Abstract.–Optimal harvesting policies were developed for a model of the Washington-Oregon-California trawl fisheries for bocaccio *Sebastes paucispinus*, chilipepper *S. goodei*, widow rockfish *S. entomelas*, splitnose rockfish *S. diploproa*, and shortbelly rockfish *S. jordani*. In the simulated management system, the annual quota for each species was based on an intended fishing mortality rate (F) and an estimate of stock biomass. Traditional constant F policies were compared with variable F policies in which F was a linear function of either stock biomass (single-species) or the combined biomass of all other species (multispecies). Variable F policies were ineffective for increasing total harvest of all species combined, when compared with constant F policies. However, both single-species and multispecies variable F policies were found to reduce the variance for total harvest substantially with no significant loss in yield. The reduction in variance was roughly equal to the reduction that would be achieved by lowering the coefficient of variation (CV) for biomass estimates from 50% to 25% or from 25% to 0%. The reduction in variance generally was greater for the multispecies than for the single-species variable F policy. Compared with the case where CV = 0%, average total yield was reduced slightly for both constant F and variable F policies when CVs for biomass estimates were greater than 0%.

Multispecies Harvesting Policies for Washington-Oregon-California Rockfish Trawl Fisheries

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In the Washington-Oregon-California (WOC) trawl fisheries for rockfish (*Sebastes* spp.), the landings are comprised of many species, including bocaccio *S. paucispinus*, chilipepper *S. goodei*, Pacific ocean perch *S. alutus*, canary rockfish *S. pinninger*, widow rockfish *S. entomelas*, and yellowtail rockfish *S. flavidus* (PFMC 1982). There is little evidence of substantial biological interaction among the adults of these species. Technological interactions (Pope 1979) are significant in the shelf rockfish fishery (Pikitch 1987), which accounts for most of the landings of bocaccio, chilipepper, and canary and yellowtail rockfish. Fishermen have some control over the species composition of the catch in this fishery by varying the areas or depths fished. The other significant rockfish fishery is the midwater trawl fishery for widow rockfish. Catches of other rockfish species are negligible in that fishery.

Most currently marketed *Sebastes* species have similar or equal value to fishermen; consequently, fishermen are more concerned about the aggregate yield than about the species composition of the catch. Thus, it seems reasonable to ask whether efforts to vary the annual proportions harvested for these species would result in benefits to the resource or to the fishing industry. For example, reducing the variability of annual quotas has been an important concern for the west coast fishing industry. The objective of this study was to evaluate multispecies harvesting policies for the WOC trawl fisheries for rockfish to determine whether total yield (all species combined) can be increased or the variance for total yield can be reduced. Specifically, I compared the performance of policies obtained using (1) risk-neutral and risk-averse objective functions, (2) constant and variable fishing mortality rates (F), and (3) abundance estimates for a single species or multiple species.

Except for widow rockfish, relatively little is known about the population dynamics of these stocks. For that reason, this study should be viewed as an exploratory analysis of alternative harvesting policies, and not as a basis for regulatory changes by the Pacific Fishery Management Council. It may be worthwhile to develop similar harvesting policies for Council review once we have adequate life-history information about the commercially important groundfish stocks. The harvesting policies examined in this study should be useful in other cases where fishermen derive income from several species and have some control over the species composition of the catch.

Methods

This section provides an overview of the model structure, harvesting policies, and life-history data. A detailed description of methods is provided elsewhere (Hightower 1990).

I developed optimal harvesting policies for two-, three-, and five-

species models in order to evaluate changes in policy performance as additional species were included. The selected species (bocaccio, chilipepper, widow rockfish, splitnose rockfish *S. diploproa*, and shortbelly rockfish *S. jordani*) all occur off California, support or could support significant commercial fisheries, and have a wide range of life-history types. I used bocaccio and chilipepper for the two-species model because they were estimated to have similar biomass levels. I included widow rockfish for the three-species model because it was estimated to have about twice the maximum sustainable yield level of biomass of bocaccio and chilipepper. For the five-species model, shortbelly and splitnose rockfish were added as examples of relatively short- and long-lived rockfish species, respectively. Shortbelly rockfish biomass also is substantially higher than that of the other four species.

Model structure

I used Schnute's (1985) generalization (eq. 2.7) of Deriso's (1980) delay-difference model to represent the dynamics of each stock:

$$B_t = (1 + \rho)S_{t-1}B_{t-1} - \rho S_{t-1}S_{t-2}B_{t-2}$$
$$+ R_t - \rho(v/V)S_{t-1}R_{t-1} \qquad (1)$$

where B_t was the fishable population biomass at the beginning of year t; S_t was the survival rate in year t; ρ, v, and V were parameters for the growth curve; and R_t was the recruitment biomass at the beginning of year t. Growth parameters ρ, v, and V were estimated by fitting the following curve relating mean weight at age a (w_a) to age:

$$w_a = v + (V - v)(1 - \rho^{1+a-k})/(1 - \rho) \qquad (2)$$

where V and v were parameters representing mean weight at the age of recruitment (age k) and at age k − 1, respectively, and ρ was a parameter describing the growth rate (Schnute 1985, eq. 1.14). Following Kimura et al. (1984), I assumed that B_0 (needed to calculate B_2) equaled the starting biomass level B_1.

Recruitment was calculated from a Beverton-Holt stock-recruitment curve (Kimura 1988):

$$R_{t+k} = R_\infty(B_t/B_\infty)/(1 - A(1 - B_t/B_\infty)) \exp(z_t) \qquad (3)$$

where R_∞ was the virgin recruitment level associated with virgin stock biomass B_∞, A was the level of density-dependence assumed in the stock-recruitment relationship, and $\exp(z_t)$ was the lognormal error term used to introduce random variability in recruitment. Estimates of A were not available for any of the stocks

used in this study. To introduce a degree of density-dependence into the model, I assumed arbitrarily that recruitment decreased by 10% when spawning stock decreased by 50%. That assumption has been used in earlier stock-assessment studies (Lenarz 1984, Henry 1986, Methot and Hightower 1988, Tagart 1988) to obtain harvest recommendations assumed to be conservative when information on the stock-recruitment relationship was unavailable. The normal random variate z_t was assumed to have mean 0 and variance σ^2. I assumed that $R_1 .. R_k$ were produced by a stock equal in size to B_1 because the actual B values producing those year-classes were not known.

Harvesting policies

In the harvesting policies used in this study, the annual fishing mortality rate for species j in year t ($F_j[t]$) was either a constant

$$F_j[t] = b_{j,0} \qquad \text{(constant F),} \qquad (4)$$

a function of stock biomass

$$F_j[t] = b_{j,0} + b_{j,1} B_j[t] / B_{\infty,j} \qquad \text{(variable F),} \qquad (5)$$

or a function of the combined biomass of all other stocks

$$F_j[t] = b_{j,0} + b_{j,1} \sum_{i \neq j} B_i[t] / \sum_{i \neq j} B_{\infty,i},$$

$$\text{(multispp. var. F)} \qquad (6)$$

Policies (5) and (6) were similar in form to a linear model Hilborn (1985) used to calculate catch as a function of stock biomass. Biomass estimates were scaled by virgin biomass so that the policy parameters were relatively independent of absolute biomass levels. Estimates of the policy parameters ($b_{j,0}, b_{j,1}; j = 1, .., s$ species in model) were obtained using stochastic approximation (Ruppert et al. 1984).

Objective functions

As in earlier optimization studies (Ruppert et al. 1984, Hilborn 1985), I obtained policies for maximizing total catch

$$\max_t \sum C[t], \text{ where } C[t] = \sum_j C_j[t]$$

(maxh objective function)

and the natural logarithm of total catch

$$\max \sum_t \log(C[t]) \qquad \text{(logh objective function)}.$$

For most of the WOC trawl fisheries, the goal of the Pacific Fishery Management Council is to maximize long-term average yield by maintaining F at a specified level. Thus the maxh objective function corresponds to the current approach to management. Relative to maxh policies, logh policies tend to provide less variable catches so they may be more appropriate in fisheries where price is sensitive to volume, the fishery provides a substantial fraction of a fisherman's annual income, or stability of volume is critical for marketing reasons (Deriso 1985). Mendelssohn (1982) and Ruppert et al. (1985) used maxh and logh policies to represent extremes along a risk continuum, in that maxh policies are risk-neutral (marginal utility does not change with increasing catch) and logh policies are risk-averse (marginal utility decreases with increasing catch).

I also evaluated a third more conservative objective function for maximizing an exponential function of total catch:

$$\max \sum_t (1 - \exp(-C[t]/\delta)) \quad \text{(negx objective function)}$$

where δ was a scaling factor (Raiffa 1968). At small values of δ (relative to $C[t]$), the marginal utility of additional units of catch decreases rapidly. If δ is large, utility increases linearly with increasing catch. In order to obtain highly risk-averse policies, I used $\delta = 5$ for $C[t]$ values of about 5 (2-species case) to 30 (5-species case). Using this δ value, negx policies were even more conservative than logh policies (Fig. 1). Of course, other objective functions (and harvesting policies) could be chosen that would provide greater reductions in the variance of catch. For example, Murawski and Idoine (1989) compared a series of constant-catch harvesting policies for Georges Bank haddock *Melanogrammus aeglefinus*. For a sufficiently low target catch (45% of the average catch under a constant $F = F_{0.1}$ policy), year-to-year variability in catch was zero. The logh and negx objective functions used in this study were intended to provide a compromise between maximizing catch and minimizing variability of catch.

Planning horizon

The optimization studies were done using a 100-year planning horizon in order to obtain steady-state harvesting policies. In the two- and three-species cases, the bocaccio, chilipepper, and widow rockfish stocks declined to varying degrees at the start of the planning horizon but reached steady-state levels by about year 50 (Fig. 2). In the five-species case, sharp initial
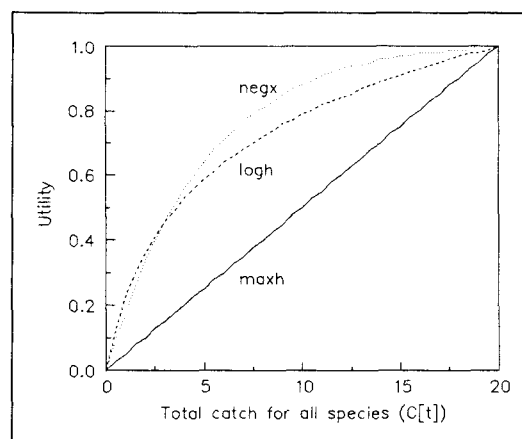

Figure 1
Alternative measures of the utility of the total rockfish catch in year t (C[t]), as determined by objective functions maxh:Utility(C[t]) = C[t], logh:Utility(C[t]) = log$_e$(C[t]), and negx:Utility(C[t]) = 1 – exp(–C[t]/5). Utilities for each objective function were scaled to a maximum value of 1.

declines were noted for the unexploited splitnose and shortbelly rockfish stocks. Because of its long life-span and slow growth-rate, the splitnose rockfish stock continued to decline throughout the planning horizon. Based on a series of optimization runs, I found that the constant F for splitnose rockfish that maximized mean harvest decreased as the horizon length increased for policies up to 200 years in length. Planning horizons greater than 100 years were impractical, however, due to computing costs. Therefore, in order to obtain results that were not dependent on the length of the planning horizon, I obtained policies for the five-species model using a 75-year transient phase within a 100-year horizon (Law and Kelton 1982). Using this approach, the objective function was based only on harvests in years 75–100. Steady-state biomass levels were reached within 100 years for all species except possibly splitnose rockfish; thus, declines in stock size at the start of the planning horizon were due only to high initial biomass levels (Fig. 3).

Errors in biomass estimates

Most of the harvesting policies evaluated in this study required biomass estimates for one or more species in order to calculate the policy Fs used to determine the annual quotas. To evaluate the practicality of these policies, I introduced a random error term so that the harvesting policy and resultant catch quota in year t were based on simulated estimates $B'_1[t]..B'_s[t]$ of
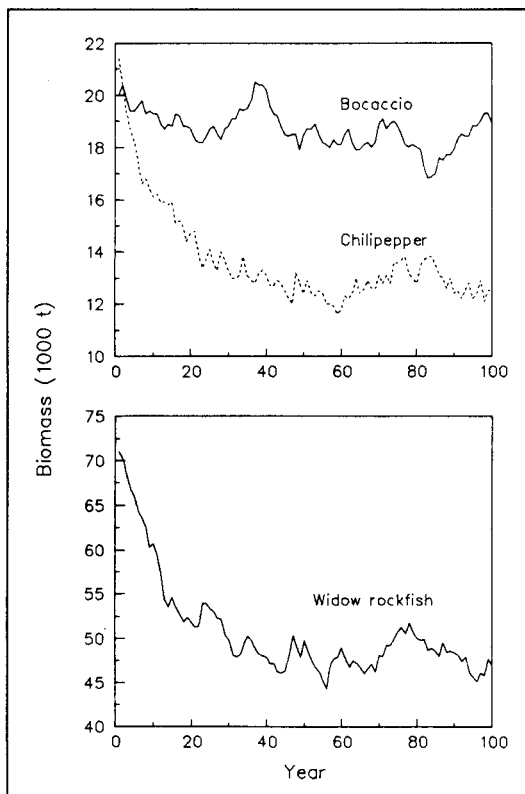
Figure 2

Mean rockfish biomass from 100 replicate 100-year simulation runs for the three-species model, using the constant fishing mortality rates that maximized harvest and assuming that the coefficient of variation for biomass estimates was 0. Results for the two-species model with only bocaccio and chilipepper were similar and are not shown here.
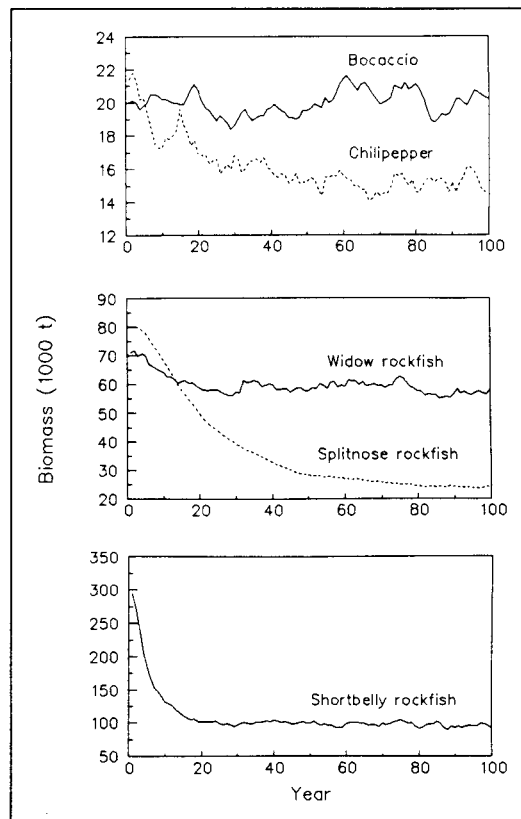

Figure 3

Mean rockfish biomass from 100 replicate 100-year simulation runs for the five-species model, using the constant fishing mortality rates that maximized harvest and assuming that the coefficient of variation for biomass estimates was 0.

the actual biomass levels $B_1[t] . . B_s[t]$. Following an assumption made by Pope and Gray (1983) regarding data used in stock assessments, I assumed that errors in biomass estimates were lognormally distributed and independent over time. The coefficient of variation (CV) for biomass estimates was either 0, 25, or 50%, based on a review of the stock-assessment literature (Rivard 1981, Pope 1983, Pope and Gray 1983, Sen 1984, Weinberg et al. 1984, Methot 1986).

Because the WOC trawl fisheries for rockfish are regulated through catch quotas, F' (the policy F based on estimates $B'_1[t] . . B'_s[t]$) was used to calculate the annual quota $C_j[t]$ as $B'_j[t]F'_j[t](1 - \exp(-M_j - F'_j[t])/Z'_j[t]$. $B_{\infty,i}$ (the virgin biomass level used in the variable F policies) and M_j were assumed to be known without error. The actual F required to obtain $C_j[t]$

from $B_j[t]$ ($F_j[t]$) was either higher or lower than the intended F ($F'_j[t]$), depending on the direction and magnitude of errors in $B'_1[t] . . B'_s[t]$.

Life-history information

The reliability of the parameter estimates (Table 1) varies, depending on the length and magnitude of the historical fishery for each species. A significant fishery for widow rockfish developed in 1979, with average 1980–85 landings of 17200 t (Hightower and Lenarz 1986). Fisheries for bocaccio and chilipepper have existed for decades; average 1980–85 landings were 3200 t for bocaccio and 1700 t for chilipepper (PFMC 1986). Preliminary stock assessments based on catch-at-age data have been completed for all three species. Land-

Table 1

Parameters used in delay-difference models for each rockfish species. Methods used to estimate the life-history parameters are described in detail by Hightower (1990).

	widow	bocaccio	chilipepper	splitnose	shortbelly
k	6	4	8	12	4
v (kg)	0.436	0.061	0.581	0.327	0.078
V (kg)	0.598	0.553	0.796	0.343	0.110
ρ	0.903	0.933	0.878	0.984	0.825
M	0.15	0.25	0.20	0.05	0.20
B_∞ (t)	180.0	60.0	47.7	80.0	295.0
B[1] (t)	71.0	20.0	21.4	80.0	295.0

Table 2

Fishing mortality rates of rockfish obtained for constant F policies maximizing harvest (maxh), log(harvest) (logh), or a negative exponential function of harvest (negx) for two-, three-, and five-species models.

Species	Objective function	Fishing mortality rate				
		bocaccio	chilipepper	widow	splitnose	shortbelly
Two	maxh	0.200	0.269	—	—	—
	logh	0.195	0.255	—	—	—
	negx	0.194	0.250	—	—	—
Three	maxh	0.201	0.264	0.181	—	—
	logh	0.196	0.254	0.174	—	—
	negx	0.191	0.242	0.163	—	—
Five	maxh	0.182	0.222	0.153	0.056	0.229
	logh	0.181	0.218	0.152	0.055	0.224
	negx	0.187	0.211	0.146	0.055	0.204

ings of splitnose and shortbelly rockfish have been negligible to date; consequently, parameter estimates for those species should be viewed as highly preliminary.

Results and discussion

Objective functions

Results were similar for constant F policies using different objective functions. Optimal constant Fs generally were comparable with M, although the F for chilipepper (M = 0.20) was higher than that for bocaccio (M = 0.25) (Table 2). That apparently was due to the higher age at first recruitment for chilipepper. (For bocaccio and chilipepper, the slight differences in constant Fs in the two- and three-species cases were due to random error.) Optimal Fs were lower for the five-species case than for the two- and three-species cases because harvests in years 1–74 were excluded from the five-species objective function. Policies obtained assuming a transient period may be unacceptable on socio-

economic grounds but can probably be viewed as a practical lower bound for F.

For each of the models, the differences in F, total yield, and variance for total yield showed a consistent trend: highest for maxh policies, intermediate for logh policies, and lowest for negx policies (Tables 2–5). Relative to the variance for maxh policies, logh constant F policies resulted in about a 2% reduction in total variance, whereas variances for the negx policies were 3 (2-species case) to 10% (5-species case) lower. These results illustrate that moderately lower variances can be achieved by using slightly lower Fs and accepting slightly lower total yields.

Constant vs. variable F policies

The variable F policies (5)–(6) for maximizing harvest did not increase total yield significantly compared to the constant F policies (Tables 3–5). Results from earlier studies suggest that the degree of increase due to a variable F policy may depend on the assumed life-history characteristics. For example, a 17% increase

Table 3

Comparison of average rockfish catches and year-100 variances for constant F, single-species variable F, and multispecies harvesting policies. CVs for biomass estimates were assumed to be 0%.

Species	Harvesting policy	Objective function	Mean yield						Var[100]					
			bocaccio	chili-pepper	widow	split-nose	short-belly	total	bocaccio	chili-pepper	widow	split-nose	short-belly	total
Two	const F	maxh	3.02	2.96	—	—	—	5.98	0.97	1.46	—	—	—	2.87
		logh	3.02	2.96	—	—	—	5.98	0.96	1.42	—	—	—	2.81
		negx	3.02	2.95	—	—	—	5.97	0.95	1.40	—	—	—	2.78
	variable F	maxh	3.05	3.02	—	—	—	6.05	1.49	3.81	—	—	—	6.00
		logh	3.03	2.96	—	—	—	5.96	0.91	1.17	—	—	—	2.44
		negx	3.02	2.95	—	—	—	5.95	0.84	1.09	—	—	—	2.27
	multispp.	maxh	3.02	2.96	—	—	—	5.98	0.95	1.48	—	—	—	2.83
		logh	3.00	2.95	—	—	—	5.95	0.92	1.36	—	—	—	1.94
		negx	2.99	2.94	—	—	—	5.93	0.95	1.32	—	—	—	1.70
Three	const F	maxh	3.02	2.95	7.78	—	—	13.75	1.01	1.28	4.92	—	—	7.40
		logh	3.04	2.94	7.77	—	—	13.75	1.01	1.26	4.85	—	—	7.29
		negx	3.03	2.93	7.75	—	—	13.71	1.00	1.23	4.72	—	—	7.12
	variable F	maxh	3.06	3.01	7.92	—	—	13.93	1.47	3.08	14.12	—	—	18.55
		logh	3.05	2.97	7.82	—	—	13.78	1.18	1.34	4.86	—	—	7.59
		negx	3.03	2.93	7.70	—	—	13.61	0.93	1.04	3.72	—	—	5.75
	multispp.	maxh	3.03	2.94	7.77	—	—	13.74	1.01	1.28	4.96	—	—	7.74
		logh	3.02	2.94	7.75	—	—	13.70	1.02	1.26	4.68	—	—	5.60
		negx	2.98	2.91	7.70	—	—	13.60	1.06	1.20	4.36	—	—	4.08
Five	const F	maxh	3.04	2.85	7.82	1.97	19.92	35.59	1.13	0.74	5.90	0.08	69.56	78.05
		logh	3.05	2.86	7.84	1.94	19.93	35.48	1.13	0.73	5.86	0.08	67.97	76.42
		negx	3.05	2.85	7.82	1.94	19.58	35.09	1.14	0.72	5.73	0.08	61.90	70.19
	variable F	maxh	3.06	2.90	7.95	2.30	20.84	36.91	1.53	1.22	16.96	0.21	431.37	460.41
		logh	3.06	2.89	7.91	2.43	20.02	36.17	1.40	0.84	7.56	0.25	70.84	82.13
		negx	3.03	2.85	7.70	1.49	18.58	33.53	0.99	0.70	3.70	0.20	26.41	32.10
	multispp.	maxh	3.03	2.87	7.85	1.99	20.07	35.67	1.18	0.74	5.90	0.08	70.92	78.16
		logh	2.89	2.58	7.52	1.37	19.61	33.83	1.28	0.93	6.01	0.63	68.64	44.60
		negx	2.46	2.64	7.72	1.41	19.37	33.46	1.64	0.69	5.52	0.20	59.66	43.70

in yield was reported for Atlantic menhaden *Brevoortia tyrannus* (Ruppert et al. 1985), compared with only 1–2% for Pacific whiting *Merluccius productus* (Swartzman et al. 1983) and widow rockfish (Hightower and Lenarz 1989). Because, in this study, there was no apparent advantage in using variable F policies to maximize harvest, the remaining results and discussion focus on a comparison of the traditional constant F policy for maximizing harvest versus variable F policies (5) and (6) for the logh and negx objective functions.

Compared with a constant F policy, variable F policies (5) and (6) provided a substantial reduction in the variance of total yield with only a negligible loss in yield. (The reductions in variance would be slightly less if constant F and variable F policies for the same objective function were compared.) The reduction in variance did not appear to be particularly sensitive to the number of species included, their life-history characteristics, or the degree of correlation among species for recruitment perturbations (Hightower 1990). How-

ever, the level of density-dependence in the stock-recruitment relationship may affect the relative performance of different harvesting policies. In limited additional runs, I found that the difference between constant F and variable F policies generally decreased as the degree of density-dependence increased (i.e., as stock-recruitment parameter A decreased). When recruitment declined markedly with reductions in spawning stock, both types of harvesting policies were necessarily quite conservative.

The advantage of the variable F policies can be illustrated by examining a Pareto Frontier (Walters 1975), which shows the relationship between mean catch and its variance. I developed frontiers for the two-, three-, and five-species cases by simulating the fishery at 20, 40, 60, 80, and 100% of the constant F levels that maximized harvest (Fig. 4). When results for the variable F policies were compared to the constant F frontiers, it was clear that the reduction in variance was much greater than could be accounted for by the lower yield

Table 4

Comparison of average rockfish catches and year-100 variances for constant F, single-species variable F, and multispecies harvesting policies. CVs for biomass estimates were assumed to be 25%.

Species	Harvesting policy	Objective function	Mean yield bocaccio	chili-pepper	widow	split-nose	short-belly	total	Var[100] bocaccio	chili-pepper	widow	split-nose	short-belly	total
Two	const F	maxh	3.01	2.95	—	—	—	5.97	1.66	2.05	—	—	—	4.10
		logh	3.01	2.95	—	—	—	5.96	1.65	2.01	—	—	—	4.04
		negx	3.01	2.95	—	—	—	5.96	1.64	2.00	—	—	—	4.02
	variable F	maxh	3.04	3.00	—	—	—	6.02	3.33	5.57	—	—	—	9.60
		logh	3.01	2.95	—	—	—	5.93	1.28	1.41	—	—	—	3.00
		negx	3.00	2.93	—	—	—	5.91	1.17	1.26	—	—	—	2.72
	multispp.	maxh	3.01	2.95	—	—	—	5.97	1.65	2.06	—	—	—	4.10
		logh	2.99	2.94	—	—	—	5.92	1.79	1.96	—	—	—	2.44
		negx	2.98	2.93	—	—	—	5.90	1.86	1.95	—	—	—	2.25
Three	const F	maxh	3.03	2.94	7.76	—	—	13.72	1.61	2.05	8.58	—	—	11.58
		logh	3.02	2.94	7.75	—	—	13.72	1.61	2.03	8.51	—	—	11.50
		negx	3.02	2.93	7.73	—	—	13.68	1.60	2.00	8.39	—	—	11.34
	variable F	maxh	3.03	2.99	7.84	—	—	13.80	6.48	4.66	11.25	—	—	22.37
		logh	3.04	2.95	7.74	—	—	13.67	1.58	1.78	6.09	—	—	9.01
		negx	3.01	2.92	7.65	—	—	13.53	1.16	1.48	5.16	—	—	7.47
	multispp.	maxh	3.03	2.94	7.76	—	—	13.72	1.61	2.04	8.56	—	—	12.17
		logh	3.01	2.93	7.73	—	—	13.67	1.83	2.15	8.73	—	—	7.97
		negx	2.93	2.88	7.72	—	—	13.53	2.33	2.36	8.39	—	—	6.01
Five	const F	maxh	3.04	2.86	7.84	1.97	20.00	35.56	1.64	1.26	7.06	0.19	108.60	120.11
		logh	3.04	2.86	7.82	1.97	19.92	35.46	1.63	1.25	7.03	0.19	105.84	117.31
		negx	3.03	2.83	7.80	1.91	19.54	34.96	1.62	1.22	6.95	0.18	96.32	107.63
	variable F	maxh	3.05	2.89	7.90	2.33	20.70	36.74	2.88	3.95	14.34	2.75	958.44	987.02
		logh	3.04	2.87	7.84	2.25	19.55	35.43	1.80	1.54	6.71	0.34	66.07	78.42
		negx	2.99	2.82	7.66	2.22	18.10	33.67	1.04	0.84	4.70	0.34	31.20	40.20
	multispp.	maxh	3.01	2.86	7.84	2.00	20.01	35.59	1.71	1.27	7.07	0.19	107.71	115.41
		logh	2.91	2.56	7.35	1.39	19.60	33.66	1.82	1.51	8.72	1.13	110.50	66.74
		negx	2.22	2.31	7.08	1.14	19.47	32.09	2.79	1.77	9.08	1.48	95.97	40.77

obtained. In some cases, the reduction was comparable to the reduction that would be achieved by lowering the CVs for biomass estimates from 50% to 25% or from 25% to 0%. The percent reduction typically increased as the CVs for biomass estimates increased, although the loss in mean yield also increased somewhat (Hightower 1990).

Single-species vs. multispecies policies

When single-species (5) and multispecies (6) policies were compared, the variance for total catch generally was lower for the multispecies policy, except for some cases for the five- species model or when biomass CVs were 50%. In those cases, the better performance of the single-species policy probably was due to the feedback mechanism it contained. For example, in the five-species models, the single-species policies for shortbelly and splitnose rockfish could adapt to the large changes in the size of those stocks. When the five-species model

was rerun using five "stocks" having chilipepper life-history characteristics, the variance for total catch was lower for the multispecies policy.

For the single-species policy, the variance of total catch typically was reduced by stabilizing the catch of each individual species (Tables 3–5). For the multispecies policy, reductions in the variance for total catch were sometimes achieved by increasing the variance for some of the less abundant individual species (Tables 3–5). The reduction in variance obtained using policy (6) is consistent with Clark's (1984) prediction that a multispecies system could be managed to reduce the variance of total yield, relative to the variance of the individual yields.

For the multispecies policies, the optimal parameter estimates were relatively insensitive to the objective function and to the CV for biomass estimates (Hightower 1990). The slope parameter $b_{j,1}$ was less than zero for all cases; consequently, fishing pressure varied inversely with the abundance of the other species.

Table 5

Comparison of average rockfish catches and year-100 variances for constant F, single-species variable F, and multispecies harvesting policies. CVs for biomass estimates were assumed to be 50%.

Species	Harvesting policy	Objective function	Mean yield						Var[100]					
			bocaccio	chili-pepper	widow	split-nose	short-belly	total	bocaccio	chili-pepper	widow	split-nose	short-belly	total
Two	const F	maxh	3.00	2.94	—	—	—	5.93	3.40	3.63	—	—	—	7.39
		logh	3.00	2.93	—	—	—	5.93	3.38	3.59	—	—	—	7.33
		negx	2.99	2.93	—	—	—	5.92	3.38	3.58	—	—	—	7.31
	variable F	maxh	3.02	2.97	—	—	—	5.96	8.49	12.36	—	—	—	21.14
		logh	2.97	2.91	—	—	—	5.85	1.84	1.83	—	—	—	4.06
		negx	2.95	2.90	—	—	—	5.83	1.68	1.69	—	—	—	3.77
	multispp.	maxh	3.00	2.94	—	—	—	5.93	3.40	3.65	—	—	—	7.48
		logh	2.96	2.91	—	—	—	5.87	4.04	3.76	—	—	—	4.24
		negx	2.96	2.90	—	—	—	5.86	4.06	3.91	—	—	—	4.09
Three	const F	maxh	3.01	2.92	7.72	—	—	13.65	3.35	4.42	19.06	—	—	24.74
		logh	3.01	2.92	7.72	—	—	13.64	3.35	4.37	19.03	—	—	24.70
		negx	3.01	2.91	7.69	—	—	13.61	3.34	4.30	18.90	—	—	24.53
	variable F	maxh	3.02	2.94	7.78	—	—	13.70	11.44	6.07	33.98	—	—	48.11
		logh	3.00	2.92	7.66	—	—	13.53	2.17	2.64	10.35	—	—	14.49
		negx	2.97	2.88	7.58	—	—	13.37	1.66	2.02	9.47	—	—	12.76
	multispp.	maxh	3.01	2.92	7.72	—	—	13.65	3.43	4.42	18.91	—	—	24.88
		logh	2.97	2.89	7.69	—	—	13.55	4.58	5.09	20.90	—	—	15.79
		negx	2.91	2.84	7.68	—	—	13.43	6.01	5.34	20.42	—	—	13.29
Five	const F	maxh	3.02	2.84	7.80	1.96	19.84	35.32	3.15	3.87	15.26	0.47	192.76	219.04
		logh	3.02	2.84	7.78	1.96	19.73	35.18	3.14	3.85	15.21	0.47	188.46	214.56
		negx	3.02	2.82	7.72	1.95	19.38	34.75	3.16	3.80	14.96	0.47	177.72	203.35
	variable F	maxh	3.03	2.86	7.81	2.18	20.43	36.18	5.26	10.09	120.32	4.15	1356.71	1540.97
		logh	3.02	2.82	7.78	1.43	18.64	33.56	2.90	1.52	11.61	0.54	64.10	84.87
		negx	2.96	2.78	7.51	1.52	17.32	31.96	1.53	1.26	7.28	0.42	43.02	55.69
	multispp.	maxh	3.00	2.84	7.79	1.97	19.91	35.38	3.34	3.88	15.26	0.47	191.10	209.32
		logh	2.92	2.64	7.44	1.57	19.58	34.01	3.58	3.45	18.95	1.68	208.31	135.32
		negx	2.08	2.28	7.05	1.37	19.20	31.84	7.13	4.10	20.26	2.46	173.92	81.64

Particularly in the three- and five-species cases, it appeared that the optimal multispecies strategy was to maintain stable catches for the species accounting for the majority of total yield, such as shortbelly or widow rockfish. Catches of less-abundant species (e.g., bocaccio or splitnose rockfish) varied depending on the abundance of the dominant species. For example, in the five-species case, the annual catch of splitnose rockfish was 0 in 24–30 of 100 years for the logh policies.

Errors in biomass estimates

Constant F policies were essentially identical when different CVs for biomass estimates were used. This indicates that the current management approach for Pacific Coast groundfish is robust to random, non-autocorrelated errors in estimating biomass. One obvious impact in the simulated fishery of introducing errors in estimating biomass was that the variance for total catch increased substantially (Tables 3–5, Fig. 4). This increased variability was due to differences between the intended (F) and actual (F') fishing mortality rate. Such errors are nonlinearly related to estimated stock size and can be substantial (Rivard 1981). Rivard (1981) argued for higher precision in estimates of stock size in order to reduce the biological risk of applying $F' \gg F$ or the economic loss if $F' \ll F$. In this study, the variation in F due to errors in estimating biomass was much greater than that caused by using the variable F policies. For example, when CV = 0%, Fs for chilipepper in the five-species case ranged from 0.00 to 0.24 when using the multispecies logh model. When CV = 25%, the actual Fs ranged from 0.06 to 0.61 when the intended policy was a constant F of 0.22. Actual Fs ranged from 0.00 to 0.63 when CV = 25% and a multispecies logh policy was used, which suggests that multispecies policies do not introduce substantial additional risk, relative to the risk introduced by estimating biomass with error.
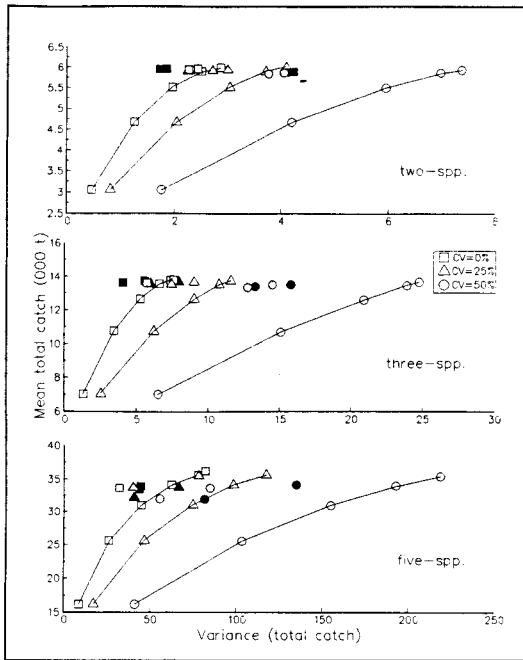
Figure 4
Relationship between mean total rockfish catch and the variance of total catch for the two- (bocaccio, chilipepper), three- (bocaccio, chilipepper, widow rockfish), and five-species (bocaccio, chilipepper, widow, splitnose, and shortbelly rockfish) models. Open symbols represent Pareto Frontiers derived by simulating the fishery at 20, 40, 60, 80, and 100% of the constant fishing mortality rate (F) that maximized harvest. Shaded and closed symbols represent the catch:variance relationship for the variable F and multispecies policies, respectively (equations 5–6). Simulation runs were made assuming a 0, 25, or 50% coefficient of variation for annual estimates of stock size.

Table 6
Average total rockfish catches and year-100 variances for constant F, variable F, multispecies, and three-parameter harvesting policies for the three-species model.

Biomass CVs	Policy	Objective function	Yield	Var[100]
0	(4)	maxh	13.75	7.40
	(5)	logh	13.78	7.59
	(6)	logh	13.70	5.60
	(7)	logh	13.77	6.39
	(5)	negx	13.61	5.75
	(6)	negx	13.60	4.08
	(7)	negx	13.60	4.09
25	(4)	maxh	13.72	11.58
	(5)	logh	13.67	9.01
	(6)	logh	13.67	7.97
	(7)	logh	13.63	6.99
	(5)	negx	13.53	7.47
	(6)	negx	13.53	6.01
	(7)	negx	13.51	5.40
50	(4)	maxh	13.70	24.74
	(5)	logh	13.53	14.49
	(6)	logh	13.55	15.79
	(7)	logh	13.50	11.39
	(5)	negx	13.37	12.76
	(6)	negx	13.43	13.29
	(7)	negx	13.33	8.21

Mean yield was only slightly lower at higher biomass CVs; the decrease was similar for constant F and variable F policies (Tables 3–5). Thus, in this model at least, there was no apparent disadvantage in using the more complex policies, even when biomass was estimated imprecisely. This was an interesting result because, although all policies used biomass estimates to calculate catch, the variable F policies also use the estimates to calculate Fs.

When biomass CVs were 50%, the variance for total catch was in all cases lower for the single-species (5) than for the multispecies policy (6). Apparently it was important to readjust continuously for the changes in stock size due to previous errors in estimating biomass. Based on limited additional runs using the three-species model, it appears that further gains in stability of total

catch could be achieved by using a three-parameter harvesting policy (Table 6):

$$F_j[t] = b_{j,0} + b_{j,1} B_j[t] /$$

$$B_{\infty,j} + b_{j,2} \sum_{i \neq j} B_i[t] / \sum_{i \neq j} B_{\infty,i}. \qquad (7)$$

The primary disadvantage of this policy is the computational expense required to obtain the policy parameter estimates.

Model limitations

One of the primary assumptions underlying this model is that trawlers can, on an annual basis, control the relative proportions of the individual rockfish species in the catch. That appears to be a reasonable assumption for widow rockfish, which are caught primarily in a directed midwater trawl fishery. Catches of other rockfish species should be low in a midwater trawl fishery for shortbelly rockfish (Lenarz 1980), and the Pacific Fishery Management Council is unlikely to permit a bottomtrawl fishery for that species. Peak abundance of splitnose rockfish is in deeper water than for the other species used in this model; however, some

catches (particularly in the 100–149 fm depth interval) would likely contain bocaccio and chilipepper as well (Gunderson and Sample 1980). The greatest degree of overlap would be for bocaccio and chilipepper. Bocaccio occur over a greater latitudinal range than chilipepper, but in the area off California where both species are abundant, it could be difficult to maintain markedly different catch levels for the two species. An improved version of this model would incorporate probabilities for different levels of bycatch, so that the optimal policies would be constrained by the degree of targeting that was feasible (Pope 1979).

Another important assumption is that the species included in the objective function are interchangeable in the marketplace. That is a valid assumption for the commerically important *Sebastes* species, including widow rockfish, bocaccio, and chilipepper. However, demand for splitnose rockfish has been low because of its small size and low fillet yield (Lenarz 1986). A low price would be expected for shortbelly rockfish because they are small in size and must be processed rapidly (Lenarz 1986). Lenarz (1986) suggested that better marketing approaches will be needed before significant quantities of either splitnose or shortbelly rockfish can be harvested. For the model used in this study, differences in price among species could be accommodated easily and the objective function could be modified to maximize some function of income. It would also be of practical importance to determine whether all vessels participating in these fisheries caught all the species used in the objective function. Policies that result in variable catches of the species used in the model would be less appropriate if some fishermen did not catch or were unable to market some of the species.

The objective function could also be modified to include costs of fishing (see, for example, Pikitch 1987). However, the current practice of the Pacific Fishery Management Council is to manage for maximum sustainable yield; costs of fishing are not considered. Stock assessments are restricted to estimation of Acceptable Biological Catch (ABC), and the Council considers some socioeconomic factors when determining "Optimum Yield" from the ABC.

A limitation of this study was the assumption that model parameters M, B_∞, and A were known. Those parameters strongly affect equilibrium yields; consequently, when they are not well estimated, the passive policies used in this study might be outperformed by an adaptive probing strategy (Walters 1986). Under such a strategy, short-term fluctuations in fishing mortality and yield would be accepted in order to better estimate the productivity of the stock and improve long-term management.

Another potential limitation of the model used in this study was the assumption that errors in estimating biomass were not autocorrelated. That assumption may be valid when estimates are based on methods such as a swept-area trawl survey, although the fishery manager would be expected to balance any single estimate of stock size against observations from prior years. Autocorrelated errors would be likely in cases where estimates were based on a time-series of catch data. Such errors would be expected to have more serious consequences than the independent errors assumed here. An approach for introducing autocorrelated errors might be to use CVs of the same magnitude as assumed here but to use a 2- or 3-year moving-average estimate of biomass to set quotas. Errors in estimating biomass might also be correlated among species; for example, swept-area trawl surveys may underestimate the biomass of several species.

A possible limitation of this model was the assumption that the reliability of assessment data was equivalant for all species. If differences in the reliability of estimates were substantial, it might be found that a reliable single-species policy would be preferable to a multispecies policy that incorporated unreliable information on additional species.

Summary

1 When constant F policies for different objective functions were compared, the optimal F, total yield, and variance for total yield decreased as the level of risk aversion increased.
2 Single-species and multispecies variable F policies for maximizing harvest did not increase total yield significantly compared with constant F policies.
3 Single-species and multispecies variable F policies for the logh and negx objective functions provided a substantial reduction in the variance of total yield, compared with a constant F policy for maximizing harvest.
4 For the logh and negx objective functions, the variance for total catch was lower for the multispecies than for the single-species variable F policies, except for some cases for a five-species model or when biomass CVs were 50%.
5 Constant F policies for maximizing harvest (the current management approach) were essentially identical for different levels of random, non-autocorrelated errors in estimating biomass. Mean yield was slightly lower at higher biomass CVs for both constant F and variable F policies.

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Citations

Clark, C.W.
> 1984 Strategies for multispecies management: Objectives and
> constraints. *In* May, R.M. (ed.), Exploitation of marine com-
> munities, p. 303–312. Springer-Verlag, Berlin.

Deriso, R.B.
> 1980 Harvesting strategies and parameter estimation for an
> age-structured model. Can. J. Fish. Aquat. Sci. 37:268–282.
> 1985 Risk adverse harvesting strategies. Lect. Notes
> Biomath. 61:65–73.

Gunderson, D.R., and T.M. Sample
> 1980 Distribution and abundance of rockfish off Washington,
> Oregon, and California during 1977. Mar. Fish. Rev. 42(3-4):
> 2–16.

Henry, F.D. Jr.
> 1986 Status of the coastwide chilipepper (*Sebastes goodei*)
> fishery. *In* Status of the Pacific Coast groundfish fishery
> through 1986 and recommended acceptable biological catches
> for 1987, Appendix 5. Pac. Fish. Manage. Counc., Portland,
> OR.

Hightower, J.E.
> 1990 Biomass-based models and harvesting policies for
> Washington-Oregon-California rockfish stocks with correlated
> recruitment patterns. NOAA-TM-NMFS-SWFC-137, Tiburon
> Lab., Southwest Fish. Cent., Natl. Mar. Fish. Serv., NOAA,
> Tiburon, CA 94920, 39 p.

Hightower, J.E., and W.H. Lenarz
> 1986 Status of the widow rockfish fishery. *In* Status of the
> Pacific Coast groundfish fishery through 1986 and recom-
> mended acceptable biological catches for 1987, Appendix 4.
> Pac. Fish. Manage. Counc., Portland, OR.
> 1989 Optimal harvesting policies for the widow rockfish
> fishery. Am. Fish. Soc. Symp. 6:83–91.

Hilborn, R.
> 1985 A comparison of harvest policies for mixed stock
> fisheries. Lect. Notes Biomath. 61:75–87.

Kimura, D.K.
> 1988 Stock-recruitment curves as used in the stock-reduction
> analysis model. J. Cons. 44:253–258.

Kimura, D.K., J.W. Balsiger, and D.H. Ito
> 1984 Generalized stock reduction analysis. Can. J. Fish.
> Aquat. Sci. 41:1325–1333.

Law, A.M., and W.D. Kelton
> 1982 Simulation modeling and analysis. McGraw-Hill, NY,
> 400 p.

Lenarz, W.H.
> 1980 Shortbelly rockfish, *Sebastes jordani*: A large unfished
> resource in waters off California. Mar. Fish. Rev. 42(3-4):
> 34–40.
> 1984 Status of the widow rockfish fishery. *In* Status of the
> Pacific Coast groundfish fishery and recommendations for
> management in 1985, Appendix 4. Pac. Fish. Manage. Counc.,
> Portland, OR.

> 1986 A history of California rockfish fisheries. *In* Proc. Int.
> Rockfish Symp., Anchorage, Alaska, Oct. 1986, p. 35–41.
> Lowell Wakefield Fish. Symp. Ser. 5, Alaska Sea Grant, Univ.
> Alaska, Fairbanks.

Mendelssohn, R.
> 1982 Discount factors and risk aversion in managing random
> fish populations. Can. J. Fish. Aquat. Sci. 39:1252–1257.

Methot, R.D.
> 1986 Synthetic estimates of historical abundance and mortality
> for northern anchovy, *Engraulis mordax*. Admin. Rep. LJ
> 86-29, Southwest Fish. Cent., Natl. Mar. Fish. Serv., NOAA,
> La Jolla, CA 92038, 85 p.

Methot, R., and J. Hightower
> 1988 Status of the Washington-Oregon-California sablefish
> stock in 1988. *In* Status of the Pacific Coast groundfish fishery
> through 1988 and recommended acceptable biological catches
> for 1989, Appendix B. Pac. Fish. Manage. Counc., Portland,
> OR.

Murawski, S.A., and J.S. Idoine
> 1989 Yield sustainability under constant-catch policy and
> stochastic recruitment. Trans. Am. Fish. Soc. 118:349–367.

Pikitch, E.K.
> 1987 Use of a mixed-species yield-per-recruit model to explore
> the consequences of various management policies for the
> Oregon flatfish fishery. Can. J. Fish. Aquat. Sci. 44(Suppl.
> 2):349–359.

PFMC (Pacific Fishery Management Council)
> 1982 Final fishery management plan and supplemental en-
> vironmental impact statement for the Washington, Oregon,
> and California groundfish fishery. Pac. Fish. Manage. Counc.,
> Portland, OR.
> 1986 Status of the Pacific Coast groundfish fishery through
> 1986 and recommended acceptable biological catches for
> 1987. Pac. Fish. Manage. Counc., Portland, OR.

Pope, J.
> 1979 Stock assessment in multispecies fisheries, with special
> reference to the trawl fishery in the Gulf of Thailand. Rep.
> SCS/DEV/79/19, FAO South China Sea Fish. Dev. Coord.
> Prog., Manila, Philippines, 106 p. [ISBN 92-852-1011-2].

Pope, J.G.
> 1983 Analogies to the status quo TACs: Their nature and
> variance. *In* Doubleday, W.G., and D. Rivard (eds.), Sampling
> commercial catches of marine fish and invertebrates, p.
> 99–113. Can. Spec. Publ. Fish. Aquat. Sci. 66.

Pope, J.G., and D. Gray
> 1983 An investigation of the relationship between the preci-
> sion of assessment data and the precision of total allowable
> catches. *In* Doubleday, W.G., and D. Rivard (eds.), Sampling
> commercial catches of marine fish and invertebrates, p.
> 151–157. Can. Spec. Publ. Fish. Aquat. Sci. 66.

Raiffa, H.
> 1968 Decision analysis. Introductory lectures on choices under
> uncertainty. Addison-Wesley, Reading, MA, 309 p.

Rivard, D.
> 1981 Catch projections and their relation to sampling error
> of research surveys. *In* Doubleday, W.G., and D. Rivard (eds.),
> Bottom trawl surveys, p. 93–109. Can. Spec. Publ. Fish.
> Aquat. Sci. 58.

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.
> 1985 A stochastic population model for managing the Atlan-
> tic menhaden (*Brevoortia tyrannus*) fishery and assessing
> managerial risks. Can. J. Fish. Aquat. Sci. 42:1371–1379.

Schnute, J.
1985 A general theory for analysis of catch and effort data. Can. J. Fish. Aquat. Sci. 42:414–429.

Sen, A.R.
1984 Sampling commercial rockfish landings in California. Tech. Memo. NOAA-TM-NMFS-SWFC-45, Tiburon Lab., Southwest Fish. Cent., Natl. Mar. Fish. Serv., Tiburon, CA 94920, 95 p.

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. Can. J. Fish. Aquat. Sci. 40:524–539.

Tagart, J.V.
1988 Status of the yellowtail rockfish stocks in the International North Pacific Fishery Commission Vancouver and Columbia areas. In Status of the Pacific Coast groundfish fishery through 1988 and recommended acceptable biological catches for 1989, Appendix D. Pac. Fish. Manage. Counc., Portland, OR.

Walters, C.J.
1975 Optimal harvesting strategies for salmon in relation to environmental variability and uncertain production parameters. J. Fish. Res. Board Can. 32:1777–1784.

Walters, C.
1986 Adaptive management of renewable resources. Macmillian, NY, 374 p.

Weinberg, K.L., M.E. Wilkins, and T.A. Dark
1984 The 1983 Pacific west coast bottom trawl survey of groundfish resources: Estimates of distribution, abundance, age and length composition. Tech. Memo. NMFS-F/NWC-70, Alaska Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA, Seattle, WA 98115-0070, 376 p.