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Risk Analysis in Fishery Management

R. I. C. C. Francis
Fisheries Research Centre, P. O. Box 297
Wellington, New Zealand

Abstract

Risk analysis is shown to be a useful means of expressing, in advice to fishery managers, the extent of uncertainty in stock assessments. When applied to the evaluation of alternative management strategies for specific fisheries this technique allows the presentation of the major conclusions in a single graph; alternative approaches tend to lead to several graphs, none of which express the inherent risk. It also provides a means of evaluating management rules of thumb (e.g. target constant catch level of two-thirds the deterministic maximum sustainable yield, or a constant target fishing mortality of $F_{0.1}$), although the question of what is an acceptable level of risk remains to be resolved. The technique is discussed in the context of, and illustrated with examples from, New Zealand's system of fishery management using individual transferable quotas.

Introduction

There is always some uncertainty associated with advice provided by stock assessment scientists to fishery managers. In New Zealand this uncertainty has usually been expressed in the form of confidence intervals (e.g. the optimum yield may be given as 5,000 ± 1,500 tons), or graphs showing likely outcomes of various management strategies under alternative scenarios (e.g. showing what might happen according to 'optimistic', 'best guess', and 'pessimistic' assumptions about the present status of the stock).

In this paper an alternative way is discussed of expressing uncertainty. This is in terms of risk to the fishery. Risk may be defined, in this context, as the probability of 'something bad' occurring within a given time period. This definition provokes four questions:

"What is the best definition of 'something bad'?",

"What is an appropriate time period?";

"What is an acceptable level of risk?";

"How should risk be calculated?".

Two examples are used to illustrate some possible answers to these questions. The first is a completed analysis involving the evaluation of alternative management strategies for a specific fishery. The second is work in progress that is aimed towards the quantification of the risk associated with two rules of thumb used in New Zealand for calculating reference yield levels.

In what follows 'biomass' always refers to recruited biomass which, for both examples, is the same as spawning biomass.

The Problems

First example. New Zealand's major fishery for orange roughy (*Hoplostethus atlanticus*) takes place on the Chatham Rise, to the east of the South Island (quota management area 3B). In 1990 the main problem facing the managers of this stock was how fast the total allowable catch (TAC) should be reduced from its 1990 level of 28,787 tons to a proposed 'safe' level of 7,500 tons. Too fast a reduction would pose severe restructuring problems for the fishing industry; too slow a reduction could cause a collapse of the fishery.

Most of the uncertainty about the current status of the stock was restricted to two parameters: the virgin (1978) stock size, B_0, and natural mortality, M. B_0 was estimated, for each of a range of possible values of M, from a series of relative biomass estimates derived from random trawl surveys. The stock reduction technique used (Francis, MS 1990) expressed the uncertainty in the estimates of B_0 in the form of probability distributions (Fig. 1). The third element of uncertainty to be considered in the risk analysis was future recruitment to the fishery.

The problem was to evaluate the risk associated with a previously agreed strategy (reducing the TAC by 5,000 tons/year), and to compare this with the risks associated with alternative rates of reduction: 3,000, 7,000, 9,000 and 12,000 tons/year.

Second example. Most of New Zealand's marine fisheries are managed by individual transferable quotas. The main management tool is thus a TAC for each stock. In assessing stocks, fishery scientists compare the TAC for each stock with two reference yields

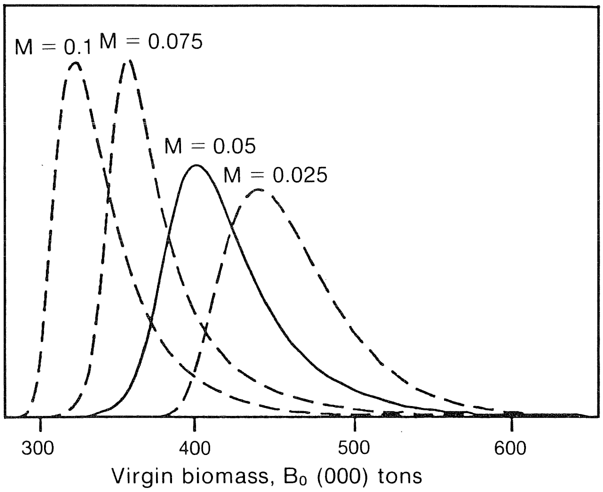

Fig. 1. Uncertainty in virgin biomass, B_0, of area 3B orange roughy for four possible values of natural mortality, M (0.05 is considered the most likely value). Each curve is a probability distribution: the higher the curve, the more likely the corresponding value of B_0 is.

(where they can be calculated). These are defined as follows:

1) The maximum constant yield (MCY) is the maximum constant catch that is estimated to be sustainable, with an acceptable level of risk, at all probable future levels of biomass;

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

Note that both definitions include reference to 'an acceptable level of risk'. Because insufficient data are available to allow a meaningful quantification of risk for most stocks, rules of thumb have been developed which are thought, judging by experience and analyses from other parts of the world (Mace, MS 1988), to be reasonably safe, i.e. to involve an acceptable level of risk.

Two of these rules of thumb are, MCY = 2/3 MSY and $F_{ref} = F_{0.1}$, where MSY is the (deterministic) maximum sustainable yield, and $F_{0.1}$ is the instantaneous fishing mortality for which the slope of the yield-per-recruit curve is 0.1 times the slope at F = 0. The problem here is to devise a method of evaluating the risks associated with these rules of thumb.

Two New Zealand species are used here to illustrate the approach. Hoki (*Macruronus novaezelandiae*) has moderately high productivity (with M = 0.2 to 0.3) and reaches maturity (when it enters the fishery) at age 5. (These values, and the growth and length-weight parameters used, are actually those estimated for female hoki. The corresponding parameters for male hoki are slightly different. To avoid the unnecessary complexity of two sets of parameters in an initial investigation, only the female values were used). The other species was, as referred above, orange roughy: a very low productivity fish (M = 0.05) with a long juvenile phase (age at maturity, and recruitment, = 23).

From a comparison with data from related species (Beddington and Cooke, 1983; table 2) hoki was judged to have medium to high recruitment variability (standard deviation of $\log_e$(recruitment), $\sigma = 0.6$–1.0). Simulations of an unfished stock show this corresponds to fluctuations about a mean virgin biomass from ± 25% (for σ = 0.6) to ±50% (for σ = 1.0) (Fig. 2). Juvenile surveys (Francis and Robertson, MS 1990) suggest high recruitment variability for orange roughy ($\sigma = 1$ is used here).

The Solutions

For both examples the method of calculating risk was broadly the same. A stochastic age-structured population model was used to simulate, over a given time period, the effect of a given management strategy on the fishery. The simulation was run a large number of times and the risk was then calculated as the proportion of the simulation runs in which 'something bad' happened to the fishery. Uncertainties concerning life history parameters, or the current state of the stock, were incorporated as stochastic elements in the model. Expected recruitment was calculated from the Beverton and Holt stock-recruitment equation (Beverton and Holt, 1957) and, where recruitment was stochastic, it was assumed to follow a lognormal distribution. For both examples a 'steepness' of 0.95 was assumed for the stock-recruitment relationship (this means that the expected recruitment falls to 95% of the virgin recruitment when the spawning biomass falls to 20% of its virgin value).

First example. Full details of this risk analysis are given by Francis and Robertson (MS 1990). In the present paper only detail sufficient to illustrate the technique is given. (For simplicity, only the case where future TAC overrun is assumed to be 30% is presented here).

'Something bad' was taken to be the biomass falling so low that the TAC could not be caught (assuming a maximum instantaneous fishing mortality of F = 1 yr^{-1}). The time period used was 5 years.

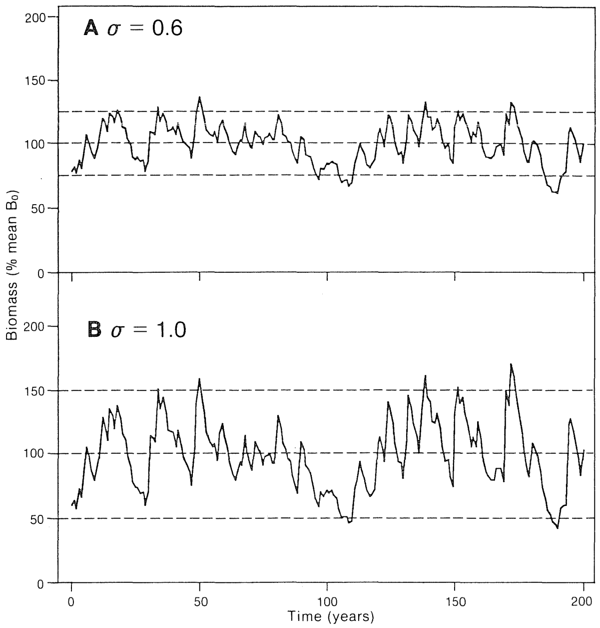

Fig. 2. Variation in biomass of an unfished stock of hoki with (**A**) moderate recruitment variability, and (**B**) high recruitment variability.

Separate sets of simulations were carried out for each of the twenty possible combinations of M and rate of reduction. For each simulation run, a random value of B_0 was picked from the appropriate probability distribution (Fig. 1). The model was run up to 1989 with deterministic recruitment and then on to 1995 with random recruitment. (Since deterministic recruitment was used in estimating B_0, it was felt that this must also be used in simulations up to the present. Otherwise, some simulations would produce biomass histories that were inconsistent with the trawl survey data.)

Second example. Following Beddington and Cooke (1983), 'something bad' was taken to be the event of biomass falling below 20% of B_0, and the time period was set at 20 years (here B_0 refers to the mean biomass of the unfished stock). Another measure of risk, suggested by the results of the simulations, was also considered — the percentage of time that the biomass falls below 20% of B_0.

In assessing the risk of the constant catch rule (catch = 2/3 MSY) the following steps were followed:

1) Generate a random starting point (this results in an initial biomass from the appropriate distribution in Fig. 2);
2) Simulate a random trawl survey to estimate the initial biomass (so the estimated initial biomass is set equal to the actual initial biomass plus a random error — normally distributed with coefficient of variation, c);
3) Calculate the (deterministic) MSY based on the estimated initial biomass;
4) Set the catch equal to pMSY for constant p;
5) Fish for an initial period at this catch level to allow the biomass to stabilize;
6) Fish for a further 20 years and note whether the biomass falls below 20% of B_0.

Steps 1–6 were repeated 200 times for each of a range of values of p.

A similar procedure was followed in evaluating the constant mortality rule ($F = F_{0.1}$) with the difference that a trawl survey was simulated at the beginning of each year and the target catch for that year was calculated by applying the target fishing mortality to that biomass. Thus the actual fishing mortality varied from year to year.

For all simulations c was set to 0.2.

The initial period used was 20 years for the hoki simulations and 40 years for orange roughy. To ensure stabilization, constant mortality was used in the initial period for the orange roughy constant catch scenario. The level of mortality was calculated as that producing, with deterministic recruitment, long-term catches at the constant catch level.

Results

First example. For the most likely value of natural mortality of M = 0.05, the risk to the area 3B orange roughy stock was strongly dependent on the rate of TAC reduction (Fig. 3). The dependence on natural mortality was, however, not so great (Fig. 4), especially at the proposed reduction rate of 5,000 tons/year. Further, this dependence was not linear. For example, for the 5,000 tons/year strategy the risk was lowest for M = 0.05 and greater for both lower (0.025) and higher (0.075, 0.1) values of M (Fig. 4).

Second example. As might be expected, the risk associated with constant catch (or constant mortality) fishing rises sharply with increasing catch (or mortality) and is strongly dependent on the assumed level of recruitment variability (Fig. 5 and 6). The constant catch and constant mortality rules are both much more conservative for orange roughy than for hoki. When compared with the threshold adopted by Beddington and Cooke (1983) (i.e. a 10% probability that biomass <20% of B_0 at some point over 20 years), both rules appear too liberal for hoki while for orange roughy the constant catch rule seems conservative, and the constant mortality rule slightly liberal (Fig. 7). According to

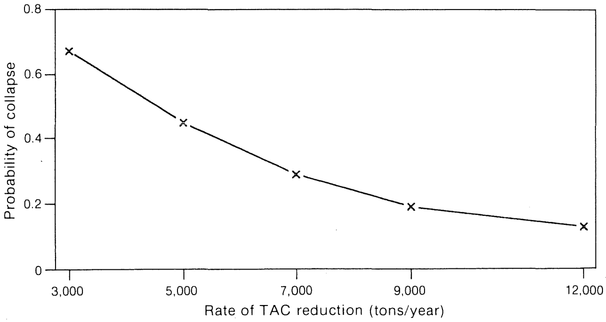

Fig. 3. Risk to the area 3B orange roughy fishery (expressed as the probability of collapse within five years) as a function of the rate of TAC reduction, assuming natural mortality, M = 0.05.

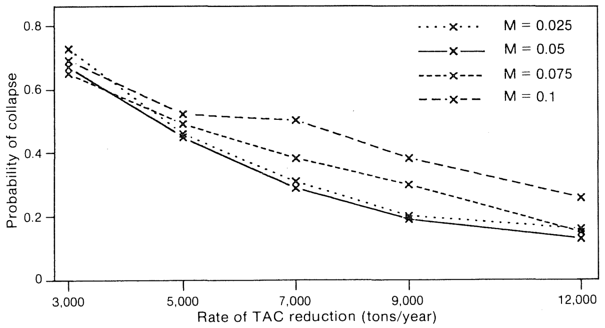

Fig. 4. The effect of the natural mortality parameter, M, on the risk to the area 3B orange roughy fishery for a range of rates of TAC reduction.

the first measure of risk the constant catch rule is more conservative than the constant mortality rule for both species. However, the alternative measure of risk (percentage of time biomass <20% of B_0) suggests this is only true for orange roughy.

Discussion

My conclusions about these simulations are discussed in terms of the four questions which sprang from my working definition of risk; *viz*:

"What is the best definition of 'something bad'?";

"What is an appropriate time period?";

"What is an acceptable level of risk?";

"How should risk be calculated?".

No further comment about the last question is needed since this has been answered, in general terms, above. Though the answer to each of the other questions must be 'it depends on the context', some principles can be stated.

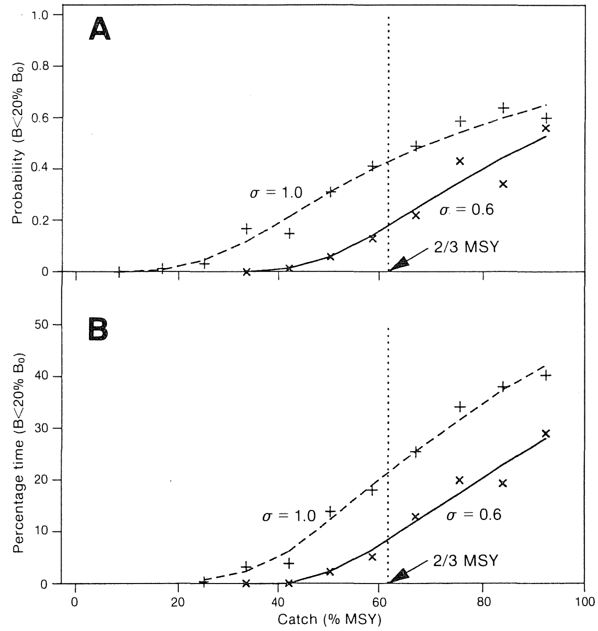

Fig. 5. The risk associated with a constant catch policy for hoki with moderate (σ = 0.6) or high (σ = 1.0) recruitment variability. Risk is expressed as (**A**) the probability the biomass falls below 20% B_0 within 20 years, or (**B**) the percentage of time that the biomass falls below 20% B_0.

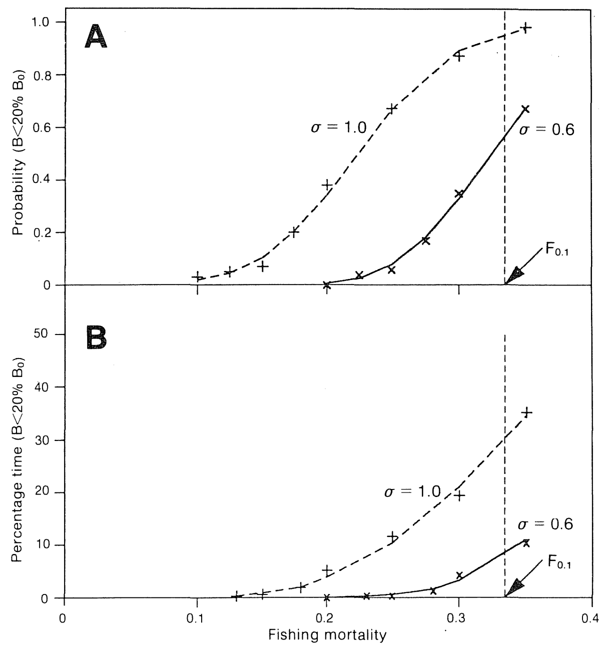

Fig. 6. The risk associated with a constant mortality policy for hoki with moderate (σ = 0.6) or high (σ = 1.0) recruitment variability. Risk is expressed as (**A**) the probability the biomass falls below 20% B_0 within 20 years, or (**B**) the percentage of time that the biomass falls below 20% B_0.

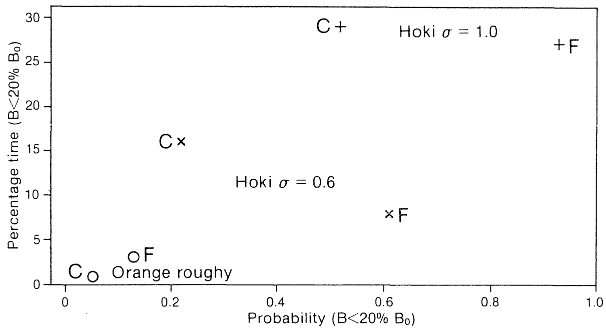

Fig. 7. Comparison of the risks associated with the constant catch policy, catch = 2/3 MSY (C), and the constant mortality policy, $F = F_{0.1}$ (E), applied to hoki, with moderate (σ = 0.6) and high (σ = 1.0) recruitment variability, and to orange roughy (with σ = 1.0).

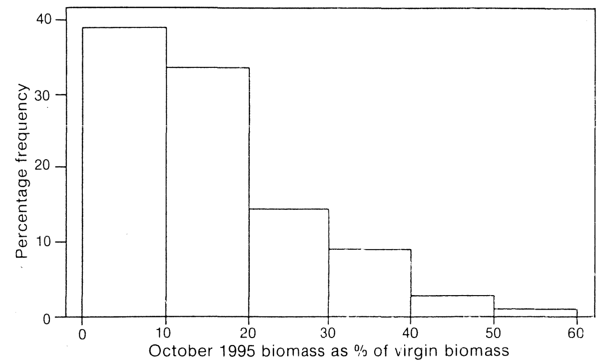

Fig. 8. Distribution of area 3B orange roughy biomass at the end of the five year simulation period (with a TAC reduction rate of 5,000 tons/year, and assuming M = 0.05) for those simulation runs in which the fishery did not collapse. The existence of very low values (<10% B_0) shows that, even if the fishery does survive the five year period, it is not necessarily out of danger.

Of the two versions of 'something bad' considered here, the second (B <20% of B_0) is more conservative and generally preferable. As biomass declines to smaller and smaller fractions of its virgin level, two things happen. First, the risk of recruitment failure increases. Second, the ability to predict decreases. For reasonable levels of biomass (say B >20% of B_0) it is probably close enough, for most stocks, to consider recruitment as a simple random variable independent of spawning stock size. When the biomass is lower, this is possibly no longer true but it is hard to say what is true. Thus it is prudent to adopt some fraction of B_0 as a danger threshold above which it is desired to maintain a stock. Of course there is still room for debate as to whether the fraction should be 20, 15, or 25%, etc.

However, in the first example the 'danger level' of B <20% of B_0 was useless since the biomass was expected to fall to 20% of B_0 in the 1990 season and, under all the strategies considered, remain below that level for more than five years. A lower threshold could have been used, e.g. B <10% of B_0. However, this risk analysis was aimed at managers (and fishermen). For this audience the possibility (or threat!) that the biomass might fall so low that the TAC would not be able to be caught seems a more immediate and compelling danger than the crossing of an arbitrary and artificial biomass threshold. The second example is more abstract, concerning as it does general management policy and long-term goals. Thus the more conservative threshold is appropriate.

The question of an appropriate time period must also depend on context. The fact of an immediate risk to a fishery will only be conveyed to managers and fishermen by using a short time period. However, the time period should be long enough to allow evaluation of alternative strategies. For the first example five years appears a reasonable compromise, though it does not encompass all the risk to the fishery (Fig. 8). In the second example there is no sense of urgency. Since the interest is in long-term behaviour, long time periods are appropriate.

The matter of 'an acceptable level of risk' is perhaps the hardest to come to terms with. In the case of the area 3B orange roughy stock assessment this cannot be done in isolation from the other major factor the fishery manager (and politican) must consider: the effect on the fishing industry (and associated voters). Had suitable economic data been available, some help in this direction could have been obtained by extending the above analysis to provide estimates of the risk to the industry (in terms of net present value, for instance). On top of this, though, there will always be the subjective evaluation of what Pope (1983) called 'minimum sustainable whinge' [whinge: verb, to complain in an annoying way], where the evaluation relates to what level of complaint from industry managers can withstand.

These non-biological considerations are of less importance in relationship to the second example. What is sought here is a property of a fish population: the maximum yield (imposed by either a constant catch or constant fishing mortality) that a population can safely sustain. Economics are irrelevant to the determination of this biological boundary, though they should be considered in selecting an optimal harvesting level within this boundary and charting a course towards it.

There is not yet a conclusion as to what is an acceptable level of risk in this context (or even how one might determine it). However, the sorts of analyses described above do allow comparisons to be made. For example, for orange roughy the 2/3 MSY rule seems to be more conservative than $F_{0.1}$ (Fig. 7). Also, both rules seem more conservative for orange roughy than for

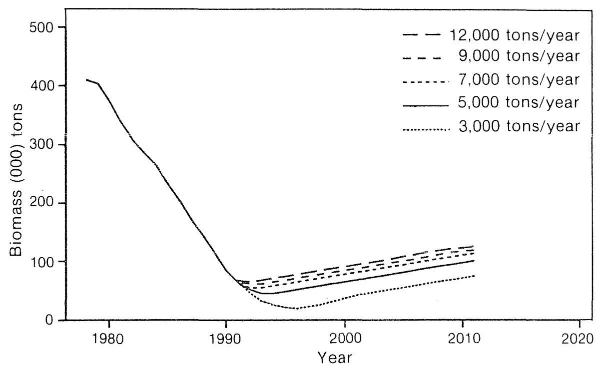

Fig. 9. An alternative presentation of management advice for the area 3B orange roughy stock. The graph shows the 'best guess' biomass projections under the five TAC reduction strategies, and assuming M = 0.05. To convey some measure of uncertainty it would be necessary to produce several versions of this graph with different possible values of B_0 and M. There is no simple way to include uncertainty about future recruitment to the fishery.

hoki. These conclusions can only be tentative until further simulations are done. The effect of uncertainty in various life history parameters (notably natural mortality) and the influence of the trawl survey coefficient of variation, are two areas to be investigated.

It is likely that populations with many mature year-classes can safely sustain longer periods of low biomass than those where spawning abundance is dependent on few cohorts.

The second of the two measures of risk (percentage of time that B <20% of B_0) used in the second example seems the better. It is less important to ask whether the biomass will fall below a threshold value, than it is to ask how often this happens. The second measure also has the merit of removing one arbitrary element from the definition of risk — the time period. Although a specific time period will be used in calculating the percentage of time 'something bad' happens, the answer should be independent of this time period.

I conclude that risk analysis is a useful tool in fishery management. For situations like that in the first example, it provides a natural way to incorporate uncertainty into management advice, and allows the presentation of the major part of that advice in a single graph (Fig. 3). An alternative approach would need several graphs, like Fig. 9, none of which expresses the inherent risk. Risk analysis also provides the means, as the second example illustrates, of evaluating the rules of thumb that are a necessary part of the pragmatic business of fishery management. Still unresolved, in this context, is the question 'what is an acceptable level of risk'?.

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