

# Fixed exploitation rate strategies for coping with effects of climate change

Carl Walters and Ana M. Parma

**Abstract:** Survival rates and carrying capacities for larval and juvenile fishes may be strongly affected by long-term, unpredictable climatic fluctuations. When climate impacts produce strongly autocorrelated interannual variations in recruitment, harvesting a constant fraction of the stock each year allows the spawning stock to track such variations. Dynamic programming analysis indicates that this tracking effect is likely to produce long-term harvests that are very close (within 15%) to the theoretical optimum that could be achieved if all future climatic variations were known in advance. Fixed harvest rate strategies are likely to degrade performance more than 10% only when there is little interannual correlation in environmental effects or when there is a large, abrupt climate change that can be predicted well in advance if it is going to increase carrying capacity, or detected immediately if it causes a decrease in capacity. This finding implies that it may be more cost effective to invest in research on how to implement fixed harvest rate strategies than to invest in research on explaining and predicting climatic effects. Successful implementation may require a combination of improved stock size assessments, and stringent regulatory measures to substantially restrict the proportion of fish at risk to fishing each year.

**Résumé :** Les taux de survie des larves et des juvéniles de poissons et la capacité portante de leurs habitats peuvent être profondément affectés par des fluctuations climatiques imprévisibles et à long terme. Quand l'impact du climat produit des variations interannuelles du recrutement qui sont fortement autocorrélées, le prélèvement d'une fraction constante de la population chaque année permet au stock reproducteur de s'aligner sur ces variations. L'analyse par programmation dynamique indique que cet effet d'alignement doit vraisemblablement produire à long terme des prélèvements qui sont très proches (en-deçà de 15%) de l'optimum théorique qui pourrait être atteint si on connaissait d'avance toutes les variations climatiques futures. Les stratégies du taux fixe de prélèvement ne réduisent la production de plus de 10% que lorsqu'il y a peu de corrélation interannuelle dans les effets environnementaux ou que se produit une modification climatique importante et brutale que l'on peut prévoir longtemps à l'avance si elle doit accroître la capacité portante, ou que l'on peut détecter immédiatement si elle cause une baisse de la capacité. Cette découverte permet de penser qu'il serait plus rentable d'investir dans la recherche sur les façons de mettre en oeuvre des stratégies de taux de prélèvement fixe plutôt que d'investir dans la recherche sur l'explication et la prédiction des effets climatiques. Pour mettre en oeuvre avec succès de telles stratégies, il peut être nécessaire de combiner des évaluations plus fiables de la taille des stocks et des mesures de réglementation stricte de façon à restreindre substantiellement la proportion de poissons susceptibles d'être pêchés chaque année.

[Traduit par la Rédaction]

## Introduction

Long-term changes in marine and freshwater environments are one of the largest threats to fisheries sustainability. Such changes affect production (especially recruitment) directly and cause severe confusion in management systems when assessment scientists cannot distinguish between climatic and

harvesting impacts. Probably every major fisheries decline has engendered fierce debate about whether environmental factors or fishing (or both) is the culprit, and this debate can lead to very damaging delays in corrective responses such as reduced allowable catches. There is little prospect that fisheries research will provide quick enough answers in such debates (Walters and Collie 1988), and therefore there is a critical need to develop management strategies that are robust to causes of fluctuation (provide near optimal long-term harvest no matter what the cause), are easily understood by all management stakeholders, are practical to implement, and avoid unnecessarily high variation in catches from year to year. The fixed exploitation rate strategy, where management aims to take the same proportion of the stock each year, is one popular possibility for meeting these criteria (Aron 1979; Deriso 1985; Hilborn 1986; Walters and Ludwig 1987; Hall et al. 1988; Hanneson 1989; Hilborn and Walters 1992; Pelletier and

Received March 28, 1995. Accepted July 21, 1995.  
J12842

**C. Walters.** Fisheries Centre, University of British Columbia, Vancouver, BC V6T 1Z4, Canada.

**A.M. Parma.**<sup>1</sup> International Pacific Halibut Commission, P.O. Box 95009, Seattle, WA 98145, U.S.A.

<sup>1</sup> Author to whom all correspondence should be addressed.  
e-mail: ana@iphc.washington.edu

Laurec 1992; Mace 1994); criticisms of it have been mainly related to concerns about implementation when using inaccurate stock assessment data (Eggers 1993), especially where there is risk of depensatory effects (consistently high exploitation rates when stock size is low).

This paper compares the performance (total long-term catch) of fixed harvest rate strategies with the theoretical optimal performance that would be possible if all future environmental changes were known today. The comparison is done by generating simulated populations with complex, plausible patterns of recruitment variation, but using population dynamics models that are structurally simple enough to permit direct calculation (by dynamic programming) of the theoretical optimal performance. The analysis extends previous work by Parma (1990), who showed that optimal harvesting policies in nonstationary environments involve anticipatory adjustment of escapements (build up spawning stock before good conditions develop) to best capitalize on increased production opportunities. Results for cyclic environments indicate that such adjustments may lead to (i) only slight improvement over fixed harvest rate strategies that passively allow spawning stock to build up in response to favorable environmental changes, and (ii) greatly increased interannual catch variation. Parma speculated that cycles and other strongly autocorrelated patterns of environmental effects on recruitment would enhance the performance of fixed harvest rate strategies relative to that of the simpler fixed escapement strategy that is optimal when environmental effects are stationary and uncorrelated, adding to the variety of reasons that other authors (e.g., Hilborn and Walters 1992) have offered for preferring fixed harvest rate to fixed escapement strategies. Here we show that this speculation was indeed correct; we demonstrate that fixed harvest rate strategies, if implemented accurately, should generally result in long-term performance that is within 15% or so of the theoretical optimum, for a wide variety of populations; much lower performance is expected only in the case of extremely productive stocks (very high optimal harvest rates) with recruitments that are strongly influenced by uncorrelated environmental effects.

The following sections first derive a fairly general model for representing effects of environmental change on recruitment and population performance, then use this model to compare performances of fixed harvest rate and theoretical optimal policies. A final section discusses alternative approaches to implementation of fixed harvest rate strategies.

## A model for environmental impacts on population dynamics

It is likely that future climate changes will affect mainly juvenile survival rates, and hence the recruitment process. Discussion of fixed harvest rate policies requires precise definition of how juvenile mortality rates may be influenced, since some types of effects have no consequence for the assessment of the best fixed harvest rate. Some discussions of effects of climate change on fisheries focus on notions of change in marine carrying capacity (e.g., Beamish and Bouillion 1993) while others emphasize physical changes that could influence either maximal recruitment rates or reproductive performance in depressed populations (or both, e.g., Mann 1992). We begin with the basic model suggested by Beverton and Holt (1957) that

represents mortality during the juvenile stage as being linearly related to juvenile density at any moment:

$$[1] \quad \frac{dN}{dt} = -MN$$

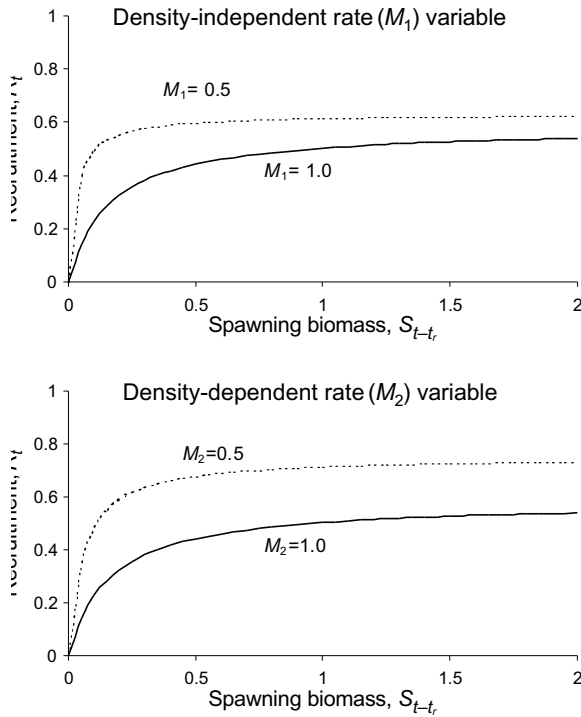
where  $M = M_1 + M_2N$ . Here  $M_1$  represents density-independent mortality risk owing to processes such as larval advection from favorable rearing areas, while  $M_2$  represents density-dependent risk related to juvenile crowding of available habitat (food, space) and possibly attraction of predators at higher juvenile densities. Obviously some environmental changes may simply kill more juveniles indiscriminately (increase  $M_1$ ), while others may influence the basic habitat size over which juvenile interactions occur (influence  $M_2$ ). The common observation that total recruitment is unrelated to egg numbers over a wide range of spawning densities requires that the density-dependent effect  $M_2$  be quite large; when  $M_2 = 0$ , eq. 1 results in a basic prediction of recruitment proportional to egg production ( $N$  at time 0), not independent of egg production. Assuming that egg production is proportional to spawning biomass  $S_t$  (eggs =  $fS_t$ , where  $f$  is fecundity per unit spawning biomass), then integrating eq. 1 to an age at recruitment  $t_r$  results in the familiar Beverton–Holt recruitment model for recruits  $R_t$  in year  $t$ :

$$[2] \quad R_t = \frac{S_{t-t_r} f e^{-M_1 t_r}}{1 + \frac{M_2}{M_1} (1 - e^{-M_1 t_r}) f S_{t-t_r}} \\ = \frac{A S_{t-t_r}}{1 + A S_{t-t_r} / K}$$

where  $A = f e^{-M_1 t_r}$ , and  $K = M_1 / (M_2 (e^{M_1 t_r} - 1))$ . Note here that changes in  $M_1$  influence both  $A$ , the slope of the recruitment curve at low spawning abundances, and  $K$ , the asymptotic recruitment rate at high spawning abundance. Changes in  $M_2$  are expected to influence only  $K$ . Thus we can model long-term, stochastic changes in factors that determine habitat size by treating only  $K$  as stochastic, whereas both  $A$  and  $K$  must be varied to represent stochastic changes in factors that influence the  $M_1$  values of juveniles (Fig. 1). To avoid unnecessary complication in optimization calculations, we deal only with the case  $t_r = 1$  (1 year lag to recruitment); see Parma (1990) for discussion of effects of longer delays on optimal policies.

To simulate long-term environmental effects on recruitment, we represented either  $M_1$  ( $A$ - $K$  variation) or  $M_2$  ( $K$  variation) as an autoregressive random process of the form  $M_{it} = \bar{M}_i + d_t$ , where  $d_t = r d_{t-1} + \omega_t$  has lag-1 autocorrelation  $0 \leq r < 1$  and independent, normally distributed changes  $\omega_t$ , with mean zero and variance  $\sigma^2$ . This model produces a total variance for the  $d_t$  of  $\sigma^2 / (1 - r^2)$ . Thus, we could control the magnitude or violence of  $A$  and  $K$  changes by varying both  $r$  and  $\sigma^2$ , and the persistence of these changes by varying  $r$  (annual survival rate also influences persistence of effects on harvestable biomass; see below). When combined with growth–survival dynamics, the autoregressive process produces surprisingly realistic patterns of long-term population variation (Fig. 2), with periods of apparently cyclic behavior interspersed with periods of more erratic population change. For comparison of policy alternatives, it certainly produces perverse enough variation to

**Fig. 1.** Environmental factors may cause changes in both density-independent and density-dependent mortality rates of juvenile fish; changes in density-independent rates are predicted to affect both reproductive performance at low stock sizes and the “carrying capacity” maximal recruitment rate, while changes in density-dependent mortality rates are predicted to affect only the maximal recruitment rate.



challenge any decision rule for responding to or anticipating environmental change.

Growth–survival effects of population age structure were represented by incorporating the recruitment dynamics into a Deriso (1980) – Schnute (1985) delay-difference model of the form

$$[3] \quad \begin{aligned} B_{t+1} &= g_t S_t + W_k R_{t+1} \\ S_t &= B_t - C_t \end{aligned}$$

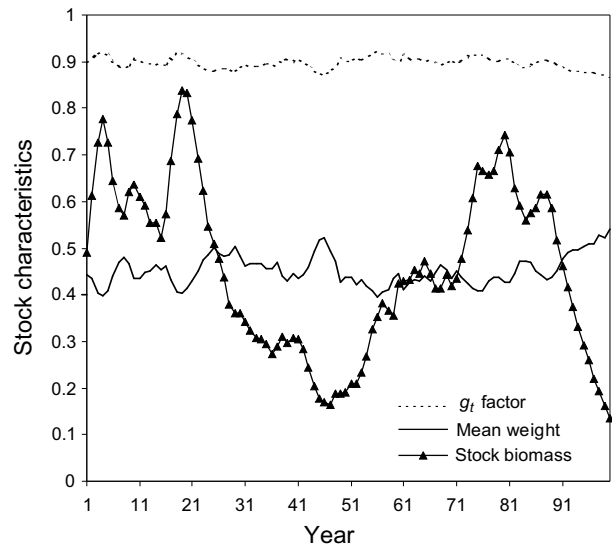
where  $B_t$  and  $C_t$  are stock biomass and catch in year  $t$ ,  $W_k$  is body weight at entry to the harvestable population, and  $g_t$  is the growth–survival factor (Hilborn and Walters 1992).

$$[4] \quad g_t = s \left( \frac{\alpha}{\bar{W}_t} + \rho \right)$$

Here,  $s$  is the annual natural survival rate ( $s = e^{-M}$ ),  $\alpha$  and  $\rho$  are the Walford plot intercept and slope for weight at age against weight at the previous age, and  $\bar{W}_t$  is the mean body weight of animals in the exploitable population in year  $t$ . We noticed in simulations (Fig. 2) that  $\bar{W}_t$  and  $g_t$  are relatively stable provided the exploitation rate is also stable. Then, for any fixed exploitation rate  $u$ ,  $\bar{W}_t$  is near the value predicted by the equilibrium mean weight relationship

$$[5] \quad \bar{W}_e = \frac{s(1-u)\alpha + W_k(1-s(1-u))}{1-\rho s(1-u)}$$

**Fig. 2.** Simulation of long-term population changes using a delay-difference model and strongly autocorrelated deviations from long-term average recruitment relationship. Fluctuations are typical of simulations used to compare fixed harvest rate and optimal escapement policies in later figures; note the relatively small changes in average body size  $\bar{W}_t$  and growth–survival factor  $g_t$ .



and 
$$g_t \cong g_e = s \left( \frac{\alpha}{\bar{W}_e} + \rho \right)$$

Stability of  $g_t$  permits a dramatic simplification of optimization calculations for long-term yield; for the assessments below, we replaced  $g_t$  in eq. 3 with the equilibrium value  $g_e$  evaluated at  $u$  equal to the optimal exploitation rate, i.e., that value of  $u$  for which long-term yield is maximal.

The optimal long-term exploitation rate for the model defined by eqs. 2 and 3 can be estimated from the equilibrium relationship between  $B$  and  $S$ . The exploitation rate  $u_e$  that maximizes the average annual catch,  $B - S$ , for the deterministic case of eqs. 2 and 3 is given approximately by

$$[6] \quad u_e = 1 - \frac{1}{g_e + \sqrt{AW_k(1-g_e)}}$$

(This equation is solved iteratively: use a trial value of  $u_e$  to calculate  $g_e$  from eq. 5, use the resulting  $g_e$  to calculate an improved  $u_e$  from eq. 6; repeat until  $u_e$  stops changing.) Equation 6 is derived by maximizing the equilibrium catch with respect to  $u$  while treating  $g_e$  as constant (i.e., ignoring that  $g_e$  actually increases with  $u$  and in turn affects the catch). As a result, eq. 6 provides a lower bound to the true optimal exploitation rate. Simulation tests showed that this approximation gives very close to the maximal long-term yield obtainable from any fixed exploitation rate (even when stochastic variation is large), except that it tends to slightly underestimate the optimal  $u$  for very long-lived ( $g_e > 0.9$ ) populations; in such cases the optimal  $u$  can be 10–20% higher than indicated by eq. 6, though the long-term yield corresponding to  $u_e$  will be within a few percent of the maximal long-term yield (the underestimation of  $u$  is compensated partly by the increase in the average biomass). Note that  $u_e$  increases with  $A$ , but it is

independent of the recruitment scaling or carrying capacity parameter  $K$ ; this is characteristic of optimal equilibrium exploitation rate calculations for population dynamics models in general (the best relative harvest rate cannot depend on units of measurement of population size), and implies that  $u_e$  may give performance that is robust to variation in carrying capacity.

Suppose it were somehow possible to predict exactly future juvenile mortality rates ( $M_{1t}$  and  $M_{2t}$ ) of each year  $t = 1, \dots, T$ , for large  $T$  (e.g., 100 years), and to exactly assess the stock biomass  $B_t$  available in each of those years. Then the lucky manager would be able to calculate the catch to take each year so as to maximize the total catch over all  $t$  years, by dynamic programming value iteration. That is, solve the sequence of simple, deterministic maximization problems:

$$[7] \quad V_t(B_t) = \text{MAX} (B_t - S_t + V_{t+1}(B_{t+1}(S_t, M_{it+1}))), \\ S_t \leq B_t \quad t = T - 1, T - 2, \dots, 1$$

where  $B_{t+1}(S_t, M_{it+1})$  is next year's biomass predicted from eqs. 2 and 3 knowing incoming recruitment mortality. The backward iteration starts with boundary condition  $V_T(B_T) = B_T$ . Numerical solution of eq. 7 over a discretized grid of  $(B, S)$  values is easily done using methods described in Walters (1986), Hilborn and Walters (1992), and Mangel and Clark (1988); for calculations reported below, we used grids with 100 discrete levels of both  $B$  and  $S$ , and interpolated  $V_{t+1}$  linearly for  $B_{t+1}$  values between grid points. The solution is a sequence of time-varying optimal spawning escapements  $S_t^*$ ,  $t = 1 \dots T$ , which would take full advantage of environmentally driven changes in recruitment capacity  $K$  and productivity  $A$ .

Fixed escapement policies ( $S^*$  not dependent on  $t$ ) are often reported to be optimal in harvest policy studies; they are in fact only best for maximizing long-term catch in cases where  $g_e$  is constant and  $M_{it}$  values are unknown but come from the same known, independent probability distribution each year ( $r = 0$  above). In the results presented below, the  $S_t^*$  values differ from the absolute theoretical optimal values (given perfect future knowledge) for the model described by eqs. 2 and 3 only through trivial effects associated with numerical discretization, and with using  $g_t = g_e$  in the dynamic programming calculation. For environments with strong, autocorrelated recruitment fluctuations as concern us, the calculated  $S_t^*$  values performed so much better than any fixed escapement alternative that we do not present any results for fixed escapement tests. However, note that simple fixed escapement policies can outperform fixed exploitation policies even in autocorrelated environmental situations, especially if there is risk of depensatory effects and associated low stock size equilibrium (Collie and Spencer 1993).

A "myopic" optimal escapement policy can be constructed by assuming that  $B_t$  and the most recent recruitment anomaly  $d_t$  are known exactly, but that future anomalies are unknown and only the probability distribution for anomaly changes is known ( $r$ , and the probability distribution of  $\omega_t$  for all future  $t$ ). In this case, dynamic programming formulation (replace  $V_{t+1}$  in eq. 7 with the expectation of  $V$  over the probability distribution of  $\omega_t$ ) indicates that the optimal policy will be a feedback function of  $(B_t, d_t)$ . This feedback function can be expressed as an optimal escapement  $S'(d_t)$  that varies with  $d_t$

(the optimal catch for year  $t$  is the surplus  $B_t - S'$ ). Parma (1990) showed for models with fixed  $g_e$  that a tight lower bound for  $S'(d_t)$  is given by the escapement level at which

$$E \left[ \frac{dR_{t+1}}{dS_t} \right] = 1 - g_e$$

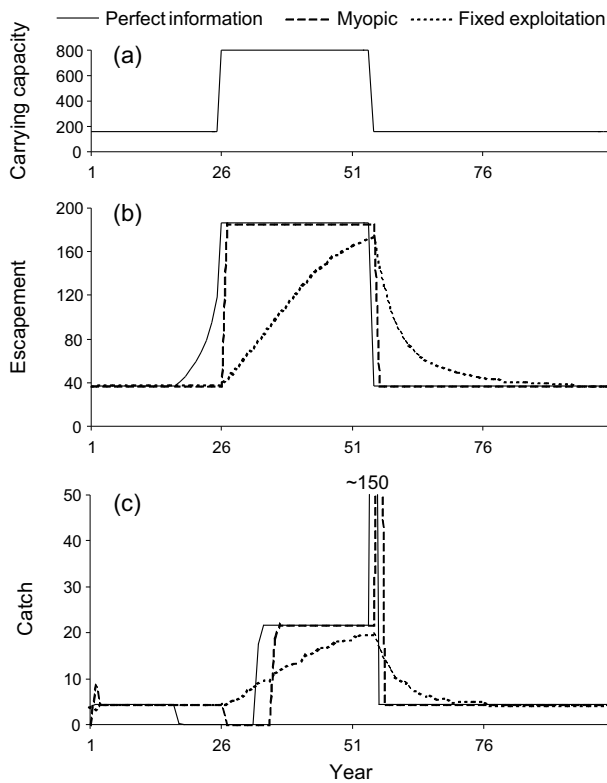
where the expectation is taken over possible recruitment anomalies in year  $t + 1$  (here represented by  $d_{t+1}$ ). When it is unlikely for  $B_{t+1}$  to be less than future possible myopic optima  $S'(d_{t+1})$ , then  $S'(d_t)$  approaches the lower bound defined by the condition above. We tried some numerical solutions of this formulation for various  $A, g_e$  combinations, and found that  $S'$  values are very close to the  $S$  value that maximizes the equilibrium value of  $B - S$  (average equilibrium catch), if  $B$  is calculated from eqs. 2 and 3 while holding  $d_{t+1}$  fixed at its expected value  $rd_t$ . That is, the myopic optimal policy is closely approximated by the results of deterministic optimization under the assumption that all future recruitment anomalies will equal the expected anomaly (if  $\omega_t = 0$ ) for next year. This approximation is obtained by applying the condition above while setting  $d_{t+1} = rd_t$ ; it thus results in escapements that increase linearly with anticipated carrying capacity at time  $t + 1$ , but may increase or decrease with changes in productivity  $A_t$  depending on the actual parameter values (see Mousalli and Hilborn 1986). Below we compare the expected harvest performance under the equilibrium approximation for myopic  $S'$  with both the theoretical best performance given by  $S^*$  and the performance using  $u_e$ .

## Policy comparisons

Figure 3 illustrates how different the policy prescriptions can be from  $S^*$  (future known with certainty),  $S'$  (current environmental state known each year), and  $u_e$  (no knowledge of environmental change, just take same fraction of stock each year). For this example, we set  $W_k = 1$  and held  $A$  in eq. 2 constant at a relatively low value implying  $u_e = 0.1$ ; we set  $g_e = 0.8$  (long-lived species), and varied  $K$  as shown (Fig. 3a) to produce a single period of years of very high recruitment carrying capacity. The numerical dynamic programming solution for  $S^*$  shows anticipatory behavior like that which Parma (1990) showed for cyclic recruitment situations; it is best to begin building up the spawning stock well in advance of a known increase in recruitment carrying capacity, so as to capitalize on the high potential production when it does arrive. In contrast, the myopic policy  $S'$  sees this opportunity only after it arrives, and shuts down the fishery just at the time when the optimal policy would begin to realize returns from the investment of increasing  $S$  before the environmental change. The fixed exploitation policy results in some benefit from the high  $K$  period (stock builds up during the period), but most of this benefit is lost when high harvests are not taken when the stock begins to collapse naturally ( $K$  falls back to low level). In this extreme case, the long-term (100 year) harvest for the perfect information policy is about 5% higher than that achieved by the myopic policy, and 15% higher than that produced by the fixed exploitation policy. The practical policies look much worse if evaluated over a shorter time period immediately surrounding the period of high carrying capacity.

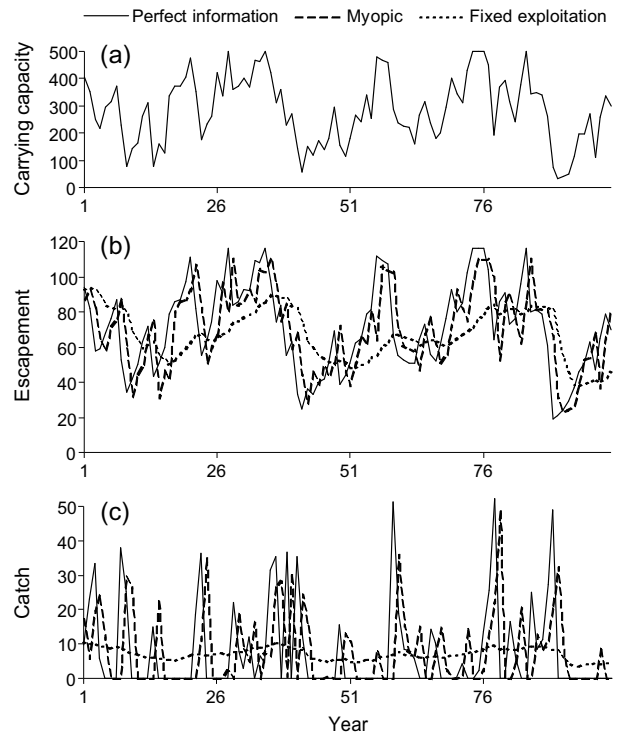
Fixed exploitation and myopic policies are better at tracking the theoretical optimal escapement in simulated

**Fig. 3.** Comparison of spawning biomasses and catches over time under three harvesting strategies for a population that shows a single period of enhanced maximal recruitment rate (a); units are arbitrary. The theoretical optimum was calculated by dynamic programming assuming full knowledge each year of all future recruitment deviations; the myopic optimum was calculated by assuming that next year's deviation will be the same as this year's; the fixed exploitation strategy takes the long-term average best fraction of the stock each year. Note how the optimal policy shuts down fishing well in advance of an increase in carrying capacity, "anticipating" opportunity for producing more from larger spawning stocks after the increase; such anticipatory behavior is not found in optimal policies for very productive stocks that can build up quickly as the environmental change occurs.



situations where autocorrelated environmental effects produce less abrupt changes in the recruitment carrying capacity (Fig. 4). In such cases, the practical policies most often achieve at least 90% of the long-term perfect information harvest, with the myopic escapement policy generally performing better as it adjusts  $S_t$  much more quickly than would occur with a fixed exploitation rate. It is a bit surprising that the fixed exploitation rate policy does so well in spite of damping escapement variation and causing large response lags (like Fig. 4) in most simulation cases for long-lived (large  $g_e$ ) species. Lags in policy response could be longer and potentially more harmful for longer lags to recruitment ( $t_r \gg 1$ ) if environmental conditions changed with a periodicity of about twice the mean age of reproduction. In such cases, trends in reproductive biomass would lag, and be out of phase with, the environmental trends affecting juvenile survival, and periods

**Fig. 4.** Comparison of spawning biomasses and catches over time under three harvesting strategies, for a simulated "cod" population (long-lived, optimal harvest rate 0.1) with strongly autocorrelated environmental effects on maximal recruitment rate (a); units are arbitrary. As in Fig. 3, the theoretical optimum was calculated by dynamic programming assuming full knowledge each year of all future recruitment deviations; the myopic optimum was calculated by assuming that next year's deviation will be the same as this year's; the fixed exploitation strategy takes the long-term average best fraction of the stock each year.



of high productivity would not be capitalized. The autoregressive processes used in our simulations generate trends in recruitment anomalies that tend to persist longer than common delays in the population dynamics, and so they can be more closely tracked by the stock.

Policy performance should depend on the source of stochastic variation in recruitment: density-independent ( $M_1$ ) or density-dependent ( $M_2$ ) parameters. In principle, variation in  $M_1$  causes variation in  $u_e$  (through effects on  $A$  in eq. 6). However, a harvest rate equal to  $u_e(M_1)$  would be the optimal fixed harvest rate only if  $M_1$  remained constant in the future. But as  $M_1$  continues to change, using the long-term mean  $\bar{M}_1$  for calculating  $A$  and  $u_e$  generally works very well. Optimal escapement policies, on the other hand, are much more sensitive to changes in  $M_2$  ( $K$  variation) than they are to changes in  $M_1$  ( $A$ - $K$  variation). Thus, environmental effects on the recruitment carrying capacity  $K$  appear to dominate simulated policy performance. The results below apply to the case where only  $K$  varies; variation in  $A$  as well does not change the basic conclusions.

Natural stochastic changes are unlikely to be as abrupt and persistent as in the case in Fig. 3, but they could vary

substantially in the frequency of occurrence of changes for which anticipatory variation in  $S^*$  (i.e., foresight about them) would really be worthwhile (i.e., a few simulation cases like Fig. 4 could be quite misleading). Therefore, we generated a large number of 100-year stochastic  $M_{it}$  sequences, computed the  $S^*$  and optimal catch sequence for each along with the  $S'$  and  $u_c$  catch sequences, and examined the resulting frequency distributions (over sequences) of  $S'$  and  $u_c$  relative performance. This tedious computational exercise allowed us to determine if autocorrelated environmental changes are at all likely to produce a recruitment anomaly sequence for which a fixed exploitation policy would perform very badly. Nature could of course be more perverse than any autocorrelation model, but variation much worse than shown in Figs. 2 and 4 (typical sequences from the simulation trials) seems unlikely to occur in most fisheries that are at all sustainable.

We generated 1000  $M_{it}$  sequences of 100 years for different types of populations ("salmon," "herring," and "cod") and autocorrelation levels  $r$  (0, 0.3, and 0.8). Figure 5 summarizes 9000 such simulations when the variance of  $\omega_t$  was 0.05 (giving 2- to 3-fold variation in carrying capacity). The salmon example represents a productive, semelparous species with  $g_c = 0$  and  $AW_k = 4$  so  $u_c = 0.5$ . The herring example is a relatively short-lived species of intermediate productivity, with  $g_c = 0.6$  and  $AW_k = 1.35$  so  $u_c = 0.25$ . The cod example is long-lived and unproductive, with  $g_c = 0.9$  and  $AW_k = 0.45$  so  $u_c = 0.1$ . Biomass was initially set to the deterministic equilibrium for  $u_c$  and average environmental conditions. The most important determinant of relative performance for the practical policies was persistence of population response, as influenced by both  $g_c$  and  $r$ . The lowest relative performance was for the salmon case lacking population carry-over and environmental autocorrelation, but the practical policies do well even for this case when  $r$  is high. Performance was generally good (85% or better) for the long-lived cod case even when  $r = 0$ . The salmon case showed somewhat lower relative performance for fixed exploitation rates in the  $r = 0$  situation than has been reported in previous comparisons of fixed exploitation versus fixed escapement policies (review in Hilborn and Walters 1992); this is because the comparison was not to a fixed escapement policy but rather to an optimal policy where full advantage was taken each salmon generation of a capability to predict stochastic survival for the next generation. The standard fixed escapement policy used in previous published comparisons corresponds here to the myopic policy, which resulted in yields about 15% higher on average than those attained by the fixed exploitation policy.

In nature  $r$  likely lies between 0.3 and 0.8, and for such situations a fixed exploitation rate policy is almost certain to provide at least 85% of the yield that can be obtained by any practical (not requiring environmental prediction) policy alternative (Fig. 5). Put another way, investment in developing means to predict environmental change (so as to allow  $S^*$  policies) would appear to be justified only for highly productive, short-lived species in environments that do not exhibit persistent change. But even in such extremes, we question the wisdom of implementing an  $S^*$  policy even if it were feasible; as shown in Fig. 3, such policies may maximize total harvest, but also come close to maximizing year-to-year variation in harvest and hence disruption of fishing industries (see Parma 1990 for a comparison between catch-maximizing policies for

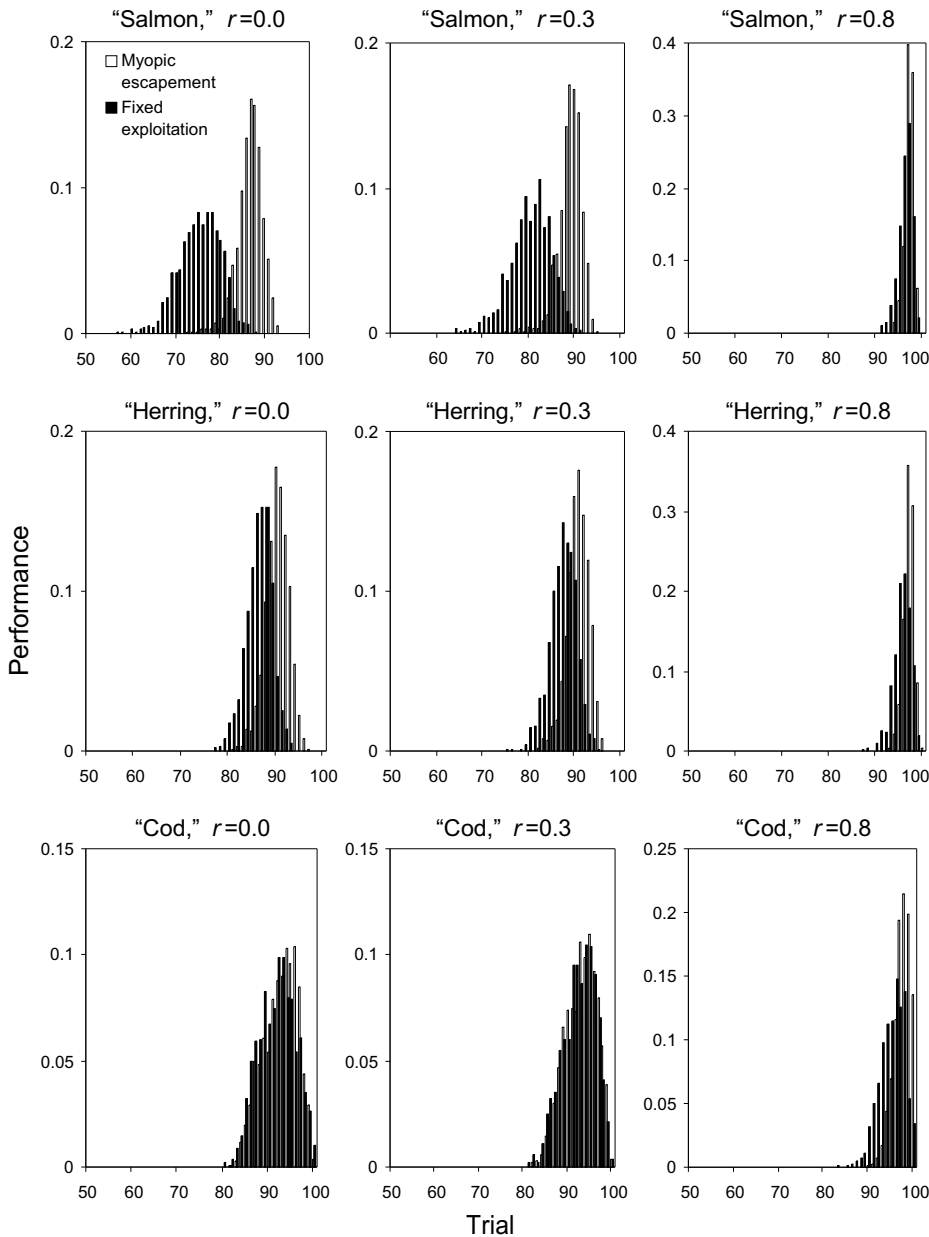
cyclic environments and policies that reduce variation in catches). The results above appear to hold for other types of stock-recruitment models, as long as long-term average environmental effects on density-independent sources of mortality are stable (mean of  $M_{it}$  constant in our case); indeed, our results are consistent with those in Parma (1990), where a dome-shaped stock-recruitment function was assumed and environmental effects were modeled as cyclic trends in the density-independent mortality rate of juveniles.

The results in Fig. 5 can be misleading for fisheries where the only practical way to implement a harvest strategy is to set (and live with) each annual allowed catch (TAC) by using a preseason biomass estimate, at either  $TAC = \hat{B} - S_t$  or  $TAC = u_c \hat{B}_t$ , if the biomass estimate has high random error. Walters (1989) showed substantial degradation in the performance of optimal escapement policies with decreasing accuracy of preseason forecasts, even though these optimal policies were actually derived by acknowledging the uncertainty in the biomass estimates. Stock assessment methods like production model fitting or VPA tuning to relative abundance time series typically result in  $\hat{B}_t$  with substantial error that is approximately log-normally distributed and, for long-lived species, strongly autocorrelated (e.g., Anonymous 1991; Parma 1993). That is,

$$[8] \quad \hat{B}_t = B_t e^{b_t} \\ b_t = kb_{t-1} + v_t$$

where  $v_t$  represents independent annual errors resulting from both observation and biological process uncertainty. The autocorrelation factor  $k$  can be as high as  $g_c$ , which can be shown using a Kalman filter to describe or approximate the estimation procedure (see Pella 1993 and Schnute 1994 for description of the Kalman filter model). Note how  $g_c$  acting as an autocorrelation factor tends to produce larger swings in the biomass estimates over time than would be predicted from annual variation in relative abundance or tuning survey data, with runs of years when the estimates are too high or low. But whether or not the assessment errors are autocorrelated, simulated management performance degrades rapidly with increases in the standard deviation of  $b_t$  (approximately the coefficient of variation of the error of the biomass estimates) as shown in Fig. 6. To obtain each plotted point in Fig. 6, we took subsets of 10 of the environmental pattern scenarios used for Fig. 5, and ran ten 100-year simulations for each scenario with catch set each year to TAC calculated from randomly varying  $\hat{B}_t$  and autocorrelated error with  $k = g_c$ . Initial biomass in each case was set to the equilibrium level corresponding to  $u_c$  and average environmental conditions. Results for  $g_c = 0$  (salmon case) confirm the finding of Eggers (1993) that the catch performance of fixed exploitation policies degrades more rapidly with increasing assessment error (coefficient of variation of  $\hat{B}_t$ ) than does the performance of spawning stock  $S^*$ ,  $S'$  strategies. This effect is not as marked for intermediate life history parameters (herring case), where the fixed exploitation policy performs similarly to the myopic one, except for very high estimation errors ( $CV \geq 0.75$ ). The average yield obtained under the three policies at CV values above 0.75 drops to less than 40–50% of that obtained when  $CV = 0$ . Interestingly,  $u_c$  policies continue to perform relatively well for long-lived, unproductive stocks (where  $u_c$  is very low in

**Fig. 5.** Distributions of performance for fixed exploitation and myopic escapement strategies, measured relative to theoretical optimum if all future environmental changes were known; each distribution represents 1000 100-year simulation trials where each trial would look qualitatively like the results in Fig. 4. Alternative life-history types are described in the text (“salmon” is semelparous, productive; “herring” is iteroparous but short lived; “cod” is long lived and unproductive).



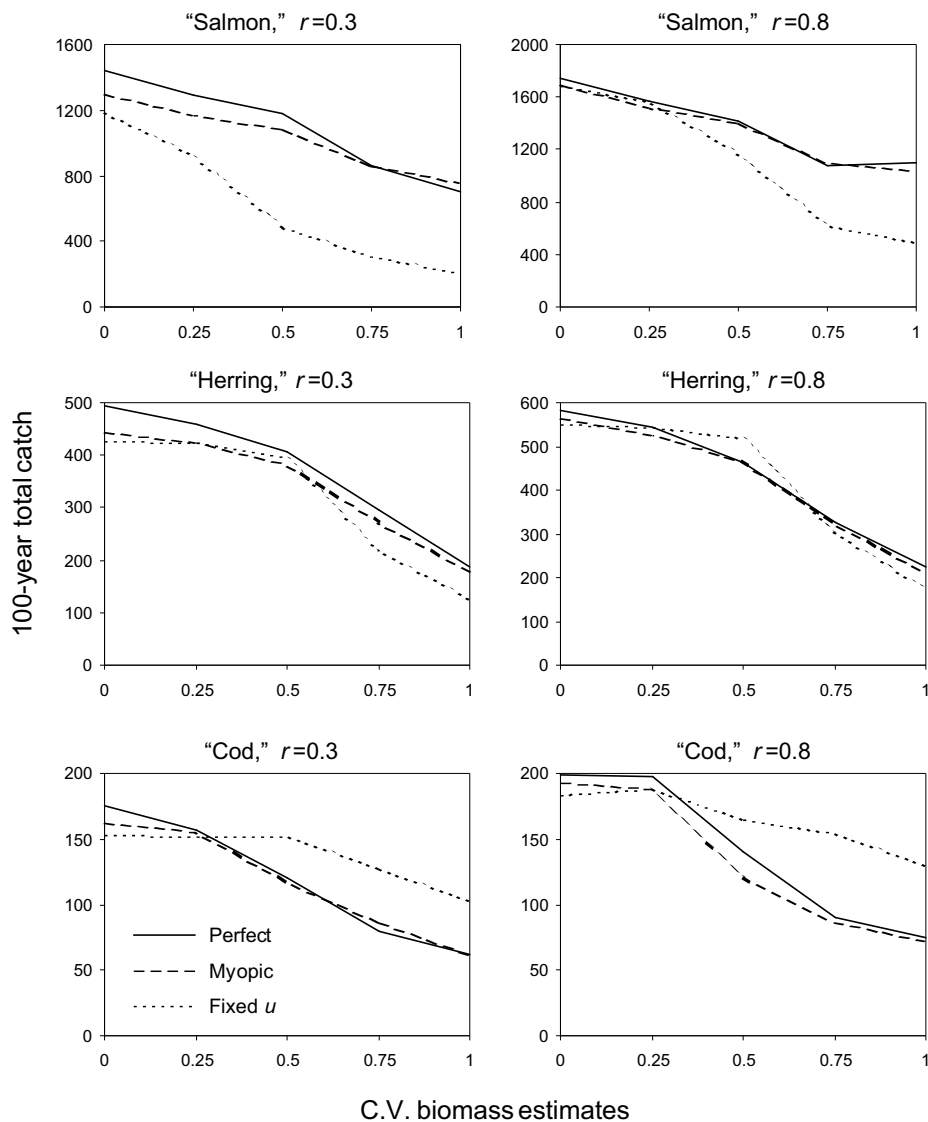
the first place) even when the simulated biomass assessments are very highly autocorrelated and noisy (commonly swinging over many years to as low as 20% of actual  $B$ , or as high as 300% of  $B$ , in the  $CV = 1.0$  cod case of Fig. 6). Escapement strategies ( $S^*$  and  $S'$ ), on the other hand, perform much worse than  $u_c$  policies, which suggests that adjusting escapement targets to changing environmental conditions may even be counterproductive when assessment errors are large and highly autocorrelated. Overall, these results suggest that careful

attention must be paid to the question of how to implement harvest strategies, and this we discuss in the next section.

### Implementation of exploitation rate policies

Two fundamental requirements for practical implementation of an optimal exploitation rate policy are that (i) the average slope of the recruitment relationship at low stock sizes ( $A$  of

**Fig. 6.** Effect of stochastic errors in annual biomass estimation on performance of escapement and fixed harvest rate strategies. Results show how performance for simulations as in Figs. 4 and 5 degrades with increase in coefficient of variation in annual biomass estimates. Biomass estimation procedures were assumed to result in autocorrelated estimation errors with the same persistence time as the effects of biological recruitment variations (as measured by the growth–survival factor  $g$ ). Degradation in performance for fixed exploitation strategies was calculated by assuming worst-case implementation where annual catch (TAC) is set as exploitation rate times biomass estimate (no direct regulation of probability of capture). The severity of this degradation is related mostly to the target exploitation rate (50% for “salmon,” 45% for “herring,” 10% for “cod”); large, persistent estimation errors were actually most severe in the “cod” simulation cases where degradation is least severe.



eq. 2) must be known, along with the growth–survival parameters that determine  $g_c$ , and (ii) a regulatory apparatus must monitor and limit the annual exploitation rate. The implementation of myopic escapement policies ( $S'$ ) further requires knowledge of the recruitment carrying capacity parameter  $K$  each year (or  $M_{it}$ ), and an accurate estimate of the current stock biomass  $B_t$  (or a means to estimate  $B_t$  or  $S_t$  adaptively within the fishing season). Thus the implementation requirements for

escapement policies are in principle substantially greater than for exploitation rate policies. Although implementation of fixed exploitation policies also would seem to require accurate estimates of both catch and  $B_t$  (e.g., Eggers 1993), this information is needed only in cases where either (i) a preseason allowable catch (TAC) is based on a biomass estimate ( $TAC = u\hat{B}$  as in the simulation results of Fig. 6), and catch is limited by tactics such as individual vessel quotas or closure



when TAC is reached, or (ii) exploitation is permitted in several adaptive steps within each year, but over fishing areas or seasons of such size and duration as to make the exploitation rate sensitive to fishing effort characteristics (catchability, fleet size) during the fishery openings. A particular concern in such cases is the depensatory effect of overestimating stock size when it is low ( $u$  consistently too high when  $B_t$  is low: see for examples Eggers 1993 and Parma 1993). The next section addresses two key questions: (i) Can we assess  $A$  or  $u_c$  without destructive overfishing along the way? (ii) Are there harvest regulation tactics that can prevent the potential depensatory effects of overestimating TAC or underestimating fishing efficiency at times when  $B_t$  is low, and in particular are there tactics that do not depend at all on knowledge of total stock size?

In principle, certainty about the recruitment curve slope  $A$  at low spawning stock sizes is only possible by observing a substantial number of recruitments under such spawning stock conditions. To suggest that we can predict  $A$  from an understanding of its biological components,  $f$  and  $M_1$ , is plainly naive. But the conditions when  $A$  becomes "visible" (recruitment proportional to stock, hence failing as stock declines) are the defining circumstances for recruitment overfishing. Opportunities now abound to gather such observations around the world, as fisheries collapse with monotonous regularity. Short of such hard experience, comparative approaches seek to predict  $A$  for a given stock from information about similar stocks elsewhere. Some useful patterns emerge from two such approaches: (i) study of historical stock-recruit data for at least identifying spawning stock size below which recruitment begins to fall rapidly (Sissenwine and Sheperd 1987; Mace 1994; Myers et al. 1994), and (ii) study of simpler stock trend data (Patterson 1992) to provide direct empirical evidence about the sustainable  $u_c$ . Patterson's (1992) finding that pelagic stocks have generally been able to sustain exploitation rates of approximately only 0.5 to 1 times the natural mortality rate, as predicted from some modeling studies (reviewed in Patterson 1992), appears to work for demersal species as well. A worrisome point about the Patterson (1992) finding is that the popular  $F_{0.1}$  harvest rate, which usually implies  $F \approx M$  and is generally considered to be quite conservative (Deriso 1987), may in fact be too high for the majority of natural populations. Because underestimation of the optimal exploitation rate for long-lived species is not particularly costly (see discussion above on derivation of  $u_c$ : using a value of  $u$  that is too low results in a compensating increase in stock biomass), we consider the prudent approach to assume  $u_c \leq 0.5 M$  and to place the burden of proof on whoever advocates a higher rate to demonstrate that it is sustainable (by substantial direct analysis of historical stock-recruit data). Therefore, our answer to the first question above is yes; we can assess  $u_c$  without destructive overfishing, provided fisheries managers are willing to operate with a standard of prudence that recognizes the modest cost of underestimating the optimum to be much less than the major costs and social upheaval often attendant upon overestimating it.

Modern fishing technology makes impractical the use of effort regulation alone to achieve stable exploitation rates, via some simple relation like  $F = qE$  with catchability  $q$  constant (Cooke and Beddington 1985). Generally  $q$  will increase dramatically with decreases in stock size and with further

technology development over time. Hyperdepletion situations (Hilborn and Walters 1992), where  $q$  actually decreases with stock size, appear to be rare and to be associated mainly with recreational fisheries and with some sedentary species where aggregations are slow to reform once cropped. However, these problems with  $q$  do not imply that space-time restriction of fishing effort will fail in general; they apply only to situations where a large proportion of the stock is exposed to fishing at once. In some Pacific salmon fisheries, like seine fisheries for Fraser River sockeye (*Oncorhynchus nerka*) during their extended spawning migration through restricted coastal straits, exploitation rates have been quite successfully restricted by allowing only very short fishery openings in small areas. In these situations, virtually every fish present in or entering the open areas is likely taken during each opening (so further technology improvement will just mean taking them sooner within each opening); such fisheries literally chop holes in the spatial distribution of the stocks as they migrate past fishing areas, and  $u$  is simply the proportion of fish exposed to fishing, i.e., the proportion of fish that do not pass through the fishing areas during closures. Placing massive amounts of effort in competition within very small fishing areas over short times may be uneconomical, but it guarantees that  $u$  remains below some target  $u_c$  established through long-term population analysis. Similar spatial closure strategies could be developed for nonmigratory species as well, for example, by having small open areas that are rotated over the stock distribution from year to year (e.g., Botsford et al. 1993; Pfister and Bradbury 1996). The potential of year-around closed areas as a management tool is now recognized and issues related to the design and evaluation of harvest refugia are now beginning to be discussed (e.g., Polacheck 1990; Roberts and Polunin 1991; Dugan and Davis 1993; Rowley 1994). Therefore, the answer to our second question above is again yes, provided area-time restrictions that create uneconomical competition (and may be very expensive to enforce) are considered an acceptable cost of insuring that exploitation rates are never too high, and that we are willing to gather the detailed spatial distribution and movement data needed to set areas and times correctly.

Area-time effort restrictions are not the only way to directly regulate exploitation rates without accurate estimates of catch and stock size. Conduct of a careful annual pre-season tagging program, with monitoring of the tag recovery rate, may provide a direct measure of exploitation rate as fishing progresses. However, this approach would not work if substantial tag loss, mortality, or underreporting of tags occurs, as these problems can lead to dangerous underestimates of the exploitation rate (fewer fish recovered than should be on the basis of the actual probability of harvest). Another option is to accompany fishing activities by large-scale abundance indexing (e.g., acoustics, survey fishing) tied directly to the spatial distribution of fishing so as to quickly measure relative depletion rates (exploitation rates) within the fishing areas. Still another (and perhaps last) resort is to revive the very old tactic of restricting fishing gears (e.g., hook and mesh sizes) so that only a safe proportion of the population size distribution is landed or retained. None of these ideas is new at all; they have not received much attention in recent years, perhaps because we have placed considerable faith in our ability to improve stock size and catch assessments enough to make many regulatory tactics unnecessary.

With strong public demand for more cautious approaches to sustainable fishery management, fisheries management agencies (and fishing industry cooperators) will very likely be forced in the future to combine increased investment in improved assessments of absolute stock size with fail-safe regulatory measures including large, closed areas, short seasons, and selective harvest of larger fish. Such combined approaches will create long-term incentives for collaboration between the scientific and industrial communities in gathering better data for assessment, because it should be possible to progressively relax the fail-safe measures that create uneconomical fishing situations if more reliable assessments do become available. It is not yet clear just how far this trade-off can be taken, especially considering that much of the recent fisheries stock assessment literature has focused on showing how large our assessment errors are rather than showing how these errors can be substantially reduced.

## Acknowledgments

We thank Jerome Pella and an anonymous referee for their detailed and helpful reviews of the manuscript.

## References

- Anonymous. 1991. The working group on methods of fish stock assessments, St. John's, Newfoundland, June 20–27, 1991. ICES C.M. 1991/Assess:25 Sess:S. International Council for the Exploration of the Sea, Charlottenlund, Denmark.
- Aron, J.L. 1979. Harvesting a protected population in an uncertain environment. *Math. Biosci.* **47**: 7–205.
- ▶ Beamish, R.J., and Bouillon, D. 1993. Pacific salmon production trends in relation to climate. *Can. J. Fish. Aquat. Sci.* **50**: 1002–1016.
- Beverton, R.J., and Holt, S.J. 1957. On the dynamics of exploited fish populations. *Fisheries Investment Series 2*. Vol. 19. U.K. Ministry of Agriculture and Fisheries, London.
- Botsford, L.W., Quinn, J.F., Wing, S.R., and Brittnacher, J.G. 1993. Rotating spatial harvest of a benthic invertebrate, the red sea urchin, *Strongylocentrotus franciscanus*. In *Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations*. Edited by G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn, II. Alaska Sea Grant College Program Report No. 93-02. University of Alaska, Fairbanks, Alaska, pp. 409–428.
- Collie, J.S., and Spencer, P.D. 1993. Management strategies for fish populations subject to long-term environmental variability and compensatory predation. In *Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations*. Edited by G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn, II. Alaska Sea Grant College Program Report No. 93-02. University of Alaska, Fairbanks, Alaska, pp. 629–650.
- ▶ Cooke, J.G., and Beddington, J.R. 1985. The relationship between catch rates and abundance in fishes. *IMA J. Math. Appl. Med. Biol.* **2**: 1–15.
- ▶ Deriso, R.B. 1980. Harvesting strategies and parameter estimation for an age-structured model. *Can. J. Fish. Aquat. Sci.* **37**: 268–282.
- Deriso, R.B. 1985. Risk adverse harvesting strategies. *Lect. Notes Biomath.* **61**: 65–72.
- Deriso, R.B. 1987. Optimal  $F_{0.1}$  criteria and their relationship to maximum sustainable yield. *Can. J. Fish. Aquat. Sci.* **44**(Suppl. 2): 339–348.
- ▶ Dugan, J.F., and Davis, G.E. 1993. Applications of marine refugia to coastal fisheries management. *Can. J. Fish. Aquat. Sci.* **50**: 2029–2042.
- Eggers, D.M. 1993. Robust harvest policies for Pacific salmon fisheries. In *Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations*. Edited by G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn, II. Alaska Sea Grant College Program Report No. 93-02. University of Alaska, Fairbanks, Alaska, pp. 85–106.
- ▶ Hall, D.L., Hilborn, R., Stocker, M., and Walters, C. 1988. Alternative harvest strategies for Pacific herring (*Clupea harengus pallasi*). *Can. J. Fish. Aquat. Sci.* **45**: 888–897.
- Hannesson, R. 1989. Fixed or variable catch quotas? The importance of population dynamics and stock dependent costs. In *Rights based fishing*. Edited by P.A. Neher, R. Arnason, and N. Mollet. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 459–465.
- Hilborn, R. 1986. A comparison of alternative harvest tactics for invertebrate fisheries. In *North Pacific workshop on stock assessment and management of invertebrates*. Edited by G.S. Jamieson and N. Bourne. *Can. Spec. Publ. Fish. Aquat. Sci.* No. 92. pp. 313–317.
- Hilborn, R., and Walters, C. 1992. *Quantitative fisheries stock assessment and management: choice, dynamics, and uncertainty*. Chapman Hall Publishing Co., New York.
- ▶ Mace, P. 1994. Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. *Can. J. Fish. Aquat. Sci.* **51**: 110–122.
- Mangel, M., and Clark, C. 1988. *Dynamic modeling in behavioral ecology*. Princeton University Press, Princeton, N.J.
- ▶ Mann, K.H. 1992. Physical oceanography, food chains, and fish stocks: a review. *ICES J. Mar. Sci.* **50**: 105–119.
- Mousalli, E., and R. Hilborn. 1986. Optimal stock size and harvest rate in multistage life history models. *Can. J. Fish. Aquat. Sci.* **43**: 135–141.
- ▶ Myers, R.A., Rosenberg, A.A., Mace, P.M., Barrowman, N., and Restrepo, V.R. 1994. In search of thresholds for recruitment overfishing. *ICES J. Mar. Sci.* **51**: 191–205.
- Parma, A. 1990. Optimal harvesting of fish populations with non-stationary stock-recruit relationships. *Nat. Resour. Model.* **4**: 39–76.
- Parma, A. 1993. Retrospective catch-at-age analysis of Pacific halibut: implications on assessment of harvesting policies. In *Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations*. Edited by G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn, II. Alaska Sea Grant College Program Report No. 93-02. University of Alaska, Fairbanks, Alaska, pp. 247–265.
- ▶ Patterson, K. 1992. Fisheries for small pelagic species: an empirical approach to management targets. *Rev. Fish Biol. Fish.* **2**: 321–338.
- Pella, J.J. 1993. Utility of structural time series models and the Kalman filter for predicting consequences of fishery actions. In *Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations*. Edited by G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn, II. Alaska Sea Grant College Program Report No. 93-02. University of Alaska, Fairbanks, Alaska, pp. 571–594.
- ▶ Pelletier, D., and LaRec, A. 1992. Management under uncertainty: defining strategies for reducing overexploitation. *ICES J. Mar. Sci.* **49**: 389–401.
- Pfister, C.A., and Bradbury, A. 1996. Harvesting red sea urchins: recent effects and future predictions. *Ecol. Appl.* In press.
- Polacheck, T. 1990. Year around closed areas as a management tool. *Nat. Resour. Model.* **4**: 327–354.
- ▶ Roberts, C.M., and Polunin, N.V.C. 1991. Are marine reserves effective in management of reef fisheries? *Rev. Fish Biol. Fish.* **1**: 65–91.
- ▶ Rowley, R.J. 1994. Case studies and reviews. *Marine reserves in*

- fisheries management. *Aquat. Conserv. Mar. Freshwater Ecosyst.* **4**: 233–254.
- ▶ Schnute, J. 1985. A general theory for analysis of catch and effort data. *Can. J. Fish. Aquat. Sci.* **42**: 414–429.
  - ▶ Schnute, J. 1994. A general framework for developing sequential fisheries models. *Can. J. Fish. Aquat. Sci.* **51**: 1676–1688.
  - ▶ Sissenwine, M.P., and Shepherd, J.G. 1987. An alternative perspective on recruitment overfishing and biological reference points. *Can. J. Fish. Aquat. Sci.* **44**: 913–918.
- Walters, C.J. 1986. *Adaptive management of renewable resources*. McMillan Publishing Co., New York.
- ▶ Walters, C.J. 1989. Value of short-term forecasts of recruitment variation for harvest management. *Can. J. Fish. Aquat. Sci.* **46**: 1969–1976.
  - ▶ Walters, C.J., and Collie, J.S. 1988. Is research on environmental factors useful to fisheries management? *Can. J. Fish. Aquat. Sci.* **45**: 1848–1854.
- Walters, C.J., and Ludwig, D. 1987. Adaptive management of harvest rates in the presence of a risk averse utility function. *Nat. Resour. Model.* **1**: 321–337.

**This article has been cited by:**

1. Nicolás E. Talloni-Álvarez, Rashid U. Sumaila, Philippe Le Billon, William W.L. Cheung. 2019. Climate change impact on Canada's Pacific marine ecosystem: The current state of knowledge. *Marine Policy* **104**, 163-176. [[Crossref](#)]
2. Mark A. Grubert, Carl J. Walters, Rik C. Buckworth, Shane S. Penny. 2019. Simple Modeling to Inform Harvest Strategy Policy for a Data-Moderate Crab Fishery. *Marine and Coastal Fisheries* **11**:2, 125-138. [[Crossref](#)]
3. Éva E. Plagányi, Michael D.E. Haywood, Rebecca J. Gorton, Margaret C. Siple, Roy Aijun Deng. 2019. Management implications of modelling fisheries recruitment. *Fisheries Research* . [[Crossref](#)]
4. Margaret C. Siple, Timothy E. Essington, Éva E. Plagányi. 2019. Forage fish fisheries management requires a tailored approach to balance trade-offs. *Fish and Fisheries* **20**:1, 110-124. [[Crossref](#)]
5. Timothy J. Miller, Loretta O'Brien, Paula S. Fratantoni. 2018. Temporal and environmental variation in growth and maturity and effects on management reference points of Georges Bank Atlantic cod. *Canadian Journal of Fisheries and Aquatic Sciences* **75**:12, 2159-2171. [[Abstract](#)] [[Full Text](#)] [[PDF](#)] [[PDF Plus](#)] [[Supplemental Material](#)]
6. Mark N. Maunder, James T. Thorson. 2018. Modeling temporal variation in recruitment in fisheries stock assessment: A review of theory and practice. *Fisheries Research* . [[Crossref](#)]
7. Javier Ruiz, Margarita M. Rincón. 2018. Anchovy dynamics and the colour of climate noise: Assessing climatic scenarios and exploitation strategies in the Gulf of Cádiz. *Fisheries Oceanography* **27**:6, 560-570. [[Crossref](#)]
8. Robyn E. Forrest, Kendra R. Holt, A. Robert Kronlund. 2018. Performance of alternative harvest control rules for two Pacific groundfish stocks with uncertain natural mortality: Bias, robustness and trade-offs. *Fisheries Research* **206**, 259-286. [[Crossref](#)]
9. Christopher R. Middaugh, Daniel D. Magoulick. 2018. Forecasting effects of angler harvest and climate change on smallmouth bass abundance at the southern edge of their range. *PLOS ONE* **13**:8, e0202737. [[Crossref](#)]
10. Steven D. Gaines, Christopher Costello, Brandon Owashi, Tracey Mangin, Jennifer Bone, Jorge García Molinos, Merrick Burden, Heather Dennis, Benjamin S. Halpern, Carrie V. Kappel, Kristin M. Kleisner, Daniel Ovando. 2018. Improved fisheries management could offset many negative effects of climate change. *Science Advances* **4**:8, eaao1378. [[Crossref](#)]
11. A. Ben-Hasan, M. Al-Husaini, C. Walters. 2017. Adaptive management of declining fisheries: When is it worth trying to rebuild stocks through fishery regulation?. *Marine Policy* **85**, 107-113. [[Crossref](#)]
12. Bryan S. Stevens, James R. Bence, William F. Porter, Michael L. Jones. 2017. Identifying target reference points for harvesting assessment-limited wildlife populations: a case study. *Ecological Applications* **27**:6, 1916-1931. [[Crossref](#)]
13. Ray Hilborn, Ricardo O. Amoroso, Eugenia Bogazzi, Olaf P. Jensen, Ana M. Parma, Cody Szuwalski, Carl J. Walters. 2017. When does fishing forage species affect their predators?. *Fisheries Research* **191**, 211-221. [[Crossref](#)]
14. Juan Segura, Frank M. Hilker, Daniel Franco. 2017. Population control methods in stochastic extinction and outbreak scenarios. *PLOS ONE* **12**:2, e0170837. [[Crossref](#)]
15. Thomas R. Carruthers, David J. Agnew. 2016. Using simulation to determine standard requirements for recovery rates of fish stocks. *Marine Policy* **73**, 146-153. [[Crossref](#)]
16. Cody S. Szuwalski, Anne B. Hollowed. 2016. Climate change and non-stationary population processes in fisheries management. *ICES Journal of Marine Science: Journal du Conseil* **73**:5, 1297-1305. [[Crossref](#)]
17. Christopher M. Legault, Michael C. Palmer. 2016. In what direction should the fishing mortality target change when natural mortality increases within an assessment?. *Canadian Journal of Fisheries and Aquatic Sciences* **73**:3, 349-357. [[Abstract](#)] [[Full Text](#)] [[PDF](#)] [[PDF Plus](#)]
18. Timothy J. Emery, Klaas Hartmann, Caleb Gardner. 2016. Management issues and options for small scale holobenthic octopus fisheries. *Ocean & Coastal Management* **120**, 180-188. [[Crossref](#)]
19. Cyril Piou, Marc H. Taylor, Julien Papaix, Etienne Prévost. 2015. Modelling the interactive effects of selective fishing and environmental change on Atlantic salmon demogenetics. *Journal of Applied Ecology* **52**:6, 1629-1637. [[Crossref](#)]
20. Neil L. Klaer, Robert N. O'Boyle, Jonathan J. Deroba, Sally E. Wayte, L. Richard Little, Larry A. Alade, Paul J. Rago. 2015. How much evidence is required for acceptance of productivity regime shifts in fish stock assessments: Are we letting managers off the hook?. *Fisheries Research* **168**, 49-55. [[Crossref](#)]
21. Darren Dennis, Éva Plagányi, Ingrid Van Putten, Trevor Hutton, Sean Pascoe. 2015. Cost benefit of fishery-independent surveys: Are they worth the money?. *Marine Policy* **58**, 108-115. [[Crossref](#)]
22. Enriqueta Velarde, Exequiel Ezcurra, Daniel W. Anderson. 2015. Seabird diet predicts following-season commercial catch of Gulf of California Pacific Sardine and Northern Anchovy. *Journal of Marine Systems* **146**, 82-88. [[Crossref](#)]

23. Michael Hawkshaw, Carl Walters. 2015. Harvest control rules for mixed-stock fisheries coping with autocorrelated recruitment variation, conservation of weak stocks, and economic well-being. *Canadian Journal of Fisheries and Aquatic Sciences* 72:5, 759-766. [[Abstract](#)] [[Full Text](#)] [[PDF](#)] [[PDF Plus](#)]
24. Simons Laura Sarah, Döring Ralf, Temming Axel. 2015. Combining area closures with catch regulations in fisheries with spatio-temporal variation: Bio-economic implications for the North Sea saithe fishery. *Marine Policy* 51, 281-292. [[Crossref](#)]
25. Yuhe Tong, Xinjun Chen, Dale Kolody. 2014. Evaluation of three harvest control rules for Bigeye Tuna (*Thunnus obesus*) fisheries in the Indian Ocean. *Journal of Ocean University of China* 13:5, 811-819. [[Crossref](#)]
26. A. E. Punt, T. A'mar, N. A. Bond, D. S. Butterworth, C. L. de Moor, J. A. A. De Oliveira, M. A. Haltuch, A. B. Hollowed, C. Szuwalski. 2014. Fisheries management under climate and environmental uncertainty: control rules and performance simulation. *ICES Journal of Marine Science* 71:8, 2208-2220. [[Crossref](#)]
27. Hiro-Sato Niwa. 2014. Uncertainty in a Measurement of Density Dependence on Population Fluctuations. *Applied Mathematics* 05:08, 1108-1119. [[Crossref](#)]
28. Kyle J. Molton, Travis O. Brenden, James R. Bence. 2013. Harvest levels that conserve spawning biomass can provide larger and more stable and sustainable yields in intermixed fisheries. *Fisheries Research* 147, 264-283. [[Crossref](#)]
29. Yuhe Tong, Xinjun Chen, Yong Chen. 2013. Evaluating alternative management strategies for bigeye tuna, *Thunnus obesus*, in the Indian Ocean. *Scientia Marina* 77:3, 449-460. [[Crossref](#)]
30. Mark N. Maunder, Richard B. Deriso. 2013. A stock-recruitment model for highly fecund species based on temporal and spatial extent of spawning. *Fisheries Research* 146, 96-101. [[Crossref](#)]
31. Dann Tyler H., Habicht Christopher, Baker Timothy T., Seeb James E.. 2013. Exploiting genetic diversity to balance conservation and harvest of migratory salmon. *Canadian Journal of Fisheries and Aquatic Sciences* 70:5, 785-793. [[Abstract](#)] [[Full Text](#)] [[PDF](#)] [[PDF Plus](#)] [[Supplemental Material](#)]
32. L. A. Rogers, D. E. Schindler, P. J. Lisi, G. W. Holtgrieve, P. R. Leavitt, L. Bunting, B. P. Finney, D. T. Selbie, G. Chen, I. Gregory-Eaves, M. J. Lisac, P. B. Walsh. 2013. Centennial-scale fluctuations and regional complexity characterize Pacific salmon population dynamics over the past five centuries. *Proceedings of the National Academy of Sciences* 110:5, 1750-1755. [[Crossref](#)]
33. K. A. Vert-pre, R. O. Amoroso, O. P. Jensen, R. Hilborn. 2013. Frequency and intensity of productivity regime shifts in marine fish stocks. *Proceedings of the National Academy of Sciences* 110:5, 1779-1784. [[Crossref](#)]
34. Malin L. Pinsky, Kristy J. Kroeker, Daniel J. Barshis, Cheryl A. Logan. Marine Conservation in a Changing Climate 32-44. [[Crossref](#)]
35. Sher Khan Panhwar, Qun Liu, Fozia Khan, Baradi Waryani. 2012. Maximum sustainable yield estimates of spiny lobster fishery in Pakistan using non-equilibrium CEDA package. *Russian Journal of Marine Biology* 38:6, 448-453. [[Crossref](#)]
36. Jonathan J. Deroba, James R. Bence. 2012. Evaluating harvest control rules for lake whitefish in the Great Lakes: Accounting for variable life-history traits. *Fisheries Research* 121-122, 88-103. [[Crossref](#)]
37. Sher Khan Panhwar, Qun Liu, Fozia Khan, Pirzada J. A. Siddiqui. 2012. Maximum sustainable yield estimates of Ladypees, *Sillago sihama* (Forsskål), fishery in Pakistan using the ASPIC and CEDA packages. *Journal of Ocean University of China* 11:1, 93-98. [[Crossref](#)]
38. Yajie Liu, Ussif Rashid Sumaila, John Paul Volpe. 2011. Potential ecological and economic impacts of sea lice from farmed salmon on wild salmon fisheries. *Ecological Economics* 70:10, 1746-1755. [[Crossref](#)]
39. KyujiWatanabeK. Watanabe, KazumiSakuramotoK. Sakuramoto, HidekiSugiyamaH. Sugiyama, NaokiSuzukiN. Suzuki. 2011. Dynamics of two sailfin sandfish (*Arctoscopus japonicus*) stocks in the Sea of Japan, and their management. *Canadian Journal of Fisheries and Aquatic Sciences* 68:3, 458-468. [[Abstract](#)] [[Full Text](#)] [[PDF](#)] [[PDF Plus](#)]
40. Éva E. Plagányi, Johann D. Bell, Rodrigo H. Bustamante, Jeffrey M. Dambacher, Darren M. Dennis, Cathy M. Dichmont, Leo X. C. Dutra, Elizabeth A. Fulton, Alistair J. Hobday, E. Ingrid van Putten, Franz Smith, Anthony D. M. Smith, Shijie Zhou. 2011. Modelling climate-change effects on Australian and Pacific aquatic ecosystems: a review of analytical tools and management implications. *Marine and Freshwater Research* 62:9, 1132. [[Crossref](#)]
41. Robyn E.ForrestR.E. Forrest, Murdoch K.McAllisterM.K. McAllister, Martin W.DornM.W. Dorn, Steven J.D.MartellS.J. Martell, Richard D.StanleyR.D. Stanley. 2010. Hierarchical Bayesian estimation of recruitment parameters and reference points for Pacific rockfishes (*Sebastes* spp.) under alternative assumptions about the stock-recruit function. *Canadian Journal of Fisheries and Aquatic Sciences* 67:10, 1611-1634. [[Abstract](#)] [[Full Text](#)] [[PDF](#)] [[PDF Plus](#)]
42. Ahmed S. Khan, Barb Neis. 2010. The rebuilding imperative in fisheries: Clumsy solutions for a wicked problem?. *Progress in Oceanography* 87:1-4, 347-356. [[Crossref](#)]

43. BrigitteDornerB. Dorner, Randall M.PetermanR.M. Peterman, ZhenmingSuZ. Su. 2009. Evaluation of performance of alternative management models of Pacific salmon (*Oncorhynchus* spp.) in the presence of climatic change and outcome uncertainty using Monte Carlo simulations. *Canadian Journal of Fisheries and Aquatic Sciences* **66**:12, 2199-2221. [[Abstract](#)] [[Full Text](#)] [[PDF](#)] [[PDF Plus](#)] [[Supplemental Material](#)]
44. Susana Martínez-Aguilar, Juan Antonio de Anda-Montañez, Francisco Arreguín-Sánchez, Miguel Ángel Cisneros-Mata. 2009. Constant harvest rate for the Pacific sardine (*Sardinops caeruleus*) fishery in the Gulf of California based on catchability-at-length estimations. *Fisheries Research* **99**:2, 74-82. [[Crossref](#)]
45. A. Dale Marsden, Steven J.D. Martell, U. Rashid Sumaila. 2009. Retrospective bioeconomic analysis of Fraser River sockeye salmon fishery management. *Fisheries Research* **97**:1-2, 32-41. [[Crossref](#)]
46. Richard T. Carson, Clive Granger, Jeremy Jackson, Wolfram Schlenker. 2009. Fisheries Management Under Cyclical Population Dynamics. *Environmental and Resource Economics* **42**:3, 379-410. [[Crossref](#)]
47. André E. Punt, Martin W. Dorn, Melissa A. Haltuch. 2008. Evaluation of threshold management strategies for groundfish off the U.S. West Coast. *Fisheries Research* **94**:3, 251-266. [[Crossref](#)]
48. Jonathan J. Deroba, James R. Bence. 2008. A review of harvest policies: Understanding relative performance of control rules. *Fisheries Research* **94**:3, 210-223. [[Crossref](#)]
49. Brian J. Irwin, Michael J. Wilberg, James R. Bence, Michael L. Jones. 2008. Evaluating alternative harvest policies for yellow perch in southern Lake Michigan. *Fisheries Research* **94**:3, 267-281. [[Crossref](#)]
50. Robert B.LessardR.B. Lessard, RayHilbornR. Hilborn, Brandon E.ChascoB.E. Chasco. 2008. Escapement goal analysis and stock reconstruction of sockeye salmon populations (*Oncorhynchus nerka*) using life-history models. *Canadian Journal of Fisheries and Aquatic Sciences* **65**:10, 2269-2278. [[Abstract](#)] [[Full Text](#)] [[PDF](#)] [[PDF Plus](#)]
51. Steven J.D. Martell, Carl J Walters, Ray Hilborn. 2008. Retrospective analysis of harvest management performance for Bristol Bay and Fraser River sockeye salmon (*Oncorhynchus nerka*). *Canadian Journal of Fisheries and Aquatic Sciences* **65**:3, 409-424. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
52. Franz J Mueter, Jennifer L Boldt, Bernard A Megrey, Randall M Peterman. 2007. Recruitment and survival of Northeast Pacific Ocean fish stocks: temporal trends, covariation, and regime shifts. *Canadian Journal of Fisheries and Aquatic Sciences* **64**:6, 911-927. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
53. Daniel E Schindler, Peter R Leavitt, Susan P Johnson, Curtis S Brock. 2006. A 500-year context for the recent surge in sockeye salmon (*Oncorhynchus nerka*) abundance in the Alagnak River, Alaska. *Canadian Journal of Fisheries and Aquatic Sciences* **63**:7, 1439-1444. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
54. William A Bennett, Kimy Roinestad, Laura Rogers-Bennett, Les Kaufman, Deb Wilson-Vandenberg, Burr Heneman. 2004. Inverse regional responses to climate change and fishing intensity by the recreational rockfish (*Sebastes* spp.) fishery in California. *Canadian Journal of Fisheries and Aquatic Sciences* **61**:12, 2499-2510. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
55. Massimiliano Cardinale, Henrik Svedäng. 2004. Modelling recruitment and abundance of Atlantic cod, *Gadus morhua*, in the eastern Skagerrak-Kattegat (North Sea): evidence of severe depletion due to a prolonged period of high fishing pressure. *Fisheries Research* **69**:2, 263-282. [[Crossref](#)]
56. Michael J Fogarty, Louise Gendron. 2004. Biological reference points for American lobster (*Homarus americanus*) populations: limits to exploitation and the precautionary approach. *Canadian Journal of Fisheries and Aquatic Sciences* **61**:8, 1392-1403. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
57. Geoffrey A. Meester, Anuj Mehrotra, Jerald S. Ault, Edward K. Baker. 2004. Designing Marine Reserves for Fishery Management. *Management Science* **50**:8, 1031-1043. [[Crossref](#)]
58. Villy Christensen, Carl J Walters. 2004. Ecopath with Ecosim: methods, capabilities and limitations. *Ecological Modelling* **172**:2-4, 109-139. [[Crossref](#)]
59. J.F. Caddy, D.J. Agnew. 2004. An overview of recent global experience with recovery plans for depleted marine resources and suggested guidelines for recovery planning. *Reviews in Fish Biology and Fisheries* **14**:1, 43-112. [[Crossref](#)]
60. TERRANCE J. QUINN. 2003. RUMINATIONS ON THE DEVELOPMENT AND FUTURE OF POPULATION DYNAMICS MODELS IN FISHERIES. *Natural Resource Modeling* **16**:4, 341-392. [[Crossref](#)]
61. WILLIAM G. CLARK. 2003. A MODEL FOR THE WORLD: 80 YEARS OF MODEL DEVELOPMENT AND APPLICATION AT THE INTERNATIONAL PACIFIC HALIBUT COMMISSION. *Natural Resource Modeling* **16**:4, 491-503. [[Crossref](#)]

62. Randall M Peterman, Brian J Pyper, Brice W MacGregor. 2003. Use of the Kalman filter to reconstruct historical trends in productivity of Bristol Bay sockeye salmon (*Oncorhynchus nerka*). *Canadian Journal of Fisheries and Aquatic Sciences* **60**:7, 809-824. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
63. E.C.E. Potter, J.C. MacLean, R.J. Wyatt, R.N.B. Campbell. 2003. Managing the exploitation of migratory salmonids. *Fisheries Research* **62**:2, 127-142. [[Crossref](#)]
64. Toshio Katsukawa, Hiroyuki Matsuda. 2003. Simulated effects of target switching on yield and sustainability of fish stocks. *Fisheries Research* **60**:2-3, 515-525. [[Crossref](#)]
65. Marcelo Vasconcellos. 2003. An analysis of harvest strategies and information needs in the purse seine fishery for the Brazilian sardine. *Fisheries Research* **59**:3, 363-378. [[Crossref](#)]
66. Niclas Jonzen, Esa Ranta, Per Lundberg, Veijo Kaitala, Harto Lindén. 2003. Harvesting-induced population fluctuations?. *Wildlife Biology* **9**:1, 59-65. [[Crossref](#)]
67. Niclas Jonzén, Jörgen Ripa, Per Lundberg. 2002. A Theory of Stochastic Harvesting in Stochastic Environments. *The American Naturalist* **159**:5, 427-437. [[Crossref](#)]
68. Maria Cristina Cergole, Suzana Anita Saccardo, Carmen L. D. B. Rossi-Wongtschowski. 2002. Fluctuations in the spawning stock biomass and recruitment of the Brazilian sardine (*Sardinella brasiliensis*) 1977-1997. *Revista Brasileira de Oceanografia* **50**:unico, 13-26. [[Crossref](#)]
69. Olle Hjerne, Sture Hansson. 2001. Constant catch or constant harvest rate?. *Fisheries Research* **53**:1, 57-70. [[Crossref](#)]
70. Jon T Schnute, Laura J Richards. 2001. Use and abuse of fishery models. *Canadian Journal of Fisheries and Aquatic Sciences* **58**:1, 10-17. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
71. William J. Sutherland. 2001. Sustainable exploitation: a review of principles and methods. *Wildlife Biology* **7**:1, 131-140. [[Crossref](#)]
72. Gordon A McFarlane, Jacquelynne R King, Richard J Beamish. 2000. Have there been recent changes in climate? Ask the fish. *Progress in Oceanography* **47**:2-4, 147-169. [[Crossref](#)]
73. Michael J Bradford, Ransom A Myers, James R Irvine. 2000. Reference points for coho salmon (*Oncorhynchus kisutch*) harvest rates and escapement goals based on freshwater production. *Canadian Journal of Fisheries and Aquatic Sciences* **57**:4, 677-686. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
74. Randall M Peterman, Brian J Pyper, Jeff A Grout. 2000. Comparison of parameter estimation methods for detecting climate-induced changes in productivity of Pacific salmon (*Oncorhynchus* spp.). *Canadian Journal of Fisheries and Aquatic Sciences* **57**:1, 181-191. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
75. E Eric Knudsen. Managing Pacific Salmon Escapements . [[Crossref](#)]
76. Laura J Richards, Jean-Jacques Maguire. 1998. Recent international agreements and the precautionary approach: new directions for fisheries management science. *Canadian Journal of Fisheries and Aquatic Sciences* **55**:6, 1545-1552. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
77. R J Beamish, C-E M Neville, A J Cass. 1997. Production of Fraser River sockeye salmon (*Oncorhynchus nerka*) in relation to decadal-scale changes in the climate and the ocean. *Canadian Journal of Fisheries and Aquatic Sciences* **54**:3, 543-554. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]
78. P D Spencer. 1997. Optimal harvesting of fish populations with nonlinear rates of predation and autocorrelated environmental variability. *Canadian Journal of Fisheries and Aquatic Sciences* **54**:1, 59-74. [[Abstract](#)] [[PDF](#)] [[PDF Plus](#)]