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Toward More Efficient TAC Policies with Error-prone Data

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Abstract

Classical management strategies try to maximize quantities such as production in weight or in value, or stability of fishing effort or yield. As noted previously by various authors, these objectives are in principle incompatible. This study aims to determine intermediate TAC management rules that constitute a compromise between several criteria and could be more useful than the usual rules. An artificial stock and fishery are simulated, resembling the North Sea cod. The intense exploitation of this stock enables one to study the problems posed by the transition toward lower exploitation levels. Furthermore, different sources of uncertainty are considered for all input data within the simulation.

For each year, diagnoses about the stock situation are realized according to the Laurec and Shepherd tuning technique from the software used in ICES. Catches are projected for several strategies such as F_{max}, $F_{0.1}$, *status quo* F and intermediate rules. Results suggest potential benefits for the composite rules, particularly considering interannual stability of yield and fishing effort. These gains do not necessarily imply important losses with regard to other criteria.

Introduction

Management of marine fish stocks is often based on setting a total allowable catch (TAC). Determination of the TAC may rely on very different management objectives, for instance setting constant effort, constant catch or biomass escapement, or to achieve maximum catch. Comparisons of these various strategies have been much addressed in the literature. In this context, substantial attention is devoted to the influence of uncertainties in data on the resulting management policies. Many papers deal with surplus production models (Ludwig, 1981; Getz *et al.*, 1987; Koonce and Shuter, 1987; Koslow, 1989; Murawski and Idoine, 1989) and age structure analyses are also found (Ruppert *et al.*, 1985; Hightower and Grossman, 1985, 1987). When comparing management strategies under uncertainty, most papers focus on recruitment variability through a stock-recruitment relationship plus a model error. To our knowledge, no study dealing with uncertainty about other parameters could be found, although some of these, for example weights-at-age data, are known to be crucial for catch projections (Rivard, 1981). In this paper, we are interested in almost all parameters, including recruitment. Uncertainty refers to either intrinsic variability, sampling error or other estimation error. When dealing with uncertainty, our primary goal is not to estimate parameters, but to characterize strategies with respect to some predefined criteria. Besides, the paper is focused on the rehabilitation of an overexploited stock. By overexploited, we mean that the current exploitation level is far beyond the biological optimum F_{max}. Problems posed by transition toward lower fishing levels essentially consist in a tradeoff between short-term and long-term objectives. Amazingly, we could not find this problem handled in the literature, which always refers to long-term analyses. Of course, this particular point is relative to the severity of overexploitation of the stock studied. Short-term transitions imply economic and social problems connected with lower yields. Some papers include such consideration as criteria, but only in the long-term (Charles, 1989). In this study, emphasis is given to the short-term by developing analogous criteria for both short- and long-term.

Viable solutions for practical use must also exhibit some predictability properties, i.e. effort and yield must be stable rather than variable from year to year, even if evolving over time. This aim is not necessarily achieved by maximizing yield and is more characteristic of constant effort or constant catch strategies (Getz *et al.*, 1987; Murawski and Idoine, 1989). Stability criteria for fishing level and yield as well as maximization of yield are considered in this paper. However, no attention is devoted to economic quantifications.

Finally, when searching for an optimal rule, one must not forget that it must be understandable and easy to use by decision makers (Gulland and Boerema, 1973). To cope with this problem compound rules are first defined in a simple way. These rules are intermediate between rules commonly used for stock assessment. Their properties are then evaluated with respect to criteria mentioned above. The procedure used is as close as possible to actual ICES assessments in order to show that better management strategies may be built simply. These strategies explicitly realize some compromises that could happen *de facto* at a decision level.

Models and Hypotheses

Dynamic model

The simulation aims at reproducing the current procedure of assessment used in the ICES framework for age-structured stocks. Complete equations of virtual population analysis (VPA) are used, including treatment of a plus-group. Terminal fishing mortalities are estimated by an *ad hoc* tuning using the Laurec and Shepherd (1983) technique. This means that separability of fishing mortality is assumed for each fleet with catchabilities-at-age q constant from year to year as showed in:

$$F_{ayf} = q_{af} E_{yf} \qquad \ldots(1)$$

where a stands age-group, f for fleet and y for year.

For simulation purposes, the *ad hoc* tuning stage is not interactive. Among the various tuning options, years are equally weighted and terminal fishing mortality estimators are weighted by inverse catchability variances. After the final VPA, a reference fishing vector is derived as the mean F over the three last years. This reference is the *status quo* vector required for diagnoses and projections.

Prognosis is provided by an equilibrium yield-per-recruit computation following the Thompson and Bell (1934) model, i.e. mean weights-at-age are constant within a year. Considering a constant exploitation pattern, F_{max} and $F_{0.1}$ values are calculated relative to *status quo* F (F_{stq}). Catch projections are computed for the levels of exploitation defined by F_{max}, $F_{0.1}$ and F_{stq}. Corresponding TACs are noted as TAC (F_{max}), TAC ($F_{0.1}$) and TAC (F_{stq}). Intermediate management rules, described in the next section, are also tried. Once the rule has been chosen, the resulting TAC value for year y+1 is assumed totally taken with a constant exploitation pattern so that the corresponding fishing mortality vector F is obtained by iterative solution of:

$$TAC_{y+1} - \sum_{a=1}^{NA-1} W_{a,ref} N_{a,y+1} \frac{F_{a,y+1}}{F_{a,y+1}+M_a} (1-\exp(-(F_{a,y+1} + M_a))) - W_{NA,ref} N_{NA} \frac{F_{NA,y+1}}{F_{NA,y+1}+M_{NA}} = 0. \qquad \ldots (2)$$

where:

y — is the current year.

NA — is the oldest age group.

$W_{a,ref}$ — is the reference weight-at-age for predictions. It is calculated as a mean value over a chosen range of years. In the application, reference weights are last year data.

For each age-group a, fishing mortality for year y+1 is:

$$F_{a,y+1} = \mu_{y+1} Fstq_{a,y} \qquad \ldots (3)$$

where μ_{y+1} is hence obtained by solving equation (2). μ_{y+1} is first calculated with true values of fishing mortalities and stock sizes along with the TAC decided, leading to the nominal fishing effort that will actually be necessary to fish the TAC. Then, a second value is calculated from VPA results, leading to the effort required to fish the TAC as "believed" by the working group.

Concerning disaggregated data, fleets with effort data are assumed to take a constant part in the fishery, i.e. effort $E_{y+1,f}$ for fleet f is predicted by:

$$E_{y+1,f} = \mu_{y+1} E_{y,f} \qquad \ldots (4)$$

Values of catch-at-age and disaggregated data for the prediction year are inferred from the estimations of $F_{a,y+1}$ and $F_{a,y+1,f}$ respectively given by equations (3), and (1) along with (4). Again, "believed" and nominal values are computed for effort $E_{y+1,f}$. New data are hence obtained for year y+1. As we refer to annual assessment, real data calculated from actual stock values will be used for the next prediction[1]. These new data are modified by introducing estimation error and are then added to the previous dataset so that an assessment is possible for year y+1 and a prediction for year y+2. The simulation is intended to run 50 years beyond the calibration stage in order to study short- and long-term effects. As no relation is considered between stock and recruitment, actual recruitment follows a log-normal distribution over time showing its natural variability.

[1] If assessment is not annual, the program makes it possible to predict for year y+2 with "believed" data, i.e. obtained from VPA results in equations (2) and (4). In this case, no noise is added to data before assessment for year y+2.

Uncertainties in input data

The consequences of uncertainty in input data is evaluated by considering a stochastic component for most data, except for natural mortality. Weights-at-age, catches-at-age and catch-per-unit-effort (CPUE) indices are supposed to be normally distributed with given coefficients of variation, which represent the estimation error of these data. A constant, i.e. age-independent coefficient of variation implies that variance is a quadratic function of mean for each datum. Effort data also follow a normal law reflecting exploitation and catchability unpredictable variability, which perturbs the separability relation described by equation (1). Distribution parameters are estimated from the historical series of data for each fleet. Mean and variance are computed from previous VPA results. An estimation error is also associated to the real recruitment and described by a Gaussian distribution with a fixed coefficient of variation. When no information on abundance is available in due time to estimate recruitment, it is estimated by the historical mean over stock sizes at the first age obtained from VPA.

In these simulations, two levels of errors in input data were considered besides the error-free case. The first one corresponds to rather serious uncertainties, which are plausible for some assessments. The second is some minimum level of uncertainty that would be difficult to reduce without unbearable additional sampling costs. They are reported below in Table 1. Some of the values are obviously rather empirical.

Introducing uncertainty in data probably modifies assessment results. All decisions are taken from estimated stock situation and their implications are also estimated. As the example relies on artificial although realistic data, it makes it possible to evaluate the actual consequences of management based on error-prone data and to compare the real diagnoses and predictions with those previously desired.

TAC Management Strategies

Classical management options

TAC management is commonly used within both the NAFO and ICES framework. Diagnostic models lead to the definition of several fishing intensities for a given exploitation pattern such as *status quo* F, F_{max} or $F_{0.1}$. Corresponding TACs are calculated by catch projection models.

With respect to F_{max} policy, yield is maximized and fishing effort is stabilized in a deterministic model[2] when the fishery has reached an equilibrium. Logically, this is not the case for the recovery stage. The duration of this phase depends on the exploited lifespan.

TABLE 1. Different cases of uncertainty considered in the simulation. (CV = coefficient of variation.)

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%	"
(a)	no error	Actual value	0%	0%

Moreover, as recruitment is not constant, other management strategies could indeed lead to larger cumulated catches. Other data are also subject to errors and the relationship between fishing effort and fishing mortality may be perturbed. In this case, the F_{max} strategy implies variable fishing efforts, as well as yearly changes in yield due to recruitment.

The so-called *status quo* policy (referred to as F_{stq}) aims to stabilize fishing effort through fishing mortality and should lead to higher catches than F_{max} in the short-term. But, as for F_{max}, neither fishing effort nor fishing mortalities can be stabilized when uncertainties in data are taken into account. However, weights-at-age variability will affect F_{max} but not F_{stq} estimation.

Considering $F_{0.1}$, it is somewhat difficult to define the underlying criterion one should maximize. $F_{0.1}$ rather seems to be an implicit compromise between various criteria. Indeed, the $F_{0.1}$ strategy admits a moderately reduced yield as a counterpart for increased stability of annual yields, CPUE, as well as better economical returns (Smith, 1981). It also gives a safety margin with respect to the risk of recruitment overfishing, except in the case of special stock-recruitment relationships.

Compound strategies

Yearly negotiations commonly lead in practice to some intermediate choice between the policies previously mentioned. However, such intermediate rules are not found in the literature to our knowledge, except briefly in Laurec and Maucorps (MS 1981). Indeed, they correspond to multi-criteria decisions. Within the infinity of compound strategies, we focused on mixed options between F_{stq} and F_{max} on the one hand, F_{stq} and $F_{0.1}$ on the other hand. A simple composite policy between F_{stq} and F_{max} is given for each year by:

$$TAC = \lambda TAC\ (F_{stq}) + (1 - \lambda) TAC(F_{max}) \quad ... (5)$$

The parameter λ in the range [0.1] enables one to define a smoother transition toward lower fishing levels, especially for strongly overexploited stocks. Resulting TAC corresponds to a targeted level of fishing mortality compromising between F_{max} and F_{stq}. Values of 0 or 1 for λ lead to classical management options. This strategy will be referred as F_{max}–λ strategy in the following.

[2] i.e. no data is error-prone and moreover, no parameter is intrinsically variable.

A similar composite rule is achievable for F_{stq} and $F_{0.1}$ as:

$$TAC = \lambda TAC(F_{stq}) + (1 - \lambda)TAC(F_{0.1}) \quad \ldots (6)$$

It will then be referred as $F_{0.1}-\lambda$. More sophisticated combinations could of course be considered, for instance a weighted average of more than two of the basic levels of fishing mortality. One could also adapt the combination when approaching the equilibrium situation. Note that any strategy where λ is not 0 depends on initial conditions at any year of the prediction phase. This is all the more true because reference F is the mean over three years and hence introduces some inertia in the management.

Various Criteria to Assess Strategies

Management strategies are to be assessed and compared. Hence, one or more criteria must be defined. We have not tried to define an integrated bio-socio-economic criterion. The study is focused on the inevitable choice between maximization of total yield in weight and stability of exploitation or yield over time. More precisely, we are interested in year-to-year changes in yield and fishing effort, keeping out at this stage yearly variations in CPUE.

The simulated fishery is severly overexploited so that a transition phase is necessary to recover to equilibrium. Hence, short-term management has to be distinguished from that in the long-term. Analysis of several simulations show that a five year management period is the basic recovery stage. Besides, after 10 years the fishery tends in most cases to be stabilized. Some compound strategies require up to 20 years for the fishery to reach an equilibrium, but in practice, economic considerations make it irrelevant to manage beyond a 20-year horizon. In the same way, it seems dubious that the exploitation pattern is constant for such a long time. Finally, as initial conditions are consisted in 10 years data, predictability is likely to be negligible on a long-time scale. So years 10 to 20 are associated with the long-term stage. Cumulated yields are considered for each period.

Concerning stability criteria, several indices are defined for both yield and the overall measure of effort defined in equation (5) as μ. Yield stability criteria are given by:

$$I_{sht}^{yield} = \sqrt{\frac{1}{100} \sum_{i=1}^{100} \frac{1}{5} \sum_{y=1}^{5} (Y_{i,y+1} - Y_{i,y})^2} \quad \ldots (7)$$

$$I_{lgt}^{yield} = \sqrt{\frac{1}{100} \sum_{i=1}^{100} \frac{1}{11} \sum_{y=9}^{19} (Y_{i,y+1} - Y_{i,y})^2} \quad \ldots (8)$$

where i represents a simulation, and for the exploitation level:

$$I_{sht}^{fish} = \sqrt{\frac{1}{100} \sum_{i=1}^{100} \frac{1}{5} \sum_{y=1}^{5} (\mu_{i,y+1} - 1)^2} \quad \ldots (9)$$

$$I_{lgt}^{fish} = \sqrt{\frac{1}{100} \sum_{i=1}^{100} \frac{1}{11} \sum_{y=9}^{19} (\mu_{i,y+1} - 1)^2} \quad \ldots (10)$$

where sht and lgt mean short-term and long-term respectively.

Indices in equations (9) and (10) should be thought of in terms of relative variation of the exploitation level because for each age-group a:

$$\mu_{y+1} - 1 = \frac{F_{a,y+1} - F_{a,y}}{F_{a,y}} \quad \ldots (11)$$

These indices estimate the expected year-to-year variability of yield and effort. Note that the starting year is not taken into account in the above expressions because y = 1 represents the first prediction year. So, the accidental discrepancy between the first prediction and the first assessment year does not appear in the results. It is obvious that in the case of non-*status quo* strategies, some variability is hence neglected.

Mathematical expectations quoted in the previous paragraph are estimated by means over 100 simulations which may not always reflect the global behaviour of individual replicates. A simple average can smooth out interesting features of the distribution concerned. For instance, Laurec *et al.* (1980) showed that bimodal distributions could be obtained by simulations. This problem could be overcome by considering empirical distributions of results obtained by simulations. Nevertheless, the results for variances suggest that this shortcoming is not likely to occur here, so that calculated means for indices actually characterize management strategies reasonably well.

Construction of the Example

Artificial data make it possible to monitor the "actual" stock situation. Simulations allow to study the discrepancy between the estimated stock and fishery parameters but this is not our purpose herein. The main goal of this study is to evaluate the consequences on the actual stock and fishery of decisions based on estimated situations.

Data are built from working group results so that the example studied resembles the North Sea cod, i.e. a typically overexploited stock. Figure 1 shows that the

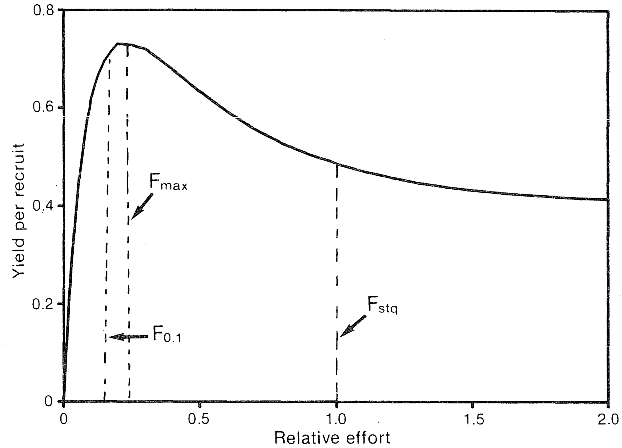

Fig. 1. Equilibrium yield curve for the simulated stock. On the X-axis, effort is relative to reference fishing mortality calculated before prediction phase.

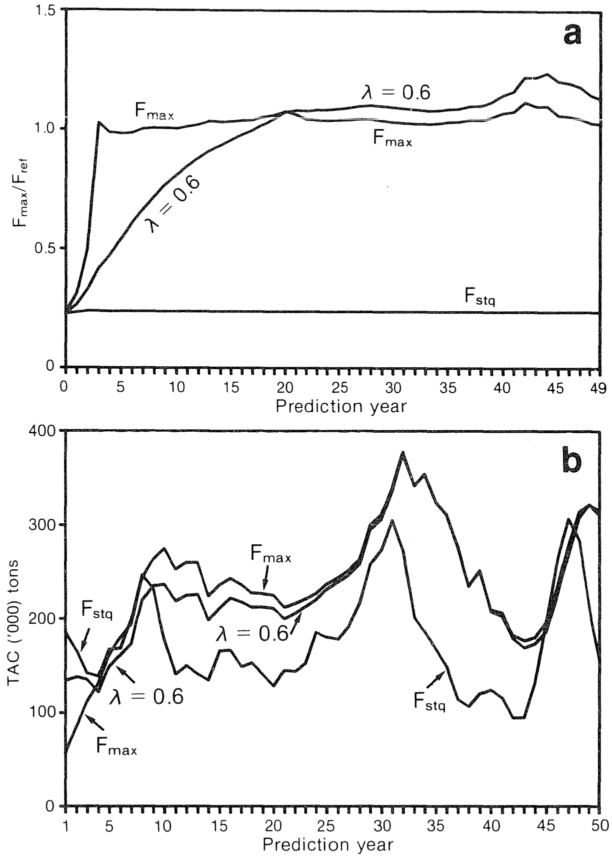

Fig. 2. Transitions of fishing level (**a**) and TAC values (**b**) towards equilibrium for a compound F_{max}–λ strategy with exact data [TAC = λTAC(F_{stq})+1(1–λ)TAC(F_{max})].

average fishing level is at present about four times above F_{max}. Actual fishing mortalities and stock sizes are hence generated, from which catches are calculated, using the classical catch equation. Effort data and catchabilities are also generated so that CPUE indices are computed. These true data are then modified by introducing uncertainty in order to obtain "estimated" data resulting for example from sampling, adjustment or any estimation methods. Finally, estimated data are used for stock assessment.

Results

Composite strategy between F_{max} and F_{stq}

Theoretical response of the stock and fishery to management: A first analysis is made without errors to assess the theoretical dynamics of the stock and fishery and their response to management with classical and compound strategies. Three values of λ are tried: 0(F_{max}), 1(F_{stq}) and 0.6. Real recruitment is randomly variable from year to year as described in a previous section. Figure 2a indicates the approach of fishing level to the F_{max} level. F_{stq} is perfectly stable as it is supposed to be. The F_{max} level is only reached after 3 years, due to the definition of reference F, which is the mean F over the three last years. This reference F influences F_{max} calculation. Note that all the other strategies imply a transition period of variable length. For a compound stretegy, equilibrium is not complete after 20 years, but it is very close to ($F_{max}/F_{ref} = 0.975$). Stabilization at a level closer to F_{max} is found to appear around 30 years. This fishing level is slightly lower than F_{max}. Years 22 and 43 show small peaks probably due to very strong recruitment that happened 10 years earlier and influenced fishing mortalities.

Recall that F_{max}/F_{ref} does not depend directly on recruitment, this explains the smooth aspect of the curve in Fig. 2a compared to Fig. 2b. TAC values show important variability in all cases, in relation to changes in recruitment. However, some remarks may be drawn from this figure. First, the F_{max} strategy generates gains in yield with respect to F_{stq} after the 4th year, whereas with the compound strategy, it occurs a little later. The main advantage of the compound strategy here is a moderate loss on the short-term and a substantial gain on the long-term.

Comparison of rules from different criteria: In the following, different error cases are referred to as in Table 1. Let us first consider long-term effects (Fig. 3a and 3b). Logically, F_{max} maximizes cumulated yield in a stabilized situation (Fig. 3a). However, yield loss compared to F_{max} is not so important for values of λ up to 0.6, say less than 30,000 tons per year (21,000 tons for λ = 0.5, 13,000 tons for λ = 0.4). In terms of interannual variation of yield, stability is maximum for λ = 0.6. F_{stq} is less stable than F_{max}, especially when data are error prone. This is due to the continuing high dependence of the fishery upon young age-groups and particularly to recruitment estimation. Note that when recruitment is better estimated (case (b)), F_{stq} shows less variability. Now, if stability of fishing effort has to be considered

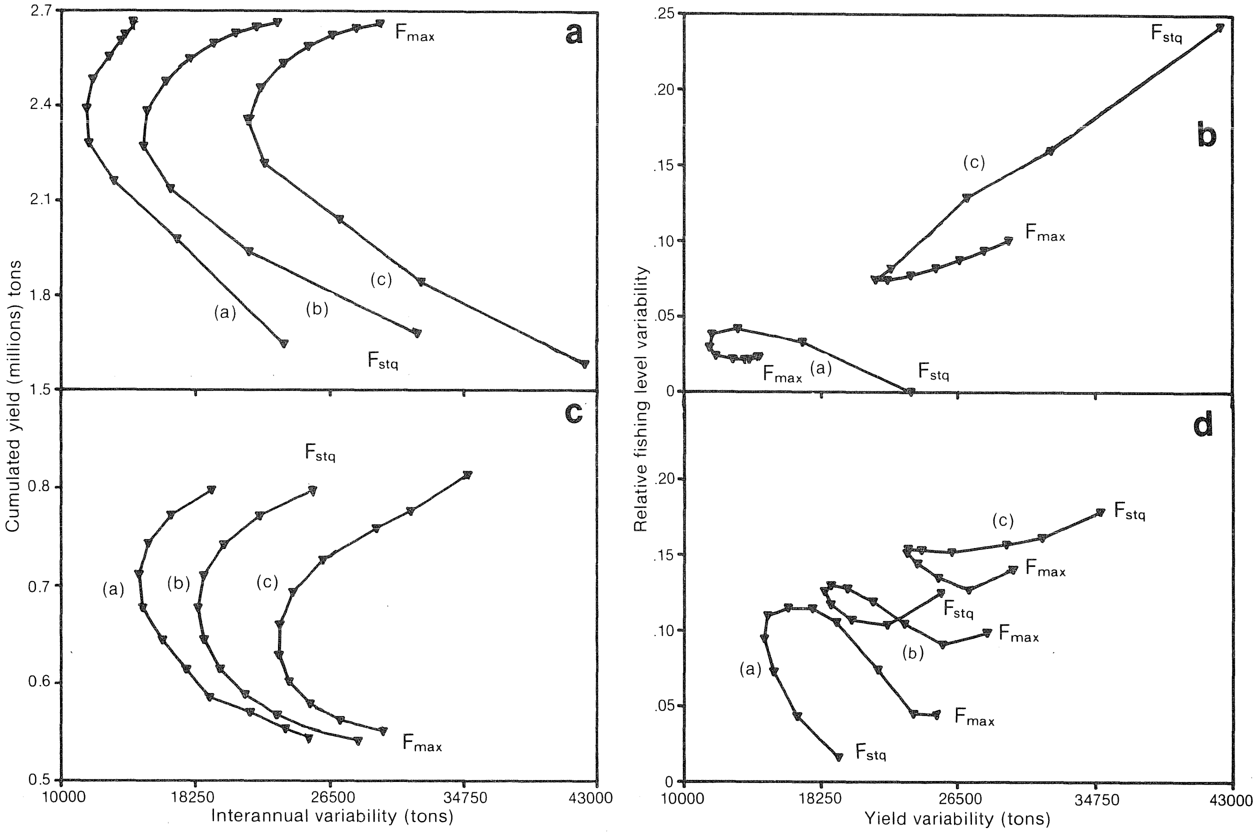

Fig. 3. Criteria values for F_{max}–λ strategies with λ ranging from 0 (F_{max}) to 1 (F_{stq}). Curves indexed by (a), (b) and (c) correspond to exact data, low error level and high error level respectively (**a**) shows long term yield (10–20 years) with (**b**) showing the corresponding stability criteria. (**c**) shows the short term yield (1–5 years) with (**d**) showing the corresponding stability criteria.

(Fig. 3b), the expediency of composite rules is most striking, as shown by the "hairpin" shape of curves (case (b) is not reported for better readability of the figure, but has the same shape as case (c)). The F_{stq} strategy gives rise to a maximum variability in both effort and yield when errors in data are considered. With perfectly known data (a), F_{stq} by definition implies constant effort, whereas some variability appears for the other strategies, due to the transition towards reduced exploitation levels. However, in the presence of errors in data (c), F_{max} yields more stable fishing effort than F_{stq}. This unexpected result is one consequence of management under uncertainty. A second effect of errors is an increased variability of yield and fishing effort as errors in data are more important. This pattern is striking in Fig. 3b for which curves (b) and (c) are shifted according to both X-axis and Y-axis. The value of λ at maximum stability is 0.6.

Consider now short-term effects that refer to a transition period in terms of management. Logically, F_{stq} maximizes cumulated yield on the short-term (Fig. 3c). As in the long-term, the mean value of cumulated yield is not really affected by the error level. One could expect the mean to be diminished by errors, but there is in fact a slight increase in case (c). Minimum yield variability is found for λ varying from 0.65 to 0.5 depending on the error level. Hence, lower levels of exploitation are less sensitive to errors in data, which is intuitively understandable. This fact is reinforced by the increased proximity of curves towards F_{max}. However, for a given level of error, the F_{max} strategy is more variable than compound strategies. Stability criteria are shown in Fig. 3d. For the error-free case, there is no joint minimum, although strategies closer to F_{stq} perform better. Fishing level variability is not zero for F_{stq} and F_{max} in relation to the reference fishing mortality averaged over the three most recent years. Intermediate rules exhibit higher variability due to the transition towards a reduced exploitation level. This stresses the short-term period as a recovery phase. Hence, losses are to be borne, either in fishing effort or in yield. But, in case of errors in data, the variability of the F_{stq} strategy implies more variability for yield and fishing effort, as was found on the long-term. F_{stq} (or similar) strategies become more variable than F_{max} (or similar) strategies. With respect to fishing effort, variability is not so different among all the strategies. F_{max} does not correspond to the minimum and F_{stq} does not maximize the effort stability any longer, although it is aimed at doing so.

On the other hand, strategies are clearly distinguished by considering yield variability. As for long-term, λ around 0.5 produces the maximum yield stability. The corresponding fishing effort variability is about 15%, which is not so high compared to the minimum (12–13%) found for $\lambda = 0.1$.

Finally, when considering error-prone data and compound rules, fishing level variability induced by a "transition effect" is balanced by some increased robustness brought by averaging between F_{stq} and F_{max}.

Individual simulation results: All the above results rely on estimations of expected values and therefore, may not reflect particular behaviours of some simulations. Up to now, no attention was given either to eventual risks of stock depletion or even collapses, nor to other outlying developments of the stock and fishery. Such unforeseen situations are all the more likely to happen since the data used in the assessment are subject to errors. Figures 4a–f show some individual evolutions obtained in simulations. Dispersion of paths is greater for *status quo* management. The fishing level tends to diverge severely during the management period (Fig. 4a) in relation with accumulation of errors and hence lower predictability. Some paths lead to very high fishing level, i.e. a dramatic overexploitation. TAC values show the same pattern (Fig. 4d), but never fall below 100,000 tons. On a longer time scale (not

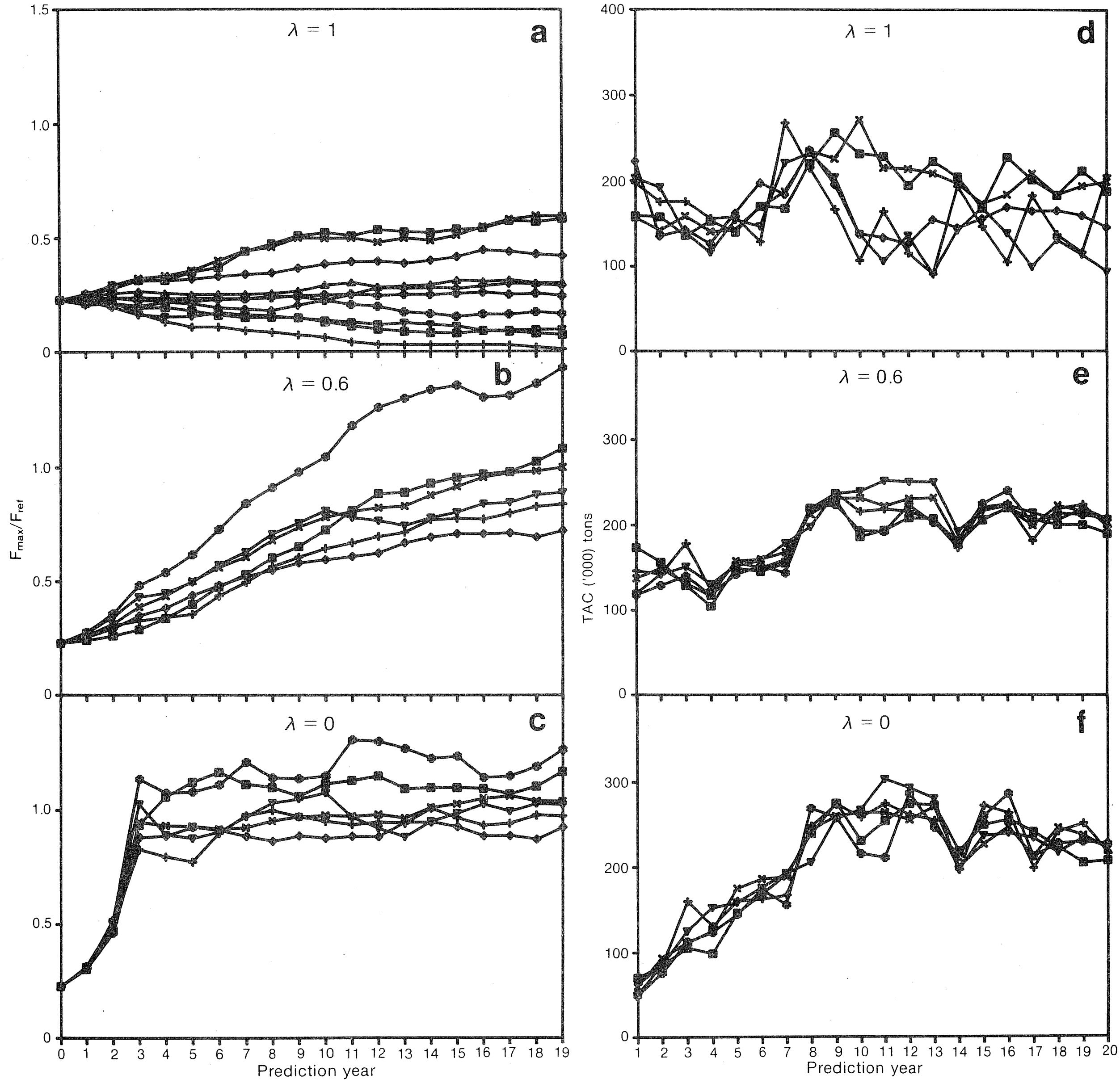

Fig. 4. Several evolutions of fishing levels (**a,b,c**) and TAC values (**d,e,f**) obtained by simulations in the case of the error level (**c**) for F_{max}–λ strategies with $\lambda = 1$ (**a** and **d**), $\lambda = 0$ (**c** and **f**) $\lambda = 0.6$ (**b** and **e**).

reported here), the stock is found to collapse in some simulations around the 35–37th year. Clearly, intermediate and F_{max} rules lead to less variable TAC and fishing mortalities (Fig. 4b, 4c, 4e and 4f). Some diverging fishing mortalities also happen for these rules, but no collapse or severe depletion could be seen on the longer term. Finally, the compound strategy is more stable than the F_{max} one, either from year-to-year or in dispersion.

Composite strategy between $F_{0.1}$ and F_{stq}

Comparison between Fig. 5a and Fig. 2a shows that for an intermediate λ value, convergence toward $F_{0.1}$ level is more linear. Hence, important changes in fishing level occur for up to 20 years. However, Fig. 5b indicates a faster stabilization of TAC values after around 10 years. The TAC level corresponding to $F_{0.1}$ is close on the average to that relative to $\lambda = 0.6$ in a compound $F_{max} - \lambda$ strategy. Individual trajectories are reported on Fig. 6a–d. As for F_{max}–λ strategies, $F_{0.1}$ and intermediate strategies exhibit rather important dispersion of fishing levels, whereas variability remains relatively quite small for TACs.

Consider now these strategies with respect to the various criteria. For reasons of legibility, Fig. 7a–d represent results only for error-free data (a) and the highest error level (c). Corresponding results for the F_{max}–λ strategies are also reported. The shapes of the curves do not differ much. As expected, introduction of errors in the model increases variability. Again, average cumulated yield is not much influenced by the error level. On the long-term, the $F_{0.1}$ strategy induces higher values than the F_{stq} one. Any compound strategy between F_{stq} and $F_{0.1}$ gives intermediate results. In this sense, analyzing intermediate F_{max}–$F_{0.1}$ rules may be instructive. With respect to interannual yield variability, $F_{0.1}$ is preferable to F_{max} only when errors are considered, as might be expected. Minimum variability is achieved for $\lambda = 0.7$ on the long-term for both error levels. Actually, this means that introducing some "F_{stq} character" in a $F_{0.1}$ policy, e.g. $\lambda = 0.3$ or 0.4, allows a decrease of yield variability as a counterpart for a modest yield loss. For a given λ value, intermediate $F_{0.1}$–λ strategies systematically induce more stable yields than corresponding F_{max}–λ. This is probably due to a reduced exploitation rate which extends the age structure of catches. The important point is that F_{max}–0.4 rule yields around 620,000 tons on the short-term compared to 400,000 tons for $F_{0.1}$ (Fig. 7c). It should be noticed (see Fig. 7a) that a F_{max} –0.4 strategy generates long-term results similar to those of a pure $F_{0.1}$ strategy in terms of cumulated yield and year-to-year yield variability. Consider now Fig. 7b. Again, fishing level variability is found to be almost negligible in the error-free model, whatever the strategy. Results are more interesting for error-prone data. $F_{0.1}$ appears more stable than F_{max}, but some compound $F_{0.1}$–λ rule are more stable. Three F_{max}–λ rules are even more stable than the pure $F_{0.1}$ rule. On the short-term (Fig. 7d), yield stability again appears more decisive than fishing stability to distinguish between rules. Finally intermediate rules perform better in terms of long-term stability of fishing effort and yield, some of which lead to moderate yield loss on the short-term.

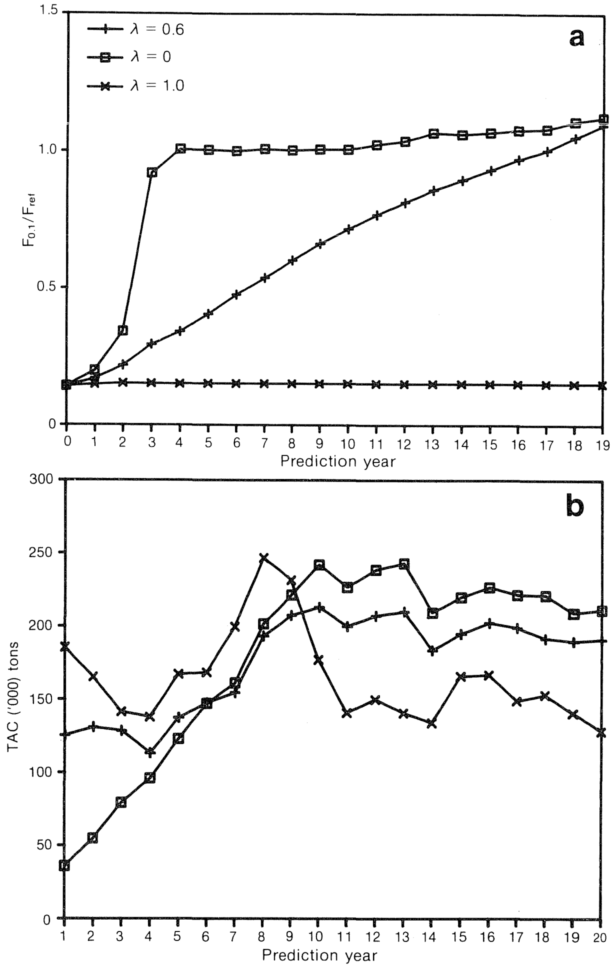

Fig. 5. Transitions of fishing level (**a**) and TAC values (**b**) towards equilibrium for a compound $F_{0.1}$–λ strategy with exact data. [TAC = λ TAC(F_{stq})+(1–λ)TAC($F_{0.1}$)].

Conclusions

In the case studied, the problem is to diminish progressively the exploitation level, so that any risk of fishery collapse may be avoided and better CPUE may be obtained. Straight-forward application of F_{max} management would induce social and economic problems. So, the question is: how could yield be increased on the long-term, without losing too much on the short-term? Solving this problem is moreover subject to stability constraints on fishing effort and yield.

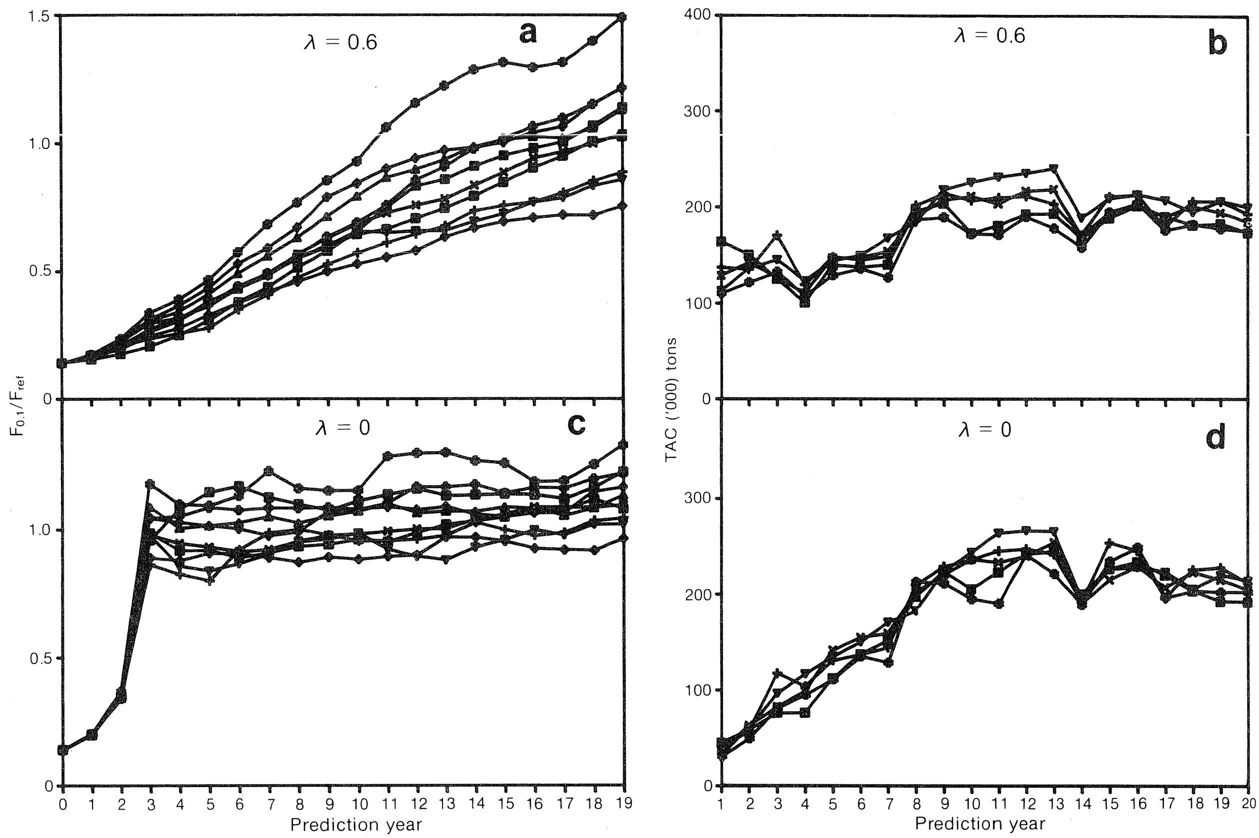

Fig. 6. Several evolutions of fishing levels (**a** and **c**) and TAC values (**b** and **d**) obtained by simulations in the case of the error level (**c**) for $F_{0.1}$–λ strategies with $\lambda = 0.6$ (**a** and **b**), $\lambda = 0$ (**c** and **d**).

In this study, no costs are associated with variability of yield and effort, nor with the cumulated yield, so that we cannot contrast the importance of a 15% fishing effort variability with for instance a 15,000 tons per year yield variability. Nevertheless, qualitative conclusions may be drawn.

First, classical strategies are found to perform in the way they were designed for when data are known perfectly, i.e. F_{stq} stabilizes fishing effort, whereas F_{max} maximizes yield in an equilibrium situation. Additional criteria and the analysis of intermediate rules stress the fact that extreme rules may not be optimum, even with error-free data. Hence, more yield stability is achievable without a great loss of cumulated yield. Note that yield variability changes qualitatively in the presence of uncertainty. On the contrary, stability criterion relating to fishing effort definitely depends upon errors in data. On the whole, for the purpose of long-term management under uncertainty, an optimal compound strategy is always proved to exist and to perform better than classical strategies, in terms of interannual variation of yield and effort. The corresponding value of λ comprises between 0.4 and 0.6. Adopting 0.4 value allows to lose less in terms of cumulated yield (with respect to F_{max}), say 13,000 tons per year during the stabilized period. On the short-term, reducing exploitation implies yield losses with respect to F_{stq}. Therefore, a modest reduction in fishing effort would be desirable for social and economic reasons. Maximum stability is achieved for $\lambda = 0.5$. The loss of cumulated yield induced by this choice is about 30,000 tons per year on the short-term (24,000 tons per year for $\lambda = 0.6$) with respect to F_{stq}. Comparison of F_{max}–λ and $F_{0.1}$–λ strategies lead to the conclusion that introduction of some "F_{stq} character" stabilizes yield at any time. More, some compound F_{max}–λ rules are as stable as a pure $F_{0.1}$ rule, and at the same time increase yield on the short-term.

As the short-term period is a transition period, there is a tradeoff between different criteria and the quantification of respective costs of objectives will help to choose between compound rules that are suited on the long-term.

Finally, these results reveal the particular nature of compound strategies on long-term. They show intrinsic properties that are more than a weighted mean between classical rules. On the short-term, they just appear as compromises. But, the fact is that, considering several objectives, these rules may outperform classical rules such as F_{stq}, F_{max} or $F_{0.1}$. Taking uncer-

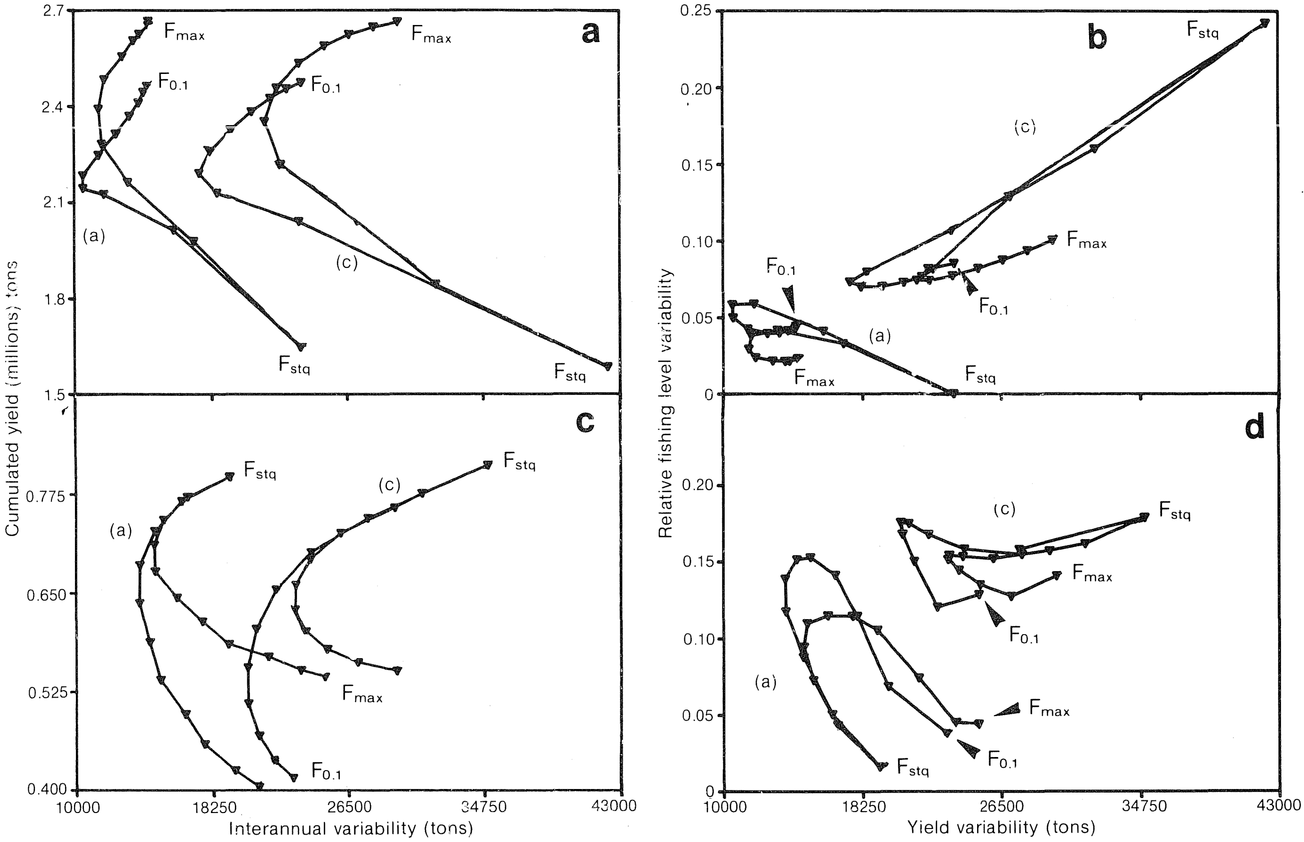

Fig. 7. Criteria values for $F_{max}-\lambda$ and $F_{0.1}-\lambda$ strategies with λ ranging from 0 (F_{max}) to 1 (F_{stq}). Curves (a) and (c) correspond to exact data and high error level respectively (**a**) shows long term yield (10–20 years) with (**b**) showing the corresponding stability criteria. (**c**) shows the short term yield (1–5 years) with (**d**) showing the corresponding stability criteria.

tainties into account, some compound rules are even found to perform better than classical ones with respect to the objective theoretically pursued by the latter. Although these results should not be carelessly generalized to any stock assessment, they are of some interest for real-world fisheries. Various compromises between classical strategies could be analyzed explicitly for each fishery situation. Management strategies studied herein are only some of the potential compound strategies. Besides, other criteria may be considered such as for instance catch rates or integrated loss functions defined with the help of fishery economists. It would be possible to analyze the influence of the various sources of uncertainty, to quantify the benefits associated to their reduction. Also, criteria used should be valued, so that they may be contrasted in a quantitative way. This is outside our scope and is more within the competence of socio-economists.

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