



**SCIENTIFIC COUNCIL MEETING, JUNE 2004**

Report of the NAFO Study Group on Limit Reference Points Lorient, France, 15-20 April, 2004

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**Participants in the NAFO Study Group on Limit Reference Points, 15-20 April 2004, IFREMER, Lorient, France:**

(Back – left to right): Brian Healey, Ricardo Alpoim, Hilario Murua, Bill Brodie, Antonio Vazquez, Jean-Claude Mahé, Mike Prager, Denis Rivard, Paul Rago, Dave Kulka, Konstanin Gorchinsky, Ray Bowering

(Front – left to right): Susana Junquera, Fernando Gonzalez-Costas, Peter Shelton, Noel Cadigan, Mike Armstrong

## 1. Opening

The Chair, Peter Shelton, welcomed participants to the Study Group meeting and thanked Jean-Claude Mahé and IFREMER for agreeing to host the meeting. Jean-Claude Mahé was appointed Co-Chair and Bill Brodie was appointed Rapporteur. At the Scientific Council Workshop on the Precautionary Approach held March-April 2003 (NAFO 2003) it was noted that it is the responsibility of Scientific Council to calculate limit reference points (LRPs). Given that a number of approaches for LRPs have been discussed in the literature, it was recognized that there is a need to review the strengths and weaknesses of these alternative approaches and to make recommendations to Scientific Council on which are the most appropriate for defining LRPs. These recommendations are needed for stocks ranging from data-rich to data-poor and with a range of life-history parameters. Detailed Terms of Reference (ToR) are given in Appendix I.

The Chair reviewed the ToR for the Study Group meeting and noted that an attempt would be made to work mostly in plenary, although sub-groups may be required to accelerate progress on the three case studies. A provisional Agenda was reviewed (Appendix I) and accepted in general terms, with the acknowledgement that some flexibility was required to accomplish the ToRs in the most productive manner.

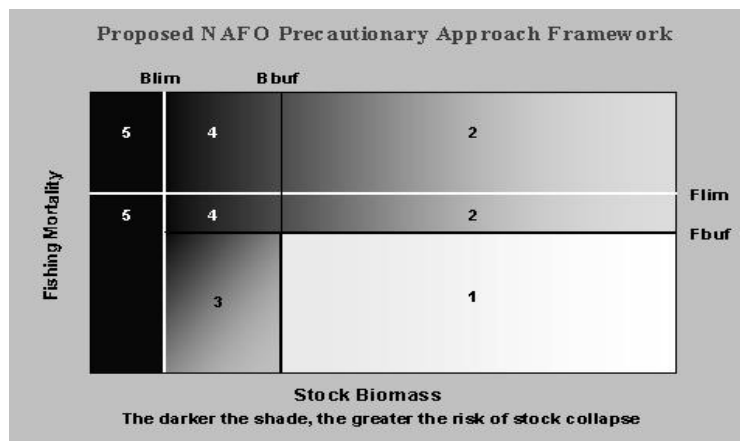
### Reference

NAFO SC 2003. Report of NAFO Scientific Council Workshop on the Precautionary Approach to Fisheries Management. NAFO SCS Doc. 03/05.

## 2. Development of the Precautionary Approach framework within NAFO – the need for limits (Bill Brodie)

NAFO Scientific Council (SC) commenced work on a PA framework in 1997 (Serchuk *et al.*, 1997), incorporating limit, buffer and target reference points specified in terms of both fishing mortality (F) and spawner stock biomass (SSB). Subsequently, numerous meetings of a joint working group (WG) of Scientific Council and Fisheries Commission (FC) were held to further develop and guide implementation of the PA within NAFO. The joint WG focused on the different roles of FC and SC in the process, and developed PA implementation plans for some NAFO stocks, setting the stage for development of a new NAFO SC framework on the PA at the SC Workshop on PA in St John's March/April 2003 (NAFO SC 2003a). That framework was subsequently modified by SC at its meetings in June and September 2003, and presented to FC at the September 2003 meeting (NAFO SC 2003b).

The 2003 NAFO PA Framework (Fig. 2.1) attempts to provide a flexible approach (Shelton *et al.*, 2002), addressing a number of concerns of Fisheries Commission while still retaining those elements considered essential to the implementation of the PA in terms of the FAO Code of Conduct for Responsible Fisheries and the United Nations Fisheries Agreement. The 2003 Framework describes 5 zones and defines proposed management strategies and courses of action within each zone (Table 2.1).



**Fig. 2.1.** The 2003 version of the SC NAFO PA Framework.

**Table 2.1.** The definition of zones and associated management strategies/courses of action proposed by SC.

<b>MANAGEMENT STRATEGIES AND COURSES OF ACTION (TIME HORIZONS AND ACCEPTABLE RISK LEVELS SPECIFIED BY MANAGERS)</b>	
<b>Zone 1</b>	<b>Safe Zone:</b> Select and set fishing mortality from a range of $F$ values that have a low probability of exceeding $F_{lim}$ in a situation where stock biomass ( $B$ ) has a low probability of being below $B_{lim}$ . In this area, target reference points are selected and set by managers based on criteria of their choosing (e.g. stable TACs; socio-economic considerations).
<b>Zone 2</b>	<b>Overfishing Zone:</b> Reduce $F$ to below $F_{buf}$ .
<b>Zone 3</b>	<b>Cautionary F Zone:</b> The closer stock biomass ( $B$ ) is to $B_{lim}$ , the lower $F$ should be below $F_{buf}$ to ensure that there is a very low probability that biomass will decline below $B_{lim}$ within the foreseeable future.
<b>Zone 4</b>	<b>Danger Zone:</b> Reduce $F$ to below $F_{buf}$ . The closer stock biomass ( $B$ ) is to $B_{lim}$ , the lower $F$ should be below $F_{buf}$ to ensure that there is a very low probability that biomass will decline below $B_{lim}$ within the foreseeable future.
<b>Zone 5</b>	<b>Collapse Zone:</b> $F$ should be set as close to zero as possible.

Reference points associated with the 2003 Framework are defined as follows:

#### *Fishing Mortality Reference Points*

- $F_{lim}$  = a fishing mortality rate that should only have a low probability of being exceeded.  $F_{lim}$  cannot be greater than  $F_{msy}$ . If  $F_{msy}$  cannot be estimated, then an appropriate surrogate may be used instead.
- $F_{buf}$  = A fishing mortality rate below  $F_{lim}$  that is required in the absence of analyses of the probability that current or projected  $F$  exceeds  $F_{lim}$ . In the absence of such analyses,  $F_{buf}$  should be specified by managers and should satisfy the requirement that there is a low probability that any  $F$  estimated to be below  $F_{buf}$  will actually be above  $F_{lim}$ . The more uncertain the stock assessment, the greater the buffer zone should be. In all cases, a buffer is required to signify the need for more restrictive measures.

When the stock is above  $B_{buf}$  and  $F < F_{buf}$ , a flexible  $F$  rate will be selected by managers to achieve desired management objectives, subject only to the constraints defined by the limit and buffer reference points. In particular, a target  $F$  should be chosen to ensure that there is a low probability that  $F$  exceeds  $F_{lim}$ , and a very low probability that biomass will decline below  $B_{lim}$  within the foreseeable future.

#### *Spawning stock biomass reference points*

- $B_{lim}$  = A biomass level, below which stock productivity is likely to be seriously impaired, that should have a very low probability of being violated.
- $B_{buf}$  = A stock biomass level above  $B_{lim}$  that is required in the absence of analyses of the probability that current or projected biomass is below  $B_{lim}$ .

In the absence of such analyses,  $B_{buf}$  should be specified by managers and should satisfy the requirement that there is a very low probability that any biomass estimated to be above  $B_{buf}$  will actually be below  $B_{lim}$ . The more uncertain the stock assessment, the greater the buffer zone should be. In all cases, a buffer is required to signify the need for more restrictive measures.

Key features of the 2003 Framework include:

- There must be a very low probability<sup>2</sup> that management actions result in projected biomass dropping below  $B_{lim}$  within the foreseeable future<sup>3</sup>. Below  $B_{lim}$ ,  $F$  should as close to zero as possible.
- The fishing mortality limit should be no higher than  $F_{msy}$ . There should be a low probability<sup>1</sup> that realized  $F$  will exceed  $F_{lim}$ .
- $F$  targets are flexible, as long as they remain in Zone 1.
- If a stock assessment generates current or projected biomass with some probability distribution, operationally the biomass distribution would be evaluated against  $B_{lim}$ . In other words, a risk analysis will provide the probability that current or projected biomass is  $< B_{lim}$ .
- If no probability distribution of biomass is available, but a value for  $B_{lim}$  exists, FC should establish a buffer zone ( $B_{buf}$ ), against which the biomass would be evaluated. The same procedure should be used to establish a fishing mortality buffer ( $F_{buf}$ ). If biomass is in the zone between  $B_{lim}$  and  $B_{buf}$ , action to reduce  $F$  below  $F_{buf}$  is required to ensure that there will be a very low probability<sup>2</sup> that biomass declines below  $B_{lim}$  in the foreseeable future<sup>3</sup>.

[1] low probability might be defined as  $\leq 20\%$ , but actual level should be specified by managers

[2] very low probability might be defined as  $\leq 5\text{-}10\%$ , but actual level should be specified by managers

[3] foreseeable future might be defined as 5-10 years, but the actual time horizon should be specified by managers

### *References*

NAFO SC 2003a. Report of NAFO Scientific Council Workshop on the Precautionary Approach to Fisheries Management. NAFO SCS Doc. 03/05.

NAFO SC 2003b. Proposed NAFO Precautionary Approach Framework from Scientific Council. NAFO SCR Doc. 03/23.

Serchuk, F. M., D. Rivard, J. Casey, and R. Mayo. 1997. Report of the Ad hoc Working Group of the NAFO Scientific Council on the Precautionary Approach. NAFO SCS Doc., No. 97/12, Serial No. N 2911.

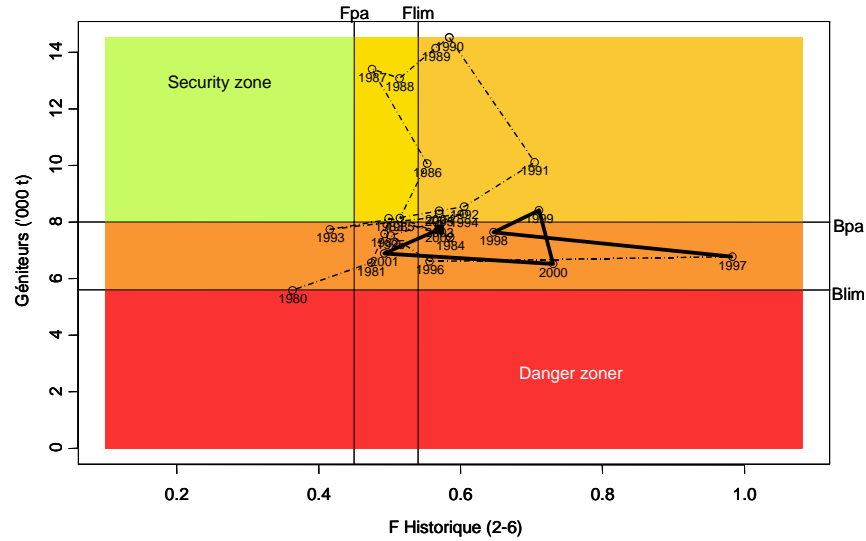
Shelton, P.A., P.M. Mace, W.B. Brodie and J.-C. Mahé. 2003. A proposal for a more flexible framework for implementing the Precautionary Approach on NAFO stocks. NAFO SCR Doc. 03/58.

## **3. PA Limits – Concepts, Estimation, Evaluation and Implementation**

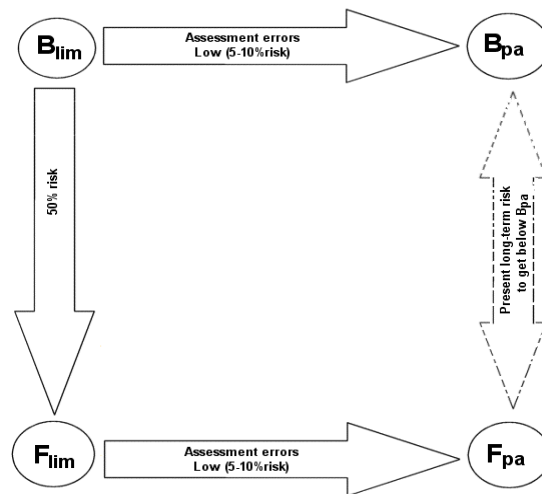
### **3.1. Implementation of the Precautionary Approach in the European Union fisheries management system (Jean-Claude Mahé)**

#### *The ICES PA Framework*

The ICES PA framework (Fig 3.1.1) is similar to the NAFO framework. Zones are defined with reference to the increasing risk of being in a “Danger Zone”, the goal being to maintain the stock in the “Security Zone”. No particular management rules are prescribed.



**Fig. 3.1.1.** The ICES PA Framework showing the risk zones. Spawner biomass is on the y-axis and is plotted against fishing mortality on the x-axis.



**Fig. 3.1.2.** The ICES PA Framework showing the process for estimating reference points. Under the ICES Framework, reference points are defined as follows:

$B_{lim}$  is the SSB below which there is a high risk that recruitment will “be impaired” (seriously decline) or the dynamics of the stock is unknown.  $F_{lim}$  is the fishing mortality that will drive the SSB to that biomass limit.

Because of uncertainty in the annual estimation of  $F$  and SSB, ICES defines the more conservative operational reference points,  $B_{pa}$  (higher than  $B_{lim}$ ), and  $F_{pa}$  (lower than  $F_{lim}$ ), where the subscript  $pa$  stands for precautionary approach. When a stock is estimated to be at  $B_{pa}$  there should be a high probability that it will be above  $B_{lim}$  and similarly if  $F$  is estimated to be at  $F_{pa}$  there should be a low probability that  $F$  is higher than  $F_{lim}$ .

The process for the estimation of reference point in the ICES Framework (Fig. 3.1.2) puts the emphasis on  $B_{lim}$ .  $B_{lim}$  is the cornerstone of the framework and  $F_{lim}$  is linked to  $B_{lim}$  deterministically. The  $pa$  reference points are estimated taking into account assessment uncertainties.

### *The decision path in the provision of advice in ICES*

The decision path in the provision of advice for ICES can be summarized as:

#### **ICES WG -> ICES ACFM -> STECF -> EU Council of Ministers**

The ICES Working Groups (WG): group of scientists; they assess the stocks and propose reference points.

The ICES Advisory Committee on Fisheries Management (ACFM): group of scientists; they review the WG assessments and give management advices and decide on reference points.

The Scientific, Technical and Economic Committee for Fisheries (STECF): group of scientists, economists, gear technologists; they review ACFM advice and take into consideration economic and technical aspects in formulating advice.

The EU Council of Ministers makes the final decision on management measures.

### *Some ICES case examples*

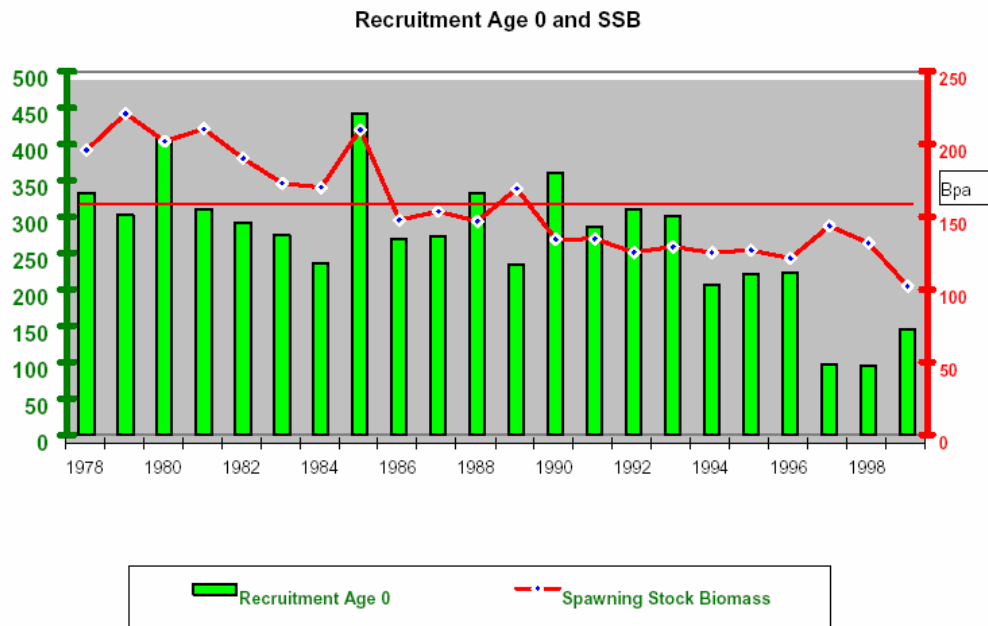
#### Northern Hake

$B_{lim}$  for this stock was set at 120,000 t ( $B_{loss}$  from the 1998 assessment) and  $B_{pa} = B_{lim} * e^{1.645*0.2} = 165,000$  t (Fig. 3.1.3).

In 2000, the assessment WG warned that there was a risk of collapse for the Northern hake stock (outside safe biological limits,  $SSB_{1999} < B_{lim}$ ).

At its December 2000 meeting, the EU Council of Ministers asked the EU Commission to set up a recovery plan for Northern hake to ensure that:

- quotas were not overshot,
- to protect spawning fish, and
- to make fishing gears more selective in order to enhance the escape of immature fish from these gears.



**Fig. 3.1.3.** Trends in SSB and Recruitment from the Northern Hake 2000 assessment.



The EU Council requested transparent control and monitoring measures to ensure the implementation of the technical rules. In June 2001 emergency measures were set up for the recovery of the Northern hake stock (from Skagerrak to the Bay of Biscay). These measures aimed to reduce catches of juvenile hake. They were complemented by additional technical measures in March 2002. Two geographical areas were defined in the Southwest of Ireland and in the Bay of Biscay where juvenile hake occur in high abundance. Fishing with towed gears in these areas was subject to a mesh size increase, (except beam trawl). In these areas the mesh size of fixed gears was also increased. Outside these areas fishing hake with usual towed gears was allowed provided that hake by-catches were not in excess of 20% of the total catch. This did not apply on vessels under 12 m engaged on day trips.

A recovery plan for the northern hake was proposed in July 2003 by the European Commission (COM (2003) 374 final) but has not yet been adopted. This plan involves:

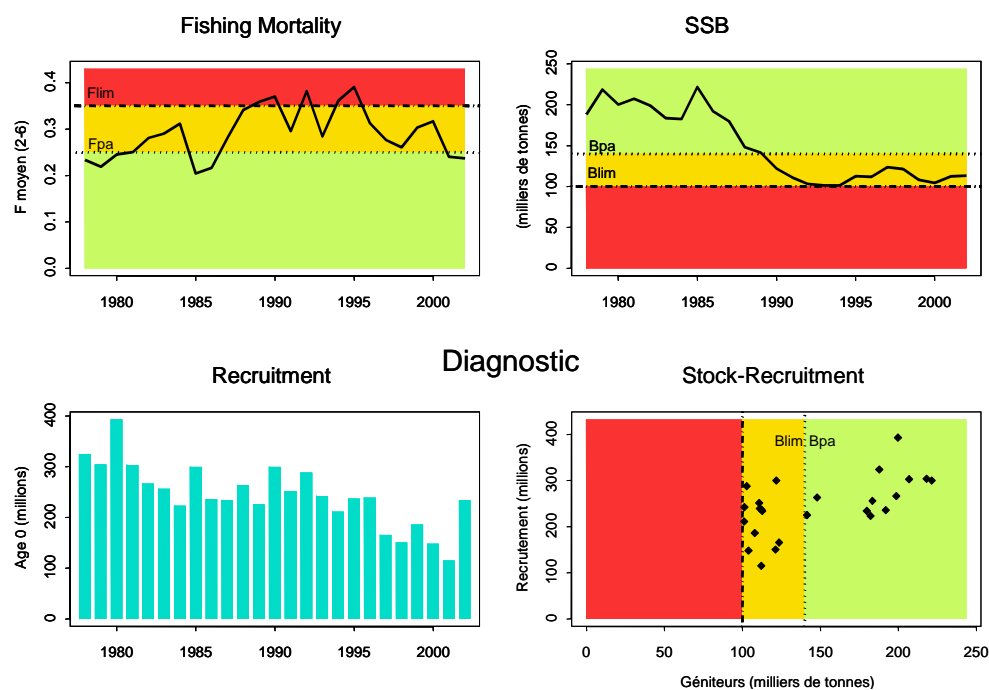
- recovery of the SSB to safe limits by an increase in SSB of 10% by year
- a limit on the annual TAC variation set at 15%
- fishing effort limitation to achieve the above objectives

Several STECF ad-hoc WGs were set up by the Commission in this process:

A Subgroup on Review of Stocks (SGRST) was tasked with the review of recovery plans (for hake and cod) and met 20-22 March 2002 to test various scenarios of recoveries.

A STECF Subgroup on Hake Technical Measures met 27-31 October 2003 to evaluate the impact of technical measures implemented for the past two years.

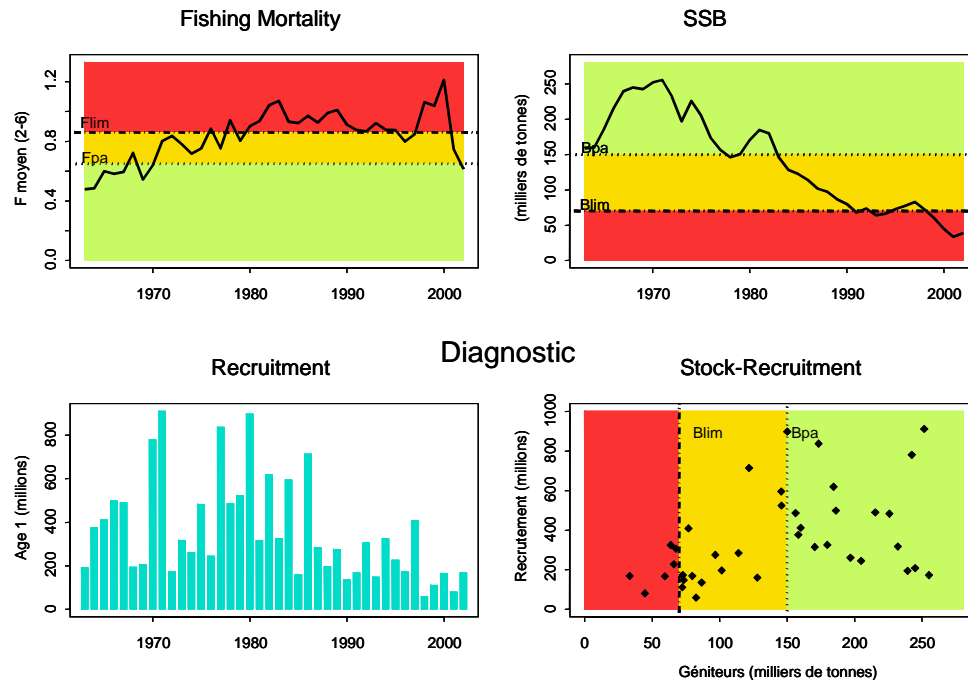
The 2003 assessment showed that the stock was in a less severe state than in previous years when the initial recovery plan was proposed (Fig. 3.1.4). Nevertheless, the SSB was still below  $B_{pa}$  and close to  $B_{lim}$ . The Council of Ministers decided in December 2003 to cut fishing mortality by 4% in the first year (2004). The same rate in fishing mortality (0.25) will be maintained in the following years until SSB reaches 140,000 t.



**Fig. 3.1.4.** Summary plot from the Northern Hake 2003 assessment.

## North Sea Cod

The North Sea cod stock is considered to have been outside safe biological limits from 2001 onwards (Fig. 3.1.5). Advice has been, successively, lowest possible catch leading to closure in 2003 and zero catch in 2004. Catches estimated by the WG were as high as 54,000 t in 2002.



**Fig. 3.1.5.** Summary figures of the North Sea Cod 2003 assessment.

In 2003 ICES evaluated the recovery plan for north sea cod:

“ICES ... notes that the current SSB is so far below historic stock sizes that both the biological dynamics of the stock and the behaviour of the fleets are unknown, and therefore historic experience and data are not considered a reliable basis for medium-term forecasts of stock dynamics under various rebuilding scenarios. On the basis of this evaluation ICES concludes that the proposed rebuilding plan cannot be accepted as likely to lead to safe and rapid rebuilding of this cod stock.”

### Conclusion

The two examples show that, although a precautionary approach has been implemented in fisheries management under ICES, it is too often the case that measures are taken when a stock is already outside biological limits rather than before. This delay between the warning and implementation of measures has to be taken into account in establishing reference points and management strategies under a precautionary approach.

### 3.2. From assessment models to limit and target reference points (Mike Prager)

#### Introduction

The precautionary approach in fishery management is often implemented by establishing biological reference points that govern exploitation according to the strength of the stock. The details and terminology used in the PA vary from one arena to another. In one common scheme, a limit reference point (LRP) describes a rate of fishing mortality (F) that should be exceeded only infrequently, if at all. A corresponding target reference point (TRP) describes a desired rate of exploitation, lower than the LRP that is compatible with current stock status.

It appears to the author that NAFO's concept of a "buffer F" appears similar or identical to the TRP as it is used here. Each term is used to represent an F set by managers in accordance with some precautionary harvest control rule, which may be either general or detailed.

When a fishery is managed using a precautionary approach, an LRP must be set, and  $F_{lim}$  in several forum has been established as the level  $F = F_{msy}$ . Then, a compatible TRP must be derived. This summary describes two methods for computing a TRP that is compatible with an existing LRP. The methods were originally described in two related papers: Caddy and McGarvey (1996) [whose method is here termed CM]; and Prager *et al.* (2003) [whose method is termed REPAST]. This document is mostly derived, with modification, from the latter paper.

#### *Method of Caddy & McGarvey (CM)*

Both the methods to be described here are based on simple statistical theory, but the approach described by Caddy and McGarvey (1996) is somewhat simpler. Under the CM method, it is necessary to first estimate an LRP, which is considered deterministic. The method further assumes that the TRP is the central tendency of a probability density function (pdf) that describes the uncertain (stochastic) outcome of whatever management rules (e.g., level of F) will be applied in the next time period. The actual outcome from that distribution is symbolized  $F_{next}$  (which is thus a random variable). The CM method also assumes that the shape of the pdf of  $F_{next}$  is known (normal or lognormal with known CV), and that managers have specified a permitted probability  $P^*$  of exceeding the LRP in the next period. Under those assumptions, the probability that the realized F in the next period exceeds the LRP is expressed by the integral

$$\Pr(F_{next} > F_{\lambda}) = \int_{F_{\lambda}}^{\infty} pdf_{F_{next}}(F) dF = P^* . \quad (3.2.1)$$

The assumption that the pdf of  $F_{next}$  is centered on the TRP implies that implementation of the TRP, although imprecise, is accurate (unbiased). Consequently, when the TRP is increased or decreased,  $\Pr(F_{next} > LRP)$  will increase or decrease accordingly, so that some particular value of F for the TRP provides the desired probability  $P^*$ . Generally, that value can be found by a computer optimization routine. Conveniently, numerical routines are available to compute the inverse-normal function, and when such a routine is available, it is possible to compute the desired TRP directly (assuming normality in  $F_{next}$ ) as

$$F_{\tau} = \frac{F_{\lambda}}{1 + CV_{F_{next}} \cdot Z^{-1}(1 - p^*)} . \quad (3.2.2)$$

The most interesting properties of CM method could be considered:

- its conceptual simplicity,
- its basis in probability theory,
- its recognition of uncertainty in  $F_{next}$ , which results from implementation uncertainty in the target F, and
- its requirement that  $P^*$  be specified a priori, which serves to make explicit the nonscientific aspects of choosing a TRP.

The most obvious limitation of the CM method is its treatment of the LRP as deterministic. Because LRPs are generally estimated from imprecise data through fitting assessment models, they are in fact imprecise themselves.

#### *Method of Prager et al. (REPAST)*

The framework of Prager *et al.* (2003), which the authors termed REPAST, extends the preceding framework in two main ways. The first extension consists of treating the LRP as imprecise, which of course it is. Thus the estimated LRP is then considered the central tendency of its own probability distribution. Given that, equation (1), expressed in general terms, becomes

$$\Pr(F_{next} > F_{\lambda}) = \int_{-\infty}^{\infty} \Pr(F_{next} > F) \cdot \Pr(F_{\lambda} = F) dF, \quad (3.2.3)$$

which in terms of probability distributions is equivalent to

$$\Pr(F_{next} > F_{\lambda}) = \int_{-\infty}^{\infty} [1 - \text{cdf}_{F_{next}}(F)] \text{pdf}_{F_{\lambda}}(F) dF. \quad (3.2.4)$$

In equation (4)  $F_{next}$ , the realization of the F target, is represented by its cumulative distribution function (cdf), rather than its probability density function (pdf) as previously. Equation (4) then contains an implied double integral, because the cdf represents an integration of some pdf (an integration that may be done analytically or through numerical approximation).

The second extension provided by REPAST is to consider the LRP and TRP relative to the present level of F ( $F_{now}$ ). As LRP and  $F_{now}$  are usually estimated from the same assessment procedure, the use of a ratio estimate reduces variance in the estimated LRP. Another reason for using ratios is that the TRP is usually derived as an adjustment to  $F_{now}$ ; e.g., as a proportional reduction or increase in  $F_{now}$ .

The probability equations used for relative reference points are identical to those used for absolute reference points. Thus the REPAST procedure, without modification, can be used with either relative or absolute reference points.

The REPAST procedure provides a method with all the properties of CM, but also recognizing uncertainty in the estimate of the LRP.

The information needed to use REPAST is as follows:

- An estimate of the LRP (relative to  $F_{now}$ ),
- The approximate form of variability in estimation of the LRP and implementation of the TRP (usually assumed normal or lognormal),
- An estimate of the CV of the LRP (usually obtained from the assessment model),
- An estimate of the CV of the TRP (possibly obtainable from examining the history of the fishery), and
- The value of  $P^*$ , the permitted probability of exceeding the LRP in any year (a management decision).

In applying REPAST, the authors have often used  $P^* = 0.22$ . That value was chosen because, under the assumption of independence in implementation error from year to year, it results in a probability of exceeding  $F_{lim}$  three years in a row at  $P^* = 0.22$  of 0.01.

In conclusion, REPAST provides an objective and theoretically-based method for deriving a target reference point from a limit reference point. Although reference points in F have been described here, the method is adaptable to reference points in biomass. The REPAST method is consistent with the precautionary approach, as the difference between TRP and LRP increases as precision of the estimates decreases. The method is also compatible with results of most assessment models, and it can be implemented with a short computer program. (Such a program is available as part of the “ASPIC Suite” from M. H. Prager’s Web site, <http://shrimp.ccfhrb.noaa.gov/~mprager/>.) The procedure is explained in much greater detail in Prager *et al.* (2003), which also includes several worked examples, and to which interested readers are referred.

## References

- Caddy, J. F., and R. McGarvey. 1996. Targets or limits for management of fisheries? North American Journal of Fish. Man. 16:479–487.
- Prager, M. H., C. E. Porch, K. W. Shertzer, and J. F. Caddy. 2003. Targets and limits for management of fisheries: A simple probability-based approach. North Am. J. Fish. Man. 23:249–361.

### 3.3. Confidence intervals for the change point in a stock-recruit model: A simulation study of the profile likelihood method based on the logistic hockey stick model (Brian Healey and Noel Cadigan)

In fisheries science considerable attention has recently been given to estimating the size of a stock at which recruitment is substantially impaired (e.g. Barrowman and Myers, 2000; O'Brien and Maxwell, 2002). The breakpoint in a simple two segment linear regression or hockey stick (HS) model, involving estimates of stock size and subsequent recruitments, has been utilized to identify such stock productivity limit reference points. However, there are statistical inference difficulties with this piece-wise linear model.

Stock-recruit models typically express recruitment (R) in a stock as a function of stock size (S); that is, if R is considered to be a random variable then  $E(R|S) = \mu(S)$ . The HS model consists of two linear segments which meet at a change-point,  $\delta$ :

$$\mu(S) = \begin{cases} \alpha S & S \leq \delta \\ \alpha \delta & S > \delta \end{cases} \quad (3.3.1)$$

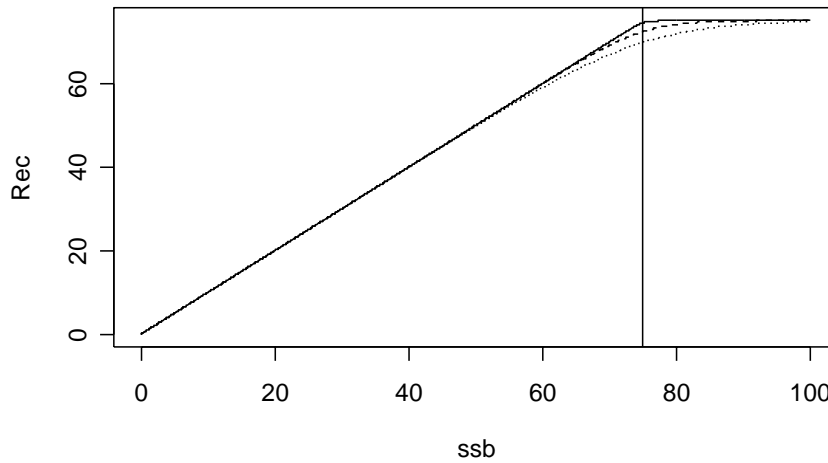
Barrowman and Myers (2000) and O'Brien and Maxwell (2002) have discussed statistical inference difficulties with the HS model (also see Hinkley, 1969; Julious, 2001; Toms and Lesperance, 2003). Barrowman and Myers (2000) examined smooth versions of the HS model and noted that these resulted in far fewer estimation and inference problems.

The logistic hockey stick (LHS) model (presented below) is based on the smooth derivative function,

$$\frac{\partial \mu(S)}{\partial S} = \frac{\alpha \left(1 + e^{-1/\theta}\right)}{1 + e^{\frac{(S-\delta)/\theta\delta}}}. \quad (3.3.2)$$

This is a somewhat complicated looking function, but it is simply a logistic function that decreases from  $\alpha$  at  $S = 0$  to zero as  $S \rightarrow \infty$ . The derivative function is symmetric about  $\delta$ . The rate at which the function decreases is controlled by  $\theta$ , which is a smoothness parameter scaled relative to the change-point. The LHS model can be obtained by integrating the derivative (see Barrowman and Myers, 2000). The LHS model is:

$$\mu(S) = \alpha \theta \delta \left(1 + e^{-1/\theta}\right) \left\{ \frac{S}{\theta \delta} - \log \left( \frac{1 + e^{\frac{(S-\delta)/\theta\delta}}}{1 + e^{-1/\theta}} \right) \right\}. \quad (3.3.3)$$



**Fig. 3.3.1.** Illustrative plots of logistic hockey-stick function with  $\alpha=1$ ,  $\delta = 75$ ,  $\theta = 0.01$  (solid line), 0.05 (dashed line), and 0.1 (dotted line).

We used SAS/OR<sup>®</sup> PROC NLP software to estimate the LHS parameters and to compute profile confidence intervals for  $\delta$ . The profile likelihood method for constructing confidence intervals has some desirable properties (e.g. see Section 4.2 in Cox and Barndorff-Nielsen, 1994).

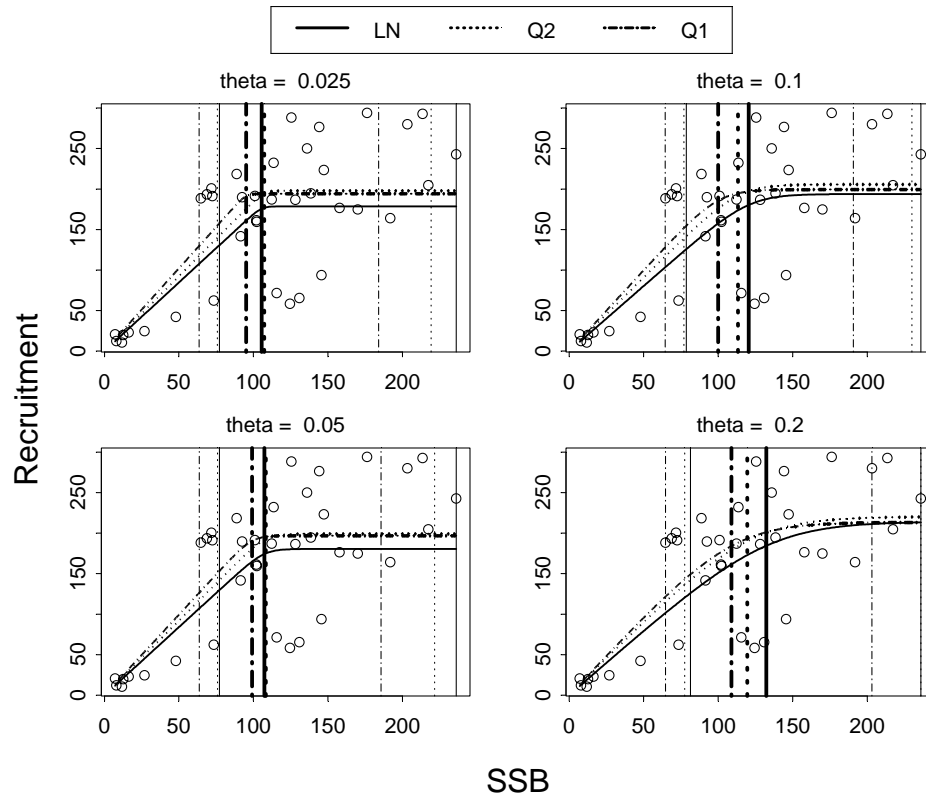
A simulation study was conducted to assess the accuracy of estimators and confidence intervals for the change-point. Random recruitments were generated from HS models. Stock sizes were randomly generated as equally spaced values within the interval [0,100]. Simulation parameters were the sample size  $N$ , the amount of variability in the data, and the location of the change-point.

Simulation results indicate that biases for  $\delta$  was relatively small. They are largest when the true value for  $\delta$  is located much to the right of the center of the stock size observations, and in many simulations  $\delta$  is estimated at its upper bound. The MSE for  $\delta$  is also relatively large in this situation. The exceedance probabilities (i.e. one minus the coverage probabilities) of the profile likelihood confidence intervals were computed and were found to be close to their nominal values.

We found that profile likelihood confidence intervals based on the lognormal distribution were very accurate (i.e. correct coverage probabilities) for the change point in segmented regression stock-recruit models. This conclusion only applies when the “true” population stock-recruit relationship is piecewise linear.

We compute profile likelihood confidence intervals for the American plaice (*Hippoglossoides platessoides*) stock in NAFO Div. 3LNO. The SSB and  $R$  (age 5) data come from Morgan *et al.* (2003). Also, to assess the sensitivity of the confidence intervals to the assumed distribution, we computed profile quasi-likelihood (see McCullagh and Nelder, 1989) confidence intervals for two power of the mean variance functions,  $\text{Var}(R) = \phi\mu^2$  and  $\text{Var}(R) = \phi\mu$ . The estimated  $\delta$ 's increase as  $\theta$  increases. Estimates and confidence intervals for  $\delta$  also vary depending on the fitting method.

In our case study (American plaice in NAFO Div. 3LNO) we found that estimates of the segmented regression change-point had high variability. The upper bound in the profile likelihood confidence interval was very high and quite variable for different methods which indicated that the stock data were uninformative about how high the breakpoint may be; however, the lower bound was more reliable because it was more consistent between methods. The lower bound indicated that it is highly probable that the breakpoint was greater than 70 Kt SSB.



**Fig. 3.3.2.** Profile likelihood confidence intervals for  $\delta$  based on the lognormal distribution (LN), and profile quasi-likelihood intervals based on  $\text{Var} = \text{Mean}^2$  (Q2) and  $\text{Var} = \text{Mean}$  (Q1), for American Plaice in Div. 3LNO. The heavy solid vertical line denotes the breakpoint estimates, and the thin lines denote the confidence interval endpoints. The line types correspond to the fitting method, are defined along the top of the panel.

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### 3.4. Summary of Index Methodology and the NMFS Toolbox (Paul Rago)

The replacement ratio methodology (RRM) was previously summarized in NAFO SC 2003 and NEFSC (2002a, b). This method can be viewed as a generalized method for exploring the general properties of catch and abundance index data and interrelationships among derived quantities, such as the replacement ratio and relative fishing mortality. The approach is technically simple but based on linear population models, modern graphical methods, and robust statistical models. It is considered here as an analytical tool for examining the historical behavior of a population and any potential influence of removals due to fishing activities. In particular it can be used to identify the limit relative fishing mortality rate (relF) that is associated with stock replacement, in the long term. In other applications, the replacement ratio methodology has been used primarily on data-poor stocks which may lack age-structured indices of abundance. However, it can also be used to examine the general behavior of data rich stocks.

Mathematical models that are used to describe the dynamics of exploited fish populations range from relatively simple models with 2 to 4 parameters to complex age-structured models with hundreds of parameters. Along this spectrum of model parameterizations, high dimensionality models may fail when the available data fail to support the model complexity or when confounding of parameters renders them inestimable. Low dimensionality models may fail when the dynamic range of population responses and/or fishing mortality rates is small. For example, a time series characterized by continuously declining abundance indices contains relatively little information about the productive capacity of that stock. Under these circumstances, the maximum population biomass (K) is estimable only if it is assumed that the initial population size represents an unfished stock. This assumption is rarely tenable for Northwest Atlantic stocks that have been fished for hundreds of years but monitored for only decades. Highly complex models may also fail unless external information can be used to confirm the hypothesized mechanisms.

Consider a typical data set consisting of one or more relative abundance indices, with  $I_{j,s,t}$  as the  $j$ -th relative abundance index for species-stock unit  $s$  at time  $t$  and  $C_{s,t}$  as the catch (or landings) of species-stock unit  $s$  at time  $t$ . The simple relative fishing mortality rate with respect to index type  $j$ , stock  $s$  and time  $t$  is defined as the ratio of  $C_{s,t}$  to  $I_{j,s,t}$ .

Using these data, the replacement method methodology can be summarized in outline form as follows:

1. Compute relative fishing mortality rate (relF) as the ratio of catch to some function of an abundance index. To account for sampling variability, relative  $F$  is often represented as a ratio of catch to a  $k$  year average as shown below for a 3 year centered moving average.

$$relF_{j,s,t} = \frac{C_{s,t}}{\left( \frac{I_{j,s,t-1} + I_{j,s,t} + I_{j,s,t+1}}{3} \right)} \quad 3.4.1$$

2. Compute the replacement ratio  $\Psi_t$  as the ratio of current stock size to the average size of the parental stocks that produced it. Using a simple life history model, it can be shown that this ratio is proportional to a weighted-moving average of the  $A$  stock sizes as shown below. Several exploratory analyses have suggested that the  $\phi_j$  values are often close to  $1/A$ .

$$\Psi_t = \frac{I_t}{\sum_{j=1}^A \phi_j I_{t-j}} \quad 3.4.2$$

The number of terms in the moving average and the actual weights can be derived from a life history model or one can simply approximate the weights as a simple moving average expression. The replacement ratio can be used as a smooth measure of population rate of change. When the productive capacity of the population is in balance with



the rates of loss, then the replacement ratio will equal one. When rates of loss are dominated by removals by the fishery then  $\Psi_t$  and  $\text{rel}F_t$  are expected to vary inversely.

3. Compute the correlation between  $\Psi_t$  and  $\text{rel}F_t$  and test its significance using randomization tests. Both  $\Psi_t$  and  $\text{rel}F_t$  depend on  $I_t$  and are expected to have a correlation less than zero. The randomization test provides a measure of the probability that the correlation is significantly lower than expected due to chance alone.

4. Compute the regression estimate  $\text{rel}F_t$  where  $\Psi_t = 1$ . This value of  $\text{rel}F$  termed,  $\text{rel}F_{\text{replacement}}$  implies a local equilibrium point consistent with the behavior of the stock over time period for which data are available.

5. Compute the sampling distribution of the  $\text{rel}F_{\text{replacement}}$  using bootstrap methods. The sampling distribution of the replacement  $F$  can be used to characterize the range of values over which the population is expected to be stable.

6. Create a set of linked graphs to display the relationships. A detailed description of the construction and interpretation of these graphs is provided in NAFO SC 2003. The graphs employ Lowess smoothing to aid in the identification of trends.

It is important to note that the replacement ratio methodology is designed to estimate the relative  $F$  associated with stock stability. When relative  $F$  is below the  $F$  at replacement the stock is expected to increase and vice versa. Thus the methodology provides valuable information on stock status and contemporary rates of harvest. To move in the direction of increased biomass, the model can be used to estimate the magnitude of change in relative  $F$  AND total catch necessary for rebuilding. It can also provide a measure of uncertainty with respect to efficacy of possible management measures. The model is not sufficient to identify the target biomass associated with safe biological limits such as  $B_{\text{lim}}$  or  $B_{\text{buf}}$ . A more complicated model employing some form of density dependence or an assumed average level of recruitment is required to define reference biomass values such as  $B_{\text{lim}}$ . Alternatively, one might choose an arbitrary index level, say the 75%ile, depending on the history of the resource. One can argue that the appropriate biomass target is a second order question in instances where the population is severely depleted. In these cases, the appropriate biomass limit will become more evident as the stock recovers.

The replacement ratio methodology is implemented in a computer program currently called AIM (An Index Method). Copies are available upon request to Paul Rago ([Paul.Rago@noaa.gov](mailto:Paul.Rago@noaa.gov)). The AIM model is part of a suite of computer programs known as the NOAA Fisheries Toolbox (NFT). The toolbox contains standard methods for VPA, catch-survey analysis, yield per recruit, population projection and so forth. Two groups of programs are available. The first consists of models that have been thoroughly tested in the context of stock assessments. The second group of models are in beta test mode and are still being refined. These models include a number of ADMB (Auto-Differentiation Model Builder) programs for forward projection. The National Marine Fisheries Service has not formalized the release of either group of programs but the programs are available upon request to researchers and analysts for evaluation by sending an email to [NFTToolbox.support@noaa.gov](mailto:NFTToolbox.support@noaa.gov).

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### 3.5. **Defining serious harm for exploited fish stocks in the Canadian context** (Denis Rivard)

In an attempt to include “precaution” as part of a management consideration in many sectors, from health to environment, a debate took place in Canada in recent years on when precaution needs to be invoked in decision making. That debate concluded that a precautionary approach is indicated in situations where decision making is associated with a high degree of uncertainty and where ‘serious or irreversible harm’ could occur. Precautionary measures aim at avoiding, with a high probability, situations where serious or irreversible harm could occur.

In an attempt to define serious harm in the context of fisheries management, a national DFO workshop was held in 2001 (Rice and Rivard, 2001). For commercially-exploited fish stocks, serious harm was linked to impaired productivity, i.e. impaired ability of the stock to reproduce itself. Accordingly, in fish stocks, serious harm can be related to recruitment overfishing, which is often characterized by impaired recruitment at low spawning stock biomass.

A second national DFO workshop (Rivard and Rice, 2002) was held in 2002 to develop conservation limits for selected stocks of Atlantic cod. A series of methods based on SR relationships were used in an attempt to define LRPs. As a follow up to the above, a further workshop was convened in 2004 to refine methods for selecting LRPs and to apply these methods to a wide range of fish stocks. Many of the methods based on stock-recruit data proved difficult to use as a basis for defining LRPs. They produced a wide range of estimates depending on how well the underlying stock-recruit curves were estimated. In particular, the parametric stock-recruitment models (e.g. Beverton-Holt), the Serebryakov method and biomass associated with previous recovery (Brecovey) did not perform well as methods to estimate a biomass limit. Methods based on non-parametric smoothers and segmented regression were considered more promising but require additional evaluation. Other methods, based on population production, were also proposed as alternatives to recruitment-based LRPs. Two production-based approaches were proposed: 1) define the limit as the biomass from which the stock has only a low probability of recovering to its healthy state within one generation under good conditions (consistent with the notion of “serious harm”), or 2) define the limit as the threshold low biomass level at which negative production occurs. The LRP would be based on the larger of these two biomass estimates. These approaches are still under investigation (Mohn and Chouinard, 2004).

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### 3.6. **Influential cases in stock and recruit models** (Noel Cadigan)

Limit reference points are often estimated from information on stock size and recruitment that in many cases is quite uncertain. It is important to understand the precision and accuracy of the reference point estimators and associated statements of uncertainty (e.g. confidence intervals). It is also important to understand how sensitive the estimates are to modelling assumptions. If the sensitivity is large then mis-specification bias may be large. In this section we examine the sensitivity of a particular candidate LRP to the stock and recruit information that is used to estimate the limit. The reference point we consider is the stock size that corresponds to 50% of the maximum recruitment, which we denote as  $S_{50\%}$ . We consider influence for three stock-recruit functions: Ricker, Beverton-Holt (BH), and Hockey-Stick (HS). We also consider three estimation methods: Lognormal, and Quasi-likelihood based on the Gamma and Poisson variance models (see McCullagh and Nelder, 1989). We apply our results to the Divisions 3LNO American plaice (*Hippoglossoides platessoides*) stock and recruit data (age 5).

The assessment of influence for simple models usually involves examining the impact of deleting observations on model outputs. Such diagnostics are called case deletion diagnostics and they involve changing the estimation

weight for a case from one to zero. In a stock-recruit analysis, a case is a pair of estimates of stock size and recruitment. It is usually not possible to describe a case deletion diagnostic mathematically, and this makes it difficult to understand what features in the data cause influence.

The local influence approach (Cook, 1986) is another type of influence analysis that involves studying the effect of small perturbations of model inputs and structural assumptions including case weights. Cadigan and Farrell (2002) showed how this approach can be used to study influence for an arbitrary but smooth function  $g(\theta)$  of model parameters  $\theta$ . The influence analysis involves examining the geometry of the influence graph resulting from the perturbations. This is done near or at the origin of the influence graph, which is the point of no perturbation. When the influence surface is approximately linear, which is often the case, then the effect of a case deletion can be described by a single slope. This approach can give good approximations to the effects of larger perturbations like case deletions. The advantage of producing a mathematical equation for the local slope is that the equation can provide insights about the nature of influence and how it is affected by model inputs. This allows us to assess influence for different data sets, or additional data, without computing anything.

#### *Estimation of stock-recruit models and $S_{50\%}$*

We estimate  $S_{50\%}$ , which is the stock size at 50% of the maximum recruitment, using three stock recruitment functions. Let  $R$  denote recruitment, and let  $S$  denote parental stock size. The recruitment information is assumed to be observations of random variables, so the stock-recruit models are expressed in terms of recruitment expectations,  $\mu(S, \theta) = E(R|S)$ . For simplicity we refer to  $\mu(S, \theta)$  as  $\mu(S)$ . In what follows  $\mu_{\max} = \max_S \mu(S)$ .

The Ricker model is  $\mu(S) = \alpha S \exp(-\beta S)$ , for which  $\mu_{\max} = \alpha/\beta \exp(1)$ . This maximum occurs when  $S = \beta^{-1}$ . A closed form expression for  $S_{50\%}$  does not exist and we must find it numerically from the equation  $\mu(S_{50\%}) = \mu_{\max}/2$ . A good approximation of the solution is  $S_{50\%} \approx 1/(4.44 \times \beta)$ . We do not use this approximation but it is a useful starting value when numerically solving for  $S_{50\%}$ .

The Beverton-Holt (BH) model is  $\mu(S) = \alpha S/(\beta + S)$ , for which  $\mu_{\max} = \alpha$  and  $S_{50\%} = \beta$ .

The Hockey-stick (HS) model is:

$$\mu(S) = \begin{cases} \alpha S & S \leq \delta \\ \alpha \delta & S > \delta \end{cases} \quad (3.6.1)$$

For this model  $\mu_{\max} = \alpha \delta$  and  $S_{50\%} = \delta/2$ .

We estimate the stock-recruit model parameters using a fit function  $F(\theta)$ , which we denote more simply as  $F$ , that can often be expressed as a sum of fits for each case,  $F = \sum_{i=1}^n f_i$ . For example, if  $F$  is the log error sum of squares then  $f_i$  is the  $i$ th squared model residual,  $f_i = \{\log(r_i/\mu_i)\}^2$ . Estimation based on the log error sum of squares fit function is commonly used in stock-recruit analyses. We consider two other estimation methods which are based on the quasi-likelihood (QL; see McCullagh and Nelder, 1989) with a power  $\nu$  of the mean variance function,  $\nu = 1$  and 2, and a single dispersion parameter. The QL( $\nu=2$ ) estimators of model parameters are identical to gamma maximum likelihood estimates (mle's). Cadigan and Myers (2001) found that gamma mle's were preferable to lognormal mle's for estimating parameters in a sequential population analysis. Firth (1988) also advocated gamma mle's over lognormal mle's based on theoretical considerations. Hence, QL estimation may be preferable for estimating stock-recruit models and it is useful to examine the sensitivity of QL( $\nu=2$ ) estimates of  $S_{50\%}$ . The rationale for considering  $\nu=1$ , which is a Poisson-type of variation assumption, is that this method tends to result in estimates that are less sensitive to small recruitment values, which may be preferable for some data sets. Better estimation methods that more properly account for the stochastic nature of the stock-recruit information (i.e. modelled output, auto-correlated, etc) are beyond the scope of this section.

#### *Case weight (CW) local influence*

We apply the local influence methods presented in Cadigan and Farrell (2002) to case weight (CW) influence for  $S_{50\%}$  from a stock-recruitment analyses. The CW perturbation scheme involves changing the weight  $\omega_i$  that each  $f_i$

contributes to the sum. The perturbed fit function is  $F_{\omega} = \sum_{i=1}^n \omega_i f_i$ . We express CW perturbations as  $\omega = 1 + h$ , where 1 is the default value and  $h$  is the size of the perturbation; for example, a case deletion is obtained using  $h = -1$ .

The primary diagnostic used by Cadigan and Farrell (2002) was the local slope,  $\partial S_{\omega,50\%} / \partial \omega|_{\omega=0}$ .  $S_{\omega,50\%}$  is the estimate of  $S_{50\%}$  obtained by changing the estimation weights. The local slope for the  $i$ th case is given by

$$\left. \frac{\partial S_{\omega,50\%}}{\partial \omega_i} \right|_{\omega_i=0} = \left. \frac{\partial f_i}{\partial \theta} \right|_{\theta=\hat{\theta}} \left( \left. \frac{\partial F(\theta)}{\partial \theta \partial \theta} \right|_{\theta=\hat{\theta}} \right)^{-1} \left. \frac{\partial S_{50\%}(\theta)}{\partial \theta} \right|_{\theta=\hat{\theta}}. \quad (3.6.2)$$

The local slope is obtained using derivatives evaluated at the un-perturbed stock-recruit parameter estimates. The first derivative  $\partial f_i / \partial \theta$  and Hessian are common computations. The last term on the right-hand side of this equation is the reference point derivative. It is a  $2 \times 1$  vector whose first element is zero because  $S_{50\%}(\theta)$  does not involve the  $\alpha$  parameter for the Ricker, BH, or HS models. The derivative of  $S_{50\%}$  with respect to  $\beta$  (Ricker, BH) or  $\delta$  (HS) is not difficult to compute. For example, for the BH model:

$$\left. \frac{\partial S_{50\%}(\theta)}{\partial \theta} \right|_{\theta=\hat{\theta}} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \quad (3.6.3)$$

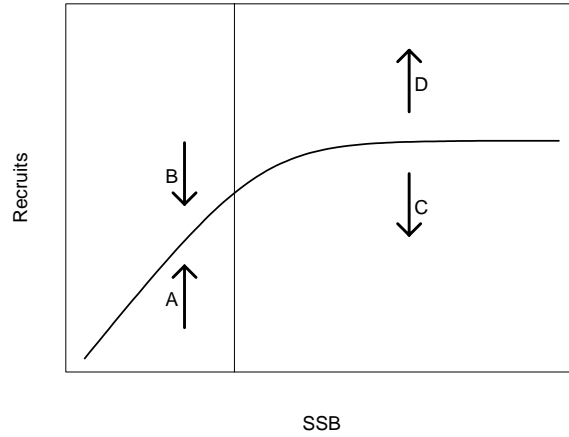
In the following sections we denote the sample residual as  $e_i$ , which for the Lognormal (LN) approach is  $e_i = \log(r_i/\mu_i)$ , and for the QL approach is  $e_i = r_i - \mu_i$ . The local influence slopes for the three models and three estimation methods have comparable analytic expressions. They involve weighted averages. The weights always sum to one, but some individual weights can occasionally be negative. We use a  $w$  subscript to indicate that differential weighting is used.

The local slopes for case  $i$  and the Ricker model are:

$$\begin{aligned} \text{Lognormal} : & \frac{S_{50\%}}{n \times \text{var}(s) \hat{\beta}} \times e_i (s_i - \bar{s}), \\ \text{QL}(v=2) : & \frac{S_{50\%}}{n \times \text{var}_{wr}(s) \hat{\beta}} \times \frac{e_i}{\hat{\mu}_i} (s_i - \bar{s}), \\ \text{QL}(v=1) : & \frac{S_{50\%}}{n \times \text{var}_{wp}(s) \hat{\beta}} \times \frac{e_i}{\hat{\mu}_{ave}} (s_i - \bar{s}_{wp}). \end{aligned} \quad (3.6.4)$$

where  $\bar{s} = \sum_i s_i$ ,  $\text{var}(s) = \sum_i (s_i - \bar{s})^2$ , and  $\text{var}_{wr}(s)$  and  $\bar{s}_{wp}$  are weighted versions. The  $wr$  weights will usually be close to  $n^{-1}$ , but the  $wp$  are proportional to  $\hat{\mu}_i$ .

The Ricker-LN slopes are proportional to  $e_i (s_i - \bar{s})$ , which suggests that those  $(s, r)$  cases that are remote in the stock axis and have large absolute residuals are influential. Using this equation we can see that if  $s_i \ll \bar{s}$  and  $e_i \ll 0$  then increasing the weight for case  $i$  will increase  $S_{50\%}$ . Another way of interpreting this is that adding a new observation,  $(s_{\text{new}}, r_{\text{new}})$ , such that  $r_{\text{new}} < \hat{r}_{new}$  and  $s_{\text{new}} < \bar{s}$  will cause  $S_{50\%}$  to increase. Note that adding an observation is the same as increasing its weight from zero to one. We can use the LN slope to "predict" the effect that adding an observation has on  $S_{50\%}$ . All we need to know is whether the new observation's  $r$  value is less than the estimated value from the stock-recruit curve, and whether the new observation's  $s$  value is less than  $\bar{s}$ . We illustrate this in Fig. 6.1. The vertical solid line represents the location of  $\bar{s}$ . Adding an observation in region A causes  $S_{50\%}$  to increase, while adding an observation in region B causes  $S_{50\%}$  to decrease, etc. The amount of change in  $S_{50\%}$  depends on the size of  $e_i$  and  $s_i - \bar{s}$  as well as  $S_{50\%}$  and the other leading terms in the LN local slope equation. The qualitative influence patterns in Fig. 3.6.1 also apply to both of the quasi-likelihood estimators we consider and the BH and HS models, although the location of the vertical line may differ for these methods.



**Fig. 3.6.1.** Qualitative case weight (CW) local influence for  $S_{50\%}$  from a stock-recruit curve. The arrows indicate the direction of change in  $S_{50\%}$  caused by increasing the weight of cases in each of the four regions. The solid vertical line indicates the point at which the effect of a CW perturbation changes. This point depends on the stock-recruit model and estimation method.

The Ricker-Q2 slope is similar to the LN slope. Note that the LN residual is approximately equivalent to the Q2 residual when scaled by  $\hat{\mu}_i^{-1}$ . However, if there are small values for R that the model can not predict well, then we expect the LN estimate of  $S_{50\%}$  to be more sensitive to these cases than the Q2 estimate, and if there are large values of R that the model cannot fit then the Q2 estimate will be more sensitive. The Ricker-Q1 slopes are more different than the Q2 and LN slopes. For example, the sign of the effect of a CW perturbation changes around  $\bar{s}_{wp}$  for the Q1 slopes compared to  $\bar{s}$  for the Q2 and LN slopes. Unless the Q1 estimated Ricker curve exhibits substantial concavity (i.e. density-dependence) then  $\bar{s}_{wp} > \bar{s}$ . In addition, Q1 residuals are not influential in a relative manner which suggests that Q1 estimates will be much less sensitive than Q2 and LN estimates to residuals whose absolute differences are small but whose relative differences are large, and Q1 estimates will be more sensitive to cases whose absolute differences are large but whose relative differences are small. Whether this is preferable will be case-specific.

The local slopes for the BH model are:

$$\begin{aligned}
 \text{Lognormal} : & \frac{-\hat{\mu}_{\max}}{n \times \text{var}_{we}(\pi)} \times e_i(\pi_i - \bar{\pi}), \\
 QL(v=2) : & \frac{-\hat{\mu}_{\max}}{n \times \text{var}(\pi)} \times \frac{e_i}{\hat{\mu}_i}(\pi_i - \bar{\pi}), \\
 QL(v=1) : & \frac{-\hat{\mu}_{\max}}{n \times \text{var}_{wd}(\pi)} \times \frac{e_i}{\hat{\mu}_{ave}}(\pi_i - \bar{\pi}_{wd}),
 \end{aligned} \tag{3.6.5}$$

where  $\pi_i = \hat{\mu}_i / s_i$  is the BH estimated stock productivity at  $s_i$ . The *we* weights are proportional to  $1 - e_i$ . The *wd* are proportional to  $2\hat{\mu}_i - r_i$  and are similar to the *wp* weights. Note that for Q1 estimates of the BH model,  $\bar{\pi}_{wd} = \bar{\pi}_{wp}$ .

The CW slopes for the BH model appear to have opposite signs compared to the Ricker model; however, for the BH model  $\pi$  is a monotonic decreasing function of  $s$  so that  $\pi_i - \bar{\pi}$  and  $s_i - \bar{s}$  are opposite in sign. This means that the signs of the BH slopes are usually the same as the signs of the Ricker slopes. The basic effect of CW perturbations on  $S_{50\%}$  is the same as that illustrated in Fig. 6.1. The main difference is that the vertical line is determined by  $\bar{\pi}$ , although we can still plot the line in terms of the  $s$  value that corresponds to  $\bar{\pi}$ . Otherwise the BH diagnostics are

different in that the leading terms (except  $n$ ) in the slopes are different than the Ricker diagnostics. Also, the slopes are a function of the remoteness of the estimated productivity rather than the remoteness of  $s$ . We can not make general conclusions about if and when the Ricker model is more CW sensitive than the BH model. This appears to be case-specific. The effect of the estimation methods on BH CW sensitivities are similar to the Ricker model.

The local slopes for the HS model are:

$$\begin{aligned} \text{Lognormal} &: \frac{S_{50\%}}{n_1 n_2} \times e_i \{n_1 I_{\delta}(s_i) - n_2 I_{\delta}^c(s_i)\}, \\ \text{QL}(v=2) &: \frac{S_{50\%}}{n_1 n_2} \times \frac{e_i}{\hat{\mu}_i} \{n_1 I_{\delta}(s_i) - n_2 I_{\delta}^c(s_i)\}, \\ \text{QL}(v=1) &: \frac{S_{50\%}}{n_1 n_2} \times e_i \left\{ \frac{n_1 I_{\delta}(s_i)}{\hat{\mu}_{1,ave}} - \frac{n_2 I_{\delta}^c(s_i)}{\hat{\mu}_{2,ave}} \right\}, \end{aligned} \quad (3.6.6)$$

where  $I_{\delta}(s) = 0$  if  $s < \delta$  and zero otherwise, and  $I_{\delta}^c(s) = 1 - I_{\delta}(s)$ . Also,  $n_1$  and  $n_2$  are the number of cases to the left and right of  $\delta$ , respectively, and  $\hat{\mu}_{1,ave}$  and  $\hat{\mu}_{2,ave}$  are averages of the recruitment predictions at the sample stock size values to the left and right of the change point. A major difference between the HS slopes and those for the Ricker and BH models is that the HS slopes do not depend on the remoteness of the  $s$  values.

#### Case Study, 3LNO American plaice

The case study in this working paper involves American plaice (*Hippoglossoides platessoides*) in NAFO Div.3LNO. The SSB and R (numbers at age 5) data come from Morgan *et al.* (2003). We estimate the Ricker, BH, and HS models using three estimation methods (LN, Q1, Q2), which gives a total of nine estimated SR curves. The results are plotted in Fig. 3.6.2-3.6.4 at the end of this section. Clearly none of these models fitted the data very well, and they produced a wide range of estimates of  $S_{50\%}$  (48-419 Kt). The BH estimates are particularly unsatisfactory because the estimates of  $\mu_{max}$  greatly exceeded the observed maximum recruitment, with the Q1 estimate (437 Kt; see Fig. 3.6.4) closest to the observed maximum of about 300 Kt. The HS estimates of  $S_{50\%}$  were the smallest and most stable; they ranged from 48-54 Kt. Based on biological considerations one may reject the BH estimates of the stock-recruit relationship; however, the other six estimates appear plausible and still result in a substantial range of  $S_{50\%}$  estimates (48-113 Kt).

Residual plots did not help much to identify the best choice of estimation method and model. The residual scatter plots for each estimation method were equally acceptable. The fit statistics (lognormal:  $-2 \times$  the full loglikelihood, QL: extended deviance) did not seem to strongly suggest one approach as being more appropriate.

Another criterion that can be used to decide on the appropriate model and estimation method is sensitivity. We should be more comfortable with a plausible model that does not result in large changes in  $S_{50\%}$  (and other quantities) when CWs are changed. We examine the local influence slopes to assess how sensitive estimates of  $S_{50\%}$  are to CWs. Note that the local slope times  $-100/S_{50\%}$  is a local linear approximation of the percentage change in  $S_{50\%}$  caused by a case deletion, and for convenience we display the results in this fashion. This also facilitates comparisons with deletion diagnostics to partially assess the linearity of the influence surface. If the influence surface is not linear then the utility of the local influence diagnostics is diminished (see Cadigan and Farrell, 2002).

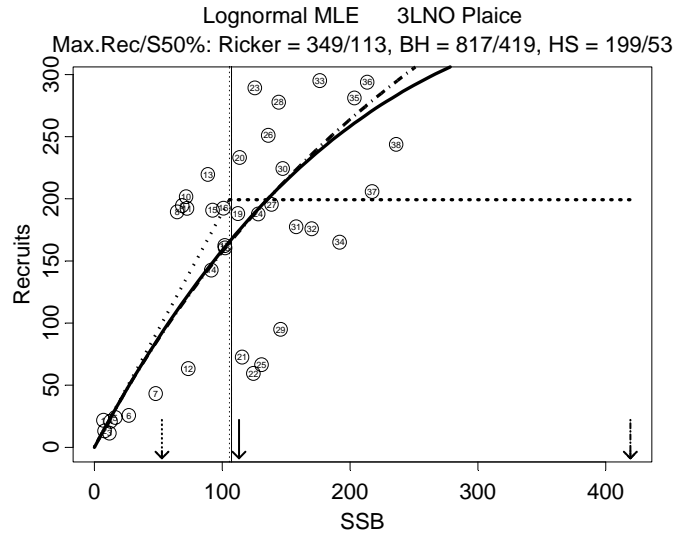
The influence diagnostics are shown in Fig. 3.6.5. We do not show the Q2 results, although the Q2 estimates were slightly less sensitive than the LN estimates. The maximum local slope diagnostic shown at the top of each panel is not the maximum of the individual slopes, but is the maximum slope when all cases are perturbed simultaneously (see Cadigan and Farrell, 2002). It gives an overall measure of CW sensitivity for all cases. The BH model is most sensitive to CW perturbations with the 3LNO plaice data, followed by the Ricker curve and the HS curve. The HS curve is substantially less sensitive to changes in CWs. Lognormal and Q2 estimates of  $S_{50\%}$  from the Ricker and BH models are very sensitive to the weights of some cases (numbers 1, 3, 6-11) with relatively small  $r$  and  $s$  values and large relative residuals. Cases 1 and 3 are much less sensitive for Q1 estimation.

We can also check that the qualitative understanding of  $S_{50\%}$  CW influence shown in Fig. 3.6.1 is very accurate for 3LNO plaice. Note that Fig. 6.1 is based on the effect of increasing CWs and the arrows need to be reversed to evaluate the effect of decreasing CWs. For example, case 21 in Fig. 3.6.4 is in region C, and Fig. 3.6.1 suggests that deleting this case will cause  $S_{50\%}$  to increase. This is what we observe in Fig. 3.6.5, although the change is small. Case 21 is in region A for the Ricker and BH models, and deleting this case results in a decrease in  $S_{50\%}$  for these models. This is also what Fig. 3.6.1 suggests.

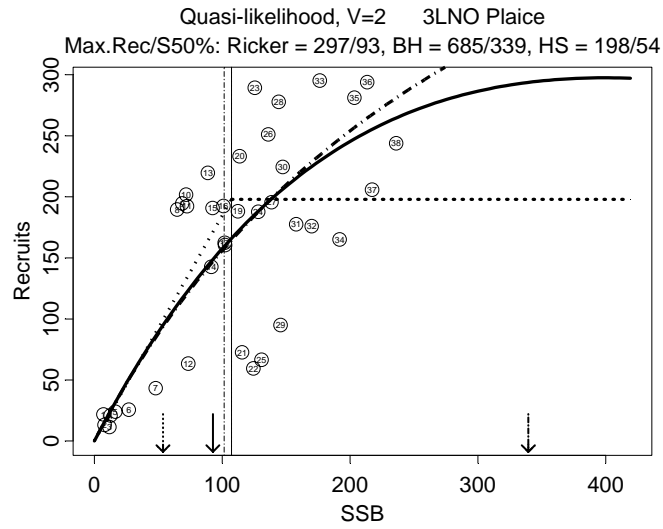
### Main Conclusions

In our case study the Hockey-stick (HS) model estimates of  $S_{50\%}$  were more robust to changes in case weights (CWs) than the Ricker and Beverton-Holt model estimates. This is practically important because it suggests that the HS model may provide more stable estimates as additional stock and recruitment data are acquired. If, in the next several years, we expect to acquire new stock-recruit information in region A of Fig. 3.6.1 then our estimates of  $S_{50\%}$  will increase. This needs to be considered in the Precautionary Approach context.

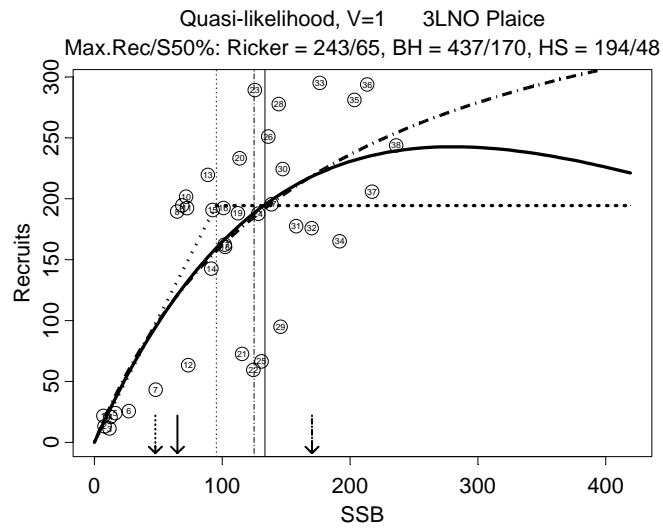
In our case study the quasi-likelihood approach with Poisson variation produced estimates that were more robust to CW assumptions. Note that other factors, like goodness-of-fit, need to be considered when choosing an appropriate error structure for estimation and inference. The method of estimation can have a large effect on estimates of conservation limits and other quantities, and this needs to be considered when providing management advice.



**Fig. 3.6.2.** Lognormal estimates of stock-recruit models. The same line type is used for results from each model: Ricker (solid), Beverton-Holt (dashed), and Hockey-stick (dotted). Observations are plotted as  $\square$ 's, with their case numbers. Values for  $\mu_{\max}$  and  $S_{50\%}$  are shown at the top of the figure. Thin vertical lines through the entire panel show the location of the change in  $S_{50\%}$  case weight influence (described in text). The arrows point to  $S_{50\%}$  for each model.

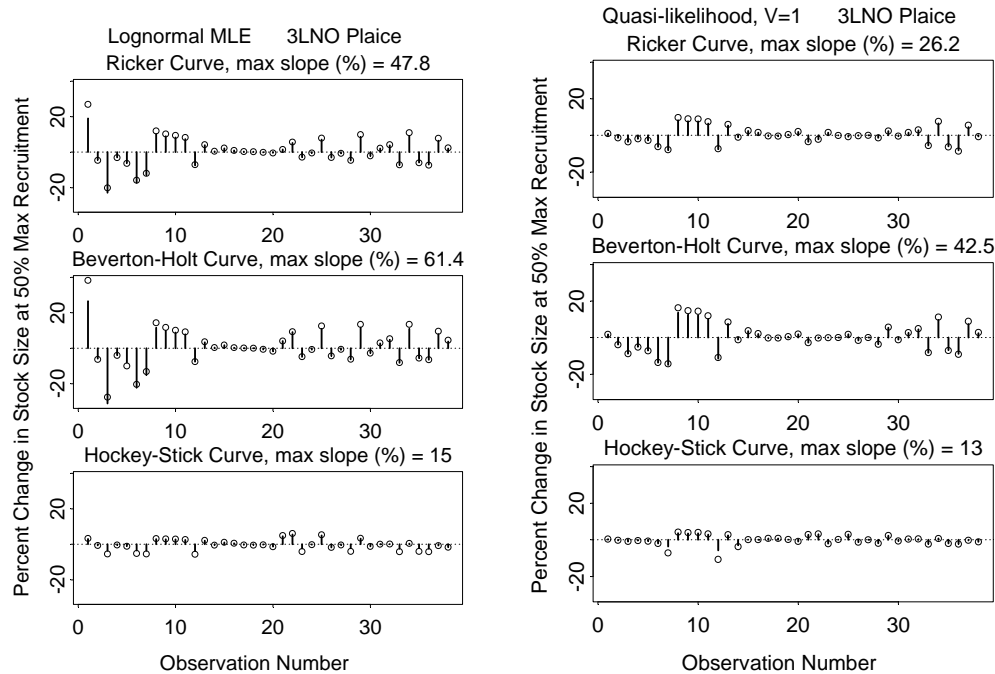


**Fig. 3.6.3.** Quasi-likelihood (Gamma variation) estimates of stock-recruit models. See Fig. 3.6.2 for a figure description.



**Fig. 3.6.4.** Quasi-likelihood (Poisson variation) estimates of stock-recruit models. See Fig. 3.6.2 for a figure description.





**Fig. 3.6.5.** Case deletion lognormal estimates ( $\square$ 's) of the % change in  $S_{50\%}$ . The solid vertical lines are the local influence predictions of the case deletion effects. The maximum local case weight slope (in % of  $S_{50\%}$ ) is shown at the top of each panel.

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### 3.7. Simulation testing of SSB at 50% $R_{max}$ and Serebryakov's approach (Peter Shelton)

SSB LRPs can be used as "corner-stones" around which fisheries management frameworks encompassing the precautionary approach can be based. Although a variety of SSB LRPs are described in the literature (see Shelton and Rice, 2002), the properties of these estimators are generally not well known. Applying LRPs that have not been evaluated, either empirically or through simulation analysis, cannot be defended scientifically.

If SSB and  $R$  estimates are available and a model can be fit from which maximum recruitment for the population can be estimated, then 50% of this value may provide a definition of poor recruitment and the spawner biomass corresponding to this estimate,  $B_{50\%R_{max}}$ , may be considered to be a SSB LRP (Mace, 1994). Myers *et al.* (1994) suggested that  $B_{50\%R_{max}}$  is a relatively robust reference point if only data at low stock sizes are available, and that,

based on empirical evidence from a large number of stocks, higher levels of recruitment are normally associated with SSBs above this level.

As an alternative to  $B50\%R_{max}$ , Serebryakov (1991) and Shepherd (1991) suggested an SSB LRP based on percentiles of recruitment ( $R$ ) and recruits per spawner ( $R/S$ ). A version of the Serebryakov LRP considered at the November 2002 DFO Precautionary Approach Workshop in Ottawa, (Rivard and Rice, 2003) was based on computing the SSB corresponding to the 50<sup>th</sup> percentile of  $R$  and the 90<sup>th</sup> percentile  $R/S$ .

In this working paper I attempt to evaluate some of the statistical properties associated with these two LRP estimators through simulation experiments using fake data generated from a Beverton-Holt model with lognormal error. The estimates are compared with the true SSB corresponding to  $50\%R_{max}$ . For BH50, this is a comparison of how well this reference point can be estimated relative to the true value. For the Serebryakov method, the true SSB corresponding to  $50\%R_{max}$  provides a useful reference value for comparison with the SB50/90 estimates. Clearly in this case bias cannot be evaluated, but the relative difference between the two values can provide insight into the performance of the Serebryakov estimator. Work is underway by the author to carry out a similar evaluation of the segmented regression approach (O'Brien and Maxwell, 2002) relative to the true BH50.

### Methods

In each simulation experiment a 1000 samples of fake recruitment data  $y$  years in length were generated randomly from the error distribution around the  $R$  value predicted from a Beverton-Holt model for a range of spawner biomass values  $S$ . To obtain samples of fake SR, values of  $R$  for experiment  $i = 1 \dots 1000$  and year  $t = 1 \dots y$ ,  $R_{it}$ , were drawn randomly from a lognormal distribution around the model predicted value:

$$R_{it} = \exp\left(\ln\left(\frac{\alpha S_{it}}{1 + (S_{it} / K)}\right) + \varepsilon_{it}\right), \text{ where } \varepsilon_{it} \sim N(0, \sigma^2). \quad (3.7.1)$$

$S_{it}$  were drawn randomly from a uniform distribution  $U[\text{Min}, \text{Max}]$  with  $\text{Min} = 0.1\%$  of the SSB corresponding to  $p \cdot R_{max}$  and  $\text{Max} = \text{SSB}$  corresponding to  $p \cdot R_{max}$  where  $p$  is the proportion of  $R_{max}$ . Simulation experiments were carried out for all combinations of the following values of  $p$ ,  $\sigma$  and  $y$ :

$$\begin{aligned} p &= 0.4, 0.6, 0.8, 0.9, 0.95 \\ \sigma &= 0.2, 0.4, 0.6, 0.8, 1.0 \\ y &= 20, 30 \end{aligned}$$

BH50 is defined as the spawner biomass corresponding to 50% of the maximum recruitment ( $50\%R_{max}$ ). The model was fitted to the samples of fake data using a maximum likelihood approach described in Myers *et al.* (1995). In this approach lognormal error is assumed and the probability density function is expressed in terms of the median. Note that it is not necessary to explore the sensitivity of the  $B_{lim}$  estimators for a range of  $\alpha$  and  $K$  for the Beverton-Holt model because these parameters merely scale the SSB axis relative to  $R_{max}$  (Shelton and Healey 1999).

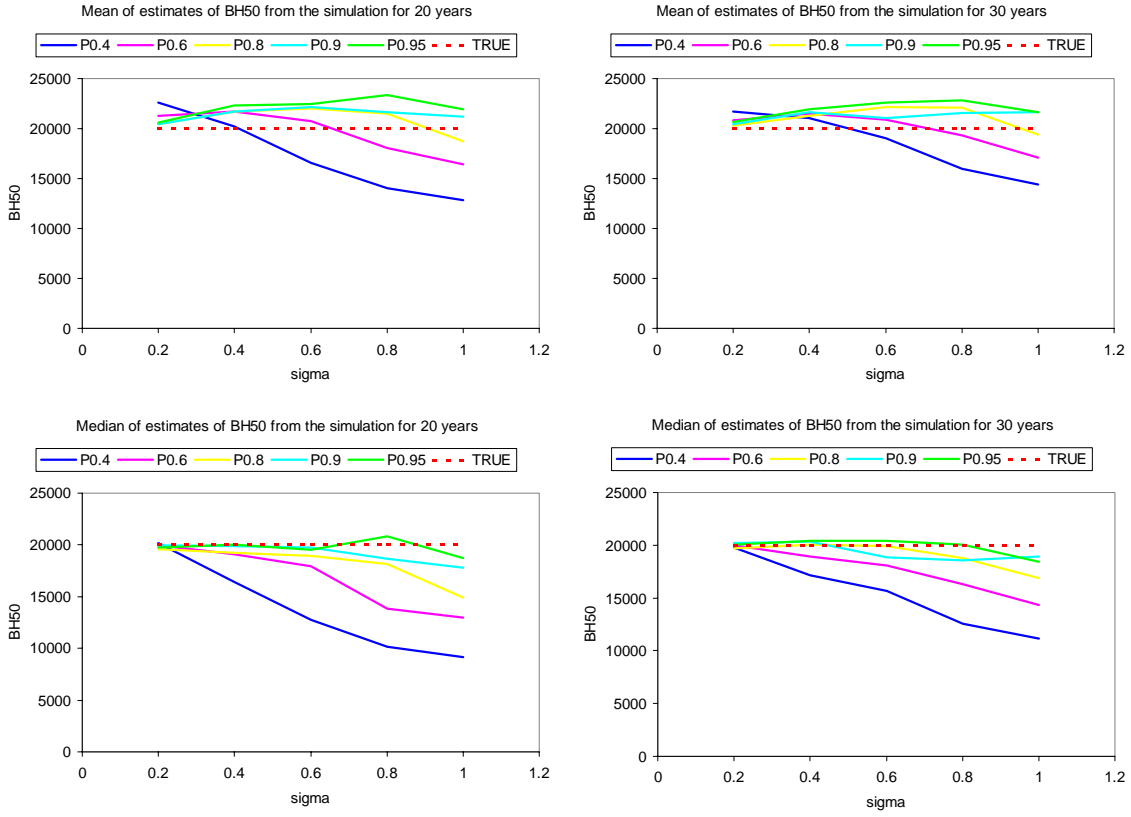
For some samples of fake data, especially at high  $\sigma$ , unrealistic estimates of  $50\%R_{max}$  and BH50 were obtained. Samples were rejected if the estimated  $50\%R_{max} > \text{three times the true } 50\%R_{max}$ , if the estimated BH50  $> \text{three times the true BH50}$  or if  $\text{BH50} < 5\% \text{ of the true BH50}$ . The number of rejected samples out of the 1000 simulated samples was recorded in the results for each experiment. BH50 was estimated for each sample of fake data and summary statistics were compiled.

SB50/90 is defined as the SSB corresponding to the intersection of the 50<sup>th</sup> percentile of  $R$  and the 90<sup>th</sup> percentile  $R/S$ . The percentiles were computed for each sample of fake data and summary statistics for the LRP were compiled.

### Results

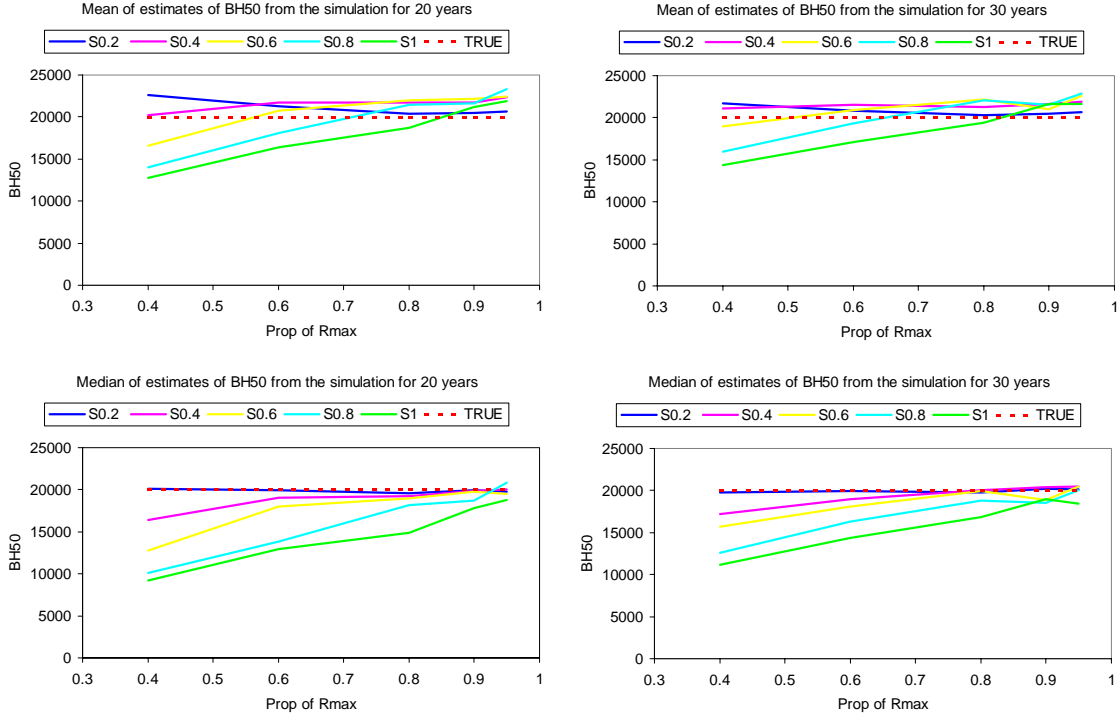
As  $\sigma$  increased there was a tendency for the estimates of BH50 to become negatively biased particularly for low values of  $p$  (Fig. 3.7.1). The bias was greater for  $y = 20$  than it was for  $y = 30$ . For high  $p$ , the means of the

estimates tended to be somewhat positively biased at all values of  $\sigma$ . The medians of the estimates were close to the true value for high  $p$  experiments except at the highest values of  $\sigma$ .



**Fig. 3.7.1.** Plots of means and medians of the distribution of estimates of BH50 based on simulated SR data for a range of  $p$  plotted against  $\sigma$  for 20 and 30 years of SR data.

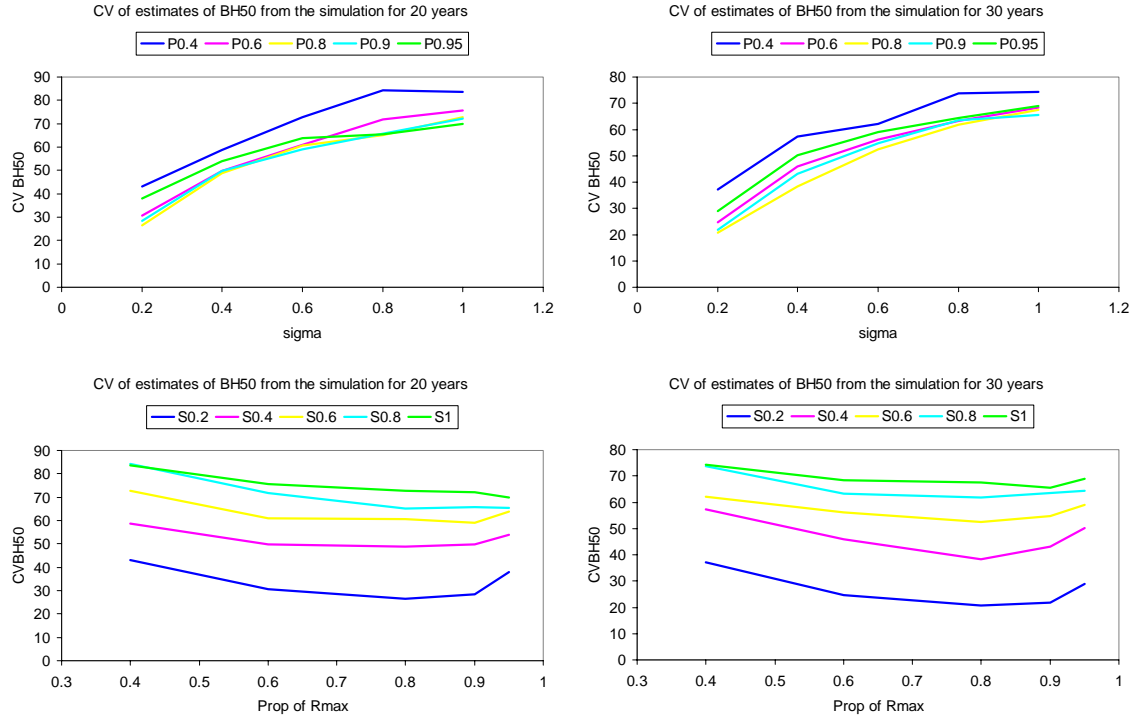
When plotted against  $p$ , the results show that the mean and the median of the estimates of BH50 are negatively biased for low  $p$  values, except at the lowest levels of  $\sigma$  (Fig. 3.7.2).



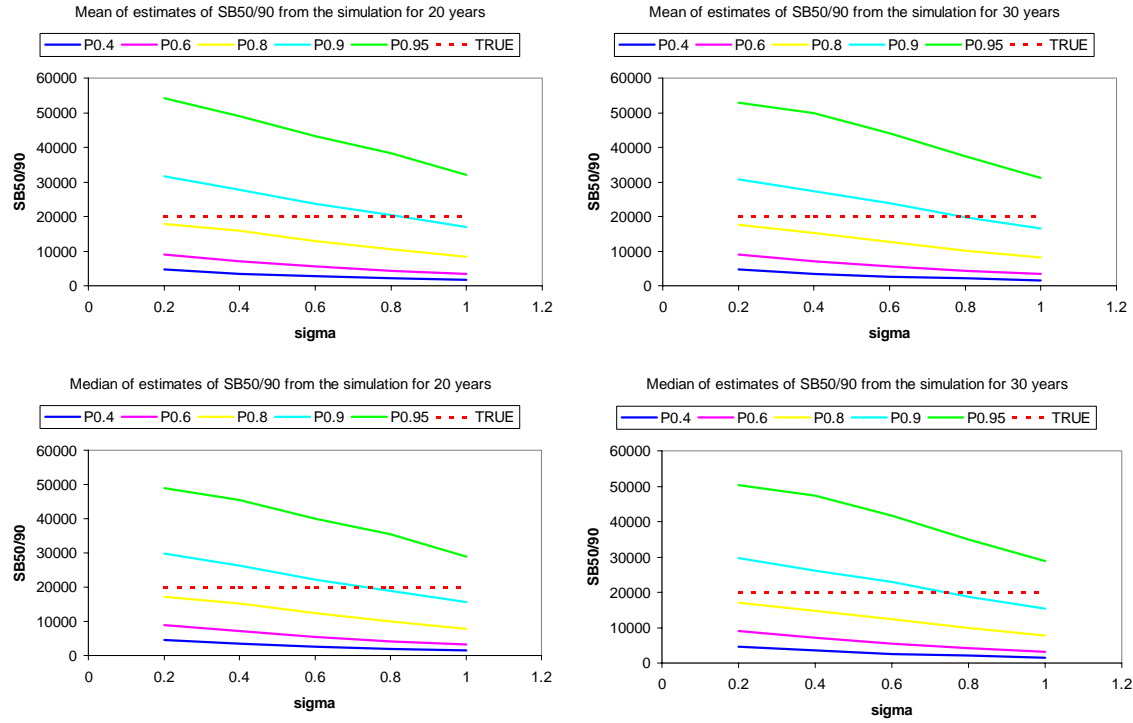
**Fig. 3.7.2.** Plots of means and medians of the distribution of estimates of BH50 from simulated data based on simulated SR data for a range of  $\sigma$  values plotted against  $p$  for 20 and 30 years of SR data.

The variability in the estimates of BH50 based on the simulated data increases with increasing  $\sigma$  (Fig. 3.7.3). This increase is somewhat less for the experiments based on 30 years of data. Under common conditions there may be limited data contrast and the CV in the estimate of BH50 may exceed 50%. (e.g.  $p = 0.6$ ,  $\sigma = 0.6$ ). Although the CV of the estimates of BH50 decreases somewhat with increasing  $p$ , at the highest values of  $p$  the CV again increases, a consequence of a greater proportion of the data coming from the near-asymptotic part of the BH curve, and thus providing less information about the slope.

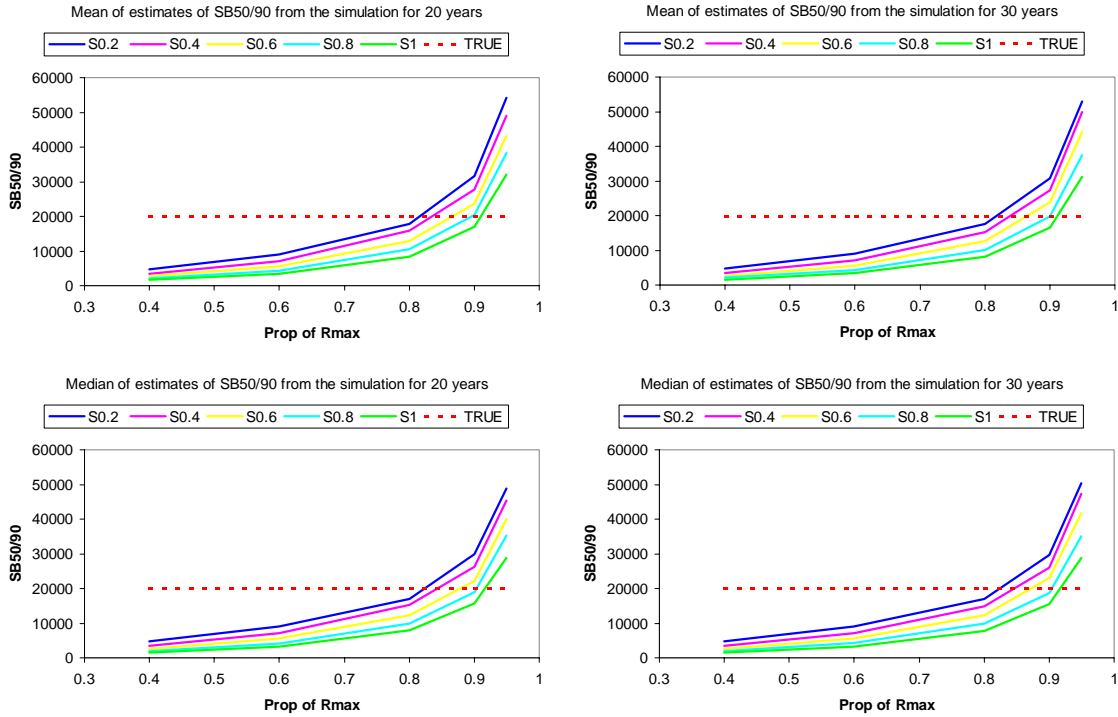
The means and medians of the estimates of SB50/90 decrease with increasing  $\sigma$  (Fig. 3.7.4). Estimates from experiments at values of  $p = 0.4$  to  $0.8$  were all below the true BH50 value, whereas experiments at  $p = 0.9$  crossed the true BH50 line as  $\sigma$  increased while estimates at  $p = 0.95$  were all above the line. There was very little difference in the results from experiments with  $y = 20$  and  $y = 30$ .



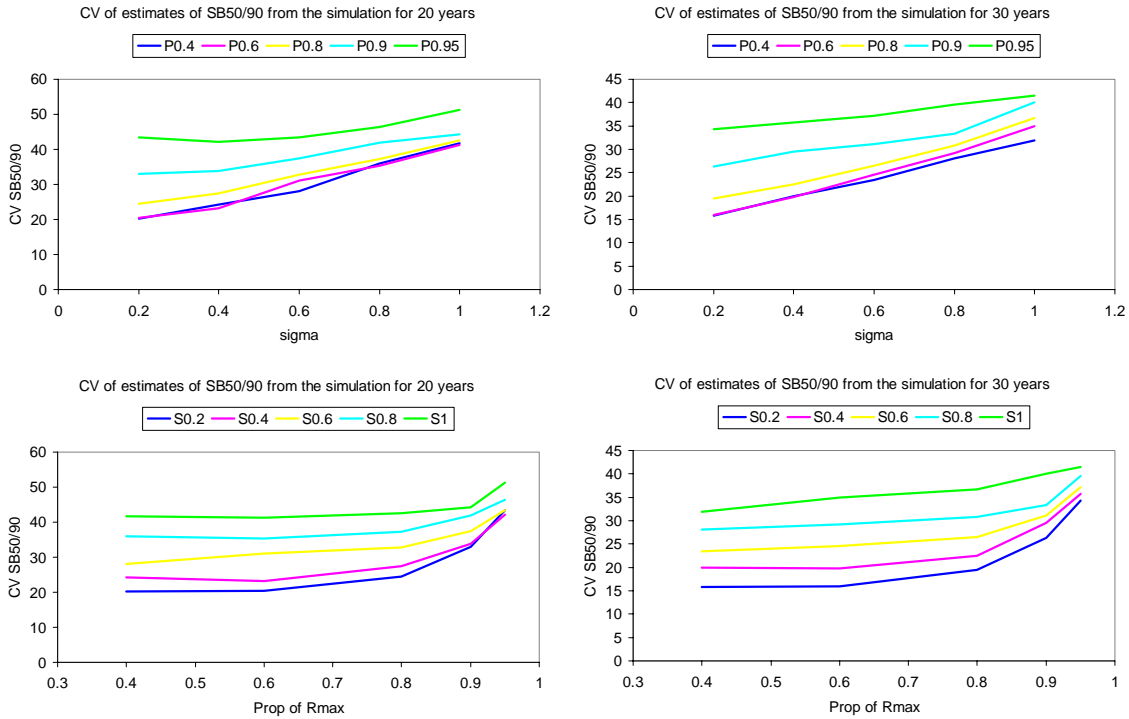
**Fig. 3.7.3.** Plot of the CV of the estimates of BH50 against  $\sigma$  and  $p$  for simulated data.



**Fig. 3.7.4.** Plots of means and medians of the distribution of estimates of SB50/90 based on simulated SR data for a range of  $p$  plotted against  $\sigma$  for 20 and 30 years of SR data.



**Fig. 3.7.5.** Plots of means and medians of the distribution of estimates of SB50/90 based on simulated SR data for a range of  $\sigma$  plotted against  $p$  for 20 and 30 years of SR data.



**Fig. 3.7.6.** Plot of the CV of the estimates of SH50/90 against  $\sigma$  and  $p$  for simulated data.

The means and the medians of the estimates of SB50/90 increase as a power function with respect to  $p$  at all  $\sigma$ , crossing over the true value of BH50 between  $p = 0.8$  and  $p = 0.9$ . There is not much difference in the results for  $y = 20$  and  $y = 30$  (Fig. 3.7.5).

The variability of the estimates of SB50/90 is relatively insensitive to increasing  $\sigma$  and the CV overall is relatively small compared with comparable estimates of BH50 (Fig. 3.7.6).

### Conclusions

Estimates of BH50 are relatively unbiased at low  $\sigma$  and high  $p$  but become negatively biased with increasing  $\sigma$  at low  $p$  values or decreasing  $p$  at high  $\sigma$  values. CVs are high and increase with increasing  $\sigma$ . The CV is relatively insensitive to  $p$ , decreasing with increasing  $p$  at intermediate values, but increasing again somewhat at higher values of  $p$ . Estimates of SB50/90 decrease with increasing  $\sigma$  at all levels of  $p$  and increase as a power function of increasing  $p$  at all levels of  $\sigma$ . CVs of the estimates of SB50/90 are relatively low (compared with BH50), increasing somewhat with increasing  $\sigma$ . While BH50 can be expected to be reliably estimated at low levels of noise in SR data and good levels of data contrast (i.e. high  $p$ ), SB50/90 would appear to be very unreliable in terms of providing a reference point consistent with the SSB corresponding to 50%Rmax and its further use should be discouraged. The tendency for both BH50 and SB50/90 to give lower estimates as the amount of noise increases is of concern. This implies that, the more noisy the SR data are, the lower the value of the LRP (i.e. more risk-prone). This is less of a problem for high data contrast situations for BH50. The tendency for both BH50 and SB50/90 to give lower estimates under situations of a small amount of data contrast (most of the data coming from the lower left corner of the SR relationship, i.e. low  $p$ ) is also cause for concern and was noted to be an undesirable property of the SB50/90 approach in the empirical study of Myers *et al.* (1994). However, with respect to BH50, Myers *et al.* (1994) found that BH50 was somewhat more robust in this regard. In the results of the simulation study presented here, there are particular concerns regarding the low estimates of BH50 when low data contrast occurs in combination with high noise levels. In these cases estimates of BH50 may display large negative biases, approaching 50%. A further undesirable property of BH50 is the large amount of variability in the estimates under conditions that are likely to pertain in the real world with respect to  $p$  and  $\sigma$ . Uncertainty in the estimate of the reference point has implications in terms of the application of HCRs which respond to perceived risk levels.

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### 3.8. Discussion of concepts related to limits

#### 3.8.1. General concept issues

The current NAFO PA framework (NAFO SC 2003) provides a number of implementation challenges, both in terms of developing a biological basis for limits and buffers and in terms of statistical estimation of these reference points (see Sections 3.3, 3.6, 3.7). From a biological perspective there does not appear to be a completely non-arbitrary method of determining the point at which serious harm can be considered to have taken place in the absence of a compensatory response in the recruitment or production function. Therefore it is inevitable that there will be some subjectivity in the determination of limit reference points. In some cases the onset of harm may be more easy to define biologically, for example the spawner biomass level at which recruitment overfishing commences as determined by segmented regression.

The 2003 NAFO framework shifts the emphasis from buffers to limits, in arguing that buffers are only required in the absence of an analysis capable of determining the risk of exceeding the limit. The 2003 framework also replaces the concept of a target reference point with the more flexible concept of a “Safe Zone” in which managers can choose different targets depending on circumstances and objectives. It is generally considered desirable to evaluate limit reference points through simulation experiments in which they are incorporated into harvest control rules (HCRs). Concerns were expressed that this would be difficult to do in a meaningful way without first specifying target reference points, and in some cases buffer reference points and harvesting strategies as well. Such an evaluation could nevertheless proceed by evaluating alternative scenarios assuming different target and buffer reference points.

The 2003 NAFO framework requires that “There must be a very low probability that management actions result in projected biomass dropping below  $B_{lim}$  within the foreseeable future”, where “very low probability” is considered to be in the range of 5-10% and the “foreseeable future” to be in the range of 5 to 10 years. This requirement suggests that it will be necessary to take into account some of the uncertainty in the estimate of the limit reference point and the uncertainty in the current and projected future stock sizes (see Section 3.2).

Estimating the ratio of  $F$  relative to  $F_{lim}$  or  $B$  relative to  $B_{lim}$  has a number of advantages over using absolute values. These include greater precision and accuracy of the estimators and therefore possibly more stability as assessments are updated (see Section 3.2). Although relative values may be less intuitive to fishery managers, they are in fact more informative.

It was noted that there may be feedback between the application of a HCR and the ability to implement the rule in subsequent years. For example a reduction in TAC might result in increased uncertainty in future reporting of catches, by-catches and discarding.

In some fisheries large declines have occurred and emergency measures and recovery plans have been put in place to reverse the harm to a stock once it has already occurred, rather than effectively implementing LRPs within HCRs before the decline became serious (see Section 3.1). Under a precautionary approach it is clearly desirable to reduce the negative impacts of a fishery before serious harm has been done and in the process increase long-term yield from a fishery.

The lag effect in some fisheries assessment-management systems may contribute to a declining stock overshooting the LRP. There are, however, some examples of NAFO stocks, such as Div. 3LNO Yellowtail flounder, where precautionary management decisions reversed a decline before serious harm had occurred. There have also been a number of cases in the management of US fisheries under the Magnuson-Stevens Act in which stock declines have been successfully arrested before serious harm has been done. Under this Act, if the stock falls below half  $B_{msy}$ , then a rebuilding plan must be instituted to ensure that the stock rebuilds to  $B_{msy}$  within a prescribed period, usually one generation time or 10 years, whichever is shorter. NAFO has recently halved the TAC on the declining Subarea 2+ Div. 3KLMNO Greenland halibut stock as part of a 15 year “rebuilding plan” which could be considered to be



consistent with a precautionary approach. However, analysis suggests the stock decline may continue for a number of years and that  $F$  will continue to increase for the next few years under this plan.

### 3.8.2. Definition of serious harm

There is widespread acceptance in fisheries and other areas in which decisions have to be made in the context of high uncertainty and serious consequences, that under a precautionary approach, management measures should be adopted consistent with a very low probability of serious harm. For many fish populations, serious harm can be interpreted in terms of increased probability of poor recruitment as spawning stock size decreases, and/or the deterioration in other aspects of a population's ability to exceed replacement and grow when at low spawning stock size. Determining the actual value of spawning biomass consistent with serious harm cannot be done in a completely non-arbitrary way in the absence of processes such as depensation in recruitment or a similar change in some other process associated with stock productivity. It should be noted that the power for detecting depensation is extremely low (Shelton and Healey, 1999). Although the determination of a limit reference point will be partly arbitrary, it needs to meet a number of requirements.

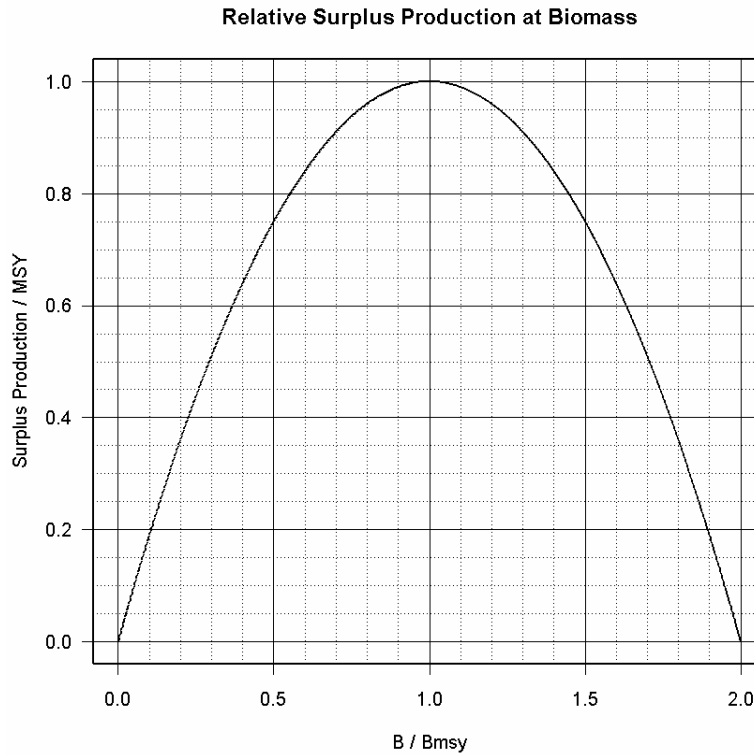
The SG took the approach of being prescriptive with respect to defining LRPs and the rules for deciding how they should be estimated. This is a conscious decision. It attempts to reflect current best practice as reflected by SG participants at the time of the meeting. It is anticipated that further work will be undertaken within NAFO, particularly in the area of HCR simulations incorporating the definitions and rules described in this document, to evaluate their sensitivity, consistency and reliability in terms of the 2003 NAFO PA framework.

There should be only a very low probability of a biomass LRP being transgressed when the stock is considered to be in what is described in the 2003 NAFO Scientific Council PA framework as the "Safe Zone". The LRP should be estimable and the estimates should be reasonably robust with respect to the addition of new data (see Section 3.6) and with respect to small changes in the formulation of the assessment model. ICES currently defines  $B_{lim}$  as the spawning biomass below which recruitment becomes impaired (i.e. the change point in a segmented regression) or the dynamics of the stocks are unknown. This definition is considerably different from the definition of an LRP under NAFO. Under the NAFO framework, it seems too likely that a stock that is in the safe zone will fall below the change point too frequently for the change point to provide a valid definition of serious harm.

SSB corresponding to 50% of the maximum recruitment ( $B_{50\%R_{max}}$ ) has been considered elsewhere in terms of a limit reference point (Mace, 1994; Myers *et al.*, 1994) and has been proposed within Canada as definition of the onset of serious harm (Rice and Rivard, 2001; Shelton and Rice, 2002; Rivard and Rice, 2002). The SG considers that, when it can be reliably estimated,  $B_{50\%R_{max}}$  can represent a good approach for determining  $B_{lim}$ , but that sensitivity/robustness to the form of the SR model and other factors should be examined. Estimates of  $B_{50\%R_{max}}$  outside the range of the SR data should not be considered a valid reference point without further consideration.

NAFO Scientific Council has already agreed on  $F_{msy}$  as a definition of  $F_{lim}$  and fishing above  $F_{msy}$  for a prolonged period would constitute serious harm (NAFO, SC 2003). This is endorsed by the Study Group.  $F_{msy}$  can be estimated for both age-aggregated production models and age-disaggregated models for which there is some evidence of compensation. For age-aggregated production models,  $F_{msy}$  as a definition of  $F_{lim}$  implies that biomass in a well managed stock might be expected to vary around a value above  $B_{msy}$ , but to fall below  $B_{msy}$  from time to time.

The discussion of thorny skate case study led to consideration of the appropriate  $\%B_{msy}$  to use as an LRP when the production function of the stock can be modeled.



**Fig. 3.8.2.1.** Plot of Production to MSY ratio as a function of the Biomass to  $B_{msy}$  ratio.

If  $50\%B_{msy}$  is adopted as  $B_{lim}$  the  $P/MSY$  ratio is 75% under the assumptions of the Schaefer model (Fig. 3.8.2.1). This level may be too high for consideration as a state in which serious harm has been done. Alternatively, the SG considered that the biomass giving production of 50% of MSY might be an appropriate  $B_{lim}$ . Under the Schaefer model this is 30% of  $B_{msy}$ . While the SG considers this to be current best scientific practice for all stocks where a production can be computed, where possible life history considerations should be evaluated to determine if this LRP is in fact appropriate. The consistency between  $B_{lim} = SSB$  at 50% $R_{max}$  and  $B_{lim} = 30\%B_{msy}$  should be examined for stocks assessed with an age-disaggregated model.

For populations which provide no clear indication of compensation in the recruitment or overall stock production functions, there is no clear basis for defining a  $B_{lim}$  and maintaining fishing mortality at a level sufficiently below the replacement fishing mortality when the stock is considered to be low, becomes a primary concern. Diagnostics of the lack of evidence of compensation would include a segmented regression with  $\delta$  at the maximum observed SSB, or a lack of fit in a production model. Under the circumstances where stock size is outside of the Safe Zone and no compensation is evident,  $F$  should be such that the resulting replacement line has probability of less than 10% of exceeding  $F_{med}$  (the  $F$  giving a replacement line corresponding to the median  $R/S$ ). Under these circumstances  $F_{lim} = F_{med}$ .

Where  $B_{lim}$  cannot be computed and by any other method, a  $B_{buf}$  should be specified by managers (in consultation with science).  $B_{lim}$  can then be estimated based on a very low probability (10%) that a stock that is estimated to be at  $B_{buf}$  is actually below  $B_{lim}$ . When  $B_{lim}$  cannot be set based on the risk of being below this  $B_{buf}$ , then a proxy for  $B_{lim}$  can be expressed in terms of the SSB for which there is no less than a 20% probability that the stock could recover to the “Safe Zone” (above  $B_{buf}$ ) in one generation under good productivity conditions (see Section 3.5). Generation time is computed as the equilibrium weighted mean age of mature fish resulting from fishing at target  $F$ . Good stock productivity conditions is defined as the 90<sup>th</sup> percentile RPS and 90<sup>th</sup> percentile SPR from the available observations. Note that it is important that  $B_{buf}$  be objectively set for this approach to have validity.

For data-poor stocks where formal assessments cannot be carried out and where it is not possible to estimate  $B_{lim}$  or  $F_{lim}$ , it may be necessary to determine serious harm directly from survey data. A decline of more than 85% from highest observed index level could be considered as a proxy for  $B_{lim}$  (this is consistent with  $B_0 = K$  in a Schaefer production model and the SGs conclusion that  $B_{lim}$  is 30% of  $B_{msy}$ ). If one assumes that the highest index of stock size is equal to  $B_{msy}$  (i.e. the stock had already been exploited for a period of time and had declined from the virgin state to  $0.5B_{max}$ ), then it would be consistent for  $B_{lim}$  to be 30% of that level. If the highest observed survey index is considered to be below  $B_{msy}$  (i.e. the stock was overfished prior to the initiation of the survey), then this should be taken into account in a similar way.

In addition to direct measures of stock productivity such as recruitment and surplus production, changes in processes that may influence stock productivity need to also be taken into consideration in determining limit reference points. The level of fishing mortality that is likely to drive the stock to the origin will change the productivity of the spawning stock to an extent that is not comparable to the earlier period. Such stocks become much less resilient to a number of years of unfavorable environmental conditions. Some of these processes that are negatively impacted by high levels of  $F$  may indicate that serious harm is occurring long before it becomes evident in a noisy set of stock-recruit data. For example, a stock which has been subject to a prolonged period of excessive fishing mortality may have a severely truncated age composition, a large proportion of first-time spawners which may produce young with inferior survival rates, a narrowed spatial distribution, a genotypic slowing of growth rates or other signs of a population under stress. While it would be sound scientific practice to consider these aspects in a precautionary approach, heuristic measures have yet to be developed to a stage where the SG felt they could be used unambiguously as limit reference points. However, with further research, these types of considerations could have potential as early warning indicators in HCRs.

### 3.8.3. Recruitment model selection and breakpoint determination

A variety of models may be applicable depending on the pattern in the data and the biology of the population. The segmented regression or hockey-stick model provides one simple way of summarizing stock-recruit data to determine whether a break point occurs within the range of SSB values observed.

Estimates of the SSB corresponding to 50%  $R_{max}$  can be quite sensitive to assumptions regarding error distributions. Under a lognormal error assumption, estimates of 50% $R_{max}$  are very sensitive to data near the origin. The SG felt that in addition to the common assumption of lognormal error, other error distributions should be explored (see Section 3.6). The stock-recruit scatter can also be very sensitive to the VPA/SPA formulation and approach used in the assessment. It should be stressed that, whereas in the past age structured assessments may have been most concerned with the estimation of the exploitable biomass, the added demands of implementing the PA places importance on obtaining best estimates of recruitment and spawner biomass, in addition to exploitable biomass, in future assessments.

### 3.8.4. Regime shift issue in terms of recruitment and production functions

Apparent regime shifts represent extreme non-stationarity in stock-recruit data, sometimes occurring abruptly. Invoking regime shifts may lead managers to foreclose on stock rebuilding objectives and to adopt reference points that ensure that the stock will remain in an unproductive state. When regime shifts are invoked, there should be clear evidence in the stock-recruit data. There should be a broad basis, including similar observations in co-occurring or adjacent stocks and viable hypothesis related to biological or physical environmental causation. Several groundfish stocks in the Northwest Atlantic have provided reasonably compelling evidence regarding substantial non-stationarity in the stock-recruit data which may constitute evidence of regime shifts. Regime shifts cannot be predicted and recovery projections should be based on re-sampling recruitment rates ( $R/S$ ) from the recent past (i.e. from the current regime).

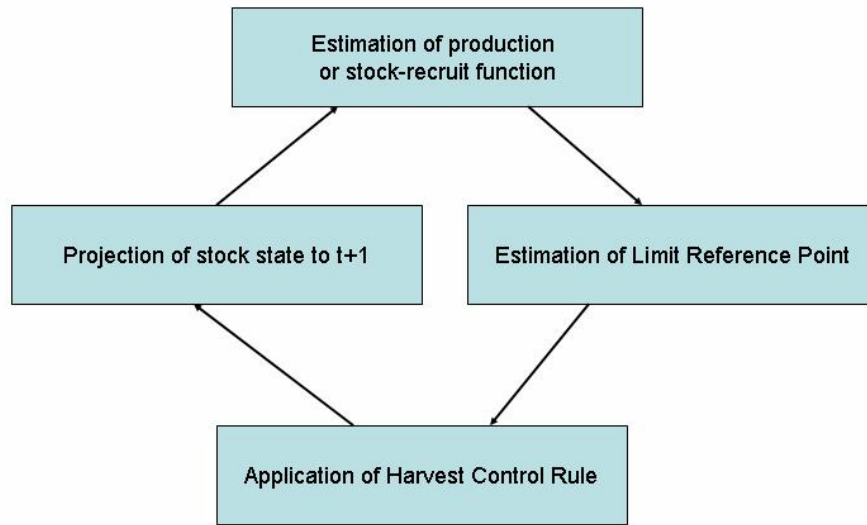
The influence of the temporal pattern in the relationship in SR data on the estimation of LRPs can be examined by fitting to some early portion of the data and some later portion separately and comparing the estimates. Where these differ greatly it can be indicative of non-stationarity. Additional information should be examined to see if this is supported by other information. In some cases what appears to be a regime shift may in fact be a reflection of reduced productivity of the stock as a consequence of prolonged periods of over-fishing leading to the loss of age

structure and also possibly changes to the genetic composition of the population (e.g. selection for slow growth). LRPs defined in this document are likely to be sensitive to such non-stationarity.

### 3.8.5. The need to evaluate limits within harvest control rule simulations

LRPs should be evaluated in the context of HCRs to ensure that they are compatible in ensuring that biomass does not fall outside the Safe Zone at frequent intervals.

The emphasis on determining the risk of serious harm requires estimation of the uncertainty in both the limit reference point and the uncertainty in the current and future states of the stock (see Section 3.2). Thus the simulation requires estimation of the SR or production functions, estimation of the LRPs, projecting the stock to year  $t+1$  while applying the HCR, updating the assessment to obtain new estimates of production or stock-recruit functions, re-estimating the LRPs, projecting the stock to year  $t+2$  while reapplying the HCR, and so on (Fig. 3.8.5.1).



**Fig. 3.8.5.1.** The harvest control rule cycle involving re-estimation of the SR or production function and thus updating the estimates of the limit reference point.

Where the assessment and management intervals are greater than annual, then this should be mimicked in the simulation (i.e. the estimates of limit reference points may only be updated every 3 years if this is the timetable for the assessment, or the annual harvest may be computed for 3 years based on a medium term projection if this is consistent with the timescale of management decisions). The projection period needs to meet the required “foreseeable future” time horizon and acceptable risk levels determined by the managers. It would be difficult to constrain the magnitude of the set of feasible HCRs without considerable input from fisheries managers, particularly given the flexibility of targets and objectives when the stock is in the “Safe Zone”.

### 3.8.6. The treatment of uncertainty in the estimation and application of LRPs

The 2003 NAFO PA framework places considerable emphasis on probability and risk for determining the zones. The SG discussed some aspects of uncertainty in the estimation of LRPs and their application in HCRs. This topic was addressed in a number of presentations summarized in Sections 3.2-3.7 and discussed in Section 3.8. Some general issues, such as the preference for the use of ratio estimators in the context of the PA, were discussed in detail. The SG felt that risk analyses should be used where possible to assess the probability of transgressing the LRPs, but a thorough treatment of the subject was considered to be worthy of more attention than the SG could devote to it within the space of the meeting.

### 3.8.7. Conclusions on concepts, estimation, evaluation and implementation

1. The SG considered Serious Harm to be defined as a state for which there would be a very low probability of the stock falling within when being managed within the Safe Zone.
2.  $F_{lim}$  is accepted as a non-arbitrary definition of a fishing mortality which, if exceeded for a number of consecutive years, would constitute serious harm to the stock.
3. There is no completely non-arbitrary definition of  $B_{lim}$  in the absence of a change in a functional response such as dispensation in recruitment or a similar change in some other process associated with stock productivity.
4. Although the determination of a limit reference point will be partly arbitrary, it needs to meet a number of requirements. There should be only a very low probability of a  $B_{lim}$  being transgressed when the stock is in the “Safe Zone”.  $F_{lim}$  should only be exceeding occasionally. LRPs should be estimable and the estimates should be reasonably robust.
5. The SSB corresponding to 50% of the maximum recruitment ( $B_{50\%R_{max}}$ ) for stocks for which such estimation is reliable provides a definition of  $B_{lim}$  under current best practice.
6. The SG considered that the biomass giving production of 50% of MSY might be an appropriate  $B_{lim}$ . Under the Schaefer model this is 30% of  $B_{msy}$ . While the SG considers this to be current best scientific practice for all stocks where production can be computed, where possible life history considerations should be evaluated to determine if this LRP is appropriate in specific cases.
7. For populations which provide no clear indication of compensation in the recruitment or overall stock production function, there is no clear basis for defining a  $B_{lim}$  and maintaining fishing mortality at a level sufficiently below the replacement fishing mortality when the stock is considered to be low becomes a primary concern. Under the circumstances where stock size is outside of the Safe Zone and no compensation is evident,  $F$  should be such that the resulting replacement line has probability of less than 10% of exceeding  $F_{med}$  (the  $F$  giving a replacement line corresponding to the median  $R/S$ ). Under these circumstances  $F_{lim} = F_{med}$ .
8. Where  $B_{lim}$  cannot be computed by any other method, a  $B_{buf}$  should be specified by managers (in consultation with science).  $B_{lim}$  can then be determined based on very low probability (10%) that a stock that is estimated to be at  $B_{buf}$  is actually below  $B_{lim}$ . When  $B_{lim}$  cannot be set based on the risk of being below this  $B_{buf}$ , then a proxy for  $B_{lim}$  can be expressed in terms of the SSB for which there is no less than a 20% probability that the stock could recover to the “Safe Zone” (above  $B_{buf}$ ) in one generation under good productivity conditions.
9. For data-poor stocks, the point at which a valid index of stock size has declined by 85% from the maximum observed index level provides a proxy for  $B_{lim}$ . If the highest index of stock size is equal to  $B_{msy}$ , then it would be consistent for  $B_{lim}$  to be 30% of that level. If the highest observed survey index is considered to be below  $B_{msy}$ , then this should be taken into account in a similar way.
10. A variety of SR models may be applicable depending on the pattern in the data and the biology of the population. The segmented regression or hockey-stick model provides one simple way of summarizing stock-recruit data to determine whether a break point occurs within the range of SSB values observed.
11. Where possible, the ratio of  $B_{current}$  to  $B_{lim}$  and  $F_{current}$  to  $F_{lim}$  should be computed and provided in the scientific advice, in addition to the absolute estimates. Such ratios will have better statistical properties than the absolute estimates.
12. Apparent evidence of regime shifts should be treated with caution and the implications should be examined. Invoking regime-shift changes as an explanation for changes in recruitment may not be precautionary in some cases.

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## 4. Case Studies

### 4.1. Background information and basis for the most recent assessment

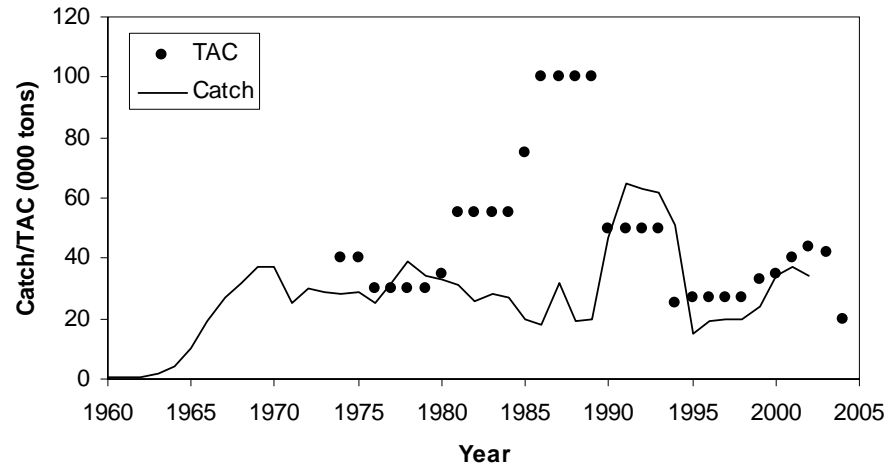
#### 4.1.1. Subarea 2 and Divisions 3KLMNO Greenland halibut (Species Experts: Ray Bowering and Brian Healey)

The Greenland halibut stock in Subarea 2 and Div. 3KLMNO is considered to be part of a biological stock complex, which includes Subareas 0 and 1.

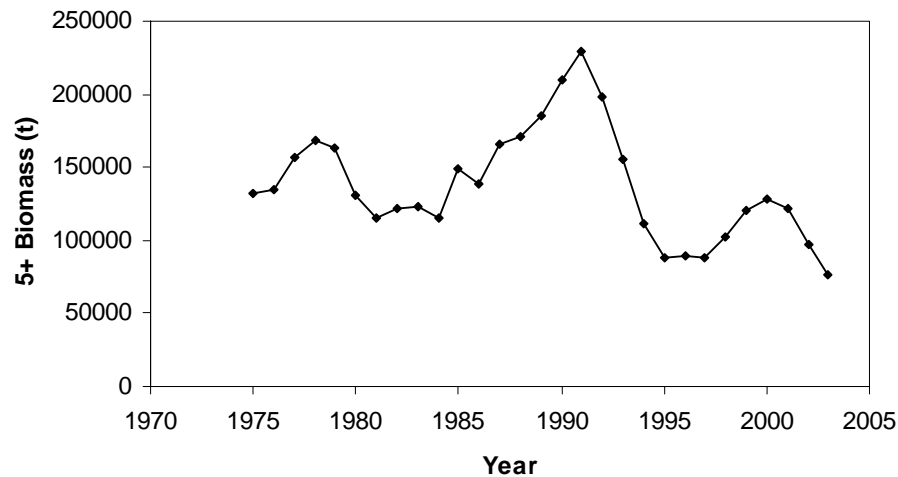
Historic catch records show that a small Greenland halibut fishery using longlines existed off Labrador and eastern Newfoundland as early as mid 1800s (Lear, 1970). However, annual catches were very low, usually less than 1,000 tons prior to the 1960s. With the introduction of synthetic gillnets to the inshore domestic fishery during the mid 1960s and the increased interest by large foreign otter trawlers both as directed fisheries and by-catches in other deepwater fisheries, Greenland halibut catches rose quickly to peak at 37,000 tons by 1969 (Fig. 4.1.1.1). Catches remained relatively stable during the 1970s and early-1980s averaging about 32,000 tons from 1970-83 after which they declined to about 20,000 tons during the late-1980s.

In 1990, an intense unregulated fishery for Greenland halibut developed in the NAFO Regulatory Area (NRA) of NAFO Div. 3L and 3M (and in later years also included NAFO Div. 3N and 3O) in the deep waters of Flemish Pass. Catches escalated rapidly and were estimated to be about 47,000 tons in 1990 and to be at least as high as 62-65,000 tons annually for 1991-93 and 51,000 tons in 1994 (Fig. 4.1.1.1). Getting accurate catch data from the NRA during this period of high unregulated fishing effort was especially difficult. Reported catches were well below those estimated from other sources and used by the NAFO Scientific Council in conducting resource assessments. With the introduction of severe catch restrictions and 100% observer coverage in the NRA by the NAFO Fisheries Commission in 1995, catches declined to between 15-20,000 tons for the entire management area during 1995-98 and during this period reported catches and estimated catches were very similar.

As improvements to the resource occurred through good recruitment, catches began to increase again and by 2000-2002 were estimated to be in the range of 34-38,000 tons. Once again, however, the reported catches from the NRA were below those estimated from other sources such as the NAFO Observer Program.



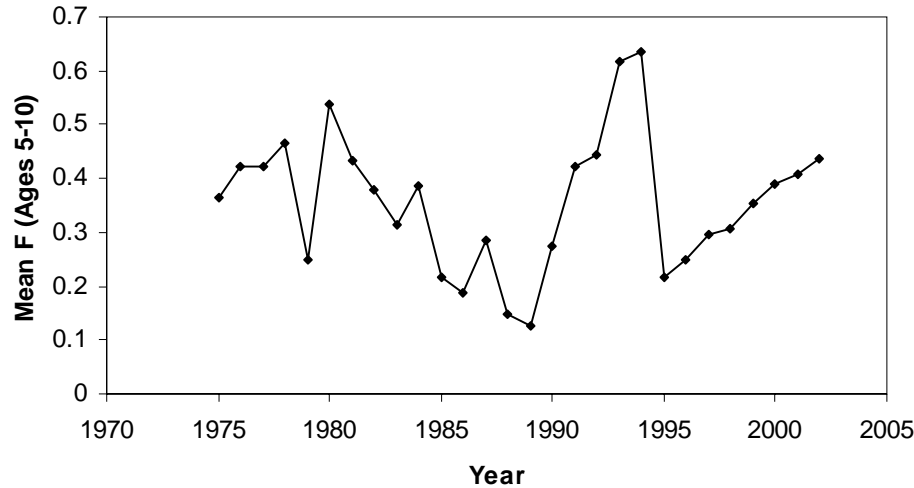
**Fig 4.1.1.1.** Catches and Total Allowable Catches (TAC) for Greenland Halibut in Subarea 2 and Div. 3KLMNO.



**Fig 4.1.1.2.** Exploitable (5+) Biomass of Greenland Halibut in Subarea 2 and Div. 3KLMNO, from Darby *et al.* (2003).

In 2003, Scientific Council for the first time accepted an age-disaggregated analysis (XSA) for Greenland halibut in Subarea 2 and Div. 3KLMNO (Darby *et al.*, 2003), which was deemed to be a reliable estimate of exploitable biomass (ages 5+ biomass; Fig. 4.1.1.2). The exploitable biomass at the beginning of 2003 was estimated to be the lowest in the time series which began in 1975. The assessment determined that SSB was not reliably estimated, although ages 10+ were considered as a proxy for estimating of spawning stock biomass. The focus of the 2003 assessment was determination of estimates of exploitable biomass and fishing mortality, rather than SSB.

Scientific Council expressed considerable concern regarding the increasing trend in fishing mortality (Fig. 4.1.1.3), that exploitable biomass in 2003 was estimated to be the lowest in the time series, and that all incoming year-classes were below average. These concerns formed the basis of its advice on management to the Fisheries Commission for 2004. In response, the Fisheries Commission developed a fifteen year recovery plan for this stock which establishes reduced TACs over the initial four-year period, with the remaining TACs to be subsequently determined based upon stock status and pre-established criteria.



**Fig. 4.1.1.3.** Average Fishing Mortality (over ages 5-10) of Greenland Halibut in Subarea 2 and Div. 3KLMNO, from Darby *et al.* (2003).

#### *Previous Precautionary Approach Considerations*

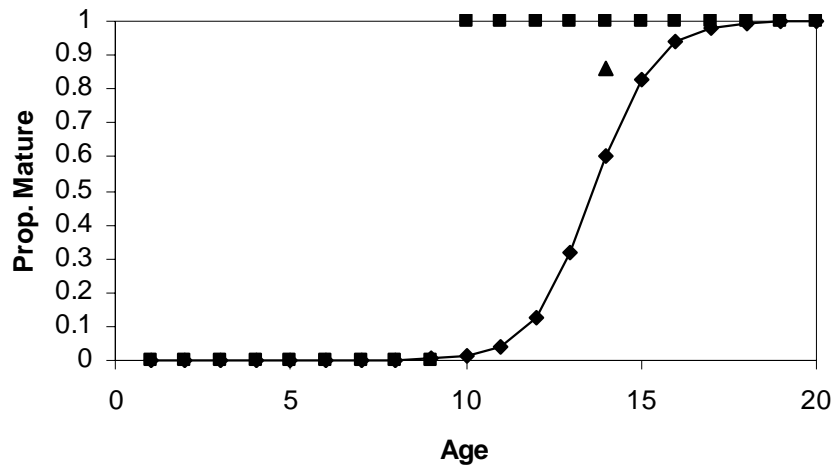
Greenland Halibut in Subarea 2 and Div. 3KLMNO and limit reference points (LRPs) have been discussed at several previous NAFO Scientific Council meetings (NAFO, 1998, Rivard and Casey, 1998; NAFO, 2003). Although no LRPs have been established for this stock, Rivard and Casey (1998) suggested that escapement to maturation should be considered in any PA approach developed. At the 2003 Scientific Council workshop on the PA, the Rago replacement ratio method (RRM; NAFO 2003; see Section 3.4) was applied to Greenland Halibut in Subarea 2 and Div. 3KLMNO. RRM is an index-based method, utilizing catch data and a single index to produce the replacement ratio, defined as a measure of the current population size relative to a linear combination of the parental stocks that produced it. Detailed discussion on the method and illustration of its applicability may be found in NEFSC (2002a, b), in NAFO (2003) and a summary is provided in Section 3.4. In implementing this approach at the 2003 NAFO PA meeting, concerns were expressed about the reliability of the results for Greenland Halibut: “above average recruitment during a period of low adult stock size may have artificially inflated the estimates of the replacement ratio” (NAFO, 2003). No reference points were established from this analysis in the 2003 SC Workshop.

#### *Difficulties in implementing the PA for Greenland Halibut*

Several difficulties exist which have prevented establishing LRPs for Greenland halibut thus far. For biomass reference points, the primary concern is defining and measuring the spawning stock biomass (SSB) for this stock. Mature fish are rarely observed in surveys and commercial catches. Spawning occurs over a wide geographic range, from as far north as Davis Strait (Div. 0B) south to the Grand Bank and Flemish Pass (Div. 3LMNO). Research indicates that spawning does not occur annually (Bowering, 1999; Junquera and Zamarro, 1994; Federov, 1971). Further, the fishery primarily selects fish ages 5-8, which are immature.

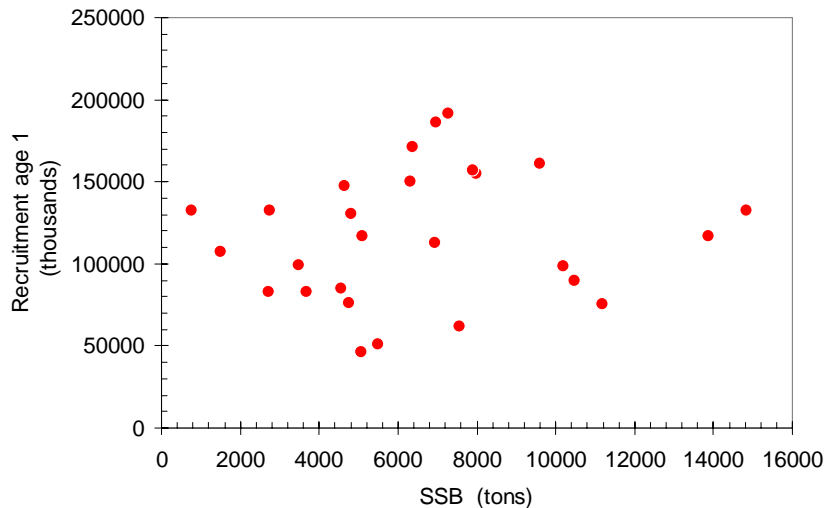
Although estimates of proportion mature-at-age for Greenland Halibut (Morgan and Bowering, 2001) are available, they were not considered in the 2003 Scientific Council assessment. An SSB proxy of 10+ biomass was calculated, but was not a focal point of the 2003 assessment. Computing SSB using the estimated maturities instead of the ages 10+ proxy leads to lower estimates of SSB, as the estimates of percent mature from ages 10-14 are much less than 100% (Fig. 4.1.1.4).





**Fig. 4.1.1.4.** Proportions mature at age. The diamonds indicate model estimates from Morgan and Bowering (1998). The triangle for age 14 denotes a mortality-weighted average applied to the plus group in the XSA. The 10+ proxy from the 2003 assessment is plotted for comparison (squares).

The resulting SR plot from the application of this maturation ogive to the 2003 assessment estimates of numbers at age produces no clear SR relationship (Fig. 4.1.1.5). This plot has not been reviewed by SC so should be considered provisional.



**Fig. 4.1.1.5.** SR relationship for Subarea 2 + Div. 3KLMNO Greenland halibut, with SSB computed using a year-invariant maturation ogive from Morgan and Bowering (1998).

Another issue with respect to Greenland halibut is the sensitivity of the stock-recruit scatter to the XSA formulation. This issue is amplified due to the fact that the accepted XSA incorporates tuning data from 1995-2002, yet catch data are available back to 1975. Therefore, most of the historical estimates of numbers at age are generated from the catch data and the fishing mortality constraints. Thus, any change to these constraints will substantially alter perception of past stock dynamics.

Since the 2003 Scientific Council assessment is considered to be a reliable measure of fishable biomass, consideration was given to projection of younger ages out to spawning ages, to see if the relationship between

spawners and recruits would be amenable to more traditional methods of establishing PA LRPs (e.g. fitting of parametric models). Results were found to be uninformative and LRPs could not be computed.

The replacement ratio method (RRM) was updated at this meeting (see Section 4.2.1). Concerns were raised about the validity of some of the methodological assumptions with respect to Greenland halibut, e.g. the assumption that recruitment is proportional to spawning stock biomass.

No reference points for Greenland halibut in Subarea 2 and Div. 3KLMNO have been established within SC thus far, however application of the rule-based expert system developed below (see Section 5) could assist in deciding on a specific approach for obtaining an LRP in future assessments.

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#### 4.1.2. Divisions 3LNO Yellowtail flounder (Species Expert: Bill Brodie)

This stock was last assessed by Scientific Council in June 2002, and at that time SC provided advice for 2003 and 2004. SC undertook an update of stock status in June 2003, and no change in advice was considered necessary. The next full assessment of the stock is scheduled for June 2004, when SC will provide advice for 2005 and 2006. TACs and quotas are set by NAFO FC. Canada is allocated 97.5% of the TAC. The fisheries in the Canadian EEZ (inside 200 n. mile limit) and in the NAFO Regulatory Area (outside EEZ) are managed differently. Otter trawl is the main fishing gear in all areas and years.

### *Assessment summary*

- A moratorium on directed fishing existed for this stock from Jan 1, 1994 to July 31, 1998.
- Stock production model (ASPIC) estimates of stock size are well above the level of the mid-1980s, and above  $B_{msy}$ . Recent fishing mortality estimates are relatively low at  $2/3 F_{msy}$ .
- Surveys indicate increased biomass and wider distribution of fish on Grand Banks since mid 1990s. Recent survey biomass estimates (Canadian and Spanish) are the highest in each series.
- Recruitment has improved since 1990, despite low SSB in the early to mid 90's.
- Projected yield in 2003-2004 at  $2/3 F_{msy}$  is 14,500 tons.
- Projections (2002 assessment) at  $2/3 F_{msy}$  indicate yield should slowly increase over the next several years, to a maximum of about 17,000 t, maintaining low probability that B will fall below  $B_{msy}$ .
- Current studies on age, growth, and longevity are aimed at allowing age-structured models to be used in near future.

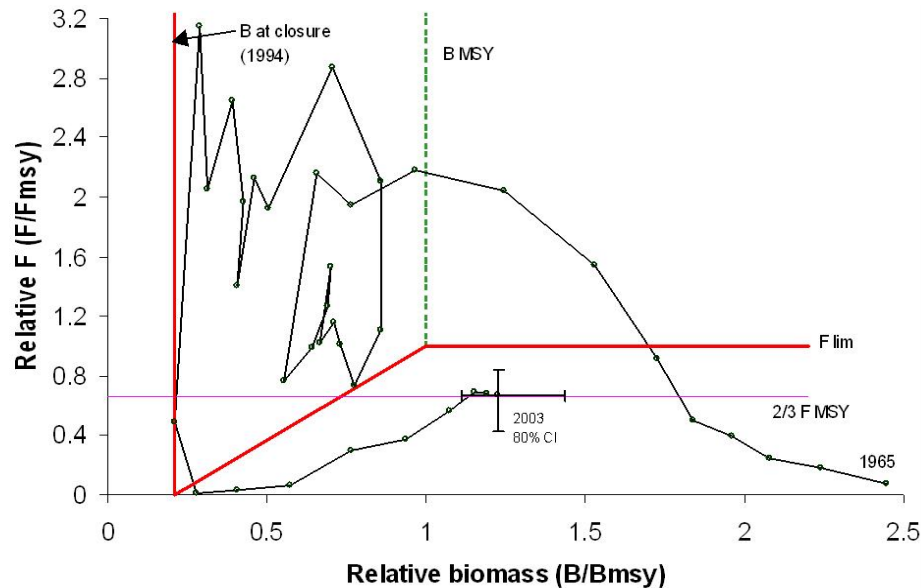
There has been some development of the Precautionary Approach on this stock, as follows:

- The first SC PA work on this stock was in 1999.
- The ASPIC production model has been used in recent assessments, and the results for biomass and fishing mortality are given relative to MSY values.
- $F_{lim} = F_{msy}$ , by definition in the NAFO PA framework. The probability distributions of  $F_{msy}$  from bootstrapped ASPIC model could be used to calculate  $F_{buf}$ .  $2/3 F_{msy}$  is suggested as a target F, and FC has set the TAC at this level for several years.
- No SSB-based reference points have been defined, as ASPIC is based on total stock biomass, not SSB. Years with low SSB (survey data) could be compared to low biomass points from ASPIC to suggest lower limits for biomass reference points.
- An estimate of  $B_{msy}$  is available from ASPIC and could be used by managers as a target reference point.
- Lack of a stock-recruit curve and age-structured models preclude use of many PA reference point calculation methods.

Although FC has not yet adopted a PA Framework to manage stocks, in 2000 it developed a PA implementation plan for 3LNO yellowtail and some other stocks, including the following 8 objectives:

- Maintain harvest levels that will continue to rebuild and maintain the stock biomass above the rebuilt biomass level.
- Continue with a comprehensive suite of management measures.
- Ensure that the fishery will not jeopardize recovery of other stocks in the area under moratorium, specifically Atlantic cod and American plaice.
- For managers stock performance measures could be expressed in terms of biomass, including how the biomass levels relate to reference points and catch levels.
- Production models do not permit determination of all reference points. Scientists should move toward using age-structured models.
- Production modelling could be used to evaluate real F limits, and to provide insight in what will happen if there are lower or higher Fs.
- Need to develop "target" biomass levels, higher than the biological limits, to take into account fisheries management objectives such as economics.
- Endorse work of the SC to develop a better understanding of the SR relationship.

Progress has been achieved towards some objectives, but not all. Scientific advice in recent years has been provided to correspond to the SC PA framework developed in 1997 (see for example Fig. 4.1.2.1).



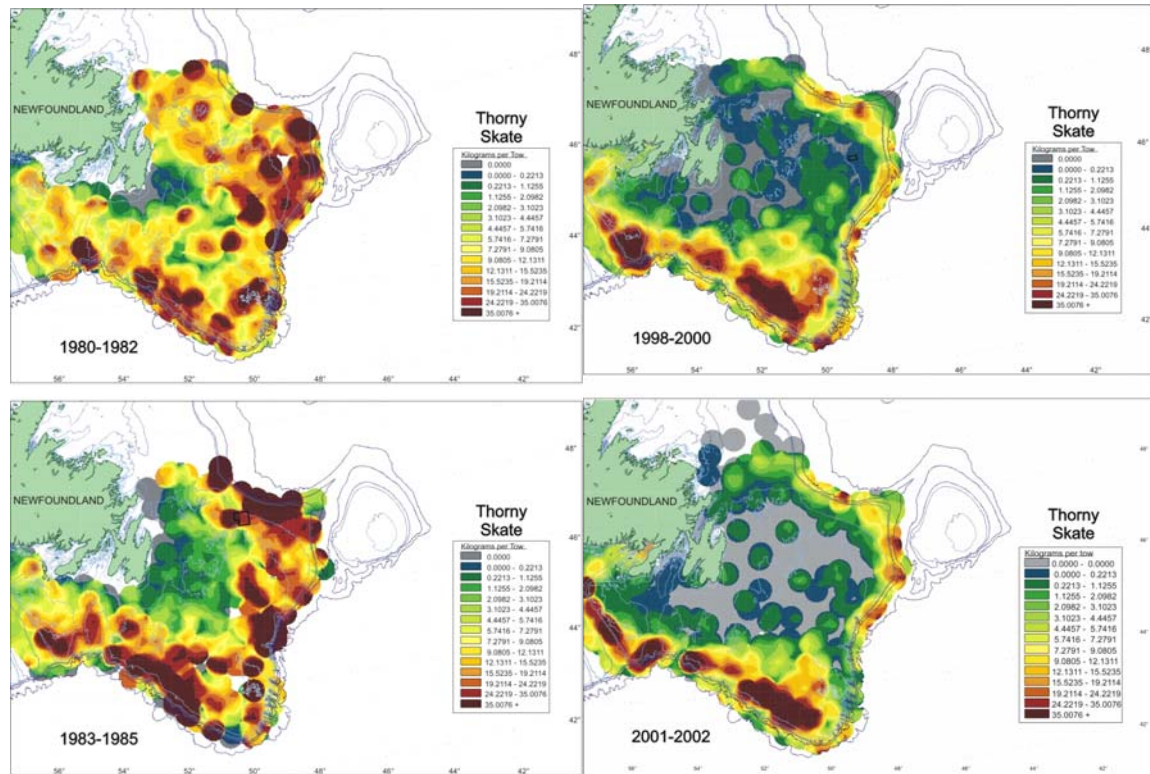
**Fig. 4.1.2.1.** Div. 3LNO yellowtail flounder stock trajectory, from 2002 assessment, presented in the original NAFO SC framework.

#### 4.1.3. Divisions 3LNO Thorny skate (Species Expert: Dave Kulka)

Information on thorny skate on the Grand Banks presented at the June 2003 NAFO Scientific Council meeting is summarized here. In addition, some new staged-based analyses are presented in order to look at the relationship between recruitment and biomass. These new analyses have not been reviewed by SC and are therefore considered to be tentative.

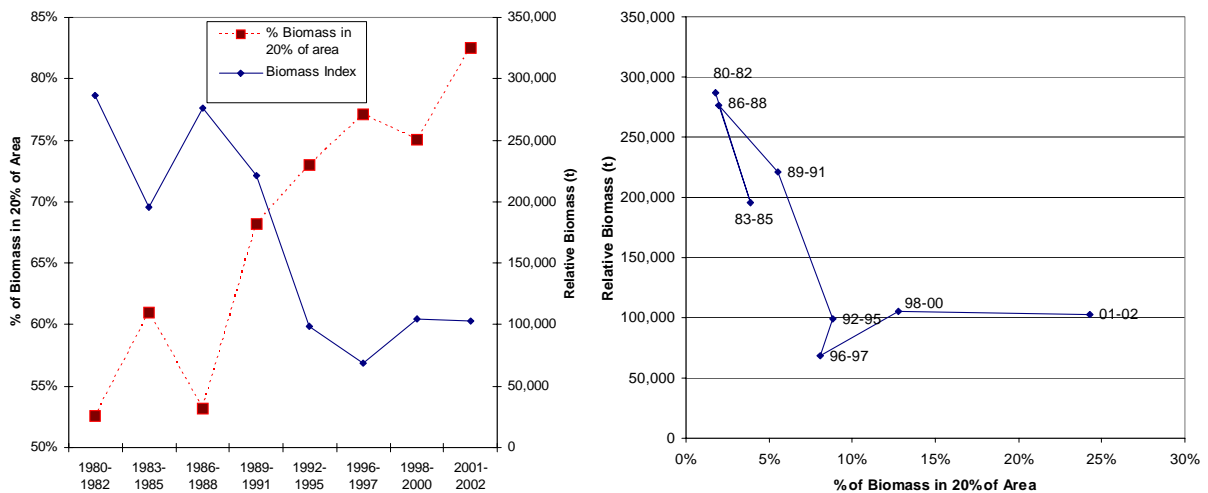
Elasmobranchs, including thorny skate (*Amblyraja radiata*) have a lower reproductive potential than most teleosts due to slow growth, late sexual maturation, low fecundity, and long reproductive cycles (referred to as K-selected species). These characteristics result in low intrinsic rates of increase for the species, and thus they are thought to have very low resilience to fishing pressure. Although skates are not as fecund as most teleosts, it does not necessarily follow that they have a lower net reproductive rate because newly hatched skates have a much higher probability of early stage survival. A more appropriate comparison would be the number of juveniles produced per female per year. The difference lies in the potential of teleosts to produce very large year-classes, bumper crops from small a SSB; this is not the case for skates. Thus, recovery of a depleted skate population can only occur gradually. Given their vulnerability to overexploitation, as evidenced worldwide, and their inability for rapid recovery from depletion, a conservative approach to their management is appropriate.

Thorny skate, the dominant batoid on the Grand Banks is distributed continuously on the outer bank and shelf edge, from the Laurentian Channel to the northern extent of the Flemish Pass. It undertakes a seasonal migration, moving into deeper water along the shelf edge in the winter/spring. Juveniles are widely distributed across the Bank while adults and young of the year (YOY) form a band around the perimeter of the Bank, YOY occupying a narrower band around the perimeter. All components of the population have been steadily diminishing from the northern extent (particularly YOY) since the late 1980s. Previously dispersed over the entire Banks, more than 80% of the biomass is now concentrated in 20% of the area along the shelf break in 3NOPs (Fig. 4.1.3.1).



**Fig. 4.1.3.1.** Distribution of thorny skate during two early time periods compared to two recent time periods.

Little is known about the biology of thorny skate. Mostly the Grand Banks biological work is that of Templeman from the 1980s. However, Canadian spring survey indices indicate that, following an increase in abundance in the early-970s, the stock trajectory was flat until the late-980s (~250,000 t). The stock underwent a significant decline in the late-1980s to early-1990s, but has stabilized at a low level (~90,000 t) since the mid-1990s. However, during the latter period, the distribution has continued to become more truncated (Fig. 4.1.3.2).

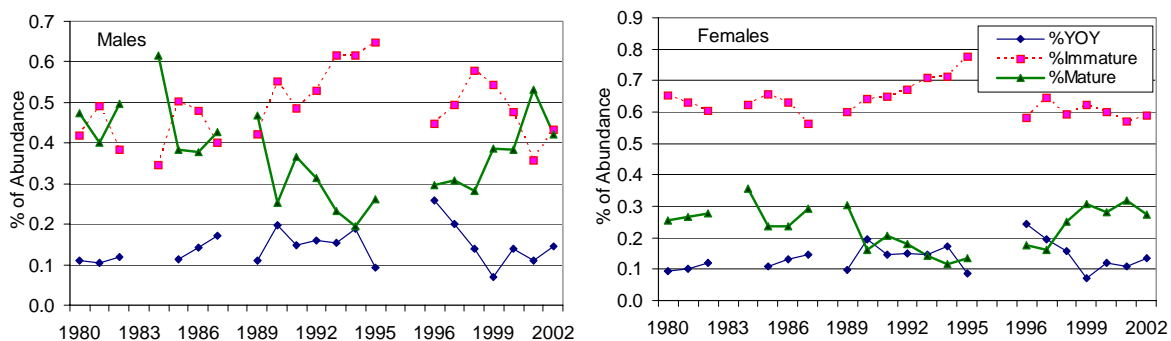


**Fig. 4.1.3.2.** Relationship between biomass and degree of concentration of thorny skate in Div. 3LNOPs.

A directed trawl fishery (by Spain, Portugal, Russia) has been prosecuted outside of 200 n. miles in NAFO Div. 3N since mid-1980s. A Canadian directed fishery in 3O and 3Ps, using mainly gillnets, started in 1994. Prior to that period, skate constituted a significant by-catch in a numbers of other fisheries. About 13,000 t were taken in 2002, close to the average of the previous 5 years and about half what was taken in the mid-1980s. More than 2/3rds of the catch comes from the NRA. Commercial frequencies from recent years show that trawl catches capture a significant portion of juveniles while gillnets and longlines take nearly all mature fish. Details of the biology, distribution and catch history presented at 2003 Scientific Council of NAFO are provided in Kulka and Miri (2003)

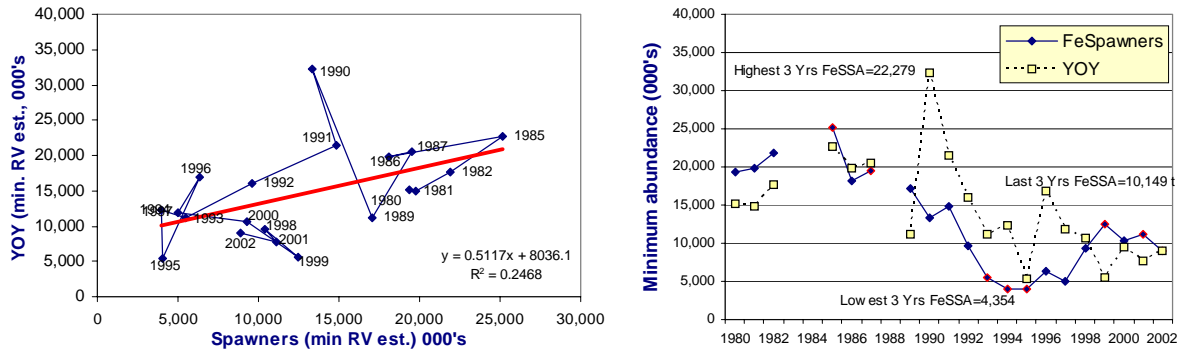
Following a recommendation by the NAFO Symposium on Elasmobranch Fisheries: Managing for Sustainable Use and Biodiversity Conservation (2001) to establish effective management measures for thorny skate in NAFO waters, the Fisheries Commission (FC) of NAFO requested information on exploitation rates, advice on reference points, conservation measures, annual yield potential. The FC questions were posed in regard to NAFO Div. 3LNO, the statistical areas that overlap the 200-mile limit, whereas Canada assesses thorny skate within Divisions 3LNO and Subdiv. 3Ps, based on distributional and morphological evidence that skate within this entire area constitute a single biological unit. Thus the current exercise was applied to the entire management unit of thorny skate, 3LNOPs, consistent with the approach to some other NAFO assessed stocks.

No age- based analyses have been done (the case for most skates). However, recent research by Spanish scientists on maturity facilitated a stage-based analysis allowing an examination of SR relationships. SSB and R are likely to be correlated. The three population components, YOY, juveniles and mature adults underwent different changes over time relative to the total population. In absolute terms, all three components declined in the late-1980s to mid-1990s, but to varying degrees: YOY as a percentage of total population remained relatively constant, percentage of mature fish declined, while the percentage of juveniles increased, showing that the greatest declines occurred in mature fish during the late-1980s to mid-1990s.



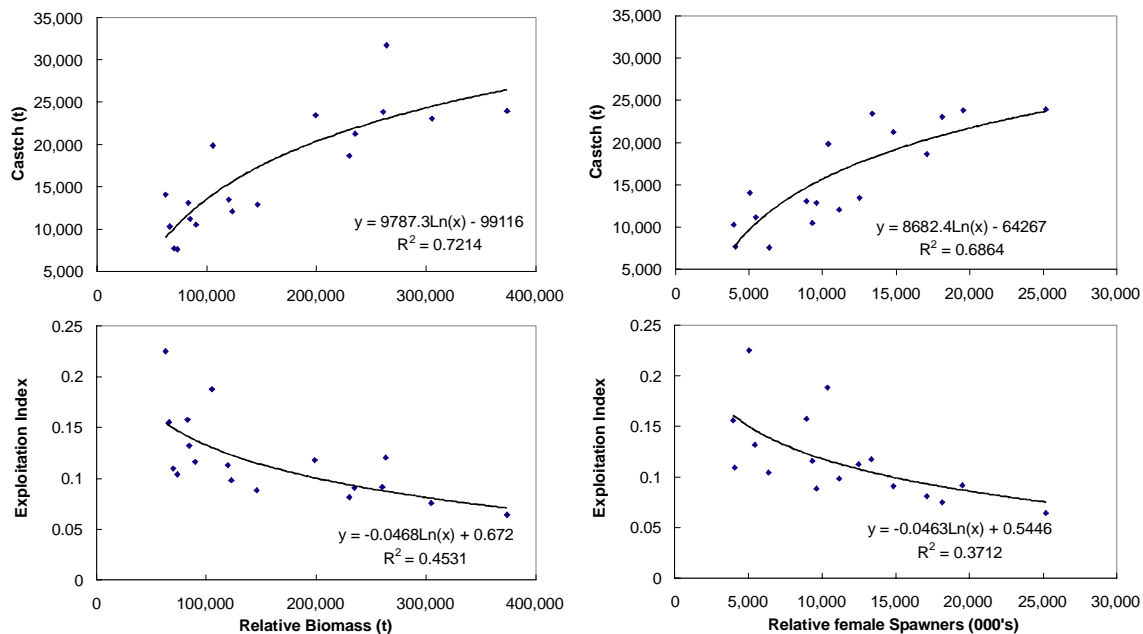
**Fig. 4.1.3.3.** Population components as a percent of the total population over time.

Based on hatch size, an estimate of recruitment (abundance) from the initial peak in the survey size frequency was derived. Spawner abundance was determined using maturity ogives derived by del Rio (2002). Fig. 4.1.3.4 indicates that, within the range of the data, abundance of recruits tended to increase linearly with abundance of female spawners



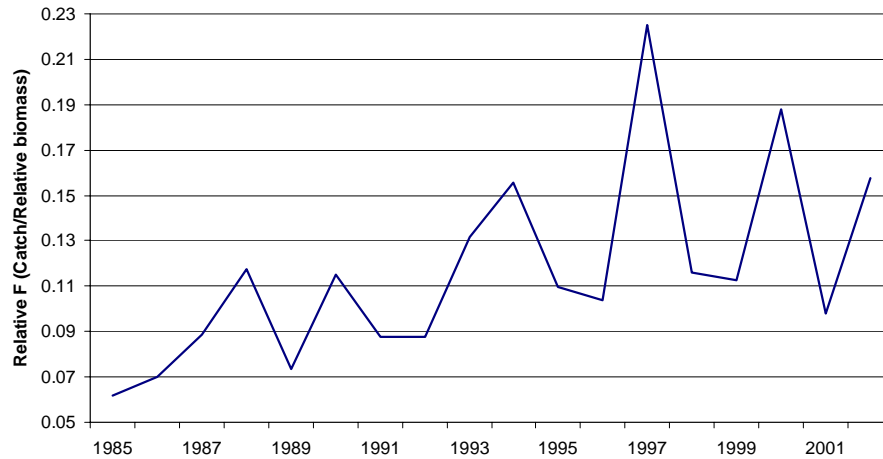
**Fig 4.1.3.4.** Left panel: Minimum abundance RV trawl survey estimate of recently hatched skates (YOY from the same year) in relation to abundance of spawning females. The line represents a linear fit. Right panel: Survey minimum trawlable estimates of abundance of recruits and female spawners.

Catch was shown to increase with relative biomass, both in relation to total population and female spawners over the series (1985-2002) while exploitation decreased Fig. 4.1.3.5). The lower left panel of Fig. 4.1.3.5 suggests that an inflexion occurs at a Relative F (exploitation index) of about 0.1. Relative F above this may represent an excessive level for thorny skate.



**Fig. 4.1.3.5.** Catch and index of exploitation in relation to relative biomass and abundance, 1985-2002.

Relative exploitation is estimated to have exceeded 0.1 since the late-1980s (Fig. 4.1.3.6).



**Fig. 4.1.3.6.** Relative exploitation index for thorny skate.

### References

- del Río J.L. MS 2002. Some aspects of the thorny skate, *Amblyraja radiata*, reproductive biology in NAFO Division 3N. NAFO SCR Doc. 02/118, Ser. No. N4739. 14p.
- Kulka, D.W., and C.M. Miri. 2003 The status of Thorny skate (*Amblyraja radiata* Donovan, 1808) in NAFO Divisions 3L, 3N, 3O, and Subdivision 3Ps. SCR Doc. 03/57, Ser. No. N4875. 100p.

## 4.2. Report-back from case study subgroups

### 4.2.1. Subarea 2 and Divisions 3KLMNO Greenland halibut (Sub-group leader - Brian Healey)

#### *Consideration of the draft rule based expert system*

The Greenland halibut case study sub-group considered a draft of the proposed expert system decision-tree framework presented in plenary (note, the expert system was subsequently revised based on feedback from this and the other sub-groups and further discussion in plenary and is presented in Section 5). Discussion was focused on the generic situation in which a data rich/age-disaggregated assessment is available, but particular emphasis was given to the Greenland halibut case study, given the problems in determining LRPs for this stock.

The Greenland halibut sub-group discussion began at the data rich/age-disaggregated node of the original Decision Framework, originally stated as: “Can SSB be estimated from SPA?”. The sub-group felt that this question was not the appropriate one to ask. It was felt that SPA may not be required to estimate SSB, or at least not required to estimate a relative index of SSB (e.g. survey information). In particular, for the case of Greenland halibut, the VPA is considered to be a reliable estimate of exploitable biomass, but not a reliable estimate of spawning stock biomass, as the older fish are not well represented in surveys, and the spawning stock component is poorly understood. Also, it was pointed out that following the “yes” branch from this node, it is important to have recruitment or an index of recruitment to continue with SR analyses. The sub-group suggested amending the question to read: “Can indices of SSB and recruitment be estimated?”. In the proposed decision framework, the next step is to “Use R/SSB scatter plot to define  $B_{lim}$ ”, followed by the decision node: “Good dynamic range in data. Evidence of asymptote?”. The sub-group felt that a more reasonable approach was to replace these by “Characterize SSB-recruit relationship” (similar to the ICES characterizations in ICES CM 2003/ACFM:15), and “Is there good evidence of impaired recruitment at low SSB?”. In the opinion of the sub-group, this question was more suited to incorporation into the expert system, on the basis that, if compensatory dynamics do not exist, then estimation of LRPs via standard stock-recruit models may not be advisable. The sub-group decided that if there was good evidence of impaired recruitment at low SSB, then the decision framework should lead to a conclusion (for biomass LRPs) that  $B_{lim}$  is defined as the point below which recruitment is likely to be seriously reduced or impaired.



Following the “No” node from the revised question: “Can indices of SSB and recruitment be estimated?”, the sub-group discussed many options for determining  $F_{lim}$ , and also simple biomass reference points (e.g.  $B_{recover}$ ). Much discussion was centered on the utility of production model approaches given that one is on the decision branch on which it has been determined that indices of SSB and recruitment are considered not sufficiently reliable to proceed further in the determination of SR reference points. The sub-group expressed concerns that, if an age-disaggregated assessment failed to yield reliable biomass reference points, there may also be some issues with the application of production model approaches (e.g. determination of  $F_{msy}$ ). Nevertheless, it was considered desirable that  $F_{lim}$  be defined as “ $F_{msy}$  or an appropriate surrogate” if possible. However, the sub-group considered that, even in the case of a data rich/age-disaggregated assessment, the determination that “no limit reference points are possible” may occur. This conclusion is reached when indices of SSB and  $R$  are not estimable, or when good evidence of impaired recruitment at low SSB does not exist. In such instances, the sub-group suggested amending the draft expert system to read “If stock size is low, keep  $F$  at level where stock would rebuild”. The definition of the rebuilding point was not resolved in the sub-group discussions.

The sub-group discussed an approach proposed by Mohn and Chouinard (2004) based on “recover to healthy state within one generation. It was agreed within the sub-group that this approach required further evaluation. It has some similarities to  $B_{recover}$  (the lowest SSB from which the stock has previously sustained a rapid recovery). There were varying opinions as to the utility of  $B_{recover}$  and the Mohn-Chouinard approach as a proxy for  $B_{lim}$ . The sub-group discussed instances in which  $B_{recover}$  would be more suitable as a buffer reference point rather than as a limit reference point. The sub-group noted that it may be difficult to apply  $B_{recover}$  if it has already been determined that a reliable index of SSB is not available.

#### *Application of Replacement Ratio Index Methodology*

The replacement ratio methodology (see Section 3.4 for a description of this method) was applied to the Greenland halibut catch (landings + by-catch) and Canadian Research Trawl survey index data (kg/tow) for the period 1978-2002. Survey index values were lagged 1 yr to account for consideration that the spring survey in year  $t+1$  was a more appropriate measure of abundance in year  $t$ . The replacement ratio was defined as the ratio of the current index value to a five-year moving average of the index. Relative  $F$  was defined as the ratio of current catch to a three-year average of index stock size. Using these definitions, the replacement ratio was estimable for 1983-2002 and relative  $F$  was available for 1980-2002.

Landings of Greenland halibut declined from 1978 to 1986 and then increased rapidly from 1988, remaining high through 1994. Since historic low catches in 1995, catches have increased steadily. Survey estimates dropped from early high levels (30-40 kg/tow) prior to 1985 to historic lows in 1993. Survey estimates increased until 1999 but have declined since then. These changes in survey and catch data generate a high degree of contrast in relative  $F$  and replacement ratios. Randomization tests of the relationship between replacement ratio and relative  $F$  suggest a low probability that the relationship ( $r = -0.59$ ) is due to chance alone ( $P \sim 0.02$ ). Results suggest that the relative  $F$  consistent with replacement is approximately 0.998 with an 80% bootstrap confidence interval of 0.657 to 1.317. Current estimates of relative  $F$  indicate the fishing mortality has been above the 90%-ile of replacement for the last two years (2001-2002) for which data are available. Continuation of the current rate of removals are predicted, under this model formulation, to result in a declining biomass (index level of 14 kg/tow) in 2005 and declining catches over the next 3 years. This model assumes that population behavior is linear in the vicinity of the current population size and longer-term projections may be unreliable.

#### *References*

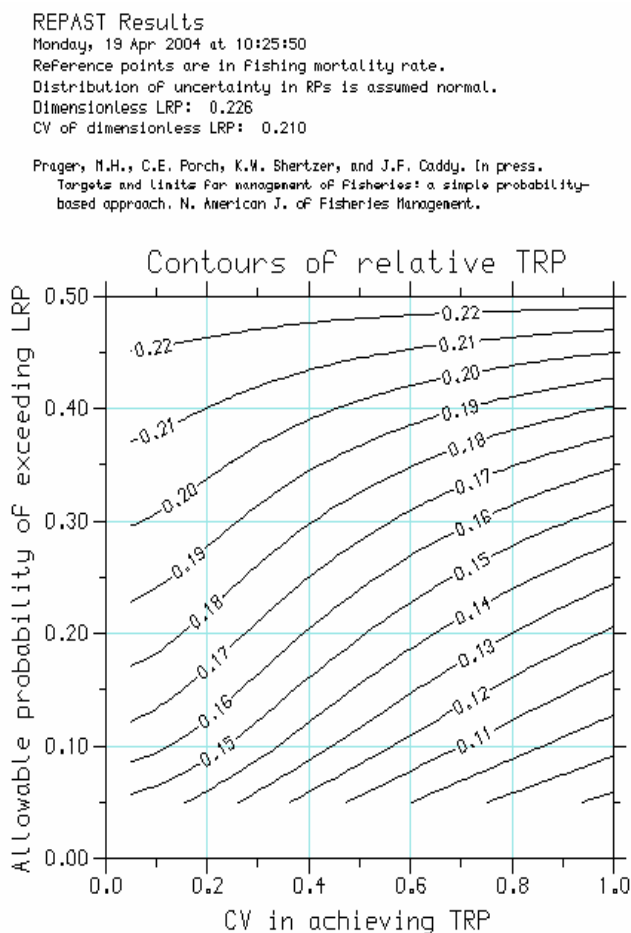
- ICES 2003. Report of the Study Group on Precautionary Reference Points For Advice on Fishery Management. ICES CM 2003/ACFM:15.
- Mohn, R., and G.A. Chouinard. 2004. MS. Production analysis of southern Gulf of St. Lawrence cod for the identification of biological reference points. Unpublished manuscript

#### 4.2.2. Divisions 3LNO Yellowtail flounder (Sub-group leader – Bill Brodie)

##### *Application of REPAST*

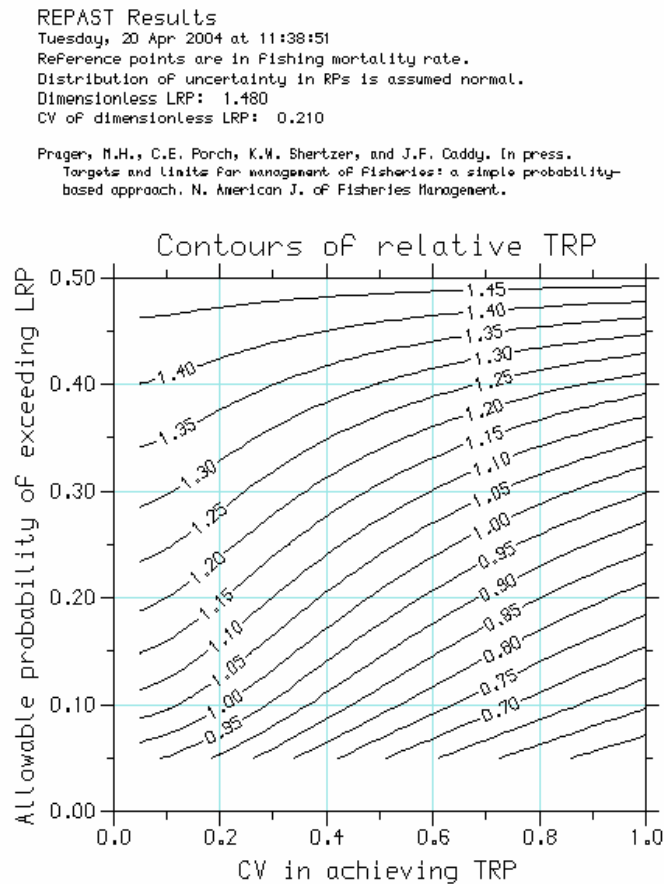
The sub-group applied the REPAST procedure of Prager *et al.* (2003), (see Section 3.2 for a description of this method) which allows computing a suggested  $F_{buf}$  (labeled a TRP by REPAST software). This is derived from assessment results, the CV on the  $F$  realized from that set by managers, and the allowable probability  $P^*$  of exceeding the LRP in  $F$  in any year. The sub-group considered this a good approach for computing a buffer should FC asks NAFO SC to do this (recall that a buffer is not needed in the 2003 Framework if SC can provide the probability that  $F$  is  $< F_{lim}$  ( $F_{lim} = F_{msy}$ )). If managers tell SC what level of risk they are prepared to accept, then SC can determine the buffer.

The results from application of the approach in terms of  $F$  on an absolute scale are shown in Fig. 4.2.2.1. On the Y-axis is the allowable probability (set by managers) of exceeding the LRP in a single year. One suggestion in the sub-group was that, in the absence of other information, one could use  $P^* = 0.22$ , which is equivalent to a probability of 1% of exceeding the LRP for three years in a row. On the X-axis is the CV of achieving the TRP (target  $F$ ). This CV recognizes that if  $F$  is set at (for example) 0.2/yr, the realized  $F$  will not be exactly 0.2/yr. The figure also reflects the LRP estimated by fitting a production model;  $F_{msy} = 0.226$ , and its estimated CV = 0.21. The contours reflect the suggested  $F$  in the coming period. For example, if the CV of achieving the buffer  $F$  (CV of TRP) is thought to be 40% (0.40 on the X-axis) and  $P^*$  is set at 0.20 (Y-axis), the suggested  $F$  in the next period is very close to (the contour of) 0.16/yr.



**Fig. 4.2.2.1.** Results of REPAST for 3LNO yellowtail flounder, expressed in terms of fishing mortality on an absolute scale.

Fig. 4.2.2.2 shows the same information in terms of relative  $F$ , i.e.  $F$  relative to the estimate of  $F$  at present (2002 in the example). This is generally how the results of the ASPIC production model are presented in the 3LNO yellowtail assessment. This shows that for the same values of  $CV(TRP)$  (40%) and  $P^*$  (0.2), the suggested  $F$  is 1.05 times the present  $F$ .



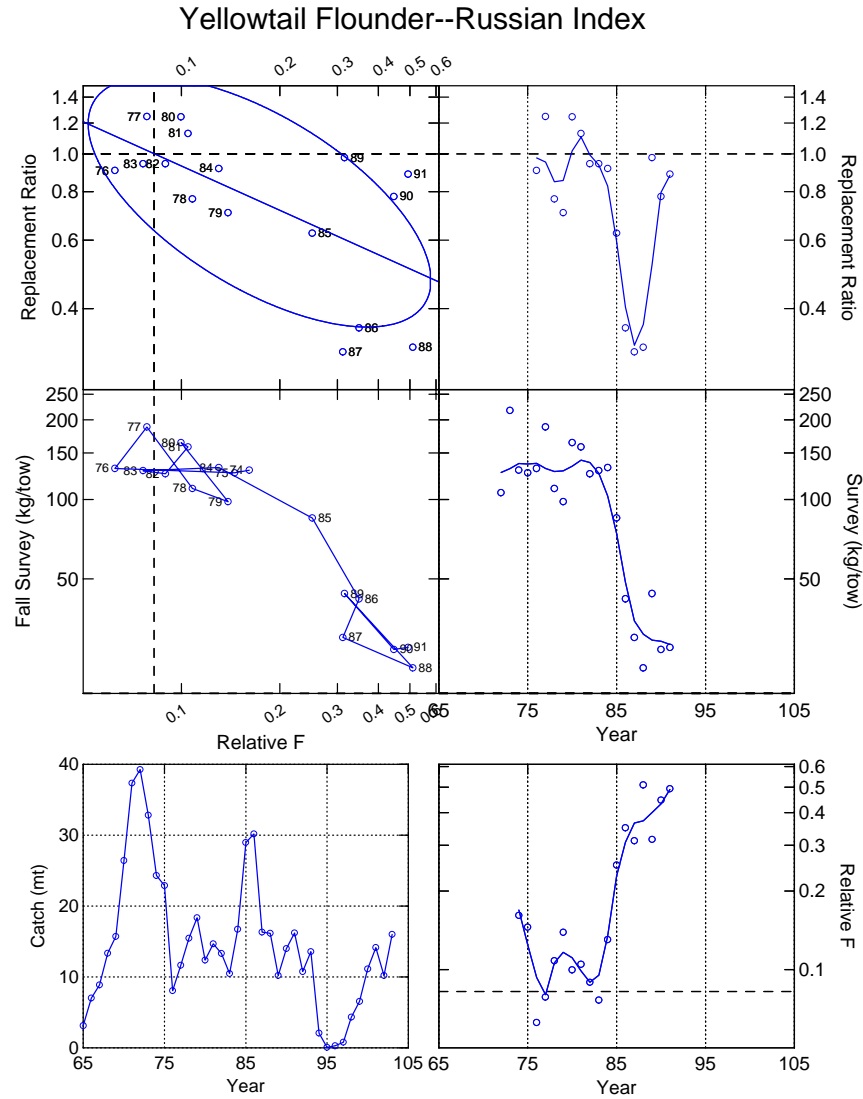
**Fig. 4.2.2.2.** Results of REPASt for 3LNO yellowtail flounder, expressed in terms of fishing mortality on a relative scale.

#### *Application of Replacement Ratio Index Methodology*

The replacement ratio methodology (see Section 3.4) was applied to the yellowtail flounder landings and various relative abundance indices based on trawl surveys (kg/tow) for the period 1972-2003. For this species the replacement ratio was defined as the ratio of the current index value to a four-year moving average of the index. Relative  $F$  was defined as the ratio of current catch to a three-year average of index stock size. Using these definitions, the replacement ratio was estimable for 1976-2002 and relative  $F$  was estimable for 1974-2002 for at least some of the index series. Survey indices considered were the Russian survey 1972-1991, Canadian Spring (1984-2003) and Fall Survey (1990-2003). The Canadian Spring survey and Russian surveys overlapped between 1984 and 1992 which allowed for the development of a statistically significant regression between these two indices. This allowed for the provisional examination of a combined Russian and Canadian Spring Trawl Index, expressed in units of the Campelen-Adjusted trawl index. Despite the differences in the durations of the available time series, the population responses are consistent across all abundance metrics (Fig. 4.2.2.3-5). Reduction in fishing mortality rates had a strong positive effect on population density and growth rate. The Russian survey covers a period in which relative  $F$  increased continuously and abundance declined consistently (Fig. 4.2.2.3). The spring Campelen index overlaps with the period of decline and traces the rapid recovery between 1993 and 1998 (Fig. 4.3.3.4). Recent fishing mortalities appear to be stable or gradually increasing in the vicinity of the relative  $F$  at replacement, and the population appears to be stable. The combination of both indices (Fig. 4.2.2.5) provides a clear indication of population decline and rebuilding in response to changes in relative  $F$ . Results suggest that relative fishing mortality

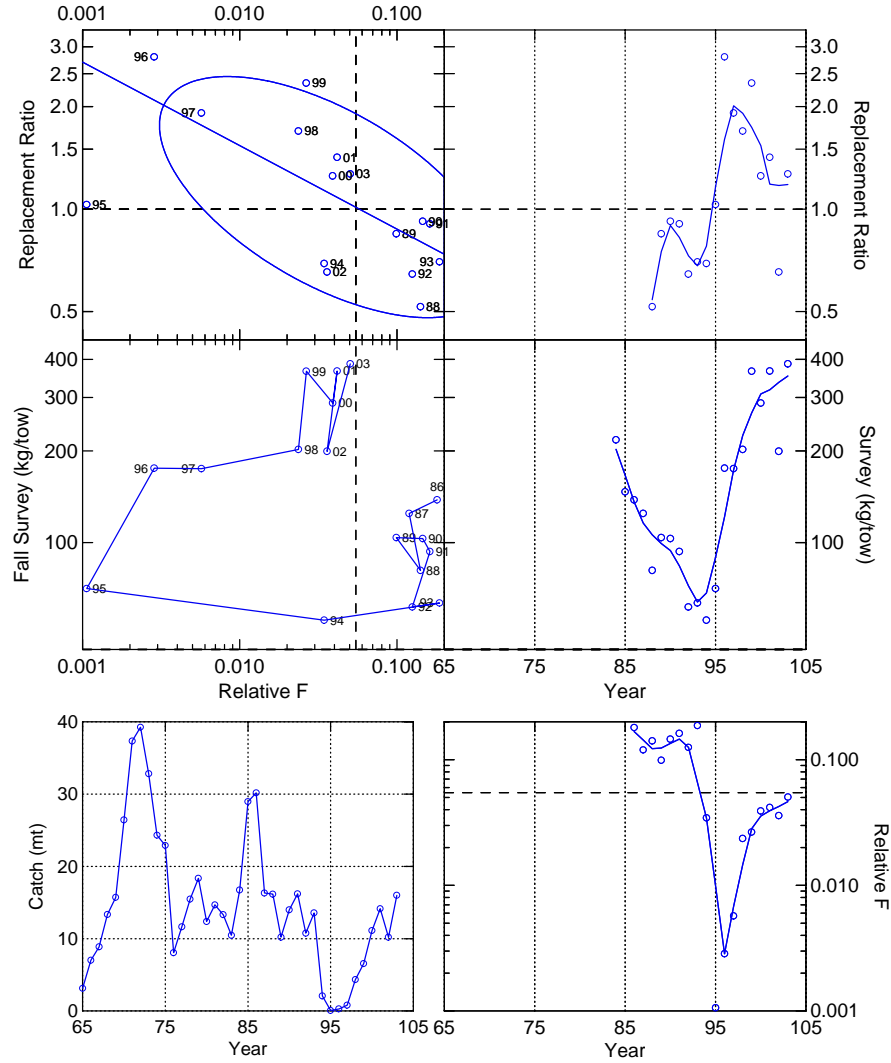
rates significantly greater than 0.05 are likely to cause the population to decline. Application of the replacement ratio methodology provides confirmatory results to the production model results. In instances where parametric models are appropriate, the replacement ratio method can be used to confirm results and provide additional insights into population responses. When parametric models do not fit the data well, the replacement ratio methodology can be used to identify possible causes of model miss-specification.

Finally, the sub-group considered ways to define  $B_{lim}$  for this stock in the absence of age structured models and related SSB-R data. It was thought that the biomass giving production of 50% of MSY might be an appropriate  $B_{lim}$ ; under the Schaefer model, this is 30% of  $B_{msy}$ . At its lowest observed point, in 1993-95, the biomass of 3LNO yellowtail was estimated from ASPIC to be between 22 and 29 % of  $B_{msy}$ . Although the stock recovered quickly from this level, there were mitigating circumstances, such as the presence of good recruitment, and a moratorium on fishing which led to 4+ years of much reduced catch. Nonetheless, it appears that 30%  $B_{msy}$  may be a reasonable proxy for  $B_{lim}$  for this stock, noting that the units of  $B_{lim}$  would be total biomass, and not SSB. It was noted that the properties of 30%  $B_{msy}$  are not really known, or whether or not it defines a point of “serious harm”. One idea would be to look at 30%  $B_{msy}$  from stocks where SR based LRP are available, and see how 30% $B_{msy}$  compares (e.g. with 50%  $R_{max}$ ). This could be examined for a number of stocks (3LNO plaice was suggested as a SC example). Another approach considered by the sub-group was to define  $B_{lim}$  as the biomass from which the stock could grow to  $> B_{buf}$  within 1 generation (Mohn and Chouinard, 2004 MS).

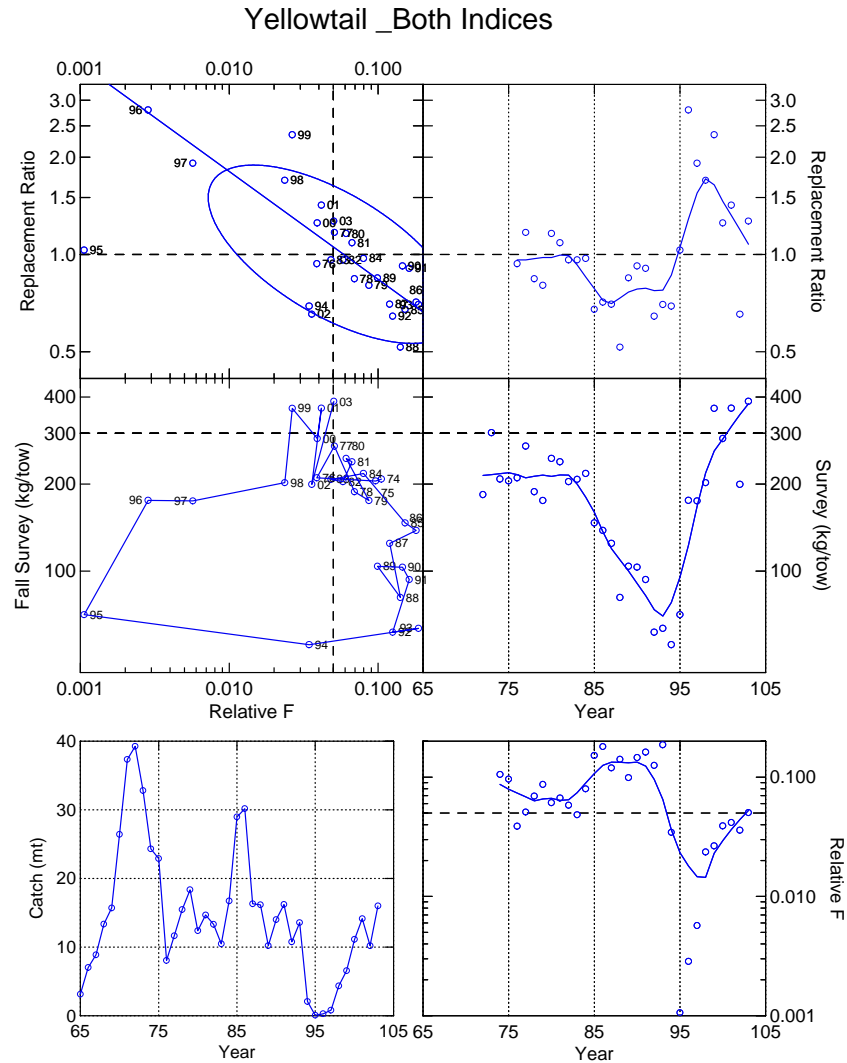


**Fig. 4.2.2.3.** Six panel plot for yellowtail flounder depicting trends in relative biomass, landings, relative fishing mortality and replacement ratios for the Russian survey index. Horizontal dashed lines (---) represent replacement ratios in the top two panels and the replacement F in the lower right panel. Smooth lines represent Lowess smooths (tension = 0.3). The confidence ellipse in the top left panel has a nominal probability level of 0.68. The regression line in the top left panel is a robust regression using bisquare downweighting of residuals.

## Yellowtail Flounder--Canada, Compelen Survey



**Fig. 4.2.2.4.** Six panel plot for yellowtail flounder depicting trends in relative biomass, landings, relative fishing mortality and replacement ratios for the Canadian spring Compelen survey index. Horizontal dashed lines (---) represent replacement ratios in the top two panels and the replacement F in the lower right panel. Smooth lines represent Lowess smooths (tension = 0.3). The confidence ellipse in the top left panel has a nominal



**Fig. 4.2.2.5.** Six panel plot for yellowtail flounder depicting trends in relative biomass, landings, relative fishing mortality and replacement ratios for a combined Canadian spring Compelen survey index and Russian survey index. Horizontal dashed lines (---) represent replacement ratios in the top two panels and the replacement F in the lower right panel. Smooth lines represent Lowess smooths (tension = 0.3). The confidence ellipse in the top left panel has a nominal probability level of 0.68. The regression line in the top left panel is a robust regression using bisquare downweighting of residuals.

#### References

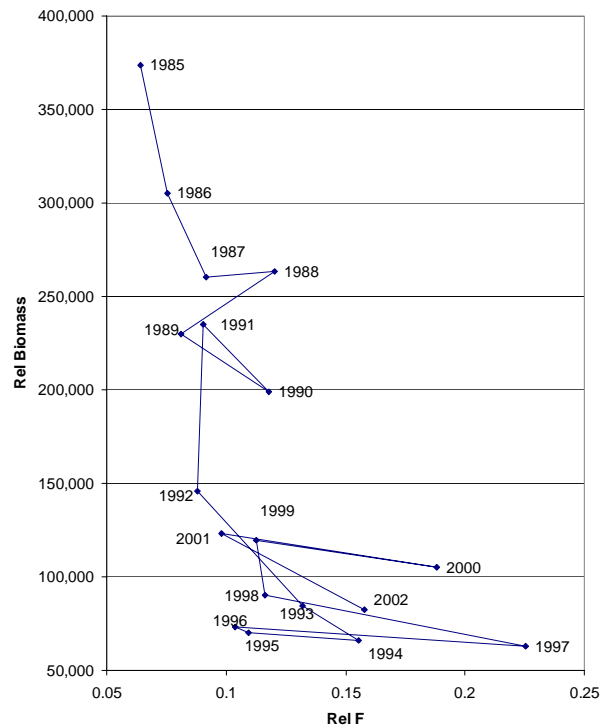
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#### 4.2.3. Divisions 3LNO Thorny skate (Sub-group leader – Dave Kulka)

The sub-group looked at several options for estimating LRPs from staged survey data and commercial catch information. Such analyses for this species are constrained by the lack of age-disaggregated data. However, data from the catch (relatively reliable from the mid-1980s following the start of the directed fishery) and survey biomass (from the early 1970s) provide information that can be examined in the context of a production model and a segmented regression approach. As well, stage based analyses, namely recruitment in relation to the spawning stock component is possible.

##### *Relative F/Biomass*

Inspection of a plot of Relative F to Relative Biomass (Fig. 4.2.3.1) shows a rapid decline in Relative Biomass at Relative F values of 0.15 or less, suggesting that sustainable levels of Relative F will be lower than this value.



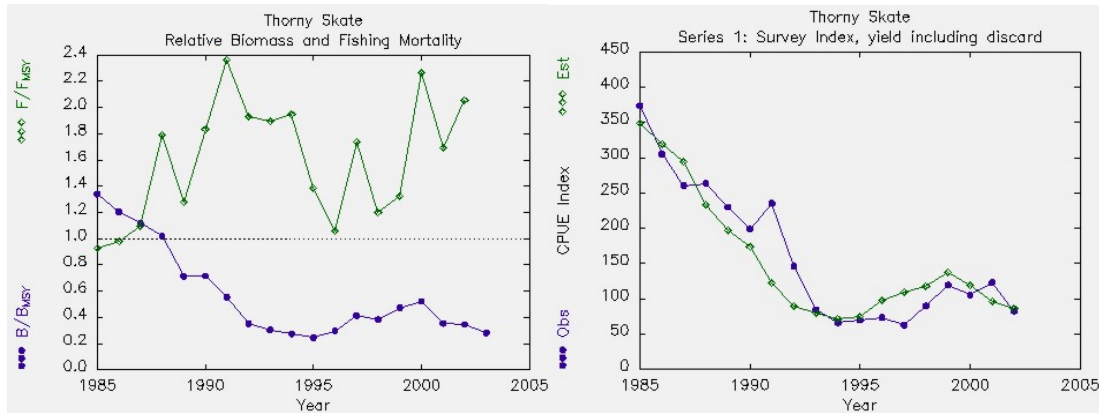
**Fig. 4.2.3.1.** Relative Biomass (total population) of thorny skate in relation to Relative F (Catch/Biomass).

##### *Surplus production*

To explore the feasibility of using a surplus production model for this stock, catch and biomass history were modeled using ASPIC (Prager, 1994). ASPIC provides estimates under a non-equilibrium Schaefer model. Data comprised series of catch and relative biomass from spring surveys, 1985-2002.

Estimates of biomass relative to  $B_{msy}$  and  $F$  relative to  $F_{msy}$  are shown in Fig 4.2.3.2. If  $F_{msy}$  is the LRP in terms of fishing mortality rate, the stock is estimated to have been exploited in excess of its LRP since the late-1980s. As a consequence, the stock biomass is estimated to have been below  $B_{msy}$  since about that time.





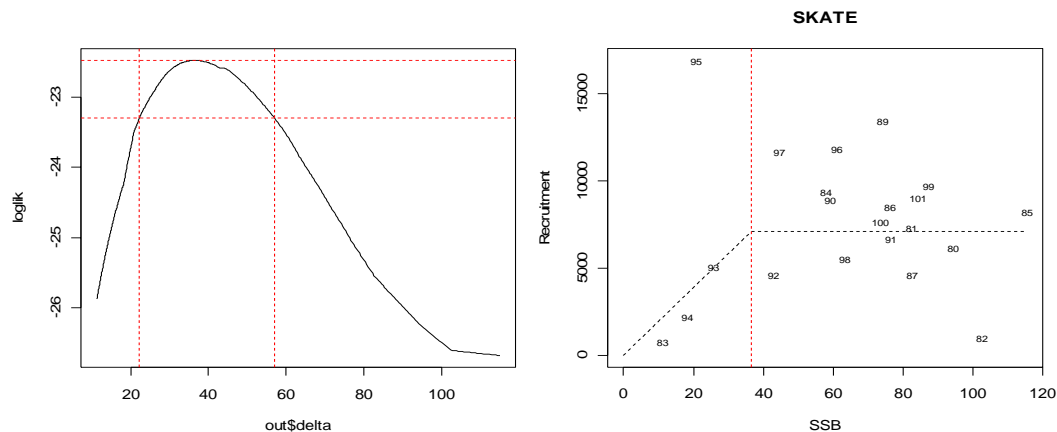
**Fig. 4.2.3.2.** Left panel: Relative biomass ( $B/B_{msy}$ ) and fishing mortality ( $F/F_{msy}$ ). Right panel: Observed survey index (relative Biomass/1000, blue line) and model fit (green line).

In Fig. 4.2.3.2 (right), the fit of the model to the observed index of relative abundance (labeled CPUE Index) is shown. The model seems to capture the major features of the dynamics of this stock.

#### *Segmented regression*

SSB (mature males and females) was calculated by applying the parameters of the length/weight relationship from Spanish surveys to the length distributions of the Canadian surveys. The maturity ogive for females (Del Rio, 2002) was applied. R was calculated from Canadian survey data, considering all individuals smaller than 19 centimetres as age 1.

The segmented regression fit is statistically significant at the 95 % level ( $p$  value = 0.0018), and the model explains 25% of variability in recruitment (coefficient of determination). Maximum likelihood estimate of the change point, the SSB at which recruitment begins to become impaired with decreasing SSB, is 36 500 tons, and the 80% profile likelihood confidence interval is given by 22 250 tons and 57 000 tons (Fig. 4.2.3.3). The LRP corresponding to 50% $R_{max}$  from the segmented regression, SG50, is somewhat less than 20,000 t SSB.



**Fig. 4.2.3.3.** Segmented regression results for thorny skate.

The Serebryakov method (SB50/90) was applied to the same data, and the resulting estimate for the LRP was about 40,000 t (Fig. 4.2.3.4).

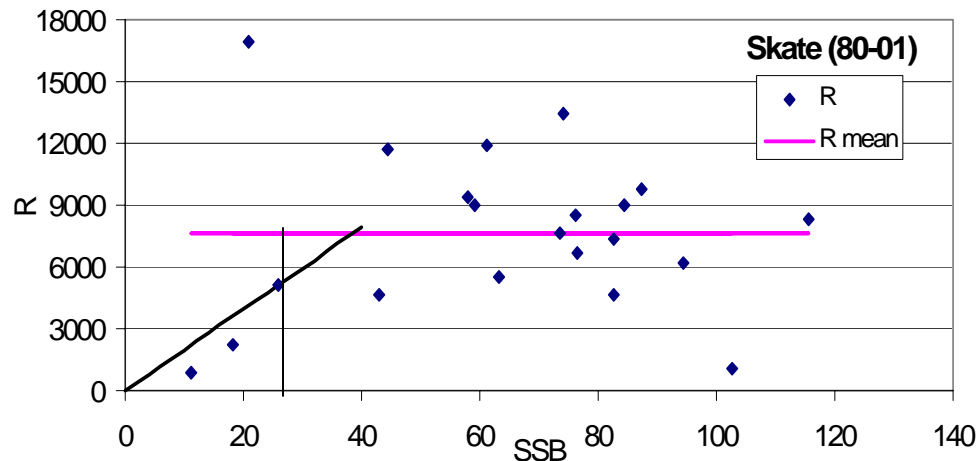


Fig. 4.2.3.4. Serebryakov SB50/90 plot for thorny skate.

#### Replacement ratio method

The replacement ratio methodology was applied to the thorny skate catch (landings + by-catch) and Canadian Research Trawl survey index data (kg/tow) for the period 1985-2002. The replacement ratio was defined as the ratio of the current index value to a five-year moving average of the index. Relative F was defined as the ratio of current catch to a two-year average of index stock size. Using these definitions, the replacement ratio was estimable for 1990-2002 and relative F was available for 1986-2002.

Catches declined consistently between 1985 and 1995, but have increased since 1996. Survey indices followed a similar pattern of decline and increase through 2002. The survey index declined markedly in 2003. Relative F increased consistently between 1985 and 1997 but has declined since then. The replacement ratio declined through 1995, then increased above 1.0 between 1998-2001. In 2002 the replacement ratio fell below 1.0. The relationship between replacement ratio and relative F is poorly specified and suggests an improbable positive correlation ( $r = 0.2385$ ). Randomization tests results suggest that the probability of obtaining a correlation higher lower than 0.2385 is 0.993.

Causes for the improbable slope are unknown, but it appears that additional work on the number of smoothing terms for relative F and replacement ratio are required. One difficulty with this species is the lack of life history information which in general can allow for more refined definition of the replacement ratio. Difficulties in interpretation of replacement ratio for thorny skate preclude its application without further work. In particular it would be useful to extend the historical time series of catch to be consistent with the available survey data. In addition it would be helpful to review the conversion factor for thorny skate associated with the change in survey gear between the Engel and Campelen trawl gear in Canadian RV surveys. As the replacement ratio is dependent on the change in survey values over time, the replacement ratio may be sensitive to the scale of the change in gear type conversions.

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### 4.3. Discussion of case studies

#### 4.3.1. SR relationships

The estimation of spawning stock and recruitment and the relationship between these two quantities is central to the determination of LRPS for stocks for which such estimates can be obtained. The SG gave this topic considerable attention with special reference to the Greenland halibut case study. For stocks for which there is an accepted age-disaggregated assessment of exploitable population size, it should be possible to compute spawner biomass and recruitment provided the catches at younger and older ages are known, estimates of proportion mature at age are available and an appropriate assumption about natural mortality ( $M$ ) can be made. In some cases this may require projecting cohorts beyond the age range for which there are reliable survey and catch at age data and there may be reasons why such projections are considered to be unreliable (for example a change in  $M$  or unknown growth and maturation beyond a certain age, senescence beyond some age).

The use of a plus group in SPAs may be considered best practice in assessments where the age determination is considered to be unreliable beyond a certain age or where, where the estimated number in the catch at age matrix is low with unreliable numbers at age occurring in older age groups. There may be considerable impact on the way in which the plus group is estimated on the determination of SSB and this may influence the SR scatter. This is particularly the case with respect to the Greenland halibut case study where the plus group occurs within the age range in which fish are maturing. Where a plus group is used, it would be useful to evaluate different plus group options to determine the impact on the SPA and the SR scatter. This may be informative about the kind of selectivity pattern that should be applied to the plus group in the SPA. The  $F$  applied to a plus group may have a large impact on the estimate of SSB, and this needs to be carefully evaluated in the assessment. The constraint on the last true age is commonly assume to be the average of some number of preceding ages, thus not allowing for a domed shaped selectivity pattern to extend to older ages within the age range influenced by the constraint.

The report of the ICES Study Group on Precautionary Reference Points For Advice on Fishery Management (ICES CM 2003/ACFM:15) provides examples of 6 characteristic SR scatter types. The SG considered the case where the SR relationship shows only a negative linear decrease in  $R$  with increasing SSB, despite the fact that the stock has traversed a wide range of SSB (i.e. no compensation). This case raises questions regarding the reliability of the assessment. Explanations for such situations include recruitment coming from outside the stock area or over-estimation of the decline that has occurred in SSB. The case where there is zero slope in the SR relationship in a situation with a wide range of SSB has been traversed might also be a concern. Recruitment overfishing may occur at a lower biomass than has been observed but the possibility should be considered that the estimate of spawner biomass or recruitment from the SPA/VPA is in error.

Among other factors which could effect the ability to detect a SR relationship, skipped-spawning, which is known to occur in some groundfish populations (Federov, 1971; Junquera, and Zamarro, 1994; Bowering, 1999) is also an important consideration in interpreting SR patterns in that the SSB may be effectively reduced. If this is a function of age then this could impart spurious pattern into the data. The SG acknowledges the work of ICES SG GROMAT and the NAFO WG on Reproductive Potential, and considers their deliberations to be very important in the determination of LRPs and the implementation of the PA.

#### 4.3.2. Life history considerations

Life history considerations are extremely important in the selection of limit reference points, developing harvest control rules and implementing the PA. Slow-growing, late maturing species are particularly vulnerable to overfishing. Such populations are likely to decline quickly if over-harvested and take a very long time to recover. The SG gave consideration as to whether  $B_{lim}$  and  $F_{lim}$  should be differently determined for such populations, with particular reference to the Thorny Skate case study. In this case study there is a scarcity of information on life history in terms of growth, maximum age and fecundity. Information on these aspects of the biology would add significantly to the interpretation of the data with regard to determining LRPs.

The SG considered whether or not  $30\%B_{msy}$  and  $F_{msy}$  would be considered useful as LRPs for skate type (K-selected) species. Tentative analyses on the Div. 3LNO thorny skate stock were considered.  $F_{msy}$  was estimated to

be about 0.06. Under the assumptions of the Schaefer model, the intrinsic rate of natural increase of the population ( $r$ ) is double  $F_{msy}$  or 0.12. If this is exponentiated it gives an annual population growth rate of 10%. This is in keeping with results from other cartilaginous species such as sharks and dogfish. Although this is a very low population growth rate, the SG felt that if the Schaefer model holds for such species, there was no compelling reason to not consider  $30\%B_{msy}$  and  $F_{msy}$  as LRPs for these stocks.

#### 4.3.3. When to use SPR for determining LRPs

The SG considered that when a SR relationship or a production relationship cannot be determined from the available data, consideration should be given to SPR analysis as a means of determining  $F_{lim}$ . The determination of the appropriate %SPR for use as an  $F_{lim}$  depends on the biology of the population. For some stocks 35%SPR may be too low and values of 40% or 50% may be more appropriate. Although this approach provides a useful way to scale the  $F$  to the biology of the species, it is not easy to link it to sustainable  $F$  levels equivalent to  $F_{msy}$ . In some cases %SPR of 40% has been found to be unsustainable. It was noted that, for the Greenland halibut case study, current %SPR is tentatively computed by the SG to be about 5%. Clearly this is not precautionary but the point at which it would be appropriate to consider that serious harm has been done is not clear. It was noted that %SPR would be very sensitive to changes in stock productivity such as an increase in  $M$ . Despite these shortcomings, %SPR provides an approach that can be applied to stocks when other analyses are not possible. %SPR of 35% should be used as a default  $F_{lim}$  for such stocks in the absence of meta analysis considerations or other considerations to suggest it should be higher or lower.

#### 4.3.4. When to apply the replacement ratio method

The SG considered that where possible an SPA-SR approach or a production model approach would be used preferentially over the replacement ratio. RRM cannot determine a  $B_{lim}$  - it has to be provided externally. In such cases the replacement index approach can provide a proxy for  $F_{lim}$  and may constitute a useful diagnostic tool. In cases where there is little or no evidence of compensation in an SR plot or in a production analysis, and the stock is at a low size where the relationship between  $R$  and  $SSB$  is expected to be linear, the replacement ratio will be most applicable. In this approach  $B_{lim}$  has to be externally specified but the relative  $F$  at which the replacement ratio is 1 can be informative regarding  $F_{lim}$ . For stocks where the SR relationship or the production relationship cannot be determined, 50% of the relative  $F$  at replacement ratio=1 should be used as a temporary proxy for  $F_{lim}$ . It can also provide short-term information on directional change in fishing mortality and catch.

#### 4.3.5. When should spatial aspects be considered in the context of LRPs?

The SG considered the circumstances under which spatial patterns of distribution would be a factor in the determination of limit reference points. For species in which there is no dispersal stage or very limited dispersal, of the early life history stages, then a metric of spatial pattern has particular importance in determining and LRP. Thorny skate fit the definition of a species with limited early stage dispersal, although there are considerable ontogenetic and seasonal patterns to the spatial distribution. Skate are essentially a two dimensional species and can't live "shoulder to shoulder" or wing to wing. When changes in pattern occur that are consistent with the McCall Basin Model (MacCall, 1990), then the reduction in spatial distribution will over-estimate the reduction in population size. This over-estimation will be greater should hyper-aggregation occur (density in the preferred habitat increases with decreasing population size). A complicating factor is that habitat in fish populations is highly variable spatially as a consequence of changes in spatial patterns of temperature and other physical and biological factors. The SG considered that, bearing in mind the wide prevalence of the Basin model type distribution, a decrease in the area of distribution of more than 75% would be consistent with serious harm. There are other metrics such as the Gini index and the design-weighted area of occupancy which can provide metrics that are more applicable to determining when serious harm has been done (Smedbol *et al.*, 2002). These should be used preferentially over raw computations of spatial extent where possible and work should be undertaken to develop appropriate  $B_{lim}$  proxies from these metrics.

#### 4.3.6. Evaluating LRPs through HCR simulations

The SG considered that it was highly desirable to evaluate LRPs and other reference points such as target and buffer reference points, through simulations in which the reference points are linked with HCRs. Such simulations need to

taken into account uncertainty in estimates of the LRP and in the state of the stock. Both estimates are updated in each year (or some other time step) of the simulation (see Section 3.8.5, Fig. 3.8.5.1).

Production models are easier to test than SPA-based models and the SG suggests that NAFO start by taking the Div. 3LNO Yellowtail stock as a test case for developing and testing HCRs, making use of the LRPs defined in this report. HCR simulations will be particularly informative regarding the propagation of uncertainty and highlight situations such as when  $F$  is estimated with so high a CV that there is a problem of too high a probability of being on the wrong side of the limit even when in Safe Zone. For example, the target reference point of  $2/3F_{msy}$  accepted by FC might result in a greater than 10% risk of falling below  $B_{lim}$ . Such an outcome would indicate an inconsistency in the LRP and acceptable risk levels, given the accuracy and precision of the assessment - either the LRP is too high, the risk tolerance too low, or the assessment is too uncertain. It should be noted that using ratio estimators would be advantageous in controlling for at least some of the uncertainty. In some assessments there could be so much uncertainty that there is no Safe Zone within the decision space of the PA framework. Although Buffers are not required to implement HCRs under the 2003 NAFO framework, these can be output as part of the HCR evaluation process if managers provide desired risk levels. Such simulations would also indicate the effect of lags in the system and illustrate that, for example, fishing at  $F_{msy}$  in a fluctuating environment will result in considerable overshooting MSY in some circumstances.

There are some similarities to the problems that are being evaluated with respect to LRPs and those associated with control theory and dynamic programming. Knowledge available within these disciplines should be appropriated where possible.

#### 4.3.7. Conclusions based on examination of the case studies

1. The SG considered the case where the SR relationship shows only a negative linear decrease in  $R$  with increasing SSB or where there is zero slope in the SR relationship and the stock has traversed a wide range of SSB. Such situations should raise concerns that the results from SPA/VPA may be in error.
2. The SG considered whether or not  $30\%B_{msy}$  and  $F_{msy}$  would be considered useful as LRPs for skate type (K-selected) species. The SG felt that if the Schaefer model holds for such species,  $30\%B_{msy}$  and  $F_{msy}$  as LRPs would be appropriate for these stocks.
3. The SG considered that when a SR relationship or a production relationship cannot be determined from the available data and RRM cannot be applied, consideration should be given to SPR analysis as a means of determining  $F_{lim}$ .  $F$  giving %SPR of 35% should be used as a default  $F_{lim}$  for such stocks in the absence of meta analysis considerations or other considerations to suggest it should be higher or lower.
4. The SG considered that, where possible, an SPA-SR approach or a production model approach would be used preferentially over the replacement ratio method (RRM). The RRM cannot determine a  $B_{lim}$  - it has to be provided externally. For stocks where the SR relationship or the production relationship cannot be determined, 50% of the relative  $F$  at replacement ratio=1 should be used as a temporary proxy for  $F_{lim}$ .
5. The SG considered the circumstances under which spatial patterns of distribution would be a factor into the determination of limit reference points. For species in which there is no dispersal stage or very limited dispersal, of the early life history stages, then a metric of spatial pattern has particular importance in determining a LRP. The SG considered that, bearing in mind the wide prevalence of the Basin Model type distribution, a decrease in the area of distribution of more than 75% would be consistent with serious harm.
6. The SG considered that it was highly desirable to evaluate LRPs and other reference points such as target and buffer reference points, through simulations in which the reference points are linked with HCRs.

#### References

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## 5. A Rule-based expert system approach to determining limit reference points

A rule-based expert system approach provides one way of capturing the knowledge base that comprises current best scientific practice for deciding on the appropriate avenue for determining limit reference points. The expert system can be built in the form of chains of questions, rules and decisions. The answers to the questions trigger “if then” rules in order to reach a decision. Explanations for the questions and the decisions can also be incorporated into the system, deepening the knowledge base. For such decision-support systems to be useful to stock assessors, the expert reasoning comprising best scientific practice must be captured in sufficient detail to allow it be understood and implemented in, for example, a June NAFO SC meeting. The system can incorporate both factual knowledge (e.g. are there more than 20 years of data?) and heuristic knowledge (e.g. outcomes of experiments, model estimates and rules of thumb that seem to work). The system should provide a transparent and logical account of the reasoning applied in reaching each decision. This can be incorporated in terms of a “trail” or “trace” feature in the expert system. The approach is particularly useful when multiple considerations have to be taken into account in reaching a decision, expertise is limited, there are time and pressure constraints, and the reasoning for a decision needs to be captured.

The Study Group considered that a forward chaining rule-based expert system could provide a good way of assembling existing expert knowledge related to the approach to adopt for obtaining a limit reference point for a range of conditions of data richness, life history patterns and biological relationships. Such a system attempts to mimic the process an actual group of experts would use to decide on appropriate ways for determining SSB and F limit reference points or some other metric of serious harm if appropriate. A member of the SG (Rivard) updated a draft schematic of the expert system rule-based approach through the course of the meeting (Fig. 5.1). This schematic is illustrative of the approach. Some of the rules and decisions described in it form part of the recommendations of this report, whereas other rules and decisions were discussed and not necessarily adopted in the end by the SG.

The SG thought it useful to present to SC a simpler working version of the expert system that is consistent with the final conclusions and recommendations of the report (Fig. 5.2). While more limited in scope than Fig. 5.1, it provides a basis for deciding on the appropriate way of computing an LRP that can be immediately implemented. The expert system can be updated as the knowledge base on which it is depends deepens and broadens in scope.

### *Description of simplified expert system*

The expert system (Fig. 5.2) consists of questions, rules, and decisions. These are currently arranged in 5 branches (0-4). Question boxes are blue, decision boxes are pink and boxes that link to another branch in the system are yellow. The left arrow reflects a “yes” answer to the question and a right arrow reflects a “no” answer. Branch 0 is an initial branch to determine which analysis approach is appropriate to the available data. Branch 1 queries whether compensation can be determined from SR data. If it can, then  $F_{lim} = F_{msy}$  and  $B_{lim} = SSB$  corresponding to a model estimate of 50% of the predicted maximum recruitment.

If no compensatory SR relationship can be determined from the data, then a link is made to Branch 2. If a production model is found to provide a valid fit, then  $F_{lim} = F_{msy}$  and  $B_{lim} = 30\%B_{msy}$ . If no valid production model fit is obtained, then a link is made to Branch 3. This branch determines whether some of the other approaches considered by the SG can be applied when no compensatory SR or production relationship can be determined. If the SR scatter is considered usable despite the inability to establish a compensatory response, then  $F_{lim} = F_{med}$ . If there are not SR estimates, or the estimates are considered to be unusable, then methods using catch and survey data may be appropriate, such as RRM. If RRM can be applied, then  $F_{lim} = 50\%$  of the relative F at a replacement ratio of 1. If RRM cannot be applied, then the possibility of carrying out a spawner-per-recruit analysis should be explored. If this can be done the  $F_{lim} = 30\%SPR$ . If not, it is not possible to determine  $F_{lim}$  based on the available data for this

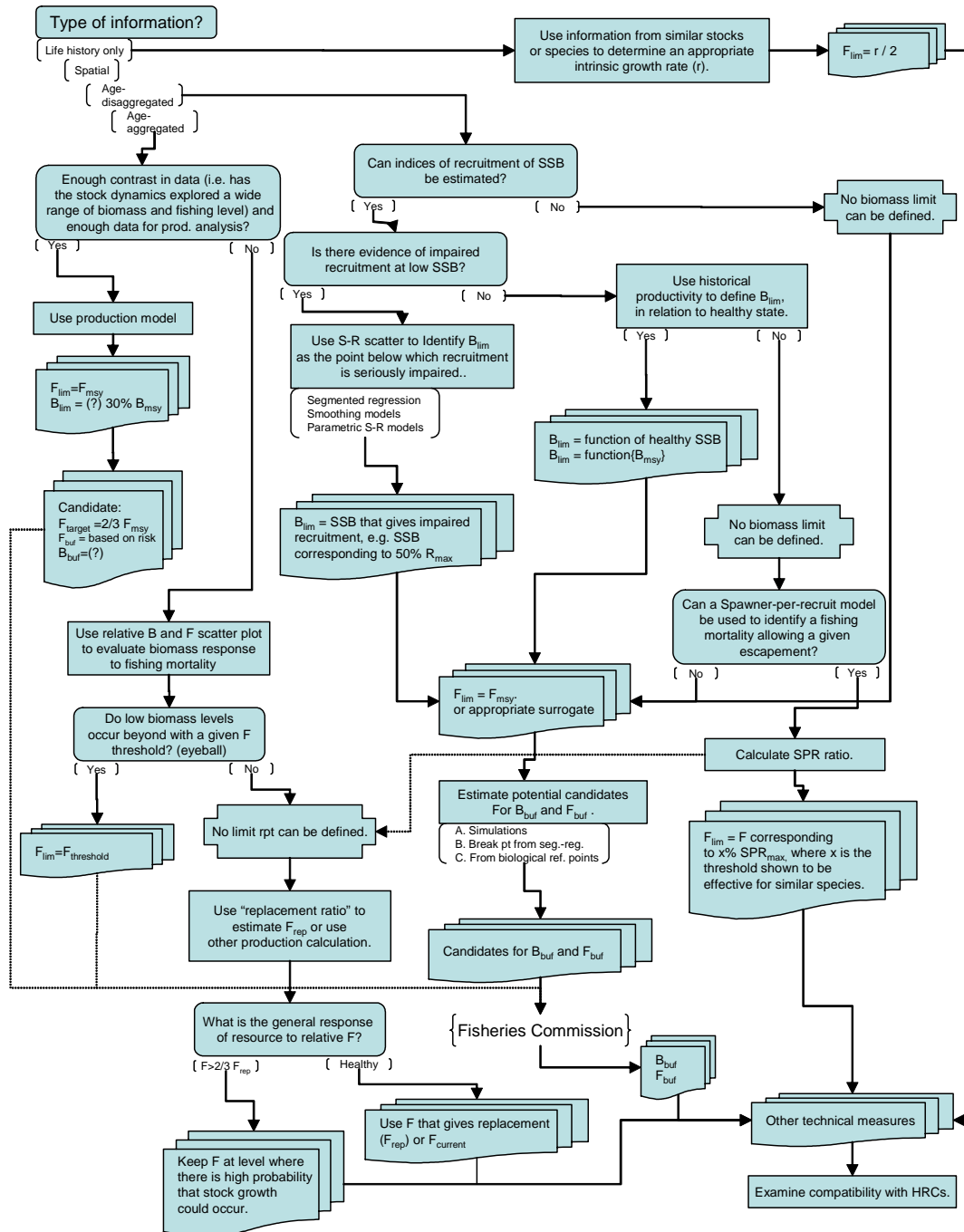
stock. It may still be possible to develop some useful guidelines regarding precautionary exploitation levels by analogy with better studied stocks with similar life history characteristics.

Once an outcome is obtained with respect to  $F_{lim}$ , Branch 3 of the expert system continues to see if a  $B_{lim}$  can be determined from the survey data based on the decline in a valid index. If the highest value of the index coincides with what is thought to be the unexploited state of the stock, then an 85% decline is considered to be an appropriate  $B_{lim}$ . If, on the other hand, the highest value of the index is consistent with when the stock is thought to have been fully exploited, i.e. at  $B_{msy}$ , then a 30% decline would be appropriate. This logic, based on the assumption of an underlying Schaefer production model, can be extended for other situations.

If there are no valid indices of stock size, it may be appropriate to consider changes in spatial distribution. This is explored in Branch 4. For populations with limited dispersal in the early stages, a decrease in the area of occupancy (1 or more animals) relative to greatest area of occupancy of 75% provides a proxy  $B_{lim}$ . This criterion is based on the assumption of a MacCall basin model-like distribution pattern and it may be desirable to develop spatial distribution proxies for  $B_{lim}$  that take into account more of the actual information on time changes in fish density of fish over the stock area if available.

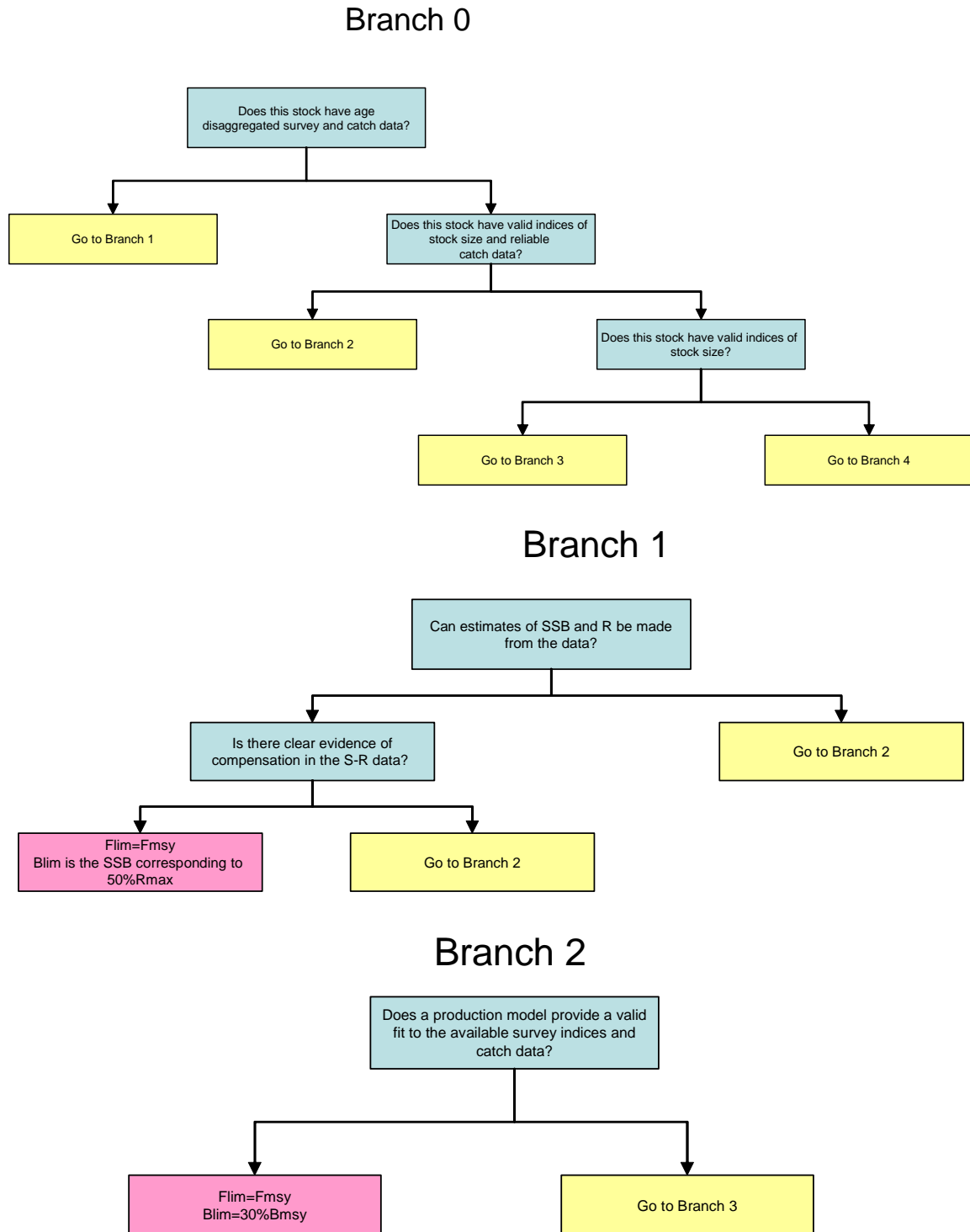
There are approaches that were considered by the SG (some of which are included in Fig. 5.1) that are not included in the simple expert system described in Fig. 5.2. The SSB from which the stock could recover to the “safe zone” in one generation under good productivity conditions was considered as a fallback approach, however this would require a fair amount of data and the approach is still under evaluation. A plot of  $F$  against SSB might be useful in some circumstances, and although this was discussed by the SG, it did not lead to clear rules regarding when and how it would be used. Lastly, the 2003 NAFO PA framework suggests that when SC is unable to compute the risk of a stock being below  $B_{lim}$ , FC may decide on an appropriate  $B_{buf}$  such that when the stock is estimated to be at  $B_{buf}$  there is a very low risk that it is below  $B_{lim}$ . Attempts to incorporate this into the rule-based system were made by the SG but it is not clear how to avoid circularity in the logic of linking  $B_{buf}$  and  $B_{lim}$ , and therefore no clear rules could be developed.

While the SG does not consider the current system to be a final product, it provides a structure that SC could consider using to capture the knowledge base constituting best scientific practice with respect to LRPs within NAFO. The expert system can be updated on an ongoing basis as methodology and thinking with respect to LRPs advance, and can thus stand as an ordered repository for current scientific knowledge. Expert system shells are available for encoding the logic within the schematic. These shells are particularly useful for ordering more complex systems and for capturing the “why” information related to rules and decisions. They also often have useful “trace” features show the logic path that was followed in reaching a decision. While it is in preliminary form, an attempt has been made to be consistent with the conclusions and recommendations of the SG and it is therefore recommended that SC consider making use of the expert system in its present form until better advice is provided to update and expand the expert system.



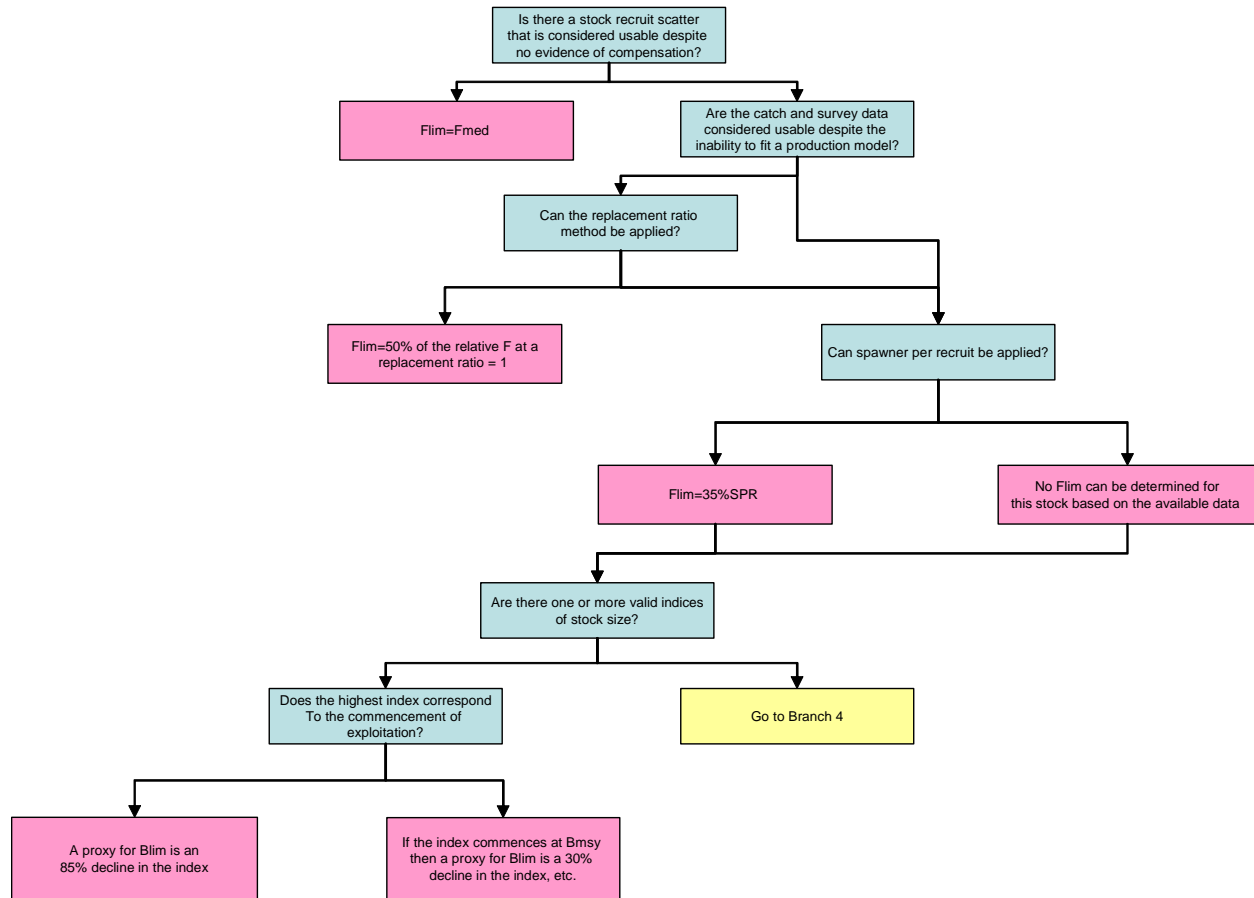
**Fig. 5.1.** Schematic used to describe a complex rule-based expert system reflecting the deliberations of the SG over the course of the meeting. While very useful for keeping track of the logic of the discussions at the SG meeting, the decision was made to implement a simplified version consistent with the final conclusions and recommendations of the SG.



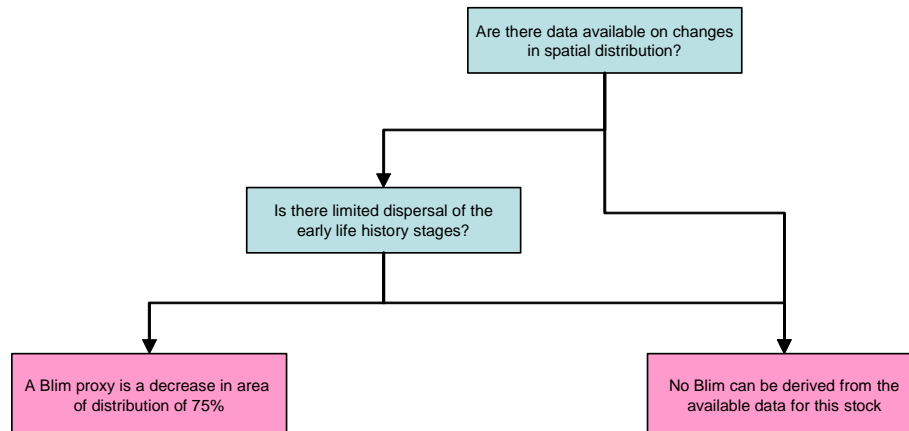


**Fig. 5.2.** A simplified expert system for determining LRP's consistent with the final conclusions and recommendations of the SG.

## Branch 3



## Branch 4



**Fig. 5.2 contd.** A simplified expert system for determining LRPs consistent with the final conclusions and recommendations of the SG.

## 6. Recommendations to Scientific Council regarding determination of LRPs for NAFO stocks

- 6.1  $F_{lim}$  should be accepted as a non-arbitrary definition of a fishing mortality which, if exceeded for a number of consecutive years, would constitute serious harm to the stock.
- 6.2 There should be only a very low probability of  $B_{lim}$  being transgressed when the stock is in the “Safe Zone”.  $F_{lim}$  should only be exceeded occasionally. The LRPs should be estimable and the estimates should be reasonably robust.
- 6.3 The SSB corresponding to 50% of the maximum recruitment ( $B_{50\% R_{max}}$ ) for stocks for which such estimation is reliable, should be considered to provide a definition of  $B_{lim}$  under current best practice.
- 6.4 The biomass giving production of 50% of MSY should be considered as an appropriate  $B_{lim}$  for stocks assessed using production models. Under the Schaefer model this is 30% of  $B_{msy}$ .
- 6.5 For populations which provide no clear indication of compensation in the recruitment or overall stock production function, there is no clear basis for defining a  $B_{lim}$ , and maintaining fishing mortality at a level sufficiently below the replacement fishing mortality when the stock is considered to be low becomes a primary concern. Under the circumstances where stock size is outside of the Safe Zone and no compensation is evident,  $F_{lim}$  should be taken to equal  $F_{med}$ .
- 6.6 When other methods cannot be applied, it may be possible to express  $B_{lim}$  in terms of the SSB for which there is no less than a 20% probability that the stock could recover to the “Safe Zone” (above  $B_{buf}$ ) in one generation under good productivity conditions.
- 6.7 For stocks where compensatory stock recruitment (SR) or production functions cannot be determined, the point at which a valid index of stock size has declined by 85% from the maximum observed index level should be used as a proxy for  $B_{lim}$ . If the highest index of stock size is equal to  $B_{msy}$ , then it would be consistent for  $B_{lim}$  to be 30% of that level. If the highest observed survey index is considered to be below  $B_{msy}$ , then this should be taken into account in a similar way.
- 6.8 Apparent evidence of regime shifts should be treated with caution and the implications should be examined. Invoking regime-shift changes as an explanation for changes in recruitment may not be precautionary in some cases.
- 6.9 The SG considered whether or not  $F_{msy}$  and 30%  $B_{msy}$  would be considered useful as LRPs for skate type species (K-selected). The SG recommends that, if the Schaefer model holds for such species,  $F_{msy}$  and 30%  $B_{msy}$  as LRPs be used for these stocks.
- 6.10 When a stock-recruitment (SR) relationship or a production relationship cannot be determined from the available data and replacement ratio method (RRM) cannot be applied, consideration should be given to spawner-per-recruit (SPR) analysis as a means of determining  $F_{lim}$ .  $F$  giving % SPR of 35% should be used as a default  $F_{lim}$  for such stocks in the absence of meta-analysis considerations or other considerations to suggest it should be higher or lower.
- 6.11 Where possible an SPA-SR approach or a production model approach would be used preferentially over the replacement ratio method (RRM) because the RRM cannot determine a  $B_{lim}$  (it has to be provided externally). For stocks where the SR relationship or the production relationship cannot be determined, 50% of the relative  $F$  at replacement ratio = 1 should be used as a temporary proxy for  $F_{lim}$ .
- 6.12 The SG considered the circumstances under which spatial patterns of distribution would be a factor in the determination of limit reference points. For species in which there is no dispersal, or very limited dispersal, of the early life history stages, then a metric of spatial pattern has particular importance in determining and LRP. A decrease in the area of distribution (presence/absence) of more than 75% should be considered to be consistent with serious harm.

- 6.13 LRPs put forward by the SG should be incorporated into HCR simulations. Div. 3LNO yellowtail should be selected as an initial case study.
- 6.14 It was agreed that the Scientific Council should continue to provide advice to FC on the adoption of Precautionary Approach in decision making and should make use of the best current scientific practice as outlined in this report, and encoded in the rule-based expert system provided, until better advice is provided to update the expert system.
- 6.15 The SG strongly urged that NAFO SC recommend to Fisheries Commission that the 2003 NAFO SC PA framework be endorsed and implemented by FC without further delay.

## 7. **Closure of Meeting**

The Conclusions (Sections 3.8.7 and 4.3.7) and Recommendations (6) were adopted by consensus in plenary. The Chair thanked all participants for their expert input throughout the meeting. In particular, three technical experts not usually associated with NAFO, Drs. Mike Armstrong, Paul Rago and Mike Prager were thanked for their generosity in freeing up time to attend the SG meeting and for providing stimulating input and new ideas. Dr. Prager was formally invited by the Chair of SC as an external, independent expert and deserved special recognition. The Chair thanked Bill Brodie for providing comprehensive rapporteur's notes throughout the meeting. Thanks were extended to the NAFO Secretariat for administrative support and providing a website for the SG. Lastly the Chair thanked the Co-Chair, Dr. Jean-Claude Mahé and the host agency, IFREMER Lorient, for local organization and providing exceptional hospitality and facilities throughout the duration. The Chair closed the meeting at 1630h on Thursday 20 April.

## APPENDIX I. AGENDA

### NAFO LRP Study Group, 15-20 April, 2004 IFREMER, Lorient, France

#### **Thursday 15 April**

9:00 am: Welcome, introduction, ToR, and housekeeping

10:00 am: Development of the Precautionary Approach framework within NAFO – the need for limits – Bill Brodie

10:30 am: Tea/coffee

11:00 am: Plenary Session on **PA Limits - Concepts, Estimation, Evaluation and Implementation**: participants are encouraged to submit working paper titles (extended summaries will be included in the report) and to make short (20 min) power-point presentations

12:30 pm: Lunch (to be ordered in daily, approx 12 Euros, including wine)

1:30 pm: Plenary Session on Concepts, Estimation, Evaluation and Implementation continues

3:30 pm: Tea/coffee

4:00 pm: Plenary Session on Concepts, Estimation, Evaluation and Implementation concludes – summary discussion

#### **Friday 16 April**

9:00 am: Plenary Introduction to case studies by species experts

2+3KLMNO Greenland halibut - Ray Bowering  
3LNO Yellowtail flounder – Bill Brodie  
3LNO Thorny skate – Dave Kulka

10:30 am: Tea/coffee

11:00 am: Plenary to discuss general approach and form case study teams

12:30 pm: Lunch

1:30 pm: Case study teams develop work plans and carry out analyses

3:30 pm: Tea/coffee

4:00 pm: Plenary - Case study teams report back on progress - discussion

#### **Saturday 17 April**

9:00 am: Case study teams continue work

10:30 am: Tea/coffee

11:00 am: Case study teams continue work

12:30 pm: Lunch

1:30 pm: Case study teams continue work

3:30 pm: Tea/coffee

4:00 pm: Case study teams continue work

### **Monday 19 April**

9:00 am: Plenary presentation and discussion of progress by case study teams

10:30 am: Tea/coffee

11:00 am: Plenary presentation and discussion of progress by case study teams continues

1:30 pm: Commence drafting meeting report (to be an SCS Document for presentation to Scientific Council in June)

### **Tuesday 20 April**

9:00 am: Plenary discussion and adoption of report (this is expected to take most of the day)

## **Terms of Reference**

At the Scientific Council Workshop on the Precautionary Approach held March-April 2003 it was noted that it is the responsibility of Scientific Council to calculate LRPs. Given that a number of approaches for LRPs have been discussed in the literature, it was recognized that there is a need to review the strengths and weaknesses of these alternative approaches and to make recommendations to Scientific Council on which are the most appropriate for defining LRPs. These recommendations are needed for stocks ranging from data-rich to data-poor and with a range of life-history parameters.

As a result Scientific Council recommended that a Study Group on the estimation of limit reference points be established. Peter Shelton (Canada) was named as a co-Chair with other co-Chairs to be selected, and the Co-Chairs explore with colleagues possible themes for a Study Group working session in 2004.

The following are the Terms of Reference for the Study Group:

1. Review the properties of alternative LRPs, including the ability to quantify risk, and determine strengths and weaknesses of various alternatives.
2. Provide guidance regarding the most appropriate approaches for stocks ranging from data rich to data poor and for a range of life-history strategies.
3. Provide example applications to Subarea 2 + Div. 3KLMNO Greenland halibut, Div. 3LNO yellowtail flounder and Div. 3LNO Thorny skate based on existing and recent biological, fisheries and survey data; recent stock assessments; and management measures. Other example stocks may also be explored.

**APPENDIX II. LIST OF PARTICIPANTS**

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### APPENDIX III. LIST OF ACRONYMS AND ABBREVIATIONS

ACFM	ICES Advisory Committee on Fisheries Management
ADMB	Auto-Differentiation Model Builder
ASPIC	Method by Prager for fitting a non-equilibrium stock-production model
B	Biomass, sometimes assume to be spawning stock biomass
BH	Beverton-Holt stock-recruit model
BH50	Spawning stock biomass corresponding to 50% of the maximum recruitment
Bbuf	Spawning stock biomass limit reference point
Blim	Spawning stock biomass limit reference point
Bloss	Lowest observed spawning stock biomass
Bpa	Spawning stock biomass precautionary reference point
Brecover	The lowest spawning stock biomass from which there has previously been a rapid and sustained recovery
CM	Caddy-McGarvey framework for setting a target reference point
CPUE	Catch per unit effort
CV	Coefficient of variation
CW	Case weight
EEZ	Exclusive Economic Zone
EU	European Union
F	Fishing mortality
Fbuf	Fishing mortality buffer reference point
FC	NAFO Fisheries Commission
Flim	Fishing mortality limit reference point
Fpa	Fishing mortality precautionary reference point
Fmed	F giving a replacement line in a stock-recruit plot corresponding to the median R/S
Fmsy	Fishing mortality corresponding to MSY
FAO	Food and Agricultural Organization
HS	Hockey stick model for stock-recruit data
HCR	Harvest control rule
ICES	International Council for Exploration of the Sea
IFREMER	French Research Institute for Exploitation of the Sea
LRP	Limit Reference Point
LHS	Logistic hockey stick model for stock-recruit data
LN	Lognormal
NAFO	Northwest Atlantic Fisheries Organization
NEFSC	Northeast Fisheries Science Center
NFT	NOAA Fisheries Toolbox
NOAA	National Oceanic and Atmospheric Administration
P	Production
PA	Precautionary Approach
PDF	Probability density function
R	Recruitment
REPAST	Statistical method by Prager for choosing a target reference point when a corresponding limit reference point is known
Rmax	Maximum recruitment predicted by a model
RRM	Rago's replacement ratio methodology
SB50/90	Spawning stock biomass corresponding to the intersection of the 50 <sup>th</sup> percentile of R and the 90 <sup>th</sup> percentile of R/S, based on the method of Serebryakov
SC	Scientific Council of NAFO
SG GROMAT	ICES Study Group on Growth and Maturation
SGRST	ICES Study Group on Review of Stocks
SPR	Spawner per recruit
SSB	Spawner stock biomass
STECF	ICES Scientific, Technical and Economic Committee for Fisheries
ToR	Terms of Reference
TRP	Target reference point
Var	Variance
WG	Working group