The Effect of Recruitment Variability on the Choice of a Target Level of Spawning Biomass Per Recruit

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Abstract

Deterministic computations with a range of spawner-recruit curves and groundfish life history parameters have shown that a high average yield virtually can be assured by applying the fishing mortality rate that reduces spawning biomass per recruit to 35% of the unfished level (denoted $F_{35\%}$). Stochastic trials reported here indicate that the presence of random variation in recruitment calls for a slightly higher target level of spawning biomass per recruit—around 40%—especially if the recruitment deviations have a high serial correlation. The year-to-year variability of yield is hardly affected by the target level of spawning biomass per recruit, but the frequency of episodes of low spawning biomass—if defined as less than 20% of the unfished level—may be reduced substantially by fishing at $F_{40\%}$ rather than $F_{35\%}$, even though there is only a small difference in average spawning biomass between $F_{35\%}$ and $F_{40\%}$.

Introduction

Most of the scientific quota recommendations for Alaska groundfish are determined by applying fixed exploitation rates to estimates of exploitable biomass. If perfect information were available; if a stock were in good condition; and if there were no other factors (e.g., marine mammal considerations) requiring restraint, the exploitation rate corresponding to F_{MSY} would be used. (F_{MSY} is defined here as the instantaneous full-recruitment rate of fishing mortality that

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provides the maximum average yield in the long-term when applied continuously.) The ideal procedure rarely is used in practice because information is far from perfect for most stocks; therefore, a reliable estimate of F_{MSY} is not available. Instead, some surrogate for F_{MSY} has been used, such as $F_{0.1}$ or $F = M$. ($F_{0.1}$ is the rate of fishing mortality at which the marginal yield per recruit is 10% of the unfished marginal yield per recruit, and $F = M$ is the instantaneous rate of natural mortality.) These rates are calculated from the stock's life history parameters, meaning the age-specific schedules of growth, natural mortality, maturity, and fishery selectivity.

The intent in using a surrogate exploitation rate is to achieve the same practical effect as fishing at the F_{MSY} level: a yield close to *MSY* and a low probability of reducing the stock to dangerously low levels. But because the value of F_{MSY} is determined by unknown density dependent mechanisms, while the surrogate rates are determined entirely by life history parameters, there is no *a priori* assurance that any of the customary surrogates will be effective.

A previous paper (Clark 1991) investigated the possibility choosing a surrogate rate solely on the basis of life history parameters that could be expected to provide a yield close to *MSY*. The approach was to consider a range of life history parameters centered on the values typical of North Pacific and North Atlantic groundfish stocks (Figure 1a) and a set of spawner-recruit curves of both the Beverton-Holt and Ricker forms that spanned a range of density dependence approximating the range observed in well-studied groundfish stocks (Figure 1b). Deterministic yield computations over the range of life history parameter values and spawner-recruit curves showed that a robust strategy was to apply the fishing mortality rate that reduced spawning biomass per recruit to about 35% of the unfished value (denoted $F_{35\%}$). The range of optimum values among all the cases considered was about 33% to 39%. This strategy assured that the yield would be at least 75% of *MSY*, and would be higher if the true spawner-recruit curve was one of the intermediate forms rather than one of the extreme forms (Figure 2).

The results also showed that $F_{35\%}$ was very close to $F_{0.1}$ and slightly higher than $F = M$ in most cases. The exceptional cases were life histories where the schedules of sexual maturity and recruitment to the fishery did not coincide. Where fish recruited to the fishery before reaching maturity, $F_{0.1}$ was far too high for some of the spawner-recruit curves. Where fish matured before recruiting to the fishery, $F_{0.1}$ (and more so $F = M$) was too low for some spawner-recruit curves. The conclusion was that while $F_{35\%}$ and $F_{0.1}$ were often nearly equal, $F_{35\%}$ was generally preferable because it would maintain the proper level of spawning biomass per recruit for any combination of maturity and recruitment schedules. On the basis of these results, $F_{35\%}$ has been adopted as a target fishing mortality rate in making quota recommendations for a number of stocks in Alaska and on the Pacific coast of the United States.

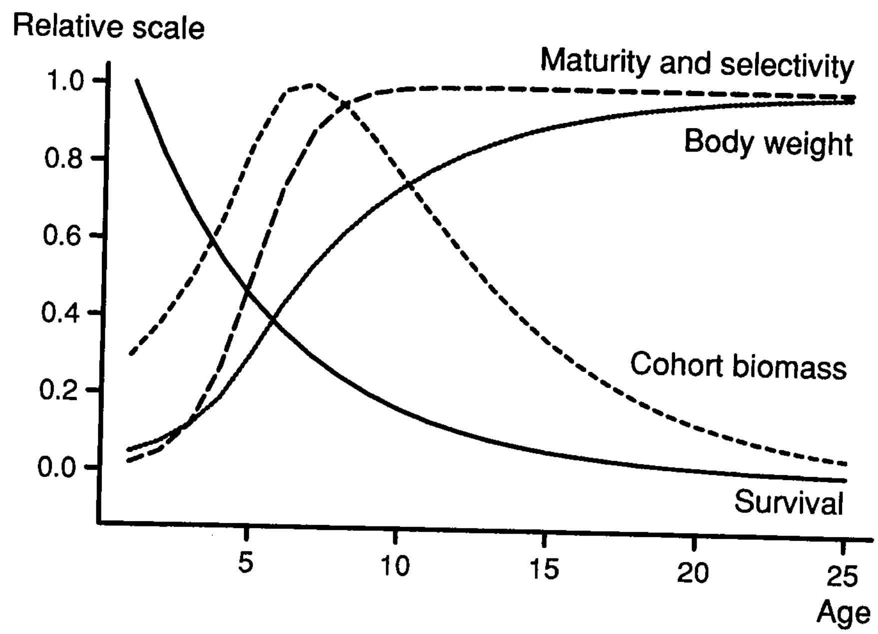

Figure 1a. Life history schedules typical of groundfish stocks.

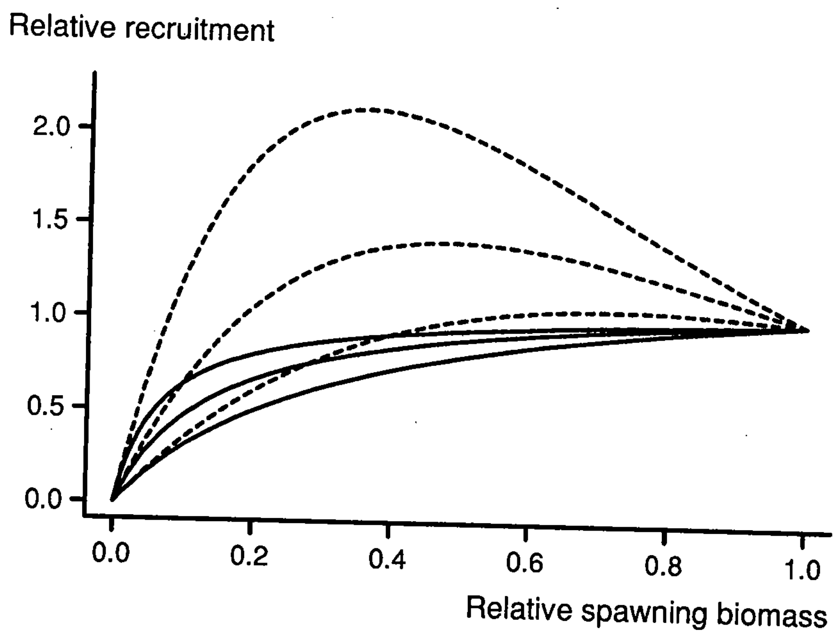

Figure 1b. The range of spawner-recruit relationships used in the computations. Beverton-Holt curves are shown as solid lines, Ricker curves as broken lines. Both spawning biomass and recruitment are shown as proportions of the deterministic unfished levels.

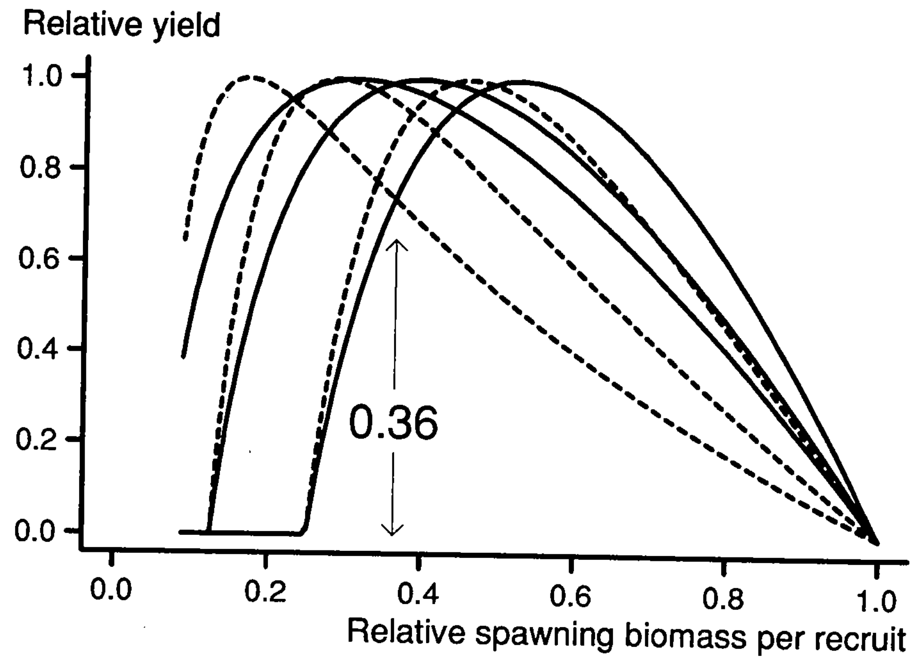

Figure 2. Deterministic relative yield (proportion of deterministic MSY) as a function of relative spawning biomass per recruit (proportion of the unfished level), for a range of spawner-recruit relationships. Beverton-Holt curves are shown as solid lines, Ricker curves as broken lines.

Other authors have been concerned primarily with the level of spawning biomass per recruit corresponding to the maximum rate of fishing mortality that a stock can sustain (without being driven to extinction). Goodyear (1993) reviewed work on this question in the 1970s that was prompted by the mortality of juvenile fish in power plant cooling systems. Shepherd (1982) pointed out that a stock will be driven to extinction if spawning biomass per recruit is reduced below a level equal to the reciprocal of the slope of the spawner-recruit curve at the origin. Sissenwine and Shepherd (1987) called the corresponding level of fishing mortality F_{rep} (for replacement) and advocated its use in defining overfishing, as U.S. regional fishery management councils are required to do. Mace and Sissenwine (1993) compiled spawner-recruit data on a large number of marine stocks and estimated minimum sustainable levels of spawning biomass per recruit, arriving at a recommendation of 20-30% of the unfished level to avoid overfishing stocks where the spawner-recruit relationship is unknown. Thompson (1993) recommended 30% of the unfished level as appropriate in cases where the spawner-recruit relationship was inflected (i.e., depensatory), and this is the working definition of overfishing at present for most Alaska groundfish stocks.

There remains considerable scope for discussion about both optimal target levels and minimum sustainable levels of spawning biomass per recruit, including such issues as what range of density dependence to allow for in the spawner-recruit relationships considered and what forms of spawner-recruit relationships to entertain. (For example, if only Beverton-Holt curves had been considered in the author's previous paper, the optimal level would have turned out to be around 45% rather than 35%.) This paper considers two questions relating to the choice of a target level of spawning biomass per recruit:

1. The recommendation of 35% as a target resulted from deterministic yield computations. Would the same recommendation result from trials that include a large random variation in recruitment of the sort normally seen in groundfish stocks?

2. The previous study (Clark 1991) showed 35% to be the best target level in terms of average yield, but yield is not the only consideration in choosing a good exploitation rate. Large year-to-year changes in quota recommendations are disturbing to managers, and declines in stock biomass to levels regarded as low are disturbing to both biologists and managers. With these concerns in mind, is it possible to achieve substantial reductions in the variability of yield and the frequency of low biomass levels without sacrificing very much yield by choosing a somewhat higher target level of spawning biomass per recruit?

Methods

The general approach was to use the same typical groundfish life history parameters and the same set of spawner-recruit curves as in the previous paper, and to calculate the consequences of fishing at rates ranging from $F_{50\%}$ up to $F_{20\%}$ when recruitment is allowed to vary randomly and widely from year to year. The calculations were not repeated for the range of life history parameters considered in Clark (1991), because it was shown there that altering the life history parameters had only a minor effect on the location of the optimal level of spawning biomass per recruit.

The typical groundfish life history parameters (Figure 1a) consisted of an instantaneous natural mortality rate (M) and von Bertalanffy growth parameter (K), both equal to 0.2, and coincident age-specific schedules of selectivity and sexual maturity described by a logistic with a value of 50% at age 5 and 90% at age 7. The spawner-recruit curves were chosen so that according to the least resilient curves, the stock would be driven to extinction by a fishing mortality rate of about 0.4 (twice M), and according to the most resilient curves, they could sustain a fishing mortality rate of 1.4 indefinitely. It was argued in the previous paper (Clark 1991) that this range of density dependence covers the bulk of the range that occurs in nature.

Recruitment variability was represented by a lognormal multiplicative error, the logarithm of the error having mean zero and standard deviation $\sigma = 0.6$. This implies a difference on the order of 10:1 between the strongest and weakest year-classes in 20 years of observations, which is a somewhat larger variation than is observed in most Alaska stocks (North Pacific Fishery Management Council 1992). A set of artificial data is plotted in Figure 3.

To generate the random recruitments, the spawner-recruit function was scaled down by $\exp(-\sigma^2/2)$ so that the expectation of the stochastic form would be equal to the value of the deterministic form. A single sequence of normal deviates $\langle d_i \rangle$ was used in every trial. This sequence was drawn from a random number generator and then recentered and rescaled to assure the proper mean and variance.

Year-class strengths appear to be serially correlated for many groundfish stocks (e.g., Koslow et al. 1987). That is, there appear to be runs of good and poor year-classes rather than a purely random sequence. Figure 4 shows artificial sequences of equal variance that differ in the degree of serial correlation. The sequence with correlation coefficient zero (independent deviations) looks like white noise. At higher levels of correlation, the sequences still look like noise, but with lower frequencies. At a correlation of 0.9, the sequence contains the persistent highs and lows seen in some groundfish recruitment data.

Each set of trials was performed first with independent (uncorrelated) random recruitment deviations and then with recruitment deviations that had a serial correlation of 0.9. For the purely random trials, the sequence of deviates $\langle d_i \rangle$ described above was used directly. For the trials with serial correlation coefficient $\rho = 0.9$, a sequence of correlated values $\langle c_i \rangle$ was generated with the recursive equation:

$$c_i = \rho \times c_{i-1} + d_i \times \sqrt{1-\rho^2}$$

which produces the desired serial correlation ρ while preserving the overall variance σ^2.

Stochastic trials were performed with the typical life history parameters for the six spawner-recruit relationships and the fishing mortality rates corresponding to target levels of spawning biomass per recruit ranging from 20% to 50% of the unfished level. Each trial consisted of initializing stock size and age composition to the deterministic equilibrium corresponding to the given spawner-recruit relationship and fishing mortality rate, and then simulating 100 years of fishing at that rate with the calculated recruitments multiplied by one of the error sequences described above (independent or correlated).

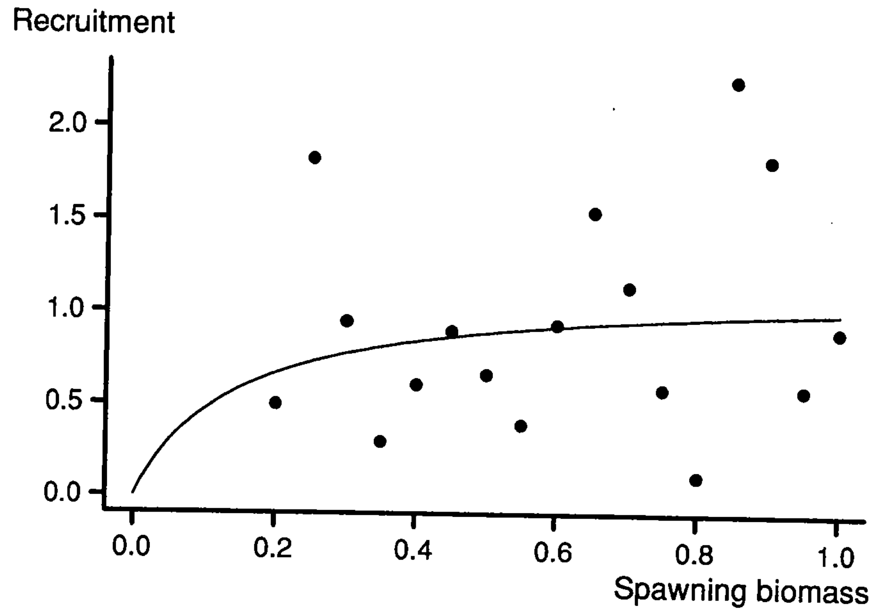

Figure 3. Artificial spawner-recruit data generated with an underlying Beverton-Holt relationship and a multiplicative lognormal error. The logarithm of the error term has mean zero and standard deviation 0.6.

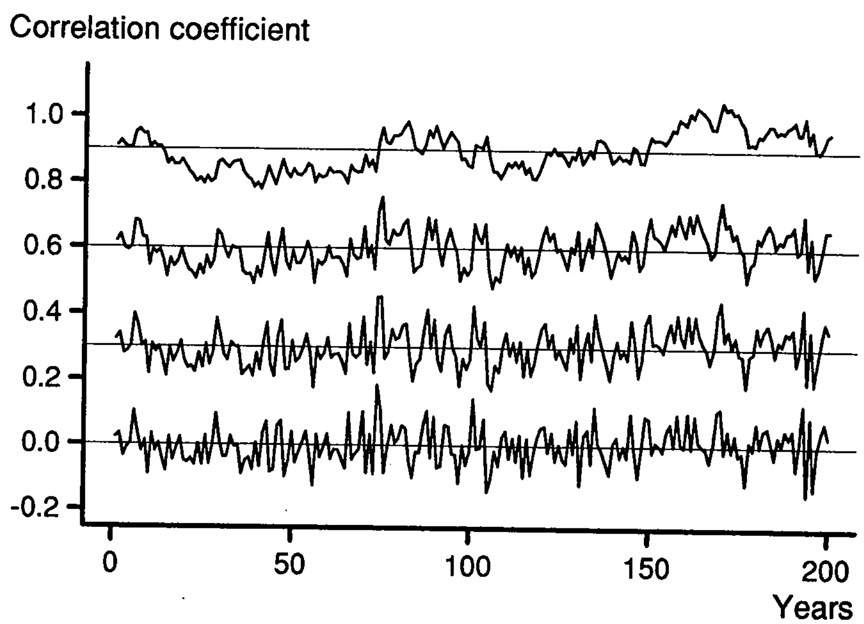

Figure 4. Artificial series of recruitment residuals with equal variances and increasing levels of serial correlation. The vertical axis shows the serial correlation coefficient of each series; the values plotted are deviations from a long-term mean (the horizontal line) on an arbitrary scale.

Results

Each trial produced a distribution of results for quantities of interest such as average yield, yield variability, average spawning biomass, and the frequency of occurrence of specified levels of spawning biomass. The main features are as follows:

Average yield

With purely random recruitment variation, average yield varies with spawning biomass per recruit in much the same way as in the deterministic results reported in the previous study. (Figure 5a shows relative yield, meaning average yield as a proportion of the deterministic *MSY*, plotted against relative spawning biomass per recruit, meaning relative to the unfished level.) For each spawner-recruit curve, the entire deterministic *MSY* is, in fact, achieved at some fishing mortality rate, and a large fraction of *MSY* can be taken with any of the spawner-recruit curves at the fishing mortality rate that reduces spawning biomass per recruit to about 35% of the unfished value. The location of the optimum differs slightly from the previous study, however; the deterministic optimum is 36% for the typical life history parameters, while the stochastic optimum is 38%.

With serially correlated recruitment variation, the results are quite different (Figure 5b). Only about 90% at best of the deterministic *MSY* is taken at any fishing mortality rate. The optimal level of spawning biomass per recruit is about 42%, and fishing at the corresponding level of fishing mortality guarantees only about 60% of the deterministic *MSY* (compared with 75% in the deterministic case).

Yield variability

Yield variability is about the same for all levels of spawning biomass per recruit above about 30% (Figures 6a and 6b). It is high with random recruitment variation (coefficient of variation 30-40%) and very high with serially correlated recruitment variation (coefficient of variation 60-80%).

Average spawning biomass

Average spawning biomass increases moderately with spawning biomass per recruit for either kind of recruitment variation (Figures 7a and 7b), but for most spawner-recruit curves it is, on average, only 10-30% of the unfished level for fishing mortality rates between $F_{35\%}$ and $F_{45\%}$.

Frequency of low spawning biomass

Rightly or wrongly, levels of spawning biomass below 20% of the unfished level are regarded as unsafe or at least worrisome by many people. By this standard,

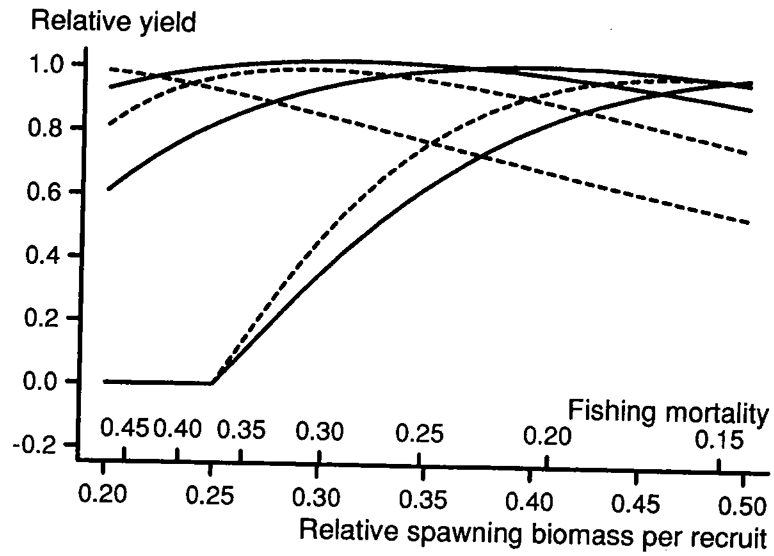

Figure 5a. Mean stochastic relative yield (mean proportion of deterministic MSY) as a function of relative spawning biomass per recruit (proportion of the unfished level), for a range of spawner-recruit relationships. Beverton-Holt curves are shown as solid lines, Ricker curves as broken lines. Recruitment residuals were generated with a lognormal multiplicative error. The logarithm of the error term had mean zero, standard deviation 0.6, and serial correlation coefficient zero.

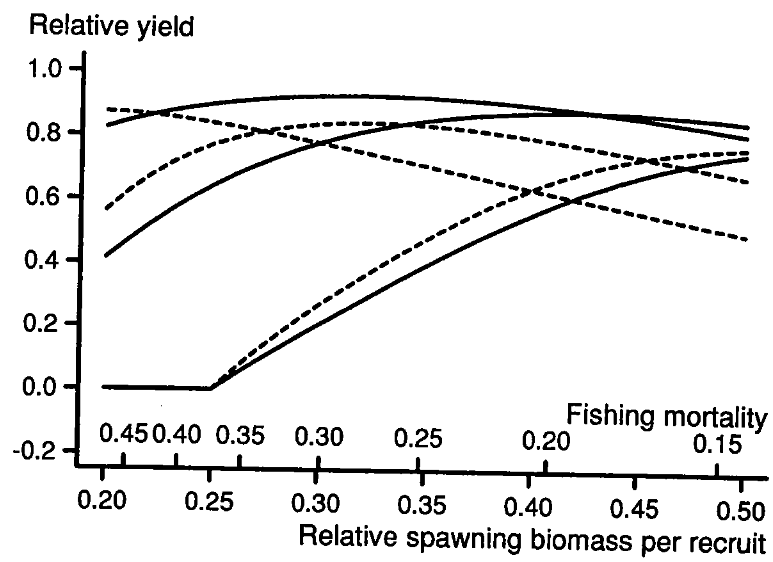

Figure 5b. Same as Figure 5a, except that the logarithm of the multiplicative recruitment residuals had a serial correlation coefficient of 0.9.

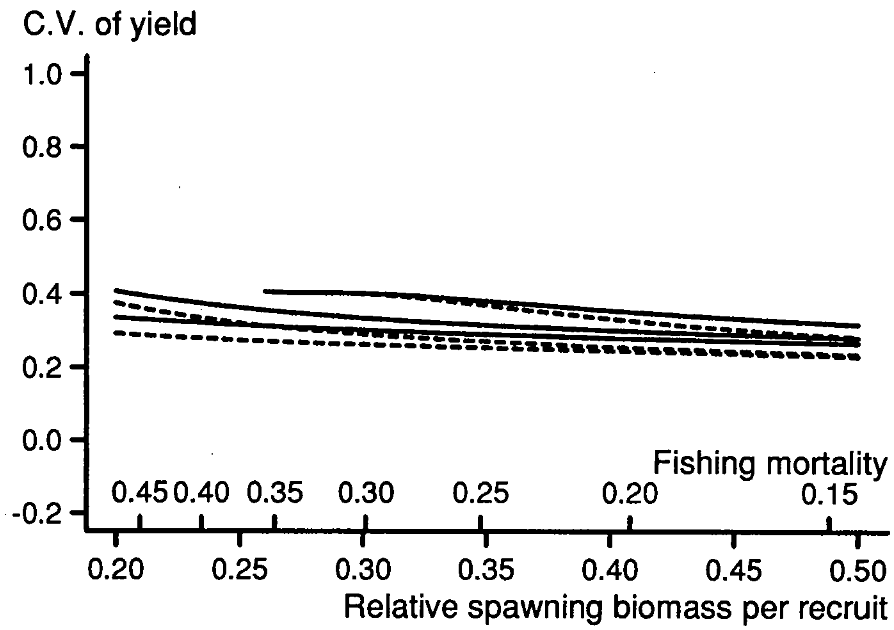

Figure 6a. Same as Figure 5a (variable recruitment with uncorrelated residuals), except that the dependent variable plotted is the coefficient of variation of yield.

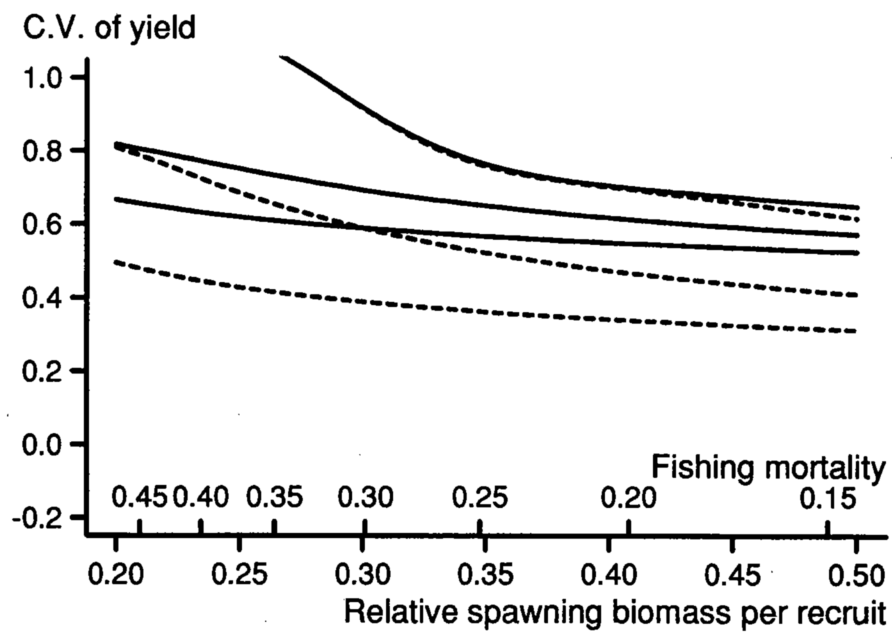

Figure 6b. Same as Figure 6a, except that the logarithm of the multiplicative recruitment residuals had a serial correlation coefficient of 0.9.

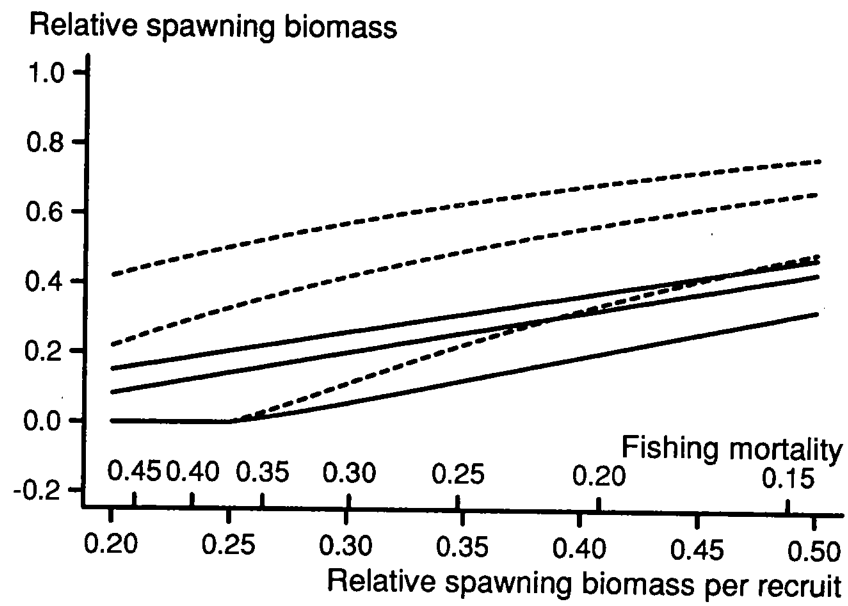

Figure 7a. Same as Figure 5a (variable recruitment with uncorrelated residuals), except that the dependent variable plotted is mean stochastic relative spawning biomass (mean proportion of the deterministic unfished total spawning biomass).

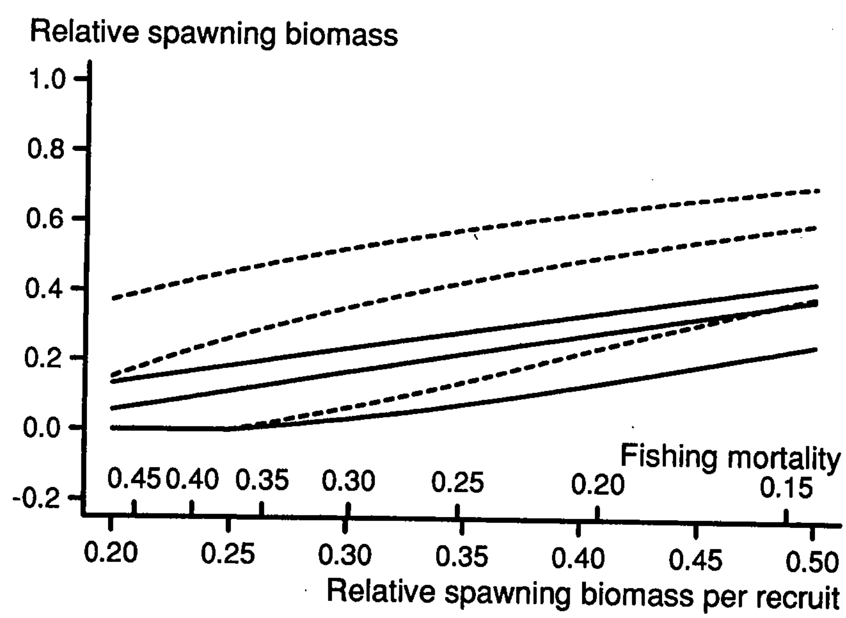

Figure 7b. Same as Figure 7a, except that the logarithm of the multiplicative recruitment residuals had a serial correlation coefficient of 0.9

fishing at $F_{35\%}$ entails frequent worries under the operation of half of the spawner-recruit curves when recruitment variation is uncorrelated, while fishing at a rate of $F_{40\%}$ or lower avoids the problem entirely for all but one of the spawner-recruit curves (Figure 8a). When recruitment variation is correlated, the prospects are not hopeful (Figure 8b); spawning biomass will often decline below 20% for most spawner-recruit curves and any fishing mortality rate between $F_{35\%}$ and $F_{45\%}$.

As shown in Figures 7a and 7b, there is only a small difference between the average relative spawning biomass levels corresponding to $F_{35\%}$ and $F_{40\%}$, but because both are near 20% of the unfished level, the 20% reference point produces the illusion of a large difference. This demonstrates the importance, when considering the effect of alternative exploitation rates on spawning biomass, of examining the actual means (or distributions) of the spawning biomass levels, and not just the probability of falling below a particular reference point.

Discussion and Conclusions

For the levels of recruitment variability considered here, which are similar to those observed in Alaska groundfish stocks, it appears that the optimal target levels of relative spawning biomass per recruit—optimal in the sense of obtaining the largest assured proportion of *MSY*—are clustered around 40%, whereas in deterministic computations they were clustered around 35%. This suggests choosing $F_{40\%}$ as a rule of thumb (as also recommended by Mace 1994), but there are enough differences among particular cases that it would be silly to argue very hard for or against any specific rate between $F_{35\%}$ and $F_{45\%}$.

On the other hand, the results do provide a good case for keeping spawning biomass per recruit in the 35-45% range, lacking a good estimate of the true spawner-recruit relationship. Fishing at rates above $F_{35\%}$ runs the risk of fishing less resilient stocks down to very low levels (and low yields). Fishing at rates below $F_{45\%}$ carries the risk of forgoing yield from more resilient stocks, at a rate of about 1.5% of *MSY* for each percentage point increase in spawning biomass per recruit.

Until recently, most quota recommendations for Alaska groundfish were based on $F_{0.1}$ and $F = M$, and these rates are still used elsewhere. For the typical groundfish life history parameters, $F_{0.1}$ corresponds approximately to $F_{35\%}$ and $F = M$ to $F_{42\%}$. In most cases, therefore, these rates probably are quite sensible in light of the results presented here. In cases where selectivity and mortality schedules differ, however, either $F_{0.1}$ or $F = M$ can fall outside the range recommended here. In those cases, it would be wise to consider changing the exploitation rate in order to achieve a better level of spawning biomass per recruit.

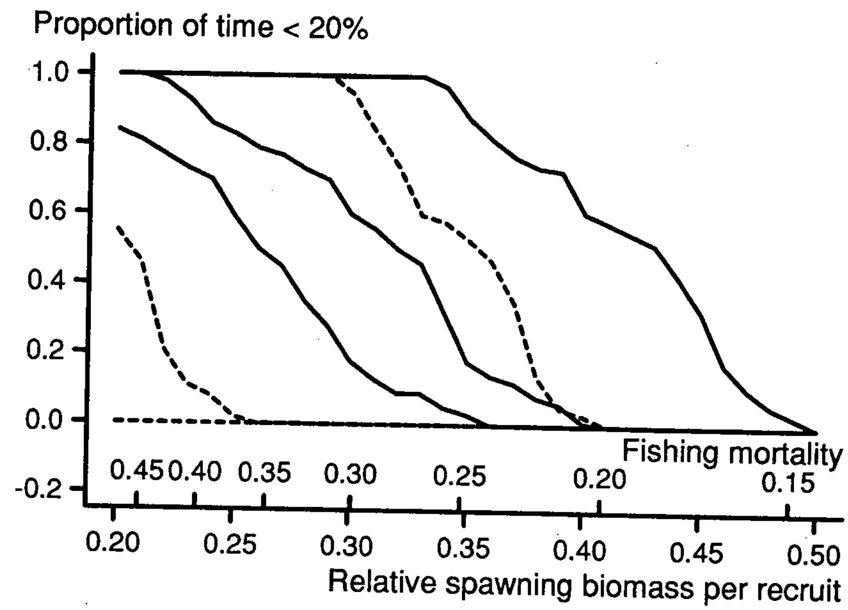

Figure 8a. Same as Figure 5a (variable recruitment with uncorrelated residuals), except that the dependent variable plotted is the proportion of years in which total spawning biomass is less than 20% of the deterministic unfished total spawning biomass.

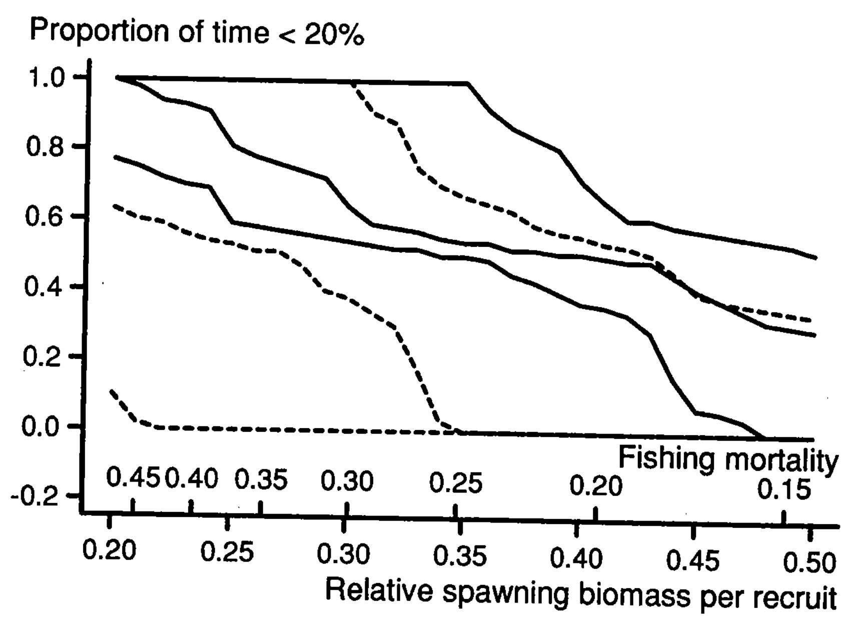

Figure 8b. Same as Figure 8a, except that the logarithm of the multiplicative recruitment residuals had a serial correlation of 0.9.

Within the recommended range of $F_{35\%}$ to $F_{45\%}$, lower fishing mortality rates will not provide much relief from year-to-year variability in yield, but may reduce substantially the frequency of low spawning biomass levels, if low is defined as less than 20% of the unfished spawning biomass. Strong serial correlation of recruitment deviations substantially reduces the yield obtainable at any fixed exploitation rate and increases the incidence of low spawning biomass levels.

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