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Optimal Harvesting Policies for the Widow Rockfish Fishery

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Abstract.—We developed optimal harvesting policies for the widow rockfish *Sebastes entomelas* fishery using a microcomputer-based age-structured model. We compared traditional constant effort policies to more complex escapement policies (control of spawning stock size) using three criteria: the difficulty of estimating policy parameters, the average harvest obtained, and the variability in harvest. Substantial computational effort was required to obtain optimal estimates for the two-parameter escapement policies, and a single run usually required 24 h or more to complete on a microcomputer. Conservative escapement policies were similar in form and in performance to constant effort policies. Mean harvest under the least-conservative escapement policy was only about 2% greater than mean harvest under a constant effort policy, yet variability in harvest increased by 49%. For stocks where density dependence is not strong, we suggest that only minor improvement will be gained through the use of two-parameter escapement policies.

Harvest guidelines for multiaged fish stocks traditionally have been based on either constant catch or constant effort policies. Both of these policies can be viewed as special cases of a more general harvesting policy proposed by Ruppert et al. (1984):

$$h = \begin{cases} \gamma(S - \delta)^{\theta} & \text{if } S > \delta \\ 0 & \text{otherwise;} \end{cases} \tag{1}$$

h is harvest, S is stock size, and γ, δ, and θ are policy parameters. The parameter δ represents the minimum acceptable stock size; the fishery would be closed whenever $S \leq \delta$. An advantage of this more general harvesting policy is that an optimization routine can be used to determine which type of policy is most appropriate for a particular fishery and management objective. Special cases of interest are policies that provide constant catch ($\theta = 0$) or approximately constant effort ($\delta = 0$, $\theta = 1$) or escapement ($\theta = 1$, $\delta > 0$, γ properly chosen) (Ruppert et al. 1985).

Although it is possible to estimate the optimal values of all three parameters, more might be learned about policy behavior by fixing θ at several different levels (Ruppert et al. 1984). An advantage of setting $\theta = 1.0$ is that harvest will then be a linear function of stock size. A disadvantage is that annual fluctuations in harvest will tend to be large, and for that reason, $\theta = 0.5$ has also been used as a more conservative alternative (Ruppert et al. 1984, 1985).

The objective of this study was to develop optimal harvesting policies for the widow rockfish *Sebastes entomelas* fishery. These policies were obtained by using a microcomputer-based age-structured model. We compared traditional constant effort policies with escapement policies obtained by using equation (1). Policy performance was evaluated on the basis of average harvest obtained, variability in harvest, and the difficulty in obtaining parameter estimates.

History of the Fishery

Landings of widow rockfish were small prior to 1979 because processors believed that this fish had several negative characteristics, including a short shelf life for both fresh and frozen products and poor quality of the defrosted product (Ueber 1987). Advances in fishing and processing techniques around 1978 resulted in improved marketability. Widow rockfish fillets began to be sold in volume, and there were few complaints about quality (Ueber 1987). Landings increased rapidly to a peak of 27,691 tonnes in 1981, then declined to about 10,000 tonnes in 1983–1985 (Table 1). The rapid decline in harvest can be attributed not only to the reduction in stock size due to fishing, but also to restrictions on harvest implemented by the Pacific Fishery Management Council (PFMC). The annual quota, referred to as optimum yield (OY), was based on an estimate of acceptable biological catch (ABC) but sometimes exceeded ABC due to nonbiological considerations (Table 1). The ABC is determined annually and may be lower or higher than maximum sustained yield, depending on the current condition of the stock (PFMC 1982).

Assessment during this early phase of the fishery was difficult not only because historical catch data were not available, but also because tradi-

TABLE 1.—Total weight landed (Lenarz and Hightower in PFMC 1985), optimal yield (OY), and acceptable biological catch (ABC), in tonnes, for widow rockfish in the Washington–Oregon–California fishery, 1979–1986 (PFMC 1985).

Year	Total landings	OY	ABC
1979	4,941		
1980	20,390		
1981	27,691		
1982	26,513	26,000	16,800[a]
1983	10,211	10,500	10,500
1984	9,722	9,300	9,300
1985	9,023[b]	9,300	7,400
1986		10,200[b]	9,300

[a]Gunderson (1984).
[b]Preliminary reports from the Pacific Fishery Information Network (PacFIN).

tional bottom-trawl surveys provided little information about this pelagic stock (PFMC 1982). In one respect, however, management is simpler than for most species in the Pacific coast groundfish fishery. The midwater fishery for widow rockfish is highly directed, with minimal bycatch, so restrictions on harvest do not directly affect catches of other species.

Methods

Estimating Model Parameters

Lenarz and Hightower[1] used cohort analysis (Murphy 1965) of the 1980–1984 catch-at-age data to estimate age-specific fishing mortality (F) for widow rockfish. A separate analysis was done for natural mortalities (M) of 0.15 and 0.20 (assumed to be lower and upper bounds for M). For this study, we scaled 1980–1984 average age-specific fishing mortalities so that relative vulnerability ranged from 0 to 1 (Table 2). Using those values as catchability coefficients, fishing effort corresponded to the F at ages 9 and 10, the estimated ages at which fishing mortality is greatest (and assumed to be equal). Length at age was obtained as an average of values from sex-specific von Bertalanffy growth curves (Lenarz 1987). Weight at age was then obtained from a pooled length–weight relationship (Barss and Echeverria 1987; Table 2). We obtained an index of fecundity (Table 2) by multiplying weight at age and percent maturity (Barss and Echeverria 1987).

Lenarz and Hightower[1] used a deterministic model to represent the spawner–recruit relationship, and they assumed that the number of age-4 recruits (x_4) and the size of spawning stock were either independent or weakly dependent. For this study, we considered only the latter, more conservative assumption because the optimal harvest-maximizing policy may not exist if recruitment is assumed to be constant. We used a stochastic version of the model and obtained an estimate of variability in recruitment by fitting the model

$$x_4 = \mu \exp(v);$$

μ represents mean recruitment, and v represents a normally distributed random variate with mean 0 and variance σ^2. An estimate of σ^2 was obtained

[1]Lenarz, W. H., and J. E. Hightower. 1985. Status of the widow rockfish fishery. This document is included in an annual report published by the Pacific Fishery Management Council (PFMC 1985). It contains a detailed description of assessment methods as well as landings data, catch-at-age data, and age-specific estimates of fishing mortality and population size obtained from cohort analysis.

TABLE 2.—Parameter estimates for an age-structured model of the widow rockfish fishery. Number-at-age vectors at the beginning of 1986 were obtained from results of cohort analysis for assumed natural mortalities (M) of 0.15 or 0.20. Parameter estimates for the Beverton–Holt spawner–recruit relationship were α = 0.0472, β = 0.8560, and lognormal error variance σ^2 = 0.8665 for M = 0.15; α = 0.0365, β = 0.6336, and σ^2 = 1.0438 for M = 0.20.

Age years	Fecundity index[a]	Weight (kg)	Catchability[b] M = 0.15	Catchability[b] M = 0.20	Number at age (millions) M = 0.15	Number at age (millions) M = 0.20
4	0.000	0.4	0.038	0.036	21.7	30.9
5	0.075	0.5	0.179	0.176	18.4	25.1
6	0.102	0.6	0.499	0.494	2.4	2.2
7	0.490	0.7	0.716	0.715	8.3	7.9
8	0.711	0.9	0.886	0.887	16.6	15.6
9	0.950	1.0	1.000	1.000	8.9	8.3
10	1.067	1.1	1.000	1.000	1.2	1.1
11	1.164	1.2	0.826	0.835	0.9	0.8
12	1.300	1.3	0.601	0.614	0.4	0.4
13+	1.600	1.6	0.601	0.614	9.6	8.7

[a]Fecundity index = weight × proportion mature.
[b]Catchability = vulnerability to fishing (1.0 = fully recruited).

as the variance of $\log_e(x_4)$. We then obtained estimates of the parameters α and β for a Beverton–Holt spawner-recruit curve of the form,

$$x_4 = 1/(\alpha + \beta/S),$$

by assuming that (1) the spawning stock in 1980 was representative of the spawning stock prior to exploitation (S_∞); (2) μ was an estimate of recruitment at S_∞; and (3) recruitment would be reduced by 10% if spawning stock was reduced by 50% from S_∞. This approach was used because we did not have sufficient data on spawning stock size and recruitment to estimate α and β directly. Because few studies have shown a statistically significant relationship between spawning stock size and recruitment (Hennemuth 1979), we viewed the above approach as a conservative way of estimating the productivity of the fishery.

Model of the Fishery

The number-at-age vector in year $k + 1$ ($x[k+1]$) was obtained from $x[k]$ by using the following equations:

$$x_{i+1}[k+1] = x_i[k] \exp(-M - q_i f[k]);$$
$$k = 0, \ldots, N - 1;$$
$$i = 4, \ldots, \lambda - 2;$$

$$x_\lambda[k+1] = x_{\lambda-1}[k] \exp(-M - q_{\lambda-1} f[k]) + x_\lambda[k] \exp(-M - q_\lambda f[k]);$$

$x_i[k]$ = number of age-i fish in year k;
λ = maximum age-class used in the model;
q_i = catchability coefficient for age-i fish;
M = annual instantaneous natural mortality (assumed to be constant over all ages);
$f[k]$ = level of fishing effort in year k.

Fishing effort was permitted to vary from 0 to $f_{\max}$; $f_{\max}$ was assumed to be 1.0 for widow rockfish. Harvest in year k was defined as

$$h[k] = \sum_{i=4}^{\lambda} x_i[k]\, w_i\, q_i\, f[k] \cdot \{1 - \exp(-M - q_i f[k])\}/(M + q_i f[k]);$$

w_i was the average weight of age-i fish.

Optimization Methodology

We identified the constant effort policies that maximized harvest by simulating the fishery at effort levels ranging from 0.0 to 1.0. Each simulation was 65 years in length, or five times λ, the maximum age-class used in the model. Using a replication–deletion approach (Law and Kelton 1982), we estimated mean harvest from the last 33 harvests of each 65-year period for each of 100 replicates. This approach was used to minimize the influence of the starting conditions.

A 65-year horizon also was used to obtain parameter estimates for the escapement policies. We did a limited number of optimization runs using shorter and longer planning horizons but found that the optimal policy for a 25-year horizon was to deplete the stock. Results for a 100-year horizon were similar to those reported here.

Following Ruppert et al. (1984, 1985), we defined an optimal escapement policy (control of spawning potential) as one that maximized harvest, $\Sigma h[k]$, or log-harvest, $\Sigma\log_e(h[k] + 1)$; harvest was determined from equation (1) and spawning stock size was used as a measure of spawning potential. These management objectives were selected to represent extremes along a risk continuum, representing willingness to accept risk (and fluctuations in harvest) for $\Sigma h[k]$ and extreme risk aversion for $\Sigma\log_e(h[k] + 1)$ (Ruppert et al. 1985).

Because the escapement rule determines only total harvest, the fishing mortality that produce that harvest must be determined iteratively. We used Newton's method (Dew and James 1983) to determine fishing effort as

$$f_{j+1} = f_j - (h_j - h[k])/h'[k];$$

f_j is the level of fishing effort at step j in the iterative sequence, h_j is the jth estimate of $h[k]$, and $h'[k]$ is the derivative of $h[k]$ obtained at $f = f_j$. We obtained acceptably accurate estimates more quickly using Newton's method than using a binary search but, nevertheless, simulation runs with an escapement rule took substantially longer than runs with constant effort.

We used an iterative approach termed stochastic approximation to estimate optimal values of γ and δ (Ruppert et al. 1984, 1985). The approach we used was essentially equivalent to the approach Ruppert et al. (1984) used, except our version was intended for use with several species so it was slightly less specific. Default starting values for γ and δ were obtained by using a deterministic version of the model to (1) solve iteratively for the level of fishing effort producing maximum sustained yield (f_{msy}), (2) determine h_{msy} and S_{msy}, and (3) obtain $\gamma = h_{msy}/S^{\theta}_{msy}$ for $\delta = 0$. To account for the effect of a lognormal error term, expected recruitment was estimated as

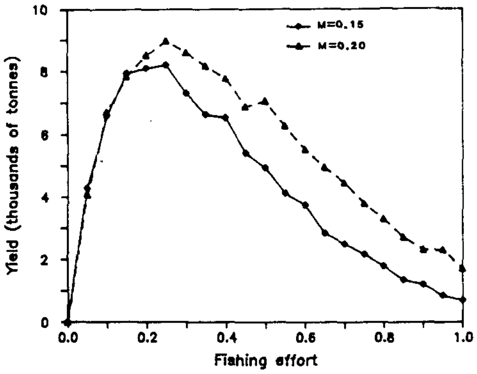

FIGURE 1.—Relationship between yield and fishing effort (fishing mortality for fully recruited fish) for widow rockfish at two levels of natural mortality (M).

$$1/(\alpha + \beta/S)\ \exp(\sigma^2/2).$$

This modification was used because $\exp(\sigma^2/2)$ was the expected value of the lognormal random variate $\exp(\nu)$; ν was normally distributed with mean 0 and variance σ^2 (Hogg and Craig 1978). The assumption that $\delta = 0$ was used to begin the search in the region where closures would be infrequent. In addition, setting δ to 0 insured that the starting policy would perform similarly to a constant effort policy, a type that has performed well in earlier optimization studies (Swartzman et al. 1983; Getz 1985). This starting point worked reasonably well in the cases we examined even though final δ values were not necessarily close to 0. It was important to obtain good starting estimates of γ and δ; otherwise, the estimate of the Hessian (matrix of second derivatives) was poor, and estimates of γ and δ converged slowly or not at all. Because the optimum for the deterministic model differed from that for the stochastic model, we refined the starting estimates of γ and δ using a steepest ascent approach (Kiefer and Wolfowitz 1952) before attempting to estimate the Hessian. (The optimization and simulation routines used in this study are incorporated into the microcomputer program GENMOD. Copies of this program can be obtained from the American Fisheries Society Computer Users Section library.)

Results and Discussion

Steady-state yield under the constant effort policies appeared to be highest when effort (F_9) was about 0.25 (Figure 1), and that value was used in the comparative studies that follow. The relationship between yield and effort was similar for both values of natural mortality. In previous studies with a deterministic model, Lenarz and Hightower[1] suggested that F_9 should be about 0.30. Results were slightly more conservative in this study because the constant recruitment case was not considered.

Optimal parameter estimates for the escapement policies were difficult to obtain on a microcomputer, often requiring several hundred iterations that took 24 h or more to complete. The run length can be attributed, in part, to the stringency of the stopping rule (Ruppert et al. 1984) and to the use of an iterative routine to obtain fishing mortality. However, the primary reason was that nine 65-year simulation runs were made at each iteration to numerically estimate the first and second derivatives of harvest with respect to γ and δ. These derivatives were used in the stochastic approximation routine to obtain updated estimates of the parameters (Ruppert et al. 1984). Our observations regarding the number of iterations required were similar to those of Ruppert et al. (1984), although the implications were greater in our study because we were using microcomputers.

For the harvest-maximizing policies, we obtained similar values for δ with $\theta = 0.5$ and $\theta = 1.0$ (Table 3; Figure 2). To better understand the implications of different δ values, we estimated steady-state spawning stock at constant levels of fishing effort ranging from 0.0 to 1.0 (Figure 3). Results for both levels of natural mortality suggested that spawning stock could drop below 25,000 tonnes periodically, because average spawning stock was only about 40,000 tonnes when fishing at the MSY level ($F_9 = 0.25$). Thus, under any of the four harvest-maximizing policies, occasional closures would be expected. Using additional simulation studies, we estimated that the fishery would be closed from 0.8 to 14.8% of the time if a harvest-maximizing policy was used (Figure 4).

Our results for the log-harvest policies when $\theta = 1.0$ were similar to those obtained by Ruppert et al. (1985) in that δ was less than 0, so no closure could occur under that policy (Table 3; Figure 2). Closures would be unexpected for $\theta = 0.5$ because a spawning stock of about 10,000 tonnes would correspond to a fishing mortality rate of twice the optimal level (Figure 3). These results are in agreement with those of earlier studies in that policies for maximizing log harvest limit

TABLE 3.—Parameter estimates for the optimal harvesting policies, estimate of steady-state mean harvest, coefficients of variation (CV = 100 × SD/mean) for harvest in the final year of the planning horizon (year 65, or 2051), and recommended harvests for widow rockfish in 1986 for assumed natural mortalities (M) of 0.15 or 0.20. Parameters θ and γ are dimensionless; δ, mean harvest, and recommended 1986 harvest are given in thousands of tonnes.

Policy	θ	γ	δ	Mean harvest	CV in year 65	Recommended 1986 harvest
			M = 0.15			
Constant effort				7.79	39	8.62
Log_e(harvest)	0.5	1.569	12.893	7.73	35	8.78
Log_e(harvest)	1.0	0.181	−3.508	7.79	38	8.63
Harvest	0.5	2.581	27.373	7.97	49	10.57
Harvest	1.0	0.643	25.018	7.96	58	12.31
			M = 0.20			
Constant effort				8.63	48	8.04
Log_e(harvest)	0.5	1.727	11.075	8.40	40	9.53
Log_e(harvest)	1.0	0.218	−3.203	8.52	49	9.75
Harvest	0.5	3.658	26.960	8.82	69	13.95
Harvest	1.0	0.674	20.707	8.80	68	14.01

variability in harvest and reduce the frequency of closure (Mendelssohn 1982; Deriso 1985; Ruppert et al. 1985).

The short-term management implications of the five optimal policies were examined by determining the recommended 1986 harvest under each policy. Results from the escapement policies for maximizing log harvest (Table 3) were in good agreement with the earlier recommendation that the acceptable biological catch be set at 9,300 tonnes (Table 1). Results for the harvest-maximizing policies suggested that the 1986 harvest could be somewhat higher; however, the penalty for increased harvest would be increased variability in harvest (Table 3). Fishermen have often stressed the importance of continuity in harvest regulations; thus, we believe that more weight should be given to the more conservative policies for maximizing log harvest.

We evaluated the long-term performance of the escapement policies by comparing the results with

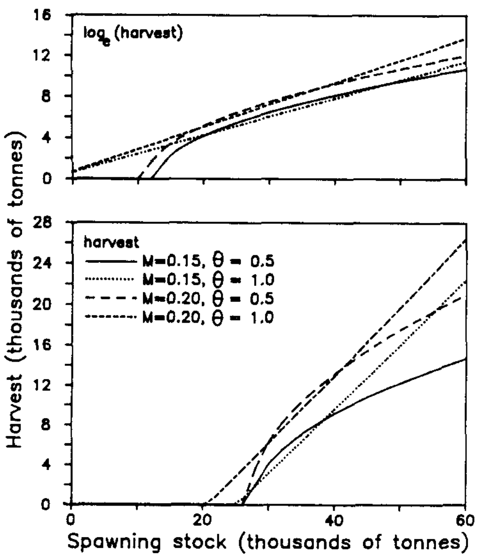

FIGURE 2.—Escapement policies for maximizing $\log_e$ (harvest) and harvest obtained for widow rockfish at two levels of natural mortality (M) and two values for the policy parameter θ.

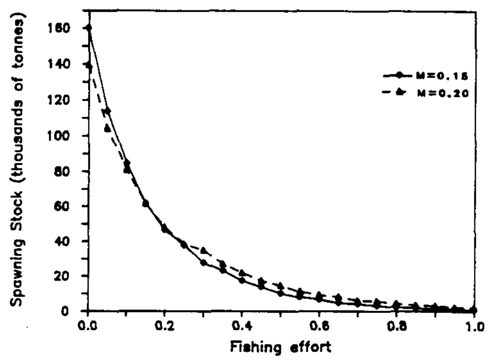

FIGURE 3.—Relationship between mean spawning stock and fishing effort (fishing mortality for fully recruited fish) for widow rockfish at two levels of natural mortality (M).

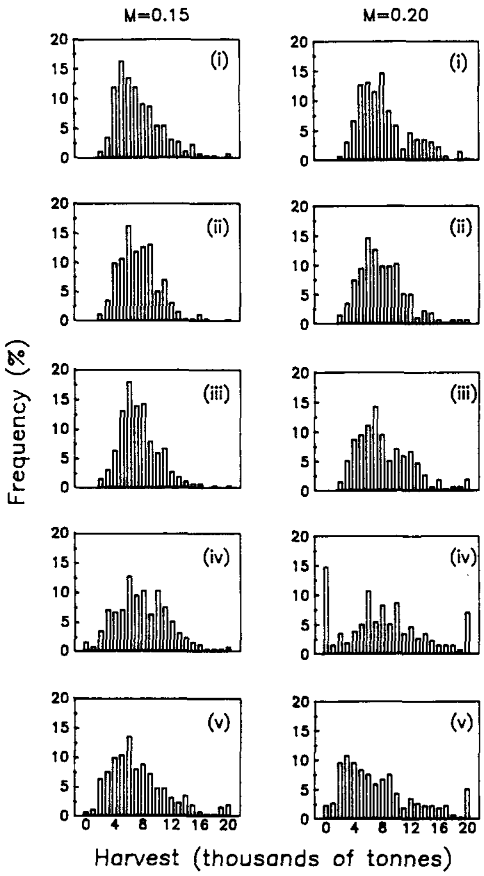

FIGURE 4.—Frequency distributions for annual harvests of widow rockfish obtained at two levels of natural mortality (M) with the use of (i) constant effort policies, (ii) policies for maximizing $\log_e$(harvest) with policy parameter $\theta = 0.5$ and (iii) $\theta = 1.0$, and (iv) policies for maximizing harvest with $\theta = 0.5$ and (v) $\theta = 1.0$. Each sample distribution is based on 250 independent observations of harvest in year 65.

those of constant effort policies. In each case, mean harvest was estimated from 250 replicate 65-year simulations by the replication–deletion approach described earlier (Table 3). We also calculated the coefficients of variation for harvest in year 65 as a measure of year-to-year variability in harvest. A common random-number stream was used at each level of natural mortality so that differences in mean harvest could be attributed directly to differences in policy performance. Our results indicate that, for widow rockfish, mean harvest under the least conservative escapement policy was only about 2% greater than mean harvest under a constant effort policy. This small increase in harvest was accompanied by a 49% increase in the variability of harvest. Under the most conservative escapement policy, both mean harvest and variability in harvest were slightly lower than under the constant effort policy. For the log-escapement policies with $\theta = 1.0$, results were quite similar to those from constant effort policies. Similar performance would be expected because the policies for maximizing log harvest were similar in form to constant effort policies (Figure 2), and because constant effort policies maximize log harvest for some models (Deriso 1985).

Much better relative performance for the escapement policies was reported by Ruppert et al. (1985), who examined the same five policies for the Atlantic menhaden *Brevoortia tyrannus* fishery. They reported that steady-state yield was nearly 20% higher under the four escapement policies than under the optimal constant effort policy. Variability in yield was comparable for the constant effort policy and three of the four escapement policies, with a considerably higher variance for the least conservative escapement policy (maximize harvest, $\theta = 1.0$).

Results more similar to ours were obtained by Swartzman et al. (1983) in simulation studies of the Pacific hake[2] *Merluccius productus* fishery. They compared the optimal constant effort policy to several "policy algorithms" in which harvest depended on an index of stock size. The intent of the policy algorithm was to fully exploit strong year classes but to protect the stock when in poor condition. Mean harvest under a constant effort policy was comparable to that obtained under the policy algorithms, and variability in harvest was considerably lower. The policy algorithms did maintain a higher catch per effort than did the constant effort policy, which illustrates that one cannot manage simultaneously for high yields, low variability in yield, and high catch per effort.

To better understand the relationship between different types of harvesting policies, we used simulation studies to compare alternative policies of the form

$$h = b_0 + b_1 S; \qquad (2)$$

that is, equation (1) with $b_0 = -\gamma\delta$, $b_1 = \gamma$, and $\theta = 1.0$ (Hilborn 1985). Following Hilborn (1985),

[2]Marketed as Pacific whiting.

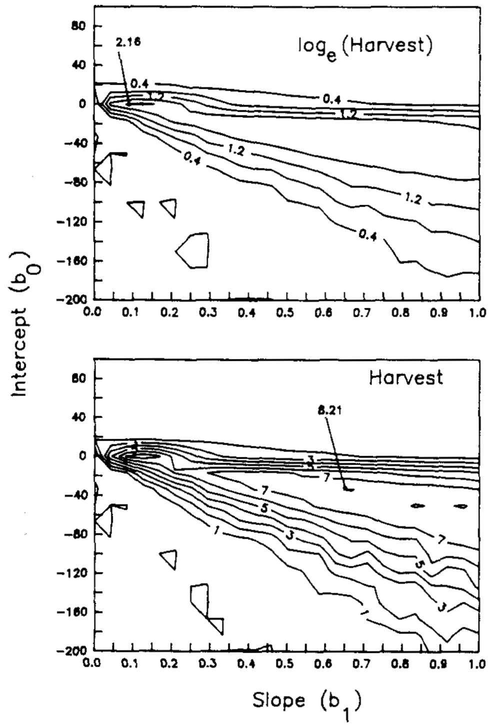

FIGURE 5.—Contour plots of average $\log_e$(harvest) and harvest for widow rockfish based on the harvesting policy $h = b_0 + b_1S$, for which h and S represent harvest and stock biomass, respectively. Points 2.16 and 8.21 represent maximum values for average $\log_e$(harvest) and harvest, respectively. These plots were obtained by assuming a natural mortality rate (M) of 0.15; results for M = 0.20 were similar and are not shown here.

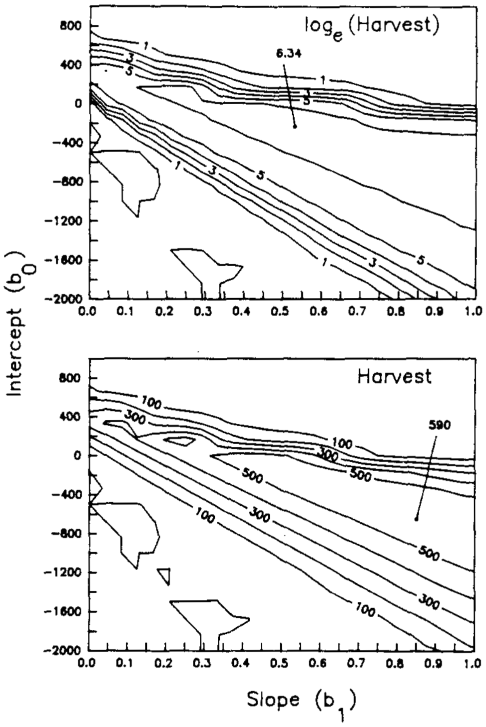

FIGURE 6.—Contour plots of average $\log_e$(harvest) and harvest for Atlantic menhaden based on the harvesting policy $h = b_0 + b_1S$, where h and S represent harvest and stock biomass, respectively. Points 6.34 and 590 represent maximum values for average $\log_e$(harvest) and harvest, respectively.

we used total stock biomass as S and examined a grid of policies for $b_0 = -S_{max}$ to S_{max} and b_1 = 0.0 to 1.0. We obtained an estimate of S_{max}, the equilibrium stock biomass in the absence of fishing, from a deterministic model using the estimate of expected recruitment described earlier. As was the case for equation (1), there are several policies of special interest: constant catch ($b_1 = 0$, $b_0 > 0$); approximately constant effort ($b_0 = 0$); and constant escapement ($b_1 = 1$, $b_0 < 0$) (Hilborn 1985).

By plotting contours for average harvest or log harvest, the relative performance of alternative types of policies can readily be seen (Hilborn 1985). Each contour plot in Figures 5 and 6 represents a grid of 625 policies that was obtained by varying both b_0 and b_1 over 25 evenly spaced levels. For each policy, an estimate of mean harvest and mean log harvest was obtained from 10 replicate simulation runs, each of which was 5λ years in length. In the region about the optimum, we used 100 replicates per point to obtain a smoother surface, but found, as did Hilborn (1985), that the results were essentially equivalent to those from 10 replicates. Our results also indicated that, if the only objective was to locate those policies that maximized harvest or log harvest, the search could have been restricted to the set of policies where

$$b_0 + b_1(1.5S_{msy}) > 0, \text{ and}$$
$$b_0 + b_1(0.5S_{msy}) < S_{msy}.$$

This range was obtained by assuming that the optimal stock size would be ±50% of S_{msy} and that the equilibrium harvest under that policy would be greater than 0 but less than S_{msy}. Substantial computational effort can be saved by restricting the search to this region, although less information would be obtained about suboptimal policies. Reducing computational effort is worthwhile when microcomputers are used because about 21 h were required to calculate all 625 points when 10 replicates per point were used.

The harvest-maximizing policy for widow rockfish was neither a constant effort nor constant escapement policy, but rather an intermediate form (Figure 5). When log harvest was plotted, the peak of the response surface shifted away from constant escapement policies, and the policy that maximized log harvest was a constant effort policy. These results are in general agreement with the more refined estimates obtained in the optimization studies. Mean harvest was similar although the best policies from the contour plots were slightly inferior (about 2%) to those obtained in the optimization studies.

For comparison, we also simulated the Atlantic menhaden fishery, using a simpler model (Hightower and Grossman 1985) than that used by Ruppert et al. (1985). We found that the harvest-maximizing policy for Atlantic menhaden was more similar to a constant escapement policy than was the policy for widow rockfish (Figure 6). This is a reasonable result because our Atlantic menhaden model incorporated a dome-shaped (Ricker) spawner–recruit relationship, whereas the widow rockfish model used a weak Beverton–Holt relationship. When a dome-shaped curve is used, the optimal policy may be to maintain constant escapement in order to produce a particular level of recruitment. There would be less incentive for maintaining a constant stock size when a Beverton–Holt curve is used. Using a simpler population model, Deriso (1985) suggested that constant effort policies maximize log harvest except in cases where the recruitment curve is dome-shaped. The policy that maximized log harvest for Atlantic menhaden was intermediate in form (Figure 6). It should be noted, however, that differences in performance were less than 1% among constant effort, constant escapement, and intermediate policies.

Results from the contour plots and optimization studies both showed that, for widow rockfish, the two-parameter harvesting policies (equation 1 with θ fixed or equation 2) provided only a negligible increase in mean harvest over the simpler constant effort policies. Furthermore, the increase in harvest would be accompanied by a much greater proportional increase in the variability of harvest. We also failed to detect any increase in harvest for Atlantic menhaden, although our model differed in several respects from the model used by Ruppert et al. (1985). They used a Beverton–Holt spawner–recruit relationship and a different error term, as well as density-dependent functions for both weight and fecundity. These results suggest that improvement in harvest may depend on model formulation or, ultimately, on how accurately the model represents the fishery. For stocks where density dependence is not strong, we suggest that only minor improvement will be gained through the use of two-parameter harvesting policies.

Acknowledgments

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References

Barss, W. H., and T. W. Echeverria. 1987. Maturity of widow rockfish *Sebastes entomelas* from the northeastern Pacific 1977–1982. NOAA (National Oceanic and Atmospheric Administration) Technical Report NMFS (National Marine Fisheries Service) 48:13–18.

Deriso, R. 1985. Risk adverse harvesting strategies. Lecture Notes in Biomathematics 61:65–73.

Dew, P. M., and K. R. James. 1983. Introduction to numerical computation in Pascal. Springer-Verlag, New York.

Getz, W. M. 1985. Optimal and feedback strategies for managing multicohort populations. Journal of Optimization Theory and Applications 46:505–514.

Gunderson, D. R. 1984. The great widow rockfish hunt of 1980–1982. North American Journal of Fisheries Management 4:465–468.

Hennemuth, R. C. 1979. Man as predator. Pages 507–532 *in* G. P. Patil and M. L. Rosenzweig, editors. Contemporary quantitative ecology and related ecometrics. International Cooperative Publishing House, Fairland, Maryland.

Hightower, J. E., and G. D. Grossman. 1985. Comparison of constant effort harvest policies for fish stocks with variable recruitment. Canadian Journal of Fisheries and Aquatic Sciences 42:982–988.

Hilborn, R. 1985. A comparison of harvest policies for mixed stock fisheries. Lecture Notes in Biomathematics 61:75–87.

Hogg, R. V., and A. T. Craig. 1978. Introduction to mathematical statistics, 4th edition. Macmillan, New York.

Kiefer, J., and J. Wolfowitz. 1952. Stochastic estimation of the maximum of a regression function. Annals of Mathematical Statistics 23:462–466.

Law, A. M., and W. D. Kelton. 1982. Simulation modeling and analysis. McGraw-Hill, New York.

Lenarz, W. H. 1987. Ageing and growth of widow rockfish. NOAA (National Oceanic and Atmospheric Administration) Technical Report NMFS (National Marine Fisheries Service) 48:31–35.

Mendelssohn, R. 1982. Discount factors and risk aversion in managing random fish populations. Canadian Journal of Fisheries and Aquatic Sciences 39:1252–1257.

Murphy, G. 1965. A solution of the catch equation. Journal of the Fisheries Research Board of Canada 22:191–202.

PFMC (Pacific Fishery Management Council). 1982. Final fishery management plan and supplemental environmental impact statement for the Washington, Oregon, and California groundfish fishery. PFMC, Portland, Oregon.

PFMC (Pacific Fishery Management Council). 1985. Status of the Pacific Coast groundfish fishery through 1985 and recommended acceptable biological catches for 1986. PFMC, Portland, Oregon.

Ruppert, D., R. L. Reish, R. B. Deriso, and R. J. Carroll. 1984. Optimization using stochastic approximation and Monte Carlo simulation (with application to harvesting of Atlantic menhaden). Biometrics 40:535–545.

Ruppert, D., R. L. Reish, R. B. Deriso, and R. J. Carroll. 1985. A stochastic population model for managing the Atlantic menhaden (*Brevoortia tyrannus*) fishery and assessing managerial risks. Canadian Journal of Fisheries and Aquatic Sciences 42:1371–1379.

Swartzman, G. L., W. M. Getz, R. C. Francis, R. T. Haar, and K. Rose. 1983. A management analysis of the Pacific whiting (*Merluccius productus*) fishery using an age-structured stochastic recruitment model. Canadian Journal of Fisheries and Aquatic Sciences 40:524–539.

Ueber, E. 1987. Widow rockfish fishery. NOAA (National Oceanic and Atmospheric Administration) Technical Report NMFS (National Marine Fisheries Service) 48:53–56.