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# Management under uncertainty: defining strategies for reducing overexploitation

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To reduce overexploitation is a familiar problem for fisheries management. A direct reduction of fishing mortality rate to $F_{max}$ (or $F_{0.1}$) implies a corresponding decrease in total allowable catch (TAC) in the short term which is likely to create severe problems for the industry. Moreover, conventional management strategies usually aim at either maximizing yield ($F_{max}$) or stabilizing fishing effort ($F_{stq}$), and, as noted previously by various authors, these criteria are often simultaneously incompatible. Hence, fishery managers have to find a compromise between several objectives: short term versus long term, maximum yield versus stability of fishing effort and yield, and so forth. This study aims at determining compromise TAC management rules that could fulfil these conditions. Uncertainties in data used for assessment are taken into account as a potential source of error in scientific advice. A simulation-based approach allows the properties of conventional and compromise strategies to be analysed on both short- and long-term time horizons. In the case of compromise strategies, yield and fishing effort are found to be less sensitive to uncertainties and hence more stable and easier to forecast. By these measures, overexploitation can be rectified relatively quickly without serious loss of yield in the short term.

Key words: overexploitation, management strategy, stock assessment, uncertainties.

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## Introduction

This paper focuses on the problem of reducing the fishing mortality rate in an overexploited stock. By overexploited, we mean one in which the current fishing intensity is substantially greater than the biological optimum $F_{max}$. We do not attempt to determine any one particular optimal strategy by maximizing some criterion, e.g. the expected yield (Getz, 1985), the economical rent (Deriso, 1980; Clark, 1985; Ruppert *et al.*, 1985; Horwood, 1987), or more elaborate criteria (Hightower and Grossman, 1987; Charles, 1989; Quinn *et al.*, 1990). In addition to the conventional $F_{max}$ and $F_{0.1}$ management strategies, we define a family of strategies that compromise between the status quo management (herein referred to as $F_{stq}$) and $F_{max}$ or $F_{0.1}$. Management rules must be understandable to decision makers and practicable (Gulland and Boerema, 1973); our compromise strategies are therefore defined in a simple way and, in fact, one has already been intuitively implemented (Rivard and Maguire, 1991). The properties of both conventional ($F_{stq}$, $F_{max}$, and $F_{0.1}$) and compromise management strategies are then compared in the situation where assessment is error-prone, due to uncertainties in the parameters used for stock assessment. Desirable properties for management purposes include the average yield and the year-to-year stability of both yield and fishing effort. In other instances, these objectives were found to be simultaneously incompatible (May *et al.*, 1978; Hightower and Grossman, 1985; Getz *et al.*, 1987; Koonce and Shuter, 1987; Murawski and Idoine, 1989).

In the case of a severely overfished stock, reducing the fishing level to $F_{max}$ (or $F_{0.1}$) generates a short-term decline of yield, which is likely to create serious socioeconomic problems for the industry. The transitional phase following reductions of fishing mortality from an initially overfished condition was studied by Beverton and Holt (1957) with a constant parameter yield-per-recruit model. They showed that certain simple criteria could be used to compare various options, such as: (a) the time elapsing before the previous level of yield is regained, and (b) the further period before the cumulative initial losses are balanced by the latter cumulative gains. More general properties of yield trajectories have been explored by Horwood (1987), using an age-structured deterministic model incorporating the Beverton–Holt stock-recruitment relationship.

In this paper we consider an age-structured model with recruitment varying randomly around a constant mean.

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Table 1. Successive steps of the stock assessment in relation to the models used, the input parameters, and the outputs.

| Step | Input parameters | Output |
|---|---|---|
| Virtual population analysis | Catch and effort data<br>Natural mortality | Fishing mortalities and $F^{current}$ vector<br>Stock sizes |
| Yield per recruit computations | $F^{current}$ vector<br>Fishing intensity $\mu$<br>Mean weights<br>Natural mortality | Yield curve: yield as a function of $\mu$<br>$F_{max}$ and $F_{0.1}$ estimates |
| TAC computations for several target fishing mortalities | $F^{current}$, $F_{max}$, and $F_{0.1}$<br>Stock sizes for the forthcoming year, including recruitment<br>Mean weights<br>Natural mortality | TAC($F_{stq}$)<br>TAC($F_{max}$)<br>TAC($F_{0.1}$) |

Input parameters to the model are subject to estimation error. Given these uncertainties, a systematic analysis is carried out of the transitional period following reductions in fishing intensity, in terms of criteria involving average annual yield, and year-to-year stability of yield and fishing effort. The transition problem is stressed by considering separately short- and long-term consequences for each management strategy. The short-term period corresponds to the time required to reduce substantially the fishing intensity; in the long term, the average fishing intensity is quasi-stabilized (see below). The analysis is then extended to other levels of initial overexploitation so that the results are not tied exclusively to initial conditions. Lastly, the stability properties of all the strategies are related to their differential sensitivity to uncertainties in model parameters.

# Models and hypotheses

## Age-structured models used for stock assessment

The simulation aims at reproducing the procedure currently used for assessing stocks with age-structured models (Table 1) (see Appendix). The first step is a virtual population analysis (VPA) which estimates fishing mortalities and stock sizes from catch and effort data. In the following, the term fishing mortality corresponds to a vector of fishing mortality rates per age group, whereas the term fishing intensity quantifies an overall fishing mortality, i.e. a scalar value. Following VPA, an average fishing mortality vector is computed over the last three years; this reference vector, which characterizes the current exploitation, is referred in the following as $\mathbf{F}^{current}$. In the second step, diagnoses are made by the equilibrium yield-per-recruit model. The fishing intensity corresponding to $\mathbf{F}^{current}$ may then be compared with biological reference points such as $F_{max}$ and $F_{0.1}$; as this fishing intensity corresponds to a status quo management strategy, it will be designated $F_{stq}$. In the third step, catch projections are computed for various target mortality vectors relative e.g. to $F_{max}$, $F_{0.1}$, or $F_{stq}$. Corresponding total allowable catches (TACs) are noted TAC($F_{max}$), TAC($F_{0.1}$) and TAC($F_{stq}$). In this study, compromise TAC options described in the next section are also explored.

## Simulating the management process and the resulting evolution of the fishery

For a given management option, the TAC for year y+1, derived from the assessment in year y, is assumed totally caught during year y+1. So, the corresponding fishing mortality vector $\mathbf{F}_{y+1}$ is obtained by solving the equation (A.8) previously used for computing the TAC:

$$\sum_{a=1}^{A-1} W_a N_{a,y+1} \frac{F_{a,y+1}}{F_{a,y+1}+M_a}\{1-\exp[-(F_{a,y+1}+M_a)]\} - W_A N_A \frac{F_{A,y+1}}{F_{A,y+1}+M_A} = \mathrm{TAC} \quad (1)$$

under the constraint that the exploitation pattern, i.e. the distribution of fishing mortalities over ages, is constant:

$$F_{a,y+1} = \mu_{y+1} F_{a,y}^{current}. \quad (2)$$

Hence, solving equation (1) leads to an estimate of $\mu_{y+1}$. It is calculated with the true values of fishing mortalities and stock sizes along with the prescribed TAC, and specifies the fishing intensity that will *actually* be necessary for catching all that TAC (Fig. 1).

Stock sizes-, fishing mortalities-, and catch numbers-at-age for year y+1 are then computed from equations (2), (A.1) and (A.2), respectively. An additional assumption is required for computing fishing effort $E_{y+1,f}$ and catch numbers $C_{a,y+1,f}$ per fleet f for year y+1, namely that each fleet will contribute a constant proportion of the total exploitation. This enables effort $E_{y+1,f}$ for fleet f to be predicted by:

$$E_{y+1,f} = \mu_{y+1} E_{y,f}. \quad (3)$$

Values of fishing mortalities $F_{a,y+1,f}$ and catch-at-age $C_{a,y+1,f}$ per fleet are then inferred from $C_{a,y+1}$ using equations (A.4) and (A.5).

Annual recruitment is assumed to follow a log-normal distribution around a constant mean, implying that within the range of stock size considered, there is no relationship between stock and recruitment.

The above process is repeated annually over a period of 50 years, estimation error being added each year to exact parameter values (Fig. 1). The 50-year time horizon

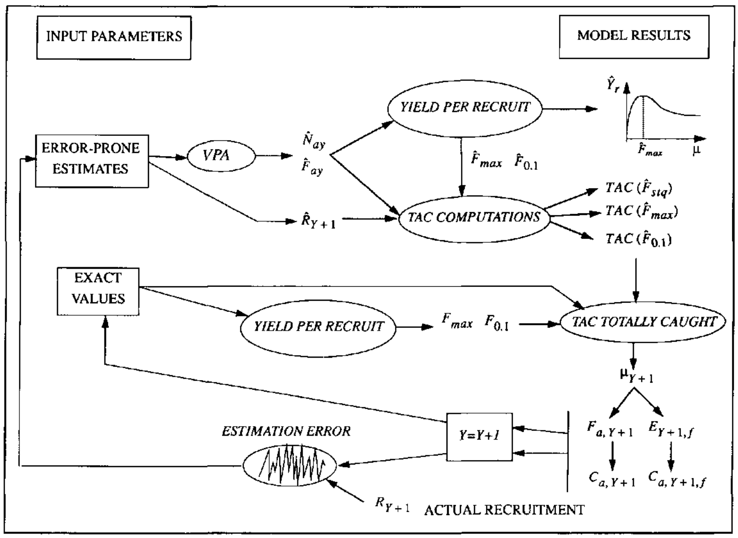


Figure 1. Flow-chart of the sequence over years of stock assessments and exploitation of the TAC decided. Y indexes the current year, i.e. the assessment year. Actual recruitment $R_{Y+1}$ is randomly varying.

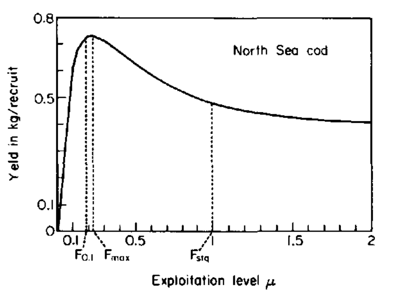


Figure 2. Equilibrium yield curve for the simulated stock. On the x-axis, effort is relative to the reference vector $F^{current}$ calculated from VPA results before prediction phase.

allows short- and long-term effects to be studied. This procedure makes it possible to evaluate the consequences of decisions inferred from imperfect information about the actual stock and fishery.

## Input data and associated uncertainties

Input parameters were chosen to simulate the population dynamics and the exploitation of North Sea cod, which is typical of a stock subject to growth overfishing. From a yield per recruit model (see appendix), the average fishing intensity is at present about four times $F_{max}$ (Fig. 2). In the first year, the assessment is simulated from 10 years data over 13 age groups. Equation (1) yields global catches, and catches per fleet are computed via equations (A.4) and (A.5) (Fig. 3). The mean and variance for the annual recruitment are calculated from historical stock sizes at age 1.

Knowledge of the true values of the parameters enables the evolution of the fishery to be precisely calculated. However, the data used for simulating the assessment are subject to estimation error (Fig. 3). Catch-at-age, weight-at-age, and recruitment estimates are assumed to be independent and normally distributed with constant coefficient of variation (CV) (Table 2). Hence, there are two sources of uncertainty for recruitment forecast: estimation error and year-to-year variability of actual recruitment. Estimation errors in the effort were modelled in another way, because the log of effort was used in the calibration. Hence, effort estimates are assumed to be log-normally distributed with a CV calculated from historical data. For each parameter, the mean is given by the actual parameter value; systematic errors, e.g. bias in estimating natural mortality or catches, are thus ignored.

In these simulations, two levels of errors in input data were considered as well as the error-free case (Table 2). The first one implies rather large uncertainties. In particular, it assumes that no information on abundance, e.g. research survey indices, is available soon enough to estimate recruitment, which is therefore estimated from the historical mean from VPA results. The second level of

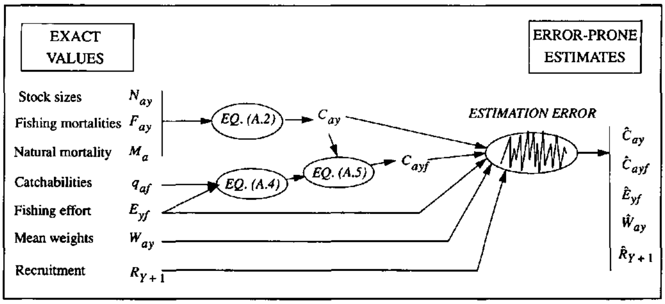


Figure 3. Construction of the set of error-prone data from the exact parameter values. The perturbation consists in simulating a normal distribution for each parameter, except for effort (log-normal) and natural mortality supposed exact.

Table 2. Different cases of estimation error considered in the simulation. Numerical values correspond to percentage coefficients of variation (CV). The estimation errors for catches, weights, and recruitment follow a normal distribution, while both the real recruitment and the estimation error of effort follow a log-normal distribution.

| Ref. as | Level of uncertainty | Recruitment estimation | Catch and weight data | Effort |
|---|---|---|---|---|
| (c) | Rather high | Historical mean value | 20% | Historical CV for each fleet |
| (b) | "Minimum" | Actual value +CV=30% | 10% | Historical CV for each fleet |
| (a) | No error | Actual value | 0% | 0% |

error is some minimum level which it would be difficult to reduce further without unacceptable additional sampling costs. One hundred simulations are carried out for each management strategy, each simulation corresponding to a 50-year management period.

## TAC management strategies and their assessment

### Definition of strategies

In the case of growth-overfished stocks, the $F_{max}$ (or $F_{0.1}$) management is seldom chosen, and practical management often leads to some compromise choice between $F_{max}$ (or $F_{0.1}$) and $F_{stq}$. However, such compromise rules are not studied in the literature to our knowledge, except by Ludwig (1981) who defines rules that range between the constant effort strategy and the strategy which maximizes the expected discounted yield. Indeed, compound strategies intuitively correspond to multi-criteria decisions.

In this analysis, the TACs corresponding to $F_{max}$, $F_{0.1}$, and $F_{stq}$ were first computed. Then, compromise options between $F_{stq}$ and $F_{max}$ on one hand, $F_{stq}$ and $F_{0.1}$ on the other hand are explored. A simple compromise policy between $F_{stq}$ and $F_{max}$ is given for each year by:

$$TAC_{y+1} = \lambda TAC_{y+1}(F^{[y]}_{stq}) + (1-\lambda)TAC_{y+1}(F^{[y]}_{max}), \quad (4)$$

where the superscript [y] indicates that $F_{stq}$ and $F_{max}$ are estimated afresh at each assessment. Whatever the year y, $F_y^{current}$ remains the mean vector over the last 3 years, i.e. y-2, y-1, and y. $F_{stq}^{(y)}$ which is the associated fishing level, evolves over time as regulation is carried out.

The parameter $\lambda$ in the range [0,1] enables a smoother transition towards lower fishing intensities to be defined, especially for heavily overexploited stocks. Resulting TACs correspond to a compromise target fishing intensity intermediate between $F_{max}$ and $F_{stq}$. Values of 0 or 1 for $\lambda$ lead to conventional management options. This strategy will be referred as $F_{max}(\lambda)$ strategy in the following. An intermediate fishing intensity could have been specified directly, but in our opinion, to work in terms of catch makes more sense to managers than does the fishing intensity. A similar composite rule is achievable for $F_{stq}$ and $F_{0.1}$, which is referred to as $F_{0.1}(\lambda)$.

### Criteria used to assess strategies

Management strategies need to be assessed and compared by means of various criteria. Among the criteria relevant for the industry, we are concentrating here on the average yield, and the year-to-year stability of both fishing effort and yield. Yield refers to the total catch per year, which is assumed to be equal to the TAC [see equation (1)]. Short-term criteria are appropriate to study the transition phase leading to the new equilibrium. The analysis of several simulations shows that a 5-year management period covers the main transitional stage; after 10 years, the fishery tends in most cases to be stabilized. Some compromise strategies may require up to 20 years before equilibrium is reached, but in practice, economic considerations make it irrelevant to manage beyond a 20-year horizon, even in the unlikely event of the exploitation pattern remaining constant for such a long time. So years 10 to 20 are associated with the long-term stage. An average annual yield is computed over simulations and over years for each period, i.e. years 1 to 5 for the short-term period, and years 10 to 20 for the long-term one.

The stability criteria are defined for both yield and the overall measure of fishing intensity defined in equation (2) as $\mu$. For each variable, they are quantified by the year-to-year variability. The year-to-year standard deviation (S.D.) of yield is averaged over the 100 simulations in both short and long term:

$$\sqrt{\frac{1}{100}\sum_{i=1}^{100}\frac{1}{5}\sum_{y=1}^{5}(Y_{i,y+1}-Y_{i,y})^2} \tag{5}$$

$$\sqrt{\frac{1}{100}\sum_{i=1}^{100}\frac{1}{11}\sum_{y=9}^{19}(Y_{i,y+1}-Y_{i,y})^2}, \tag{6}$$

where $Y_{iy}$ represents the total catch in year y obtained from the $i^{th}$ simulation replicate.

For the fishing intensity, we define similarly:

$$\sqrt{\frac{1}{100}\sum_{i=1}^{100}\frac{1}{5}\sum_{y=1}^{5}(\mu_{i,y+1}-1)^2} \tag{7}$$

$$\sqrt{\frac{1}{100}\sum_{i=1}^{100}\frac{1}{11}\sum_{y=9}^{19}(\mu_{i,y+1}-1)^2}. \tag{8}$$

Indices in (7) and (8) also correspond to the relative variation of the fishing mortality rate and the fishing effort, because for each age-group a and each fleet f:

$$\mu_{y+1}-1=\frac{F_{a,y+1}-F_{a,y}}{F_{a,y}}=\frac{E_{y+1,f}-F_{y,f}}{E_{y,f}}. \tag{9}$$

All the criteria, i.e. average yields and indices (5) to (8), are computed from real values of yield and fishing intensity $\mu$. Note that the starting year is not taken into account in the above expressions because y = 1 represents the first prediction year. So, any accidental discrepancy between the first prediction and the first assessment year does not appear in the results, so that in the case of non-status quo strategies, some variability is hence neglected.

The previous criteria are estimated by averaging over 100 simulations which may not always reflect the global behaviour of individual replicates. However, a simple average can smooth out significant features of the distribution concerned. Therefore, in this study, this problem is overcome by considering some trajectories over time of yield and effort obtained from individual simulations.

# Results

## Fishery management with exactly known data

The simulation without estimation error in the input data was used to analyse the theoretical dynamics of the stock and fishery and their response to management with conventional and compromise strategies. It will be recalled that recruitment is randomly variable from year to year as described in a previous section.

Evolution of the fishing intensity and TAC value is shown for three values of $\lambda$:0 ($F_{max}$), 1 ($F_{stq}$) and 0.6 (Fig. 4a and b). Figure 4a illustrates the approach of current fishing intensity $F_{stq}$ to the $F_{max}$ level. With the status quo strategy the fishing intensity remains unchanged, by definition. The other strategies imply a transition period of variable length, depending only on $\lambda$ value. For the $F_{max}$ strategy, the equilibrium is reached only after 3 years, because the computation of $F_{stq}$ and $F_{max}$ is based on $F^{current}$, which is the average vector over the last 3 years. Thus, fishing intensities in the second and third prediction year are still computed from fishing mortalities prior to regulation. For the $F_{max}(0.6)$ strategy, equilibrium is approached asymptotically and is reached effectively after 20 years ($F_{max}/F_{stq}=0.975$). Initial year-class size mainly influences stock size estimates and not fishing mortalities, which explains the relatively smooth profile of the $F_{max}/F_{stq}$ curve (Fig. 4a) compared to that of annual yield (Fig. 4b). The variability of TAC values is in fact dominated by changes in recruitment and not by the regulation of fishing intensity. The conventional $F_{max}$ strategy generates gains in yield relative to the initial level corresponding to $F_{stq}$ after the 4th year, whereas with the $F_{max}(0.6)$ strategy, this occurs a little later. The main advantage of this compromise strategy is a moderate loss in the short-term and a catch level close to that corresponding to $F_{max}$ after stabilization.

A similar analysis is performed for $F_{0.1}(\lambda)$ strategies, with same $\lambda$ values, i.e. 0 ($F_{0.1}$), 1 ($F_{stq}$) and 0.6. Results are quite similar to the previous ones, but, with $F_{0.1}(\lambda)$ strategies, TAC values are more stable from year to year, compared to the $F_{max}(\lambda)$ and $F_{stq}$ ones (Fig. 4c, d). This is because the fishing intensity is so low that yield does not depend much on current recruitment.

The management implications according to the criteria defined previously can now be examined. The relationship between average yield and SD of yields [indices (5) and (6)] is shown for short- and long-term stages in Figure 5a, b respectively, while variabilities of yield and fishing intensity are shown in Figure 5c, d. Cases (b) and (c) refer to runs with error-prone data, the results of which are discussed further below. The error-free case is referred to as (a). With perfectly known data, conventional strategies are found to perform as intended. Thus, $F_{max}$ maximizes average yield in a stabilized situation (Fig. 5b) and $F_{stq}$ implies constant effort (Fig. 5c, d). In terms of average

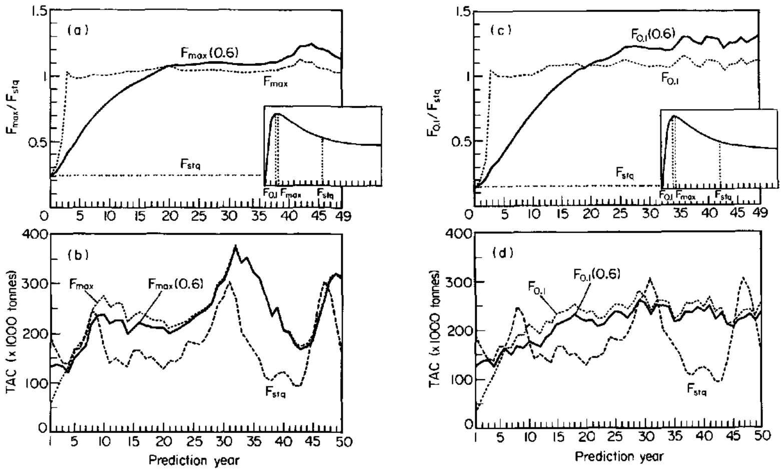


Figure 4. Transitions of fishing level (a) and (c) and TAC values (b) and (d) towards equilibrium for three $F_{max}(\lambda)$ strategies and three $F_{0.1}(\lambda)$ strategies, respectively. Data are supposed exactly known. Real recruitment is randomly variable. Years 22 and 43 in (a) show small peaks due to very strong recruitment that happened 10 years earlier (b) and indirectly affected the computation of fishing mortalities.

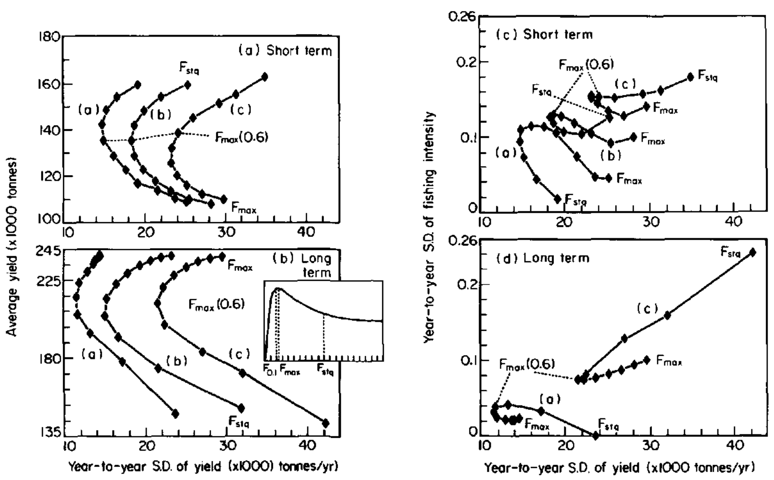


Figure 5. Criteria values for $F_{max}(\lambda)$ strategies with $\lambda$ ranging from 0 ($F_{max}$) to 1 ($F_{stq}$). Each point of the three curves corresponds to criteria for a $\lambda$ value. Curves indexed by (a), (b), and (c) correspond to exact data, low error level, and high error level, respectively (Table 2). The main difference between (b) and (c) lies in the quality of recruitment estimation. Case (b) is not reported in Fig. (d) for better readability, but has the same shape as case (c). In Fig. (c), fishing level variability is not zero for $F_{stq}$ in relation to the reference fishing mortality $F^{current}$ averaged over the three most recent years.

Table 3. Discrepancies between average yields obtained from $F_{max}$, $F_{max}(0.6)$, and $F_{stq}$ strategies. $F_{max}(0.6)$ realizes a compromise between short and long term.

| Strategy | Short term | Long term |
|---|---|---|
| $F_{max}$ vs. $F_{stq}$ | −50 000 t/yr | +100 000 t/yr |
| $F_{max}(0.6)$ vs. $F_{max}$ | +26 000 t/yr | −27 000 t/yr |
| $F_{max}(0.6)$ vs. $F_{stq}$ | −24 000 t/yr | +73 000 t/yr |

yield, any reduction in fishing effort towards $F_{max}$ level induces immediate losses with respect to that corresponding to $F_{stq}$ (Fig. 5a). A compromise between short- and long-term yield criteria is achieved with the $F_{max}(0.6)$ strategy (Table 3).

Concerning stability criteria, the transition phase generates short-term variability for other strategies than $F_{stq}$ (Fig. 5c). This transition mainly implies variation in fishing effort. Another source of variability is the random nature of real recruitment which mainly influences yield variation when the stock is heavily exploited ($F_{stq}$ in Fig. 5d). Maximum stability of yield is found for the $F_{max}(0.6)$ strategy. $F_{max}(0.6)$ is more stable than $F_{stq}$, because it is less dependent on recruitment; it is more stable than $F_{max}$, because spreading the reduction of overexploitation over a longer period reduces the interannual variation of yield.

In the same way, $F_{0.1}(\lambda)$ strategies are compared according to the various criteria in case (a) (Fig. 6). Results are quite similar to the ones obtained for $F_{max}(\lambda)$ strategies. The stability properties of $F_{0.1}$ are essentially the same as those of $F_{max}$ (Fig. 6c, d), but several $F_{max}(\lambda)$ strategies are more stable than $F_{0.1}$.

## Comparison of management strategies with error-prone data

We now consider criteria values for each $F_{max}(\lambda)$ strategy when data are subject to errors (Fig. 5). The average yield is not affected by the error level (Fig. 5a, b), results being the same as in the error-free case, but uncertainties have a big influence on stability criteria. Thus, variability of both fishing effort and yield increases with the level of error in data (Fig. 5c, d). Management strategies close to $F_{stq}$ are the most affected by estimation errors, mainly because of the continuing high dependence of the fishery upon young age-groups; this makes the accuracy of the recruitment estimation particularly important. It will be noted that when recruitment is estimated better [case (b)], $F_{stq}$ shows much less yield variability (Fig. 5c) whereas $F_{max}$ is not much modified. Figure 5c and d shows that the estimation errors influence the variability of fishing intensity in a different way, depending on the management strategy. In particular, the $F_{stq}$ strategy does not stabilize fishing effort as in the error-free case (a), although it is aimed at doing so. It even gives rise to the highest variability in both fishing intensity and yield at any time scale. Conversely, $F_{max}$ yields a more stable fishing intensity than $F_{stq}$, which was not expected *a priori*.

Compromise strategies generate the most stable yields and fishing intensity (Fig. 5c, d). In the long term (Fig. 5d), there is a joint minimum variability of both yield and fishing intensity with the $F_{max}(0.6)$ strategy; these results do not differ much for $\lambda$ ranging from 0.4 to 0.7. On the contrary, there is no common minimum in the short term (Fig. 5c). But in this case, the range of fishing intensity variability is quite narrow and yield variability is the more decisive in discriminating between strategies. The latter is at a minimum for $\lambda$ between 0.65 and 0.5, depending on the error level. Corresponding fishing intensity variability is about 15%, which is not very high compared to the minimum (12–13%) found for $\lambda = 0.1$.

Results are rather similar for $F_{0.1}(\lambda)$ strategies with error-prone data [Fig. 6 in case (c)]. Basically, the $F_{0.1}$ strategy induces a less variable yield and fishing intensity compared to $F_{max}$ (Fig. 6c, d). But once again, compromise strategies are far more stable than conventional ones. For a given $\lambda$ value, a $F_{0.1}(\lambda)$ strategy systematically induces a more stable yield than the corresponding $F_{max}(\lambda)$ strategy. This is probably due to a reduced dependence upon recruitment. An important point is that at least three $F_{max}(\lambda)$ strategies (0.4 to 0.6) are more stable than the conventional $F_{0.1}$ strategy (Fig. 6c, d). For instance, $F_{max}(0.4)$ is very close to $F_{0.1}$ in terms of stability and long-term yield (Fig. 6b, d), but it results in much higher short-term yields (Table 4).

## Unexpected extreme cases

One issue left from the analysis to this point is the possibility of some exceptional development of the stock and fishery. All the above results rely on estimations of expected values and therefore may not reflect particular behaviours of some simulations. However, uncertainties in fishery assessment may actually induce management errors, and in particular growth overfishing may increase unwantedly in the case of heavily exploited stocks. Such unforeseen situations are all the more likely to happen since the data used in the assessment are subject to errors.

Individual developments of the fishing intensities and TAC values were examined from the simulations (Fig. 7). Divergence of trajectories is greater for status quo management. The fishing intensity tends to diverge markedly during the management period (Fig. 7a) as errors accumulate and predictions become more uncertain. Some trajectories lead to a very marked overexploitation. TAC values show the same pattern (Fig. 7d), but they never fall below 100 000 tonnes because the average recruitment is kept constant at its historical mean value, any stock-recruitment relationship being neglected. The

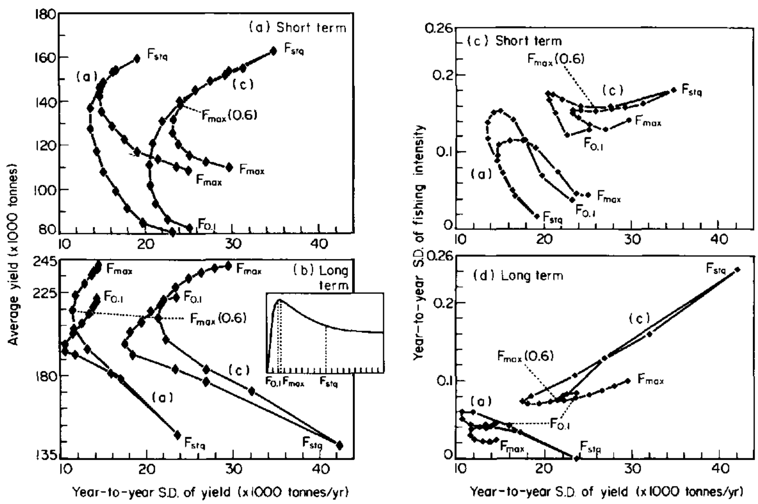


Figure 6. Criteria values for $F_{0.1}(\lambda)$ strategies with $\lambda$ ranging from 0 ($F_{0.1}$) to 1 ($F_{stq}$). Curves (a) and (c) correspond to exact data and high error level, respectively. Results for $F_{max}(\lambda)$ strategies are also reported so that these two families of strategies may be compared.

Table 4. Discrepancies between average yields obtained from $F_{0.1}$, $F_{max}(0.4)$, and $F_{stq}$ strategies.

| Strategy | Short term | Long term |
|---|---|---|
| $F_{0.1}$ vs. $F_{stq}$ | −80 000 t/yr | +81 500 t/yr |
| $F_{max}(0.4)$ vs. $F_{stq}$ | −36 000 t/yr | +86 000 t/yr |
| $F_{max}(0.4)$ vs. $F_{0.1}$ | +46 000 t/yr | +4500 t/yr |

procedure of setting average recruitment at its historical mean leads to optimistic yield values and may hide a decline of the stock. In some simulations (not reported herein), the stock is found to collapse around the 35–37th year. Such a situation is only found to occur for management following $F_{stq}$ and $F_{max}(0.9)$ strategies, and relates to the particularly high variability of fishing intensity these strategies exhibit in the long term in the case of error-prone assessments (Fig. 5d). Clearly, compromise and $F_{max}$ strategies lead to less variable yield and fishing effort (Fig. 7b–f) and the risk of increasing overexploitation in relation to assessment errors is avoided. Individual trajectories for $F_{0.1}(\lambda)$ strategies are not reported since results are quite similar.

## Influence of initial level of overexploitation

The implications of different management strategies will necessarily depend on the initial degree of overexploitation; this applies particularly to the stability properties of compromise strategies. In order to study the sensitivity of strategies to initial conditions, a range of several initial fishing mortalities were defined from the previous example and a parameter Q as follows:

$$F'_{ay} = Q\,F_{ay}. \tag{10}$$

For consistency with equation (A.4), effort data were modified as:

$$E'_{yf} = Q\,E_{yf}. \tag{11}$$

Similarly, stock sizes were computed from VPA equation as:

$$N'_{a+1,y+1} = N'_{a,y}\exp(-QF_{ay} + M_a)$$
$$N'_{a,1} = N_{a,1}. \tag{12}$$

Stability criteria were calculated for each value of Q and for each strategy $F_{max}(\lambda)$ with $\lambda$ ranging from 0 to 1. An optimum value of $\lambda$ was determined for each stability criteria (Table 5). The average yields were not computed since they were proved to be insensitive to the uncertainties considered.

Yield variability is shown to increase with initial overexploitation, while the opposite is true for the variability of fishing intensity (Fig. 8). However, whatever the compromise strategy, this latter variability does not depend much on the initial overexploitation, most values ranging between 14 and 18% in the short term (7–15% in the long term).

Conventional $F_{stq}$ and $F_{max}$ management strategies behave in unexpected ways in these circumstances. Thus,

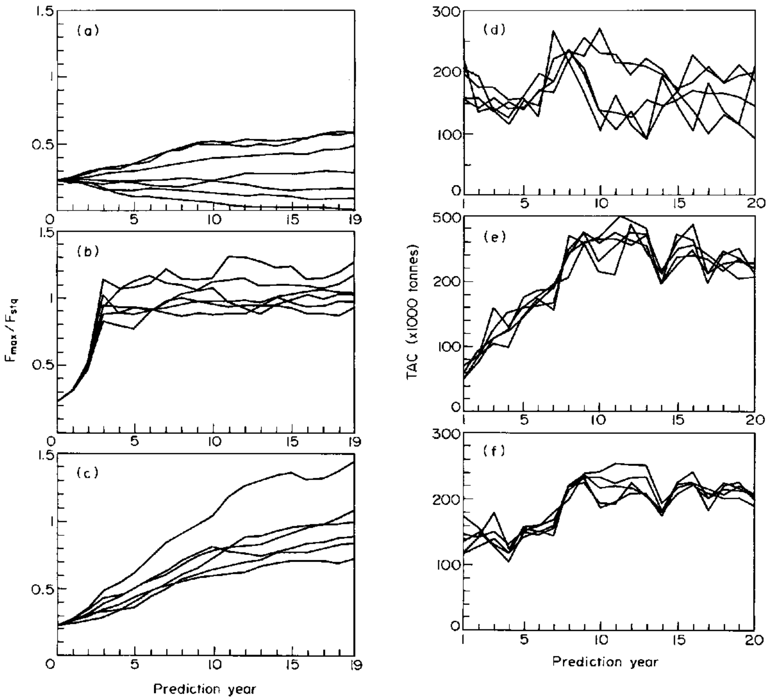


Figure 7. (a)–(c) Some individual developments of fishing level obtained by simulations for three $F_{max}(\lambda)$ strategies with $\lambda = 1$ (a), $\lambda = 0$ (b), $\lambda = 0.6$ (c). The error level (c) is chosen. Scattering evolutions are the consequences of estimation errors in input data plus the variability of recruitment. (d)–(f) Some individual developments of TAC values obtained by simulations for three $F_{max}(\lambda)$ strategies with $\lambda = 1$ (d), $\lambda = 0$ (e), $\lambda = 0.6$ (f). These plots correspond to those of Figs 7(a)–(c).

Table 5. Optimum values of $\lambda$ for several initial exploitation levels. A Q value can be compared to the initial level of overexploitation quantified by $F_{max}/F_{stq}$.

| | | Short term | | Long term | |
|---|---|---|---|---|---|
| Q | $F_{max}/F_{stq}$ | Stab(Y) | Stab(F) | Stab(Y) | Stab(F) |
| 1 | 0.228 | 0.4 | 0.1 | 0.6 | 0.6 |
| 0.9 | 0.254 | 0.5 | 0.1 | 0.7 | 0.6 |
| 0.5 | 0.457 | 0.6 | 0.2 | 0.9 | 0.7 |
| 0.25 | 0.914 | 0.8 | 0.4 | 1 | 0.8 |

$F_{stq}$ induces maximum variability only when the initial overexploitation is very severe (Q = 1) (Fig. 8) but it results in the most stable yield for an initial fishing intensity close to $F_{max}$, which was not expected *apriori*. Conversely, $F_{max}$ is the less stable strategy as soon as Q is lower than 1. When the stock is exploited around $F_{max}$ level, $F_{stq}$ is even more stable.

Whatever the initial degree of overexploitation, optimum regimes in terms of the criteria studied almost always require compromise strategies (Table 5). Optimum values of $\lambda$ increase as the initial fishing intensity falls, i.e. strategies close to $F_{stq}$ become more acceptable when the stock is initially less heavily overexploited. In the long term, there is nearly always a joint minimum variability of yield and fishing intensity with $\lambda$ ranging from 0.6 to 0.8 (Fig. 8b). Short-term optimum values do not coincide as well, although the stabilities of compromise strategies converge as initial overexploitation decreases (Fig. 8a).

## Stability of strategies and uncertainties in input parameters

The previous results illustrate how the behaviour of the model changes in relation to (i) the level of uncertainty, (ii)

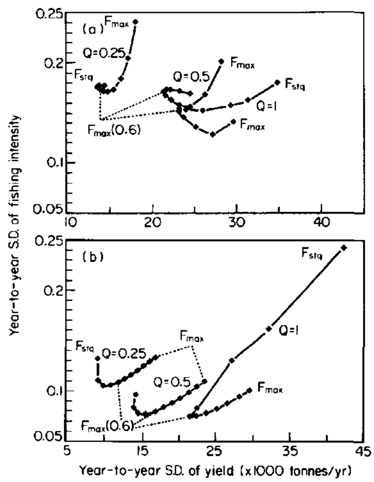

Figure 8. Stability criteria values (a = short-term, b = long-term variability) plotted for three initial levels of overexploitation represented by the value of Q. Q = 1, 0.5 and 0.25, respectively correspond to the very high overexploitation already analysed before, a serious overexploitation, and an initial fishing level close to $F_{max}$ (Table 5). The highest error level (c) is chosen.

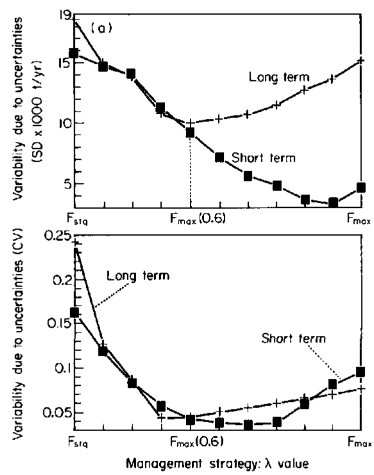

Figure 9. Variabilities of yield (a) and fishing effort (b) caused by uncertainties in the initial case where Q = 1. These quantities correspond to the discrepancy between results for the maximum error level (c) and for the error-free case (a). It is hence assumed that variabilities due to regulation and to uncertainties are additive.

the initial fishing intensity and (iii) the management strategy. These changes are caused by different sensitivities to parameters. When data are perfectly known, variability is caused either by regulation of fishing effort, or by natural variability of recruitment. On the other hand, when data are error-prone, all the sources of variation, including uncertainties in data, interact within the model. So, running the model with and without uncertainties in particular data enables one to determine which parameter causes the variability associated with a given management strategy. Obviously, compromise strategies are less sensitive to parameter uncertainties (Fig. 9) and this is true whatever the initial conditions. Approximately half the corresponding short-term variability is due to uncertainties and half to the regulation of fishing effort. Long-term variability is mainly due to uncertainties, because the mean fishing intensity is quasi-stabilized.

A prime cause of variability is recruitment, whether due to its natural variation or to estimation error, especially at very high levels of exploitation such as $F_{stq}$ in the initial example (Q = 1) (Fig. 8). Notice the difference between curves for Q = 0.5 and Q = 1 in Fig. 8b: the increased stability of strategies close to $F_{stq}$ when Q decreases is due to a lesser dependence of the fishery state upon the recruiting year-class. Yield is more sensitive to recruitment than fishing effort, because of the formulation of the model.

Variability may also be due to uncertainties in other parameters, e.g. VPA parameters. This is enhanced by a poor convergence of VPA at low fishing intensities (Pope, 1972). For instance, the sensitivity of the conventional $F_{max}$ strategy, which generates the most variable yield and fishing intensity in any case, except for Q = 1, is not really tied to $F_{max}$ estimation but to a poor convergence of VPA. Indeed, additional results (not reported herein) indicate that in this case, the error in $F_{max}$ estimation may even compensate some other sources of errors in $F_{max}$ strategies. The lack of convergence for VPA is also evident at an initial fishing intensity close to $F_{max}$ (Q = 0.25); fishing intensity is then more variable, e.g. $F_{max}$ for Q = 0.25 in Fig. 8b. In general, fishing intensity seems more sensitive than yield to a poor VPA convergence.

Finally, apart from VPA parameters, weight-at-age data are also needed for assessment, and estimation errors in them influence results at any fishing intensity and for any strategy. Furthermore, as fishing intensity decreases, a higher proportion of the yield consists of older fish. In this example, the coefficient of variation of weights is constant over ages, so that the variance of weight-at-age is greater for older age-groups. Errors in weight-at-age will therefore matter more when fishing intensity diminishes, namely at a low Q values and for strategies close to $F_{max}$.

## Conclusions

This analysis first explores the dependence of model sensitivity upon the initial state of the stock on the one hand, and upon the chosen management strategy on the other hand. Sensitivity is determined by studying how the model responds to error-prone data, and appears highly dependent upon the error level. In particular, $F_{stq}$ and $F_{0.1}$ management strategies are then diverted from their initial targets.

The different sources of uncertainty considered in the study do not affect the value of average yield, but they influence the variability of both fishing intensity and yield. At high fishing intensities, the risk of increasing growth overfishing, which is zero when there are no estimation errors in input data, increases with these uncertainties. In this case, the increased variability and risks are mainly the consequence of uncertainties in recruitment. At low fishing intensities, variability is due to uncertainties in VPA data coupled with a poor VPA convergence. Errors in weight-at-age data influence variability in all circumstances.

These results provide guidelines for the choice of a management strategy appropriate for reducing overexploitation to a $F_{max}$ level, taking account of the uncertainties inherent to assessments. A straightforward application of $F_{max}$ or $F_{0.1}$ management would induce social and economic problems and continuing with $F_{stq}$ would perpetuate the initial overfished state. So, the question is: How to increase yield in the long term, without losing too much in the short term? Solving this problem is moreover subject to stability constraints on fishing intensity and yield, in relation to the industry. In this respect, $F_{max}$ and $F_{0.1}$ strategies do not perform well because the consequences of uncertainties in VPA input parameters are serious owing to the lack of convergence of VPA. In addition to leaving the regulation question unsolved, the $F_{stq}$ strategy is not suitable for severely overexploited stocks because of its important dependence upon recruitment, estimation of which is a perennial problem for stock assessments.

Given the criteria chosen in this study, compromise $F_{max}(\lambda)$ strategies outperform $F_{max}$, $F_{0.1}$ and $F_{stq}$ and $F_{0.1}(\lambda)$ strategies. Firstly, they allow for a simple and efficient regulation within a few years. Short-term yield is modestly reduced (with respect to the initial situation) and only for 3 years. The fishing intensity can be reduced to $F_{max}$ within about 15 years. Secondly, a compromise strategy stabilizes yield and effort at best in the long term. In the short term, there is a trade-off for stability between yield and fishing effort. For compromise strategies, the interannual variability is both due to uncertainties and to the continuous descending trend of fishing level. Uncertainties generate random variation, but the trend over time of fishing intensity can, in principle, be anticipated, which is important for the industry purpose, and therefore it enhances the relevance of compromise strategies.

The new strategies studied herein exhibit properties that represent more than a compromise between conventional strategies. Although it was *a priori* obvious that such strategies allow for a trade-off of yield between short and long term, their stability was not expected to be so marked. Compromise strategies are less sensitive both to uncertainties in input parameters and to a lack of VPA convergence. Even when the fishery is close to equilibrium, they perform better with respect to uncertainties. Getz *et al.* (1987) also showed that different strategies can exhibit different behaviours even in an equilibrium situation.

Finally, one must choose more precisely a rebuilding strategy. The modulation of $\lambda$ does not change the properties of compromise strategies, but it allows for flexibility in management. As a measure of the intensity of regulation, the choice of a $\lambda$ value may be connected with the choice of a time horizon to rehabilitate the fishery (Rosenberg and Brault, 1990). Long-term properties always favour compromise strategies with $\lambda$ about 0.7, depending on the intensity of the regulation required.

However, the crucial phase is the transition one, which corresponds roughly to the short-term stage considered. During this period, a compromise has to be found between different criteria, and the quantification of respective costs of objectives will help to choose between the compromise strategies that are desired in the long term. The evaluation of the costs is largely dependent upon the fishery or even on the fleet considered. In this study, no costs are associated with variability of yield and effort, nor with the average yield, so that we cannot contrast, for example, the importance of a 15% fishing intensity variability with a 15 000 tonnes per year yield variability. For the same reasons, we cannot decide whether it is preferable for the industry to be exposed to a predictable diminution of 15% in yield (namely a descending trend due to regulation) or to a random yield variability of 10%. However, predictability is desirable in its own right, especially with overexploited stocks, since its absence encourages short-term, *ad hoc,* management.

Uncertainties in input data must be regarded as irreducible beyond a certain level, and when they cannot be reduced further, management strategies should be adapted in consequence. Thus, the concept of "management under uncertainty" becomes very relevant, particularly if stability objectives are pursued, as previously outlined by Horwood *et al.* (1990). Although these results should not be facilely generalized to any stock assessment, they are of some interest for real-world fisheries (Rivard and Maguire, 1991). The criteria used should be assessed in economic terms, so that they may be contrasted to quantify their respective interests. This is outside our scope and is more within the competence of socioeconomists.

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## Appendix: models used for the assessment of age-structured stocks

### Virtual population analysis

Complete equations of virtual population analysis (VPA) (Gulland, 1965) are used:

For each age group a and year y:

$$N_{a+1,y+1} = N_{ay} \exp[-(F_{ay} + M_a)] \tag{A.1}$$

$$C_{ay} = N_{ay} \frac{F_{ay}}{F_{ay} + M_a} \{1 - \exp[-(F_{ay} + M_a)]\}, \tag{A.2}$$

where $C_{ay}$, $N_{ay}$, $F_{ay}$, and $M_a$ are, respectively, the catches and stock sizes in numbers, the fishing mortality and the natural mortality rates in $yr^{-1}$.

Equation (A.2) is modified for the last age group which is a plus group corresponding to fishes of age A and older:

$$C_{A,y} = N_{A,y} \frac{F_{A,y}}{F_{A,y} + M_A}. \tag{A.3}$$

Terminal fishing mortalities are estimated by a so-called calibration technique according to Laurec and Shepherd (1983). This means that separability of fishing mortality is assumed for each fleet with catchabilities-at-age q constant from year to year as shown in:

$$F_{ayf} = q_{af} E_{yf}, \tag{A.4}$$

where a stands for age group, f for fleet and y for year. $F_{ayf}$ is linked to $F_{ay}$ via the relationship:

$$F_{ayf} = F_{ay} \frac{C_{ayf}}{C_{ay}}. \tag{A.5}$$

Once fishing mortalities and stock sizes are estimated, a reference fishing mortality vector is derived as the mean F over the last three years. This reference vector $\mathbf{F}^{\mathbf{current}}$ is required for diagnoses and projections.

### Equilibrium yield per recruit model

The equilibrium yield per recruit (Beverton and Holt, 1957) is computed for the fishing mortality $\mathbf{F}^{\mathbf{current}}$:

$$Y_r = \sum_{a=1}^{A-1} \frac{F_a^{current} W_a S_a}{Z_a} (1 - \exp(-Z_a)) + \frac{F_A^{current} W_A S_A}{Z_A}, \quad (A.6)$$

where a indexes age group; $W_a$ is the reference mean weight at age a in the stock, generally the estimates for the most recent year (mean weights are constant within a year); $Z_a$ is the overall mortality rate given by $Z_a = F_a^{current} + M_a$; $S_a$ is the proportion of survivors with respect to knife-edge recruitment:

$$S_a = \exp\left(\sum_{j=1}^{a-1} Z_j\right).$$

Basically, the yield per recruit model assumes that both recruitment and fishing mortality are steady over a sufficient range of time, at least for a generation of fish, allowing the stock to reach equilibrium.

Given the exploitation pattern corresponding to $\mathbf{F}^{current}$, yield per recruit may be computed for a range of fishing intensities denoted by μ:

$$Y_r = \sum_{a=1}^{A-1} \frac{\mu F_a^{current} W_a S_a}{Z_a} (1 - \exp(-Z_a)) + \frac{\mu F_A^{current} W_A S_A}{Z_A}, \quad (A.7)$$

where $Z_a = \mu F_a^{current} + M_a$.

Plotting the yield as a function of μ enables one to determine the values of $F_{max}$ and $F_{0.1}$, and to investigate the long-term consequences of changes in the fishing level.

## Total allowable catch (TAC) computations

Knowing the present stock sizes and biological parameters, a TAC may be computed for the forthcoming year from:

$$TAC_{y+1} = \sum_{a=1}^{A-1} W_a N_{a,y+1} \frac{F_a^{target}}{F_a^{target} + M_a} \{1 - \exp[-(F_a^{target} + M_a)]\} + W_A N_{A,y+1} \frac{F_A^{target}}{F_A^{target} + M_A}. \quad (A.8)$$

$\mathbf{F}^{target}$ is the "target" mortality vector. For a given exploitation pattern $\mathbf{F}^{current}$, it may correspond to different fishing intensities, i.e. $F_{max}$, $F_{0.1}$, or $F_{stq}$. Each option leads to different catch projections. Stock sizes at the beginning of the forthcoming year are computed from equation (A.1), except for the first age-group, i.e. the recruitment, which is generally estimated from abundance indices. Mean weights and natural mortality are assumed to be the same as the previous year, i.e. reference values.