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Reference Point Approaches to Management within the Precautionary Approach
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EVALUATION OF THE USE OF SEGMENTED REGRESSION THROUGH SIMULATION FOR A CHARACTERISATION OF THE NORTH SEA COD (*GADUS MORHUA* L.) STOCK, IN ORDER TO DETERMINE THE PROPERTIES OF $\mathbf{B_{lim}}$ (THE BIOMASS AT WHICH RECRUITMENT IS IMPAIRED)

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ABSTRACT

A new objective technique to determine the level of biomass ($\mathbf{B_{lim}}$) at which recruitment is impaired based upon a segmented (or piecewise linear) regression has previously been proposed and developed by O'Brien & Maxwell. The formal statistical details of the approach are presented; together with hypothesis tests and goodness-of-fit statistics, and the approach evaluated for a characterisation of the North Sea cod (*Gadus morhua* L.) stock. This paper computes the values of $\mathbf{B_{lim}}$ obtained by segmented regression for a simulated stock based upon North Sea cod. The properties of the estimators are explored for a variety of hypotheses about stock dynamics (e.g. stock-recruitment) and data quality (e.g. discarding and mis-reporting). In particular, the robustness of the method to underlying assumptions is evaluated.

Keywords: cod; evaluation; Precautionary Approach; reference points; segmented regression

1 INTRODUCTION

The ICES reference points in current use were set in 1998 using the stock and fishery data then available, as a provisional step in the implementation of the Precautionary Approach to fishery management. ICES has since revised some of the original proposals based on updated information on stock productivity and is currently in the process of reviewing all these values in 2003; although this process may not be completed until 2004.

An objective technique to determine the level of biomass (**B_{lim}**) at which recruitment is impaired based upon a segmented (or piecewise linear) regression has previously been developed by O'Brien & Maxwell (2002a) and applied to North-East Arctic cod (ICES 2003).

The formal statistical details of the approach are presented in this paper; together with hypothesis tests and goodness-of-fit statistics, and the approach is evaluated for a characterisation of the North Sea cod (*Gadus morhua* L.) stock. This paper computes the values of **B_{lim}** obtained by segmented regression for a simulated stock based upon a characterisation of the North Sea cod. The properties of the estimator are explored for a variety of hypotheses about stock dynamics (e.g. stock-recruitment) and data quality (e.g. discarding and mis-reporting). In particular, the robustness of the method to underlying assumptions is evaluated and estimates compared with those derived from **G_{loss}** the method previously used by ICES.

2 BACKGROUND – PRECAUTIONARY FRAMEWORK

The precautionary approach to fishery management provides the framework for the fishery management advice provided by the ICES advisory committee on fishery management [ACFM] (ICES 2001). This states that reference points will be stated in terms of biomass and fishing mortality rate. The use of the two indicator scales is summarized in the following extract from the ACFM advice:

In order for stocks and fisheries exploiting them to be within safe biological limits, there should be a high probability that 1) the spawning stock biomass is above the threshold where recruitment is impaired, and 2) the fishing mortality is below that which will drive the spawning stock to the biomass threshold, which must be avoided. The biomass threshold is defined as **B_{lim}** *($_{lim}$ stands for limit) and the fishing mortality threshold as* **F_{lim}**.

The ICES' definition of **B_{lim}** as the biomass below which recruitment becomes impaired implies a simple model of population dynamics in which recruitment is impaired at a particular threshold of SSB, and where fishing mortality is the only explicit factor that determines the size of the spawning stock, and that can be managed. In some stocks, where the stock-recruitment data do show a so-called *change-point* where recruitment declines, the change-point corresponds to the definition of **B_{lim}**.

The implication that SSB is influenced only by fishing mortality is often not unreasonable for heavily-exploited stocks, with the proviso that fishing mortality is usually the most omportant factor influencing SSB which fishery managers can seek to manage.

The ACFM advice continues further:

... although ICES sees its responsibility to identify limit reference points, it will suggest precautionary reference points for management use.

In the remainder of this paper the value of $\mathbf{B_{lim}}$ obtained by segmented regression is presented for North Sea cod and the properties of the estimator investigated for a simulated stock based upon North Sea cod. The steps involved in this paper are: to estimate the spawning stock biomass at which recruitment is impaired ($\mathbf{B_{lim}}$) using a segmented regression, to estimate the slope at the origin of the segmented regression in order to estimate $\mathbf{F_{lim}}$, and the properties of the estimator are explored for a variety of hypotheses about stock dynamics (e.g. stock-recruitment) and data quality (e.g. discarding and mis-reporting). In particular, the robustness of the method to underlying assumptions is evaluated

3 MATERIAL AND METHODS

The details of the statistical estimation of the biomass at which recruitment is impaired are presented in Section 3.1 and brief details of the simulation approach are presented in Section 3.2.

3.1 ICES' definition of $\mathbf{B_{lim}}$

3.1.1 Methodological basis

The objective technique whereby biomass reference points are to be developed is based upon a segmented (or piecewise linear) regression. Piecewise linear regression involves fitting linear regression where the coefficients are allowed to change at given points. For one unknown change-point, for any interval (X_0 , X_1) on the real interval, the problem is defined as,

$$\begin{aligned} f(x_i) &= \alpha_1 + \beta_1 x_i \qquad & X_0 \le x_i \le \delta, \\ &= \alpha_2 + \beta_2 x_i \qquad & \delta \le x_i \le X_1 \end{aligned}$$

For stock and recruitment data the model is simplified, it must pass through the origin ($\alpha_1 = 0$) and after the change-point the line is horizontal ($\beta_2 = 0$).

Many different terms are used for models with change-points; e.g. segmented regression, multiphase regression, change-point regression (Quandt 1958), piecewise regression and for the model above in particular; e.g. two-phase regression, split lines, hockey stick, broken stick.

Julious (2001) published a paper including an algorithm, originally from Hudson (1966) for fitting the model with one unknown change-point. Barrowman & Myers

(2000) give a thorough investigation of applying such a model to spawner-recruitment curves but they do not consider the calculation of Precautionary Approach biomass reference points. They carry out model fitting by grid search (Lerman 1980). Lerman notes a disadvantage of Hudson's method; namely, that if likelihood surfaces are required to study the relative plausibility of different parameter values then the surfaces have to be generated separately.

The algorithm in Julious (2001) has been implemented for the stock and recruitment case with $\alpha_1 = 0$, $\beta_2 = 0$ and log-Normal errors. The model is

$$
\begin{aligned}
R_i &= \beta_1 S_i e^{\varepsilon_i} \qquad 0 \le S_i \le \delta, \\
&= \alpha_2 e^{\varepsilon_i} \qquad \delta \le S_i
\end{aligned}
$$

which on the natural logarithmic scale is:

$$
\begin{aligned}
\log R_i &= \log \beta_1 + \log S_i + \varepsilon_i \qquad 0 \le S_i \le \delta, \\
&= \log \alpha_2 + \varepsilon_i \qquad \delta \le S_i
\end{aligned}
$$

where ε_i are independent and identically distributed (iid) Normal errors.

The correspondence between the notation in Julious (2001) and that used by Barrowman & Myers (2000) is as follows:

$\delta \equiv S^*$
$\beta_1 \equiv \alpha$
$\alpha_2 \equiv R^* = \alpha S^*$

An *F*-statistic can be derived (Worsley 1983) that uses the ratio of the sum of squares between a one- and two-line model (H_0 versus H_1, respectively). If the change-point has to be estimated, this test statistic does not have an exact *F*-distribution under the null hypothesis (Hinkley 1988). However, a bootstrap distribution for the *F*-test can be derived and a *p*-value can thus be calculated.

The methodology in applying the bootstrap method to the change-point problem is as follows:

step 1: for a given set of data, obtain the best fitting change-point (two-line) model and one-line models and calculate the *F*-statistic.
step 2: calculate the residuals for the two-line case.
step 3: using the original spawning stock biomass (SSB) values, re-calculate the new recruitment values, by using the values from the best fitting one-line model and adding an error term, sampled with replacement from the set of residuals from the best fitting two-line model.
step 4: to this new set of data, fit a two-line and a one-line model and calculate the *F*-statistic.
step 5: repeat steps 3 and 4 a large number of times, each time using the one-line parameters and two-line residuals from the original data.

The ANOVA table comparing the RSS from fitting a change-point model on the logarithmic scale to the residual sum of squares (RSS) from fitting an arithmetic mean on the logarithmic scale can be used to indicate the appropriateness of the change-point model over the one-line model.

The parameters S*, α and r* are not known exactly but must be estimated using an appropriate statistical procedure. Given suitable point estimates, confidence interval statements can be calculated.

If the null hypothesis is rejected then a (1-α)% profile likelihood confidence interval for S* can be appropriately calculated using the expression:

$$\text{maximum of log-likelihood} - \{ \chi^2_{1, (1-\alpha)} / 2 \}$$

For illustrative purposes, a (1-α)% of 80% has been adopted in the applications previously presented by O'Brien & Maxwell (2002b) to derive the lower 10% limit denoted by S*(10) and the upper 90% limit denoted S*(90) of S*. In principle, there is nothing that implies a symmetric treatment of the (1-α)% profile likelihood confidence interval for S*; i.e. a lower limit S*(α_1) and an upper limit S*(1-α_2) may be defined such that (1-α_1-α_2) has the specified coverage probability of (1-α) but α_1 may be different from α_2.

The choice of the appropriate level of acceptable risk in both the lower and upper tails of the empirical distribution of the SSB at which recruitment is impaired is a management decision. The approach presented here will enable that choice to be made in an objective way. The evaluation of candidate biomass reference points through the use of scenario modelling within a management procedure could be a requirement for the adoption of specific values in the future (c.f. Kell *et al.* 1999). This is discussed further later in the Section 5 of this paper.

An important plot, after fitting any statistical model, is that of standardized residuals against fitted values (with the latter transformed to the constant-information scale of the error distribution). The plot is capable of revealing isolated points with large residuals, or a general curvature, or a trend in the spread of residuals along the abscissa. Details of the technique are given in O'Brien & Kell (1996); together with residual-covariate plots. For the segmented regression model analysed in this report, it is recommended to assess distributional form by the quantile-quantile (q-q) plot with simulation envelope (Atkinson 1985). In addition, influence and leverage diagnostics are important tools with which to identify departures from model assumptions. A number of these diagnostics are presented and discussed in Section 4.1 in the context of North Sea cod stock-recruitment.

3.1.2 Technical basis for the estimation for North Sea cod

The ICES stock assessment working group [WGNSSK] estimates of spawning stock biomass and recruitment at age 1 for cod in the North Sea, Skagerrak and Eastern Channel were obtained from ICES (2002a) and are presented in Table 3.1.2.1.

The S-PLUS scripts developed by O'Brien and Maxwell for the March 2002 ICES Study Group on the Further Development of the Precautionary Approach to Fishery

Management [SGPA] meeting (ICES CM 2003/ACFM:10) were used with these data to estimate the biomass at which recruitment is impaired.

Table 3.1.2.1. Working Group estimates of spawning-stock biomass (SSB) and recruitment at age 1 for cod in the North Sea, Skagerrak and Eastern Channel. Source: ICES CM 2002/ACFM:01.

Year-class	Parental SSB (tonnes)	Recruitment (thousands)	Year-class	Parental SSB (tonnes)	Recruitment (thousands)
1963	151521	374080	1982	190227	324686
1964	166149	415425	1983	154988	596292
1965	205425	506863	1984	133415	158611
1966	230759	488789	1985	126208	716254
1967	250046	194587	1986	114215	281821
1968	258219	209061	1987	104724	197056
1969	255921	782003	1988	98643	274078
1970	276848	910808	1989	90606	133940
1971	277216	173496	1990	78046	168570
1972	231011	319648	1991	71119	305294
1973	209145	263657	1992	68904	147325
1974	230838	486359	1993	65099	323678
1975	211636	246421	1994	64828	226904
1976	182050	839198	1995	71003	173262
1977	159349	488156	1996	76361	421717
1978	159354	525424	1997	80188	69536
1979	164266	899522	1998	71542	139369
1980	181876	314766	1999	61471	215023
1981	195732	618498			

In order to evaluate the estimator S* in a fishery context, it will be necessary to derive a corresponding fishing mortality estimator. The authors propose evaluating the slope at the origin of the segmented regression in order to estimate $\mathbf{F_{lim}}$.

Previous practice within ICES has been to set $\mathbf{F_{lim}}$ based upon the biological reference point $\mathbf{F_{loss}}$ (Cook 1998; O'Brien 1999). This reference point corresponds to the fishing mortality associated with the spawner-per-recuit that is the inverse of $\mathbf{G_{loss}}$, the ratio of the expected recruitment at the lowest observed SSB to the value of the lowest observed SSB. This is derived from the stock-recruitment pairs and is a conservative proxy for the fishing mortality that would drive the stock to extinction. This assumes that the critical factor is the expected level of recruitment, which is a function of spawning stock, which in turn is determined by fishing mortality.

This paper compares the values of $\mathbf{B_{lim}}$ and $\mathbf{F_{lim}}$ obtained by segmented regression and the $\mathbf{G_{loss}}$ procedures for a characterisation of the North Sea cod stock.

3.1.3 Methodological basis for the estimation of $\mathbf{F_{lim}}$

$\mathbf{F_{lim}}$ is to be estimated by obtaining a value for the expected recruitment at **S***. This recruitment should be representative of the values to be expected at that level of SSB, and should be based on the same stock-recruitment function used for deriving $\mathbf{B_{lim}}$; namely, the segmented regression. It is proposed that $\mathbf{F_{lim}}$ is derived from **S*** as a deterministic equilibrium value. The functional relationship between spawner-per-recruit and F will then give the F associated with the R/SSB slope derived from the $\mathbf{B_{lim}}$ estimate obtained from the segmented regression.

Shepherd (1982) showed how it is possible to combine spawner-per-recruit (SPR) analyses and SSB-R estimates to generate reference fishing mortality (F) rates. The relationships are straightforward (see Gabriel *et al*. 1989; Mace & Sissenwine 1993) and involve inversion of any SPR to form the slope of a straight line through the origin of the SSB-R curve (or a proxy therefore, such as a given percentile of the survival ratios). That line represents the average survival ratio required to support the given constant *F* associated with the SPR (Rosenberg *et al*. 1994).

In this paper, a simulation approach was used to investigate the properties of **S*** and its linked estimate of fishing mortality and compare them with $\mathbf{B_{loss}}$ and $\mathbf{F_{loss}}$.

3.2 Simulation approach

A simulation comprises an operating model from which simulated data are sampled within any experimental treatment. An individual treatment within an experiment is a particular choice of operating model and management procedure. The sampled data are then used to assess stock status. Depending on the perception gained, particular controls are then implemented which feed-back to the underlying stock. Results are collected and are used to compare and evaluate the candidate reference points within the fishery. The simulation approach is described more fully in Kell *et al*. (1999).

A variety of sources of uncertainty were considered:

- ***Process error:***
  recruitment
  natural mortality
  selectivity of the fishing fleet

- ***Estimation error:***
  using the XSA stock assessment method

- ***Model error:***
  three underlying stock-recruitment relationships
  reduction in recent recruitment
  discarding

- ***Implementation error:***
  simple mis-reporting rule

Fishing mortality
The trend in fishing mortality was the same as the Working Group times series but multipliers were applied to generate different final depletion levels. Multipliers were drawn at random from a compound distribution with specified mean and coefficient of variation (CV).

The following treatments were used for the simulation experiments:

Stock-recruitment relationships
To investigate structural uncertainty three stock-recruitment (S-R) relationships were investigated, obtained by equilibrium curves fitted to the yield-SSB pairs. These were:

- Ricker S-R
- Beverton-Holt S-R with a steepness of 0.9
- constant recruitment

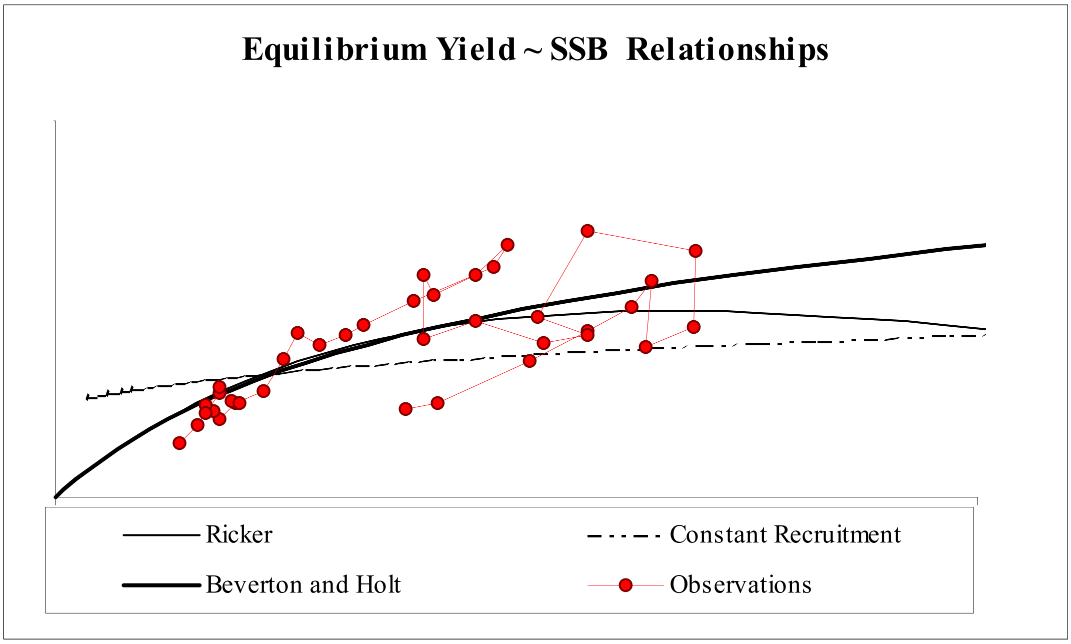


Figure 3.2.1. Equilibrium yield-SSB curves fitted to historical data for three S-R relationships.

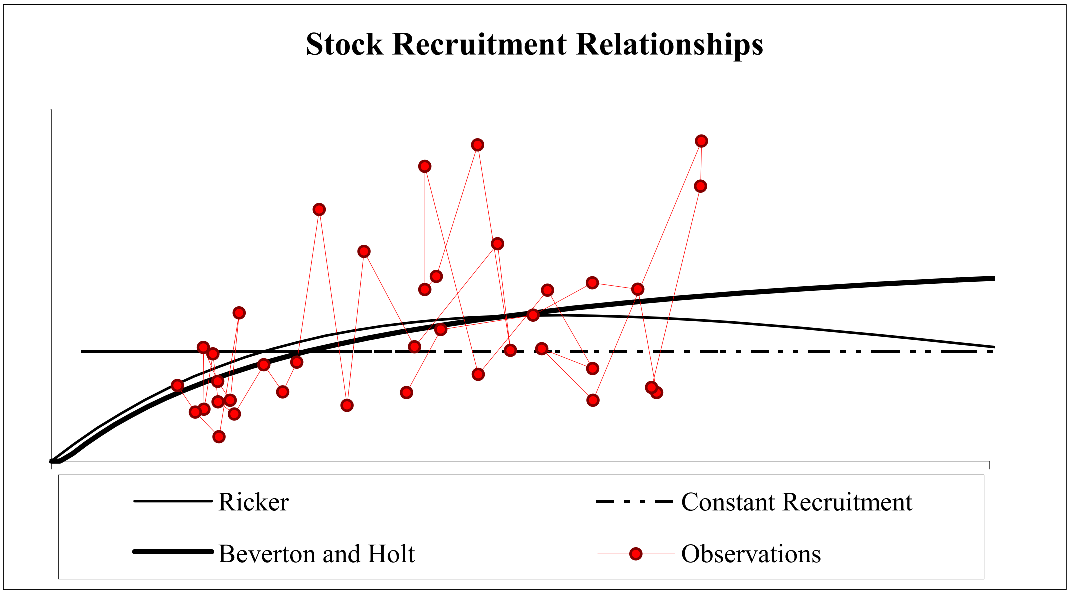


Figure 3.2.2. S-R relationships, with historic SSB-recruitment pairs, as estimated from equilibrium yield-SSB curves.

Changes in Recruitment

Two treatments designed to evaluate the effect of change in the expected recruitment due to environment were applied:

1) recruitment was given by the predicted value of the S-R relationship
2) expected recruitment from the S-R relationship was reduced by 66% in years 31 to 50.

Discarding
Estimates of discards are available from the Report of the Study Group on Discards and By-Catch Information (ICES 2002b). Figure 3.2.3 shows the proportion discarded as a function of mean weight-at-age for all fleets - there is a clear relationship between weight-at-age and the probability of being discarded. A CV of 20% was assumed for the distribution of weight-at-age.

Treatments applied were:

- discards accounted for in the assessment
- discards not included in the assessment

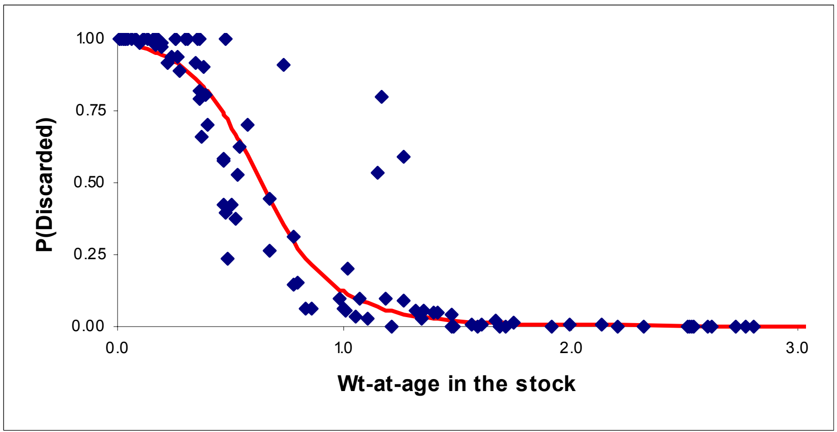


Figure 3.2.3. Proportion discarded with fitted relationship.

Mis-reporting
A simple mis-reporting scenario was investigated following the introduction of quotas in year 31 when quotas were set at 50% of the average catch between years 26 to 30. If mis-reporting occurred then catches reported to the Working Group, and used in the assessment, were taken to be the minimum of the actual yield and the quota.

3.3 Scenario statistics

Trajectories were produced for 50-year periods – the first 30 years were based upon the standard ICES North Sea cod *.sen and *.sum files and then projected forward for years 31 to 50. Four summary statistics were recorded:

a) biomass statistics:

S*

$\mathbf{B_{loss}}$

b) fishing mortality statistics:

$\mathbf{F_{lim}}$

$\mathbf{F_{loss}}$

4 RESULTS

The results of applying the segmented regression approach to the estimation of the biomass at which recruitment is impaired are presented for North Sea cod in the following Section 4.1. The results from the scenario evaluations are presented in Section 4.2.

4.1 Results of estimation and diagnostics for North Sea cod

Parameter values, including the change-point (**S*** = $\mathbf{B_{lim}}$), slope in the origin ($\hat{\alpha}$) and recruitment plateau (**R***), were computed and are presented in Table 4.1.1. The estimate **S*** produced from the algorithm in Julious (2001) is merely shown for comparison with the maximum likelihood estimate (mle) resulting from a 500x500 grid search. The latter approach provides the estimate of $\mathbf{B_{lim}}$ from the segmented regression model since the former method is constrained to consider only historical values of SSB as candidates for the biomass at which recruitment is impaired.

Table 4.1.1. Results of a) fitting a segmented regression model; together with b) the analysis of variance (ANOVA) table comparing the residual sum of squares (RSS) from fitting the segmented regression model to the RSS from fitting an arithmetic mean. The significance of the segmented regression model over the one-line (mean) model is indicated by the low p-value of the bootstrapped f-test statistic.

a)

From algorithm in Julious (2001)				**From search on 500x500 grid**		
S*	$\hat{\alpha}$	**R***		**S*(10)**	**S***	**S*(90)**
159349	2.62	417758		130609	159334	182972

b)

Model	**Resid df**	**RSS**	**Test df**	**Sum of sq**	**F value**	**Bootstrap**
mean	36	13.64				**p-value**
changepoint	35	9.52	1	4.12	15.13	< 0.001

The segmented regression fit is statistically significant at the 5% level of significance and the maximum likelihood estimate of the spawning stock biomass at which recruitment is impaired is 159 334 tonnes. An approximate 80% profile likelihood confidence interval is given by (130 609, 182 972) tonnes.

Diagnostic plots for the segmented regression model are shown in Figures 4.1.1 and 4.1.2. Of particular note is the panel in Figure 4.1.1 illustrating the influence of omitting each year-class individually from the fit of the model. The omission of each year-class individually from the estimation procedure has a similar effect on the estimate of the change-point but each revised estimate still lies well within the approximate 80% profile likelihood confidence interval for the change-point estimated based upon the full time series of data.

In Figure 4.1.3 there are summary graphs showing the parametric stock-recruitment model adopted by the ICES WGNSSK (ICES 2002a); together with the best fitting change-point regression.

4.2 Simulation evaluation

The Figures 4.2.1 and 4.2.2 show the results for the three main effects (treatments) and the three stock-recruitment relationships.

Figures 4.2.1 compare **S*** to $\mathbf{B_{loss}}$ and Figure 4.2.2 compares $\mathbf{F_{lim}}$ (derived from **S***) to $\mathbf{F_{loss}}$. In Figure 4.2.1 for each S-R relationship *times* treatment *panel*, the assumed S-R relationship is shown; the points represent **R*-S*** (blue) or the expected recruitment at $\mathbf{B_{loss}}$ (red). The grey and pink points represent the estimates without systematic departures in the data. The marginal empirical distributions of **S*** and $\mathbf{B_{loss}}$ are shown.

It can be seen that for a Ricker S-R model **B*** tends to occur at higher values of SSB and the empirical distribution is more markedly peaked than those for a Beverton-Holt S-R or constant S-R relationships. Also **B*** tends to occur at higher SSBs than $\mathbf{B_{loss}}$ for the Ricker S-R model, slightly higher for the Beverton-Holt S-R model and at $\mathbf{B_{loss}}$ for constant recruitment model. Discarding appears to have little affect on the estimates of the biomass reference points.

When mis-reporting occurs **S*** occurs at higher SSB levels whilst $\mathbf{B_{loss}}$ occurs at lower values. However, the effect is much less pronounced for **S*** than it is for $\mathbf{B_{loss}}$. The consequences for a change in the recent recruitment levels are very similar to those produced by mis-reporting and might imply that in reality it will not be possible to distinguish between the two cases.

In Figure 4.2.2 the first sub-plot shows the expected slope at the origin and contrasts it with the assumed S-R relationship. The lower sub-plots show the empirical distributions of $\mathbf{F_{lim}}$ (derived from **S***) and $\mathbf{F_{loss}}$. In contrast to the biomass reference points the fishing mortality reference points are much less sensitive either to bias in the data, to changes in the dynamics, or to the S-R relationships.

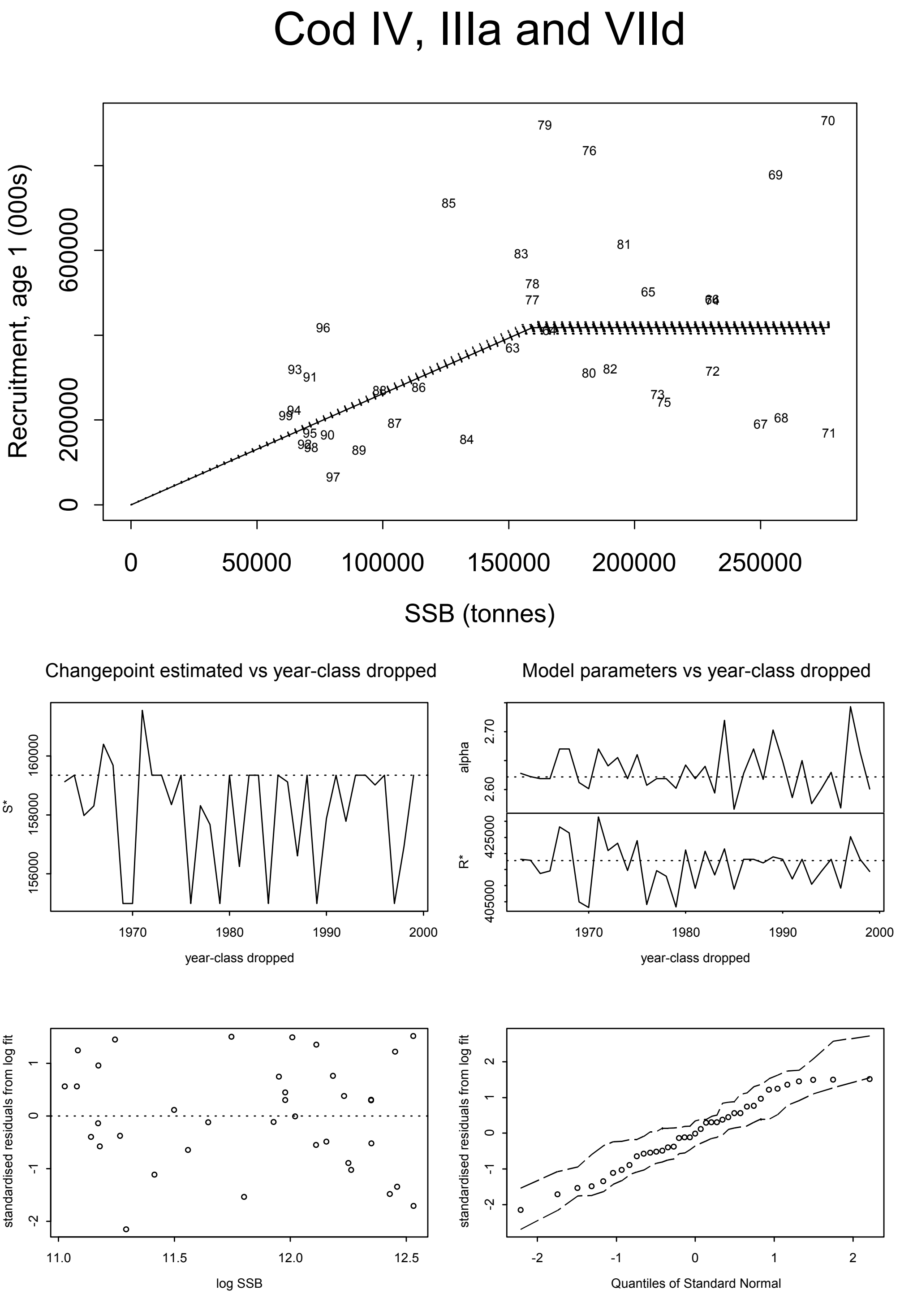


Figure 4.1.1. Diagnostic plots for the segmented regression model. Panel 1: stock-recruitment pairs identified by year-class; solid line is the change-point model estimated; dotted lines are the change-point models estimated by eliminating a single year-class in turn. Panel 2: change-point versus year-class eliminated. Panel 3: slope at the origin and recruitment estimate above change-point. Panel 4: standardised residuals versus covariate. Panel 5: q-q plot with simulation envelope.

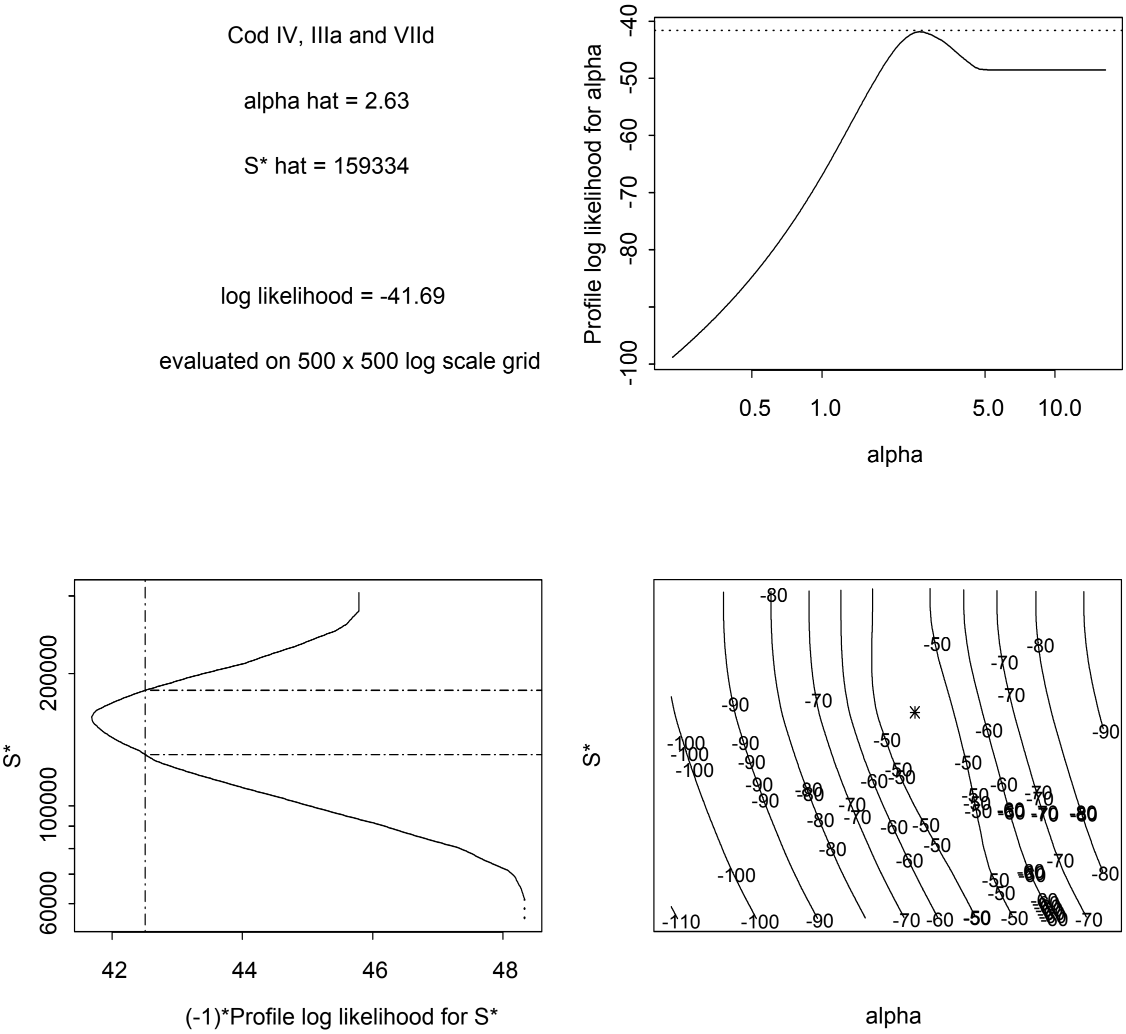


Figure 4.1.2. Profile likelihood plots. Panel 1: text. Panel 2: profile likelihood for slope at the origin. Panel 3: profile likelihood for change-point (vertical line – approximate 80% likelihood ratio confidence interval for **S***). Panel 4: contour surface.

Cod IV, IIIa and VIId

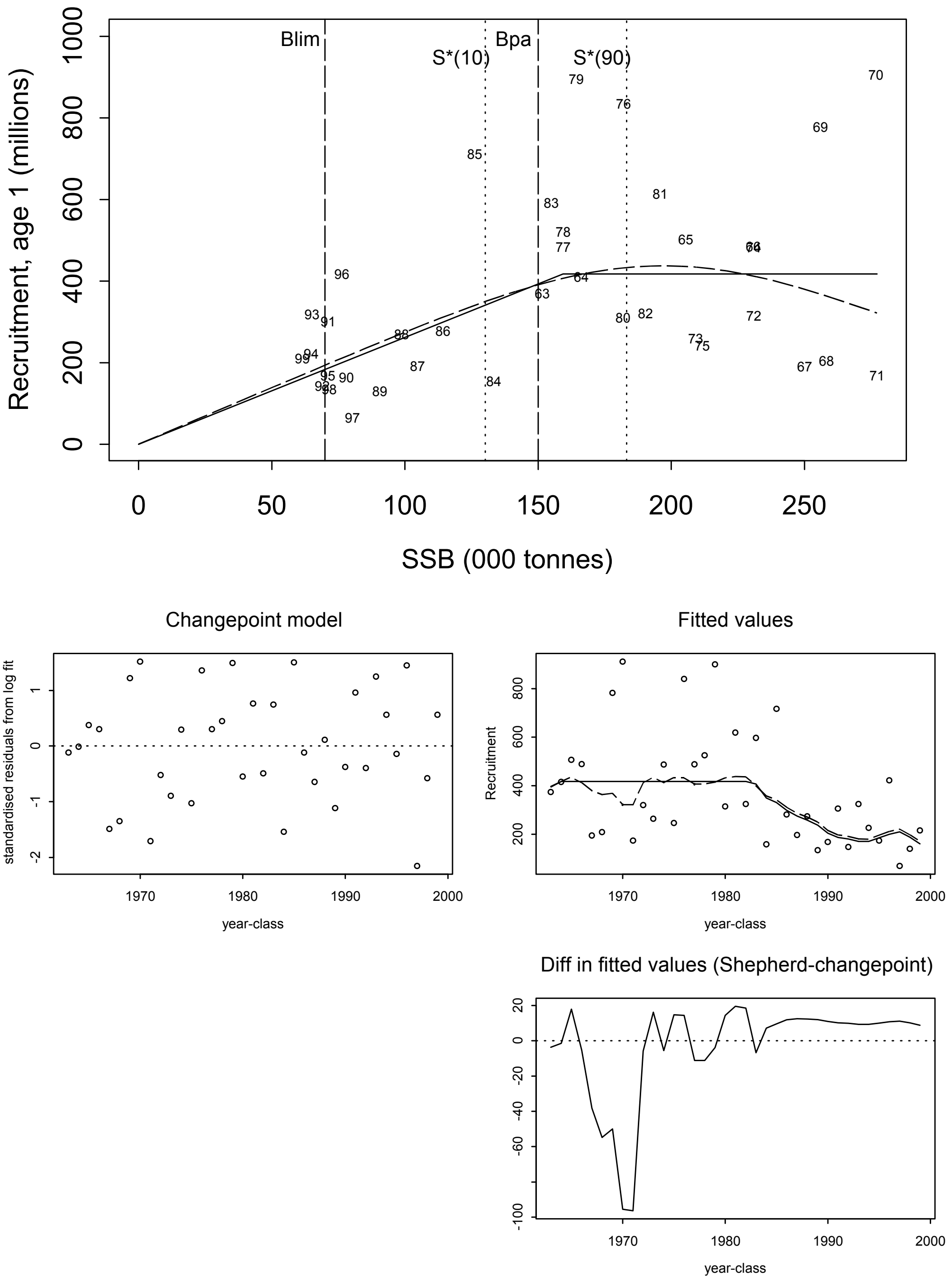


Figure 4.1.3. Summary graphs showing a comparison between the change-point regression fit and the ICES WG fit. Panel 1: stock-recruitment pairs identified by year-class; solid line is the change-point model estimated; dotted line is the ICES WG stock-recruitment curve. Panel 2: standardised residuals versus year-class. Panel 3: fitted values versus time (solid line – change-point; dotted line – WG). Panel 4: difference in fitted values (ICES stock assessment WG minus change-point).

Figure 4.2.1. Plots showing a 10% sample of the simulated values for each stock-recruitment relationship along with the marginal density for B* (blue) and B_{loss} (red). The thick lines are for estimates with systematic departures in the data; namely, discarding, mis-reporting and a decline in recruitment; the thin lines (grey and pink) show the distribution without these systematic departures. Pair wise comparisons may only be made between the grey and blue points/curves and between the pink and red points/curves as their simulations are linked.

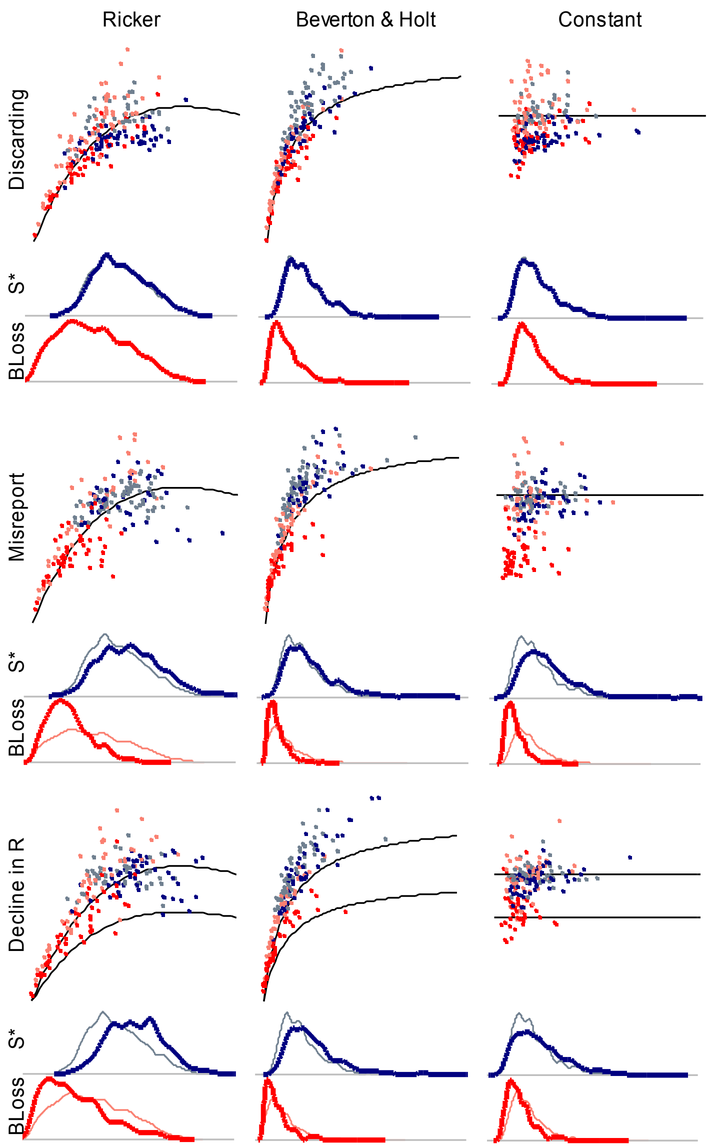
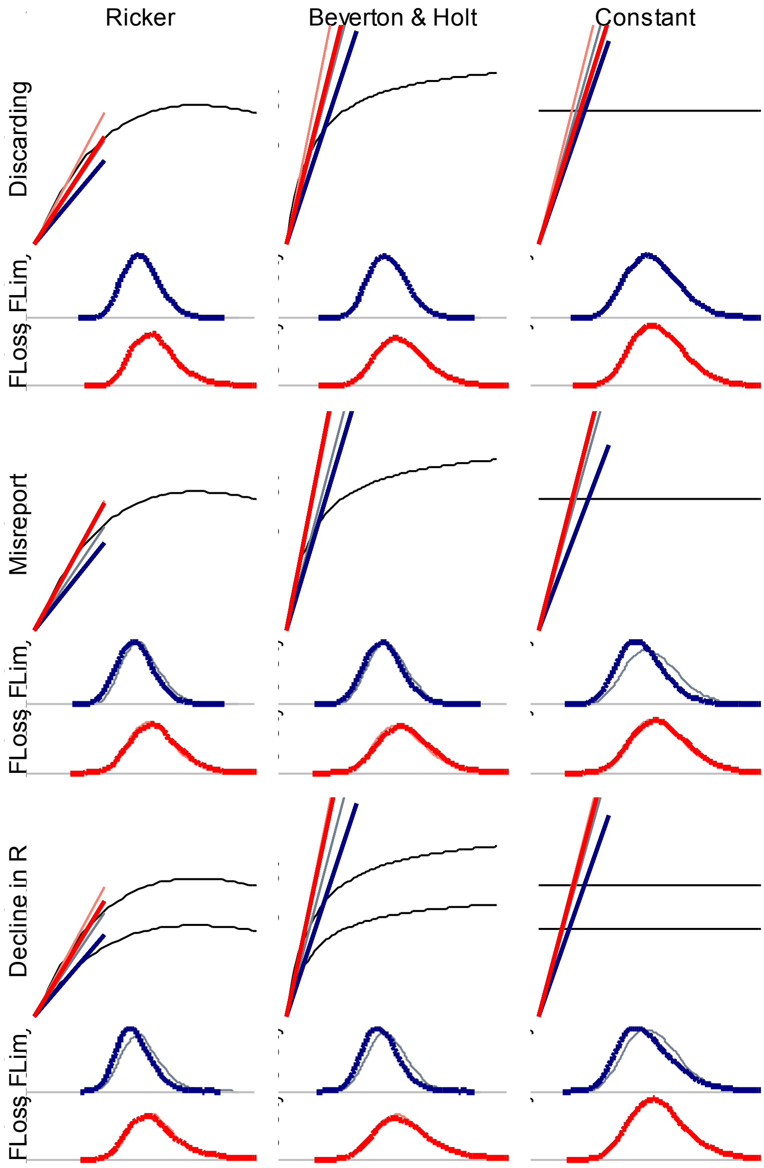


Figure 4.2.2. Plots show the expected values of the slope at the origin for each stock-recruitment relationship along with a 10% sample of the marginal density for F_{lim} (blue) and F_{loss} (red). The thick lines are for estimates with systematic departures in the data; namely, discarding, mis-reporting and a decline in recruitment; the thin lines (grey and pink) show the distribution without systematic departures. Pair wise comparisons may only be made between the grey and blue points/curves and between the pink and red points/curves as their simulations are linked.



5 DISCUSSION

The technique presented in this paper for the estimation of the biomass at which recruitment is impaired is only one of a number of candidate approaches that might be employed and has been adopted by ICES for the revision of the reference points for North-east Arctic cod (ICES 2003) at the May 2003 meeting of ACFM. Ultimately, the choice of method and estimation procedure will depend upon specific stock dynamics, knowledge of fisheries and management objectives. However, in reality our knowledge of the stock and fishery dynamics will always be incomplete and it may be difficult to choose between alternative hypotheses about the dynamics. There will also be confounding between changes in the dynamics and the response to management so that it might not be possible to distinguish between real effects and biases in the data. The provision of advice, in respect of management objectives, cannot be postponed until we have full knowledge of the relevant processes. It is therefore important, that any advice is robust to our uncertainty in the dynamic processes and our ability to monitor and control them. Therefore, a scenario approach has been used to investigate the robustness of the change-point method for estimating **S*** and its corresponding fishing mortality.

In general, it appears from the simulations that systematic departures in the data tend to increase the estimate of **S***. Presumably, this may be because all treatments cause the perceived recent recruitment to decline, recent SSBs are also lower and consequently, the change-point occurs at a higher value of SSB. However, note that the opposite effect is seen for $\mathbf{B_{loss}}$.

With respect to fishing mortality, the fishing mortality corresponding to **S*** is similar in magnitude to that estimated by $\mathbf{F_{loss}}$.

The following points are clear from the results:

- minimal difference between estimates of **S*** from the Beverton-Holt and constant stock-recruitment models;
- minimal effect of discards on biomass reference points;
- the other treatments (mis-reporting and a decline in recruitment) both suggest that $\mathbf{B_{loss}}$ is biased downwards and **S*** biased upwards;

and

- F corresponding to **S*** tends to be slightly biased downwards in the mis-reporting and decline in recruitment treatments; and
- $\mathbf{F_{loss}}$ tends to be slightly larger than the F corresponding to **S***.

The latter is not unexpected since both these estimates of F are linear proxies for $\mathbf{F_{crash}}$ but $\mathbf{F_{loss}}$ is estimated at the lower extreme range of the data margin and hence, nearer to the origin. Both of the estimates of fishing mortality seem less affected by the systematic departures explored.

The next step will be to identify appropriate pa-values for biomass and fishing mortality that avoid the lim-values with a specified probability, and take into account the management regime.

Previously, it has been demonstrated that two different ways to formulate advice – one based on a TAC constraint and the other based upon *status quo* F - imply different precautionary reference values for fishing mortality and biomass (ICES 2003). One should note that any future change to the current basis for advice is most likely to change the corresponding precautionary reference values. An example of such a change is the formulation of multi-annual advice, but the approach presented in this paper provides a potential solution. Before recommendations can be made for specific target levels or harvesting strategies scenario modelling should be used for the investigation of candidate references points and their incorporation within a management procedure. Such methodological investigations fall within the remit of the ICES Working Group on Methods on Fish Stock Assessments [WGMG] and further research is planned for presentation at their next meeting in 2004.

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