

Comparison of Constant Effort Harvest Policies for Fish Stocks with Variable Recruitment

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Environmental variability may have a substantial influence on marine fish stocks, primarily by affecting survival to the time of recruitment. Simulation studies at low, intermediate, and high levels of variability in recruitment were used to compare alternative constant effort policies for anchovy (*Engraulis capensis*), Atlantic menhaden (*Brevoortia tyrannus*), and Pacific ocean perch (*Sebastes alutus*) fisheries. These policies were either to maintain effort at the level producing maximum sustainable yield (f_{MSY}), or to permit levels of effort 25–100% greater than f_{MSY} . An increase in effort of 25% above f_{MSY} typically did not reduce annual yield significantly; however, a significant reduction in yield was apparent in all cases when effort increased by 75–100%. When recruitment is highly variable, comparable yields may be obtained at several levels of fishing effort. In such cases, environmental variability provides the fishery manager with considerable flexibility to enhance social or economic benefits without decreasing yields significantly.

La variabilité environnementale peut avoir une influence importante sur les stocks de poissons marins, surtout pour la survie jusqu'à l'époque du recrutement. On a utilisé des études de simulation à des niveaux de variabilité du recrutement faible, intermédiaire et élevé pour comparer divers régimes d'effort constant pour la pêche de l'anchois (*Engraulis capensis*), de l'aloise tyran (*Brevoortia tyrannus*) et du sébaste à longue mâchoire (*Sebastes alutus*). Ces régimes visaient soit le maintien de l'effort au niveau produisant un rendement maximal soutenu (f_{RMS}) ou un accroissement des niveaux d'effort le rendant de 25 à 100 % plus élevé que le f_{RMS} . Un effort supérieur de 25 % au f_{RMS} n'a pas abaissé le rendement annuel de façon significative ; toutefois, une baisse importante du rendement était évidente dans tous les cas quand l'effort était supérieur de 75 à 100 %. Quand le recrutement est très variable, on peut obtenir des rendements comparables à plusieurs niveaux d'effort de pêche. Dans de tels cas, la variabilité environnementale procure une grande latitude au gestionnaire des pêches pour accroître les avantages sociaux ou économiques sans abaisser nettement les rendements.

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Management plans for the regulation of commercial fisheries usually restrict either fishing effort or catch. Catch quotas have received greater use historically (Sissenwine and Kirkley 1982); however, imposition of a catch quota may lead to stock depletion after several years of poor recruitment (Swartzman et al. 1983). In addition, desired fishing mortality rates are achieved more directly by regulation of fishing effort than by catch restrictions (Sissenwine and Kirkley 1982). For these reasons, this study is based on a comparison of management plans in which harvests are regulated through restrictions on fishing effort.

Development of an effective management plan is difficult because environmental factors may have a substantial influence on fish stocks, primarily by affecting survival to the time of recruitment (Getz and Swartzman 1981). A direct effect of this variability in year-class strength is variability in annual catch (Gulland 1972, 1982; Hennemuth et al. 1980), and a fishery may be supported for several years largely by a single strong

year-class. An indirect effect of this phenomenon is that, because stock size is not constant, the optimal level of fishing effort also varies. This suggests that similar harvests may be obtained at a range of effort levels; therefore, moderate errors in estimating the optimal level of fishing effort would be acceptable. In addition, flexibility in selecting effort regulations might enable the fishery manager to enhance social or economic benefits without decreasing yields significantly.

Simulation studies have been useful in evaluating alternative fishery management plans. For example, Huang and Walters (1983) compared alternative strategies for rehabilitation of a large yellow croaker (*Pseudosciaena crocea*) stock and Archibald et al. (1983) estimated steady-state yields obtained from a Pacific ocean perch (*Sebastes alutus*) stock at different levels of fishing effort. In both studies, variability in recruitment was simulated by incorporating an error term into the stock–recruitment relationship (SRR). Simulation studies might also be used to compare frequency distributions of annual harvest obtained at different levels of fishing effort. This comparison may be informative because, even though steady-state or expected yield differs at different levels of fishing effort, such differences may not be of practical importance.

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Consider, for example, regulation of a fishery in which the stock is moderately overexploited and alternative employment is not available. In this case, expected yield will be increased by imposition of a theoretically optimal management plan (optimal in the sense that yield is maximized). The management plan also may have substantial socioeconomic impacts because maximum sustainable yield (MSY) is obtained by decreasing fishing effort, and these impacts could be unacceptable if observed yields did not increase noticeably. The success of any MSY policy depends not only on the accuracy of supporting biological data and compliance within the fishery, but also on the unpredictable effect of the environment on recruitment. By incorporating an appropriate error term into the SRR, age-structured models can be used to predict whether observed changes in yield brought about by decreasing effort will be worth the accompanying socioeconomic disruption.

In this study, we examined published data on stock size and recruitment to determine typical levels of variability in recruitment. Simulation studies at low, intermediate, and high levels of variability were used to compare alternative management policies for anchovy (*Engraulis capensis*), Atlantic menhaden (*Brevoortia tyrannus*), and Pacific ocean perch fisheries. Using maximization of yield as a management goal, these comparisons were done to predict changes in yield that result from changes in fishing effort for fish of varying life spans at three levels of environmental variability.

Methods

The Stock–Recruitment Relationship

Several models of varying complexity have been proposed to examine the relationship between parental stock and recruitment (Beverton and Holt 1957; Cushing 1971; Larkin 1973; Ricker 1975; Getz and Swartzman 1981; Shepherd 1982). Minimum features required for a biologically realistic SRR are (1) low recruitment at very low stock sizes and (2) the ability to allow recruitment to vary widely at intermediate stock sizes (Shepherd 1982; Swartzman et al. 1983; Strong 1984). The Ricker and Beverton–Holt stock–recruitment models are most commonly used to model fish populations, and both models predict lower recruitment as stock size approaches zero. To introduce an appropriate level of environmental variability into the SRR, it is first necessary to determine what form this term should take.

A multiplicative lognormal error term has been used in recent studies of stock–recruitment models (Allen 1973; Walters and Hilborn 1976; Peterman et al. 1978; Laurec et al. 1980; Peterman 1981; Walters and Ludwig 1981; Archibald et al. 1983; Huang and Walters 1983) of the general form

$$R = f(S)e^v$$

where R = recruitment, $f(S)$ = some function of parental stock, which is often represented by biomass of spawners (Beverton 1962; Doubleday 1976; Deriso 1980; Shepherd 1982), and v = normally distributed random variate with mean 0 and variance σ^2 .

This multiplicative lognormal error term has been used in studies of salmon populations, both for mathematical convenience as well as for assumed biological realism (Peterman 1981). A theoretical justification for use of this error term is that e^v can be viewed as a random survival factor resulting from several independent and multiplicative environmental factors

(Walters and Hilborn 1976). Thus, v represents the sum of several random factors and should be approximately normally distributed by the Central Limit Theorem (Walters and Hilborn 1976). The lognormal error distribution is biologically appealing because it provides a simple representation of the observed effects of environmental variability (i.e. good environmental conditions can produce very large year-classes, while poor environmental conditions can reduce recruitment to zero at most). In addition, increased variability in recruitment would seem more likely when the spawning stock is large (Gulland 1967), and use of a multiplicative error term assumes that variability will increase as stock size increases. The lognormal distribution also more accurately represents the frequency distribution of observed year-class strength (Hennemuth et al. 1980) and salmonid survival rates (Peterman 1981) than the normal distribution.

In this paper, we assume that a lognormal error term is appropriate and estimate the magnitude of the lognormal error variance for 13 multi-aged marine fish stocks (Table 1). Minimum criteria for inclusion of a data set were as follows: (1) at least 10 yr of data were available, (2) parental stock was estimated either as stock biomass, biomass of spawners, or a measure of egg production, and (3) recruitment was given as numbers of fish.

Three models were fitted to each data set for the following reasons. For a particular stock, model selection may be based on biological information (Nelson et al. 1977); however, alternative models can rarely be excluded using statistical tests (Gulland 1967). Second, because a regression estimate of the residual error variance includes both the true random error and a lack-of-fit component, we used three possible models to evaluate the sensitivity of our estimates to the form of the model:

- (1) $R = \mu e^v$
- (2) $R = \alpha S e^{-\beta S} e^v$
- (3) $R = 1/(\gamma + \delta/S) e^v$

where μ , α , β , γ , and δ are parameters. The first model assumes that no relationship exists between stock size (S) and recruitment (R). The second is the Ricker model (Ricker 1975) and the third is that of Beverton and Holt (Ricker 1975). A constant recruitment model was included to evaluate the increase in error variance which results from the use of a simpler (and conceptually different) model, although the model violates the above criterion that recruitment should decrease at very low stock sizes.

Because the log-transformed Ricker model is a linear equation and has an additive error term, the residual error variance (σ^2) was estimated using linear regression. The Beverton–Holt model was fitted with nonlinear regression as $\ln(R) = \ln(1/(\gamma + \delta/S)) + v$ to obtain an estimate of σ^2 . Initial parameter estimates for the Beverton–Holt model were obtained by transforming the model to use linear least-squares regression (Ricker 1975), and these estimates were used as starting values for nonlinear regression analysis. Bounded nonlinear regression (SAS Institute, Inc. 1982) was required to obtain reasonable parameter estimates ($\delta > 0$) for one stock, the North Sea plaice; Ricker (1975) also noted this problem when fitting a Beverton–Holt curve to these data using linear regression.

Parameterization of Age-Structured Model

To explore the relationship between number of age classes (λ) and response to overexploitation, parameter estimates were

TABLE 1. Description of the 13 fish stocks used to estimate the level of random variability in the stock–recruitment relationship. The number of observations in each data set is given as N .

Common name	Scientific name	Area	N	Source ^a
Herring	<i>Clupea harengus</i>	Norwegian ^b	20	A
		Georges Bank	13	B
		Icelandic ^b	23	C
		Icelandic ^c	29	C
Round herring	<i>Etrumeus teres</i>	South Africa	13	D
Sardine	<i>Sardinops caerulea</i>	California	33	E
Atlantic menhaden	<i>Brevoortia tyrannus</i>	Atlantic	16	F
Pacific halibut	<i>Hippoglossus stenolepis</i>	Pacific	46	G
Plaice	<i>Pleuronectes platessa</i>	North Sea	26	H
Pilchard	<i>Sardinops ocellata</i>	South Africa	26	D
Anchovy	<i>Engraulis capensis</i>	South Africa	13	D
Atlantic mackerel	<i>Scomber scombrus</i>	Northwest Atlantic	16	I
Large yellow croaker	<i>Pseudosciaena crocea</i>	China Sea	22	J

^aSource: A, Dragesund et al. 1980; B, Anthony and Waring 1980; C, Jakobsson 1980; D, Newman and Crawford 1980; E, Troadec et al. 1980; F, Nelson et al. 1977; G, Deriso and Quinn 1983; H, Ricker 1975; I, Anderson and Paciorewski 1980; J, Huang and Walters 1983.

^bSpring-spawning.

^cSummer-spawning.

TABLE 2. Parameter estimates for the age-structured model of anchovy stock dynamics (from Getz 1985). Number of age-classes (excluding age 0): $\lambda = 5$; length of harvesting season: $t' = 0.67$ yr; stock–recruitment model: Beverton–Holt (spawning after harvesting season), parameter estimates: $\hat{\gamma} = 0.0082$, $\hat{\delta} = 0.9016$; lognormal error variance: $s^2 = 0.06^a$; range of effort levels (arbitrary multipliers) used in simulations: $f = 0-4$.

Age	Weight (g)	Fecundity index (g) ^b	Catchability (normalized)	Natural mortality
1	1.6	0.8	0.24	0.8
2	6.9	6.9	0.36	0.8
3	14.0	14.0	0.42	0.8
4	19.0	19.0	1.00	0.8
5	24.0	24.0	1.00	0.8

^aAn estimate of the lognormal error variance was obtained from total stock biomass and recruitment estimates from 1964 to 1976 (Newman and Crawford 1980). Getz (1980) obtained parameter estimates for the Beverton–Holt SRR using estimates of spawning stock biomass and recruitment from 1964 to 1978 but did not publish the stock–recruitment data.

^bAverage weight multiplied by the proportion that are fecund.

obtained for a relatively short-lived anchovy stock ($\lambda = 5$) from the west coast of South Africa (Table 2; from Getz 1985) and for a relatively long-lived stock of Pacific ocean perch ($\lambda = 29$) (Table 3; from Archibald et al. 1983). Note that λ represents the maximum age-class used in the model, and not the life span of the fish. Recent aging studies using sectioned otoliths indicate that Pacific ocean perch may live for more than 70 yr (Archibald et al. 1981). Data used in this simulation study were obtained through stock reconstruction (Archibald et al. 1983), using catch-at-age data obtained by surface readings of otoliths. Sufficient data are not yet available from aging otolith sections to permit reanalysis. Parameter estimates for Atlantic menhaden, a fish of intermediate life span ($\lambda = 8$), were obtained primarily from life history studies and previous analyses of catch and effort data (Table 4). (In-depth analyses of the Atlantic menhaden fishery are given by Schaaf and Huntsman

(1972), Schaaf (1975), Nelson et al. (1977), and Schaaf (1979).) Numbers-at-age were obtained from cohort analysis (Pope 1972) using catch-at-age and fishing effort data (Schaaf 1979) and estimates of mean instantaneous natural mortality rate ($M = 0.25$) and mean catchability (Vaughan 1977). As in earlier studies of Atlantic menhaden stock dynamics (Schaaf and Huntsman 1972; Nelson et al. 1977; Schaaf 1979), the Ricker curve was used to represent the SRR. Spawning potential was represented by the estimated biomass of spawning females, and was obtained as

$$\sum_{i=1}^{\lambda} c_i N_{it}$$

where N_{it} is the number of age- i fish in year t and c_i , the fecundity parameter for age- i fish, is defined as

$$c_i = s_i f_i w_i$$

where s_i = proportion of females that are sexually mature at age i (Vaughan 1977), f_i = proportion of age i fish that are females (Reintjes 1969), and w_i = weight of females at age $i + 0.5$ from a von Bertalanffy growth curve (Reintjes 1969).

Estimates of weight-at-age were obtained by using sex-specific von Bertalanffy curves (Reintjes 1969) to predict mean weight at ages 1.5–8.5. A von Bertalanffy curve was fitted to data for both sexes and used to predict overall mean weight-at-age.

Evaluation of Alternative Constant Effort Policies

Once typical levels of variability in recruitment were determined, it was possible to evaluate the effects of this variability on alternative constant effort policies. This was done by incorporating a lognormal error term into an age-structured model containing a SRR; a complete description of such a model is given by Archibald et al. (1983) or Huang and Walters (1983).

To estimate MSY for each stock, estimates of steady-state average yield were obtained at each level of fishing mortality using the following replication–deletion approach (Law and Kelton 1982). Each of 100 replicates was run for 10λ yr, and average annual yield was obtained for the last 5λ yr. Observations from the first 5λ yr were deleted to reduce the influence of the nominal set of initial conditions.

TABLE 3. Parameter estimates for the age-structured model of Pacific ocean perch stock dynamics (from Archibald et al. 1983). Recruitment occurs at age 6, so weight, catchability, and natural mortality are set to 0 for ages 1–5. Number of age-classes (excluding age 0): $\lambda = 29$; length of harvesting season: $t' = 1.00$ yr; stock–recruitment model: Ricker (spawning at start of year), parameter estimates: $\hat{\alpha} = 0.0883$, $\hat{\beta} = 9.01 \times 10^{-5}$; lognormal error variance: $s^2 = 0.30$; range of effort levels (arbitrary multipliers) used in simulations: $f = 0.0$ – 0.40 .

Age	Weight (10^{-2} kg)	Fecundity index	Fishing mortality ^a	Natural mortality
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0.00485	0	0.010	0.05
7	0.00529	0	0.021	0.05
8	0.00572	0	0.040	0.05
9	0.00614	0	0.069	0.05
10	0.00654	0	0.111	0.05
11	0.00694	1.00	0.162	0.05
12	0.00732	1.22	0.217	0.05
13	0.00770	1.47	0.266	0.05
14	0.00806	1.72	0.297	0.05
15	0.00841	1.97	0.304	0.05
16	0.00876	2.20	0.284	0.05
17	0.00909	2.44	0.243	0.05
18	0.00942	2.67	0.190	0.05
19	0.00973	2.92	0.190	0.05
20	0.01000	3.11	0.190	0.05
21	0.01030	3.31	0.190	0.05
22	0.01060	3.48	0.190	0.05
23	0.01090	3.65	0.190	0.05
24	0.01120	3.83	0.190	0.05
25	0.01150	3.83	0.190	0.05
26	0.01170	3.83	0.190	0.05
27	0.01200	3.83	0.190	0.05
28	0.01220	3.83	0.190	0.05
29+	0.01300	3.83	0.190	0.05

^aB. M. Leaman, Department of Fisheries and Oceans, Fisheries Research Branch, Pacific Biological Station, Nanaimo, B.C., pers. comm. These estimates of fishing mortality at age in 1977 were obtained through stock reconstruction (Archibald et al. 1983) and were multiplied by arbitrary constants (termed effort) to produce desired levels of fishing mortality.

Once MSY and the associated level of fishing effort (f_{MSY}) were estimated, simulation studies were used to compare the MSY effort policy with constant effort policies where effort was 25, 50, 75, and 100% greater than f_{MSY} . Each treatment combination represented one of three levels of variability in recruitment, one of three fish stocks, and one of four pairwise comparisons of f_{MSY} versus an alternative effort level. The starting age distribution for each simulated period of $k = 5\lambda$ yr was obtained from a deterministic version of the model (Getz 1980), using the level of effort that produced MSY for the deterministic model.

Because the commercial fisherman is affected by annual changes in recruitment and subsequent fluctuations in harvest, we emphasized annual harvest rather than mean or total harvest. However, consecutive harvests in each k -yr period are not independent, and harvests in the first few years are affected by the starting conditions. To obtain independent replicates that are

TABLE 4. Parameter estimates for the age-structured model of Atlantic menhaden stock dynamics. Number of age-classes (excluding age 0): $\lambda = 8$; length of harvesting season: $t' = 1.00$ yr; stock–recruitment model: Ricker (spawning at start of year), parameter estimates: $\hat{\alpha} = 0.0205$, $\hat{\beta} = 0.0024$; lognormal error variance: $s^2 = 0.25$; range of effort levels (vessel-weeks) used in simulations: $f = 0$ – 1000 .^a

Age	Weight (g)	Fecundity index (g)	Catchability ^b	Natural mortality
1	102.77	0	0.000577	0.25
2	260.21	110.25	0.001805	0.25
3	411.73	227.37	0.001579	0.25
4	530.31	302.70	0.001540	0.25
5	614.28	354.63	0.001430	0.25
6	670.60	410.44	0.001820	0.25
7	707.23	491.98	0.001703	0.25
8	730.63	496.60	0.001703	0.25

^aEstimates of annual effective fishing effort (adjusted for changes in catchability using 1971 as the base year) are given by Schaaf (1979). The range 0–1000 vessel-weeks includes most observed values and all published estimates of the level of fishing effort that produces MSY.

^bAge-specific catchability estimates were obtained from cohort analysis. Effective fishing effort data (Schaaf 1979) and an estimate of mean catchability (Vaughan 1977) were used to obtain starting values for fishing mortality rates.

less biased by initial conditions and therefore better estimates of steady-state responses, we analyzed only the harvest from year k in each k -yr period. Harvests in years 1 through $k - 1$ also would be of interest to the fisherman and fishery manager. However, these harvests would tend to be more similar among treatments than harvests in year k due to the shared starting conditions. By focusing the analysis on the steady-state behavior of the system, we obtain conservative results about the similarity in performance of alternative policies. One hundred replicates were used for each treatment. Note that the sample size is arbitrary and that our ability to detect differences among treatments would increase with an increase in sample size. We contend that a difference of practical significance should be detectable by observing 100 independent trials, and note that only a single trial would be observed after implementation of a management plan. Differences in the frequency distribution of harvest in year k were tested at the 95% confidence level using a two-tailed Kolmogorov–Smirnov test (Siegel 1956).

Results and Discussion

Few of these stocks displayed evidence of a relationship between stock size and recruitment, and neither the Ricker nor Beverton–Holt curve appeared to account for a significant amount of variation in recruitment. Estimates of σ^2 (s^2) ranged from 0.06 to 1.20 for both the Ricker and Beverton–Holt models. Under the assumption that no relationship exists between stock size and recruitment, s^2 ranged from 0.07 to 5.68. The distribution of s^2 was similar for the three models (Fig. 1), and in all but two cases (California sardine and Icelandic spring-spawning herring), s^2 does not increase substantially when no relationship between stock size and recruitment is assumed. For the three models considered, most values were less than 0.75, and three values were selected arbitrarily to represent low (0.25), moderate (0.50), and high (0.75) levels of

TABLE 5. Comparison of annual yields obtained at the level of fishing effort that produced maximum sustainable yield (f_{MSY}) with yields obtained when effort exceeded f_{MSY} by 25, 50, 75, or 100%. For each paired comparison, frequency distributions of annual yield were compared using a Kolmogorov-Smirnov test ($\alpha = 0.05$), and significant differences are denoted by the letter *Y*. Estimates of the percentage increase in variability in steady-state average yield are given in parentheses as $100 \times (CV_i - CV_{MSY})/CV_{MSY}$, where CV_{MSY} and CV_i represent coefficients of variation when effort equals f_{MSY} or exceeds f_{MSY} by $i = 25, 50, 75$, or 100%. Three values of the lognormal error variance (σ^2) were used to represent levels of environmental variability in the period following implementation of a management plan.

	Increase in effort above f_{MSY} (%)											
	$\sigma^2 = 0.25$				$\sigma^2 = 0.50$				$\sigma^2 = 0.75$			
	25	50	75	100	25	50	75	100	25	50	75	100
Anchovy	<i>N</i> (-13)	<i>N</i> (24)	<i>Y</i> (45)	<i>Y</i> (72)	<i>N</i> (24)	<i>N</i> (23)	<i>Y</i> (48)	<i>Y</i> (50)	<i>N</i> (0)	<i>N</i> (38)	<i>Y</i> (31)	<i>Y</i> (44)
Menhaden	<i>N</i> (10)	<i>Y</i> (45)	<i>Y</i> (109)	<i>Y</i> (118)	<i>N</i> (27)	<i>Y</i> (60)	<i>Y</i> (43)	<i>Y</i> (106)	<i>N</i> (22)	<i>N</i> (13)	<i>Y</i> (60)	<i>Y</i> (113)
Perch	<i>Y</i> (57)	<i>Y</i> (13)	<i>Y</i> (114)	<i>Y</i> (138)	<i>N</i> (18)	<i>N</i> (36)	<i>Y</i> (64)	<i>Y</i> (120)	<i>N</i> (15)	<i>N</i> (31)	<i>Y</i> (90)	<i>Y</i> (164)

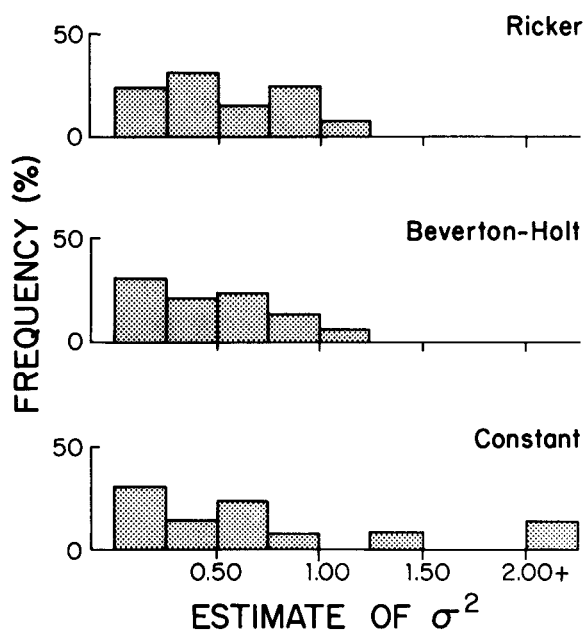


FIG. 1. Sample distribution of σ^2 , the error variance of the stock-recruitment relationship, for 13 multi-aged fish stocks. Ricker, Beverton-Holt, and constant recruitment models were fitted to each data set and a multiplicative lognormal error term was assumed.

variability for a general evaluation of the effect of variability in recruitment on alternative management scenarios.

For the simulated anchovy fishery, changes in the level of environmental variability had no detectable impact on comparisons of alternative policies (Table 5). For the Atlantic menhaden and Pacific ocean perch fisheries, increases in environmental variability obscured differences in yield obtained at different levels of fishing effort.

An increase in effort of 25% above f_{MSY} typically did not decrease yield significantly (Fig. 2; Table 5). Significantly lower yields were obtained in all cases when effort increased by 75–100% above f_{MSY} . It should be noted that the Kolmogorov-

Smirnov test is sensitive to differences in location or dispersion (Siegel 1956); hence, significant differences may be due in part to increased variability in yield associated with increased fishing effort (Table 5). These results suggest that, even if future levels of environmental variability are relatively high, reductions in effort for heavily fished stocks should provide higher and less variable annual yields. When differences between current effort and f_{MSY} are less than 25–50% of f_{MSY} , changes in the magnitude or variability of annual yield may be insufficient to justify implementation of an MSY policy.

The approach demonstrated here can be used to contrast the effectiveness of any alternative policies that require different levels of fishing effort. Alternative policies might arise from different management models, from using different parameter estimates for a single model, or from a comparison of theoretically optimal and current levels of effort. The theoretically optimal or target level of effort need not be f_{MSY} . For example, Doubleday (1976) noted that when effort is reduced below f_{MSY} , losses in average yield may be offset by increases in catch per unit effort or reductions in the variability of yield. Selection of a target level of effort or index of policy performance is dependent on the fishery manager's objectives. In this study, yield maximization was assumed to be the management objective, and we evaluated changes in the distribution of annual harvest. However, changes in the distribution of catch per unit effort or net income may be equally important outcomes of a change in the level of fishing effort. Finally, stochastic models also can be used for risk analysis; for example, they can be used to estimate the probability that stock biomass will fall below an arbitrary level (Getz and Swartzman 1981; Archibald et al. 1983).

Further evidence that yield may be comparable at several levels of fishing effort was provided by Getz and Swartzman (1981). They developed a probabilistic age-structured model that was used to estimate variability in sustained yield at a range of levels of fishing effort. Results from their study indicate that, when recruitment is highly variable, significant differences in yield may be difficult to detect unless changes in the level of fishing effort are substantial. Thus, environmental variability, which produces these fluctuations in recruitment, might be viewed as advantageous in that it provides the fishery manager with considerable flexibility to incorporate socioeconomic

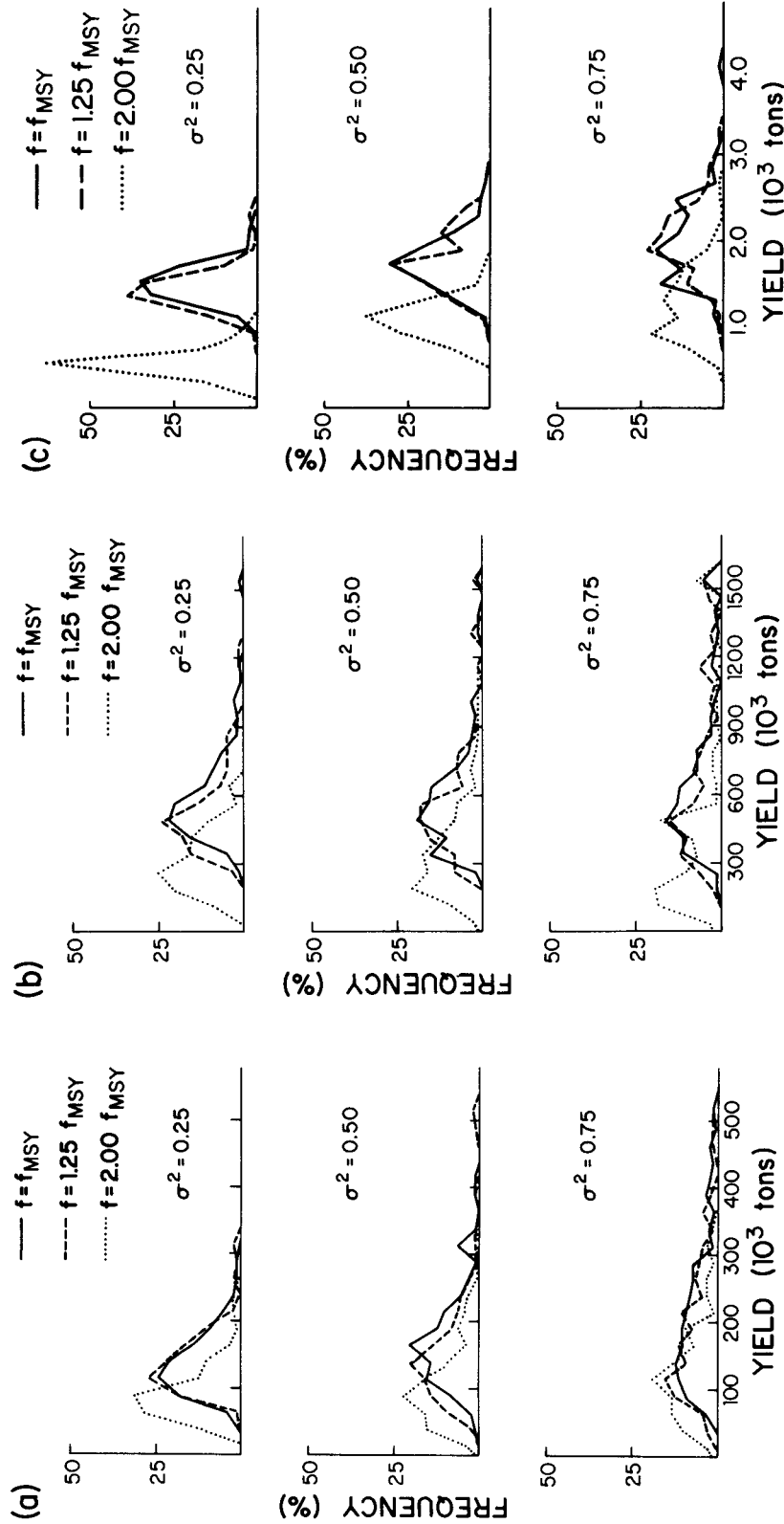


FIG. 2. Frequency distributions of harvest for (a) anchovy, (b) Atlantic menhaden, and (c) Pacific ocean perch obtained by maintaining effort at the level that produces maximum sustainable yield (f_{MSY}) or levels 25 and 100% greater than f_{MSY} . For each treatment combination, one of four frequency distributions of harvest at f_{MSY} was randomly selected for plotting. Environmental variability in the stock-recruitment relationship is given as σ^2 .

factors into a management plan. Because these factors can rarely be ignored in policy formulation (Schoning 1984), it is encouraging to know that fishing effort may differ from a theoretically optimal level without resulting in a detectable reduction in harvest.

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