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Abstract

Optimal harvesting policies were developed for a model of the Washington-Oregon-California trawl fisheries for bocaccio (S. paucispinus), chilipepper (S. goodei), widow rockfish (S. entomelas), splitnose rockfish (S. diploproa), and shortbelly rockfish (S. jordani). A biomass-based delay-difference model with knife-edge recruitment appeared to describe rockfish stock dynamics adequately. 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. By switching fishing pressure among species, multispecies policies reduced the variance for total harvest by about 30-40% with no significant loss in yield. The degree of switching and the reduction in variance were relatively insensitive to the precision of annual biomass estimates and to the level of correlation among recruitment perturbations. This report contains the methods used to construct the biological model and to estimate the optimal policy parameters. Most of the study results are presented in a companion article (Hightower, submitted).

Introduction

Two frequently stated reasons for developing multispecies management strategies are biological interactions among fish stocks and technological interactions (fisheries with significant bycatch). A third reason to consider multispecies management is that a fisherman's annual income may be derived from a large number of species. These species may have no biological or technological links and may in fact be caught at different times or areas or with different gears. Nevertheless, from an industry perspective, harvesting a large number of species can result in a more diversified seafood market and perhaps a larger or more stable income. From the fishery manager's perspective, the advantage of a multispecies approach is that overall yield might be increased or stabilized or the probability of stock depletion might be reduced by shifting fishing pressure among species. For example, when the size of one stock declines due to poor recruitment, fishing pressure might be diverted to other stocks experiencing good recent recruitment.

The objective of this study was to examine multispecies harvesting policies for the Washington-Oregon-California trawl fisheries for rockfish to determine whether total yield (all species combined) can be increased or the variance for total yield can be reduced. In this report, I present (1) the methods used to construct the biological models and to obtain parameter estimates; (2) parameter estimates for optimal constant fishing mortality (F) and multispecies harvesting policies; and (3) a sensitivity analysis of correlations in recruitment among species. A detailed comparison of constant F and variable F harvesting policies for the case where recruitment was uncorrelated among species is provided in a companion article (Hightower, submitted).

Except for widow rockfish (Sebastes entomelas), relatively little is known about the population dynamics of these stocks. For that reason, this study should be viewed as an exploratory analysis of multispecies harvesting policies, and not as a basis for regulatory changes by the Pacific Fishery Management Council. It may be worthwhile to develop multispecies harvesting policies for Council review once we have adequate life history information about the commercially important groundfish stocks.

Methods

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 (*S. paucispinus*), chilipepper (*S. goodei*), 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, as described below, they were estimated to have similar biomass levels and positively correlated recruitment perturbations. I included widow rockfish for the three-species model because it was estimated to have about twice the MSY biomass of and recruitment perturbations negatively correlated with 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) delay-difference model (equation 2.7) 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. Schnute's model is based on one developed by Deriso (1980) for the case where knife-edge recruitment can be assumed. The model describes changes in biomass as a function of prior biomass and recruitment levels. Although computationally simpler, it approximates the behavior of an age-structured model. Following Kimura et al. (1984), I assumed that B_0 (needed to calculate B_2) equalled the starting biomass level B_1.

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, equation 1.14). This growth equation can be reparameterized as the more widely used von Bertalanffy growth curve (Schnute 1985, equation 1.17).

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. It results in an A value of 0.889; however, the stock-recruitment relationship in Schnute's model is based on exploitable rather than spawning biomass. To correct for this, I used a deterministic age-structured model of the widow rockfish fishery (Hightower and Lenarz 1986) to estimate the relationship between equilibrium spawning and exploitable biomass. At the level of fishing mortality that reduced spawning biomass by 50%, exploitable biomass was reduced by 44.5%; this resulted in an A value of 0.861. Age-structured models were not available for the other species used in this study; consequently, I used A=0.861 for all five species. I also 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. The normal random variate z_t was assumed to have mean 0 and variance σ^2. An estimate of σ^2 (0.613) was obtained for widow rockfish as the variance of the log of recruitment estimates obtained from cohort analysis of catch-at-age data. Sufficient data were not available to estimate σ^2 for the other rockfish species so the estimate for widow rockfish was used for all five species. It should be noted, however, that catch-at-age data suggest that bocaccio recruitment is considerably more variable than recruitment for either widow rockfish or chilipepper.

Optimization

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

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

or a function of the combined biomass of all other stocks

$$F_j[t] = b_{j,0} + b_{j,1} \sum_{i \neq j}^{s} B_i[t] \Big/ \sum_{i \neq j}^{s} B_{\infty,i}, \qquad \text{(multispecies)} \qquad (5)$$

where s was the number of species used in the model. The linear equation used as the multispecies policy was similar to the single-species policy Hilborn (1985) used to calculate catch as a linear function of biomass. I scaled the biomass estimates in equation (5) using virgin biomass so that the policy parameters ($b_{j,0}$, $b_{j,1}$; j=1..s) were relatively independent of absolute biomass levels.

I also examined policies in which $F_j[t]$ was a function of the size of all other stocks

$$F_j[t] = b_{j,0} + \sum_{i \neq j}^{s} b_{j,i} \, (B_i[t]/B_{\infty,i}) \qquad (6)$$

or of all stocks

$$F_j[t] = b_{j,0} + \sum_{i}^{s} b_{j,i} \, (B_i[t]/B_{\infty,i}) \qquad (7)$$

Those policies were appealing because the catch for each species depended on its abundance as well as the abundance of all other individual species. Unfortunately, computational effort increased substantially as the number of policy parameters increased, and policies (6)-(7) were not practical for models with more than three species. In addition, neither policy showed significant improvement over the simpler multispecies policy. When used to maximize harvest, policies (6)-(7) provided yields similar to or slightly higher than yields from policy (5) but at the cost of substantially higher variances. When used to reduce year-to-year variability in yield, the variance for total yield under policies (6)-(7) was only slightly lower than under policy (5). Policies (6)-(7) should perform at least as well as simpler policies having fewer parameters; however, the increased difficulty of locating a nearly optimal solution apparently offset any advantages the additional parameters provided. Based on these observations, only the results from the constant F and multispecies policy (5) are included in this manuscript.

In earlier optimization studies (Ruppert et al. 1984, Hilborn 1985), harvesting policies were used to determine the annual catch as a function of stock size. Practical advantages of a policy for calculating F rather than catch were the following: (1) the policy F need not have an upper bound (simplifying the search for optimal parameter estimates), whereas the policy catch cannot exceed biomass; and (2) if a policy for calculating catch is used, the F required to obtain that catch must be solved for iteratively (substantially increasing computational effort required). The latter advantage holds only when annual biomass levels are assumed to be known. When biomass levels are assumed to be estimated with error, the policy F is applied to the estimate of current biomass ($B'_j[t]$) to derive the catch ($C_j[t]$). The actual F that the stock would be subjected to would be the iteratively calculated F required to obtain $C_j[t]$ from $B_j[t]$.

Optimal estimates of the policy parameters used to calculate Fs ($b_{j,0}$, $b_{j,1}$; $j=1,..,s$) were obtained using stochastic approximation (Ruppert et al. 1984), a sequential technique for locating the maximum of a response surface. A sequence of simulation runs were made and estimates of the policy parameters and the matrix of second derivatives (Hessian, H) were revised after each iteration. Numerically estimated first and second derivatives were used to estimate the direction and distance of the response surface maximum (e.g., the combination of policy parameters resulting in highest total catch). As noted by Ruppert et al. (1984), a critical step in locating the optimal policy was to obtain a good starting estimate of H. Ruppert et al. (1984) obtained starting estimates of H and the optimal harvesting policy by conducting simulation studies over a grid of trial policies. A second-order response-surface model was used to estimate the derivatives. I found that a grid worked well for a simple model with a well-defined maximum, but was impractical for policies with highly correlated parameter estimates or policies with a large number of parameters. When a prior estimate of H was not available, I used a trial simulation run to generate starting estimates for the main diagonal elements and assigned off-diagonal elements (cross derivatives) to 0 (Cuthbert 1987). I reversed the sign for those diagonal elements for which the starting estimate was > 0 (Gill et al. 1981). That approach resulted in initial iterations moving in the steepest ascent direction until the estimate of H was refined.

I also briefly examined steepest ascent approaches for locating the optimal policy (Kiefer and Wolfowitz 1952, Blum 1954, Wilde 1964). Those approaches required much less computational effort per iteration than the Newton-type approach developed by Ruppert et al. (1984) because second derivatives were not required. Unfortunately, changes in the policy parameters occurred extremly slowly and optimal policies were not located consistently.

Objective Functions

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

$$\max \sum_{t} C[t], \text{ where } C[t]=\sum_{j} C_j[t] \qquad \text{(maxh objective function)}$$

and the natural logarithm of total catch

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

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

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

where δ was a scaling factor (Raiffa 1970). These policies represented extremes along a risk continuum from risk neutral (maxh) to highly risk averse (negx with $\delta=5$).

Multispecies policies for maximizing harvest did not increase yield significantly compared to constant F policies (Hightower, submitted). For that reason, this report contains only a comparison of the traditional constant F policy for maximizing harvest versus the logh and negx multispecies policies for reducing variability in harvest. The reduction in variance would be slightly less if constant F and multispecies policies for the same objective function were compared. The variances for the logh and negx constant F policies were 2-10% lower than the for the maxh constant F policies (Hightower, submitted).

Planning horizon

A 100-yr planning horizon was used in order to obtain steady-state harvesting policies. However, in the five-species case, the splitnose rockfish stock continued to decline throughout the planning horizon because of its long life span and slow growth rate. 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 to 100. Steady-state biomass levels were reached within 100 yr for all species except possibly splitnose rockfish (Hightower, submitted); thus, declines in stock size at the start of the planning horizon were due only to high initial biomass levels. The only apparent disadvantage of using a transient period was that convergence was slower because only 25 of 100 years were used in the objective function.

Errors in biomass estimates

The multispecies 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 was based on simulated estimates $B'_1[t]..B'_s[t]$ of the actual biomass levels $B_1[t]..B_s[t]$. The errors for each biomass estimate were assumed to be lognormally distributed (Pope and Gray 1983) and independent over time, with a coefficient of variation (CV) of either 0, 25, or 50%. The CVs were chosen based on a review of the stock assessment literature. Reported CVs for estimates of biomass or total allowable catch (which would be proportional to biomass) ranged from about 15-50% (Rivard 1981, Pope 1983, Pope and Gray 1983, Sen 1984, Weinberg et al. 1984, Methot 1986). To obtain a lognormal random variate exp(z) with a CV of 0, 25, or 50%, the normally distributed random variate z would have mean 0 (by assumption) and variance $\sigma=\log_e(CV^2+1)$. This expression was obtained by solving $CV(\exp(z))^2=\exp(\sigma^2)-1$ for σ^2, based on the theoretical mean and variance of a lognormal random variate (Hogg and Craig 1978). Because the expected value of exp(z) ($\exp(\sigma^2/2)$ was not equal to 1, the estimate $B'_j[t]$ was obtained as $B_j[t]\exp(z)/\exp(\sigma^2/2)$ so that the expected value of B'_j was approximately equal to B_j.

Because the Washington-Oregon-California 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 policy (5)) 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 $B'_1[t]..B'_s[t]$.

Interspecific Correlations in Recruitment

There is considerable evidence for correlated recruitment patterns among West Coast groundfish species. Hollowed et al. (1987) reported widespread synchrony of extreme year classes across the entire northeast Pacific ocean. Recruitment indices typically were positively correlated within species groups or regions and negatively correlated between species groups or regions. Larson[1] identified two groups of rockfish species that seemed to vary somewhat independently, with best and worst year classes occurring in different years. The first group was comprised of widow rockfish, yellowtail rockfish, and blue rockfish (S. mystinus); the second was comprised of bocaccio, chilipepper, canary rockfish, brown rockfish (S. auriculatus), and possibly shortbelly rockfish. Both groups experienced relatively good recruitment in 1985 and poor recruitment in 1983.

The correlations among species used in this study (r=0.00, 0.25, 0.50) were based on the levels observed by Hollowed et al. (1987) for detrended recruitment values for northeast Pacific groundfish. For stocks where correlations differed significantly from 0, they reported positive correlations ranging from 0.44 to 0.63 and negative correlations ranging from

-0.41 to -0.48. To examine the effects of positive and negative correlations in recruitment, I assumed that bocaccio and chilipepper recruitment perturbations were positively correlated, whereas widow rockfish recruitment perturbations were assumed to be negatively correlated with those of both bocaccio and chilipepper. Because of the lack of information on splitnose rockfish year-class strength and the computational expense encountered for the five-species model, I restricted the sensitivity analysis of correlated recruitment perturbations to the two- and three-species cases.

As noted earlier, deviations about the stock-recruitment curve ($\exp(z_j'[t])$ for species j, year t) were assumed to be lognormally distributed. Correlated recruitment perturbations were obtained by assuming that the array $\underline{z}'[t]$ had a multivariate normal distribution with mean $\underline{0}$ and variance-covariance matrix $\sum$. Cholesky factorization (Cuthbert 1987) was used to factor the symmetric, positive-definite matrix $\sum$ as CC^T, where C was lower triangular. The $\underline{z}'[t]$ were obtained as $C\underline{z}[t]$, where $z_1[t],..,z_s[t]$ were independent, identically distributed normal random variates with mean 0 and variance 1 (Law and Kelton 1982).

Life History Information

The reliability of the parameter estimates 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 1980-1985 landings of 17,200 t (Hightower and Lenarz 1986). Fisheries for bocaccio and chilipepper have existed for decades; average 1980-1985 landings were 3,200 t for bocaccio and 1,700 t for chilipepper (PFMC 1986). Preliminary stock assessments based on catch-at-age data have been completed for all three species. Landings of splitnose and shortbelly rockfish have been negligible to date; consequently, parameter estimates for those species should be viewed as highly preliminary.

The model parameters are summarized in Table 1. The estimates of natural mortality were obtained from the literature (widow rockfish: Hightower and Lenarz (1986); bocaccio: Thomas (1985); chilipepper: Henry (1986)) or from Hoenig's (1983) regression equation relating total mortality (Z) to maximum age (splitnose rockfish, 80+ yr (Bennett et al. 1982, Boehlert and Yoklavich 1986); shortbelly rockfish, 22 yr[2]). I assumed that M equalled Z for both splitnose and shortbelly rockfish because the two stocks were assumed to be lightly exploited and unexploited, respectively. The methods used to obtain the remaining parameter estimates are described for each species in the following sections.

Widow rockfish - I assumed that the age at knife-edge recruitment (k) was equal to 6, the age at 50% vulnerability according to a cohort analysis (Hightower and Lenarz 1986). The estimates of virgin and starting (1987) biomass were obtained by adjusting published estimates (Hightower and Lenarz 1986) to exclude age-5 fish.

Bocaccio - Kimura et al. (1984) suggested using the modal age of the catch as the first estimate of the age at knife-edge recruitment. Unfortunately, the modal age for bocaccio catches changed over time in recent years as the strong 1977 year class passed through the fishery (Thomas 1985). I assumed as a first approximation that k was equal to 4, the mean modal age from 1978 to 1984 (Thomas 1985). There was little evidence upon which to base an estimate of either virgin or starting stock biomass. As a rough estimate for use in the optimization studies, I used an equilibrium form of Schnute's model (Kimura et al. 1984, Kimura 1985) to calculate yield as a function of F.

Different values were tested for B_∞ until maximum sustainable yield (MSY) was about 3,000 t (the approximate level of historical landings). I used 20,000 t as a first approximation for B_1, based on results of a highly preliminary cohort analysis (D. H. Thomas, California Department of Fish and Game, Menlo Park, CA; unpublished data), which indicated that mean 1978-1984 biomass ranged from 12,926 t (using a terminal F of 0.5) to 21,372 (terminal F of 0.2).

Chilipepper - I assumed that k was equal to 8, the age at 50% vulnerability according to a catch-at-age analysis (Henry 1986). Female chilipepper comprise over 78% of total landings; consequently, the estimates of B_∞ and B_1 were obtained from a catch-at-age analysis of female landings (Henry 1986). Estimates of B_∞ ranged from 36,500 to 64,800 t (Henry 1986), depending on the weight given to assumptions about annual changes in fishing effort. After removing the estimated biomass of fish ages 3-7 and adjusting for male chilipepper biomass (by dividing by 0.78), the revised mean estimate of B_∞ was 47,700 t. A similar series of calculations was used to obtain the estimate of starting (1983) biomass (21,400 t).

Splitnose rockfish - Limited numbers of splitnose rockfish have been observed in California port samples of trawl landings. Based on the estimated length distribution of 1986 landings, splitnose appeared to be first vulnerable to fishing at about 24 cm FL (about age 8) and fully vulnerable at about 30 cm (about age 16). Assuming linearly increasing vulnerability from 0 at age 8 to 1.0 at age 16, the age of 50% vulnerability (an estimate of k) would be age 12.

Essentially no information is available upon which to base an estimate of splitnose rockfish stock biomass. The species is thought to be quite abundant but has been lightly exploited because of its small size and low fillet yield (Lenarz 1986). There is some evidence of exploitation for fish off Washington and Oregon, probably as bycatch due to its close association with the heavily exploited Pacific ocean perch (Boehlert 1980). Results from the 1977-1983 triennial trawl surveys (Gunderson and Sample 1980, Weinberg et al. 1984, Coleman 1986) indicate that chilipepper and splitnose rockfish are similar in abundance in INPFC areas Eureka, Monterey, and Conception. Estimates of current chilipepper biomass based on a catch-at-age analysis ranged from 29,000 to 62,000 t (Henry 1986). As a first approximation, I arbitrarily assumed that current splitnose rockfish biomass in the Eureka-Conception areas was about 60,000 t. In the Vancouver and Columbia areas, survey catches of splitnose rockfish were generally lower than but roughly comparable to catches of Pacific ocean perch. Ito et al. (1987) estimated that 1986 Pacific ocean perch biomass was about 10,000 t per area in the Vancouver and Columbia INPFC areas. Thus a highly preliminary estimate of both B_∞ and B_1 for splitnose rockfish would be 80,000 t.

Shortbelly rockfish - Based on the available growth data, I assumed that knife-edge recruitment would occur at age 4. This estimate is highly preliminary because smaller mesh trawl gear than that currently used (3.0- and 4.5-inch) would be required; for example, experimental fishing has been conducted with 1.25- and 1.5-inch mesh cod ends (Lenarz 1980, Kato 1981). The mesh size chosen would depend on the amount of bycatch, which was significant for experimental bottom trawling but low for midwater tows (Lenarz 1980). Based on hydroacoustic and midwater trawl survey data, the estimated biomass in a small portion of its range was 295,000 t (Lenarz 1980). This value was used as an estimate of both virgin and starting biomass.

Results and Discussion

Delay-difference versus age-structured model

A limitation of the delay-difference model was that knife-edge recruitment was assumed. Some results from catch-at-age analyses for widow rockfish suggest that vulnerability to fishing increases gradually over several years to a maximum at about age 9 or 10 then decreases sharply for fish ages 12 and older (Lenarz and Hightower 1988). Similar recruitment patterns have been observed for other species caught in West Coast trawl fisheries (Pacific whiting (Merluccius productus), Hollowed et al. 1988; sablefish (Anoplopoma fimbria), Methot and Hightower 1988; yellowtail rockfish, Tagart 1988). To determine whether a knife-edge recruitment pattern would be a suitable approximation of the actual recruitment process, I compared both equilibrium yield curves and simulation results for widow rockfish, using delay-difference and age-structured models. The equilibrium yield curves were quite similar although shifted slightly toward the origin for the delay-difference model (i.e., at each level of yield, the F for the delay-difference model was slightly lower). Apparently, this shift occurred because F for the age-structured model referred only to fully selected ages (9 and 10) only, whereas the delay-difference F applied to all ages beyond the age at assumed knife-edge recruitment. Simulated patterns in stock biomass and catch were very similar (Figure 1). These results suggest that, even for cases where the true selectivity pattern was dome-shaped, the delay-difference model adequately characterized stock dynamics, especially given the lack of information for most of the species. Tyler et al. (1985) also reported good agreement between a delay-difference and an age-structured model for a case where mortality varied considerably by age.

Harvesting policies

When time series plots of harvest under the constant F and multispecies policies were compared, differences in yield in individual years often were slight. Year-to-year changes in total harvest tended to be slightly less extreme under the multispecies policies. In all cases, the patterns were much more strongly influenced by random variations in recruitment than by the harvesting policies. The annual changes in F under the multispecies policies were relatively small even when the abundance of other species changed considerably. In one case, when a large year class entered the simulated widow rockfish fishery and widow rockfish biomass increased from about 42,000 to 69,000 t, the chilipepper F decreased from about 0.27 to 0.24 and the bocaccio F decreased from about 0.21 to 0.18.

The optimal parameter estimates for the multispecies policies were relatively insensitive to the objective function (logh or negx) and to the CVs for biomass estimates (Tables 2-4). In all cases, fishing pressure varied inversely with the abundance of the other species. Year-to-year changes in F typically were somewhat larger for the negx than for the logh policies, due to the larger absolute value of the negx policy parameters. Year-to-year fluctuations in F also tended to be greater for less abundant species (e.g., bocaccio and chilipepper in the three-species model). The multispecies policies for the most abundant species (e.g., widow and shortbelly rockfish in the three- and five-species cases, respectively) often were similar to a constant F policies. Harvesting policies were more conservative for the five-species model because yields during the "transient" fishing-down period were excluded from the objective function.

Compared to the traditional constant F policy for maximizing harvest, the multispecies policies provided a substantial reduction in the variance of total yield with only a negligible loss in yield (Tables 5-7). The percent reduction typically increased as the CVs for biomass estimates increased, although the loss in mean yield also increased slightly. Compared to logh policies, the negx policies provided a greater reduction in variance but resulted in a slightly greater reduction in mean yield.

Effects of correlated recruitment perturbations

Constant F policies were insensitive to changes in r, the degree of correlation for recruitment perturbations (Tables 2-4). Multispecies policies changed slightly, depending on whether recruitment perturbations were positively or negatively correlated. When positively correlated (as in the two-species case), an increase in r caused the multispecies parameter (b_1) to shift toward 0 (i.e., there was less advantage in switching effort between species when recruitment for the two species was positively correlated). Consequently, the multispecies policy was slightly less effective in reducing total catch variance as the level of correlation increased (Table 5). In the three-species case, more negative b_1 values (policies with a greater degree of switching) resulted when recruitment perturbations were negatively correlated (e.g., widow rockfish versus bocaccio and chilipepper). Because the three-species model contained both positive and negative recruitment correlations, the multispecies policies produced similar reductions in total catch variance at the different levels of correlation (Table 6).

A potential limitation of this model was the assumption that recruitment perturbations were correlated among species but not autocorrelated. There is some evidence for autocorrelation (Norton 1986, Hollowed et al. 1987, Koslow et al. 1987), due perhaps to persistent changes in environmental variables such as temperature, salinity, and upwelling. If the apparent autocorrelations are due to long-term environmental change rather than to changes in spawning stock size, then multispecies harvesting policies could prove useful for protecting stocks experiencing prolonged poor recruitment.

There was a strong inverse relationship between the two parameters in the optimal multispecies policies (Figure 2). The magnitude of the two parameter values depended not only on the value of r but also on the objective function and the assumed level of variability in biomass estimates. In general, policies obtained using the negx objective function, those obtained for higher biomass CVs, and those for species with negatively correlated recruitment perturbations resulted in a greater degree of switching.

Approaches for reducing computational effort

Calculating derivatives numerically using centered differences (Cuthbert 1987) proved to be very computationally intensive. Two 100-year runs (e.g., $b_{1,0}$+c, $b_{1,0}$-c) were required to estimate each first derivative, resulting in a large number of runs at each iteration (e.g., 25 100-year runs were required to calculate first and second derivatives for a 3-parameter model). Although the optimization routines were developed on a microcomputer, all production runs were made using a supercomputer. Less computationally intensive approaches need to be developed, particularly for models with more than 2 or 3 species.

One approach for reducing computational effort might be to develop methods for rapidly obtaining nearly optimal policies. The intermediate results obtained in this study while searching for the optimal policies suggested that the response surface was relatively flat about the optimum.

This seemed particularly true for the negx policies, for which the utility function changes slowly over a substantial range of harvests. If several policies with nearly optimal performance can be located, comparisons among policies can be based on other criteria (e.g., variability in the catches of individual species or permissible levels of by-catch).

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Footnotes

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Table 1. Parameters used in delay-difference models for each species. Parameters v, V, and ρ were estimated using growth curves for length and length-weight relationships from the following sources: widow rockfish (Lenarz 1987, Barss and Echeverria 1987); bocaccio and chilipepper (Phillips 1964); splitnose rockfish (Phillips 1964, Echeverria and Lenarz 1984, Coleman 1986); shortbelly rockfish (Phillips 1964, Pearson et al. 1989).

	Widow rockfish	Bocaccio	Chilipepper	Splitnose rockfish	Shortbelly rockfish
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. Optimal constant fishing mortality (F) and multispecies harvesting policies (equations 4 and 5 in text) for the two-species model at three levels of interspecific correlation (r) for recruitment perturbations and three levels for the coefficient of variation (CV, %) for annual biomass estimates.

r	CV	Harvesting policy	Objective function	Bocaccio b_0	Bocaccio b_1	Chilipepper b_0	Chilipepper b_1
0.00	0	constant F	maxh	0.200	0.000	0.269	0.000
		multispecies	logh	0.261	-0.223	0.309	-0.165
			negx	0.266	-0.245	0.314	-0.187
	25	constant F	maxh	0.200	0.000	0.268	0.000
		multispecies	logh	0.265	-0.240	0.327	-0.220
			negx	0.271	-0.265	0.334	-0.250
	50	constant F	maxh	0.198	0.000	0.265	0.000
		multispecies	logh	0.265	-0.252	0.330	-0.251
			negx	0.266	-0.254	0.344	-0.302
0.25	0	constant F	maxh	0.200	0.000	0.269	0.000
		multispecies	logh	0.252	-0.193	0.307	-0.157
			negx	0.260	-0.226	0.305	-0.158

Table 2 (continued).

r	CV	Harvesting policy	Objective function	Bocaccio b_0	Bocaccio b_1	Chilipepper b_0	Chilipepper b_1
0.25	25	constant F	maxh	0.200	0.000	0.268	0.000
		multispecies	logh	0.258	-0.217	0.328	-0.220
			negx	0.271	-0.261	0.326	-0.230
	50	constant F	maxh	0.198	0.000	0.265	0.000
		multispecies	logh	0.261	-0.231	0.334	-0.261
			negx	0.268	-0.254	0.341	-0.290
0.50	0	constant F	maxh	0.200	0.000	0.269	0.000
		multispecies	logh	0.256	-0.210	0.296	-0.120
			negx	0.260	-0.226	0.300	-0.141
	25	constant F	maxh	0.200	0.000	0.268	0.000
		multispecies	logh	0.256	-0.210	0.309	-0.164
			negx	0.263	-0.233	0.326	-0.229
	50	constant F	maxh	0.198	0.000	0.265	0.000
		multispecies	logh	0.263	-0.238	0.323	-0.226
			negx	0.267	-0.250	0.340	-0.281

Table 3. Optimal constant fishing mortality (F) and multispecies harvesting policies (equations 4 and 5 in text) for three-species model at three levels of interspecific correlation (r) for recruitment perturbations and three levels for the coefficient of variation (CV, %) for annual biomass estimates.

		Harvesting	Objective	Widow		Bocaccio		Chilipepper	
r	CV	policy	function	b_0	b_1	b_0	b_1	b_0	b_1
0.00	0	constant F	maxh	0.181	0.000	0.201	0.000	0.264	0.000
		multispecies	logh	0.208	-0.109	0.269	-0.251	0.337	-0.279
			negx	0.216	-0.155	0.310	-0.401	0.360	-0.394
	25	constant F	maxh	0.182	0.000	0.200	0.000	0.265	0.000
		multispecies	logh	0.218	-0.142	0.283	-0.306	0.345	-0.312
			negx	0.200	-0.096	0.353	-0.564	0.408	-0.551
	50	constant F	maxh	0.180	0.000	0.198	0.000	0.262	0.000
		multispecies	logh	0.214	-0.130	0.308	-0.404	0.398	-0.511
			negx	0.201	-0.101	0.371	-0.640	0.398	-0.572
0.25	0	constant F	maxh	0.180	0.000	0.200	0.000	0.267	0.000
		multispecies	logh	0.214	-0.129	0.274	-0.270	0.332	-0.254
			negx	0.219	-0.160	0.315	-0.422	0.361	-0.385
	25	constant F	maxh	0.181	0.000	0.200	0.000	0.266	0.000
		multispecies	logh	0.217	-0.136	0.299	-0.366	0.360	-0.355
			negx	0.206	-0.118	0.329	-0.470	0.405	-0.553

Table 3 (continued).

r	CV	Harvesting policy	Objective function	Widow b_0	Widow b_1	Bocaccio b_0	Bocaccio b_1	Chilipepper b_0	Chilipepper b_1
0.25	50	constant F	maxh	0.180	0.000	0.198	0.000	0.265	0.000
		multispecies	logh	0.216	-0.138	0.315	-0.433	0.367	-0.401
			negx	0.201	-0.102	0.331	-0.500	0.434	-0.676
0.50	0	constant F	maxh	0.180	0.000	0.200	0.000	0.268	0.000
		multispecies	logh	0.219	-0.143	0.285	-0.310	0.352	-0.320
			negx	0.220	-0.165	0.309	-0.402	0.364	-0.400
	25	constant F	maxh	0.181	0.000	0.200	0.000	0.267	0.000
		multispecies	logh	0.225	-0.162	0.293	-0.342	0.355	-0.337
			negx	0.200	-0.097	0.331	-0.485	0.421	-0.610
	50	constant F	maxh	0.180	0.000	0.198	0.000	0.265	0.000
		multispecies	logh	0.210	-0.118	0.348	-0.548	0.383	-0.460
			negx	0.203	-0.108	0.347	-0.558	0.403	-0.580

Table 4. Optimal constant fishing mortality (F) and multispecies harvesting policies (equations 4 and 5 in text) for five-species model at three levels for the coefficient of variation (CV, %) for annual biomass estimates.

CV	Harvesting policy	Objective function	Widow		Bocaccio		Chilipepper		Splitnose		Shortbelly	
			b_0	b_1	b_0	b_1	b_0	b_1	b_0	b_6	b_0	b_6
0	constant F	maxh	0.153	0.000	0.182	0.000	0.222	0.000	0.056	0.000	0.229	0.000
	multispp.	logh	0.225	-0.211	0.286	-0.324	0.413	-0.571	0.180	-0.386	0.280	-0.152
		negx	0.167	-0.061	0.334	-0.575	0.268	-0.255	0.087	-0.132	0.219	-0.054
25	constant F	maxh	0.152	0.000	0.180	0.000	0.223	0.000	0.057	0.000	0.236	0.000
	multispp.	logh	0.249	-0.280	0.284	-0.305	0.421	-0.596	0.199	-0.446	0.289	-0.166
		negx	0.243	-0.273	0.361	-0.619	0.484	-0.759	0.222	-0.514	0.208	-0.018
50	constant F	maxh	0.150	0.000	0.176	0.000	0.219	0.000	0.057	0.000	0.230	0.000
	multispp.	logh	0.251	-0.289	0.286	-0.316	0.421	-0.601	0.198	-0.443	0.288	-0.164
		negx	0.228	-0.255	0.416	-0.854	0.577	-1.036	0.221	-0.491	0.194	-0.009

Table 5. Percent change for two-species model in average total catch and year-100 variance of total catch for multispecies policies, compared to a constant F policy for maximizing harvest.

Recruitment correlation	CV for biomass estimates (%)	Objective function	Percent change	
			Mean catch	Var[100]
0.00	0	logh	-0.5	-35.2
		negx	-0.7	-39.7
	25	logh	-0.8	-40.5
		negx	-1.2	-45.1
	50	logh	-1.0	-42.6
		negx	-1.2	-44.7
0.25	0	logh	-0.7	-29.2
		negx	-0.8	-33.7
	25	logh	-1.0	-36.2
		negx	-1.3	-42.2
	50	logh	-1.2	-40.6
		negx	-1.5	-43.4
0.50	0	logh	-0.7	-26.3
		negx	-1.0	-30.2
	25	logh	-1.0	-31.2
		negx	-1.5	-38.8
	50	logh	-1.4	-39.3
		negx	-1.9	-43.3

Table 6. Percent change for three-species model in average total catch and year-100 variance of total catch for multispecies policies, compared to a constant F policy for maximizing harvest.

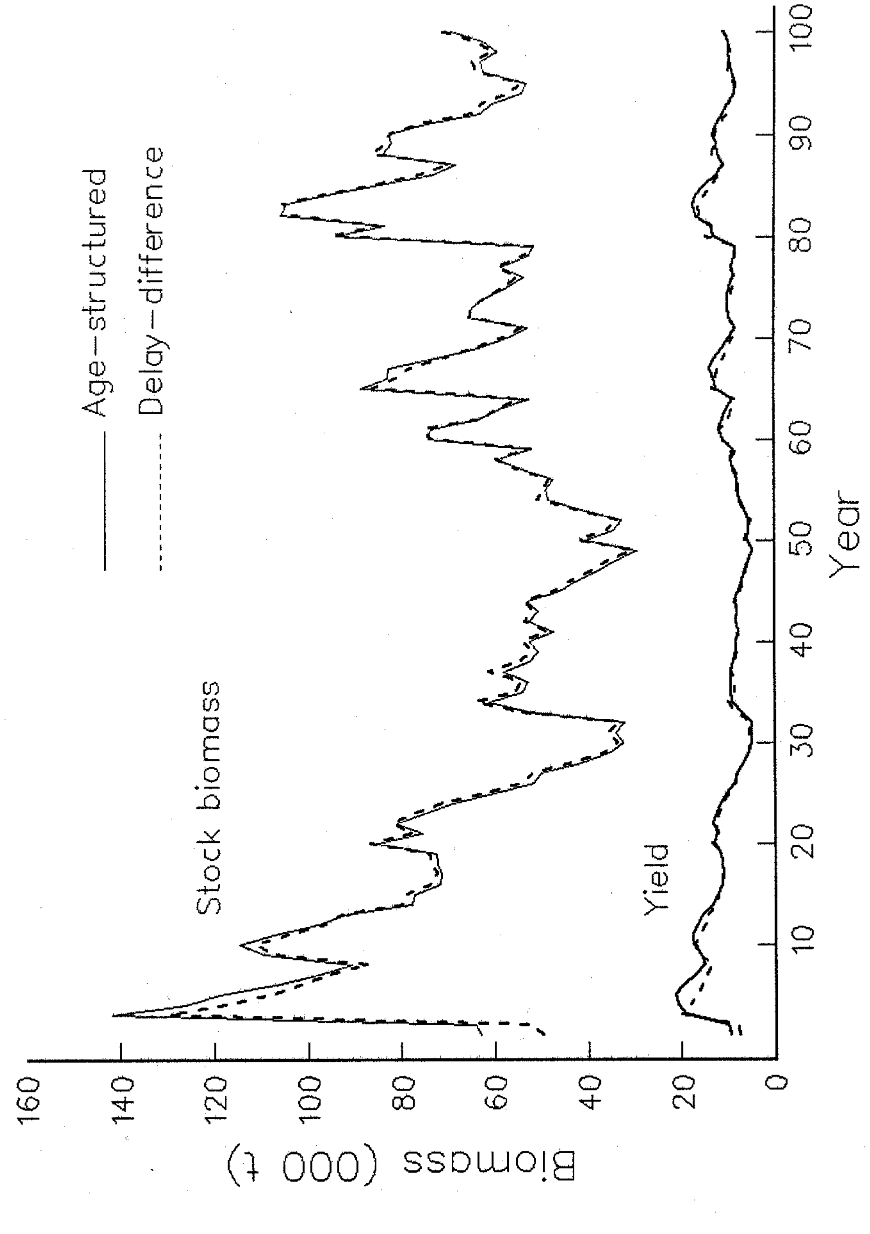
Recruitment correlation	CV for biomass estimates (%)	Objective function	Percent change Mean catch	 Var[100]
0.00	0	logh	-0.4	-24.3
		negx	-1.1	-44.9
	25	logh	-0.4	-31.2
		negx	-1.4	-48.1
	50	logh	-0.7	-36.2
		negx	-1.6	-46.3
0.25	0	logh	-0.1	-25.6
		negx	-0.7	-42.5
	25	logh	-0.4	-33.2
		negx	-1.0	-45.0
	50	logh	-0.4	-34.1
		negx	-1.0	-44.3
0.50	0	logh	-0.1	-28.9
		negx	-0.5	-40.0
	25	logh	-0.2	-31.8
		negx	-0.8	-44.7
	50	logh	-0.5	-38.2
		negx	-1.0	-44.7

Table 7. Percent change for five-species model in average total catch and year-100 variance of total catch for multispecies policies, compared to a constant F policy for maximizing harvest. The objective function was based on the mean harvest for years 75-100, a period assumed to approximate steady-state conditions. Policies were not developed for recruitment correlation levels 0.25 and 0.50 because of the lack of information about splitnose rockfish recruitment and the computational effort required for the five-species model.

Recruitment correlation	CV for biomass estimates (%)	Objective function	Percent change Mean catch yrs 1-100	 Mean catch yrs 75-100	 Var[100]
0.00	0	logh	-5.0	0.2	-42.9
		negx	-6.0	-2.0	-44.0
	25	logh	-5.3	0.5	-44.4
		negx	-9.8	-2.5	-66.1
	50	logh	-3.7	0.6	-38.2
		negx	-9.8	-3.1	-62.7

Figure 1. Simulated levels of age-6+ widow rockfish stock biomass and yield for a 100-year period, using either a delay-difference or age-structured model to represent stock dynamics. The same stream of random recruitment perturbations was used for both cases.

Figure 2. For the three-species model, relationships between the optimal parameters for the multispecies policy (equation 5). Each point represents a specific objective function, level for precision for annual biomass estimates, and level of interspecific correlation for recruitment perturbations. Results for the two-species (bocaccio, chilipepper) case were similar and are not shown here.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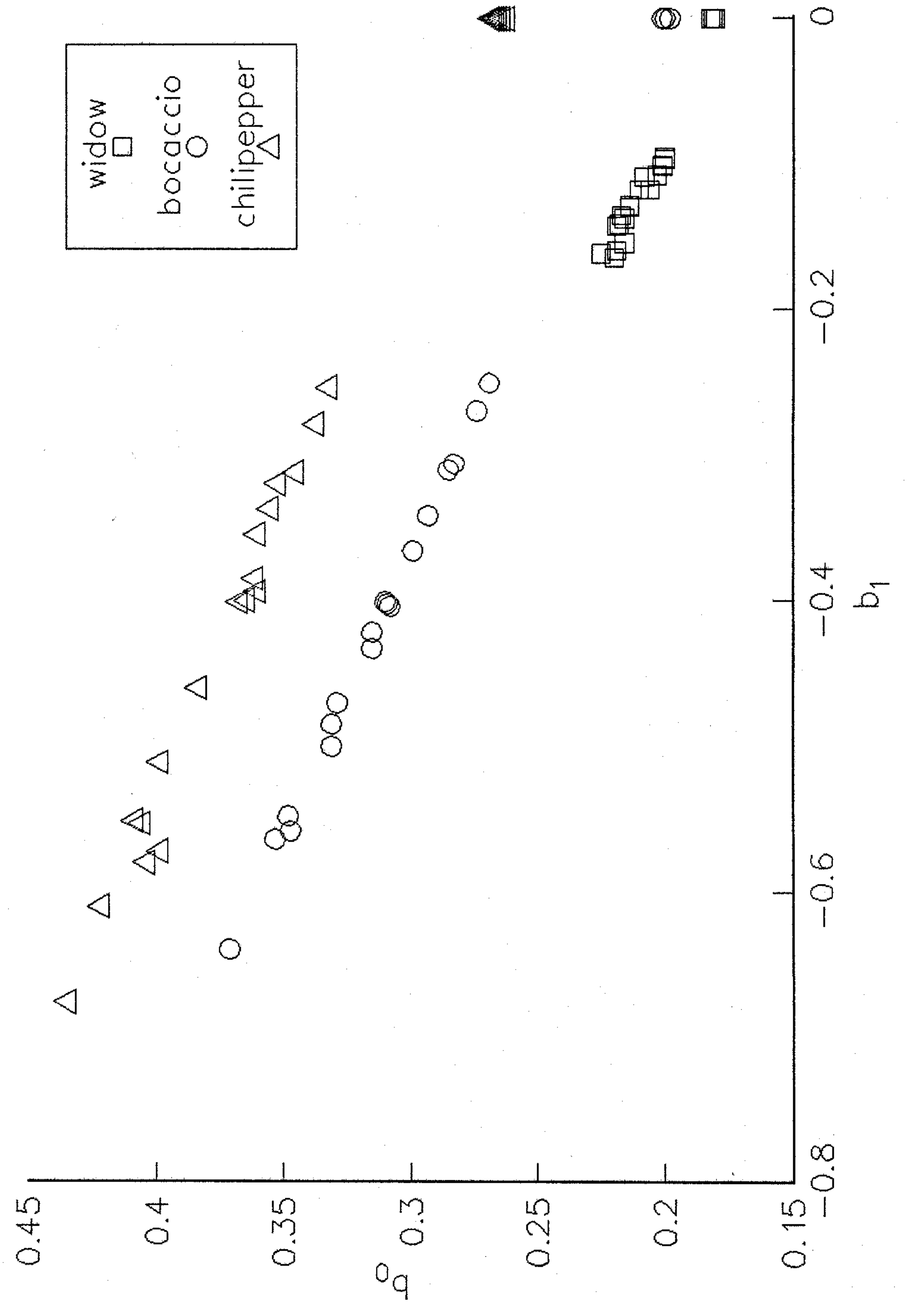
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