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Toward More Efficient Adaptive TAC Policies With Error-Prone Data

by

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SPECIAL SESSION ON MANAGEMENT UNDER UNCERTAINTIES
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Toward more efficient adaptive TAC policies with error-prone data.

Classical management strategies try to maximize different criteria such as production in weight or in value, or stabilization of *fishing effort or yield*. As noted previously by some 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 suitable than usual rules. Artificial stock and fishery are simulated, resembling the North Sea cod case. The intense exploitation of this stock enables 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 realised according to the Laurec-Shepherd (1983) tuning technique from the software used in ICES (Anon. 1988). Catches are projected for several strategies as Fmax, $F_{0.1}$, *status quo* F and intermediate rules. Results suggest potential benefits for these composite rules, particularly considering interannual stability of yield and fishing effort. These gains do not necessarily imply important losses with regard to other criteria.

Vers des stratégies de gestion efficaces en présence d'erreurs dans les données

Les stratégies de gestion évoquées dans la littérature halieutique diffèrent par les critères dont la maximisation est recherchée (production pondérale ou en valeur, stabilité de l'effort de pêche ou de la production).
L'incompatibilité de principe de ces différents objectifs a déjà été soulignée. La présente étude prolonge cette discussion en considérant d'une part l'impact des sources d'incertitude sur la capacité des règles de gestion à atteindre effectivement l'objectif fixé; d'autre part la possibilité, grâce à des stratégies intermédiaires, d'établir des compromis entre plusieurs objectifs, voire à mieux répondre qu'une stratégie classique à certains d'entre eux. L'analyse se fonde sur la *simulation* d'une pêcherie inspirée de la morue de la mer du Nord. Ce stock a été choisi en raison de son exploitation intense qui permet d'étudier les problèmes posés par la transition vers des niveaux d'exploitation inférieurs. Le modèle considéré intègre grâce à des simulations différentes sources d'incertitude reflétant les erreurs d'estimation des données d'entrée du modèle, ainsi que la variabilité naturelle de certains paramètres. Pour plusieurs années, le diagnostic sur l'état du stock est effectué selon la technique de Laurec et Shepherd (1983), en utilisant le logiciel standard du C.I.E.M. (Anon. 1988). Les stratégies de gestion envisagées correspondent à essentiellement Fmax, F *status quo*, $F_{0.1}$ et à des stratégies composites intermédiaires.
Les simulations suggèrent que ces stratégies composites permettent des gains substantiels en terme de stabilité interannuelle des apports et des efforts, sans générer nécessairement de pertes notables vis-à-vis d'autres critères.

Anon., 1990. Report of the workshop on methods of fish stock assessment. ICES CM 1990/ Assess : 15, 95p.

Laurec A., J.G. Shepherd, 1983. On the analysis of catch and effort data. *J. Cons. int. Explor. Mer*, **41** : 81-84.

Introduction

Management of marine fish stocks is often based on Total Allowable Catch (TAC). Determination of TAC may rely on very different management objectives, for instance by setting constant effort, catch or biomass escapement, or to achieve optimal biological catch. Comparison of these various strategies is much adressed in litterature. 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). Age structured analyses are also found (Rupper *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 Fmax. Problems posed by transition toward lower fishing levels essentially consist in a trade-off between short term and long term objectives. Amazingly, we could not find this problem handled in litterature, which always refers to long term analyses. Of course, this particular point is relative to the dramatic overexploitation of the stock studied. Short term transitions imply economic and social problems connected with lower yields. Some papers include such considerations as criteria, but on the long term (Charles 1989). In this study, emphasis is given to short term by developping analogous criteria for both short and long term.
Viable solutions for professionals must also exhibit some predictability properties, *i.e.* effort and yield must be rather stable than cahotic 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 it must be understandable and easy to use by decision makers (Gulland and Boerema 1973). This scope is often offset by theoretical considerations. To cope with this problem, rules are first defined in a simple way. Their properties are then evaluated with respect to above mentionned criteria. These rules are intermediate between rules commonly used for stock assessment. 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 explicitely realize some compromises that could happen *de facto* at a decision level.

I. MODELS AND HYPOTHESES:

I.1. 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 are used, considering a plus-group. Terminal fishing mortalities are estimated from an *ad hoc* tuning through a Laurec and Shepherd (1983) technique. This means that the separability of fishing mortality is assumed for each fleet with catchabilities-at-age q constant from year to year as showed in :

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

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

For simulation purpose, *ad hoc* tuning stage is not conversational any more. Among the various tuning options, years are equally weighted and terminal fishing mortality estimators are weighted by inverse catch 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.

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

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

$$- W_{NA,ref} N_{NA} \frac{F_{NA,y+1}}{F_{NA,y+1} + M_{NA}} = 0 .$$

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.

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

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

μ **is hence obtained by solving equation (2).** μ **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 $E_{n+1,f}$ for fleet f is predicted by :

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

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 data set 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.

I.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 c.p.u.e indices are supposed to be normally distributed with given coefficients of variation, which represent the estimation error of these data. An 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 (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 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 VPA results.

In these simulations, two levels of errors in input data were considered besides the error-free case. The first one corresponds to rather important 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.

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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 (2) and (4). In this case, no noise is added to data before assessment for year y+2.

II. TAC MANAGEMENT STRATEGIES :

II.1. Classical management options :

TAC management is commonly used within NAFO or ICES framework. Diagnostic yield models lead to define several fishing intensities for a given exploitation pattern as *status quo* F, Fmax or $F_{0.1}$. Corresponding TACs are calculated by catch projections models.
With respect to Fmax 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. 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, Fmax strategy implies variable fishing efforts, beyond yearly changes in yield due to recruitment.
The so-called *status quo* policy (referred to as Fstq) aims to stabilize fishing effort through fishing mortality and should lead to higher catches than Fmax in the short-term. But, as for Fmax, neither fishing effort nor fishing mortalities can be stabilized when uncertainties in data are taken into account. However, weights-at-age variability will affect Fmax but not Fstq estimation.
Considering $F_{0.1}$, it is somewhat difficult to define the underlying criterion one should maximize. Some biologists think it is based on economical considerations while economists commonly believe it corresponds to a biological option. $F_{0.1}$ rather seems to be an implicit compromise between various criteria. Indeed, $F_{0.1}$ strategy admits a moderately reduced yield as a counterpart for increased stability of annual yields, c.p.u.e., as well as better economical returns (this is where the economists opinion should be considered (Smith 1981)). It also gives a safety margin with respect to the risk of recruitment overfishing (but beware of the stock-recruitment relationships!).

II.2. Compound strategies :

Yearly negotiations commonly lead in practice to some intermediate choice between the previously mentionned policies. Though, such intermediate rules are not found in litterature to our knowledge, except briefly in Laurec and Maucorps (1981). Indeed, it corresponds to a multi-criteria decision. Within the infinity of compound strategies, we focused on mixed options between Fstq and Fmax on one hand, Fstq and $F_{0.1}$ on the other hand. A simple composite policy between Fstq and Fmax is given for each year by :

$$TAC = \lambda TAC(Fstq) + (1-\lambda) TAC(Fmax) \quad (5)$$

The parameter λ in the range [0,1] enables to define a smoother transition toward lower fishing levels, especially for strongly overexploited stocks. Resulting TAC corresponds to a targeted level of fishing mortality Ftgt comprised between Fmax and Fstq. Values of 0 or 1 for λ lead to classical management options. This strategy will be referred as Fmax-λ strategy in the following.
A similar composite rule is achievable for Fstq and $F_{0.1}$ as :

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

It will then be referred as $F_{0.1}$-λ . 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 that reference F is mean over three years and hence introduces some inertia in the management.

III. 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. Study is focused on the inevitable choice between maximization of total yield in weights 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 c.p.u.e.
The simulated fishery is severely overexploited so that a transition phase is necessary to recover equilibrium. Hence, short-term management has to be distinguished from long-term one.

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2 *i.e.* no data is error-prone and more, no parameter is intrinsically variable.

Analysis of several simulations show that a five years 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 20 years horizon. In the same way, it seems dubious that the exploitation pattern is constant for such a long time. Finally, as initial conditions consist in 10 years data, predictability is likely to be negligible on a long time scale. So years 10 to 20 are associated to 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 :

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

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

where i represents a simulation.
and for exploitation level :

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

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

where sht (resp. lgt) means short-term (resp. long-term).

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

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

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

Mathematical expectancies quoted in the previous paragraph are estimated by means over 100 simulations which may not always reflect the global behaviour of individual replicates. Indeed, simple average can smooth interesting features of the distribution of values. 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, results variances suggest this shortcoming is not likely to occur here, so that calculated means for indices actually characterize management strategies.

IV. APPLICATION :

IV.1. 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 of decisions based on estimated situations on the actual stock and fishery.

Data are built from working group results so that the example studied resembles the North Sea cod case, *i.e.* a typically overexploited stock. Figure 1 shows that the average fishing level is at present about four times above Fmax. 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 c.p.u.e indices are computed. These true data are then modified by introducing uncertainty in order to obtain "estimated" data resulting e.g. from sampling, adjustment or any estimation method. Finally, estimated data are used for stock assessment.

IV.2. Results :

IV.2.1. Composite strategy between Fmax and Fstq :

IV.2.1.1. Stock and fishery general response 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 (Fmax), 1 (Fstq) and 0.6. Only real recruitment is randomly variable from year to year as described in a previous section. Figure 2a indicates the proximity of fishing level to Fmax level. Fstq is perfectly stable as supposed to be. Fmax 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 Fmax calculation. Note that all other strategies imply a transition period of variable length. For compound strategy, equilibrium is not complete after 20 years, but it is very close to (Fmax/Fref = 0.975). Stabilization at a level closer to Fmax is found to appear around 30 years. This fishing level is slightly lower than Fmax. Years 22 and 43 show small peaks probably due to very strong recruitment that happened 10 years earlier and influenced fishing mortalities. Recall Fmax/Fref does not depend directly on recruitment, this explain the smooth aspect of the curve in fig. 2a compared to fig. 2b. TAC values show important variability in all cases, in relation with changes in recruitment. However, some remarks may be drawn from this figure. First, Fmax strategy generates gains with respect to Fstq after the 4th year, whereas with compound strategy, it occurs a little later. The main advantage of compound strategy here is a moderate loss on the short term and a substantial gain on the long term.

IV.2.1.2. Comparison of rules from different criteria:

In the following, different error cases are referred to as in table 1. Let first consider long term effects (figs 3a and 3b). Logically, Fmax maximizes cumulated yield in a stabilized situation (fig. 3a). However, yield loss compared to Fmax is not so important for values of λ up to 0.6, say less than 30000 tonnes per year (21000 tonnes for λ =0.5, 13000 tonnes for λ =0.4). In terms of yield interannual variation, stability is maximum for λ =0.6. Fstq is less stable than Fmax, especially when data are error prone. This is in relation with an increased dependance of fishery upon young age-groups and particularly recruitment estimation. Note that when recruitment is better estimated (case (b)), Fstq shows less variability. Now, if stability of fishing effort has to be considered (fig. 3b), the expediency of composite rules is most striking, as showed by the "hairpin" shape of curves. Obviously, it is due to the Y-axis scale required by the extreme point corresponding to Fstq in case (c) (Case (b) is not reported for better readibility, but has the same shape). Fstq strategy gives rise to a maximum variability in both effort and yield when errors in data are considered. With perfectly known data (a), Fstq, by definition, implies constant effort, whereas some variability appears for other strategies, due to the transition toward reduced exploitation levels. But, it is somewhat different in presence of errors in data (c). Fmax yields more stable fishing effort than Fstq. This unexpected result is one consequence of management under uncertainty. A second implication 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 term of management. Logically, Fstq maximizes cumulated yield on the short term (fig. 3c). As on 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. On the inverse, there is 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 toward Fmax. However, for a given level of error, Fmax strategy is more variable than compound strategies. Stability criteria are showed in figure 3c. For the error-free case, there is no joint minimum, although strategies closer to Fstq perform better. Fishing level variability is not zero for Fstq and Fmax in relation with the reference fishing mortality averaged over the three most recent years. Intermediate rules exhibit higher variability due to the transition toward reduced exploitation level. It stresses the short term period as a recovery phase. Hence, losses are to be withstood, either in fishing effort or in yield. But, in case of errors in data, variability of Fstq strategy (or close to) implies more variability for yield and fishing effort, as was found on the long term. Fstq (or close to) strategies become more variable than Fmax (or close to) strategies. With respect to fishing effort, variability is not so different among all strategies. Fmax does not correspond to the minimum and Fstq does not maximize the effort stability any longer although it is the first argument to apply it.

On the inverse, strategies are clearly distinguished considering yield variability. As for long term, λ around 0.5 produces the maximim yield stability. The corresponding fishing effort variability is about 15%, which not so high compared to the minimum (12-13%) found for λ =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 Fstq and Fmax.

IV.2.1.3. Individual simulation results:

All previous results rely on estimations of expected values and therefore, may not reflect particular behaviours of some simulations. Up to now, no attention was given neither to eventual risks of stock depletion or even collapsus, nor to other outlying evolution of the stock and fishery. Such unforeseen situations are all the more likely to happen that data used in the assessment are subject to errors. Figures 4a–f show some individual evolutions obtained in simulations. Dispersion of pathes is more important for *status quo* management. Fishing level tends to diverge severely during the management period (fig. 4a) in relation with accumulation of errors and hence lower predictability. Some pathes lead to very high fishing level, *i.e.* a dramatic overexploitation. TAC values show the same pattern (fig. 4d), but never fall below 100000 tonnes. On a longer time scale (not reported herein), stock is found to collapse in some simulations around the 35–37th year. Clearly, intermediate and Fmax rules lead to less variable TAC and fishing mortalities (figs 4b, 4c and 4e, 4f). Some diverging fishing mortalities also happen for these rules, but no collapse or severe depletion could be seen on the longer term. Finally, compound strategy is more stable than the Fmax one, either from year-to-year or in dispersion.

IV.2.2. Composite strategy between F0.1 and Fstq :

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

Considering now strategies with respect to criteria. On grounds of legibility, figures 7a–d represent results only for error-free data (a) and the highest error level (c). Corresponding results for Fmax– λ strategies are also reported. Curves shapes 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, $F_{0.1}$ strategy induces higher values than the Fstq one. Any compound strategy betweeen Fstq and $F_{0.1}$ gives intermediate results. It is surprising that any compound $F_{0.1}$– λ strategy produces lower cumulated yields than Fmax on the long term. It denotes the particular properties of compound strategies. In this sense, analysing intermediate Fmax–$F_{0.1}$ rules may be instructive. With respect to interannual yield variability, $F_{0.1}$ is preferable to Fmax only when errors are considered, as it is supposed to be. Minimum variability is achieved for λ =.7 on the long term for both error levels. Actually, it means that introducing some "Fstq character" in a $F_{0.1}$ policy, e.g. λ =.3 or .4, allows to decrease yield variability as a counterpart for a moderate yield loss. The important point is that Fmax–.4 rule yields around 620000 tonnes on the short term compared to 400000 tonnes for $F_{0.1}$ (fig. 7c). For a given λ value, intermediate $F_{0.1}$– λ strategies systematically induce more stable yields than corresponding Fmax– λ . It is probably due to a reduced exploitation rate which enlarges the age structure of catches. It should be noticed that a Fmax–.4 strategy generates long term results similar to those of a $F_{0.1}$ 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 Fmax. But, some compound $F_{0.1}$– λ rules are far more stable. Three Fmax– λ rules are even more stable than pure $F_{0.1}$ rule. On the short term (fig. 7d), yield stability again appears more deciding than fishing stability to distinguish 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.

Conclusion

In view of the case studied, the problem is to diminish progressively the exploitation level, so that any risk of fishery collapsus may be avoided and better c.p.u.e. are obtained. Straightforward application of Fmax management would induce social and economics problems. So, the question is : How to increase yield on the long term, without loosing too much on the short term ? Solving this problem is moreover subject to stability constraints on fishing effort and yield.

In this study, no costs are affected to these variabilities, nor to the cumulated yield, so that we cannot contrast the importance of a 15% fishing effort variability with for instance a 15000 tonnes 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.* Fstq stabilizes fishing effort, whereas Fmax 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. Concerning yield, results are not qualitatively different in presence of uncertainty. On the inverse, stability criterion relative 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 Fmax), say 13000 tonnes per year during the stabilized period.

On the short term, reducing exploitation implies yield losses with respect to Fstq. Therefore, a fishing level higher than λ 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 30000 tonnes per year on the short term (24000 tonnes per year for $\lambda = 0.6$) with respect to Fstq. Comparison of Fmax$-\lambda$ and $F_{0.1}-\lambda$ strategies lead to conclude that, even if $F_{0.1}$ is designed to be robust in face of uncertainties, introduction of some "Fstq character" stabilizes yield at any time. More, some compound Fmax$-\lambda$ rules are as stable as a pure $F_{0.1}$ rule, and induce altogether increased yield on the short term.

As the short term period is a transition period, there is a trade–off 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, results reveal the particular nature of compound strategies on long term. They show intrinsic properties that are more that 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 outweigh classical rules as Fstq, Fmax or $F_{0.1}$. Taking uncertainties 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 may not be generalized to any stock assessment, they are of some interest for real–world fisheries. Various compromises between classical strategies could be analysed explicitely for each fishery situation. Management strategies studied herein are only some of the potential compound strategies. Besides, other criteria may be considered as for instance catch rates or integrated loss functions defined with the help of fishery economists. It would be possible to analyse 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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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%

Table 1. Different cases of uncertainty considered in the simulation. CV stands for coefficient of variation.

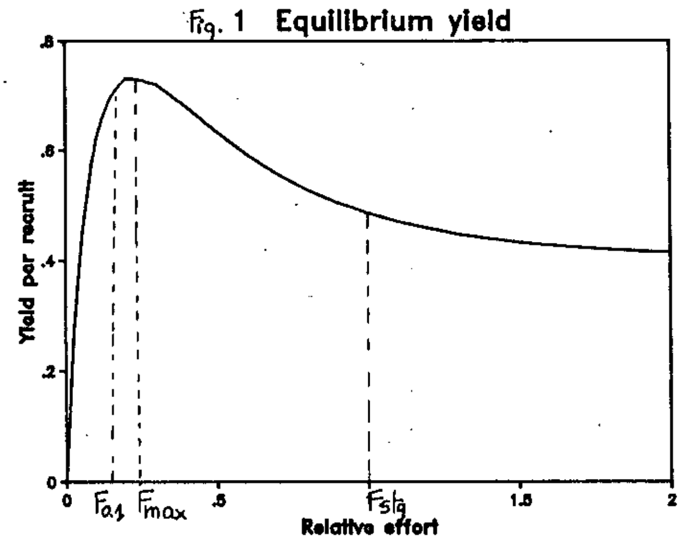
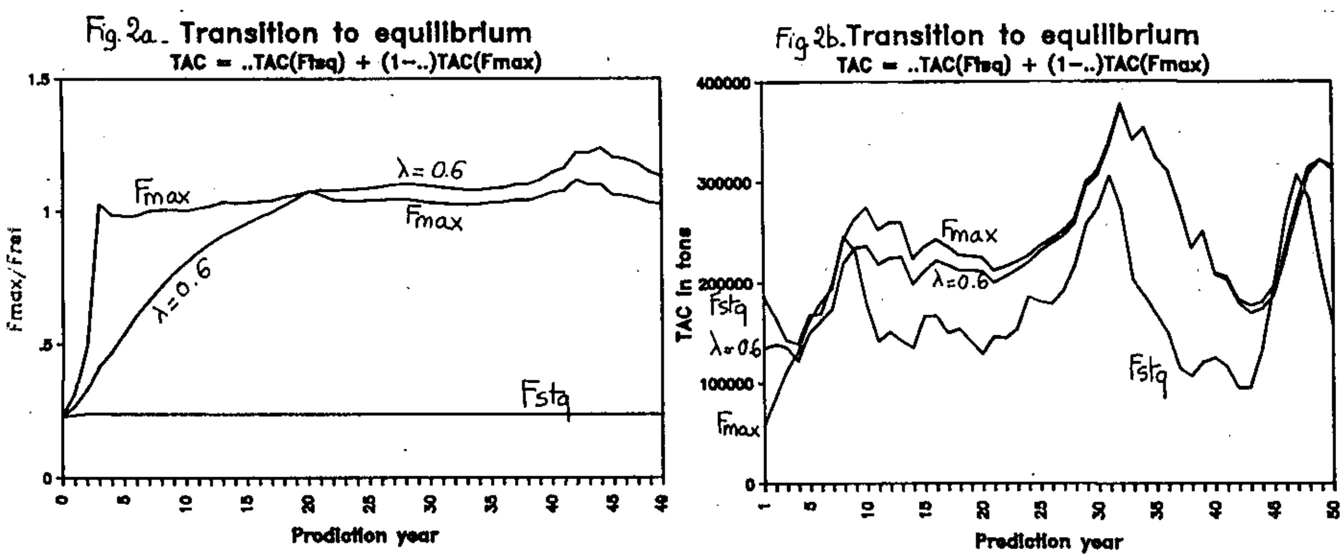
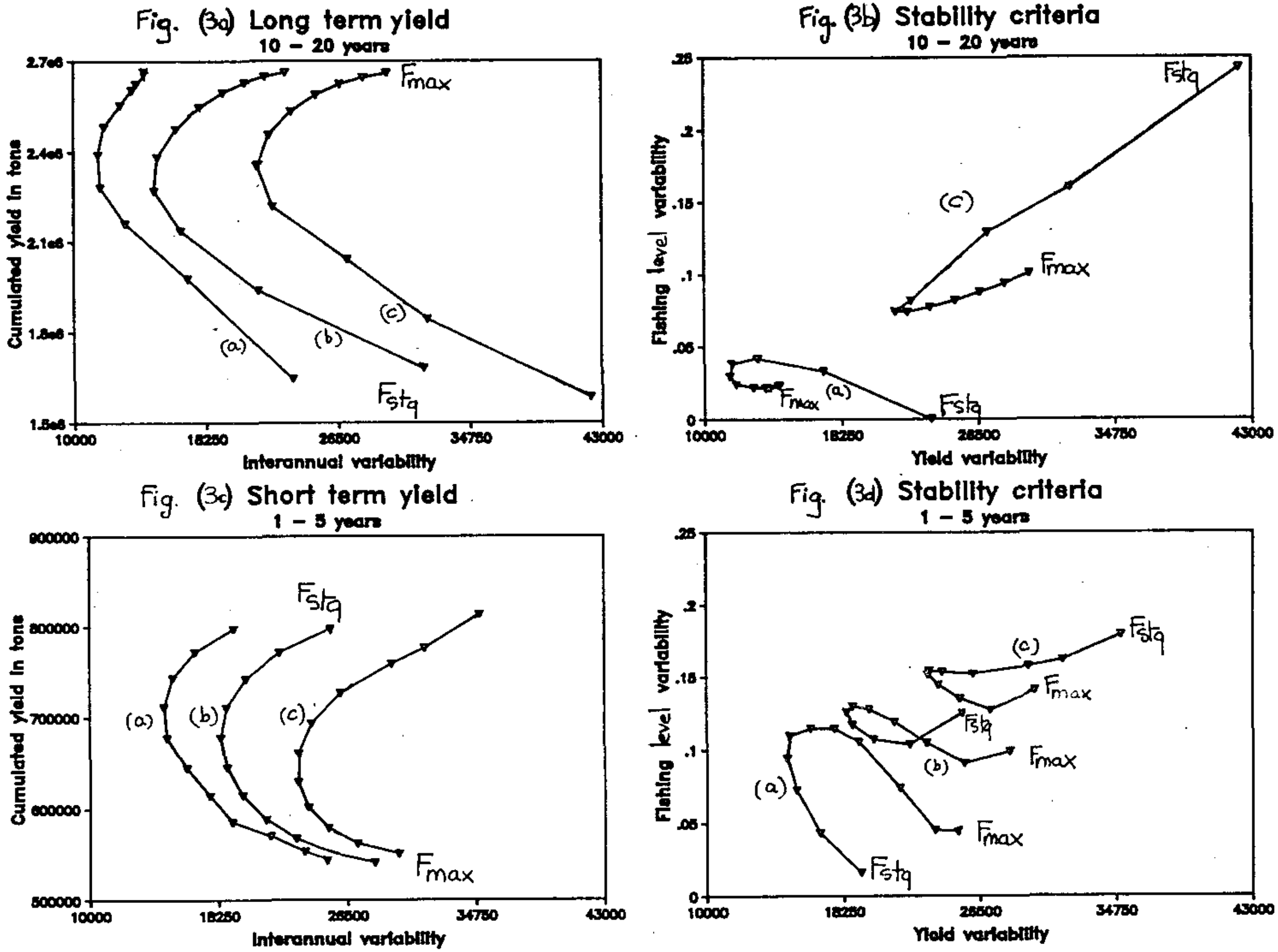


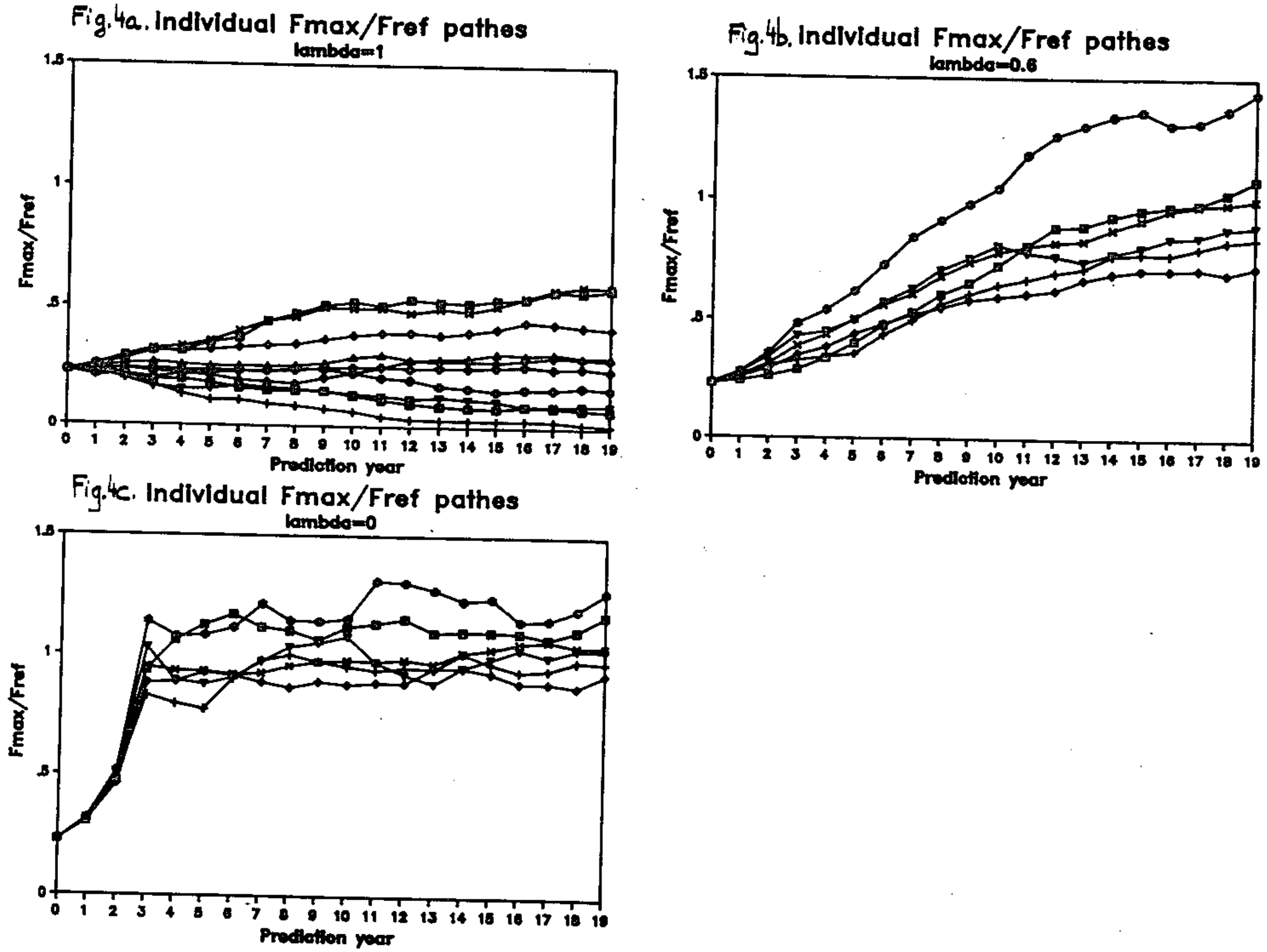
Fig. 1. Equilibrium yield curve for the simulated stock. On the X-axis, effort is relative to reference fishing mortality calculated before prediction phase.



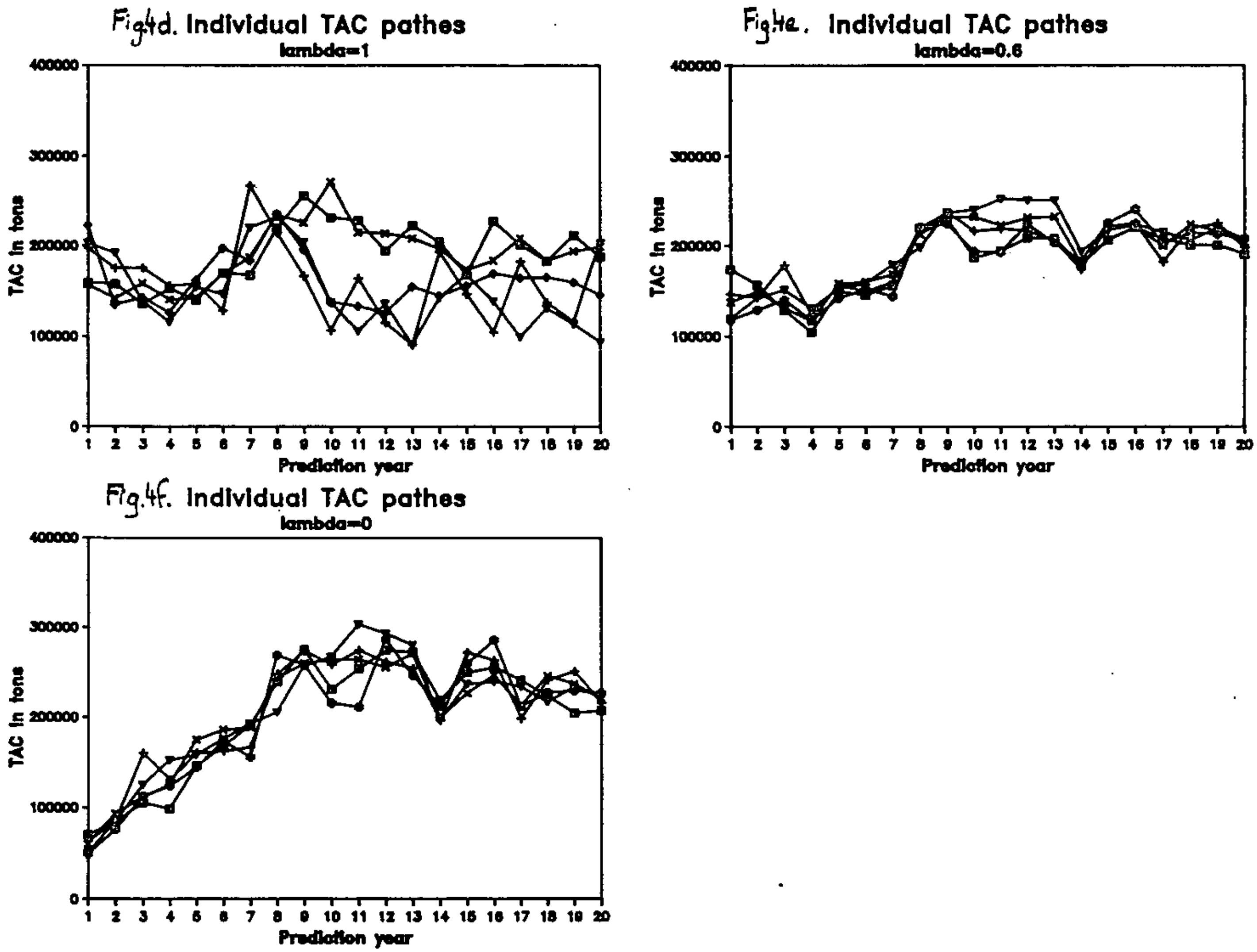
Figs 2a and b. Transitions of fishing level (a) and TAC values (b) toward equilibrium for a compound Fmax− λ strategy with exact data.



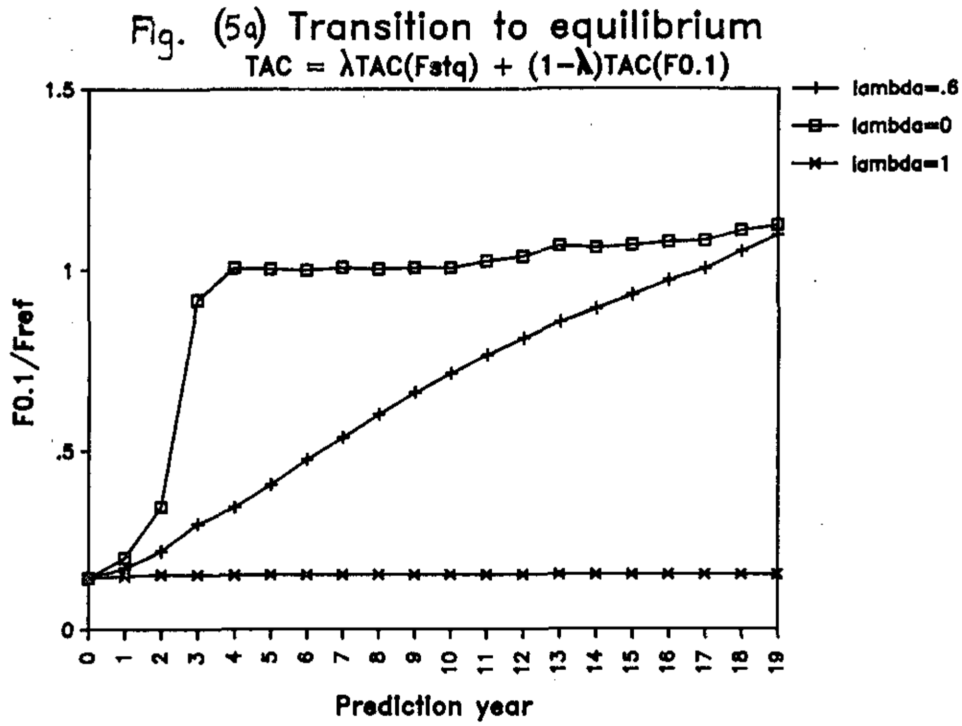
Figs 3a–d. Criteria values for Fmax– λ strategies with λ ranging from 0 (Fmax) to 1 (Fstq). Curves indexed by (a) (resp. (b) and (c)) correspond to exact data (resp. low error level and high error level).

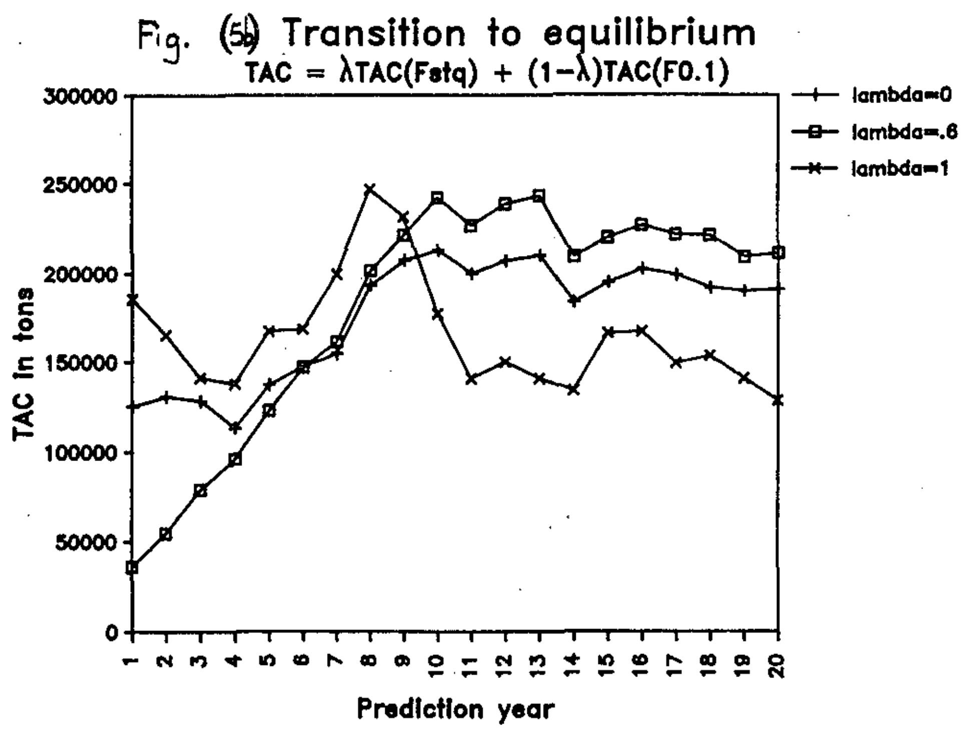


Figs 4a−c. Representation of several evolutions of fishing levels obtained by simulations in the case of a "plausible" error level for λ =1 (4a), λ =0 (4b), λ =0.6 (4c).



Figs 4d−f. Representation of several evolutions of TAC values obtained by simulations in the case of a "plausible" error level for λ =1 (4d), λ =0 (4e), λ =0.6 (4f).





Figs 5a and b. Transitions of fishing level (a) and TAC values (b) toward equilibrium for a compound $F_{0.1}-\ \lambda$ strategy with exact data.

Fig. 6a. Individual TAC pathes
lambda=0.6

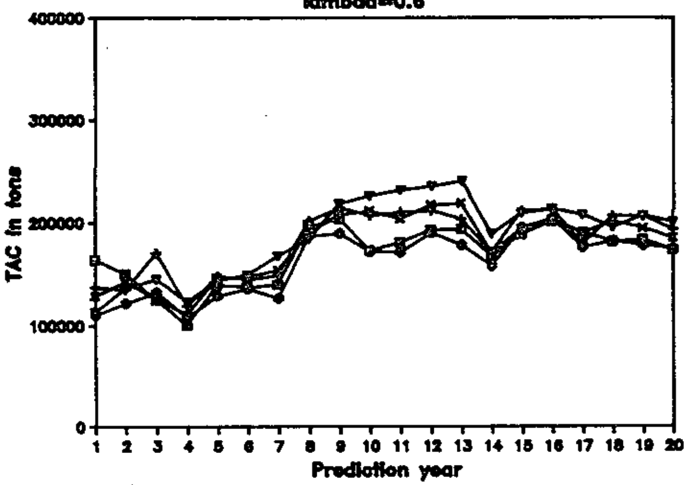


Fig. 6b. Individual F0.1/Fref pathes
lambda=0.6

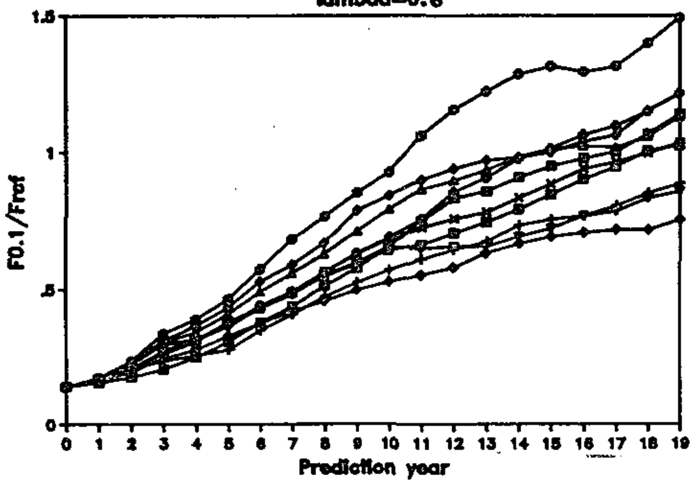


Fig. 6c. Individual TAC pathes
lambda=0

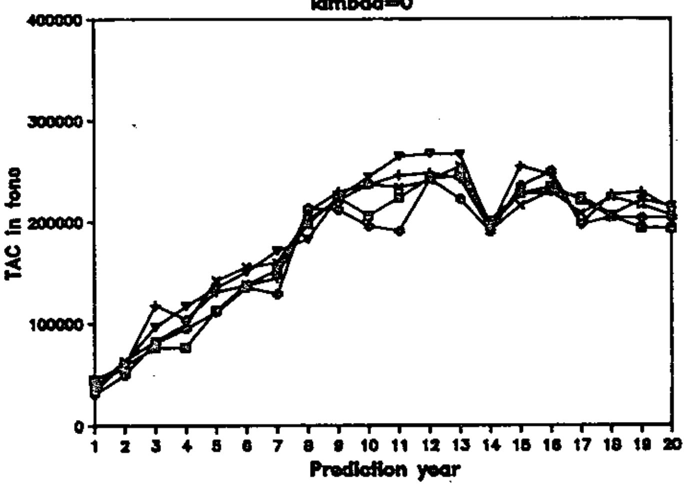
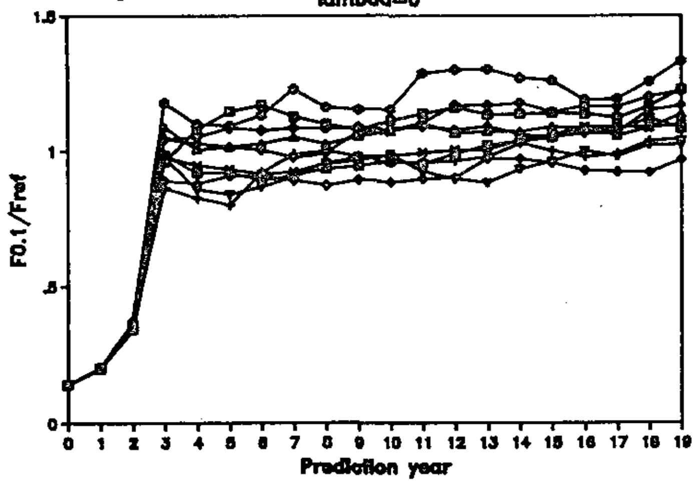
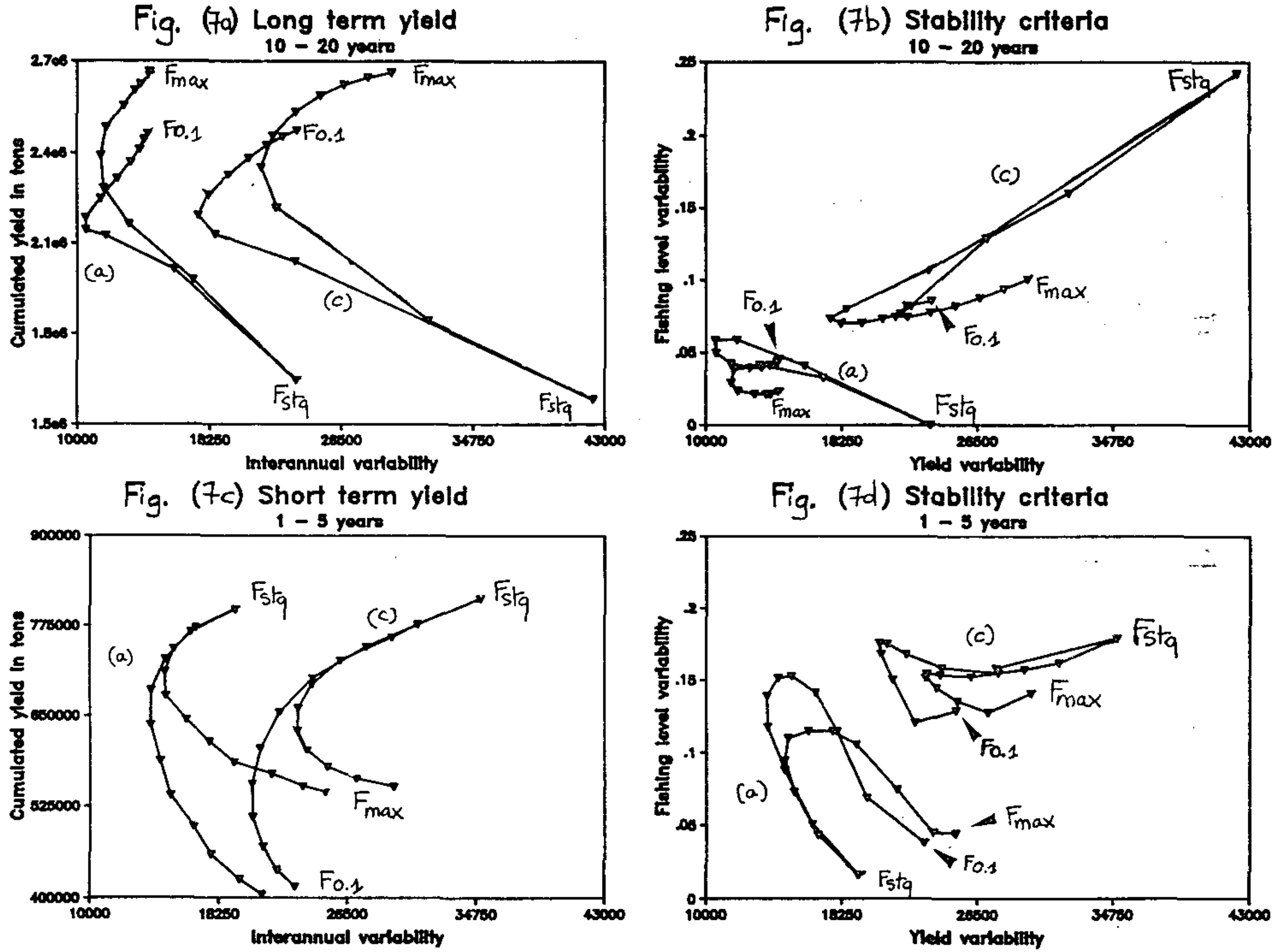


Fig. 6d. Individual F0.1/Fref pathes
lambda=0



Figs 6a and b. Representation of several evolutions of fishing levels obtained by simulations in the case of a "plausible" error level for λ =0.6 (6a), λ =0 (6b).

Figs 6c and d. Representation of several evolutions of TAC values obtained by simulations in the case of a "plausible" error level for λ λ =0.6 (6c), λ =0 (6d).



Figs 7a–d. Criteria values for Fmax– λ and $F_{0.1}$– λ strategies with λ ranging from 0 (Fmax) to 1 (Fstq). Curve (a) (resp. (c)) corresponds to exact data (resp. high error level).