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**Recommendations concerning the calculation of maximum constant yield (*MCY*) and current annual yield (*CAY*)**

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**This series documents the scientific basis for stock assessments and fisheries management advice in New Zealand. It addresses the issues of the day in the current legislative context and in the time frames required. The documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.**

## 1. Introduction

In the 'Guide to Biological Reference Points' (Annala 1992, pp. 13–21 ) the Maximum Constant Yield (*MCY*) is defined as

the maximum constant catch that is estimated to be sustainable, with an acceptable level of risk, at all probable future levels of biomass.

and the Current Annual Yield (*CAY*) is defined as

the one-year catch calculated by applying a reference fishing mortality,  $F_{CAY}$ , to an estimate of the fishable biomass present during the next fishing year;  $F_{CAY}$  is the level of (instantaneous) fishing mortality that, if applied every year, would, within an acceptable level of risk, maximise the average catch from the fishery.

(For clarity in what follows I have altered  $F_{ref}$  in the original definition to  $F_{CAY}$ .)

In the current context the key phrase in the above definitions is "an acceptable level of risk". Though a number of rules have been developed for calculating *MCY* and *CAY* (see below), these rules have not so far been based on any formal definition of risk. In this paper I describe some of the rules currently in use, propose a definition of an acceptable level of risk, and address two questions arising from this definition. First, is acceptance of the definition likely to result in suboptimal yields? Second, under this definition are the rules currently used to calculate *MCY* and *CAY* safe or unsafe?

These questions were addressed by simulating fishing, using an age-structured model, with constant catch (to evaluate the *MCY* rules), or with constant fishing mortality,  $F$ , (for the *CAY* rules). Given a definition of "an acceptable level of risk", these simulations show how safe each rule is. The simulations were repeated for five New Zealand species and a range of stock-recruit relationships.

I also show how the simulation procedure can be used to replace the rules and conclude by offering some recommendations concerning the calculation of *MCY* and *CAY* in New Zealand stock assessments.

## 2. Materials and Methods

### 2.1 The Rules

The *MCY* rules considered were  $MCY = 0.25MB_0$ ,  $MCY = 0.25F_{0.1}B_0$ , and  $MCY = 2/3MSY$ , where  $M$  is the instantaneous rate of natural mortality,  $F_{0.1}$  is the instantaneous fishing mortality for which the slope of the yield-per-recruit curve is 0.1 times the slope at the origin (Gulland and Boerema 1973),  $B_0$  is the mean recruited biomass of the virgin population, and  $MSY$  is the deterministic maximum sustainable yield.

The *CAY* rules considered were  $F_{CAY} = M$ ,  $F_{CAY} = F_{0.1}$ , and  $F_{CAY} = F_{MSY}$ , where  $F_{MSY}$  is the instantaneous fishing mortality associated with the deterministic *MSY*.

The deterministic *MSY* may be calculated either from a surplus production model or from combining a yield per recruit analysis with an assumed stock-recruit relationship. In this paper only the latter method was considered.

## 2.2 An Acceptable Level of Risk

The risk we are discussing here is the risk of fishery "collapse". By collapse I mean some change in the ecosystem so that sustainable yield levels after the change are much lower than they were before it. There are numerous examples of such collapses in the fisheries literature (see, e.g., Clark 1985, table 1.1; Thompson 1991, table 1). The reasons for these collapses are not always clear and a number of mechanisms may be responsible. Further, there is evidence that populations can collapse even in the absence of a fishery (Soutar and Isaacs 1974). However, it seems reasonable to assume, as a general principle, that the probability of collapse for a particular fish population will tend to increase as its spawning biomass decreases – i.e., risk increases as spawning biomass decreases. The increase in risk may be very slight – even zero – while the spawning population remains moderately high but can be expected to be larger for low population sizes. (Note that I distinguish between recruited biomass and spawning biomass. The former is the (natural) basis for the *MCY* rules of the preceding section; the latter is the natural quantity of concern when considering the viability of an exploited population.)

Thus, there should be, for each population, a threshold biomass level below which the risk of collapse is unacceptably high. It is natural to express this threshold level as a percentage of the mean virgin spawning biomass,  $S_0$ , and, for lack of evidence to the contrary, to assume that the threshold is the same (in percentage terms) for all populations. I propose using a threshold of 20%  $S_0$ .

In using this threshold in the present context it is not useful to apply it absolutely – i.e., to insist that the level of harvesting should never result in reducing the spawning biomass,  $S$ , below 20%  $S_0$ . This is because, even with no fishing, there will always be a non-zero probability that a sequence of unusually low recruitments will cause  $S$  to drop below the threshold.

Thus I propose the definition that a harvesting regime (with constant catch, or constant  $F$ ) has an acceptable level of risk if the probability that  $S$  falls below 20%  $S_0$  is less than 0.1 (or, equivalently, the percentage of years in which  $S$  falls below 20%  $S_0$  is less than 10%).

## 2.3 Model and Simulation Method

The age-structured model used in the simulations was the same as that described by Francis (1992) except for one modification: the parameters  $S_f$  and  $S_m$  were introduced to describe gradual recruitment and maturity, respectively.  $S_f = 0$  implies knife-edge recruitment at age  $A_f$ ; for  $S_f \neq 0$  the proportion recruited increases from 5% at age  $A_f - S_f$  to 50% at age  $A_f$ , and 95% at age  $A_f + S_f$ . (Details of the role of  $S_f$  in the model are given in Francis and Robertson (1991), in which the notation  $S_r$  is used in place of  $S_f$ . The equations for  $S_m$  are analogous to those for  $S_f$ .)

In this model two parameters describe the stock-recruit relationship: the steepness,  $h$  (= the mean recruitment at  $S = 20\% S_0$ , expressed as a fraction of the virgin recruitment) and recruitment variability,  $\sigma_R$  (= the standard deviation of the natural logarithm of the recruitment).

The aim was to estimate, for each level of harvesting (with either constant catch or constant  $F$ ), the mean catch and the probability that  $S < 20\% S_0$ . Because no time frame is mentioned in the

definitions of *MCY* and *CAY*, this probability is taken to be a long-term value - i.e., the probability calculated after the population has reached a (stochastic) equilibrium under the particular harvesting level.

The following initialisation procedure was used to obtain approximate equilibrium starting conditions. First, I calculated  $f_r$ , the equilibrium recruited biomass (expressed as a fraction of  $B_0$ ) associated with the given harvest level when recruitment is deterministic. Where the given harvest level was not sustainable with deterministic recruitment,  $f_r$  was set equal to the equilibrium recruited biomass (expressed as a fraction of  $B_0$ ) associated with  $F_{MSY}$ .  $f_u$  was then calculated as the recruitment (expressed as a fraction of the virgin recruitment) predicted by the (deterministic) stock-recruit relationship when  $S = f_r S_0$ . Next, a virgin population was generated assuming stochastic recruitment. Then the numbers at age in this population were multiplied by  $f_r$  (for recruited fish) or  $f_u$  (for unrecruited fish) to reduce the population to the approximate size expected for the given harvest level. Finally, the model was run for  $A_l$  years to stabilise, where  $A_l$  is the approximate maximum age of the species, defined by  $A_l = \log_e(100)/M$ .

The model was run for a further  $A_l$  years and the whole procedure was repeated 500 times. The mean catch (as a percentage of  $B_0$ ) and the proportion of years in which  $S < 20\% S_0$  were recorded.

Estimates of biomass are required for both the *MCY* and *CAY* rules. It was assumed that these estimates were unbiased and normally distributed with a coefficient of variation of 20% in all cases.

The *MCY* rules require an estimate of  $B_0$ . It was assumed here that what would actually be estimated for a real fishery would be the initial biomass, i.e., the biomass at the time the fishery started. This may be greater or less than  $B_0$  depending on whether recent recruitment had been above or below average. Thus, in each simulation run with constant catch, the estimate of  $B_0$  was taken as the size of the virgin population generated in the above initialisation procedure, plus a random estimation error (as described in the previous paragraph).

## 2.4 Parameter Values

To be able to draw conclusions about the general applicability of the above rules for New Zealand stock assessments, it was important that the simulations be carried out for an appropriate range of parameter values.

The most important parameters in this respect are those describing the stock-recruit relationship,  $h$  and  $\sigma_R$ . Since very little is known of either  $h$  or  $\sigma_R$  for New Zealand species, a range of values was used for each:  $h = 0.5, 0.75, 0.95$  (describing low, medium, and high compensation);  $\sigma_R = 0.4, 0.6, \text{ and } 0.8$  (describing low, medium, and high recruitment variability). The latter values were chosen with reference to the compilation of estimated  $\sigma_R$  values given by Beddington and Cooke (1983); these values are approximately the quartiles of the values in their table 2 (note that they tabulate the variance, i.e.,  $\sigma_R^2$ ).

Other life history parameters likely to affect the safety of the above rules are natural mortality,  $M$ , and the von Bertalanffy rate parameter,  $K$ . From a plot of the  $M$  and  $K$  values for 11 New Zealand species, five were selected that covered the range (Fig. 1). The life history parameters used for these species are given in Table 1.

Another aspect likely to affect the performance of the rules is whether fish recruit to the fishery before or after reaching maturity. For example, if recruitment to the fishery occurs  $n$  years before maturity ( $A_f = A_m - n$ ) then the effect on the spawning biomass of a given level of fishing will increase as  $n$  increases. Conversely, if  $A_f = A_m + n$  for sufficiently large  $n$  then no amount of fishing pressure would drive  $S$  below 20%  $S_0$ , because of the unfished reservoir of mature fish of ages  $A_m$  to  $A_m + n - 1$ . There are two species in Table 1 for which  $A_f \neq A_m$  (TAR, BYX). To investigate the effect of this inequality, analyses for these species were repeated after changing  $A_f$  to be equal to  $A_m$ .

The safety of each of the *MCY* and *CAY* rules was estimated, by simulation, for all combinations of the seven "species" (the five original species plus the two with modified  $A_f$ ), three values of  $h$ , and three values of  $\sigma_R$ . This makes a total of 63 species-parameter combinations. Harvesting levels for each rule are given in Table 2.

Additional simulations were carried out to investigate the effect of uncertainty in natural mortality,  $M$ . (This parameter is generally not well estimated, and errors in  $M$  will obviously have a marked effect on the safety of a harvesting rule.) For each simulation run a random value of  $M$  was generated from a distribution for which the median was equal to the assumed  $M$  value (from Table 1), and 95% of the values lay between half and double the assumed value. (Random  $M = \text{assumed } M \times \exp(X)$ , where  $X$  is a normal variate with mean 0 and standard deviation  $0.5 \log_e(2)$ .) The assumed  $M$  was used in calculating the harvesting level; the random  $M$  was used in modelling the population. Simulations were carried out with "uncertain  $M$ " for the 15 combinations of species and  $h$ . For all these simulations  $\sigma_R$  was fixed at its middle value (0.6).

### 3. Results

Typical results for simulations of harvesting with constant catch are shown in Fig. 2A. There are two target catches of interest in this figure: that for which  $P(S < 20\% S_0) = 0.1$  (the maximum safe target catch, = 3.7%  $B_0$ ), and that which maximises the mean catch (= 3.9%  $B_0$ ). If we accept the above definition of "an acceptable level of risk", then the *MCY* is the lower of these two target catches (= 3.7%  $B_0$ ). The maximum safe target catch tended to be just less than that which maximises the mean catch for  $h = 0.95$ , about equal for  $h = 0.75$ , and greater for  $h = 0.5$  (Table 3A).

Similarly, in Fig. 2B there are two target  $F$ s of interest: that for which  $P(S < 20\% S_0) = 0.1$  (the maximum safe  $F$ , = 0.13), and that which maximises the mean catch (= 0.12).  $F_{CAY}$  is the lower of these two target  $F$ s (= 0.12). The maximum safe target  $F$  was always less than that which maximises the mean catch for  $h = 0.95$ , about equal for  $h = 0.75$ , and always greater for  $h = 0.5$  (Table 3B).

For almost all species-parameter combinations the mean catch associated with the *MCY* (or *CAY*) was greater than or equal to 90% of the maximum mean catch achievable when fishing with constant catch (Table 4).

The acceptability of the rules for *MCY* and *CAY* depended most strongly on the steepness parameter,  $h$ . Thus the rules based on  $M$  ( $MCY = 0.25MB_0$ ,  $F_{CAY} = M$ ) and  $F_{0.1}$  ( $MCY = 0.25F_{0.1}B_0$  and  $F_{CAY} = F_{0.1}$ ) were almost always acceptable for  $h = 0.95$  and almost never

acceptable for  $h = 0.5$  (Figs. 3 and 4). For the *MSY*-based rules ( $MCY = 2/3MSY$ ,  $F_{CAY} = F_{MSY}$ ) the pattern was reversed, with acceptability decreasing as  $h$  increased.

The second most important characteristic for determining acceptability was species. For each value of  $h$ ,  $P(S < 20\% S_0)$  tended to vary more between species for a given  $\sigma_R$  than it did between values of  $\sigma_R$  for a given species. (Figs. 3 and 4).

Of the species life-history parameters in Table 1 the most important in determining the acceptability of a rule was natural mortality,  $M$ . For each of the 54 combinations of rule,  $h$ , and  $\sigma_R$  (six rules, three values of  $h$ , three values of  $\sigma_R$ ), the five species were ranked in increasing order of  $P(S < 20\% S_0)$ . The average of these rankings over the 54 rule-parameter combinations was (in increasing order): ORH = 2.28, TAR = 2.33, BYX = 2.73, SBW = 3.28, and HOK = 4.23. The same ordering is achieved by ranking the species by increasing  $M$  (Table 1). Thus a rule is more likely to be acceptable for species with low  $M$ .

Recruitment variability,  $\sigma_R$ , also affects acceptability, with acceptability decreasing as  $\sigma_R$  increases (Figs. 3 and 4). However, this effect is much less than that associated with steepness or species.

The two  $M$ -based rules performed approximately equally well: both  $MCY = 0.25MB_0$  and  $F_{CAY} = M$  were acceptable for 67% (30/45) of the species-parameter combinations. The  $F_{0.1}$ -based rules were also about equally acceptable ( $MCY = 0.25F_{0.1}B_0$  was acceptable for 42%, and  $F_{CAY} = F_{0.1}$  for 51% of combinations). However, the *MSY*-based rules differed markedly:  $MCY = 2/3MSY$  was acceptable for 96% of species-parameter combinations, whereas  $F_{CAY} = F_{MSY}$  was acceptable for only 40%.

The effect, for species TAR, of increasing  $A_f$  to equal  $A_m$  was to increase the maximum safe target catch and  $F$ , and also to increase the target harvesting levels that maximise mean catch. Decreasing  $A_f$  for species BYX had the opposite effect. As a result, the change made both of the  $M$ -based rules more acceptable (i.e.,  $P(S < 20\% S_0)$  decreased) for TAR, and less acceptable for BYX. However, the effect with the other rules was not so easily predictable. This is because the change in  $A_f$  caused  $F_{0.1}$ ,  $F_{MSY}$ , and  $MSY$  to increase for TAR, and decrease for BYX (Table 2). Thus, for example, the increase in  $A_f$  made TAR capable of sustaining higher fishing pressure but it also made the  $F_{0.1}$  and  $MSY$  rules require more fishing pressure. The rule catch =  $0.25F_{0.1}B_0$  became less acceptable for TAR, and both  $F_{0.1}$ -based rules became less acceptable for BYX. Otherwise, changes in the acceptability of the rules for these two species tended to be small and dependent on the values of  $h$  and  $\sigma_R$ . [Note added in proof: The value of  $A_m$  given for TAR (Table 1) is wrong and was used in error. This species typically matures at or before the age of recruitment (pers. comm. J.H. Annala). Thus, the results given here for TAR should be interpreted with caution.]

The effect of uncertainty in  $M$  was to decrease the acceptability of the harvesting rules. The probability of  $S$  falling below 20%  $S_0$  increased when, for  $M$  known precisely, it had been less than 0.5, and decreased when it had been greater than 0.5 (Fig. 5). Of the 90 species-rule-steepness combinations considered (five species, six rules, 3 values of steepness), the risk was acceptable ( $P(S < 20\% S_0) < 0.1$ ) for only 35 (39%) when  $M$  was uncertain. This compares to 57 acceptable combinations (63%), when  $M$  was assumed known exactly.

## 4. Discussion

### 4.1 Choice of Threshold

The first use of the 20%  $S_0$  threshold that I am aware of is by Beddington and Cooke (1983). They commented (p. 9) "this is not a conservative figure, but it represents a lower limit where recruitment declines might be expected to be observable". Two recent papers support the use of this value.

Thompson (1991) showed that, under certain very general assumptions, maintaining a stock at above 20% of its virgin level could be expected to protect it against collapse. He cites other authors who use the same threshold value or a range that includes 20%. Also, he found that, for a range of stocks (from the Bering Sea, Aleutian Islands, and Gulf of Alaska), the equilibrium biomass  $B_{MSY}$  associated with  $F_{MSY}$  was above 20% of virgin biomass (though he did not consider the effects of stochastic recruitment).

Clark (1991) found that "with a range of life history parameters typical of demersal fish and a range of realistic spawner-recruit relationships ... yield will be at least 75% of the maximum sustainable yield so long as the spawning biomass is maintained in the range of about 20-60% of the unfished level". He considered both Ricker and Beverton and Holt stock-recruit relationships; for the latter, the curves he considered have steepness between 0.5 and 0.8 (his parameter  $A$  is related to steepness,  $h$ , by the equation  $A = (5h-1)/(4h)$ ). Again he did not consider the effects of stochastic recruitment.

Thus both authors support the conclusion of the current study that the 20%  $S_0$  threshold is not so high as to restrict catches much below maximum sustainable levels. In addition, the former offers theoretical evidence that this threshold is high enough to prevent collapse. I conclude that my definition of an acceptable level of risk (i.e.,  $P(S < 20\% S_0) < 0.1$ ) is reasonable. Given this, we can address the question of how safe (or acceptable) are the six harvesting rules listed in Table 2.

### 4.2 Acceptability of Rules

The answer depends strongly on the steepness,  $h$ , of the stock-recruit relationship, less strongly on natural mortality,  $M$ , and least strongly on recruitment variability,  $\sigma_R$  (Figs. 3 and 4). This confirms the finding of Getz et al. (1987) that "the most important source of uncertainty in estimating long-term productivity of a fishery is the degree of density-dependence in the stock-recruitment relationship and not the environmental factors that influence annual recruitment rates". For  $M$  and  $\sigma_R$ , acceptability decreases as the parameter increases. This is also true for steepness with the  $M$ -based and  $F_{0.1}$ -based rules, but the opposite holds for the  $MSY$ -based rules. Uncertainty in  $M$  decreases acceptability (Fig. 5). The effect of a mismatch between the ages of recruitment and maturity depends on the rule.

### 4.3 Calculation of $MCY$ and $CAY$

$MCY$  and  $CAY$  values calculated using the above definition of an acceptable level of risk depend strongly on the steepness parameter, and less strongly on recruitment variability (Fig. 6).

Thus, to use the approach described here to estimate  $MCY$  or  $CAY$  for New Zealand species it is important to have estimates of these two parameters. For the latter, the compilation of Beddington

and Cooke (1983, table 2) may be useful in providing estimates for similar species. The steepness parameter is more difficult.

#### 4.4 Choice of Steepness

No data exist to estimate this parameter for New Zealand species. Though there are many published stock-recruit data sets for species in other countries, these do not appear to be useful in providing likely steepness values for New Zealand species. In most cases  $B_0$  is not known, and time series are often too short and too noisy, for any meaningful curve-fitting. Also, the estimates of stock size and recruitment that make up the data sets (often derived from virtual population analysis) tend to be biased, correlated, and autocorrelated.

It is important to note that the present population model includes only one compensatory mechanism: a convex stock-recruit relationship. Other mechanisms by which a population might compensate for the effect of fishing include: increased growth rate, earlier maturity, increased fecundity, and reduced natural mortality during some life stages. Thus, the steepness parameter should be seen as a simple proxy for a range of compensatory mechanisms. In this sense it may be thought of as representing the resilience of a population under fishing. High steepness implies high resilience.

Given the lack of useful data, a reasonable approach to the problem of choosing a steepness value would be to decide on a plausible range of values and pick the mid point as a default.

Since  $F = M$  is widely considered to be a conservative harvesting policy, it is tempting to use the results of these simulations to conclude that, for most species, steepness is unlikely to be as low as 0.5 (elasmobranchs, with their low fecundity, are possible exceptions). For  $h = 0.5$  even  $F = 0.8M$ , the more conservative rule proposed by Thompson (1991), was unsafe for 52% (11/21) of species-parameter combinations. Clark (1991) used a similar argument to suggest that 0.5 is a lower bound for steepness.

The highest value used here - 0.95 - must be considered an upper limit. (It is almost tantamount to assuming no relationship between stock and recruitment.)

Thus a value of 0.75 - about midway between 0.5 and 0.95 - would appear to be a reasonable default steepness. It is also close to the value of 0.69, which, until recently, was a commonly accepted default value on the west coast of the U.S.A. (W.G. Clark, pers. comm.; a steepness of 0.69 means that recruitment is 90% of its virgin level when the stock is at 50% of its virgin level.)

It may be that 0.95 is too high as an upper bound. Clark (1991) considered the plausible range to be 0.5 to 0.8 (so the mid-point of his range is 0.65). He argued that, with the life history parameters of his "typical demersal fish", even a steepness of 0.89 (his  $A = 0.969$ ) is too extreme because it implies that a population could sustain fishing at  $F = 1$  with "hardly any ill effect". By this he appears to mean that the equilibrium recruitment at this level of fishing (in a deterministic model) is not much lower than the virgin recruitment. However, for all the species-parameter combinations considered here this fishing mortality drives the stock biomass to extremely low levels (and I suspect this would be true for his "typical demersal fish"). At such levels one might expect a stock-recruit relationship to break down so the inference of "hardly any ill effect" may not be tenable.



What is clear is that a value of 0.95, which has been used in a number of New Zealand stock assessments, is at the least conservative extreme of possible values. For this reason it should no longer be used as a default value unless (or until) data supporting its use are available.

#### 4.5 *MCY* for Depressed Stocks

The *MCY* depends, by definition, on the current state of the stock. This has not been taken into account in the above simulations. As long as the current spawning biomass ( $S$ ) is above 20% of its mean virgin level ( $S_0$ ) the *MCY* calculated using these simulations should be safely sustainable. However, if  $S$  is substantially below 20%  $S_0$  then it certainly will not be. Thus, when a stock is depressed, the *MCY* should be less than the value calculated by these simulations. However, the results given here do not tell us how much less.

Until this issue has been addressed through further simulations a reasonable (though arbitrary) procedure would be to scale the *MCY* down linearly according to how far the current  $S$  is below 20%  $S_0$ .

Thus, when  $S < 20\% S_0$

$$MCY = MCY'S/(0.2S_0)$$

where *MCY'* is the maximum safe constant yield calculated according to the above simulations.

#### 4.6 Further Work

The simulations presented here are a first step in the process of defining what is meant by "an acceptable level of risk", and thus proposing methods of calculating *MCY* and *CAY* that go beyond the rules of Section 2.1. In this section I discuss some technical problems that lie in the path of further work in this direction.

Underlying the definition of acceptable risk proposed here is the tacit assumption that fishing with constant catch, or constant  $F$ , leads eventually to a (dynamic) equilibrium. That is, after an initial settling-down period, the population biomass will fluctuate around some central value in a stable way. It is assumed that the initialisation procedure of Section 2.3 (including the first  $A_l$  years of each model run) adequately covers the settling-down period. Further, it is assumed that the results of the simulations are independent of the length of the model run after the initialisation period. It is this latter assumption that allows us to avoid any mention of a time period in the definition of acceptable risk.

These assumptions appear to be reasonably sound for the constant  $F$  simulations and for the constant catch simulations with low target catch levels. However, as the target catch rises the second assumption starts to break down. For high enough target catch it seems clear that, given a long enough time period, the population will always crash (be reduced to close to zero). Thus, the proportion of years in which  $S < 20\% S_0$  for high target catch levels will depend on the time period chosen.

More simulation work is needed to determine how serious a problem this is. It may be desirable to include a time period in the definition of acceptable risk, though the time period would probably depend on the biology of the species. With short time periods the initialisation procedure becomes

more important. The inclusion of a time period would also avoid the need for the ad hoc procedure of Section 4.5.

Another possible refinement to the definition of acceptable risk would involve considering not just whether  $S$  falls below the 20%  $S_0$  threshold, but by how much. Thus,  $S = 10\% S_0$  would be treated as more serious than  $S = 19\% S_0$ . Though this approach has intuitive appeal there are problems in implementing it. There is no obvious way to decide on relative weightings: i.e., how much more serious is  $S = 10\% S_0$  than  $S = 19\% S_0$ . Thus, this refinement involves introducing a further arbitrary element into the definition of risk. This could be acceptable if it were shown that the new definition performed significantly differently from the old. This remains to be shown.

An obvious extension to the work presented here would be to use a different stock-recruit relationship. In particular, it is of interest to see the effect of a domed relationship, like Ricker's for example. A difficulty here is that domed relationships can induce cyclic behaviour (Fig. 7). Thus,  $P(S < 20\% S_0)$  will depend on the phase and frequency of the cycle and the length of the simulation period.

#### 4.7 Other Comments

The greatest area of uncertainty in stock-recruit relationships is what happens at low stock levels. Thus, predictions based on the above simulations become increasingly uncertain as harvest levels rise (and biomass declines). For this reason the right-most parts of both graphs in Fig. 2 must not be taken too literally. If, as Thompson (1991) suggests, the stock-recruit relationship were to become depensatory (concave upwards) at low stock levels, the right-hand parts of these graphs would be quite different. However, the *MCY* and *CAY* results presented here will be approximately correct as long as the Beverton and Holt relationship is reasonably accurate for stock sizes above about 20%  $S_0$ . Thus, we might think of the assumed stock-recruit relationships as being like Fig. 8B rather than Fig. 8A.

The simulations presented here are supposed to represent an idealised situation, rather than describe what might happen in a real fishery. In a real fishery where a constant  $F$  rule is applied, the annual biomass estimates will certainly be serially correlated and probably biased. For most fisheries there will be a limit to the proportion of the recruited biomass that can be caught in any one year (no such limit was assumed here). Also, harvesting rules are never followed exactly for long. Fishing industry viability, improved knowledge of the fish biology, and changes in the perception of the stock status are some of the factors that often cause rules to be modified (e.g., the change in eastern Canada from  $F_{0.1}$  to the "50% rule" (Rivard 1992)). This study is aimed at helping managers (and their advisers) to make such modifications by showing what might happen in the hypothetical case where a harvesting rule was applied rigidly for many years.

It is important to note that the values of the probability  $P(S < 20\% S_0)$  in Figs 3 and 4 were obtained by integrating over both the  $A_t$  years in each simulation run, and the 500 simulation runs. Thus, to take an extreme example, an estimated probability of 0.1 could arise from the case where  $S < 20\% S_0$  exactly 10% of the time for all 500 runs, or from the case where  $S$  was always  $< 20\% S_0$  for 50 runs and always  $> 20\% S_0$  for the other 450 runs. Simulations with constant  $F$  and  $M$  known exactly tend to produce results closer to the former extreme; those with constant catch or uncertain  $M$  gave results closer to the latter.

The simulation procedure and definition of risk used here are superficially similar to those of Beddington and Cook (1983). However, there are several important differences. They used only

a steepness of 1; they simulated only the 20-year period starting from a virgin population; they measured the proportion of runs (rather than the proportion of years) in which  $S$  fell below 20%  $S_0$ ; and they included no biomass estimation error.

## 5. Conclusions

I conclude that the definition of acceptable risk presented here is appropriate for the calculation of *MCY* and *CAY*. The advantages of adopting this definition are:

- it allows us to avoid the use of the rules of Section 2.1, which have been shown to perform poorly for some combinations of parameters (Figs. 3 and 4).
- it is based on the threshold 20%  $S_0$ , which, though arbitrary, has gained some measure of international acceptance.
- it has been shown here not to be excessively conservative (Table 4), and there is some theoretical support that it is not too liberal (Thompson 1991), and
- it has a minimum of arbitrary elements (i.e., it lacks the arbitrary time period and weighting of the alternatives described in Section 4.6).

Some disadvantages are:

- it does not work for calculating *MCY* when the stock is depressed, so the ad hoc procedure of Section 4.5 is necessary, and
- it has little empirical support.

I also conclude that it is unsafe to use a default value of 0.95 for the steepness of the Beverton and Holt stock-recruit relationship, since this is likely to be at the least conservative end of the range of likely values for this parameter.

## 6. Recommendations

I recommend that:

1. In calculations of *MCY* and *CAY*, the following definition should be adopted: the risk associated with a level of yield is acceptable if fishing at that level is expected to maintain the spawning biomass above 20% of its mean virgin level at least 90% of the time (note that this definition is solely for the "strategic" calculations of *MCY* and *CAY*; different definitions are likely to be appropriate for use in the "tactical" calculations of risk or decision analyses);
2. Where possible, *MCY* and *CAY* should be calculated using simulations similar to those described here rather than the rules of Section 2.1;
3. When a stock is depressed (spawning biomass < 20% of its mean virgin level) the *MCY* should be scaled down using the method described in Section 4.5;
4. In teleost population models using the Beverton and Holt stock-recruit relationship a default steepness of 0.75 should be used when there are insufficient data to indicate a different value

(lower steepness values are likely to be appropriate for elasmobranchs). A steepness of 0.95 (widely used in past assessments) is at the least conservative extreme of the range of possible values.

### **Acknowledgements**

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**Appendix: Sources for data in Table 1 and Figure 1**

The following references give the sources for the growth, mortality, length-weight, recruitment, and maturity parameter values in Table 1 and maturity and growth parameters in Fig. 1.

<b>Species</b>	<b>Code</b>	<b>Area</b>	<b>Reference</b>
Orange roughy	ORH	Chatham Rise	Francis and Robertson (1991)
Tarakihi <sup>1</sup>	TAR	East coast, South Is.	Annala et al. (1990)
Alfonsino	BYX	East coast, North Is.	Stocker and Blackwell (1991)
Southern Blue whiting	SBW	Sth Campbell Plateau	Hanchet (1991)
Hoki	HOK	West coast South Is.	Sullivan (1991)
Black oreo	BOE	Chatham Rise	McMillan <sup>2</sup> and Hart (1991)
Smooth oreo	SSO		
Snapper	SNA	Hauraki Gulf	Annala (1992)
Jack mackerels	JMN,JMD	Central west coast	Horn (1991)
Bluenose	BNS	West coast North Is.	Ryan and Stocker (1991)

<sup>1</sup> The age at maturity,  $A_m$  used for this species does not come from the given reference. *See* note, p.6.

<sup>2</sup> Natural mortality values for BOE and SSO are assumed to be similar to that for ORH (pers. comm., P.J. McMillan).

Table 1. Scientific names, species codes, and life history parameters for the five species used in the simulations. Full definitions of the life history parameters are given in Francis (1992) and, for  $S_f$  and  $S_m$ , in Francis and Robertson (1991). ( $A_{max}$  is the number of age classes in the population model, not the maximum age.)

	Orange roughy	Tarakihi		Alfonsino		Southern blue whiting		Hoki	
	<i>Hoplostethus atlanticus</i>	<i>Nemadactylus macropterus</i>		<i>Beryx splendens</i>		<i>Micromesistius australis</i>		<i>Macruronus novaezealandiae</i>	
		Male	Female	Male	Female	Male	Female	Male	Female
Sp. code	ORH	TAR		BYX		SBW		HOK	
$L_\infty$ (cm)	42.5	42.1	44.6	51.1	57.5	47.6	51.5	90.3	97.6
$K$ (yr <sup>-1</sup> )	0.059	0.21	0.20	0.11	0.08	0.35	0.32	0.24	0.21
$t_0$ (yr)	-0.35	-1.4	-1.1	-3.6	-4.1	-0.9	-1.0	-0.6	-0.9
$M$ (yr <sup>-1</sup> )	0.05	0.10		0.20		0.21		0.30	0.25
$a^1$	9.63	4.33	4.00	2.26		0.52	0.41	0.60	
$b$	2.68	2.77	2.79	3.02		3.09	3.15	2.85	
$A_f$ (yr)	23	3		5		3	4	5	
$S_f$ (yr)	3	1		0		1	1	1	
$A_m$ (yr)	23	4		4		3	4	5	
$S_m$ (yr)	3	0		0		1	1	1	
$A_{max}$ (yr)	70	20		50		25		20	

<sup>1</sup> weight(kg) =  $a[\text{length}(\text{cm})]^b \times 10^{-5}$



Table 2. Harvesting levels for each species for: A. the *MCY* rules (target catch expressed as a percentage of  $B_0$ ); and B. the *CAY* rules (target fishing mortality in units  $\text{yr}^{-1}$ ). (Full species names and life-history parameters are in Table 1. Parameters for *TAR'* and *BYX'* are the same as for *TAR* and *BYX* except that  $A_f$  has been set equal to  $A_m$ .)

Rule	Stock-recruit steepness, $h$	ORH	TAR	TAR'	BYX	BYX'	SBW	HOK
A. <i>MCY</i> rules								
catch = $0.25MB_0$		1.3	2.5	2.5	5.0	5.0	5.3	6.9
catch = $0.25F_{0.1}B_0$		1.8	2.8	3.3	5.5	5.0	7.5	9.5
catch = $2/3MSY$	0.95	1.8	2.9	3.2	5.8	5.1	7.6	9.5
	0.75	1.4	2.3	2.5	4.4	3.9	5.7	6.9
	0.50	0.87	1.5	1.7	2.9	2.5	3.7	4.3
B. <i>CAY</i> rules								
$F_{CAY} = M$		0.05	0.10	0.10	0.20	0.20	0.21	0.28
$F_{CAY} = F_{0.1}$		0.073	0.11	0.13	0.22	0.20	0.30	0.38
$F_{CAY} = F_{MSY}$	0.95	0.20	0.21	0.27	0.86	0.46	0.78	1.00
	0.75	0.082	0.12	0.14	0.29	0.21	0.34	0.40
	0.50	0.038	0.062	0.071	0.13	0.10	0.16	0.18

Table 3. Maximum safe harvesting level expressed as a percentage of the harvesting level that maximizes mean catch: A. harvesting with constant catch; B. harvesting with constant fishing mortality. ("safe" means that the probability that the spawning biomass will fall below 20% of its mean virgin level is less than 10%).

Stock-recruit steepness, $h$	Recruitment variability, $\sigma_R$	Species						
		ORH	TAR	TAR'	BYX	BYX'	SBW	HOK
A. Constant catch								
0.95	0.4	94	101	97	55	98	98	96
0.95	0.6	92	98	93	51	93	91	91
0.95	0.8	88	93	88	45	87	84	84
0.75	0.4	100	104	104	101	104	98	94
0.75	0.6	98	100	103	95	102	93	91
0.75	0.8	96	95	100	88	96	89	86
0.50	0.4	100	102	104	102	102	103	102
0.50	0.6	101	100	102	101	102	99	103
0.50	0.8	102	98	95	96	97	91	99
B. Constant $F$								
0.95	0.4	57	83	78	49	61	55	45
0.95	0.6	54	77	71	43	55	48	40
0.95	0.8	50	70	64	39	50	42	35
0.75	0.4	110	115	114	106	104	100	93
0.75	0.6	104	108	106	92	94	89	82
0.75	0.8	96	99	95	82	84	78	72
0.50	0.4	140	135	136	134	131	129	127
0.50	0.6	138	128	126	122	118	116	115
0.50	0.8	129	117	115	109	106	102	100



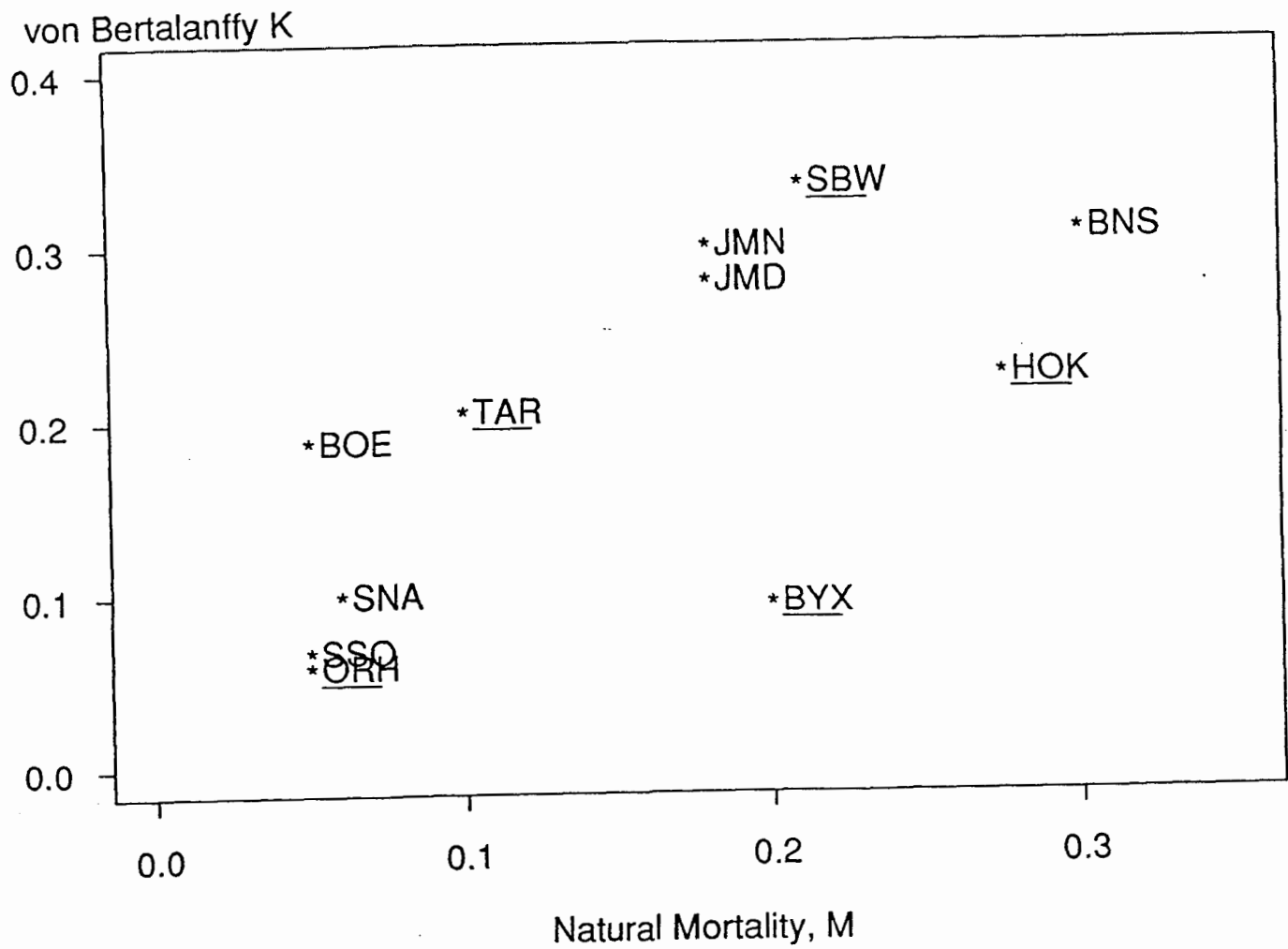


Fig. 1. Natural mortality and von Bertalanffy  $K$  for eleven New Zealand fish species. Those species used in the simulations are underlined.

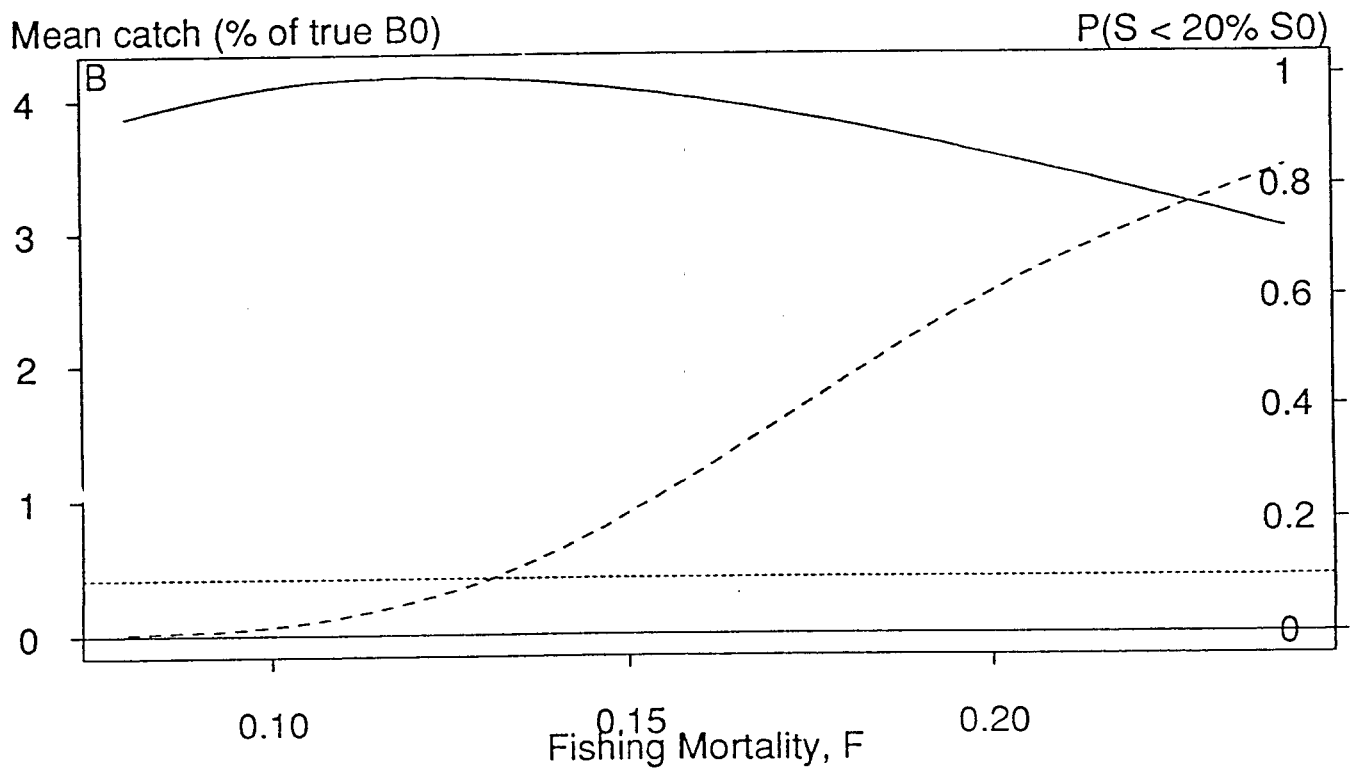
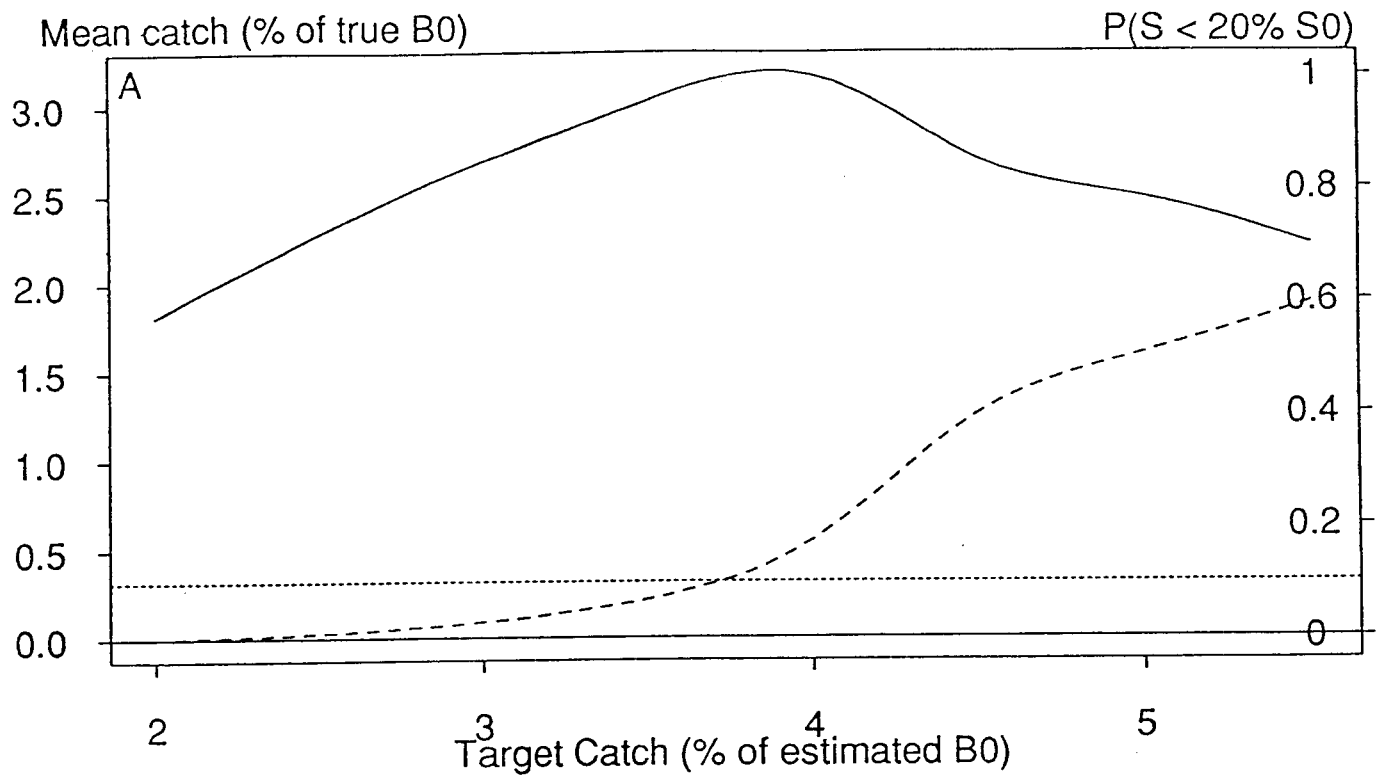


Fig. 2. Mean catch (solid line) and  $P(S < 20\% S_0)$  (broken line) for species BYX with  $h = 0.5$  and  $\sigma_R = 0.8$ , harvested at a range of fishing intensities: A. with constant catch; B. with constant fishing mortality,  $F$ .

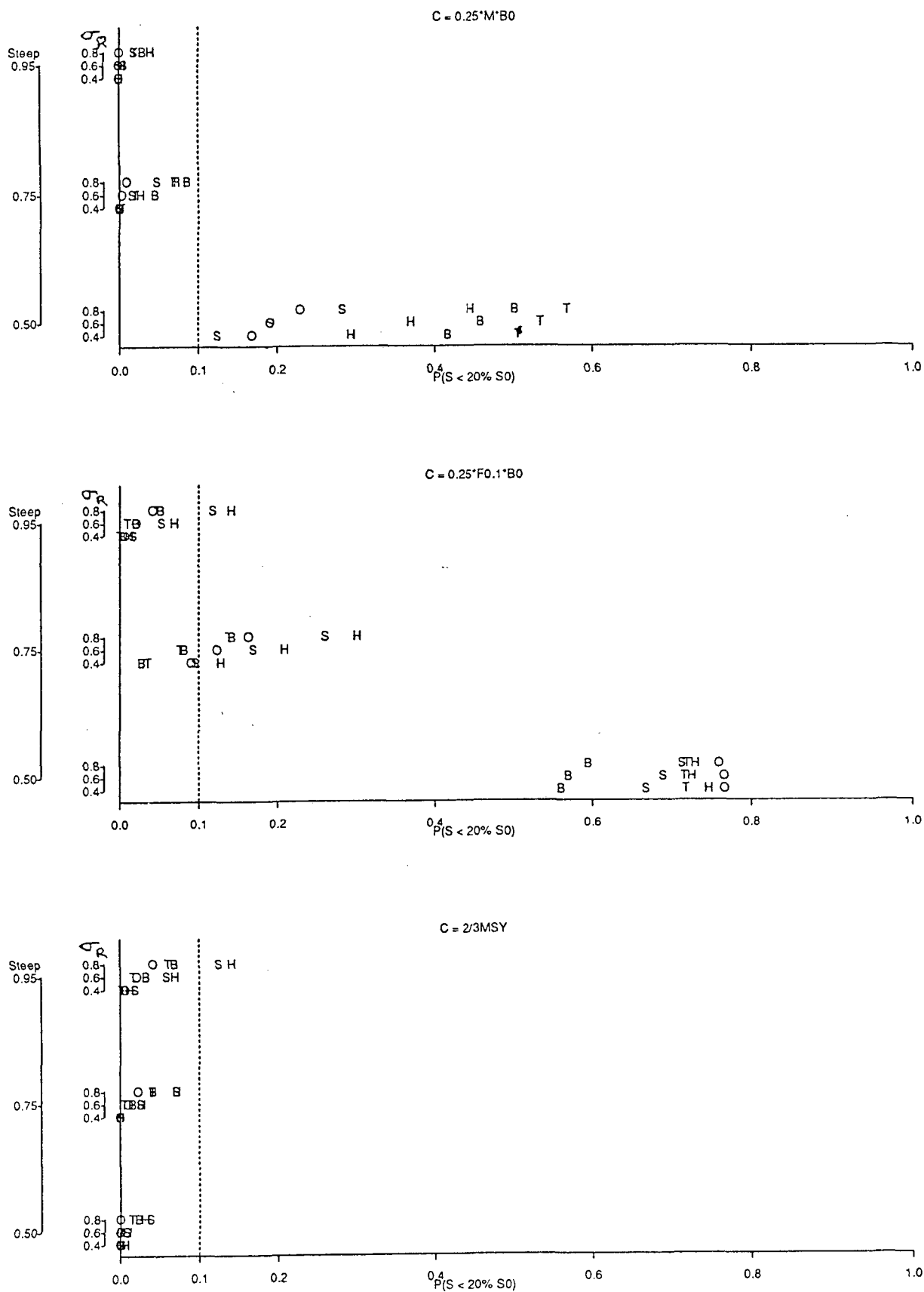


Fig. 3. The safety (or acceptability) of the three MCY rules of Table 2, as measured by the probability that the spawning biomass,  $S$ , falls below 20% of its mean virgin level. Levels of this probability below 0.1 are considered acceptable. Results are presented for three levels of stock-recruit steepness,  $h$ , three levels of recruitment variability  $\sigma_R$ , and five species. Plotting symbols represent species as follows: O = ORH, T = TAR, B = BYX, S = SBW, H = HOK (full species names and life-history parameters are given in Table 1).

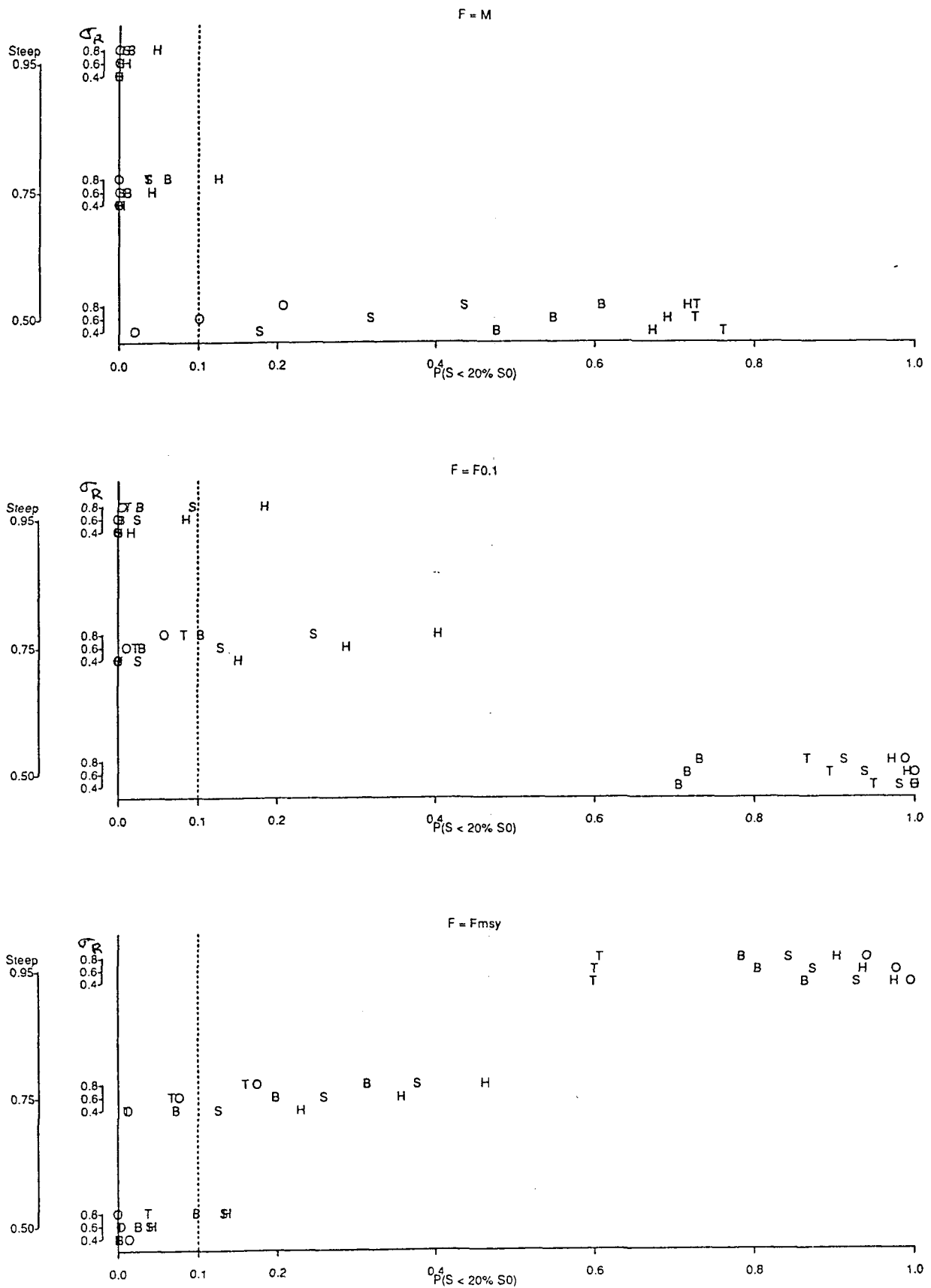


Fig. 4. The safety (or acceptability) of the three CAY rules of Table 2, as measured by the probability that the spawning biomass,  $S$ , falls below 20% of its mean virgin level. Levels of this probability below 0.1 are considered acceptable. Results are presented for three levels of stock-recruit steepness,  $h$ , three levels of recruitment variability  $\sigma_R$ , and five species. Plotting symbols represent species as follows: O = ORH, T = TAR, B = BYX, S = SBW, H = HOK (full species names and life-history parameters are given in Table 1).

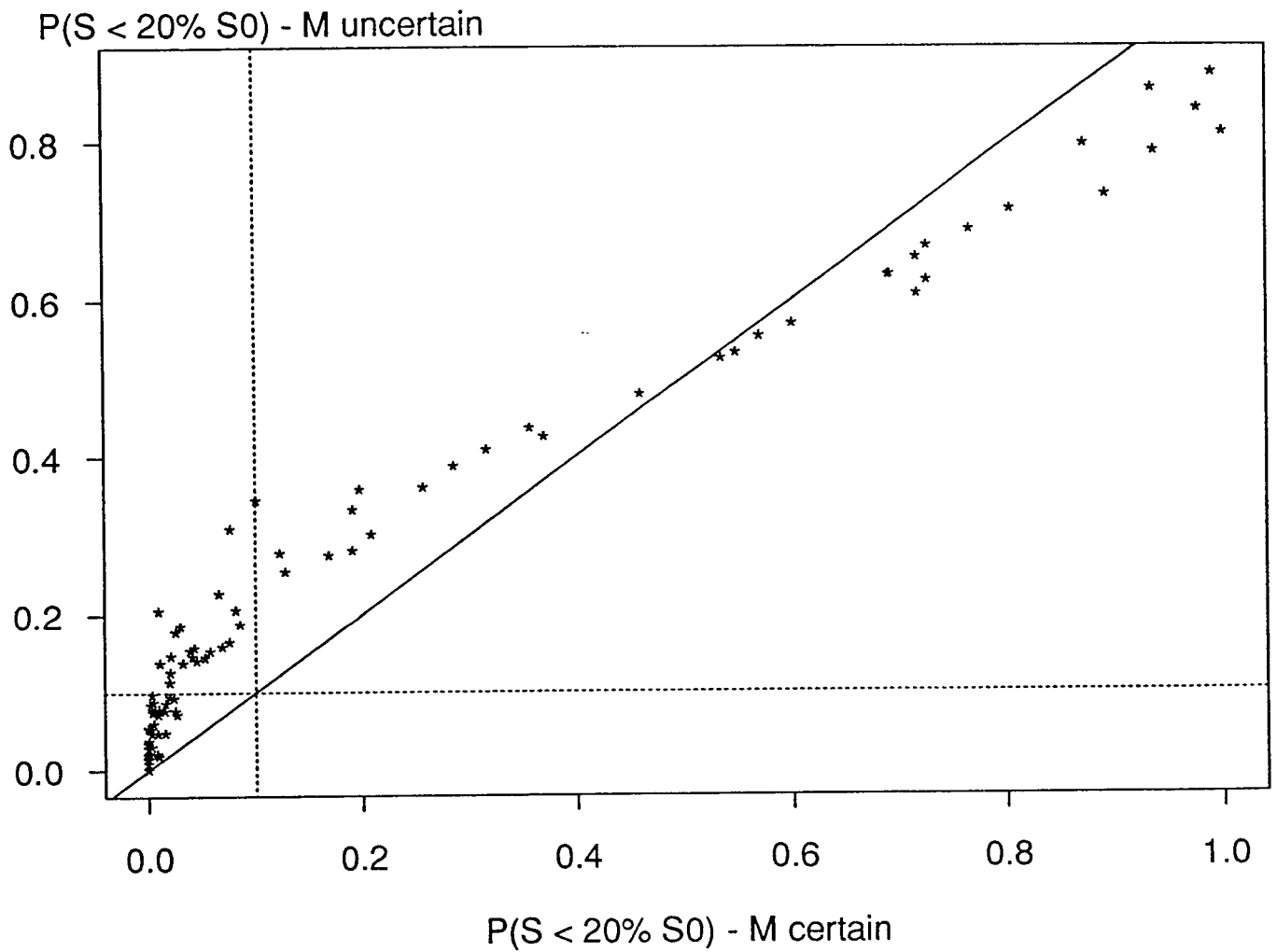


Fig. 5. The effect of uncertainty in natural mortality,  $M$ , on the risk associated with the harvesting rules. Each point in the plot represents a species-rule-parameter combination (five species, six rules, three values of stock-recruit steepness). The probability of the spawning biomass,  $S$ , falling below 20% of its mean virgin level,  $S_0$ , is plotted on both axes: x-axis, when  $M$  is assumed known exactly, y-axis, when  $M$  is uncertain. The diagonal line is  $y = x$ ; the dotted lines mark the threshold between acceptable and unacceptable risk.



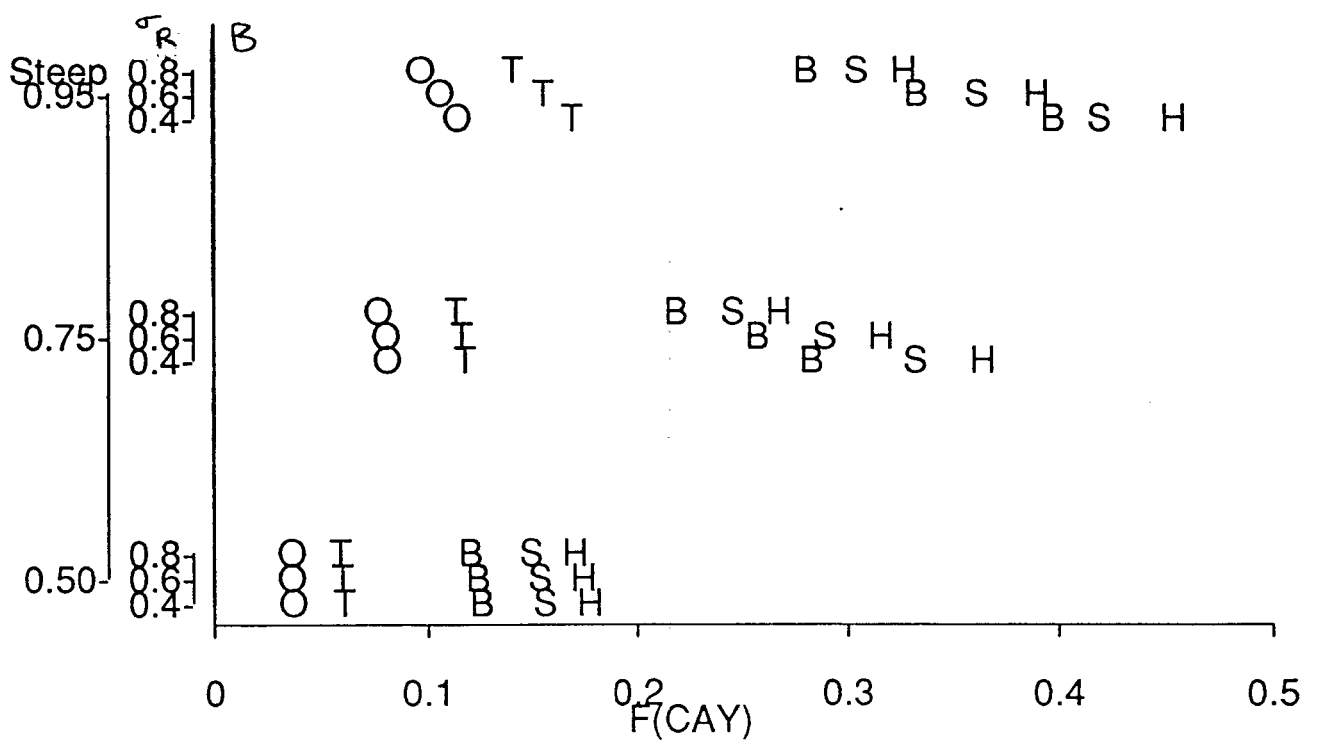
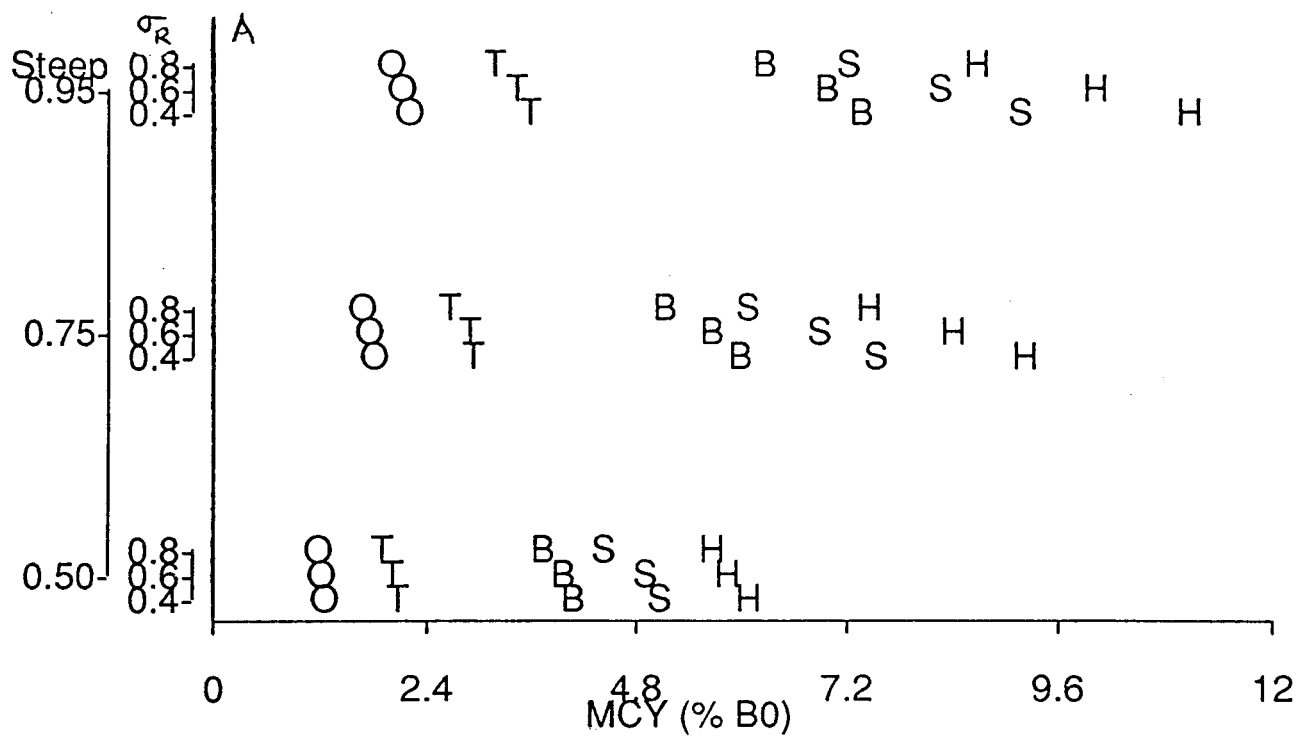


Fig. 6. Estimates of A,  $MCY$ , and B,  $F_{CAY}$ , for three levels of stock-recruit steepness, three levels of recruitment variability  $\sigma_R$ , and five species. Plotting symbols are as in Figs. 3 and 4.

Mean biomass (%B0)

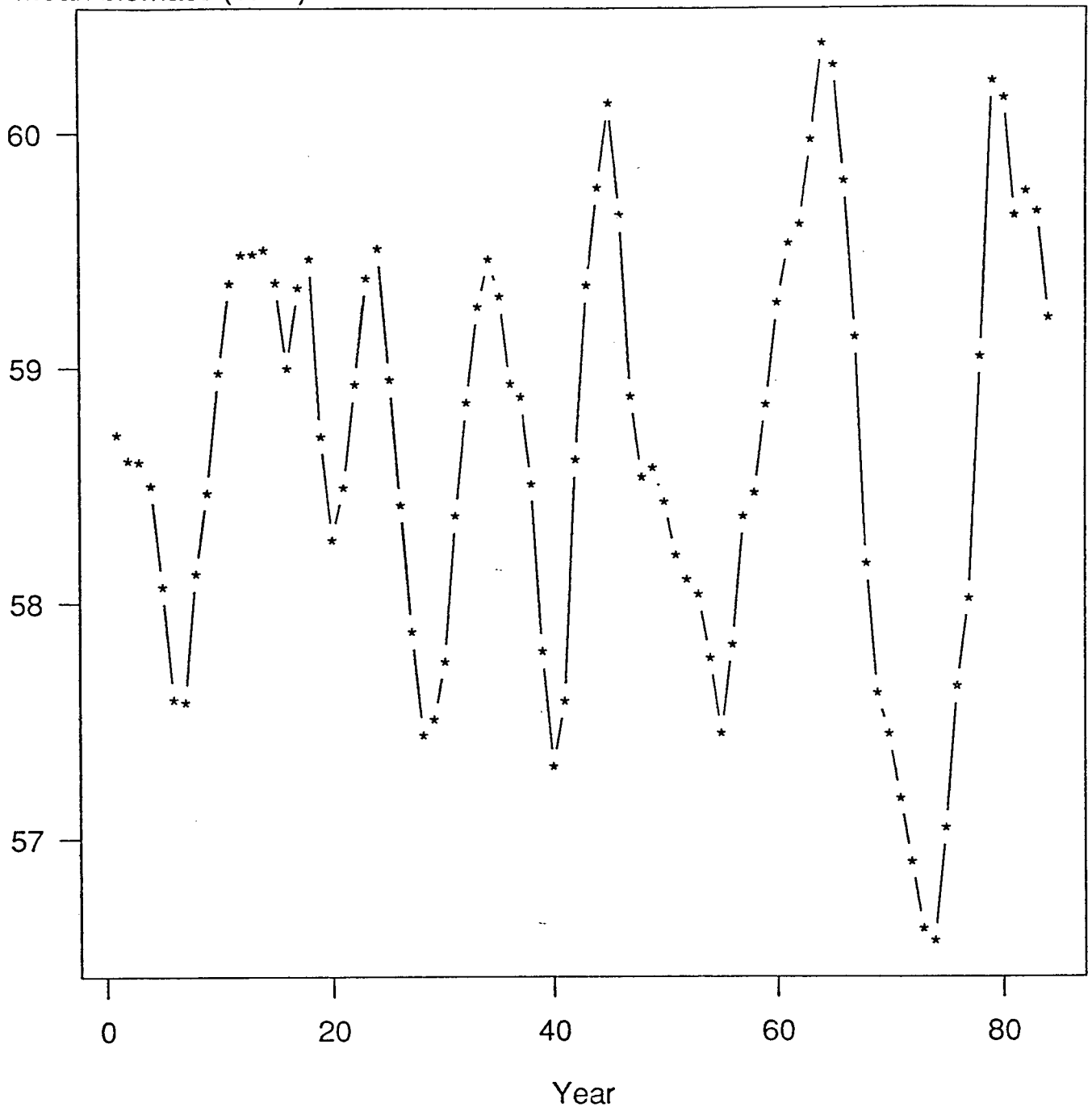


Fig. 7. Example of the cyclic behaviour of fish-population models with a Ricker stock-recruit curve. The graph shows the mean mid-year biomass (averaged over 500 replicate runs) over an 84-year period of fishing with constant  $F = 0.36$  for southern blue whiting. The Ricker curve used was  $R/R_0 = (S/S_0) \exp [3(1-S/S_0)]$ .

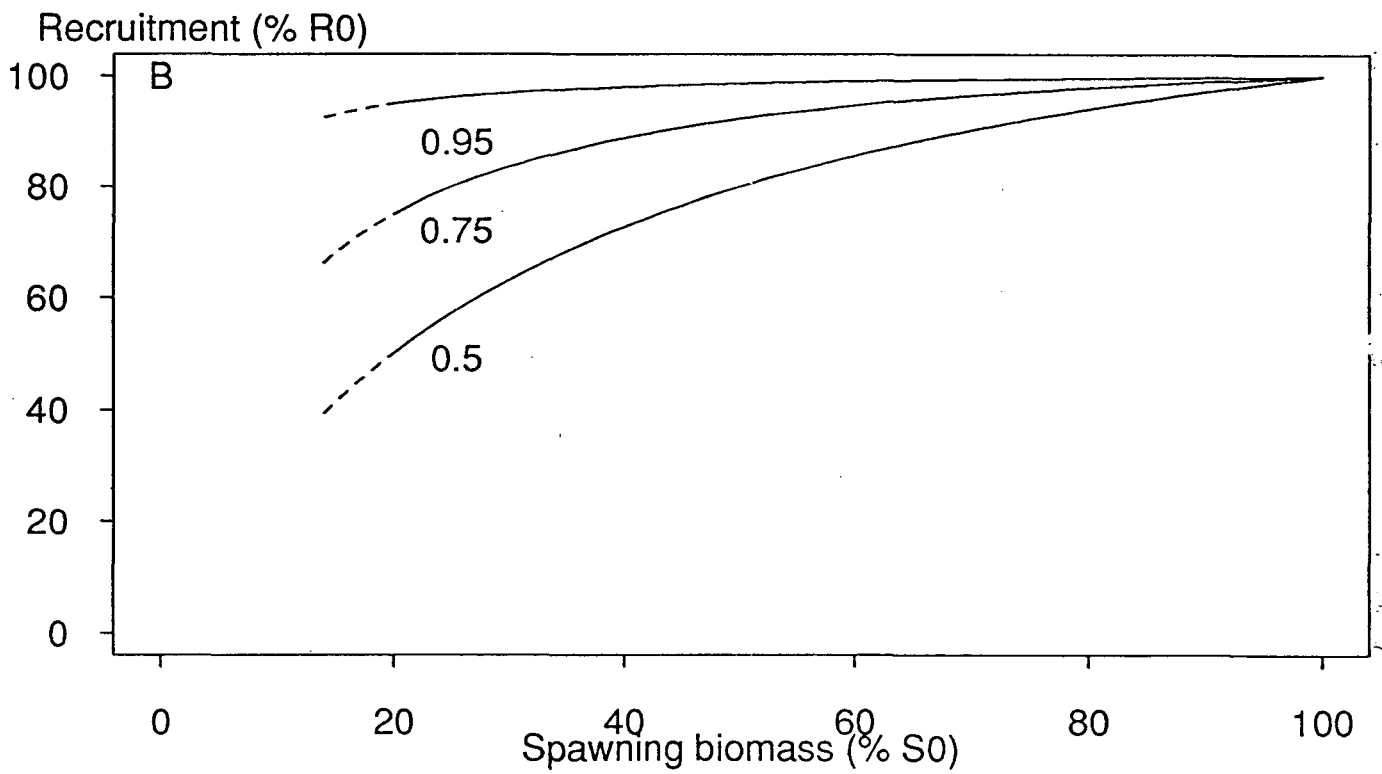
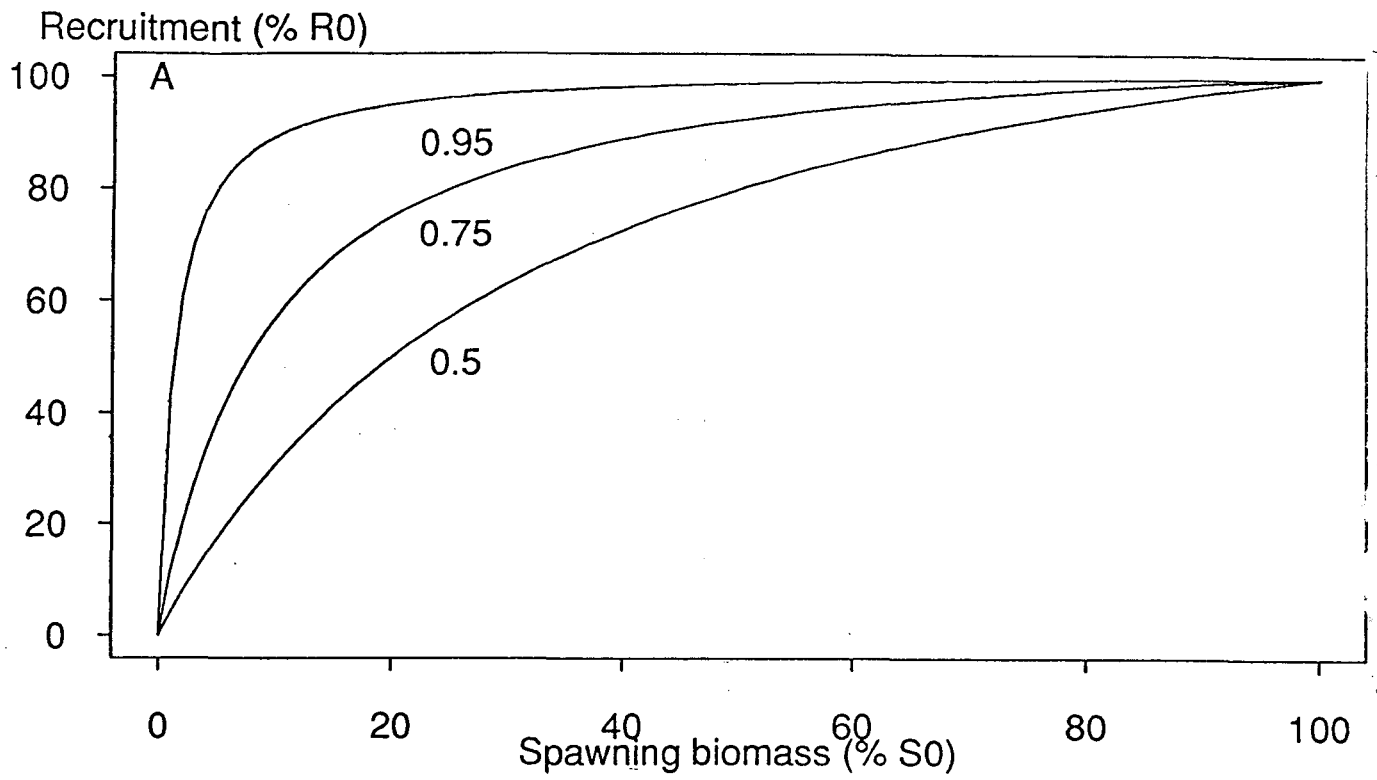


Fig. 8. The Beverton and Holt stock-recruit relationship for three values of steepness (0.5, 0.75, and 0.95): A, as described, literally, in the model; B, as effectively used in calculating *MCY* and *CAY*.