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Stock Rebuilding Strategies Over Different Time Scales

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Abstract

Scientific advice on rebuilding strategies for depleted fish stocks needs to provide more than just simple measures of long-term yield to enable managers to set appropriate policies. The type of biological information required to make an informed decision on the time scale for stock rebuilding is considered. A simple Monte Carlo simulation, with stochastic recruitment, is used to project stock size, stock structure and yield for two example stocks, Georges Bank cod and Georges Bank haddock, to illustrate the use of different measures of rebuilding.

Projections can be expressed in terms of the probability of obtaining a given yield level or spawning stock biomass level for different strategies. This is an expression of the risk to the fishery or the stock, of taking a particular action. The examples given show rapid reductions have a high cost in terms of short-term yield, while slow reductions have a high risk to the spawning stock and the rebuilding of the age composition. Medium-term strategies have the advantage of sacrificing relatively little yield in the short term, while obtaining the advantages of increased yield in the latter half of the decade and a low risk of recruitment failure by improving both age composition and spawning biomass relatively quickly.

Two major caveats are found necessary for these general conclusions. Firstly, the assumption made is that the distribution of recruitment remains unchanged from that observed over the past 15 years for these stocks. Secondly, the pattern obtained over different time scales depends on the current level of fishing mortality. No account has been taken here of the uncertainty in the estimates of fishing mortality rate, i.e. the risk analysis assumes perfect knowledge of fishing mortality. Both of these assumptions mean that the conclusions will be optimistic in terms of risk assessment.

Introduction

Fisheries resources in many areas are currently depleted to levels where their yields are below the estimated potential (U.S. Dept. of Commerce, 1989a). It is a major task of fisheries managers to improve the sustainable yield and the principle of developing fish stock rebuilding strategies has recently been set out in guidelines for the development of fishery management plans for United States resources (U.S. Dept. of Commerce, 1989b). These fishery management plans are developed by regional fishery management Councils under United States law. For stocks which have been identified as overfished by the Council, the guidelines specifically state that a stock rebuilding program must be established and that the time frame for rebuilding is to be determined by the Council.

This paper considers the question of how to present relevant scientific information to fishery managers to enable them to determine the appropriate time frame for a stock rebuilding program. A simple age structured population model is used, incorporating stochastic recruitment as one component of the uncertainty inherent to the problem of stock rebuilding. Two examples are considered, both from the Northwest Atlantic; Georges Bank cod and Georges Bank haddock. Recent assessments (NEFC, MS 1989; Gavaris, MS 1988) suggest that both stocks are depleted (NEFC, MS 1989). Of course, new, updated assessment analyses may change the current view of stock status, so these data are used here for illustration only, rather than actual predictions for advice to managers.

The target for rebuilding a stock is often expressed in terms of the fishing mortality rate (F) or spawning stock biomass. Here, it is assumed that the strategy chosen to rebuild the stock is to reduce $\dot{F}$ by 50% with a constant exploitation pattern over a time period of two to ten years. While the choice of a 50% reduction is somewhat arbitrary, it serves to illustrate the sort of information required to choose between different time scales.

The exploitation rates of the two example stocks were quite different, as were the degrees of stock depletion. In the assessment used here, the Georges Bank cod stock had an estimated instantaneous F of 0.775 (weighted average of exploited age groups) and a spawning stock biomass of under 40,000 tons compared with 80,000–90,000 tons in the early-1980s (NEFC, MS 1989). Haddock had an estimated F for 1987 of about 0.26, the $F_{0.1}$ level (Gulland and Boerema, 1973). However, the haddock biomass was at very low levels, around 10% of the level in the 1960s and, while exploitation rate was low on older haddock due to their scarcity, the assessment noted that the F on younger fish was still too high for rapid stock recovery (Gavaris, MS 1988). We examined the response to a 50% cut in exploitation rate in both cases to provide a contrast.

The central question is, what measures of stock rebuilding must managers weigh to choose the appropriate time scale for reducing exploitation of overfished stocks. We considered three basic quantities; the yield in weight, the spawning stock biomass and the compression of the age structure. Each of the measures used here makes some assumptions concerning the biology of the fish in terms of the productivity of the stock and the relationship of recruitment to parent stock. These are not extreme assumptions, and the functional relationship is not postulated, but simply a general assumption is used that a very depleted spawning stock is likely to produce poorer recruitment than a larger stock with a less skewed age composition. The inclusion of random variation in recruitment in the model implies that a probability is associated with any degree of stock rebuilding, so we have examined the probability of obtaining a given yield or spawning biomass level over different time scales to account for this uncertainty.

Model Description

An age-structured model was constructed with stochastic, gamma distributed, recruitment. The model equations were:

$$N_{t,1} = R_t \sim \text{gamma}\ (a,b)$$

$$N_{t,i} = N_{t-1,i-1} \exp[-Z_{t-1,i-1}] \quad i = 2...J$$

$$Z_{t,i} = F_{t,i} + M$$

$$C_{t,1} = F_{t,i}/Z_{t,i}\left\{1 - \exp[-Z_{t,i}]\right\} N_{t,i}$$

where N is the number of fish at time t, age i, R is the recruitment in year t which is distributed as gamma with parameters a and b, Z is the total instantaneous mortality rate which is the sum of F_{t+i} the fishing mortality at time t and age i and M, the natural mortality rate which has a constant value. C is the catch in numbers in year t and age i. The yield or spawning biomass is obtained by multiplying numbers-at-age with input weight-at-age.

For the two example stocks, numbers-at-age and instantaneous F-at-age for the most recent year in the assessment was used as input to the model, along with the weight-at-age in the most recent year, the maturity schedules and M (0.2 for both stocks). The parameters of the gamma distribution for each stock were determined by fitting data available in the assessment documents. For cod recruitment at age 1 in the years 1978–88 gave a = 3.74 and b = 0.00018. For haddock recruitment in the years 1965–87 gave a = 0.64 and b = 0.000038. The small value for b for haddock gave a distribution of recruitment which was very strongly skewed to the left, with a long tail to the right (Fig. 1A). Cod had a less skewed recruitment distribution (Fig. 1B).

Simulations for each species were run for 13 years, from 1987 until the end of the century, to project the yield, stock biomass and age structure under four different scenarios of exploitation. The first scenario ("no-reduction") was that F-at-age remained constant at the 1987 level through until the end of the century. The second scenario ("2-year") reduced F-at-age by 50% over a 2-year period beginning in 1989, i.e. reduced by 25% of the 1987 value each year, and then remained constant until the end of the century. The third scenario ("5-year") was a 50% reduction over a 5-year period beginning in 1989, i.e. reduced by 10% of the 1987 value each year for 5 years, and remained constant thereafter. The final scenario ("10-year") was to spread the reduction over 10 years.

Five hundred runs for each species were done under each scenario. Therefore, 500 sets of 13 random recruitment values were drawn from the respective gamma distributions for the species. To facilitate comparison between the methods, the same 500 sets were used for each scenario.

Results

Cod

The yield that will be obtained under a proposed scenario for controlling F is one measure of the efficacy of a strategy. The average yield for cod (Fig. 2), if the no-reduction scenario is followed, remains relatively constant near the present level. However, the variability of that yield is high. Therefore, the actual cod yield that will be realized in any given year is very uncertain.

There is a predictable pattern in expected (average) yield for each scenario for cod (Fig. 3). A rapid reduction in F results in an expected large loss in yield in the short term, before a substantial increase is realized by the end of the century. This sharp reduction in short-term yield is substantially less for the other two scenarios, and in the case of the 5-year strategy, the resulting payoff is the same.

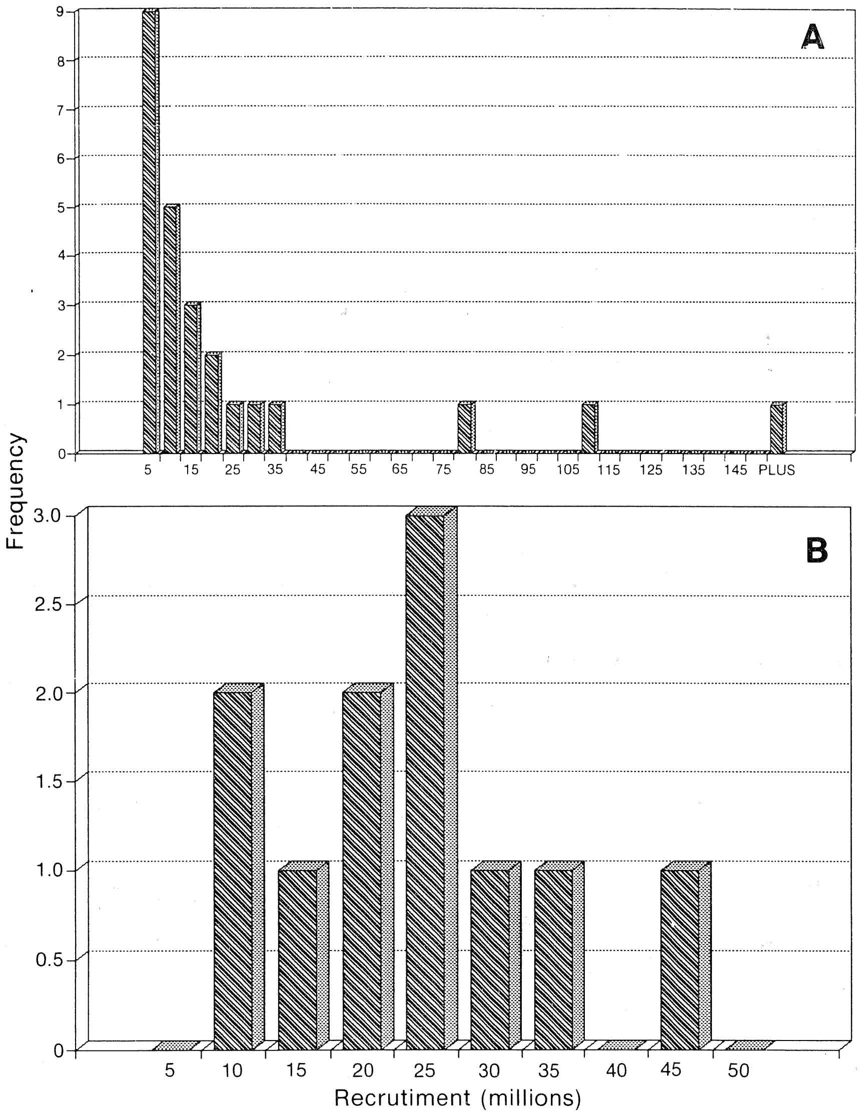

Fig. 1. (**A**) Frequency histogram of Georges Bank cod recruitment at age 1 in numbers of fish. Data are for the years 1978–88 (NEFC, 1989); (**B**) frequency histogram of Georges Bank haddock recruitment at age 1 in numbers of fish. Data are for the years 1964–88 (Gavaris, MS 1988).

The expected yield on average from 1989 to 1999 is another measure of the impact of the rebuilding strategy. This can be expressed as the probability of obtaining a given level of yield over the period by simply counting the number of simulated realizations above a given yield level. For cod, these probabilities are virtually identical for all the scenarios (Fig. 4). Therefore, there is little risk in terms of total yield resulting from adopting one of the rebuilding strategies for cod *versus* maintaining the *status quo*.

In addition to risk, it is also useful to consider the probability of obtaining a better yield in a given year than would be obtained if the no-reduction strategy was used. Figure 5 shows the probability of obtaining a cod yield greater than the no-reduction case in each year. Both the 2- and 5-year strategies rapidly increase the probability of improved yield with an obvious trade-off in the short term as indicated in Fig. 3.

The improvement of yield must be balanced with increases in the spawning stock biomass for depleted stocks. Seeking to increase the spawning stock biomass assumes that there is less risk of recruitment failure at higher stock levels, i.e. there is a relationship between stock and recruitment at least to the extent that some notional threshold level of biomass exists below which poor recruitment becomes more likely. We adopt this assumption in considering the benefits of increasing stock biomass.

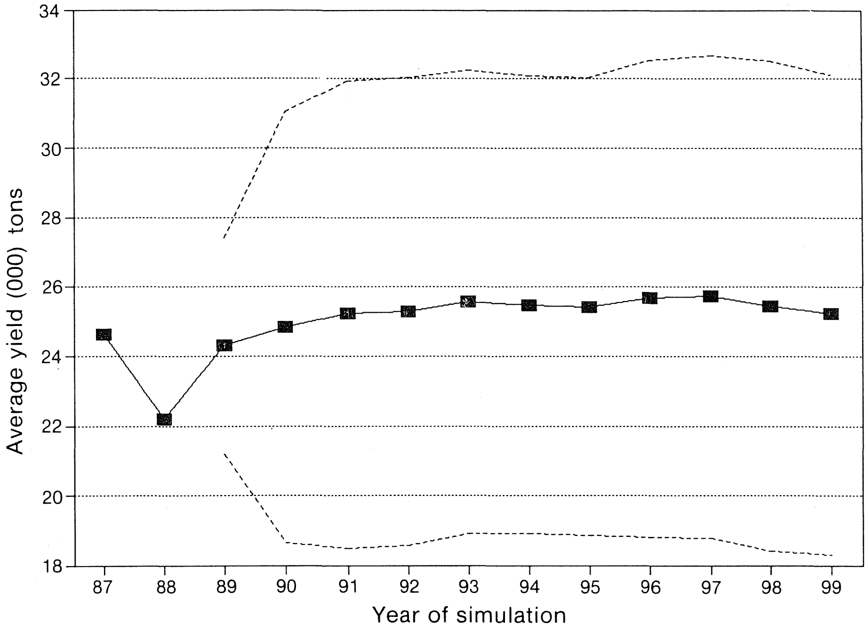

Fig. 2. Projected yield from simulations of the Georges Bank cod stock where the rate of fishing mortality remains at the 1987 level. The solid squares are the average over the 500 realizations, the dashed lines are ±1 standard deviation around the mean.

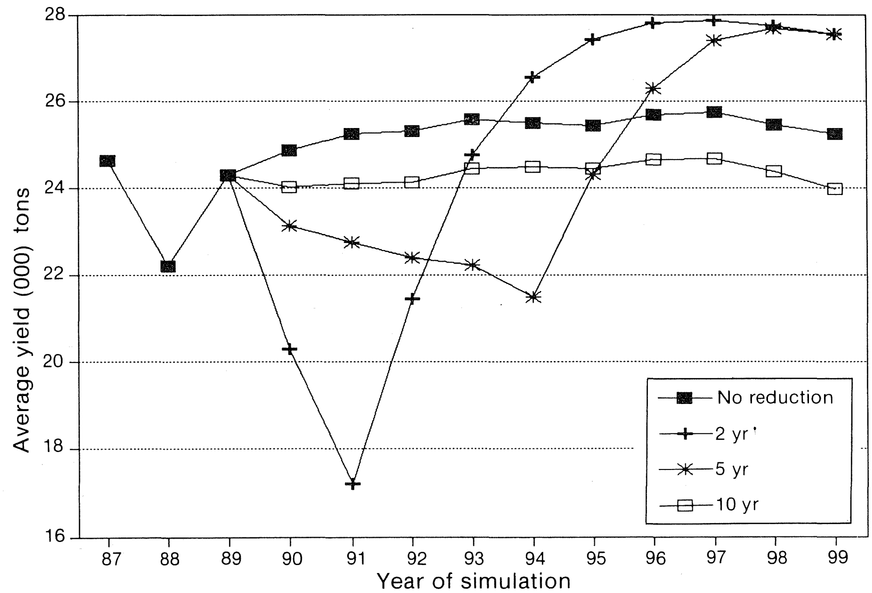

Fig. 3. Projected yield from simulations of the Georges Bank cod stock under four different scenarios for the rate of fishing mortality. Each line is the mean of 500 realizations for the given scenario.

The more rapid reductions in exploitation rate obviously rebuild the spawning stock biomass more quickly (Fig. 6) at the expense of short-term yield. In effect, the implication is that the risk of poor recruitment decreases rapidly under the 2-year or 5-year strategy. In terms of probability, it is informative to look at the chance that the average spawning stock will be above a given level over the decade (Fig. 7A) and the probability of attaining a given level of the end of the decade (Fig. 7B). There is a better chance of obtaining a higher average biomass with rapid reduction over 2 years, but the probabilities of rebuilding the spawning stock to between 60,000 and 80,000 tons by the end of the decade are virtually identical for the 2- and 5-year

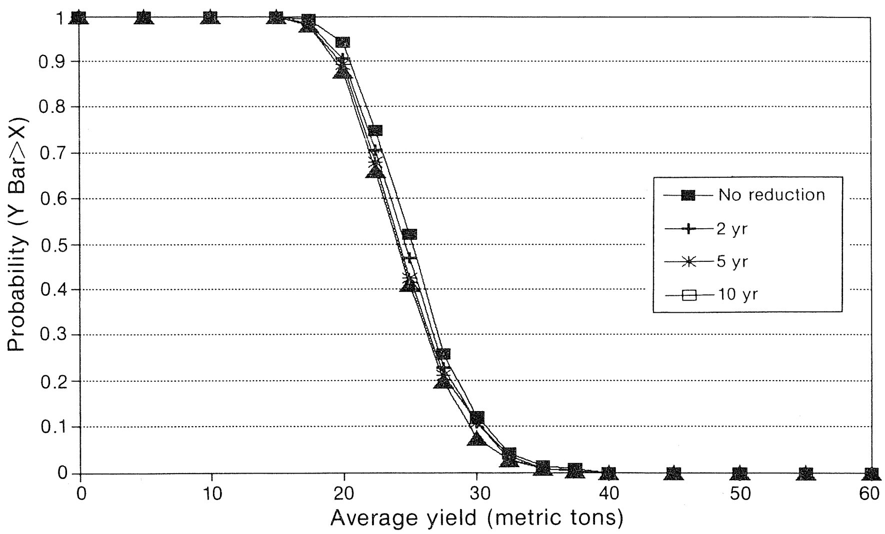

Fig. 4. Probability that the average yield over the 1990 decade is above the amount given on the abscissa for four of the scenarios of rate of fishing mortality on cod.

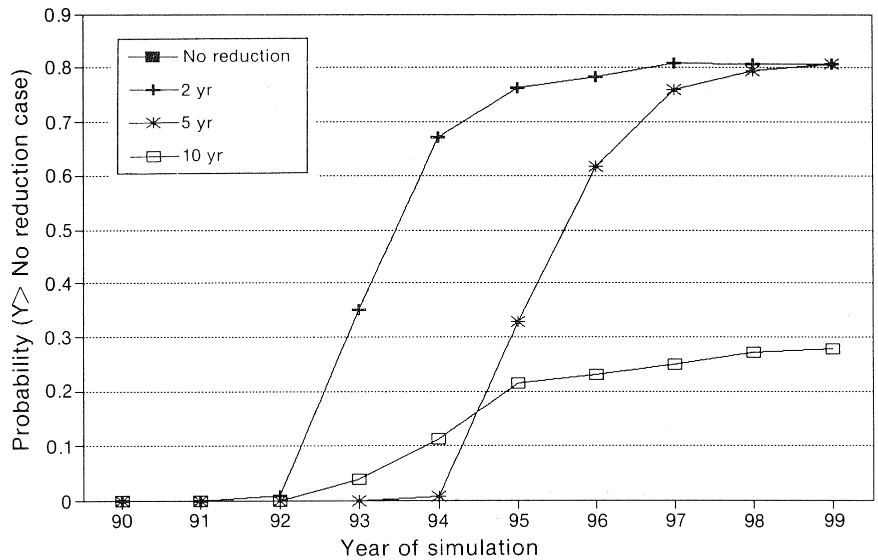

Fig. 5. Probability that the yield in each year of the simulation, for the three scenarios where the exploitation rate is reduced will be above the yield acheived by the no-reduction case for cod.

strategies. There is a substantially lower chance of obtaining this level of rebuilding with the 10-year scenario and with the no-reduction case there is little chance of having a cod stock above 50,000 tons in 1999.

The final measure of rebuilding considered is the compression or skewness of the age distribution. While a higher spawning biomass may be obtained when a good year-class matures, the productivity of the stock may largely depend on only one or two year-classes. The implicit assumption here is that if the fish are allowed to spawn for more than one season, they have a better chance of replenishing the stock than if they are all cropped after 1 or 2 years. In addition, there is some evidence that spawning success may be different for different age-groups (Rosenberg and Doyle, 1986) and therefore a fuller age composition may improve the chances of good recruitment. A simple measure for the age distribution is its skewness:

$$\text{skew}\ (X_1 \ldots X_n) = 1/N\ \text{SUM}\ \left\{(X_i - \text{Xbar})/s\right\}^3$$

where N is the number-of-age groups, X_i is the relative abundance of the ith age-group, Xbar is the average relative abundance and s is the standard deviation of

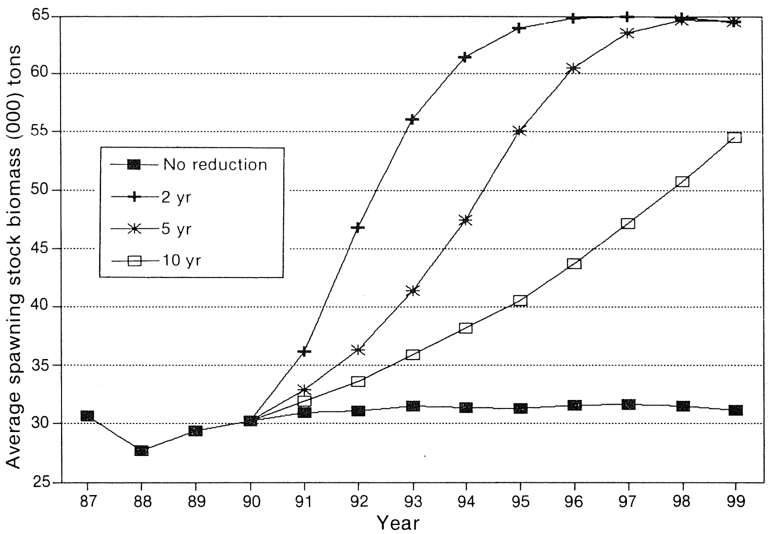

Fig. 6. Projected average spawning stock biomass of cod for the scenarios of exploitation over the 1990 decade. Each line is the average of 500 realizations.

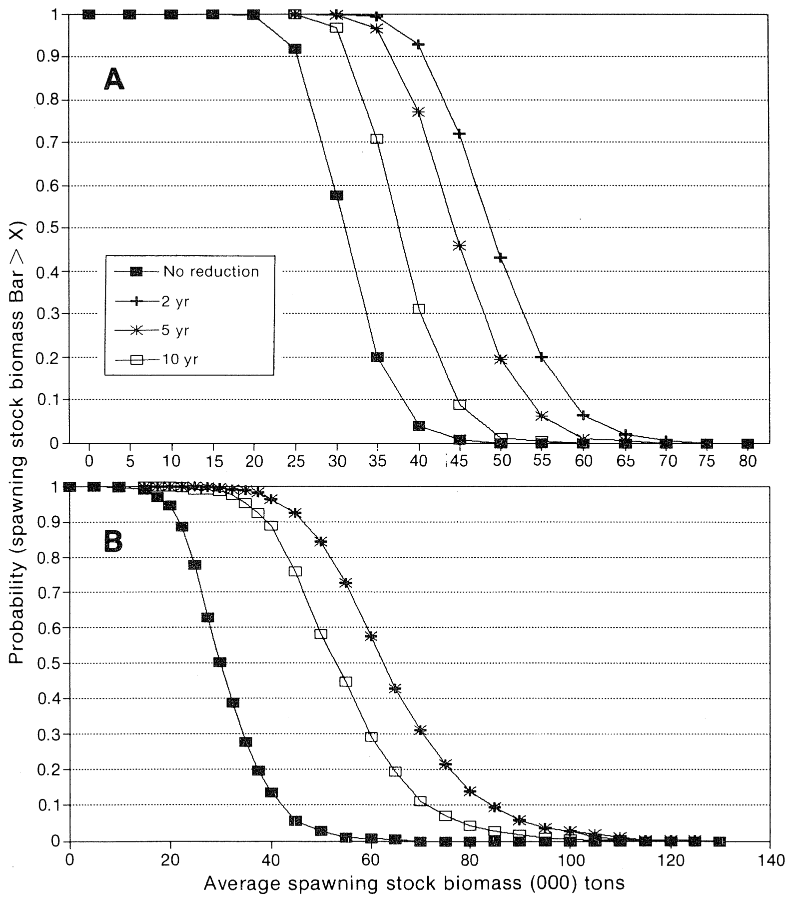

Fig. 7. (**A**) Probability that the average spawning stock biomass of cod over the 1990 decade will be greater than the amount given on the abscissa for the four scenarios; (**B**) probability that the 1990 spawning stock biomass of cod will be greater than the amount given on the abscissa for the four scenarios.

relative abundance. As a stock becomes more heavily exploited, the skewness of its age distribution will increase as more individuals will be concentrated in fewer age-classes. In this context, the skewness of an unexploited population can be calculated from a stable age distribution with total mortality rate equal to the rate of natural mortality. For cod, this unexploited skewness coefficient equals 0.71.

Under the different F reduction scenarios, the average skewness in each year across the 500 realizations shows the more rapid improvement obtained with the 2-year case (Fig. 8). Again, the 2- and 5-year strategies converge quite quickly and give essentially identical results in terms of the likely stock structure by the end of the decade.

Haddock

Under the no-reduction strategy, the haddock yield is expected to increase slightly over the next decade, but this increase is highly uncertain due to the large standard deviation of yield obtained in the simulations (Fig. 9A). The expected yield from the no-reduction strategy remains above any of the other scenarios (Fig. 9B) because the current level of F is quite low, so a 50% cutback necessitates a reduction in yield even if the stock rebuilds. For the 2- and 5-year strategies, yield initially is low, but is on an increasing trend at the end of the decade, while for the 10-year scenario it is still decreasing. In effect the reduction in exploitation rate reduces yield unless the increase in stock size resulting from this decreased exploitation compensates. For the rapid reduction scenarios, the stock begins rebuilding rapidly by the end of the decade and yield is on the increase. If F is reduced slowly, 50% in 10 years, then insufficient recovery has occurred by 1999 for yield to begin to increase.

Reducing the rate of fishing mortality on haddock from its current level is unlikely to result in a rapid increase in yield (Fig. 10A). Current landings are very low compared to potential haddock yields of 50,000 tons (U.S. Dept. Commerce 1989b). Therefore, the goal of reducing the rate of fishing mortality is stock rebuilding, rather than increasing yield in the short term. In any case, yield increases over current levels will be unlikely before the end of the century (Fig. 10B).

For haddock, because the yields are currently so low, the main issue is the recovery of the population, here measured by increasing spawning biomass and the age structure of the stock. The more rapid the reduction in F, the more rapid is the increase in spawning stock (Fig. 11). The probabilities of obtaining higher spawning stock levels is also greater with the rapid reduction strategies (Fig. 12). Note that the 2- and 5-year strategies are again very similar in terms of the level obtained by the end of the decade.

Under the no-reduction scenario, even though the F level is fairly low and may be appropriate for maintaining the stock, there is virtually no improvement in the age structure of the stock (Fig. 13). The reduction strategies all lower the degree of skewness of the stock, indicative of rebuilding (unexploited population skewness = 0.51).

Discussion

The results of this simulation exercise show the importance of looking at several measures of stock rebuilding. It would be very misleading to choose a management strategy only on the basis of a single measure, such as average yield or spawning stock biomass or F. In the cod example, the average yield over

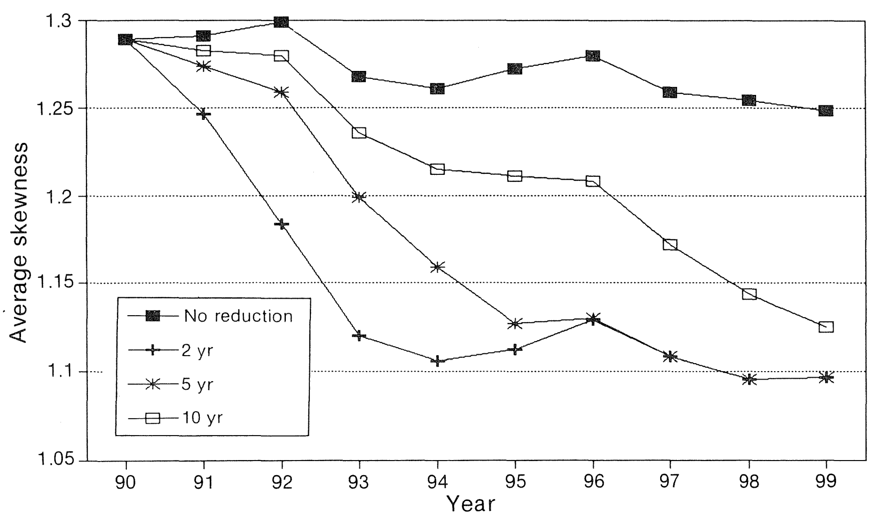

Fig. 8. Average coefficient of skewness in each year of the four scenarios. The unexploited coefficient of skewness for cod is estimated to be 0.71.

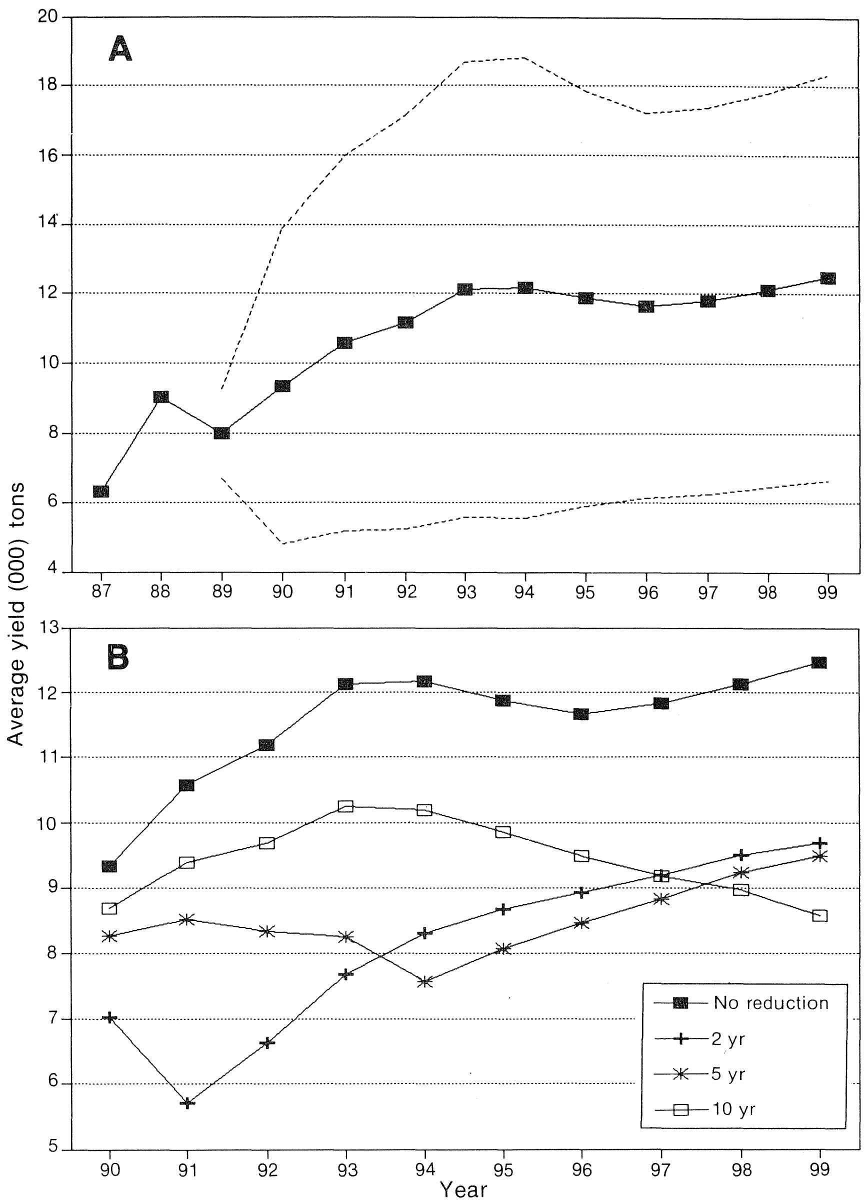

Fig. 9. (**A**) Projected yield for Georges Bank haddock over the 1990 decade. The solid squares are the means of 500 realizations with the rate of fishing mortality kept constant at the 1987 level, the dashed lines are ±1 standard deviation around the mean; (**B**) projected average yield for the four scenarios of the rate of fishing mortality for haddock. Averages are over the 500 realizations.

the 1990 decade is similar for all scenarios. However, there are large differences in the degree of stock rebuilding under the different strategies as shown by the spawning stock biomass and skewness projections. In the case of haddock the current level of mortality is low, around the $F_{0.1}$ level, but there is still little rebuilding of the stock by 1999 unless reductions are made from this level. The crucial point here is that the stock is currently at such a low level that substantial improvements in yield can only occur after massive rebuilding has been accomplished. Our results show that even though yield remains low under all strategies, rebuilding has begun in stock biomass and age composition when F is reduced by 50%. A similar result was obtained by Overholtz *et al*. (1986) in their examination of rebuilding strategies for haddock.

There are clear differences between the time scales for stock rebuilding with respect to these two examples. Rapid reduction of exploitation rate in the 2-year scenario results in a large loss in short-term yield, which is later recouped by the rebuilding of the stock. Such a short-term outlook may be undesirable in terms of the risk to the fishing industry even if the stock

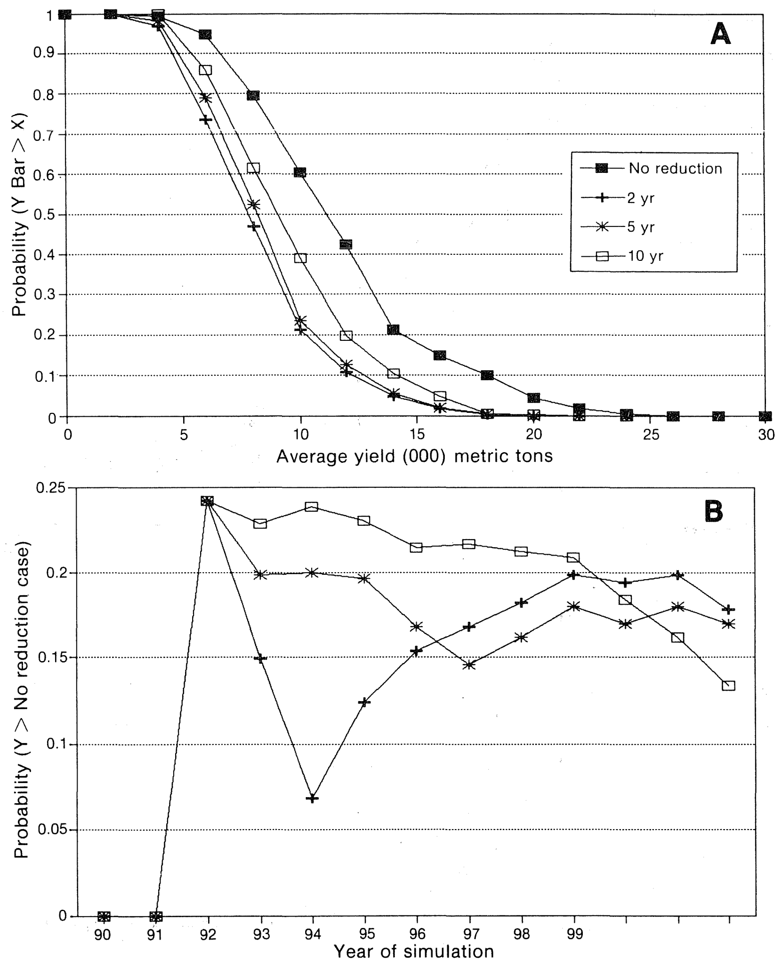

Fig. 10. (**A**) Probability that the average yield of haddock over the 1990 decade will be greater than the amount given on the abscissa for the four scenarios of exploitation; (**B**) probability that the yield will be greater than the strategy of keeping the fishing mortality rate at the 1987 level.

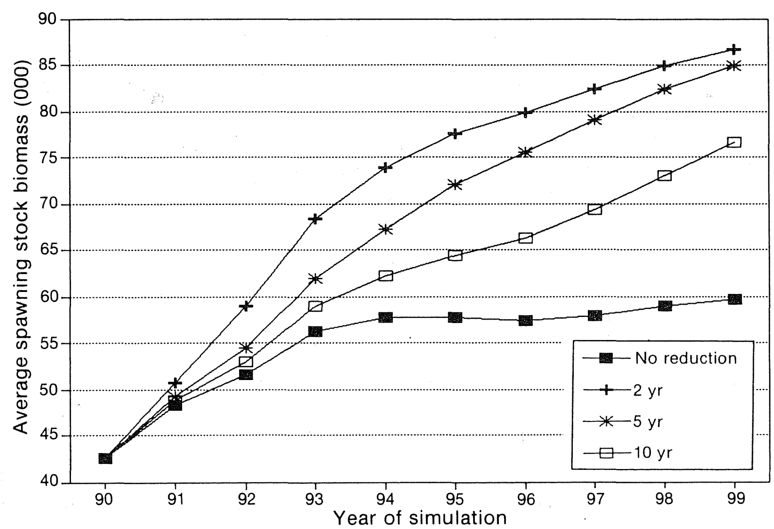

Fig. 11. Projected average spawning stock biomass of haddock for the four different scenarios of exploitation over the 1990 decade.

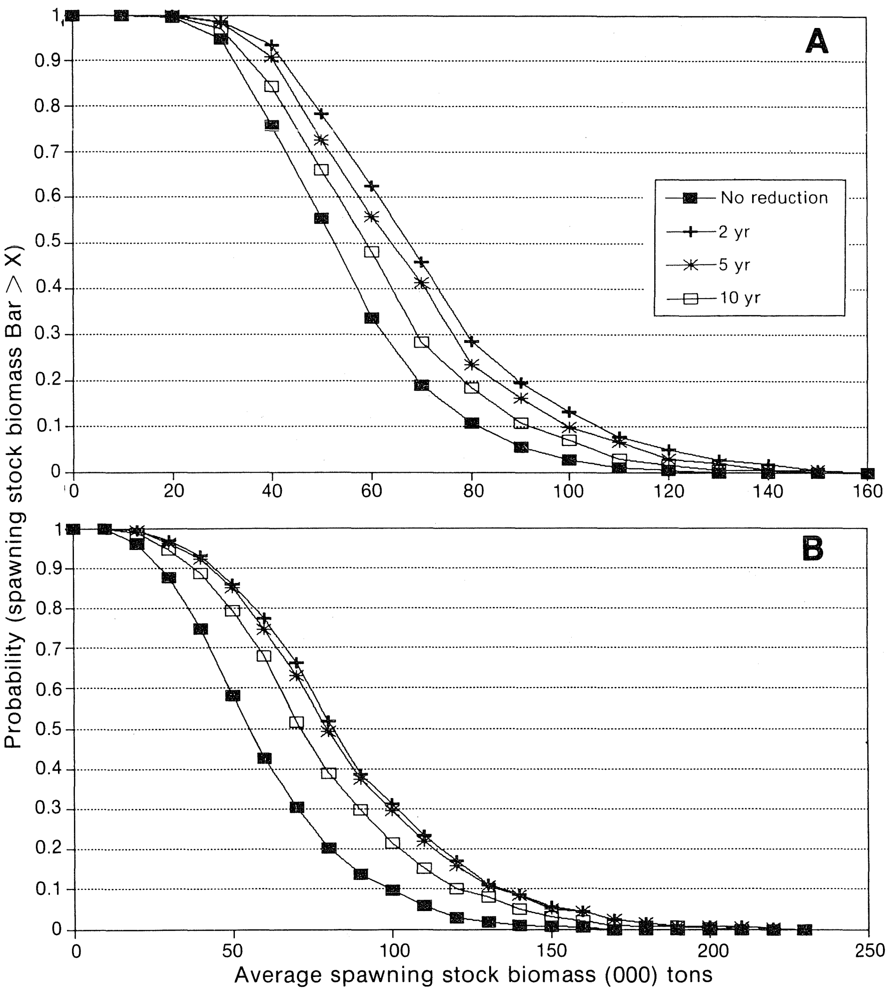

Fig. 12. (**A**) Probability that the average spawning stock biomass of haddock over the 1990 decade will be greater than the amount given on the abscissa for the four scenarios; (**B**) probability that the 1999 spawning biomass of haddock will be greater than the amount given on the abscissa for the four scenarios.

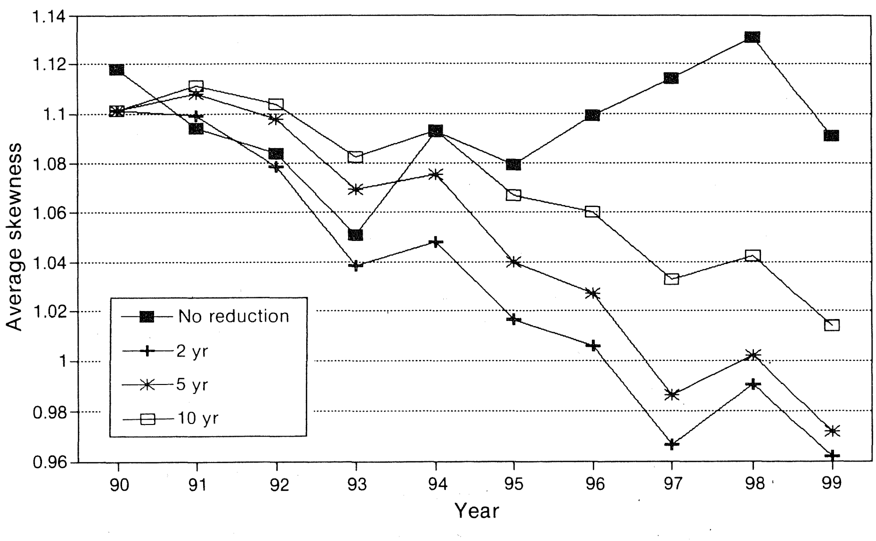

Fig. 13. Average coefficient of skewness in each year for each of the four scenarios. The unexploited coefficient of skewness for haddock is estimated to be 0.51.

benefits. The reduction spaced over 10 years on the other hand seems to be too long a time scale to see any effective recovery by the end of the century. Both the no-reduction case and the 10-year strategy have substantially higher risks to the resource but less rapid changes in yield and perhaps lower risk for the industry. For cod, decreasing F by 50% over 2 years causes a 30% drop in yield before recovery begins to take over. For both stocks, the middle, 5-year plan appears to give the least drastic changes in expected yield (lower risk to the fishery) while rebuilding the stock fairly rapidly (lower risk to the resource).

There are several major caveats which are important in interpreting the analysis presented here. Uncertainty in incoming recruitment is only one component of the uncertainty associated with rebuilding a resource (for discussion see Walters, 1986). Another major component is the uncertainty in the assessment information, i.e. the measurement error. The analysis so far has assumed that the available information on the stock is perfect and that all of the biological parameters are known and constant. This simplification is likely to result in an optimistic picture of the results of the rebuilding program. In addition, the uncertainty incorporated in recruitment is also a simplification in the sense that the distribution is assumed constant over time, and therefore, over all observed stock sizes. If sufficient data were available it may be possible to relax this assumption to some extent by fitting recruitment distributions to parts of the series separately.

A third issue in examining these results relates to our chosen time horizon, the year 1999. For many stocks, full rebuilding will obviously require more than ten years. While management regimes are usually focused on a long term or sustainable yield, rebuilding strategies are likely to be guided by intermediate term results in line with planning by the industry. Both long and intermediate term considerations must be taken into account in advising managers. Long-term advice could be given in a similar framework using stochastic recruitment and the probability of maintaining yield and stock biomass above a given level as presented in Rosenberg *et al*. (1990).

Presenting the advice to managers in terms of probabilities is an effort to quantify the risk involved with choosing a particular strategy. The probability expresses the chance that the strategy will achieve the manager's goals. Preferably, this risk analysis should include the uncertainties associated with measurement error as well as the variability in biological processes.

In summary, these results illustrate the types of scientific advice which will be useful to managers in determining the most appropriate time scale for a stock rebuilding program. The time scale will of course depend on the goal of rebuilding. We have chosen an arbitrary reduction of F by 50% here, and on the tradeoff between yield and stock size which is acceptable from a management point of view.

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