Optimal Policies for Rehabilitation of Overexploited Fish Stocks Using a Deterministic Model

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Traditional fisheries models are of limited use during the transitional period when effort is reduced to permit recovery of an overexploited stock. We used a generalized age-structured model to represent stock dynamics during this transitional period and obtained optimal harvesting policies for three overexploited fish stocks using a first-order gradient procedure. The length of the rehabilitation period was affected by (1) the demographic characteristics of the stock, (2) the historical level of exploitation, and (3) the form of the objective function. When a target stock biomass or spawning stock was specified, rehabilitation was relatively rapid due to the sharp initial reduction in fishing effort. Fishing began earlier in the planning horizon when a target harvest was specified; however, stocks recovered more slowly and fishing effort and harvest did not stabilize at the desired levels as rapidly. Policies for maximizing harvest did not usually result in closure of the fishery; however, fishing effort usually exceeded the desired level and sometimes fluctuated considerably from year to year. Our results should aid in the development of rehabilitation policies tailored to specific fisheries or specific management goals.

L'application de modèles traditionnels de pêche est limitée pendant la période de transition quand l'effort est réduit afin de permettre le rétablissement d'un stock surexploité. Les auteurs utilisent un modèle généralisé basé sur l'âge pour représenter la dynamique d'un stock pendant cette période de transition; ils ont ainsi obtenu des plans d'exploitation optimale pour trois stocks surexploités à l'aide de fréquences du premier ordre. La longueur de la période de rétablissement a varié selon les facteurs suivants : 1) les caractéristiques démographiques du stock, 2) le niveau historique d'exploitation et 3) la forme de la fonction objective. La détermination de niveaux cibles pour la biomasse du stock ou le stock reproducteur a permis un rétablissement assez rapide à cause de la forte baisse initiale de l'effort de pêche. Dans le cadre de la planification, la pêche a commencé plus tôt quand on a précisé le niveau cible d'exploitation; toutefois, la récupération des stocks a étré plus lente et l'effort de pêche et les captures ne se sont pas stabilisés aussi rapidement au niveau désiré. En général, les plans de maximalisation des captures n'ont pas entraîné une fermeture de la pêche; toutefois, l'effort de pêche a généralement dépassé le niveau désiré et a parfois varié fortement d'une année à l'autre. Les résultats obtenus devraient servir à l'élaboration de plans de rétablissement adaptés à des pêches précises ou à des buts de gestion déterminés.

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Alverson and Paulik (1973) noted that traditional management models, such as the Beverton–Holt yield-per-recruit model (Ricker 1975), were of limited value for management of developing fisheries because these fisheries typically have not reached steady-state conditions. The same limitation also applies to management of overfished stocks. The latter case is of considerable interest because many stocks are fully exploited or have been overharvested (Cushing 1981). For example, Atlantic menhaden (*Brevoortia tyrannus*) and Pacific ocean perch (*Sebastes alutus*) stocks have been overfished for several years and reductions in fishing effort have been recommended (Schaaf 1979; Archibald et al. 1983; Pacific Fishery Management Council 1984). To facilitate rehabilitation of overexploited stocks, management models are needed to provide quantitative recommendations for the transitional period to lower fishing effort.

Age-structured population models have been used to develop rehabilitation policies for several overexploited fish stocks. For example, Huang and Walters (1983) used an age-structured model to compare short-term approaches for rehabilitation of a large yellow croaker (*Pseudosciaena crocea*) stock. In their study, alternative strategies were selected arbitrarily and compared through simulation studies. Stock rehabilitation required about 15 yr under a constant effort policy, but occurred much more rapidly if the fishery was closed for 3 yr. Ruppert et al. (1985) used an age-structured model to develop optimal rehabilitation policies for the Atlantic menhaden stock. They found that the stock was restored to the optimal steady-state level in about 9 yr using either a constant effort policy or one of four "egg escapement" policies. The steady-state performance of the five policies was somewhat similar, although there were notable differences in harvest during the rehabilitation period. Archibald et al. (1983) compared several constant effort policies for rehabilitation of a Pacific ocean perch stock. Results for a 30-yr planning horizon were used to evaluate the "short-term"

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performance of these policies; however, simulation runs of 100 yr or more were required to achieve steady-state levels.

These results demonstrate that the life history characteristics of the stock and the form of the harvesting policy can have important effects on the management strategies employed during the rehabilitation period. Our objective in this study was to examine the effects of planning horizon length, stock demographic characteristics, and objective function type on the form of optimal rehabilitation policies for three overexploited fish stocks. Our results can be used to develop rehabilitation policies tailored to specific fisheries; for example, a policy with gradually decreasing effort levels might be preferable to one that achieves stock rehabilitation quickly.

Methods

Age-structured models have been used to simulate a variety of fisheries, including South African anchovy (*Engraulis capensis*) (Getz 1980, 1985), Atlantic menhaden (Schaaf 1979; Ruppert et al. 1985), Pacific ocean perch (Archibald et al. 1983), large yellow croaker (Huang and Walters 1983), and Arcto-Norwegian cod (*Gadus morhua*) (Walters 1969). The model used in this study was a slightly generalized version of a deterministic model presented by Getz (1980), who assumed that each simulated year consisted of a fishing season followed by a spawning season. We assumed that each year can be divided into a fishing season of length t' and a closed season of length $(1 - t')$. Spawning was assumed to occur either at the beginning of the year or after the fishing season. Following Getz (1980), we assumed that

$$(1)\quad x_{i+1}(k+1) = x_i(k)\exp(-M_i - q_i f(k)t') \qquad (k = 0,\ldots,N-1;\ i = 1,\ldots,\lambda-2)$$

$$(2)\quad x_\lambda(k+1) = x_{\lambda-1}(k)\exp(-M_{\lambda-1} - q_{\lambda-1} f(k)t') + x_\lambda(k)\exp(-M_\lambda - q_\lambda f(k)t')$$

where $x_i(k)$ = number of age i fish in year k, λ = maximum age class used in the model, t' = length of the fishing season, q_i = catchability coefficient for age i fish, M_i = annual instantaneous rate of natural mortality for age i fish, and $f(k)$ = level of fishing effort in year k. The stock–recruitment model was either of the form proposed by Ricker (1975):

$$(3)\quad x_1(k+1) = \alpha S(k)\exp(-\beta S(k))$$

or Beverton and Holt (1957):

$$(4)\quad x_1(k+1) = 1/(\alpha + \beta/S(k))$$

where α and β were parameters for either the Ricker or Beverton–Holt curve and $S(k)$, the spawning stock in year k, was defined as

$$(5)\quad S(k) = \sum_{i=1}^{\lambda} c_i x_i(k)$$

when spawning occurred at the beginning of the year or

$$(6)\quad S(k) = \sum_{i=1}^{\lambda} c_i x_i(k)\exp(-t'(M_i + q_i f(k)))$$

when spawning occurred after the fishing season, where c_i = fecundity index for age i fish. Harvest in year k was defined as

$$(7)\quad h(k) = \sum_{i=1}^{\lambda} x_i(k) w_i q_i f(k)(1 - \exp(-t'(M_i + q_i f(k)))) \div (M_i + q_i f(k))$$

where w_i = weight of age i fish. It should be noted that average weight-at-age may change if optimal and current levels of fishing mortality differ markedly (Ricker 1975). For example, if the mortality rate is reduced under the optimal policy, mean weight-at-age should increase because more fish survive to the larger sizes reached later in the year (Ricker 1975). Density-dependent changes in weight-at-age also might be observed if stock size changes substantially over the planning horizon. These factors may bias long-term estimates of the optimal levels of fishing effort; however, the practical consequences of this result are small if revised estimates of weight-at-age are used to update the policy periodically.

We examined harvesting policies obtained by minimizing

$$(8)\quad \sum_{k=0}^{N-1} (b(k+t') - b^*)^2$$

where b^* represented the target stock biomass at the end of the fishing season and $b(k+t')$ was defined as

$$(9)\quad b(k+t') = \sum_{i=1}^{\lambda} x_i(k) w_i \exp(-t'(M_i + q_i f(k))).$$

To determine the target stock biomass, we assumed that an appropriate level of fishing effort for the rehabilitated stock would be $f_{0.1}$, the level at which the slope of the yield–effort curve was 1/10 the slope of the curve at the origin. This marginal yield criterion frequently has been used in yield per recruit analyses to select an appropriate fishing mortality rate (Sissenwine 1981). This recommended rate of fishing mortality may be considerably lower than the rate needed to obtain maximum sustained yield (MSY), yet the loss in yield may be minor (Sissenwine 1981). In addition to greater economic efficiency (Gulland and Boerma 1973), an additional advantage of this criterion is the maintenance of a larger spawning stock (Sissenwine 1978). Similar advantages should apply when used with yield–effort curves; therefore, we defined b^* as the equilibrium stock biomass obtained at $f_{0.1}$.

The second set of harvesting policies was obtained by minimizing

$$(10)\quad \sum_{k=0}^{N-1} (s(k+t') - s^*)^2$$

where s^* represented the target spawning stock at the end of the fishing season. We defined s^* as the equilibrium spawning stock obtained at $f_{0.1}$ and obtained $s(k+t')$ from (9) by replacing w_i with c_i. Note that $s(k+t')$ is equivalent to $S(k)$ in (6) if spawning occurs after the fishing season.

The third set of harvest policies was obtained by minimizing

$$(11)\quad \sum_{k=0}^{N-1} (h(k) - h^*)^2 + \delta \sum_{i=1}^{\lambda} (x_i(N) - x_i^*)^2$$

where h^* was the equilibrium harvest obtained at $f_{0.1}$, δ was a penalty weight, and $\boldsymbol{x}^*$ (the target number-at-age vector at time N) was defined as the equilibrium number-at-age vector at $f_{0.1}$. Walters (1975) obtained harvesting strategies for Pacific salmon by minimizing

$$(12)\quad \sum_{k=0}^{N-1} (h(k) - h^*)^2$$

and suggested that those strategies conformed more closely to actual management practices than did strategies for harvest maximization. Stock rehabilitation policies that we obtained using (12) were unacceptable, however, for two reasons. First,

TABLE 1. Equilibrium number-at-age vectors obtained at the maximum sustainable level of fishing effort (f_{max}) and twice the level designated as optimal ($f_{0.1}$).

Stock	Historical level of effort	Age class	Number per age class							
Anchovy	f_{max}	1–5+	0.6	0.2	0.0	0.0	0.0			
	$2 \times f_{0.1}$		61.5	20.7	6.0	1.6	0.3			
Atlantic menhaden	f_{max}	1–8+	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	$2 \times f_{0.1}$		2.8	1.4	0.3	0.1	0.0	0.0	0.0	0.0
Pacific ocean perch	f_{max}	1–8	28	28	28	28	28	28	27	25
		9–16	24	22	20	18	15	13	11	9
		17–24	8	7	6	5	4	4	3	3
		25–29+	3	2	2	2	13			
	$2 \times f_{0.1}$	1–8	118	118	118	118	118	118	111	105
		9–16	99	91	83	75	65	56	48	41
		17–24	35	30	27	24	21	19	17	15
		25–29+	13	11	10	9	70			

any given equilibrium harvest (other than MSY) could be obtained at two different levels of fishing effort (i.e. one above and one below MSY). Stock size was lower at the higher effort level and this was the equilibrium attained by the rebuilding stock. A second problem arose with the use of the scalar quantity h^* as the target harvest from a multi-aged stock. This harvest can be obtained from more than one number-at-age vector, and harvests approximating h^* were sometimes obtained by increasing effort to offset decreases in stock size. We assumed that an appropriate rehabilitation strategy was one leading to a period of stable effort and harvests and incorporated an end point penalty (Getz 1985) into (11) to accomplish this result. Note that policies obtained from (11) or (12) could be inappropriate in some instances because deviations from h^* are treated equally, regardless of direction. Even if stability in harvest is a primary objective, most fishermen and managers would consider harvests larger than h^* to be much less of a problem than harvests smaller than h^*. An alternative approach would be to give less weight to those deviations where harvest exceeds h^*. We did not evaluate that approach but would not expect our results to change substantially because harvests generally would be less than h^* during the rehabilitation period.

The fourth set of harvesting policies was obtained by maximizing

$$(13)\quad \sum_{k=0}^{N-1} h(k) - \delta \sum_{i=1}^{\lambda} (x_i(N) - x_i^*)^2$$

where the end point penalty was used to prevent the stock from being depleted at the end of the planning horizon. A fifth set of harvesting policies was obtained by maximizing $\Sigma \log(h(k) + 1)$, using the same end point penalty as in (13). Ruppert et al. (1985) suggested that a policy for maximizing log (harvest) might be appropriate whenever there is substantial aversion to risk. In our deterministic analysis, however, policies for maximizing harvest and log (harvest) usually were similar; hence, results for the log (harvest) criterion will not be presented herein.

Fishing effort in our analysis was permitted to vary from 0 to f_{max}, where f_{max} was chosen to be the greatest level of fishing effort at which a nonzero equilibrium was attained by the simulated stock. Note that f_{max} also could represent fleet capacity (Ludwig 1981).

We obtained optimal rehabilitation policies by using a first-order gradient procedure (Dyer and McReynolds 1970; Dreyfus and Law 1977; Getz 1985). (A listing or copy of a microcomputer-based version is available from the senior author.) We assumed that the initial state of the system $x(0)$ was known; for example, through application of a stock reconstruction technique such as cohort analysis (Pope 1972). The optimal rehabilitation policy was defined as the N levels of fishing effort $f(0), \ldots, f(N-1)$ that minimized (8), (10), or (11), or that maximized (13), subject to state transformation equations (1)–(6). We obtained the optimal decision sequence by iteratively improving the value of an arbitrary initial sequence $f^0(0), \ldots, f^0(N-1)$ until increases in value were negligible (Dyer and McReynolds 1970; Dreyfus and Law 1977). Changes in the decision sequence were obtained by first expressing the value in year k, $T(k)$, as a recursive formula. For example, the value of a policy for achieving a target harvest was obtained from

$$(14)\quad T(k) = -(h(k) - h^*)^2 + T(k+1) \qquad (k = 0, \ldots, N-1)$$

where $T(N) = -\delta \Sigma_{i=1}^{\lambda} (x_i(N) - x_i^*)^2$. The gradient vector $\partial T(k)/\partial f(k)$ was computed to determine the direction for changes in the decision sequence. At the jth iteration, the updated decision sequence was obtained as

$$(15)\quad f^j(k) = f^{j-1}(k) + c\partial T(k)/\partial f(k)$$

where c was chosen to maximize the increase in value (Dreyfus and Law 1977).

We determined stock rehabilitation policies for a South African anchovy stock, the Atlantic menhaden stock, and a Pacific ocean perch stock (see Hightower and Grossman (1985) and references therein). We obtained rehabilitation strategies for two hypothetical cases by assuming that the historical level of fishing effort was either f_{max} or $2 \times f_{0.1}$ (Table 1). The former case represented a fishery for a heavily overexploited stock, whereas the latter represented a fishery in which the stock was moderately overexploited. In all cases, references to management policies refer to policies for rehabilitation of these hypothetical stocks.

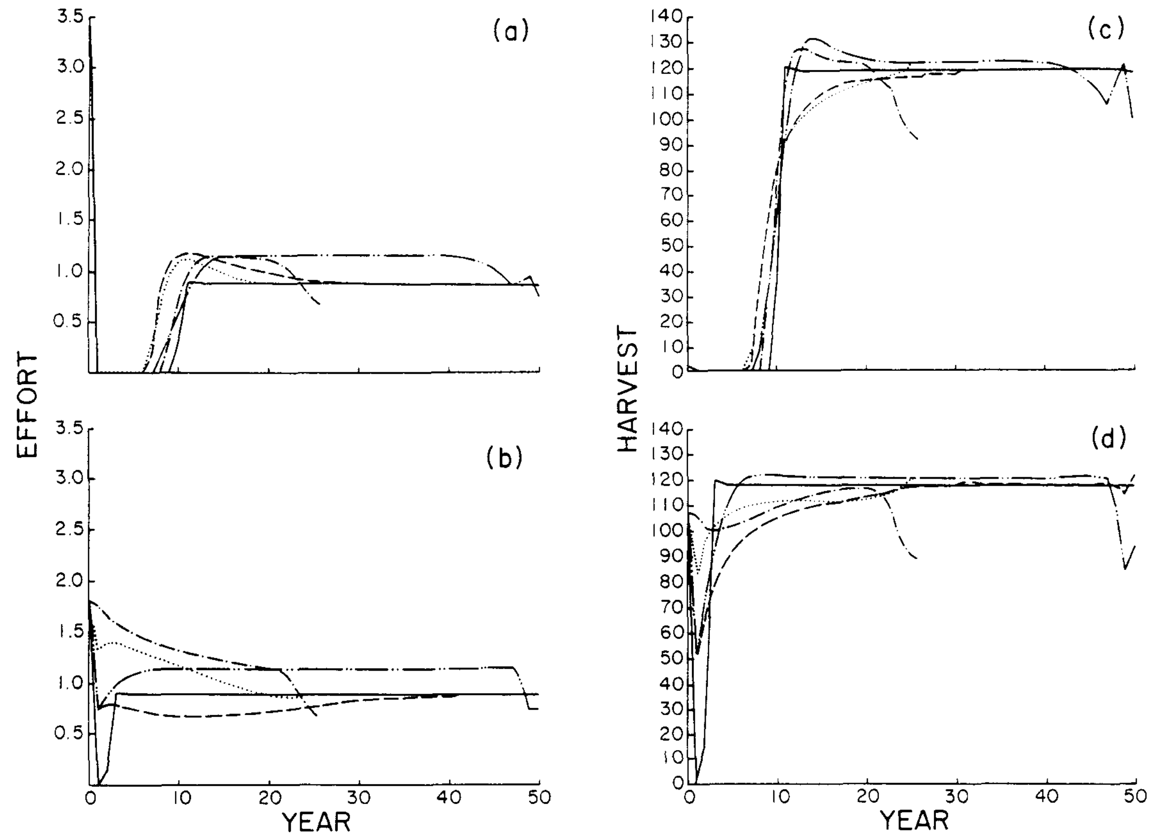

FIG. 1. Optimal levels of fishing effort and harvests for a (a, c) heavily depleted and (b, d) moderately depleted anchovy stock, obtained by maximizing harvest (— · —, 25 yr; — · · · —, 50 yr), specifying a target spawning stock s^* (—, 50 yr) or specifying a target harvest h^* (· · ·, 25 yr; — —, 50 yr). The 25- and 50-yr policies for attaining s^* differed only in the length of the final constant-effort period, so only the latter policy is shown.

Results and Discussion

Two related problems in developing a policy for stock rehabilitation are (1) determining the length of the rehabilitation period and (2) selecting an appropriate level of annual effort during the rehabilitation period. We found that a planning horizon of two to three times the life span of the fish was sufficient for rehabilitation to occur. Note that these stocks had been fished at the maximum sustainable level, so a shorter rehabilitation period could be used in most instances.

Policies for achieving a target stock biomass and target spawning stock were almost identical for the three stocks examined in this study, so results for a target stock biomass were omitted from Fig. 1–3. Both policies resulted in rapid recovery of the overexploited anchovy and Atlantic menhaden stocks (Fig. 1 and 2). Even when heavily depleted, stocks recovered fully in 5–10 yr and effort was constant during the post-rehabilitation period. A 25-yr planning horizon was sufficiently long for rehabilitation to occur, and increasing the planning horizon to 50 yr merely increased the length of the final constant-effort period. Note that rehabilitation periods were longer for the shorter-lived anchovy stock ($\lambda = 5$) than for the Atlantic menhaden stock ($\lambda = 8$). The difference in the number of age classes is misleading, however, because few Atlantic menhaden lived beyond age 5 unless the level of fishing effort was low. A more important difference between the two stocks is that a Beverton–Holt curve was used to represent the anchovy stock–recruitment relationship, whereas a Ricker curve was used for Atlantic menhaden. This difference enabled the Atlantic menhaden stock to rebuild more quickly because maximum recruitment occurred at an intermediate stock size. For example, in the heavily exploited case, the Atlantic menhaden spawning stock increased to the level producing maximum recruitment in about 4 yr if the fishery was closed. In that same period, the anchovy spawning stock also increased substantially but recruitment produced by that spawning stock was only about one-fifth the maximum level. The Pacific ocean perch stock recovered much more slowly than did the anchovy and Atlantic menhaden stocks; hence, a planning horizon of 100 yr was used. About 60 yr without fishing were needed to rebuild the heavily depleted stock, whereas a 25-yr closure was needed when the stock was only moderately overexploited (Fig. 3). The optimal policy for all three stocks was to close the fishery until stock biomass or spawning stock exceeded the target level. Once the fishery reopened, harvests stabilized at the desired level (h^*) within a few years (Fig. 1–3).

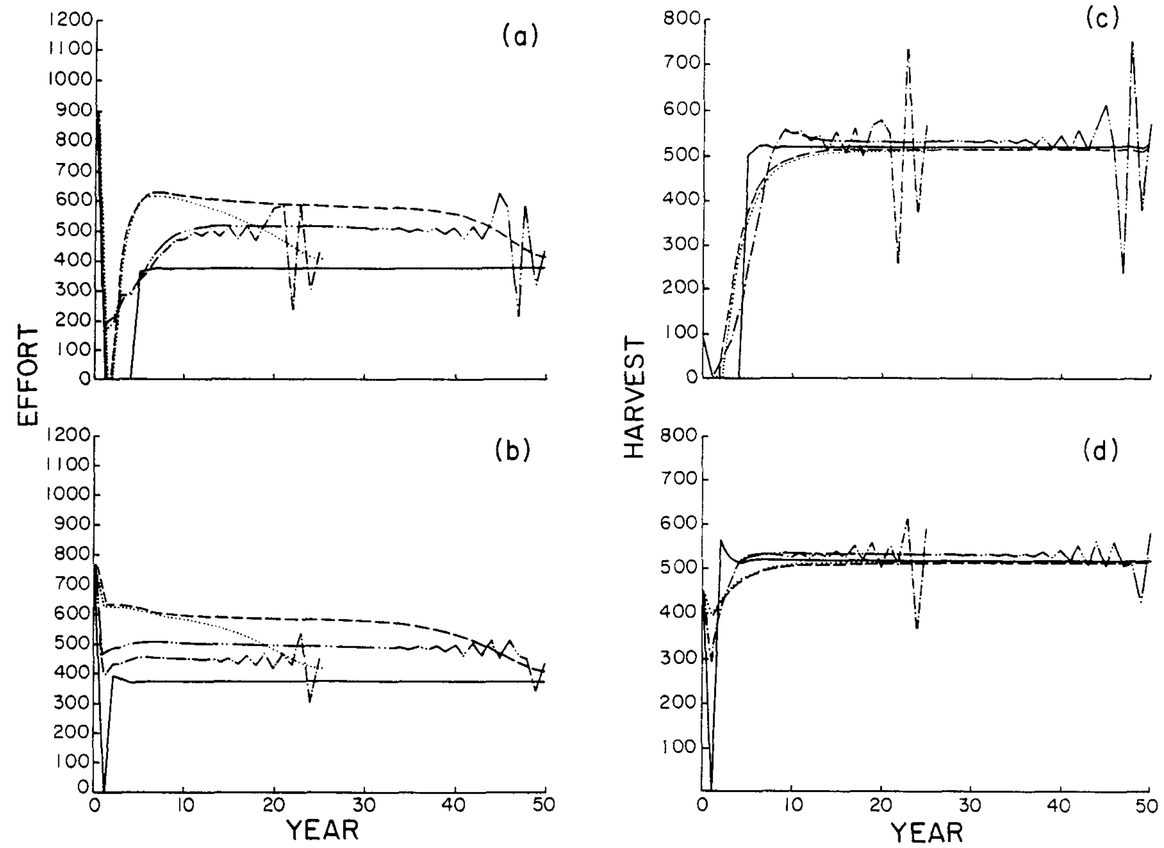

FIG. 2. Optimal levels of fishing effort and harvests for a (a, c) heavily depleted and (b, d) moderately depleted Atlantic menhaden stock, obtained by maximizing harvest (— · —, 25 yr; — · · · —, 50 yr), specifying a target spawning stock s^* (—, 50 yr) or specifying a target harvest h^* (· · ·, 25 yr; — —, 50 yr). The 25- and 50-yr policies for attaining s^* differed only in the length of the final constant-effort period, so only the latter policy is shown.

Policies obtained by specifying a target harvest resulted in a more gradual recovery for all three stocks. Fishing began earlier in the planning horizon; however, target levels of fishing effort and harvest were not reached as rapidly (Fig. 1–3). For example, in comparison with results obtained through the use of a target biomass criterion, fishing for the moderately depleted Atlantic menhaden stock began 1 yr earlier, but harvests were lower in years 2–25. One disadvantage of target harvest policies was apparent in cases where the fishery was closed at the start of the planning horizon. Once the fishery was reopened, effort levels increased to above $f_{0.1}$ in order to obtain harvests approximating h^* (Fig. 1–3). Given the difficulty of reducing fishing effort, a more practical approach might be to permit effort to increase only to $f_{0.1}$ and then allow harvest levels to increase gradually to h^*. Policies for attaining a target harvest were affected by a change in the length of the planning horizon. By increasing the time available for convergence to the target vector x^*, a more gradual reduction in fishing effort was sometimes possible (Fig. 2).

Policies for maximizing harvest appeared to be the most practical alternative in several of the cases considered herein. For example, the 25-yr policy for the moderately depleted anchovy stock required a gradual reduction in fishing effort to a level of about $f_{0.1}$. For the heavily depleted Atlantic menhaden stock and for both heavily and moderately depleted Pacific ocean perch stocks, harvest maximizing policies were the only management options that did not require closure of the fishery. In addition, harvests at the start of the rehabilitation period were only moderately below the historical level, which is shown in year 0 (Fig. 2d, 3c, 3d). The harvest maximizing policy for the heavily depleted Pacific ocean perch stock might be particularly useful if the species was taken incidentally in other fisheries, because some landings would be permitted throughout the planning horizon. The primary disadvantage of harvest maximizing policies was that, in the anchovy and Atlantic menhaden fisheries, effort frequently increased to the level producing maximum sustained yield (f_{msy}). This occurred in all cases when a 50-yr horizon was used, because convergence to x^* was achieved relatively quickly at the end of the planning horizon. The disadvantage of fishing at f_{msy} is illustrated in Fig. 1 and 2 in that only a slightly higher yield was obtained at a substantially higher effort level. An additional problem with harvest maximizing policies for Atlantic menhaden was that effort sometimes fluctuated substantially from year to year. This phenomenon only occurred near the end of the planning horizon; thus, its practical consequence

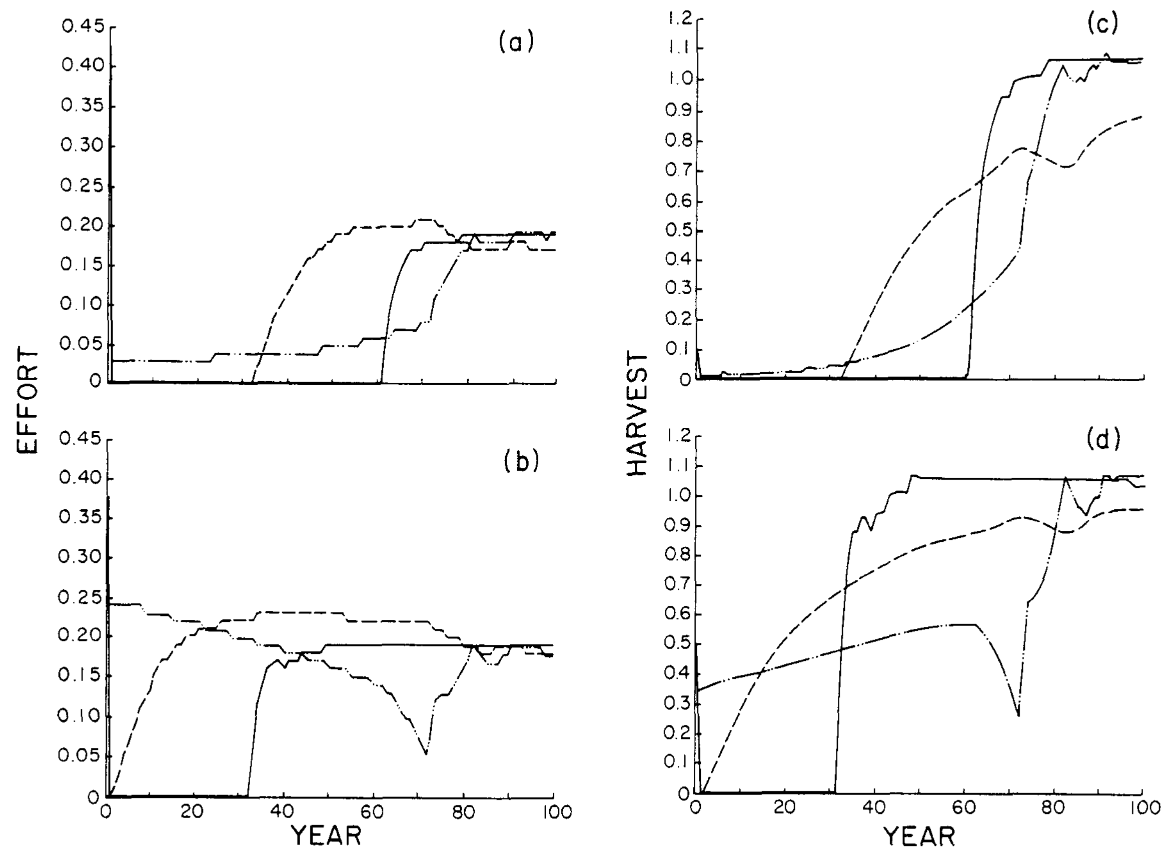

FIG. 3. Optimal levels of fishing effort and harvests for a (a, c) heavily depleted and (b, d) moderately depleted Pacific ocean perch stock, obtained by maximizing harvest (—··—), specifying a target spawning stock s^* (—), or specifying a target harvest h* (– –).

would be negligible if policies were updated regularly.

Variability in recruitment appears to be a significant feature of most commercially important fish stocks (Swartzman et al. 1983); therefore, it is reasonable to question whether the deterministic model used in our analysis is capable of providing useful information to the fishery manager. A stochastic model clearly would be preferable on theoretical grounds; however, in practice, policies obtained from stochastic and deterministic models may be similar because the relative merits of different actions tend to be similar in the two cases (Walters and Hilborn 1978). If a deterministic model is used, a more responsive policy could be obtained by updating the analysis annually. This updated policy would reflect any change in the status of the stock, whether due to random environmental factors or to a change in the level of fishing effort. Another practical advantage of periodic updating is that it can correct errors in previous harvesting policies (Ludwig 1981).

To illustrate this approach, we obtained annually updated policies for achieving a target harvest from the moderately depleted anchovy and Atlantic menhaden stocks (Fig. 4). In each year of a simulated 25-yr period, we obtained an optimal 25-yr rehabilitation policy for the current number-at-age vector $x(k)$. We then used $f(0)$ from the newly determined policy to obtain $x(k + 1)$ from equations (1)–(6). Random variation was introduced by incorporating a multiplicative lognormal error term into the stock–recruitment relationship; consequently, $f(0)$ in year k differed from $f(k)$ obtained in year 0. Thus, each annually updated policy in Fig. 4 represents 25 $f(0)$ values taken from a sequence of 25-yr rehabilitation policies. The two updated policies for the anchovy stock do not differ substantially from the policy obtained in year 0; however, the estimated variance (0.06) of the stock–recruitment relationship for this stock was relatively low (Hightower and Grossman 1985). A more pronounced divergence between original and updated policies can be seen for Atlantic menhaden, for which the estimated variance of the stock–recruitment relationship (0.25) was somewhat greater (Hightower and Grossman 1985). Note that effort decreased sharply when strong year classes entered the Atlantic menhaden fishery (Fig. 4b). These decreases were required to obtain harvests closely approximating h^*. It is unclear, however, whether commercial fishermen would be willing to forego increased harvests and accept fluctuations in effort merely to reduce variability in annual harvest. From the manager's viewpoint, the policy obtained in year 0 may be preferred in that changes in fishing effort are more gradual and known in advance; thus, implementation of a given policy would be simpler from both a practical and political standpoint. Finally, it should be noted that information regarding stock condition generally is available only after a lag of several years; hence, annual updates of

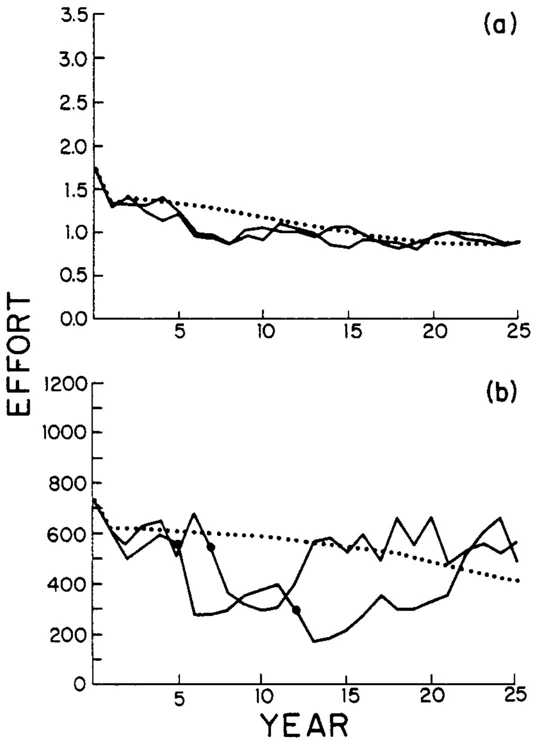

Fig. 4. Optimal (···) and annually updated (—) harvesting policies for moderately depleted (a) anchovy and (b) Atlantic menhaden stocks. For each stock, the three policies were obtained by specifying a target harvest h^*; updated policies were obtained for two simulated 25-yr periods. Closed circles denote years in which a strong year class entered the simulated Atlantic menhaden fishery.

the rehabilitation policy may not be practical.

In cases where variability in recruitment is high and periodic updating is not possible, a stochastic model may be essential. Once a random component is introduced, however, it is no longer meaningful to estimate optimal effort levels for each year of the planning horizon. A better approach would be to develop a stationary policy, where harvest depends only on stock size and not on the number of years remaining in the planning horizon (Ruppert et al. 1985). A stationary policy might have only one (constant effort) or two (egg escapement) parameters (Ruppert et al. 1985) instead of the 25–100 parameters (effort levels) used in our deterministic analysis.

The only obvious disadvantage of using a stochastic model is that much greater computational effort is required to obtain and evaluate optimal policies. An important advantage is that the model can be used to evaluate probabilistic questions that cannot be addressed with a deterministic model. For example, alternative policies could be compared using criteria such as variability in annual harvest (Ruppert et al. 1985), or the probability of full recovery (Overholtz et al. 1986) or of further declines in stock size (Archibald et al. 1983) during the planning horizon. In addition, the probability of stock depletion could be considered explicitly when developing a harvesting policy if a stochastic model was used (Swartzman et al. 1983). The deterministic approach used in this study might play a complementary role in situations where a stochastic model is required by providing insights into the expected behavior of the stock during the rehabilitation period.

In practice, any management plan represents a compromise between user groups with conflicting objectives. These user groups may have widely divergent views regarding the appropriateness of restrictions on fishing effort or of the proper balance between short- and long-term benefits. Consequently, optimization studies might best be viewed as a means to explore and compare policies obtained through the use of alternative management objectives (Peterman et al. 1978). For example, alternative policies for achieving a target harvest can be obtained by varying the length of the planning horizon. A longer planning horizon could be chosen for a stock rehabilitation plan so that changes in the level of fishing effort would be more gradual. As Gunderson (1984) illustrated, management policies requiring rapid changes in either effort or catch levels are difficult to implement. Hence, longer-term planning may be necessary, so that fishermen can attempt to offset reductions in catch by redirecting effort toward less heavily exploited stocks.

Conclusions

Our results for these hypothetical fisheries were, in a general sense, predictable in that an increase in life span or degree of prior exploitation increased the time required for rehabilitation. It appears that rehabilitation will be particularly difficult for long-lived fishes such as Pacific ocean perch, because changes in stock size will be slow and could be masked by variability in recruitment or by errors in the stock assessment. Our results also suggested that the form of the underlying stock–recruitment relationship could affect the rate of rebuilding, in that rehabilitation might be slower if recruitment increased asymptotically than if maximum recruitment occurred at an intermediate stock size. Rehabilitation would also be difficult for stocks with the type of stock–recruitment relationship Overholtz et al. (1986) reported for Georges Bank haddock (*Melanogrammus aeglefinus*). They found that, although recruitment was quite variable, poorer year classes were observed in years when spawning biomass was less than a critical minimum size. In such cases, rebuilding would be particularly slow until the critical minimum size was exceeded.

Although the form of the objective function affected both the rate at which rebuilding occurred and the patterns of annual effort and harvest, mean annual harvest was quite similar for the four cases we considered (Table 2). This suggests that alternative optimal policies might be compared using other criteria, such as the number of years without fishing, or the magnitude of year-to-year changes in effort or harvest. We found that variability in harvest was lowest for the target harvest policy and highest for the target spawning stock and stock biomass policies (Table 2). Variability was high for the latter policies because the fishery remained closed until stock size rebuilt to the target level. Therefore, the best use of those policies may be in determining the minimum time required for full rehabilitation, or alternatively, the maximum time that the fishery should remain closed. Those policies could be practical alternatives in some cases, however, if effort could be diverted to other fisheries during the rehabilitation period. Policies for attaining a target harvest should be somewhat less extreme, although closure might still be optimal for heavily depleted stocks. Closing such a fishery might be a feasible management option, however, because the equilibrium harvest from a

TABLE 2. Mean harvest and coefficient of variation (in parentheses) obtained for each of four objective functions (t = metric tons).

			Objective			
Stock	Historical level of fishing effort	Length of planning horizon (yr)	Maximize harvest (1000 t)	Target spawning stock (1000 t)	Target stock biomass (1000 t)	Target harvest (1000 t)
Anchovy	f_{max}	25	74.4 (75)	72.7 (80)	72.9 (79)	72.6 (68)
		50	97.9 (47)	95.7 (49)	95.8 (49)	95.7 (43)
	2 × $f_{0.1}$	25	108.8 (7)	109.8 (28)	109.9 (28)	110.2 (7)
		50	116.9 (12)	114.2 (19)	114.3 (19)	111.1 (13)
Atlantic menhaden	f_{max}	25	433.8 (44)	435.9 (45)	435.9 (45)	427.6 (36)
		50	483.0 (30)	477.7 (30)	477.7 (30)	473.9 (25)
	2 × $f_{0.1}$	25	513.3 (13)	500.6 (21)	500.5 (21)	500.8 (6)
		50	522.2 (7)	510.0 (14)	510.0 (14)	510.6 (4)
Pacific ocean perch	f_{max}	100	0.4 (113)	0.4 (127)	0.4 (129)	0.4 (82)
	2 × $f_{0.1}$	100	0.6 (39)	0.7 (68)	0.7 (69)	0.7 (35)

heavily depleted stock may be small (Fig. 1c, 2c, and 3c). If alternative fisheries are not available, policies for maximizing harvest may be more appropriate in that closure would rarely be optimal.

Another approach that would yield less drastic changes in effort would be to rebuild the stock in stages, beginning with a lower target stock biomass or spawning stock. For example, b^* could be the equilibrium stock biomass at f_{msy}, so it would be reached more quickly than the larger stock at $f_{0.1}$. It is likely, however, that no single objective function will provide a directly implementable harvesting policy. Nevertheless, our approach still provides a means of exploring the effects of various management options on stock dynamics and of comparing alternative policies that might be combined into a workable suboptimal policy.

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