.86	14.7

behavior of the stock and fishery under constant yield quota and constant effort quota management options. The aim of the new management policy is to

- 1) utilize strong year-classes in a practical and efficient manner, and
- 2) protect the stock against destabilization when it is in poor condition and environmental conditions do not appear conducive to stock improvement in the immediate future.

The algorithm is a 5-yr look-ahead algorithm in that it projects the stock 5 yr ahead from its present level. The projection uses information on temperatures over the previous 3 yr to forecast recruitment for the first 3 yr of the algorithm. The fourth year is forecast using the present year's temperature and the conditional probability that next year will be "warm" or "cold." In the fifth year of the algorithm, recruitment is projected using the composite (average) probability transition matrix.

The algorithm operates in the following way:

- 1) Define a desirable stock or that portion of the total stock which one wishes to monitor as an indicator of stock condition;
- 2) Set a catch quota for next year as high as possible under the conditions that:
 - a) the probability that the desirable stock drops below a critical lower threshold, SR_L , over the next 5 yr is very low; and
 - b) the probability that the desirable stock exceeds an upper threshold, SR_U , at the end of 5 yr is very low.

Lower and upper stopping rules are defined in the algorithm on these thresholds to indicate when an acceptable quota has been reached.

It is known that in certain fisheries pulse fishing produces greater biomass yield than sustained yield policies (Clark 1976). Our philosophy is equivalent to pulse fishing when the stock is at high levels. When the stock

is weak, instead of allowing fast stock recovery with very low catch quotas we spread the load over several fishing seasons. Thus we do not maximize biomass yield from periods of low stock levels, rather we try and insure that the fishery can remain operative during these times. Another approach might be to rely on economic conditions at the time to determine the yield rate so long as the desirable stock exceeds SR_u .

The algorithm is more formally defined as follows. Let

$S_d(t)$ = desirable stock at the end of year t .

$v(t)$ = fishing effort during year t .

v_0 = initial effort level taken as MSY effort level for average temperature conditions.

$T(t)$ = stock-recruit probability transition matrix produced from environmental conditions at the time of spawning in year t .

Y_t = yield during year t .

Δv = effort increment in algorithm.

SR_u = upper stopping rule taken as the expected equilibrium desirable stock level at MSY under average temperature conditions.

SR_L = lower stopping rule taken as the expected equilibrium desirable stock level at MSY under cold temperature conditions.

ΔSR_u = upper stopping rule increment.

Figure 8 is a graphical description of the input and output necessary to evaluate and implement the algorithm. The objective of the algorithm is to make a decision at time $t = 0$ as to what the effort and yield for year 1 [$v(1)$, $y(1)$] should be such that the conditions of the algorithm are met. Five years was chosen since that is the amount of time it takes a cohort to become fully recruited into the fishery and sexually mature. Therefore, input to the algorithm are $S_d(0)$, $\hat{T}(1)$, [$v(t)$; $t = 1, \dots, 5$] and output are [$y(t)$, $S_d(t)$; $t = 1, \dots, 5$].

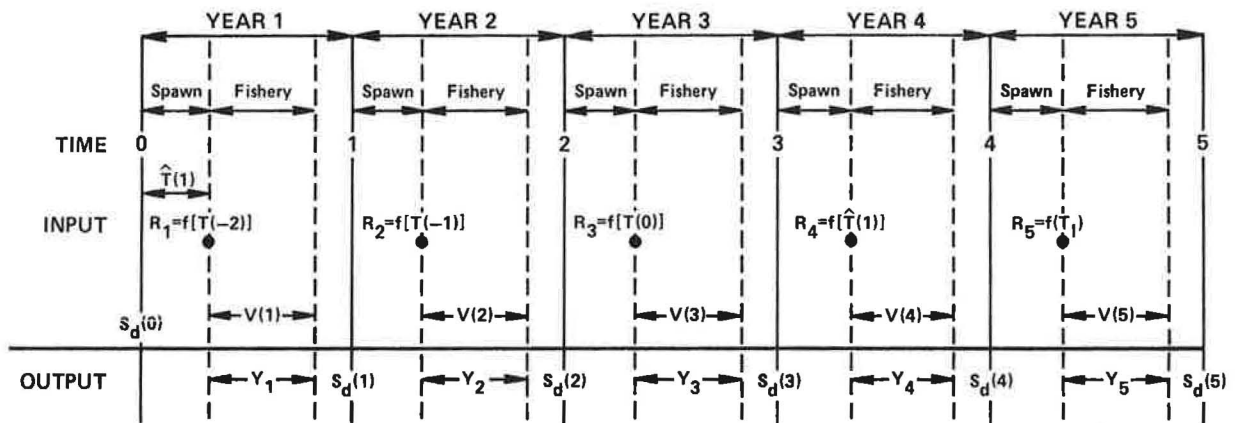


Figure 8.--Input and output data on Pacific whiting for management policy algorithm.

The algorithm operates in an iterative mode as follows until a final value of effort (v) is reached for year 1, which subsequently can be converted into a catch quota for the year.

- 1) Set SR_L and SR_U as the lower and upper stopping rules for the algorithm.
- 2) Set $v(t) = v_0$; $t = 1, \dots, 5$ --initial values for effort.
- 3) Set Δv as the increment for effort each iteration and ΔSR_U as the increment for the upper stopping rule. Then the following three paths can be followed until the algorithm is stopped:

- 1) If on iteration 1, $S_d(5) > SR_U$ and $S_d(t) > SR_L$, $t = 1, \dots, 5$
 then continue iterating $v(1) = v(1) + \Delta v$ until either
 a) $S_d(5) < SR_U$ then stop and set $v = v(1)$
 or b) $S_d(t) < SR_L$ for some t then stop and set $v = v(1) - \Delta v$
- 2) If on iteration 1, $S_d(5) < SR_U$ and $S_d(t) > SR_L$, $t=1, \dots, 5$
 then for iteration 2 set $v(t) = v(t) - \Delta v$, $t=2, \dots, 5$, and $SR_U = SR_U - \Delta SR_U$.
 If on iteration 2 $S_d(5) \geq SR_U$ then stop and set $v = v(1)$
 If on iteration 2 $S_d(5) < SR_U$
 then continue iterating $v(t) = v(t) - \Delta v$, $t=1, \dots, 5$
 and $SR_U = SR_U - \Delta SR_U$ until
 $S_d(5) \geq SR_U$, then stop and set $v = v(1)$.
- 3) If on iteration 1, $S_d(t) < SR_L$ for some t
 then continue iterating $v(t) = v(t) - \Delta v$ for all t until either
 a) $S_d(t) \geq SR_L$ $t=1, \dots, 5$ and $S_d(5) \geq SR_U$.
 then stop and set $v = v(1)$.
 or b) $S_d(t) > SR_L$ $t=1, \dots, 5$ and $S_d(5) < SR_U$.
 then continue iterating $v(t) = v(t) - \Delta v$ and $SR_U = SR_U - \Delta SR_U$
 until $S_d(5) \geq SR_U$, then stop and set $v = v(1) + \Delta v$.

RESULTS AND EVALUATION OF MANAGEMENT POLICY ALGORITHM

In order to compare a management policy based on setting quotas year by year using the management algorithm with that of instituting long-term constant catch or effort quotas, runs were made over 2 time horizons. In the first, management was instituted over a 9-yr period from 1972 to 1980. Initial conditions were those estimated to be in existence at the beginning of 1972 and recruitment at age 3 from 1972 through 1980 was affected by observed environmental conditions on the spawning grounds from 1969 through 1977. These will be referred to as short-term runs. In the second, management was instituted over a 47-yr time period, from 1934 to 1980. Initial conditions were those estimated to occur at maximum equilibrium yield under the composite probability transition matrix, and recruitment from 1934 through 1980 was affected by observed environmental conditions on the spawning grounds from 1931 through 1977 (Figure 4). These will be referred to as long-term runs. For all runs of the management algorithm, the desirable stock was the biomass of 5-yr and older animals. This decision was made because both full recruitment to the fishery and full maturity in the population appear to occur at age 5 (Bailey et al. 1981). We, therefore, decided that the critical biomass as far as the health of the stock was concerned was that of those animals 5 yr and older. Also, fish 5-yr old and older are economically preferable to younger fish. The stopping rules were determined by the levels of average desirable stock biomass which produced maximum equilibrium yield under the composite probability transition matrix ($S_d = 293 \times 10^3$ t) and that which produced maximum equilibrium yield under the cold years probability transition matrix ($S_d = 155 \times 10^3$ t).

Short-term runs--Two short-term runs of the management algorithm were made. The first is referred to as ($SR_U/SR_L =$) 293/155 and the second as 293/293. Thus

in both runs the upper stopping rule was the desirable stock level which produced "MSY" under intermediate (composite) conditions (perhaps the most realistic). In the first run, the lower stopping rule was the desirable stock level which produced "MSY" under the least favorable (cold) conditions (we felt the desirable stock should never be allowed to fall below this level), and in the second run the two stopping rules were equated. The results are presented in Figures 9 and 10 and summarized in Table 6. The average yields for these runs were 277 and 226 thousand t, respectively. Therefore, Figures 11 and 12 present the results of similar runs with constant removals (catch quotas) of 277 and 226 thousand t for comparative purposes. Perhaps the most important point that can be made is that under the management algorithm the fecund stock can be maintained at a relatively constant level with removals averaging significantly above constant catch quotas. In both the 293/155 and 293/293 runs, fecund stock is maintained at a relatively constant level; whereas in both the concomitant constant catch quota runs, fecund stock shows a definite decreasing trend. As a matter of fact, a constant removal of 277 thousand t will exhaust the stock in 1980 (Figure 11). We were surprised by how much larger the average yields under the management algorithm were than what we expected from the equilibrium yield analysis. However, if one examines environmental conditions on the spawning ground over the last 10 or 15 yr, one finds them to favor higher than average production (see Figure 4). The results of these initial runs gave us reason to make the long term runs in order to get a better idea of sustained fishery production.

Long-term runs--The runs reported in the previous section were duplicated over the 47-yr time series of environmental data on the spawning ground. The results are given in Figures 13 through 16 and summarized in Table 6. Due to the way the model was initially programmed, fecund stock rather than desirable

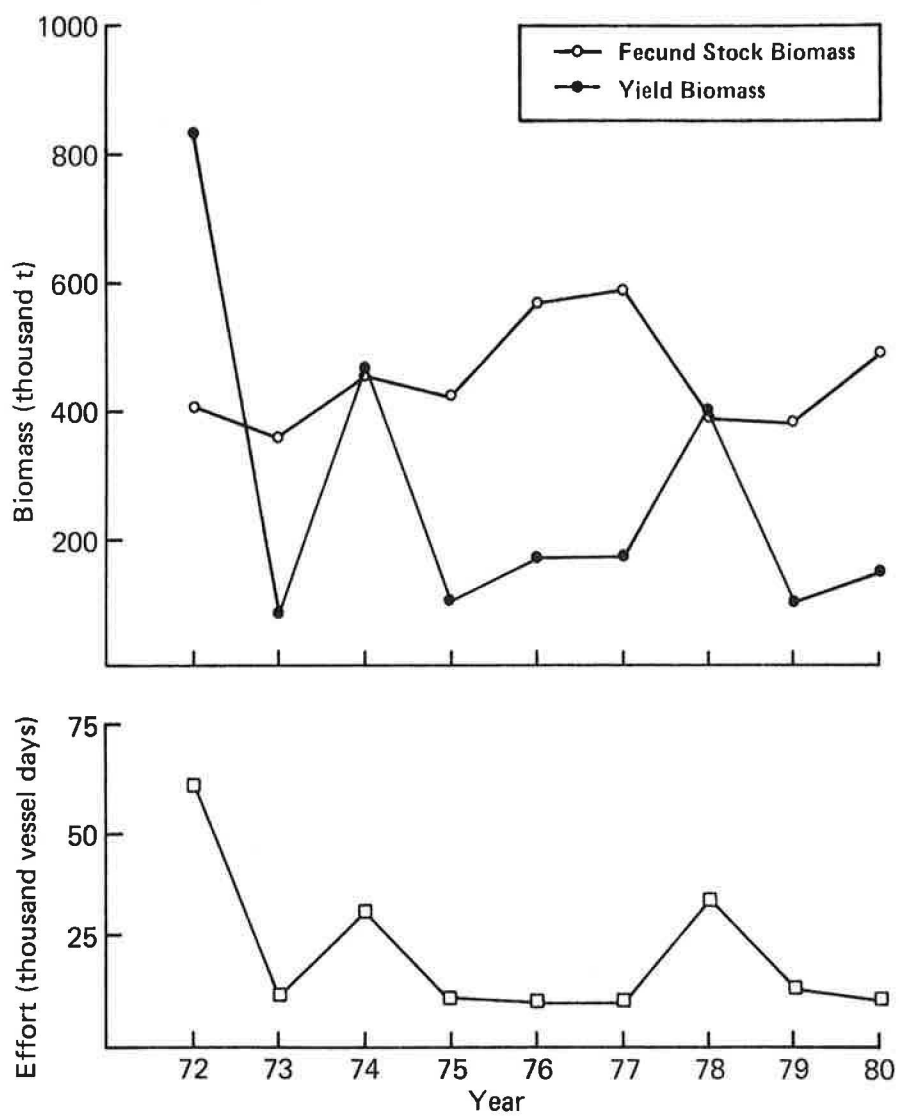


Figure 9.--Results of 1972-80 293/155 run.

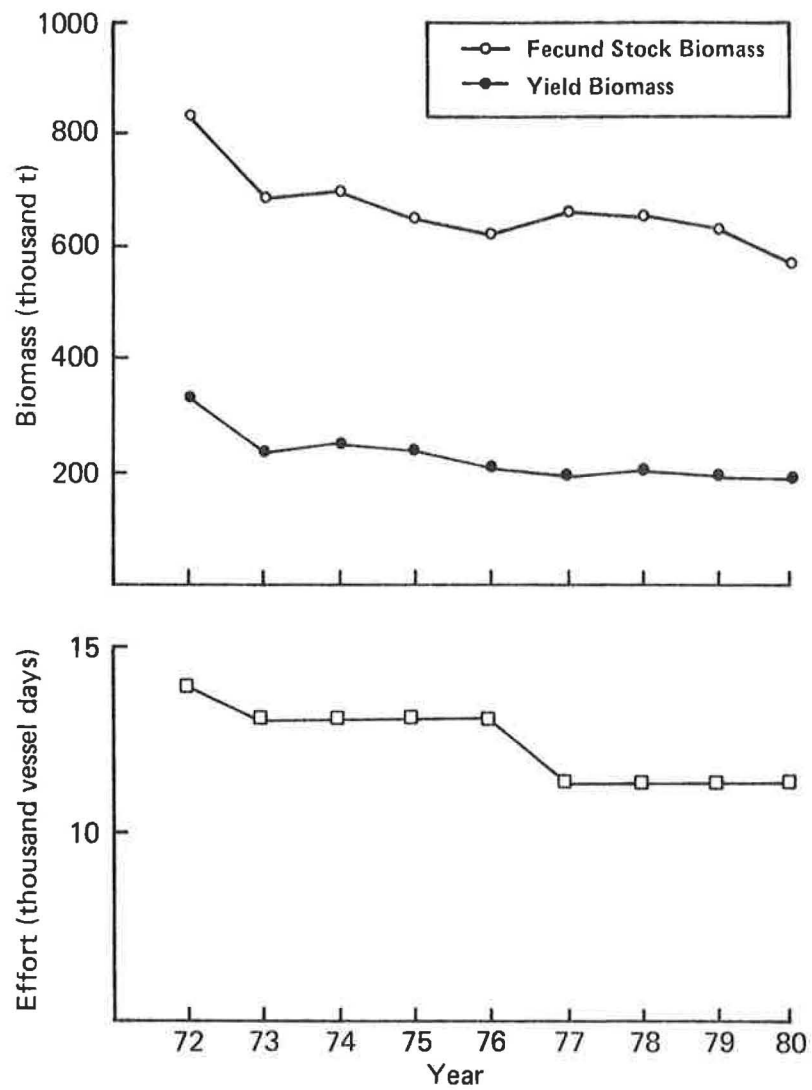


Figure 10.--Results of 1972-80 293/293 run.

Table 6.--Average catches (1000 t), effort (1000 standard days), CPUE (t/day), and coefficients of variation (in parentheses) for management runs reported in the paper.

Run	Time span	\bar{Y}	\bar{E}	\bar{Y}/\bar{E}
293/155	1972-1980	277 (.92)	21.8 (.79)	12.7
Constant Y	"	277 (0)	22.9 (.47)	12.1
293/293	1972-1980	226 (.19)	12.4 (.08)	18.1
Constant Y	"	226 (0)	11.8 (.22)	19.2
293/155	1934-1980	206 (.53)	16.8 (.56)	12.3
Constant Y	"	STOCK COLLAPSE		
293/293	1934-1980	200 (.27)	11.9 (.25)	16.8
Constant Y	"	STOCK COLLAPSE		
Constant E	"	203 (.16)	14.7 (0)	13.8
Constant Y	1934-1980	175 (0)	10.2 (.43)	17.2
400/400	"	178 (.28)	7.6 (.24)	23.4

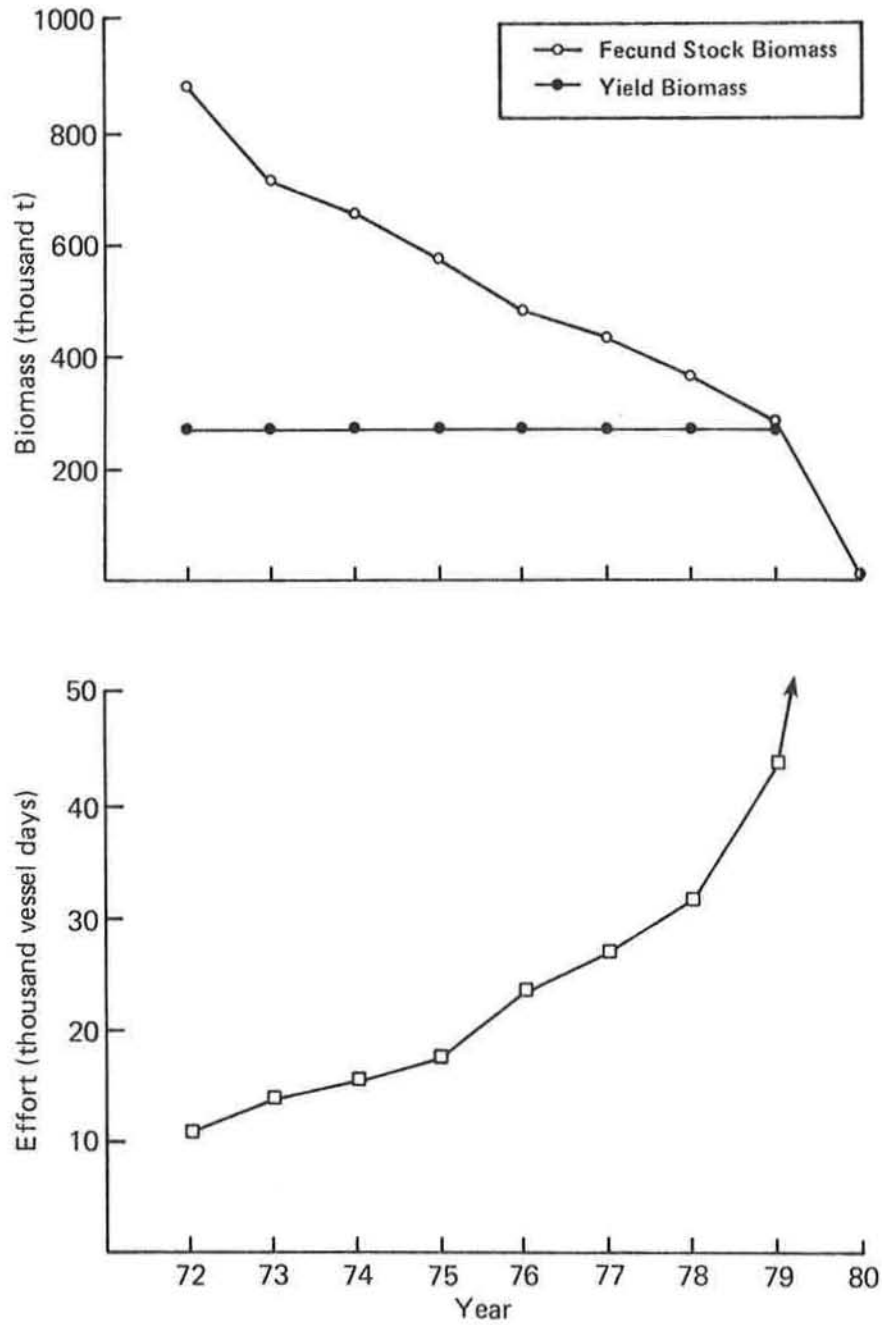


Figure 11.--Results of 1972-80 constant yield of 277 thousand t run.

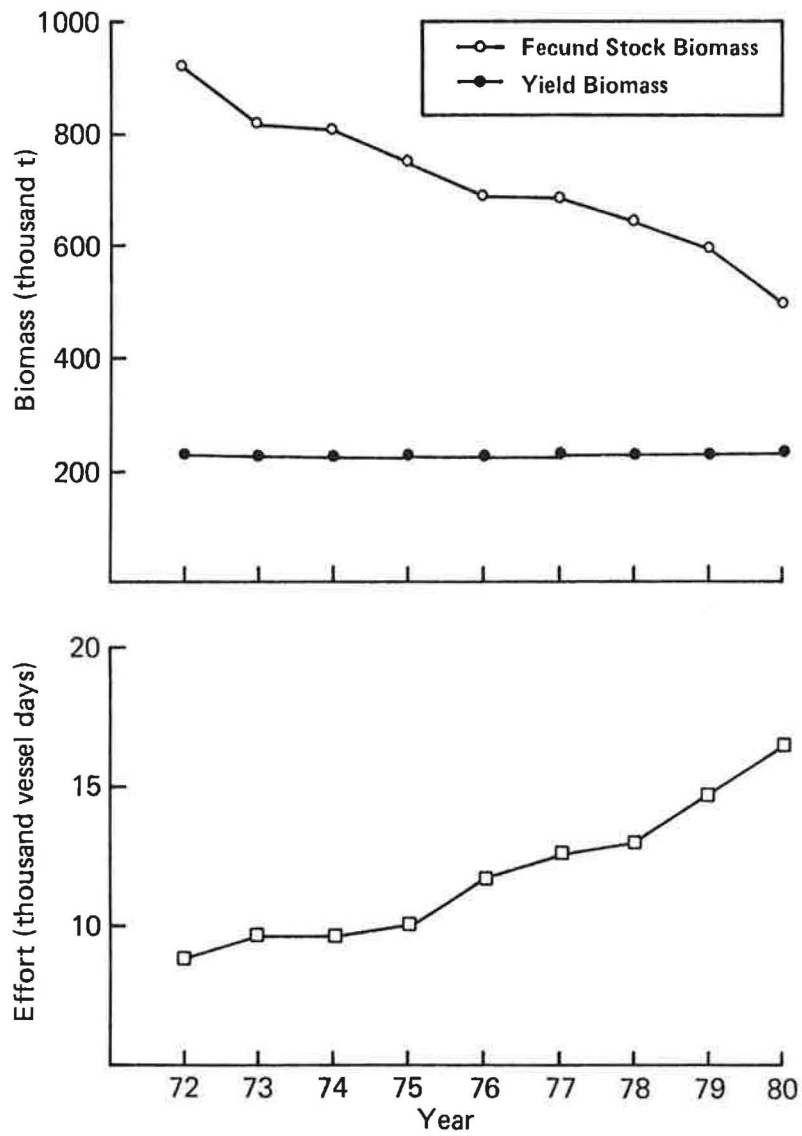


Figure 12.--Results of 1972-80 constant yield of 226 thousand t run.

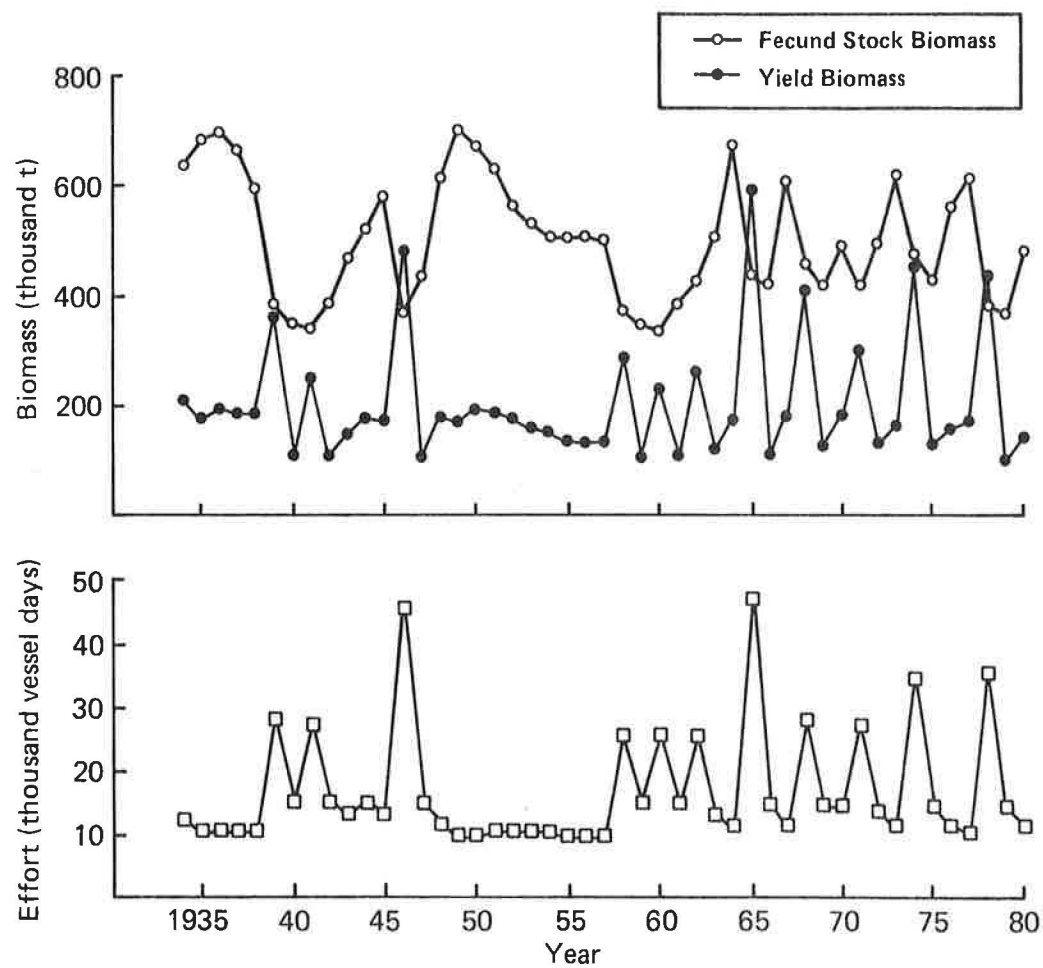


Figure 13.--Results of 1934-80 293/155 run.

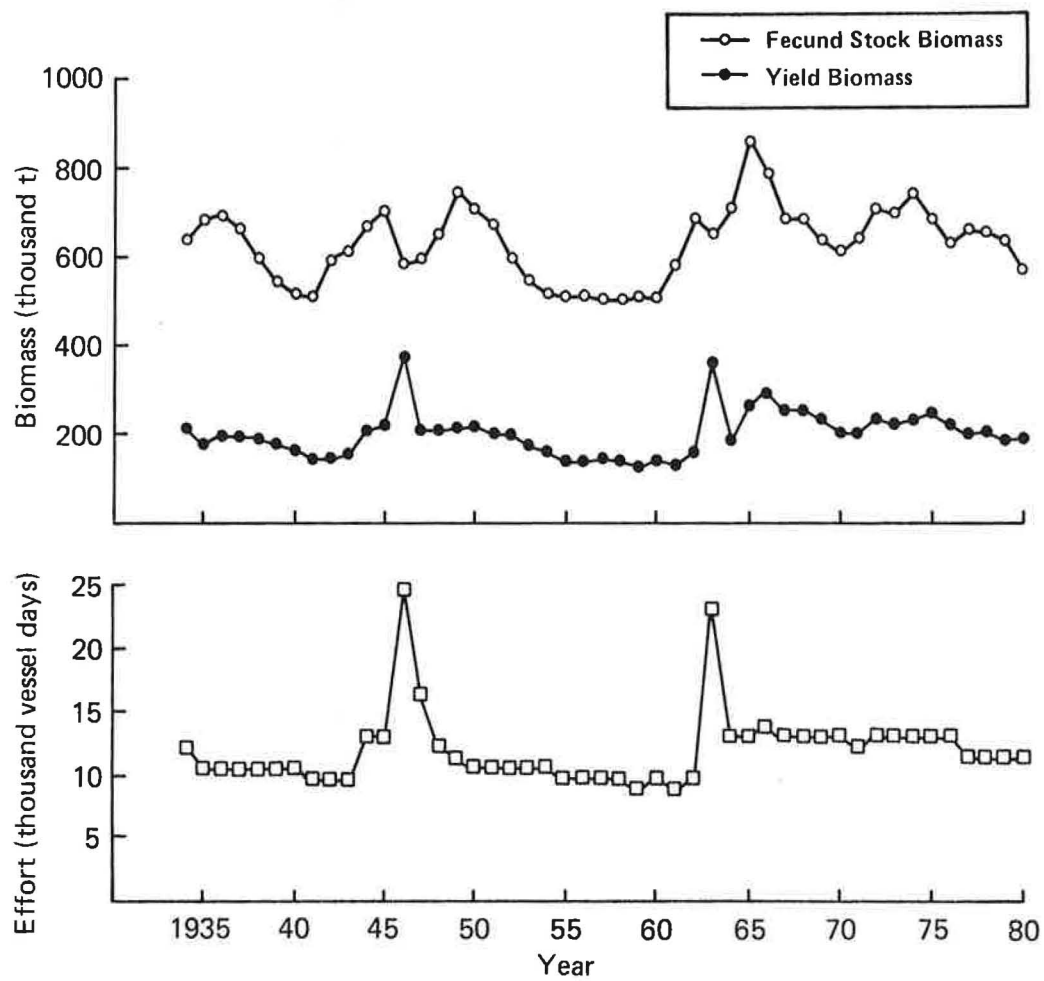


Figure 14.--Results of 1934-80 293/293 run.

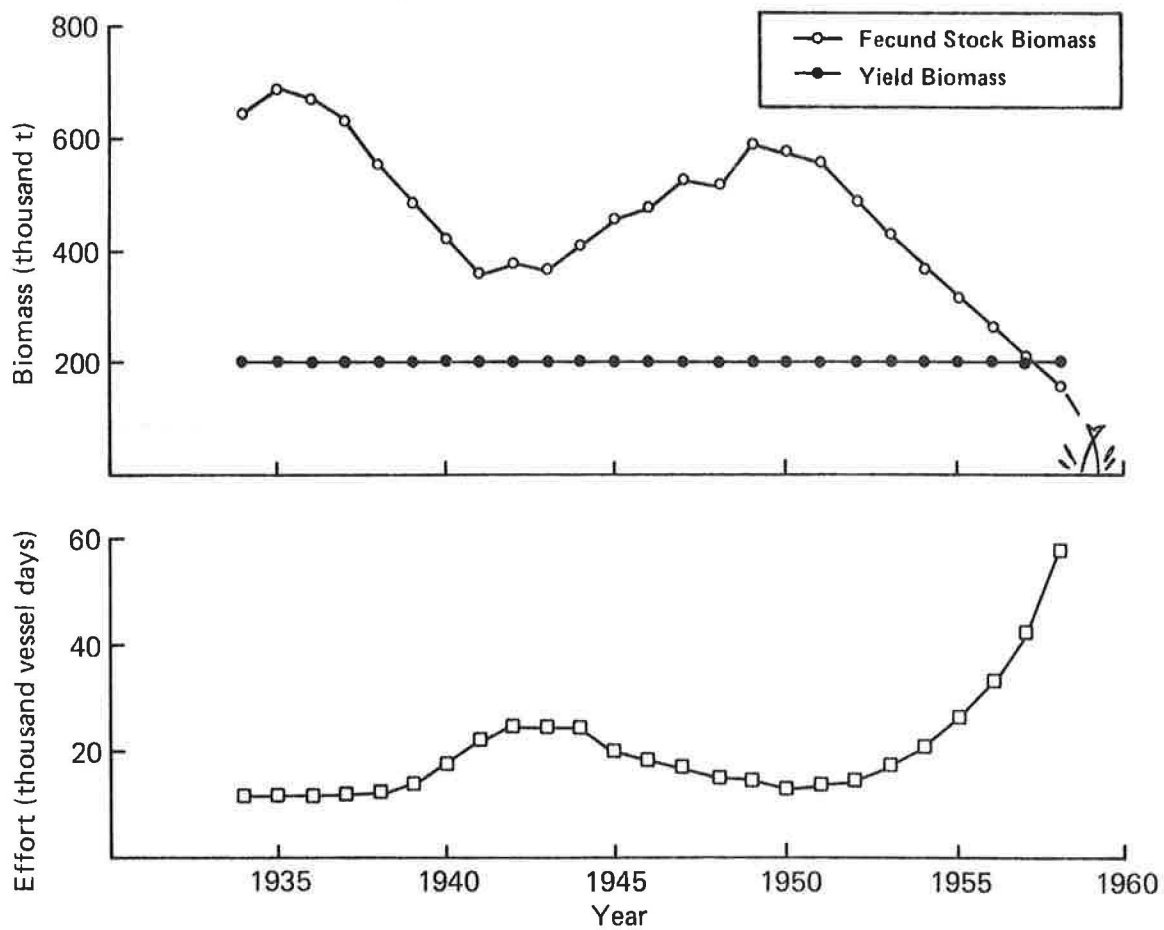


Figure 15.--Results of 1934-80 constant yield of 200 thousand t run.

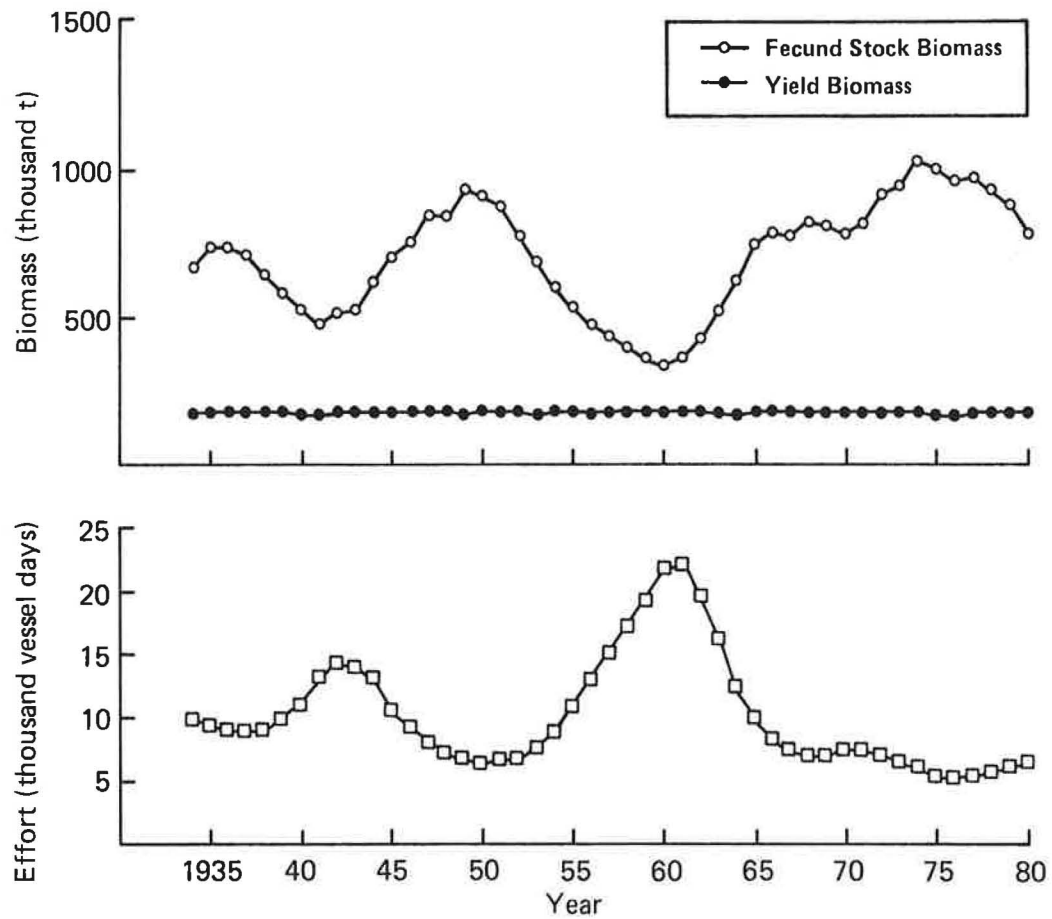


Figure 16.--Results of 1934-80 constant yield of 175 thousand t run.

stock biomasses are plotted in these figures and those that follow. The 293/293 run (Figure 14) yielded an average catch of 200 thousand t. The corresponding 200 thousand t constant catch quota run (Figure 15) decimates the stock around 1955, during the long run of consecutive cold years. A reduced constant catch quota of 175 thousand t, however, does not decimate the stock (Figure 16). The 293/155 run (Figure 13) yielded an average catch of 206 thousand t, a constant catch quota of which would have decimated the stock even earlier than 1955. The most important things to note from these runs are

- 1) The 293/293 run is certainly the most desirable of those examined over the long term in that it:
 - a) Has a significantly higher average CPUE than any of the other runs.
 - b) Produces a much more stable fishery and desirable stock than any of the other runs, a stability that one should prefer to a slightly higher average yield when the lower stopping rule is decreased (293/155-Figure 13).
 - c) Maintains the desirable (and fecund) stock at a much safer level ($B_f(t)$, never drops below around 500 thousand t in Figure 14) than any of the other runs (fecund stock, $B_f(t) < 500$ thousand t for 51% of the simulated years in Figure 13).
- 2) A policy of constant catch quotas (Figures 15 and 16) is wasteful of the surplus stock biomass during runs of favorable environmental conditions and dangerous to stock survival during runs of unfavorable environmental conditions.
- 3) To take advantage of favorable stock conditions under this algorithm requires that the fishery be able to switch to a high level of effort within a relatively short period of time (several months). Similarly, in order to protect the stock (and subsequent fishery) in times of unfavorable stock conditions, the fishery must be able to operate at reduced effort levels over several seasons. However, current knowledge of the magnitude of pre-recruit age classes,

as well as the prediction of temperature conditions on the spawning ground for the following year, help to provide lead time for both fishery managers and operators to adjust expected quota levels over a 5-yr time horizon.

Figure 17 gives the results of a 47-yr run where effort was fixed at a constant value of 14.7 thousand days per yr, the equilibrium effort level estimated to produce MSY under constant composite environmental conditions (Table 5). The resultant average yield of 203 thousand t turns out to be the maximum one can obtain under a constant 47-yr effort policy. However, a constant effort policy produces a significant reduction in efficiency of exploitation, as is reflected in both the mean and coefficient of variation of \bar{Y}/\bar{E} , from the 293/293 run of the management algorithm (Table 6).

In order to make a direct comparison of the management algorithm with a long-term constant catch quota run which does not decimate the stock, an algorithm run was made with equal upper and lower stopping rules which produced an average 47-yr yield of around 175 thousand t. This turned out to be a 400/400 run, the results of which are given in Figure 18. The important thing to note when comparing the results presented in Figures 16 and 18 is that the average efficiency of exploitation (CPUE-Table 6) is again higher with the algorithm run. In addition, the algorithm run has a significantly lower coefficient of variation of effort.

As was mentioned in the introduction, the Pacific Fishery Management Council Groundfish Management Plan (1981) states that optimum yield (OY) cannot be increased by more than 30% per yr without a plan amendment, a long and tedious process. The following table gives the absolute and percent frequency of occurrence of years where the catch increased by more than 30% during selected 47-yr management runs.

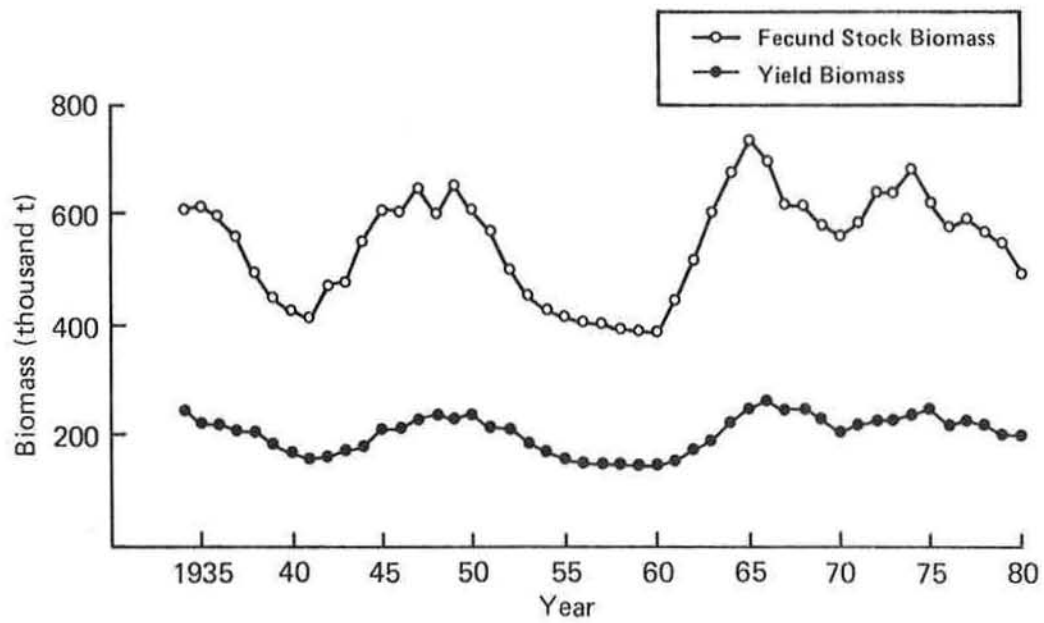


Figure 17.--Results of 1934-80 constant effort of 14.7 thousand vessel days run.

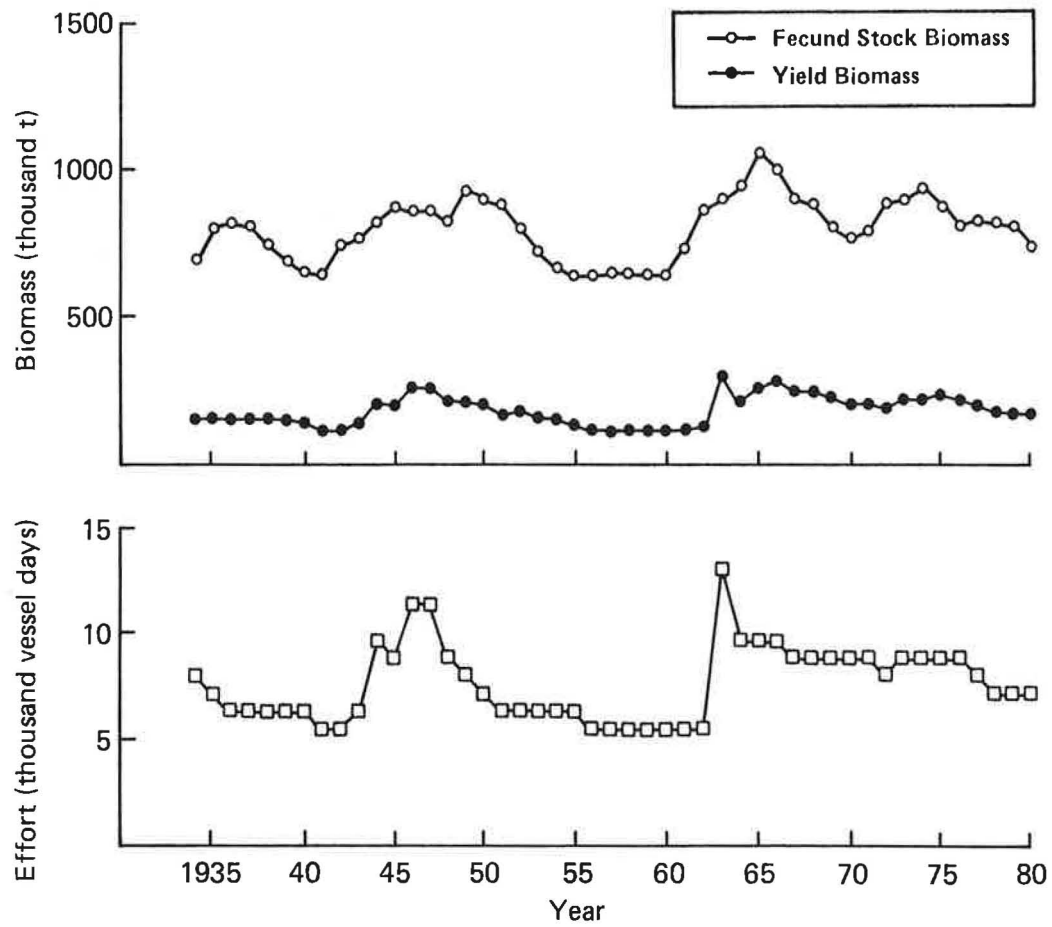


Figure 18.--Results of 1934-80 400/400 run.

47-yr run	Absolute frequency	Percent frequency
293/155	17	36%
293/293	4	9%
Constant Effort = 14.7	0	0%

Finally, the algorithm with the 293/293 stopping rules was applied to the initial conditions that would have been available to a manager at the beginning of 1977, 1978, 1979, and 1980. The initial stock conditions were drawn from the cohort analysis of Francis (1982), and the environmental conditions at the time of spawning are those used in the previous runs of the model. The results, along with the actual TAC recommended to the Pacific Fishery Management Council (U.S. TAC + 20 thousand t for the fishery in the Canadian zone) and the observed total catches, are given below in thousands of metric tons.

Year	Actual TAC	293/293 Algorithm	Total Catch
	-----thousand t-----		
1977	150	325	132
1978	150	325	104
1979	219	337	136
1980	195	284	91

The relatively high quotas predicted by the algorithm are a result of under-utilization of a relatively healthy resource in the late 1970's. The observed catches were well below those that the resource, apparently, could have sustained at that time. One should be careful to note, however, that the algorithm quotas are based on the estimated stock conditions at the beginning of each year, given the actual history of the fishery up to that point, and that, for example, if 325 thousand t had been harvested in 1977, then the stock condition

at the beginning of 1978 would have been significantly lower than that which could have sustained a 1978 harvest of 325 thousand t.

CONCLUSION

There is no question that the Getz-Swartzman model, modified to account for an appropriate environment-stock-recruitment relationship, provides a significant aid in the analysis and management of the Pacific whiting fishery, a fishery that exhibits considerable recruitment variability. In addition, it appears that the management algorithm presented in the previous section is a rational approach to the problem of taking advantage of strong year classes as they pass through the fishery while at the same time protecting the stock against potentially harmful depletion when under the dominance of weak year classes. The problem of determining if, when, and how the algorithm should be applied is up to managers of the resource. This report is an attempt to make managers aware of how a model such as this can be employed to develop alternative management policies for a resource such as Pacific whiting.

An important lesson that can be drawn from this analysis is that the concept of constant yield is rather meaningless when dealing with a resource which exhibits both short and long term variabilities in production cycles. For example, it is easy to see how an estimate of $MSY = 225-250$ thousand t could be reached for whiting due to the fact that the history of the fishery has occurred over less than a complete period of the long-term production cycle, and that, in fact, the fishery has developed during a period of environmental conditions favorable to stock production. If one were to estimate the true MSY for the entire stock as the maximum constant yield that could be removed from the stock over a long period (>20 yr) of time, this analysis

indicates that it should be no larger than 175 thousand t, the present optimum yield for the U.S. portion of the fishery.

However, the analysis presented herein indicates that if managers are willing to adjust both yield and effort on a year-to-year basis, a rather significant improvement in both average yield and average efficiency of removal (CPUE) can be attained. The bottom line of our management analysis has been to explore an approach to management of the highly variable whiting stock which uses surplus production in as efficient a manner as possible, while at the same time maintaining the productive capacity of the stock.

Our experience in this preliminary developmental work indicates that the next step in the evolution of this management tool should be a detailed sensitivity analysis of management decisions to variations in both algorithm and model parameters.

ACKNOWLEDGMENTS

This research was partially supported by the Northwest and Alaska Fisheries Center, Seattle, NMFS (Contract No. 81-ABA-2438). Discussions with Dr. Kevin Bailey contributed greatly to many of the ideas presented in this study. We thank J. Balsiger and J. Reeves for their helpful reviews of the manuscript.

REFERENCES

- Department of Commerce. 1977. Trawl fisheries of Washington, Oregon, and California--Preliminary Management Plan. U.S. Dep. Commer., Washington, D.C.
- Bailey, K.M. 1981. Larval transport and recruitment of Pacific hake, Merluccius productus. Mar. Ecol. Prog. Ser. 6:1-9.
- Bailey, K.M., R.C. Francis, and P.R. Stevens (1982). The life history and fishery of Pacific whiting, Merluccius productus. Processed Report, Northwest and Alaska Fish. Cent., Natl. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.
- Beverton, R.J.H., and S.J. Holt. 1957. On the dynamics of exploited fish populations. Ministry of Agriculture, Fisheries, and Food, London. Fish. Invest., Ser. 2, 19: 533 pp.
- Clark, C.W. 1976. Mathematical bioeconomics: The optimal management of renewable resources. John Wiley & Sons Inc., New York, N.Y.
- Cushing, D.H. 1973. Recruitment and parent stocks in fisheries. Univ. Wash., Seattle, Div. Mar. Res. Washington Sea Grant Publ. 73-1. 197 pp.
- Francis, R.C. (1982). On the population and trophic dynamics of Pacific whiting, Merluccius productus. Unpublished manuscript. Northwest and Alaska Fish. Cent., Natl. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.
- Getz, W.M., and G.L. Swartzman. 1981. A probability transition matrix model for yield estimation in fisheries with highly variable recruitment. Can. J. Fish. Aquat. Sci. 38:847-855.
- Lett, P.F., and A.C. Kohler. 1976. Recruitment: A problem of multispecies interaction and environmental perturbations, with special reference to Gulf of St. Lawrence Atlantic herring (Clupea harengus harengus). J. Fish. Res. Board Can. 33:1353-1371.

- Nelson, W.R., M.C. Ingham, and W.E. Schaaf. 1977. Larval transport and year-class strength of Atlantic Menhaden, Brevoortia tyrannus. Fish. Bull., U.S. 75:23-41.
- Pacific Fishery Management Council. 1981. Fishery management plan and supplemental environmental impact statement for the Washington, Oregon, and California groundfish fishery. Pacific Fishery Manage. Council., Portland, Oregon.
- Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Bull. Fish. Res. Board Can. 191, 382 p.
- Sissenwine, M.P. 1977. A compartmentalized simulation model of the southern New England yellowtail flounder, Limanda ferruyinea, fishery. Fish. Bull., U.S., 75:465-482.
- Swartzman, G.L., W.M. Getz, R.C. Francis, R. Haar, and K. Rose. 1982. A management analysis of the Pacific whiting fishery using an age-structured stochastic recruitment model. Unpubl. manuscr. Cent. Quant. Sci. For., Fish., and Wildl; Univ. Wash.; Seattle, WA 98115.
- VanWinckle, W., B.L. Kirk, and B.W. Rust. 1979. Periodicities in Atlantic Coast striped bass (Morone saxatilis) commercial fisheries data. J. Fish. Res. Board Can. 36:54-62.
- Walters, C.J. 1969. A generalized computer simulation model for fish population studies. Trans. Am. Fish. Soc. 98:505-512.
- Walters, C.J. 1981. Optimum escapements in the face of alternative recruitment hypotheses. Can. J. Fish. Aquat. Sci. 38:678-689.