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SCIENTIFIC COUNCIL MEETING – MARCH/APRIL 2003

Report of NAFO Scientific Council Workshop on the Precautionary Approach to Fisheries Management

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REPORT OF THE SCIENTIFIC COUNCIL WORKSHOP ON THE PRECAUTIONARY APPROACH TO FISHERIES MANAGEMENT

31 March – 4 April 2003

Chair: R. K. Mayo   Rapporteur: T. Amaratunga

I. Opening

The Scientific Council Workshop on the Precautionary Approach to Fisheries Management was held at the Delta St. John's Hotel and Conference Centre, St. John's Newfoundland, Canada during 31 March-4 April 2003.

Representatives attended from Canada, Denmark (in respect of Faroe Islands and Greenland), European Union (France, Portugal and Spain), Russia and United States of America. The Executive Secretary and the Deputy Executive Secretary were in attendance.

Scientific Council Chair, Ralph Mayo welcomed everyone to St. John's and to this Workshop. Special appreciation was extended to Canada, and in particular to Science, Oceans and Environment Branch, Northwest Atlantic Fisheries Science Centre for hosting this meeting and providing the great facilities along with a state-of-the-art wireless LAN system.

The Chair took the opportunity to welcome the new Executive Secretary, Johanne Fischer, and express his pleasure to see her attend this meeting.

The Deputy Executive Secretary, Tissa Amaratunga was appointed rapporteur, noting contributors and Designated Experts will summarize their presentations to the meeting.

The Agenda was adopted and the Terms of Reference as described for this meeting by the Scientific Council at its meeting in 16-20 September 2002 (see Appendix 1) were reviewed. The Chair noted the overall Precautionary Approach (PA) will be addressed at the plenary, while subgroups will be struck to derive PA reference points for individual stocks.

II. Review of Progress on Precautionary Approach

1. Basis for Existing PA Reference Points for NAFO Stocks

In September 1996, the Fisheries Commission, in reference to UNFA, requested Scientific Council to provide information for Fisheries Commission managed stocks. This included:

- Recommendations on limit and target reference points,
- Medium term considerations and risks,
- Longer term research requirements and monitoring to refine reference points,
- Any other aspects of UNFA Article 6 and Annex II that Scientific Council may consider useful for implementation,
- Criteria for re-opening fisheries.

Scientific Council developed a Precautionary Approach framework in 1997 (Serchuk *et al*., 1997) to include limit, buffer and target reference points for fishing mortality and biomass. The Scientific Council conducted an extensive review of recent developments in the Precautionary Approach and re-opening criteria, and

- Reviewed available documentation including recent reports from FAO, ICES, etc.,
- Endorsed the Precautionary Approach as described in UNFA Article 6 and Annex II,
- Agreed to use the practical guidance from FAO (Article 7.5 of the Code of Conduct for Responsible Fisheries),
- Initiated the development of a framework and Action Plan including conducting a Workshop in March 1998.

Scientific Council also developed the following reference point terminology:

Biomass:

- B_{lim} - SSB below which stock should not fall.
- B_{buf} - Buffer to ensure SSB does not fall below $B_{lim.}$
- B_{tr} - target B (that which would give MSY).

Fishing mortality:

- F_{lim} - rate that should not be exceeded.
- F_{buf} - buffer (lower) rate to ensure F_{lim} is not exceeded.
- F_{tr} - target zone ($\leq F_{buf}$).

In accordance with the Action Plan a Scientific Council Workshop on the Precautionary Approach to Fisheries Management was held in March 1998 (NAFO, 1998a). Data requirements were identified for most stocks, and one or more analytical methods were applied to determine reference points. Detailed analyses were developed for American plaice in Div. 3LNO as a case study. Other stocks including Greenland halibut in SA 2 and Div. 3KLMNO, shrimp in Div. 3M, redfish in Div. 3M, and Northern shortfin squid in SA 3 + 4 were analyzed using one or more models appropriate to the available data.

The report of the Workshop was presented in May 1998 to the initial meeting of the Fisheries Commission/Scientific Council Working Group on the Precautionary Approach (NAFO, 1998b). The Working Group discussed the roles of scientists and managers with respect to implementation of the Precautionary Approach. The Working Group defined the roles of scientists as:

- Determine status of stocks,
- Classify stock status with respect to biomass/fishing mortality zones,
- Calculate limit reference points and security margins (buffers),
- Describe and characterize uncertainty, and
- Conduct risk assessments.

The roles of managers were defined as:

- Specify management objectives, select target reference points, and set limit reference points,
- Specify management strategies (courses of action) for biomass/fishing mortality zones,
- Specify time horizons for stock rebuilding and for fishing mortality adjustments, and
- Specify acceptable levels of risk.

The Scientific Council held another meeting during 27 April-1 May 1999 (NAFO, 1999a) in advance of the second meeting of the Joint Fisheries Commission/Scientific Council Working Group on the Precautionary Approach that convened 3-5 May 1999. At its 1999 meeting, the Scientific Council focused on three stocks for further development of the PA methodology and estimation of reference points: cod in Div. 3NO (closed fishery), yellowtail flounder in Div. 3LNO (open fishery), and shrimp in Div. 3M (data limited fishery). Reference points derived for these stocks were as follows: B_{lim}, for cod in Div. 3NO and F_{lim} (F_{msy}) and F_{buf} for yellowtail flounder in Div. 3LNO. The Traffic Light approach (Caddy, 1998) was applied to shrimp in Div. 3M but the results were treated in a qualitative manner.

At the May 1999 Joint Working Group meeting (NAFO, 1999b), the analyses for the three stocks were reviewed and a set of management strategies was developed for each stock. The Joint Working Group **recommended** that the Fisheries Commission and the Scientific Council consider these strategies in designing and formulating further action in implementing the Precautionary Approach in 2000 and beyond. It was also **recommended** that similar actions be taken for other stocks with related characteristics that are under the NAFO purview.

A third meeting of the Joint Working Group was held during 29 February-2 March 2000 (NAFO, 2000). This meeting focused on operationalizing the Precautionary Approach into management plans for the three stocks evaluated in 1999, but the Working Group also developed an implementation plan for American plaice in Div.

3LNO based on a template for cod in Div. 3NO. The implementation plans were defined as next steps and included detailed management objectives and strategies, data collection procedures and supportive management measures/good practices.

In 2002, the Fisheries Commission charged a Working Group of Technical Experts to meet to develop recommendations for future work of the Joint Scientific Council/Fisheries Commission Working Group. This meeting occurred during June 2002 (NAFO, 2002) and the Working Group reviewed the state of existing PA Frameworks developed within NAFO and ICES. The Working Group expressed concern with both PA Frameworks. Specific concerns with the NAFO Scientific Council PA Framework included:

- Prescribed harvest control rules (no fishing) below B_{lim} or B_{buf}.
- A fishing mortality limit at F_{msy}.
- The perception of a linear decrease in fishing mortality from the biomass target to the biomass buffer.

The Working Group also agreed that the specific issues and the general question of implementation of the Precautionary Approach would benefit NAFO by addressing specific cases and problems and **recommended** that the Fisheries Commission determine one or more appropriate examples and the instruct the Joint FC/SC Working Group on the Precautionary Approach to meet intersessionally to address the above concerns as they apply to the examples. At the 24th Annual Meeting of NAFO in September 2002, the Fisheries Commission did not pursue the issue any further.

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2. Evaluation of Existing Scientific Council PA Framework

The existing framework (Fig. 1) was developed by the Scientific Council in 1997 (Serchuk *et al*., 1997), and has been discussed in several Joint Scientific Council/Fisheries Commission meetings. Some progress has been made: for example, in the definition of roles of scientists and managers in the PA process (Table 1). However, the framework was never formally adopted by the Fisheries Commission. Concerns expressed by managers include:

- Prescribed harvest control rules (no fishing) below B_{lim} or B_{buf}.
- A fishing mortality limit at F_{msy}.
- The perception of a linear decrease in fishing mortality from the biomass target to the biomass buffer.
- No consideration of the desirability for stable TACs.

- No consideration of multi-species situations.

Table 1. Roles of Scientific Council and Fisheries Commission, as previously agreed (NAFO, 1998).

Scientific Council	Fisheries Commission
1. Determine status of stocks. 2. Classify stock status with respect to biomass/fishing mortality zones. 3. Calculate limit reference points and security margins. 4. Describe and characterize uncertainty associated with current and projected stock status with respect to reference points 5. Conduct risk assessments.	1. Specify management objectives, select target reference points, and set limit reference points. 2. Specify management strategies (courses of actions) for biomass/fishing mortality zones. 3. Specify time horizons for stock rebuilding and for fishing mortality adjustments to ensure stock recovery and/or avoid stock collapse. 4. Specify acceptable levels of risk to be used in evaluating possible consequences of management actions.

To address these concerns, a revised framework is proposed (Fig. 2).

Definitions of the biological reference points based on both fishing mortality and biomass, and the zones defined in Fig. 2 together with associated actions are detailed below:

Fishing Mortality Reference Points

F_{lim} = A fishing mortality rate that should only have a low probability[1] 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 only required in the absence of analyses of the probability that current or projected fishing mortality exceeds F_{lim}. F_{buf} should be specified by managers and should satisfy the requirement that there is a low probability[1] that F_{target} exceeds F_{lim}. The more uncertain the stock assessment, the greater the buffer zone should be.

F_{target} = A flexible fishing mortality rate to be selected by managers from the hatched area in Fig. 2 to achieve desired management objectives, subject only to the constraints defined by the limit and buffer reference points. In particular, F_{target} must be chosen to ensure that there is a low probability[1] that F_{target} exceeds F_{lim} and a very low probability[2] that biomass will decline below B_{lim} within the foreseeable future[3].

[1] Low probability might be defined as <=20%, but the actual level should be specified by managers.
[2] Very low probability might be defined as <=5-10%, but the 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.

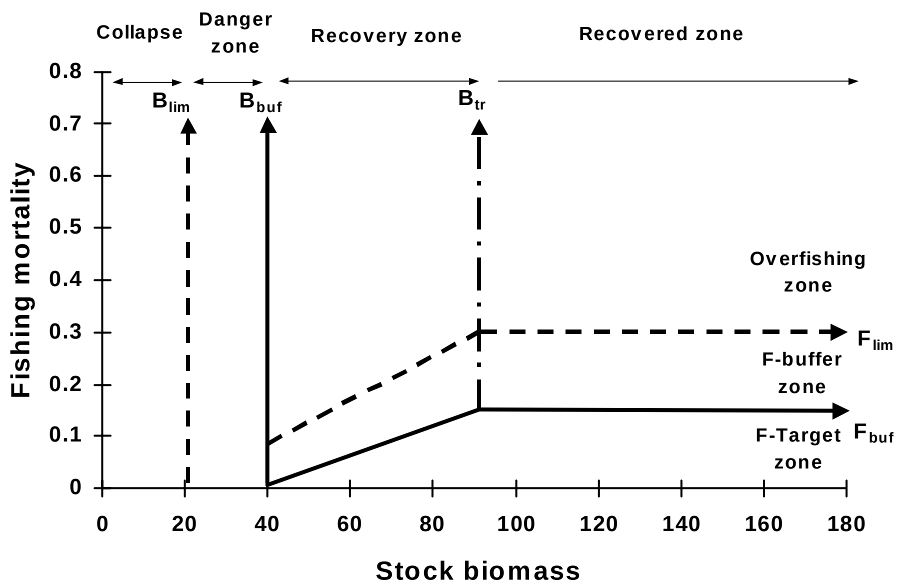

Fig. 1. Existing NAFO Scientific Council PA framework.

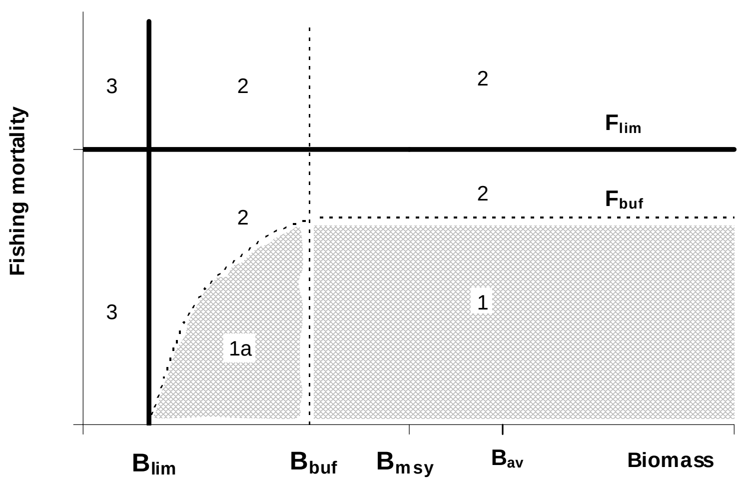

Fig. 2. A schematic representing the Scientific Council's proposed revision to the Precautionary Approach Framework. See text for definitions of biological reference points, numbered zones and associated actions.

Stock Biomass Reference Points

B_{lim} = A stock biomass level that should have a very low probability[2] of being violated. This is defined to be a biomass level below which stock productivity is likely to be seriously impaired.

B_{buf} = A stock biomass level above B_{lim} that is only required in the absence of analyses of the probability that current or projected biomass is below B_{lim}. B_{buf} should be specified by managers and should satisfy the requirement that there is a very low probability[2] 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.

B_{msy} = Average stock biomass associated with fishing at F_{msy}.

B_{av} = Average stock biomass associated with fishing at F_{buf}.

Zones and Associated Actions

Zone 1. (hatched area). The F_{target} zone. F_{target} must be selected so as to have low probability[1] of exceeding F_{lim} and a very low probability[2] of driving biomass below B_{lim} within the foreseeable future[3].

Zone 1a. The Cautionary F_{target} zone. The shape of this region in Fig. 2 is not necessarily meaningful; it simply indicates that the closer the current or projected biomass is to B_{lim}, the lower F_{target} must be to ensure that biomass remains above B_{lim}.

Zone 2. The Overfishing Zone. The fishing mortality rate must be reduced into the F_{target} zone.

Zone 3. The Collapse Zone. The fishing mortality must be as close to zero as possible.

Thus, the key features of the framework include:

i) There must be a very low probability[2] that management actions result in projected biomass dropping below B_{lim} within the foreseeable future[3]. Below B_{lim}, fishing mortality should be kept as close to zero as possible.

ii) The fishing mortality limit should be no higher than F_{msy} (see below). There should be a low probability[1] that realized fishing mortality will exceed F_{lim}.

iii) Fishing mortality targets are flexible, as long as they remain in Zone 1 of Fig. 2.

iv) If a stock assessment generates a current or projected biomass with some probability distribution, 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 below $B_{lim.}$ If no probability distribution of biomass is available, but a value for B_{lim} exists, Fisheries Commission should establish a security margin, equivalent to a buffer zone, 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[2] that biomass declines below B_{lim} in the foreseeable future[3].

The revised framework attempts to address the managers' concerns as follows:

1) Prescribed harvest control rules (no fishing) below B_{lim} or B_{buf}:

   The new framework allows fishing below B_{buf}, subject to constraints such as ensuring a very low probability[2] that biomass will fall below B_{lim} in the foreseeable future[3]. However, below B_{lim}, fishing mortality should be as close to zero as possible.

2) A fishing mortality limit at F_{msy}:

   Reasons for continuing to advise that $F_{lim} = F_{msy}$ are:

   - Perhaps most importantly, F_{msy} as a limit is in conformance with the Precautionary Approach as described in several United Nations agreements (in particular, Annex 2 of the United Nations Straddling Stocks Agreement).

- Fishing somewhat below F_{msy} results in a relatively small loss in average catch, but a large increase in average biomass (which, in turn, results in a decreased risk to the fish stock, an increase in CPUE, and a decrease in the costs of fishing)[4].
- Traditional bio-economic models indicate that the fishing mortality associated with maximum economic yield (F_{mey}) is usually considerably less than F_{msy}.
- Ensuring no major stock is fished harder than the single-species F_{msy} has often been recommended as a good first step towards ecosystem-based management (NRC, 1999; Mace, 2001). Ecosystem-based management will likely require even more conservative fishing mortality targets than "traditional" single-species-based management

3) The perception of a linear decrease in fishing mortality from the biomass target to the biomass buffer:

   There is a range of options open to managers in this part of the framework (for example, no reduction in F is prescribed if stock biomass is above B_{buf} and F is below F_{buf}). Managers also decide on the levels of B_{buf} and F_{buf} in those cases where the risk of biomass being below B_{lim} or the risk of fishing mortality being above F_{lim} cannot be provided.

4) No consideration of the desirability for stable TACs:

   This is a difficult concept to capture in a simple schematic such as Fig. 2; however, considerable flexibility exists for managers in setting target F levels. Stable TACs are easier to achieve if the fishery remains in Zone 1. Furthermore, maintenance of biomass well above B_{lim} will minimize the instability caused by fishery closures.

5) No consideration of multi-species situations:

   Although the proposed PA Framework is focused on single species, ensuring that no individual species is fished harder than the single-species F_{msy} has frequently been suggested as a first step towards satisfying several important and common ecosystem objectives (NRC 1999; Mace, 2001; Sissenwine and Mace, 2003). In addition, two other aspects of multi-species management were considered in the proposed revision of the PA Framework. First, the de-emphasis of B_{msy} avoids the problem of the impossibility of maintaining all stocks in a multi-species assemblage simultaneously at their respective single-species B_{msy} levels. Second, by replacing the requirement that fishing mortality be zero when biomass is below B_{lim} with a requirement that fishing mortality to be as close to zero as possible in this situation, there is now a recognition of the need for a certain amount of flexibility to account for technical interactions that result in unavoidable by-catch of depleted species.

Recommendation for study group

The above proposed Scientific Council PA Framework requires B_{lim} to be defined for each stock in a scientifically defensible manner. B_{lim} is a limit below which the productivity of the stock is likely to be impaired to a serious degree. Stocks that are below B_{lim} may not recover, or may take a long time to recover. A number of approaches are discussed in the primary literature and in research documents, working papers and meeting reports for defining B_{lim}. A study group is needed to review the strengths and weaknesses of alternative approaches and to make recommendations to Scientific Council on the most appropriate approach to defining B_{lim} for NAFO stocks ranging from data-rich to data-poor situations, and for a range of life history parameters. Where existing simulation trials of the robustness and other properties of each candidate reference point are available, these can be referred to, but in other cases new trials will have to be undertaken and the results evaluated. The methods to be reviewed should include approaches such as those based on parametric models, non-parametric smoothers, segmented regression, replacement ratio and other methods of interpreting stock-

[4] For example, one set of model results derived from an age-structured deterministic model showed that for 600 combinations of life history parameters and stock-recruitment relationships, fishing at 75% F_{msy} resulted in an average yield of 94-98% MSY and a biomass of 125-131% B_{msy} (Restrepo *et al.*, 1998).

recruit or stock production data in terms of the PA. The value of heuristics such as $\%B_{msy}$, $\%B_0$, $\%R_{max}$ and %SPR should be thoroughly evaluated and results from, for example, the recent NMFS and FAO experience with respect to CITES listing criteria, should be reviewed.

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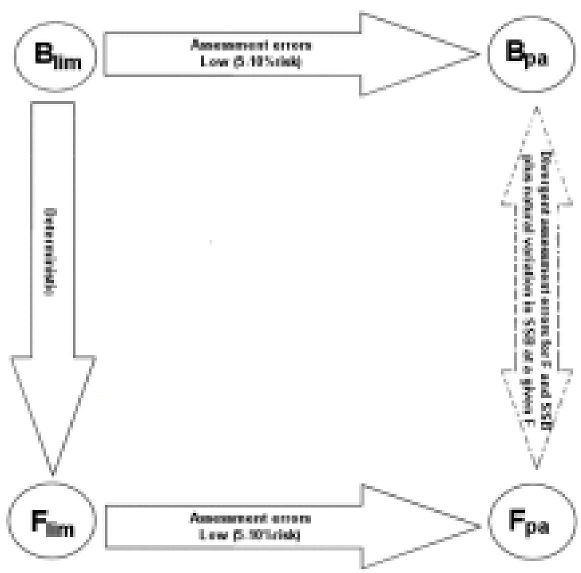
3. Report of ICES SGPA Meeting, 2-6 December 2002 and ICES SGPRP Meeting, 24-26 February 2003

SGPA (Study Group on the Further Development of the Precautionary Approach to Fishery Management) Meeting. The discussion focused primarily on the development of a new framework for defining and linking reference points taking into account uncertainty and the causes of uncertainty. After extensive discussion of the management of risk in calculating reference points, a more explicit framework, taking into account stochastic variability and assessment uncertainty, was adopted by the ICES SGPA. The links between reference points is given in the figure below.



With the new framework:

B_{lim}, the cornerstone reference point, is defined as the SSB below which there is a substantial increase in the probability of obtaining reduced (or 'impaired') recruitment. Its estimate should be risk averse.

F_{lim} will be set on the basis of B_{lim} and should be risk neutral to B_{lim}, i.e. F_{lim} should be the fishing mortality at which the deterministic equilibrium SSB is B_{lim}.

F_{pa}, derived from F_{lim}, is the value not to be exceeded such that the fishing mortality actually realized by an advised catch derived from F_{pa} should have a very low probability of being above F_{lim}. F_{pa} should therefore be estimated by a method that takes assessment uncertainty into account.

Similarly, if B_{pa} is derived from B_{lim} taking assessment uncertainty into account, there should be a very low probability that a stock currently estimated to be at B_{pa} is actually at B_{lim}
Only two methods for estimating B_{lim} were presented, the segmented regression and the Kernel method. The segmented regression had already been presented and reviewed in a previous SGPA meeting and was tested on a few stocks. The method was able to determine change points and is considered to be a candidate to estimate B_{lim}. No stand alone software was made available to test the Kernel method.

SGPRP (Study Group on Precautionary Reference Points) Meeting. The main term of reference for SGPRP was to review the proposal prepared by the ICES Secretariat on revision to Reference Points for the stocks dealt with by different Working Groups. The proposal was built on the framework developed and agreed by SGPA in December 2002 and the outcome of the Study Group on Biological Reference Points for Northeast Arctic Cod (SGBRP) held in January 2003.

The ICES Secretariat provided a compilation of limit reference points for 65 stocks for review at the ICES SGPRP in February 2003. The compilation comprised a summary of existing reference points and their technical basis as well as revised reference points based on segmented regression analyses. There was no compilation of PA reference points.

SGPRP reviewed the limit reference points and identified those that have potential for meaningful revision. It also commented on the analyses of those that were less clear and indicated the problems associated with their development.

The results of these reviews will now be sent to the respective assessment Working Groups to assist in more thorough analysis of revisions to reference points. The SGPRP also noted that this framework had worked well with the Northeast Arctic cod. However, it was recognised that to be able to compile the full set of PA reference points, integrated software was required. This has not been developed yet.

4. Recent Advances in Coastal States

a) Canada

The evolution of the Precautionary Approach in a Canadian context over the decade following major collapses of a number of cod stocks was reviewed. The collapses of these cod stocks in the late-1980s and early-1990s precipitated evaluations of alternative scientific and fisheries management approaches. Meetings and workshops in Canada in the early-1990s gave considerable momentum to move towards new and improved approaches based on a foundation of objective methods, quantification of uncertainty, establishment of management objectives, definition of reference points and the quantification of risk associated with alternative management options. These were important elements in the way Canadian scientists have approached the initiatives on "precaution" that emerged in the mid-1990s through various international initiatives such as UNFA, the Rio Declaration and the FAO Code of Conduct. It also led to discussions between Science and Fisheries Management within the Dept. of Fisheries and Oceans (DFO) in terms of developing a management framework which incorporated the Precautionary Approach.

Two National Science workshops (Rice and Schnute, 1999; Richards and Schnute, 2000) made progress on a number of technical aspects of implementing the Precautionary Approach during the late-1990s, and came up with a general framework that was considered to be consistent with UNFA. There was consensus that DFO Science should identify limits. In the early-2000s, two further National Workshops (Rice and Rivard, 2002; Rivard and Rice, 2003), the second involving fisheries managers, adopted "serious harm" as the definition of a conservation limit reference point and reviewed a number of reference points in terms of this definition (Shelton and Rice, 2002). The interpretation of serious harm as the increased probability of poor recruitment at low stock size emerged as a guiding principle and a non-parametric kernel smoother approach for computing the probability of poor recruitment was reviewed. Results from this approach were considered to be very promising in defining the probability of poor recruitment, but required further evaluation. More traditional approaches were applied for determining limit reference points. These approaches including:

- the "Serebryakov method" (Serebryakov, 1991; Shepherd, 1991) in which an SSB limit is defined below which the population fails to produce average recruitment under good early-stage survival conditions,
- SSB corresponding to the point below which the population fails, on average, to produce half the estimated maximum recruitment (Mace, 1994), and
- the SSB level below which either SSB is not expected to commence recovery quickly when fishing mortality is removed, or stock dynamics are unknown.

These approaches were applied to the three cod stocks of concern, Northern Gulf Cod (Subdiv. 3Pn + Div. 4RS), Southern Gulf Cod (Div. 4T + Subdiv. 4Vn) and northern Cod (Div. 2J+3KL), leading to the adopting of SSB limit reference points for the two Gulf stocks and a "bench mark" SSB level for Northern Cod, a point at which the appropriate limit reference point will be re-evaluated. These limits/bench marks were applied in the Canadian National assessment (ZAP) of these three stocks in March 2003 (http://www.dfo-mpo.gc.ca/csas/).

While much has been achieved in developing a Canadian PA Framework, there is still some distance to travel before the destination of a fully articulated PA Framework is arrived at. Robust limit reference points need to be developed in terms of both spawner biomass and fishing mortality, and uncertainty associated with these reference points in relation to uncertainty in the current state of the stock and uncertainty in the projected future states needs to be explicitly accounted for. Approaches for linking the harvest strategy framework to the uncertainties in the limits, current state and future projected state need to be developed. Although it is true that the Canadian Framework has yet to deal explicitly with competing risks, ecosystem considerations, or socio-economic aspects of fisheries management objectives, a broad Canadian PA Framework is now in place which is consistent with UNFA and which could provide the basis for management decisions at the present time.

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b) **United States of America**

United States domestic law does not explicitly recognize the Precautionary Approach to fisheries management. However, the most recent amendment to the Magnuson Fisheries Conservation and Management Act, termed the Sustainable Fisheries Act (SFA) of 1996 (and subsequently merged into the Magnuson-Stevens Fisheries Conservation and Management Act), embodies many of the principles of the PA. National Standard 1 (NS1) states that "Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry". Although this standard has not changed over the years, the definitions of optimum yield (OY) and overfishing have. In particular, the SFA changed the definition of OY from "maximum sustainable yield [MSY] as modified by relevant factors" to "MSY as reduced by relevant factors". This implies that MSY, or perhaps more correctly, some MSY control rule such as $F = F_{MSY}$, should represent an upper limit on fishing activity. As such, it is in conformance with Annex 2 of the United Nations Straddling Stocks Agreement of 1995, which specifies that F_{MSY} should be considered a minimum standard for a limit reference point. In addition, the SFA defined overfishing as "... a rate or level of fishing mortality that jeopardizes the capacity of a fishery to produce the maximum sustainable yield on a continuing basis".

Subsequent to passage of the SFA, the US National Marine Fisheries Service (NMFS) developed a set of guidelines for implementing NS1. The guidelines treat MSY-related reference points in a dynamic context, rather than a static one. For example, a constant fishing mortality equal to F_{MSY} will result in stock size fluctuating around B_{MSY} and annual yields fluctuating around MSY. The dynamic interpretation takes such fluctuations into account, whereas the static interpretation does not. One of the major consequences of this approach is that while F_{MSY} may be treated as an upper limit on fishing mortality, B_{MSY} is not treated as a lower limit on biomass. Rather, the minimum stock size threshold (MSST) is defined either as a biomass ($<B_{MSY}$) from which it is possible to rebuild back to the average B_{MSY} within 10 years, or ½ B_{MSY}, whichever is greater. The maximum fishing mortality threshold (MFMT) is defined by an MSY control rule. Exceeding the MFMT constitutes "overfishing", while falling below MSST denotes an "overfished" or depleted stock. Overfishing simply requires action to reduce fishing mortality below the MFMT, while an overfished stock requires the development of a formal rebuilding plan to restore the stock at least back to the level of the average B_{MSY} within a specified period of time, often as short as 10 years. Note that the MSST is not associated with closure of a fishery. The requirement to keep fishing mortality below MFMT can be thought of as a "first line of defense" which, if properly applied, should result in a low probability that a stock will fall below the MSST. The requirement to rebuild when the stock does fall below the MSST is a second line of defense. The requirement that an overfished stock be rebuilt all the way back to the average B_{MSY}, rather than just above the MSST, implies that a stock is treated differently depending on whether it is approaching the MSST from above or below. The reason for the difference is that a stock that has become overfished is likely to have a more distorted age distribution and therefore requires stronger remedial action.

Recently, a Working Group has been set up to revisit the NS1 guidelines. Problems that have been identified during almost five years of working with the guidelines include the definition and use of the MSST, acceptable surrogates for MSY-based reference points, calculation of biological reference points when environmental regime shifts have taken place, determination of maximum permissible rebuilding times, procedures to follow when rebuilding plans require revision after initiation, and more explicit guidance on the relationship between fishing limits and fishing targets.

III. Review of Methods for Determining PA Reference Points

1. Replacement Ratio Method

This section describes the development and application of an index-based assessment methodology for stocks in the NAFO area. More detailed discussions on the method and illustration of its applicability may be found in NEFSC (2002a, b). A number of index-based approaches are developed to more fully utilize the data sets from the surveys and historical landings. The methods are technically simple but are based on linear population models, modern graphical methods, and robust statistical models. General trends in abundance and fishing mortality, deducible from a time series of catch (or landings for some species) and survey indices, are explored. Relative fishing mortality rate is defined as the ratio of catch to survey index. The replacement ratio is introduced here as an analytical tool for examining the historical behavior of a population and any potential influence of removals due to fishing activities. To test these concepts and to facilitate comparisons, the analyses were applied to a number of stocks in the NAFO area.

Reduced-parameter models are often used to analyze non-age structured models. The most common example is the surplus production model (see Prager, 1994 for review and modern approaches) but the Collie-Sissenwine model (Collie and Sissenwine, 1983), and delay-difference models (Schnute, 1985) are also candidates. Even these simple models may fail when the dynamic range of population responses and/or fishing mortality rates is small (Hilborn and Walters, 1993). 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 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 and monitored since 1960.

Replacement Ratio Theory

The replacement ratio draws from the ideas underlying the Sissenwine-Shepherd model, delay- difference models, life-history theory, Collie-Sissenwine model, and statistical smoothing (Simonoff, 1996). First, begin by defining $I_{j,s,t}$ 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 $I_{j,s,t}$. This ratio can be noisy, owing to imprecision of survey estimates, and the variation can be damped by writing the relative F as a ratio of the catch to some average of the underlying indices. Following the recommendation of a reference point panel review team (Applegate *et al.*, 1998), relative F is defined as the ratio of catch in year t to a centered 3-yr average of the survey indices:

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

Note that under this definition, the estimates of relative F for the first and last years of a time series are based on only 2 years of data.

Noise in the survey indices also affects the ability to relate inter-annual changes in abundance estimates to removal from fishing. The general approach of averaging adjacent years to estimate current stock size underlies statistical smoothing procedures (e.g. LOWESS) as well as formal time series models (e.g. ARIMA methods). One of the difficulties of applying such approaches in the present context is that the derived parameters, if any, are unrelated to the species biology or any aspect of the fishery. Moreover, basic questions of whether the current stock is replacing itself and whether the current level of catch is too high or low are of primary interest. If the recent history of the fishery is uninformative, most mathematical models will fail. The underlying reasons for model failure may not be immediately obvious from analysis of standard diagnostic measures. Of greater concern is the issue of the model misspecification, wherein an inappropriate model adequately fits the data but leads to deductions inconsistent with basic biology and the fishery. The proposed replacement ratio is a data-based technique relying on fewer assumptions. No technique however, can fully compensate for model misspecification errors.

If it is assumed that the survival from eggs to the juvenile stage is largely independent of stock size, then the number of recruits will be proportional to stock size. Locally, (i.e. in the neighborhood of a given stock size) this assumption holds for any stock-recruitment function. Since a population is a weighted sum of recruitment events, the inter-annual change in total stock size tends to be small relative to the total range of stock sizes (at least in the Northeast USA). Recruitment in any year is likely to be small relative to the biomass of the total population. Thus, the change in total biomass is likely to be small relative to the change in annual recruitment. Although the mathematics are more complicated than this, the argument is based on the premise that if $Var(x/1) = \sigma^2$ then $Var(\Sigma x/n)\ \sigma^2/n$. Of course, the magnitude of such changes depends on the variation of recruitment and the magnitude of fishing mortality.

Using the linearity assumption defined above, basic life history theory can be employed to write abundance at time t as a function of the biomasses in previous time periods. The number of recruits at time t (R_t) is assumed to be proportional to the biomass at time t (B_t). More formally,

$$R_t = S_o \, Egg \, B_t \qquad (2)$$

where Egg is the number of eggs produced per unit of biomass, and S_o is the survival rate between the egg and recruit stages. Survival for recruited age groups at age a and time t ($S_{a,t}$) is defined as:

$$S_{a,t} = e^{-F_{a,t} - M_{a,t}} \qquad (3)$$

where F and M refer to the instantaneous rates of fishing and natural mortality, respectively. The weight at age a and time t ($W_{a,t}$) and the average longevity (A) of the species must also be considered.

Using these standard concepts, the biomass at time t can be written as a linear combination of the A previous years. Without loss of generality, the subscripts on the survival terms can be dropped assuming that average weight-at-age is invariant with respect to time. Further, set the product S_o Egg equal to the coefficient α. The biomass at time t can now be written as:

$$B_t = R_{t-1} S^1 W_1 + R_{t-2} S^2 W_2 + R_{t-3} S^3 W_3 + .. + . R_{t-(A-1)} S^{A-1} W_{A-1} + R_{t-A} S^A W_A \qquad (4)$$

Substituting Eq. (2) into Eq. (4) leads to:

$$B_t = \alpha B_{t-1} S^1 W_1 + \alpha B_{t-2} S^2 W_2 + \alpha B_{t-3} S^3 W_3 + .. + .\alpha B_{t-(A-1)} S^{A-1} W_{A-1} + \alpha B_{t-A} S^A W_A \qquad (5)$$

Dividing the left hand side of Eq. (5) by the right hand side specifies the identity:

$$1 = \frac{B_t}{\alpha B_{t-1} S^1 W_1 + \alpha B_{t-2} S^2 W_2 + \alpha B_{t-3} S^3 W_3 + .. + .alphaB_{t-(A-1)} S^{A-1} W_{A-1} + \alpha B_{t-A} S^A W_A} \qquad (5a)$$

In a steady state, non-growing population, $B_t = B_{t-1} = \ldots = B_{t-n}$ for all values of n. Therefore all of the biomass terms drop out of Eq. (5a) leading to:

$$1 = \alpha S^1 W_1 + \alpha S^2 W_2 + \alpha S^3 W_3 + .. + .\alpha S^{A-1} W_{A-1} + \alpha S^A W_A \qquad (5b)$$

If we write $\varphi_j = \alpha S^j W_j$ then Eq. (5b) implies that:

$$1 = \sum_{j=1}^{A} \phi_j \qquad (5c)$$

Moreover, since all of the component terms of φ_j i.e. α $S^j W_j$ are all positive non-zero values, Eq. (5c) also implies that <u>all</u> φ_j terms are less than or equal to one. Finally, Eq. 5 to 5c imply that the biomass at time t <u>must</u> be a moving average of the previous biomasses whose offspring comprise the population at time t. Equations 5-5c further imply that coefficients can be written in terms of basic life history and fishery parameters. In particular, if $F_{a,t}$ is written as the product of age specific partial recruitment and a fishing mortality rate, say F_{max}, then the φ_j terms serve as a explicit empirical test of the assumption that the population trajectory is shaped by an optimal fishing mortality rate. Writing $\varphi_j = \alpha S^j W_j = S_o$ Egg $S^j W_j$ and substituting these terms into Eq. (5c) leads to:

$$S_o = \frac{1}{\sum_{j=1}^{A} Egg\, S^j W_j} \qquad (5d)$$

Equation 5d is similar to the expression derived by Vaughan and Saila (1976) for the solution of the first year survival terms in a Leslie matrix model. The parameter S_o represents the survival rate from the egg to the age at recruitment. It also serves as the primary scaling factor for the Leslie matrix model in which the dominant eigenvalue is defined as one.

Populations are probably never at equilibrium but the relevant question is whether the departures from equilibrium are important. The structural smoothing equation proposed above constitutes an explicit hypothesis of the age-specific weighting factors that would shape a population at equilibrium.

The hypothesis that the population is at equilibrium can now be explicitly tested by substituting observed indices of abundance into the equilibrium model (Eq. 5a). If the index of abundance I_t is proportional to abundance $B_{t,}$, $I_t = q\ B_t$ can be written where q is the catchability coefficient. Substituting this relationship into Eq. 5a results in expression that we have called the replacement ratio Ψ_t:

$$\Psi_t = \frac{\frac{I_t}{q}}{\alpha \frac{I_{t-1}}{q} S^1 W_1 + \alpha \frac{I_{t-2}}{q} S^2 W_2 + \alpha \frac{I_{t-3}}{q} S^3 W_3 + .. + \alpha \frac{I_{t-(A-1)}}{q} S^{A-1} W_{A-1} + \alpha \frac{I_{t-A}}{q} S^A W_A} \qquad (6)$$

By noting that the q's cancel out, and letting $\varphi_j = \alpha\ S^j W_j$, Eq. 6 simplifies to:

$$\Psi_t = \frac{q\, I_t}{\sum_{j=1}^{A} \phi_j\, q\, I_{t-j}} \qquad (7)$$

Under the null hypothesis that the population is at equilibrium and not growing, Eq. (6) can be used as a measure of population trend. If the coefficients of the moving average are explicitly defined as from externally derived parameters (i.e. $S_{o,}$ Egg, F_{TARGET}, M, PR_j, W_j) then the replacement ratio Ψ_t can be used as an explicit test of the equilibrium assumption. Deviations from $\Psi_t = 1$ imply either violations of the assumptions embedded in the estimated φ_j weighting terms, measurement variability in the abundance indices I_t, or wide variations in recruitment. Over time, deviations attributable to either measurement error or recruitment are less important than those attributable of variations in the component terms of φ_j. The most important of these terms is fishing mortality.

Considerations on the Applicability of the Replacement Ratio

Under the assumption that recruitment is proportional to abundance $R_t = S_o$ Egg B_t, and that S_o and Egg are constants, the population will decline when F increases above its nominal value and increase when F is below its nominal level. Thus Ψ_t will be a decreasing function of F and will equal 1 when $F = F_{TARGET}$.

If recruitment is assumed to be constant then $R_t = R$, and the behavior of the replacement ratio will be fundamentally different. Increases in F will induce an initial reduction in Ψ_t as the population declines to a new equilibrium level consistent with an increased value of F. However, as the population approaches this new equilibrium level, the replacement ratio will once again approach unity. Conversely, a reduction in F will induce an increase in population size and a transient increase in Ψ_t followed by a gradual return to 1 as the population approaches its new equilibrium level associated with the decreased value of F. For these cases, the relationship between Ψ_t and relF would consist of multiple stable points. The replacement ratio will be 1 for multiple levels of relF. Values of Ψ_t above or below one would be attributable to transient population states as the population moves to its new equilibrium point. It should be noted that the assumption of constant recruitment, irrespective of stock size, invokes the most extreme form of density dependence possible. Constant recruitment implies that the R/SSB ratio approaches infinity at the stock size (SSB) approaches zero. Consistent trends in F, from low to high or *vice versa*, would tend to maintain the transient behavior in the replacement ratio for longer periods. Therefore, the relationship between Ψ_t and relative F would approximate that observed in paragraph 1 above.

The behavior of the replacement ratio in situations where the underlying stock recruitment function invokes varying degrees of compensation (say a Beverton-Holt relation), will be intermediate between behaviors described in paragraphs 1 and 2 above. If the stock is near carrying capacity then deviations from an average level of recruitment will be small. For this situation, the behavior of the replacement ratio will be similar to that described in paragraph 2. When the population is small relative to the level that produces maximum or near maximum levels of recruitment, the behavior of Ψ_t and its relationship to relative F should be similar to that described in paragraph 1. The ability to distinguish between the behaviors in Ψ_t induced by simultaneous changes in F or constancy in recruitment (as the population increases toward some designated level), will be difficult.

Many stocks in the NAFO area are at relatively low levels of abundance and have experienced, until recently, extended periods of increasing fishing mortality. If the populations are controlled by some form of density-dependent stock recruitment function, it is likely that the recruitment is nearly linear in the vicinity of the current stock size. Under these conditions it is expected that the relationship between Ψ_t and relF should be similar to that described in paragraph 1.

For stocks that are approaching a biomass at which recruitment becomes nearly constant, the utility of the derived value of the relF at replacement is compromised. In this circumstance, a piecewise examination of the data may be instructive.

Appropriate Number of Terms in Moving Average

The survival term S^j is equivalent to the l_x term in the Euler-Lotka equation for population growth (l_x is the probability of surviving to age x). For high levels of fishing mortality the S^j term is decreasing faster than the average weight W_j is increasing. Thus the importance of earlier indices rapidly diminishes. All of the I_t and φ_j terms are positive, and at equilibrium, $I_t = I_{t+1}$ and $I_t = \Sigma\ \varphi_j\ I_{t-j}$ both hold. Therefore, $\Sigma\ \varphi_j = 1$ and all of the φ_j >0. It would be desirable to express each of the φ_j weighting terms as function of the underlying population parameters. As expected, increases in fishing mortality increase the weight to more recent indices, whereas the converse hold for lower fishing mortality rates. As an approximation for this initial analyses, we assumed that all of the $\varphi_j = \varphi$ which implies that $\varphi = 1/A$. Additional information on the estimation of number of terms in the moving average function are described in NEFSC (2002b)

Relation between Replacement Ratio and Relative F

Application of any smoothing technique reflects a choice between signal and noise (Rago, 2001). A greater degree of smoothing eliminates the noise but may fail to detect true changes in the signal. Given the abrupt changes in fishing mortality that have occurred in some NAFO stocks, the current year in the numerator of the replacement ratio was chosen. Use of the current index in the numerator rather than a running average of say k years, increases the sensitivity of the ratio to detect such changes. The penalty for such sensitivity is that the proportions of false positives and false negative responses increase. This penalty was judged acceptable for two reasons. First, it is desirable to detect abrupt changes in resource condition given the magnitude of recent and proposed management regulations. Second, the current formulation of the replacement ratio has a natural relationship to stock-recruitment hypotheses and the ratio can be investigated as a function of variations in underlying parameters, especially survival. Alternative formulations of the replacement ratio, say with a 2-yr average population size in the numerator can be developed, but their basic properties have not been investigated.

When fishing mortality rates exceed the capacity of the stock to replace itself the population is expected to decline over time. The expected behavior of Ψ_t under varying fishing mortality and recruitment is complicated, but it will have a stable point = 1 when the fishing mortality rate is in balance with recruitment and growth. Variations in fishing mortality will induce complex patterns, but in general terms, Ψ_t will exceed 1 when relative F is too high, and will be below 1 when F is too low. To account for these general properties and to reduce the influence of wide changes in either Ψ_t or the relative F, we applied robust regression methods (Goodall, 1983) to estimate the relative F corresponding to $\Psi_t = 1$. The parameters of the regression model:

$$ln(\Psi_t) = a + b\, ln(relF_t) \qquad (8)$$

were estimated by minimizing the median absolute deviations. Median Absolute Deviation estimators are known as MAD estimators in the statistical literature (e.g. Mosteller and Tukey, 1977). Residuals were downweighted using a bisquare distribution in which the sum of the MAD standardized residuals was set to 6. This roughly corresponds to a rejection point of about plus or minus two standard deviations from the mean. (Goodall, 1983).

The relative F at which $\Psi_t = 1$ was estimated from Eq. 8 as:

$$relF_{threshold} = e^{-a/b} \qquad (9)$$

where the estimates of a and b from Eq. 8 were substituted into Eq. 9. This derived quantity may be appropriately labeled as a threshold since values in excess of it are expected to lead to declining populations. Alternatively, populations are expect to increase when $relF_t < relF_{threshold}$.

Randomization Tests

The usual tests of statistical significance do not apply for the model described in Eq. 8. The relation between Ψ_t and $relF_t$ is of the general form of Y/X *vs* X where X and Y are random variables. The expected correlation between Y/X and X is less than zero and is the basis for the oft stated criticism of spurious correlation. To test for spurious correlation a sampling distribution of the correlation statistic was developed using a randomization test. The randomization test is based on the null hypothesis that the catch and survey time series represent a random ordering of observations with no underlying association. The randomization test was developed as follows:

1. Create a random time series of length T of $C_{r,t}$ from the set $\{C_t\}$ and $I_{r,t}$ from the set $\{I_t\}$ by sampling with replacement.
2. Compute a random time series of relative F ($relF_{r,t}$) and replacement ratios ($\Psi_{r,t}$).
3. Compute the r-th correlation coefficient, say ρ_r between $ln(relF_{r,t})$ and $ln(\Psi_{r,t})$.
4. Repeat steps 1 to 3 1000 times.
5. Compare the observed correlation coefficient r_{obs} with the sorted set of ρ_r.
6. The approximate significance level of the observed correlation coefficient r_{obs} is the fraction of values of ρ_r less than r_{obs}.

It should be emphasized that relF is not necessarily an adequate proxy for F_{msy}, since this parameter only estimates the average mortality rate at which the stock was capable of replacing itself. Thus, while relF defined as average replacement fishing mortality is a necessary condition for an F_{msy} proxy, it is not sufficient, since the stock could theoretically be brought to the stable point under an infinite array of biomass states.

Graphical Analyses

The relationships among the catches, abundance indices, relative F, replacement ratios and time are summarized as a six-panel plot (Fig. III.1.1). Panels are aligned to facilitate interpretation of the stock dynamics and to allow for a standard approach for comparison among stocks. The top four panels illustrate the interelationships among $ln(relF_t)$, $ln(\Psi_{,t})$, I_t and time t. The variables share axes such that the temporal and phase plane interactions are easily followed. The bottom two panels illustrate the temporal patterns between catch C_t and $ln(relF_t)$. Two of the panels warrant special consideration. The upper left panel plots $ln(\Psi_t)$ *vs* $ln(relF_t)$. The strength of the linear association can be inferred from the shape of the confidence ellipse (or principle component) surrounding the points. When the association is strong the ellipse will be long and narrow; when the association is weak the ellipse will approach a circle. The diagonal line represents the robust regression estimate and the dashed horizontal line represents the replacement ratio of 1.0. The intersection of the diagonal line with the replacement line represents the estimate of $relF_{threshold}$. The middle left panel represents the phase-plane relationship between the log of the survey, $\ln(I_t)$ and the $\ln(relF_{,t})$. Each point is labeled with the survey year and the points are connected to illustrate the temporal sequence.

The six-panel plots show the interelationships among survey estimates of abundance, landings, functions of landings and relative abundance and time. The two functions are the replacement ratio (Eq. 6) and relative F (Eq. 1). The concept of using multiple panels to relate multiple variables over time has been advocated for use in fisheries science (e.g. Clark, 1976; Hilborn and Walters, 1992) and other fields (e.g. Cleveland, 1993). The example for Gulf of Maine haddock will be discussed in detail here.

The first aspect to note about the plots are the shared axes in the top four plots (A, B, C, D) and F. Panels B, D and F show the time series for the replacement ratio, the fall survey index, and the relative F, respectively. The horizontal line in A and B is the replacement ratio = 1 line. The relationship between the replacement ratio and relative F in panel A is the key to understanding the influence of fishing mortality on stock size. Panel A is a phase plane that describes the relationship between two variables ordered by time. The degree of association between these variables is characterized by a Gaussian bivariate ellipsoid with a nominal probability level of p = 0.6827 equivalent to $\pm$ 1 SD about the mean of the x and y variables. The primary and secondary axes of the ellipse are the first and second principal components, respectively. When the degree of association between relative F and replacement ratio decreases, the ellipse becomes more circle-like. The implication is that either the survey is too imprecise to detect changes induced by historical levels of fishing removals, or that the levels of fishing effort have been too low to effect changes in relative abundance. These alternatives can often be distinguished by consideration of the sampling gear and its interaction with the behavior of the species. Similarly incompleteness of the catch record, particularly for species in which the magnitude of discard mortality has varied widely, is another critical factor in the interpretation of the confidence ellipse.

The assumption that the relative F and replacement ratio have a joint bivariate normal distribution in the log-log scale may not hold for all (or any) species. In particular, the replacement ratio model is designed to be sensitive to contemporary changes, so that by definition it will be highly variable. Large changes that are subsequently validated by future observations imply true changes in population status. When the converse is true, it is proper to conclude that the change was an artifact of sampling variation. The degree to which high residuals influence the pattern is tested using the robust regression method of Tukey (Mosteller and Tukey, 1977) that downweights large residuals using a bisquare distribution (see Goodall, 1983 for details). Thus the regression line in panel A will not be aligned with the primary axis of the ellipse when high residuals distort the confidence ellipse. The expected value of correlation between the replacement rate and relative F is negative. The empirically derived estimate of the sampling distribution for the correlation coefficient, *via* the randomization test, provides a way of judging the significance of the robust regression line.

The predicted value of relative F at which the replacement ratio is 1 is defined by Eq. 8 and denoted by the vertical line in Panel A and B. The precision of that point depends largely upon where it lies within the confidence ellipse. If the confidence ellipse is nearly centered about the intersection point, then the precision of the relative F threshold will be high. This also indicates that over time, a wide range of F and replacement ratios greater than one have been observed. In contrast, when the intersection point lies in the upper right portion of ellipse, the precision will be low. This is, of course, is a common property of linear regression in which the prediction interval for Y increases with the square of the distance between the independent variable X and its mean. Thus a high degree of correlation between relative F and the replacement ratio does not necessarily ensure high precision in the threshold if relatively few observations have replacement ratios greater than one. Panel A demonstrates, in a slightly different way, the implications of the "one-way trip" described in Hilborn and Walters (1992).

Panel C depicts the phase plane for relative biomass (i.e. the index) and the relative F. If the population declines with increases in fishing mortality and increases when the fishing mortality is reduced, the population should move up and down a linear isocline. The degree of departure from linearity reflects both sampling variation as well as true variations induced by recruitment pulses and its transient influence on total biomass. Thus the trace of points can give useful insights into parametric model selection of population dynamics under exploitation. In many species it is interesting to note that the return path for biomass, when F is reduced, tends to deviate sharply from the decline path. This general result may suggest that the rebuilding of stocks will be less predictable than the path of decline. In particular, the influence of truncated age structures on reproduction may be important and certainly, the presence of strong year-classes will have a substantial, yet unpredictable influence on stock rebuilding.

The simple data of catch and survey are generally not sufficient to estimate simultaneously both the threshold F and biomass targets. This property characterizes the common property of indeterminancy of r and K in standard surplus production models. For the Gulf of Maine (GOM) haddock example, the relative biomass target is defined external to the model (Panel C and D).

To facilitate the detection of temporal patterns, LOWESS smoothing is applied in panels B, D, and F. A relatively low tension = 0.3 (i.e. 30% of the span of data are used for the estimate of each smoothed Y value) is used to allow for more sensitive flexing of the smoothed line. As noted earlier, the heightened sensitivity is desirable for this particular application in fisheries management. In a sense, the LOWESS smoothing counterbalances the sensitivity built into the definitions of replacement ratio and relative F, by damping the rates of change and allowing for detection of general trends.

The final point to note is that the 6 panel plot may allow one to develop a reasonable picture of the population dynamics in relation to exploitation. With the exception of a brief period in the late-1970s the replacement rate for GOM haddock was below 1 and continued its downward trend until 1990 (Panel A). This was accompanied by a continuously decreasing population size (Panel D). The reduction in landings from nearly 8000 tons in 1984 to less than 500 tons by 1989 (Panel E) greatly reduced the relative F (Panel F) below the threshold level and subsequently led to the replacement ratio exceeding one. The inter-relationships among Panels B, D, and F resemble the kinetics of simple chemical reactions and conceptually one should look for counteracting trends among indices and the influence of the trends in catch and relative survey abundance.

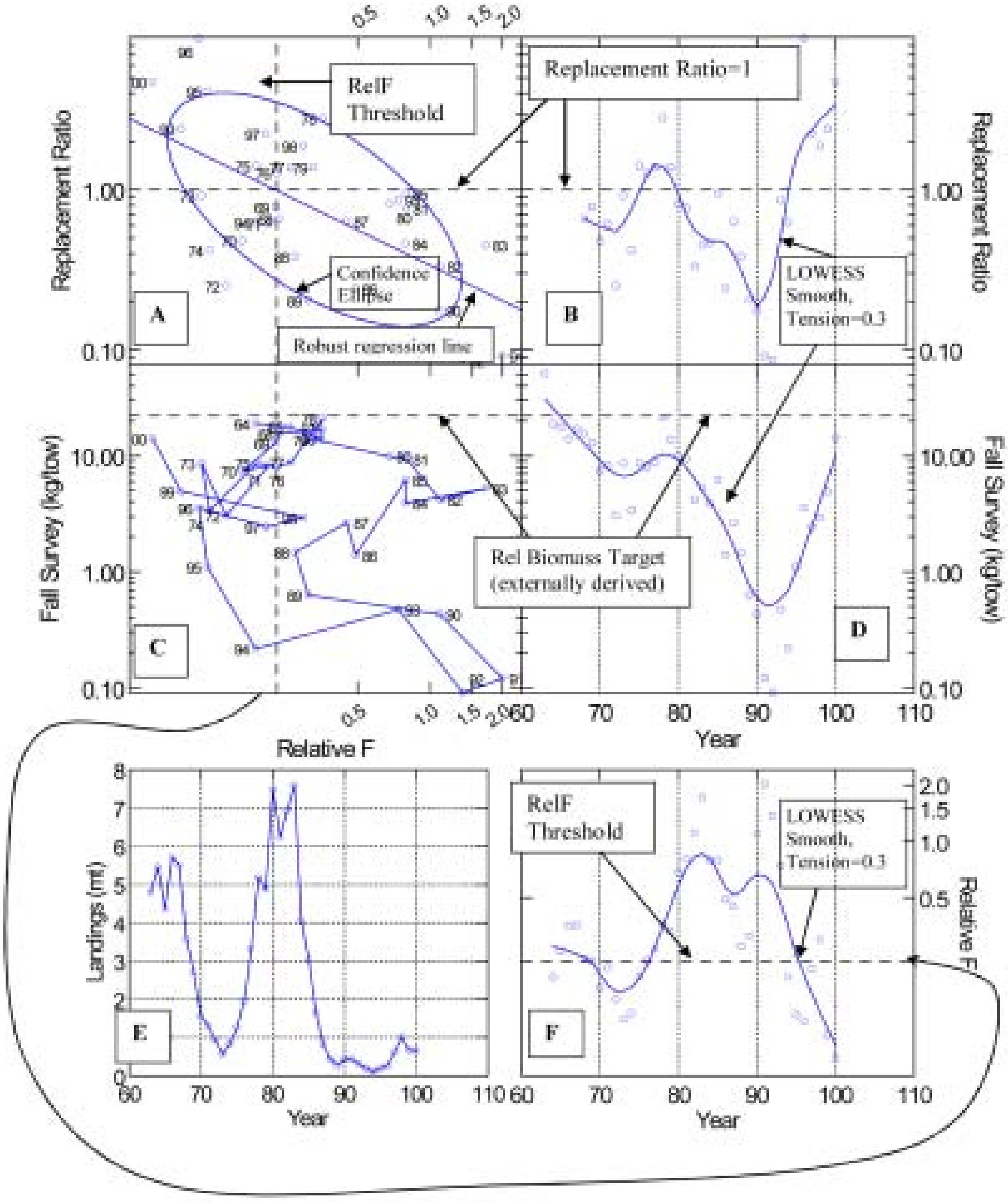

Fig. III.1.1. Annotated six-panel plot depicting trends in relative biomass, landings, relative fishing mortality rate (landings/biomass index) and replacement ratios. Horizontal dashed lines (---) represent replacement ratios = 1 in (A) and (B), threshold relF in (F) and target relative biomass in (C) and (D). Vertical dashed lines in (A) and (C) represent the derived relF thresholds. Smooth lines in (B), (D) and (F) are LOWESS smoothes (tension = 0.3). The confidence ellipse in (A) has a nominal probability level of 0.68. The regression line in (A) represents a robust regression using bisquare downweighting of residuals. See text for additional details.

Utility of f_{rep} in the NAFO PA Framework

The relationship of the replacement ratio (f_{rep}) as a proxy F_{msy} was evaluated by comparing reported estimates of f_{rep} to estimates of f_{Mmsy} from ASPIC in the same units as the replacement ratio, catch/survey biomass(see table below). Four pairs of estimates were available for three northwest Atlantic flatfish stocks. Yellowtail flounder in Div. 3LNO (ASPIC in Walsh *et al*., 2002; f_{rep} reported here), Yellowtail flounder in Div. 5Z (NEFSC, 2002a, b) and Winter flounder in Div. 5Z (NEFSC, 2002a, b). The comparisons show that f_{rep} was consistently similar to f_{MSY}, and was 6% less than f_{msy} on average (Fig. III.1.2). The theoretical basis of f_{rep} suggests that it may be a useful proxy for f_{MSY}, if the data used in its estimation come from a period when the stock was fluctuating around B_{msy}. In a peer review of biological reference points for New England groundfish, f_{rep} was proposed as a proxy for F_{msy} for six stocks (Gulf of Maine haddock, Mid-Atlantic yellowtail flounder, pollock, northern windowpane flounder, southern windowpane flounder and ocean pout; NEFSC, 2002b).

Stock	Survey	f_{msy}	f_{rep}	% difference
Yellowtail flounder in Div. 3LNO	spring	0.07	0.06	-6%
Winter flounder in Div. 5Z	fall	1.21	1.18	-3%
Yellowtail flounder in Div. 5Z	spring	2.25	1.96	-13%
Yellowtail flounder in Div. 5Z	fall	2.43	2.42	-1%
				mean -6%

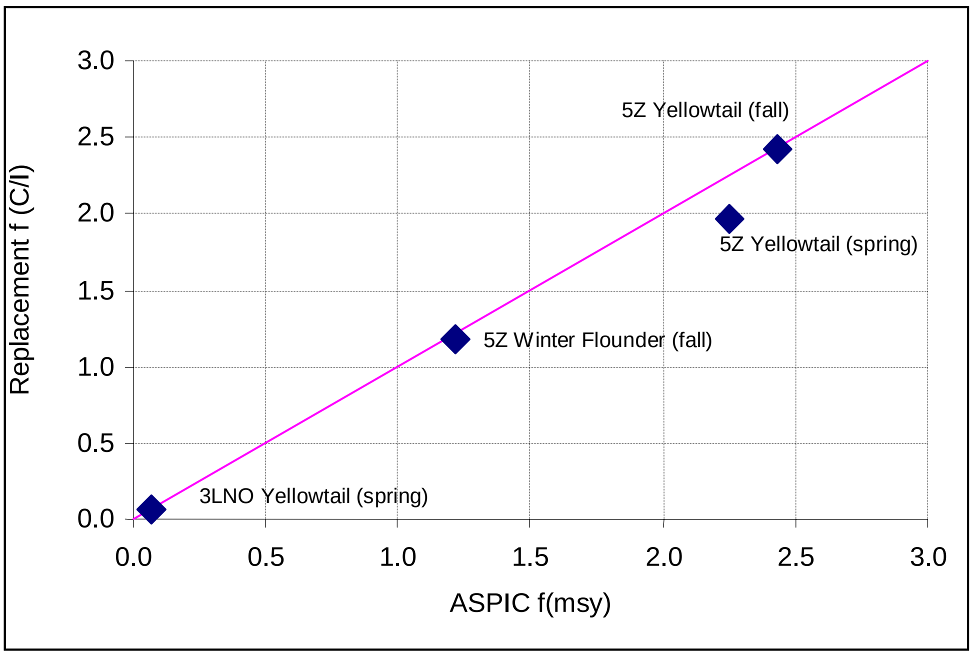

Fig. III.1.2. Comparison of ASPIC f(msy) and Replacement Ratio.

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2. Segmented Regression

The segmented regression method to estimate Biological Reference Points proposed in ICES (2002) was defined as "an objective statistical method for identifying S*, the specific value of SSB below which recruitment is impaired". The method was described in a working document in ICES (2002)(O'Brien and Maxwell, 2002. "Towards an operational implementation of the Precautionary Approach within ICES – biomass reference points" Working Document 8).

The approach is to fit a segmented regression to the current assessment data, identify the changepoint of the stock recruitment curve where recruitment is impaired, and its confidence limits, and designate this as a candidate for B_{lim}.

This method involves fitting linear regressions where the coefficients are allowed to change at given points. For one unknown change point or delta (δ) the segmented regression is defined as:

$$f(x_i) = \begin{cases} \alpha_1 + \beta_1 \chi_i & \text{if } X_0 \le \chi_i \le \delta \\ \alpha_2 + \beta_2 \chi_i & \text{if } \delta \le \chi_i \le X_1 \end{cases}$$

For S-R data the model is simplified, that is, it must pass through the origin ($\alpha_1 = 0$) and after the changepoint the line is horizontal ($\beta_2 = 0$). The biological implications for these assumptions are that before the changepoint the recruitment is somewhat proportional to the SSB and after the changepoint R is independent of any SSB value.

$$f(x_i) = \begin{cases} \beta_1 \chi_i & \text{if } X_0 \le \chi_i \le \delta \\ \alpha_2 & \text{if } \delta \le \chi_i \le X_1 \end{cases}$$

At this Workshop, this method was explored using a version of the segmented regression code in R language (L. Ibaibarriaga, AZTI, Spain, pers. comm).

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3. **Bayesian Production Model**

A new integrated framework for making quantitative assessments, predictions and risk analyses of shrimp (*Pandalus borealis*) stock development was presented. Parameters relevant for the assessment and management of the stock were estimated, based on a stochastic version of a surplus-production model that included an explicit term for predation by cod (*Gadus morhua*). Process and observation error were incorporated simultaneously using a state-space modeling framework. A Bayesian approach was used to construct probability distributions of possible values of model parameters and derived variables relevant for developing management advice – including quantification of future risk of transgressing reference points in relation to alternative management options (Hvingel and Kingsley, 2002).

The model synthesized information from input priors and the following data: a 14-year series of a survey biomass indices of shrimp larger than 17 mm CL (Kanneworff and Wieland, 2002); a 26-year series of combined CPUE indices (Hvingel, 2002); a 47-year series of a cod biomass estimates; and a short series (4 years) of estimates of the shrimp biomass consumed by cod based on stomach sampling (Hvingel and Kingsley, 2002)

Biomass was estimated on a relative scale in order to cancel out the uncertainty of the 'catchability' parameters (the parameters that scale absolute stock size). Biomass, B, is thus measured relative to the biomass that yields Maximum Sustainable Yield, B_{msy}. The estimated mortality, Z, refers to the removal of biomass by fishing and cod predation and is scaled to Z_{msy} – the combined mortality at MSY.

In this approach, buffer reference points are not needed as the risk of exceeding the limit reference can be directly calculated integrating the uncertainty associated with the entire process. Instead of limit reference 'points', limit reference probability 'distributions' were used to accommodate the uncertainty in the determination of where the border to the dangerous area actually lies. Furthermore, the framework can accommodate many types of data and take ecosystem effects into account.

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4. **Stock/Recruitment Model**

Age-based production models derive MSY reference points from stock-recruit models in combination with yield and spawning biomass-per-recruit calculations (Sissenwine and Shepherd, 1987; Mace, 1994). For iteroparous species, equilibrium recruitment at a given fishing mortality rate (R_F*) can be derived by replacing S in any stock-recruit function with ($SPR_F \cong R_F$*) where SPR_F is the SSB per recruit at the given F. For example, for a Beverton-Holt function,

$$R = (\forall S)/(\exists + S)$$

equilibrium recruitment can be calculated for each value of F:

$$R^*_F = (\forall SPR_F - \exists)/SPR_F$$

Equilibrium yield (Y^*_F) at each F can be derived as the product of YPR_F and R^*_F, and equilibrium spawning stock (S^*_F) can be derived as the product of SPR_F and R^*_F. Yield curves can be plotted as functions of F or stock size. The F that produces the greatest Y* is the estimate of F_{msy}, and the S^*_F at F_{msy} is the estimate of SSB_{msy}. One important diagnostic for such age-based production models is the comparison of equilibrium expectations to observed stock dynamics, with respect to historical SSB, F and yield. Age-based production models were explored for American plaice in Div. 3LNO, cod in Div. 3NO, redfish in Div. 3M and cod in Div. 3M.

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5. Serebryakov Method

$B_{50\%R90\%Surv}$ is defined as the level of SSB corresponding to the intersection of the 90th percentile of observed survival rate (i.e. the F corresponding to the replacement line for which 10% of the S-R data points are above the line) and the 50th percentile of the recruitment observations. This approach was suggested by Serebryakov (1991) and Shepherd (1991) as providing a widely applicable and useful definition of the critical level of SSB. The definition of "critical" provided by Serebryakov (1991) is the SSB that provides for the appearance of strong year-classes only in the best survival conditions, but fails to ensure average year class strength under average survival conditions. $SSB_{50\%R90\%Surv}$ is the point below which the population fails to produce average recruitment under good early-stage survival conditions. This method has the advantage of not requiring the fitting of a stock-recruit model and attempts to consider the impact of environmental conditions on early stage survival. However it is sensitive to the addition of stock-recruit pairs which may be a particular problem at low stock size.

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6. SSB at 50% Maximum Recruitment

$SSB_{50\%Rmax}$ is defined as the level of SSB at which average recruitment is one half of the maximum of the underlying stock-recruit relationship, it is the point below which the population fails, on average, to produce half the maximum recruitment. The level of SSB is found by first fitting a stock-recruit relationship and finding the maximum predicted recruitment. $SSB_{50\%Rmax}$ is then simply the SSB at half of the maximum predicted recruitment. This level of SSB has been suggested by Mace (1994) as a threshold biomass. She considered that, because estimates of this quantity are unlikely to be conservative, it should be considered as an absolute boundary not to be crossed. Myers *et al*. (1994), in an investigation of methods for estimating spawner biomass thresholds for recruitment overfishing applied to stock-recruit data for 72 fish stocks, concluded that, although arbitrary, $SSB_{50\%Rmax}$ is relatively robust if only data at low stock sizes are available (not always the case with other limit reference points). Myers *et al.* (1994) also found that higher levels of recruitment usually occur at SSB values above this biomass, so by inference productivity is impaired below this level. However, this approach is very sensitive to the uncertainty in stock-recruit model fits, particularly where the asymptote or peak is poorly defined (i.e. data mostly from the descending limb of a stock-recruit curve).

References

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7. Non-Parametric Smoother

An alternative way of thinking about impaired productivity and recruitment overfishing was developed in the CSAS November 2002 Workshop (Rivard and Rice, 2003). Under this approach B_{lim} can be defined, in terms of impaired productivity, as the SSB below which the probability of poor recruitment either increases sharply or rises above a predetermined probability level. The non-parametric kernel smoother approach applied to modeling stock-recruit data by Rice and Evans (1986, 1988) and Evans and Rice (1988) is particularly suitable for this kind of analysis because the kernel is a pdf (e.g. Gaussian, Cauchy, etc.) that provides the probability of any previously observed R at any specified level of SSB.

Locally weighted regression smoother (LOWESS) has been applied to S-R data in ICES, but the next step of deriving recruitment probabilities at a particular stock size from the tricube weighting function with the assumed span has not been investigated in ICES. The non-parametric kernel approach has been applied extensively to the Div. 2J+3KL cod stock (Rice and Evans, 1986, 1988; Shelton and Morgan, 1993, 1994) and in the assessment of the cod stock in Div. 3NO (Stansbury *et al.*, 1999; Rivard *et al.*, 1999) to obtain recruitment probabilities at different SSB levels. The Rice-Evans method appears to perform well and a cross-validation prediction sums of squares method using the kernel weighted mean as the predictor can be used to obtain the optimal shape parameter for the pdf. Generally, clear minima for both Cauchy and Gaussian distributions are found – the only two that have been examined in the context of the cod S-R data.

Having obtained a non-parametric smoother that allows the probability of recruitment to be computed at any SSB level in the range of observed data, it follows that the method can also be used to compute the probability of recruitment being less than or equal to any particular value. If poor recruitment can be defined, such as for example the 10^{th} percentile of observed recruitment values, then the probability of recruitment being less than or equal to the 10^{th} percentile value can be used to define a B_{lim}. B_{lim} could be defined as the point below which the probability of poor recruitment increases substantially with further decrease in SSB. Alternatively, B_{lim} could be the point at which the probability of poor recruitment rises to some level, for example 0.5.

The non-parametric approach is easy to apply to any set of S-R data. The statistics involved in applying the method constitute nothing more complicated than computing a weighted mean. A suite of SAS code programs for carrying out the necessary steps and plotting the results are available (sheltonp@dfo-mpo.gc.ca) and can be easily modified for any stock-recruit data set. One noted advantage is that the method translates what might look like a somewhat flat smoother through the recruitment data to a probability profile for poor recruitment that often has some distinct features useful in applying the Precautionary Approach. The method is applied to cod in Div. 3NO in Section IV.3 below as an example, and to illustrate the steps involved and the results that can be obtained.

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IV. Application to NAFO Stocks

1. Greenland Halibut in Subarea 2 and Div. 3KLMNO

a) Replacement Ratio Method

This method was applied to the total commercial catches of Greenland halibut throughout Subarea 2 and Div. 3KLMNO and the Canadian fall surveys in Div. 2J and 3K during 1978-2001 (Fig. IV.1.1). Since the surveys are conducted near the end of the year the commercial catches were lagged by one year in comparison to the survey data.

Based upon the description of the method described above, the annual replacement ratios were estimated as the ratio of the current stock size estimate divided by the average of the stock size estimates from the five previous years. This was considered to provide a reasonable approximation of replacement rate given the life history of the species. The relative F estimates were computed as the ratio of the current catch divided by a centered 3-year average of relative abundance. This degree of smoothing was judged to be reasonable especially since the development of the survey index for Greenland halibut was generally systematic with no major fluctuations between years.

Estimates of relative F show a marked increase between 1991 and 1994 resulting from a rapid increase in catches complemented by a declining stock size index. Relative F during this period was 4-5 higher than other years in the time series. A general decline in stock abundance appeared to commence about 1985, at a time immediately prior to the large increase in catches. Several above average year classes during the mid-1990s, combined with a sharp decline in relative F resulted in a rapid rate of increase in the stock during the late-1990s. The replacement ratio in the late-1990s exceeded a value of 1.0 but appears to have declined to near 1.0 in the most recent two years. A replacement ratio of 1.0 occurs when the fishing mortality rate is in balance with recruitment and growth.

The relationship between the replacement ratio and relative F shows a reasonably high degree of coherence with an underlying correlation of –0.67. The randomization test for spurious correlation suggests an expected median correlation of –0.19 and a significance level <0.01. In other words, the randomization test suggests that the association between the replacement ratio and the relative F is not simply an artifact of the data manipulations. A relative F =1.08 corresponding to a replacement ratio of 1.0 defines the replacement F. Therefore, when the replacement F is multiplied by a survey index that best represents current stock size, an estimate of catch, which allows for stock stability is obtained. Based on the results presented here, the model indicates that the relative F has exceeded the replacement F by about 35% in the last two years.

There are a number of important factors to consider when applying the replacement ratio methodology. For Greenland halibut, above average recruitment during a period of low adult stock size may have artificially inflated the estimates of the replacement ratio. The robust regression method downweights the importance of such estimates but cannot eliminate their influence entirely. Another important consideration is the issue of population closure. Removals are assumed to occur from the area surveyed and large deviations from this basic tenet could be problematic. Nevertheless, for Greenland halibut this factor is thought not to be too problematic since the survey series used here is believed to track the status of the resource throughout the area reasonably well.

The estimation of relative F at replacement provides an objective means of estimating an appropriate level of fishing. This exploitation rate is independent of stock size in the vicinity of the average stock size observed. The combination of statistical graphics and randomization tests provide a measure of the uncertainty of the results. In particular it is noted that the model may be useful for characterizing the relative risk of alternative catch levels to the population status.

Within the range of the data set analyzed here it is considered that the estimated replacement F (frep) is a reasonable proxy for the commonly used biological reference point F_{rep}. For several other stocks it has been noted that f_{rep} from similar analyses could also be representative of F_{msy} as described in Section III.1 above. However, without a more thorough examination of the stock dynamics it is premature to infer any such relationship between f_{rep} and F_{msy} for Greenland halibut.

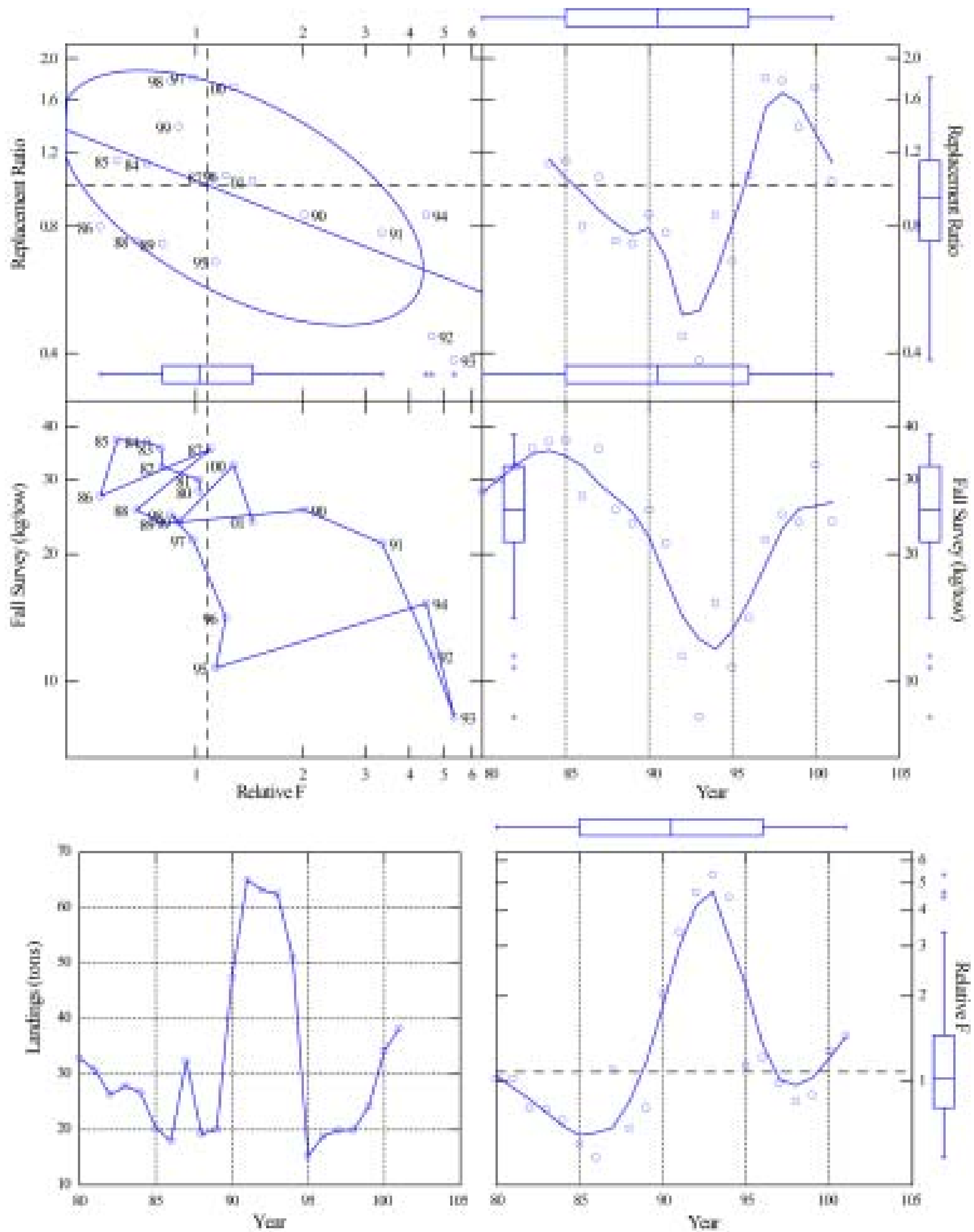

Fig. IV.1.1 Trends in relative biomass, estimated catches, relative fishing mortality rate (estimated catches/index) and replacement ratios for Subarea 2 and Div. 3KLMNO Greenland halibut, using the fall survey series in Div. 2J and 3K and estimated catches. Horizontal dashed lines represent replacement ratios = 1. The confidence ellipse has a nominal probability level of 0.68, and the diagonal line uses a robust regression estimator. (See section III.1 for full description).

2. American plaice in Div. 3LNO

The current B_{lim} for American plaice in Div. 3LNO of 50 000 tons is based on a visual examination of the stock recruit scatter from the VPA which indicates that there was no good recruitment below this level (Morgan et al 2002, Fig IV 2.1). This was based on recruitment at age 5 which is the first age in the VPA. Further analyses were conducted in an attempt to examine the validity of this B_{lim}.

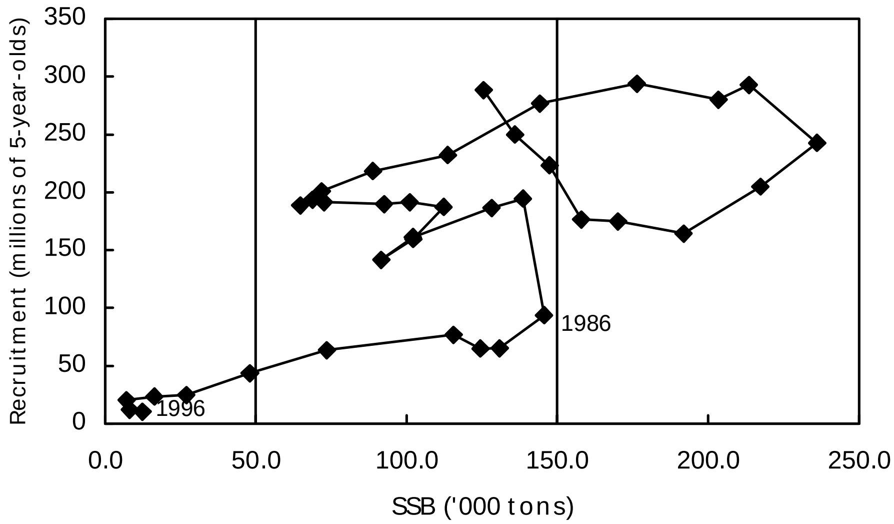

Fig. IV.2.1 American plaice in Div. 3LNO: stock-recruit scatter. The vertical lines indicate the three zones of recruitment: below 50 000 tons where only poor recruitment is observed, between 50 and 150 000 tons where both poor and good recruitment is observed, and above 150 000 tons where only good recruitment is observed.

a) SSB at 50% Maximum Recruitment (age 5 recruits)

The SSB which produced 50% of the maximum recruitment was determined by fitting a Beverton-Holt stock recruit relationship to the data by maximum likelihood. The asymptote of the relationship lies well outside the range of the observed data (Fig. IV 2.2). 50% R_{max} was estimated to be 415 million 5 year olds and the SSB giving this level of recruitment was 425 000 tons. This is not likely to be a realistic value given that the asymptote of the relationship is beyond the range of the data and given the history of the stock.

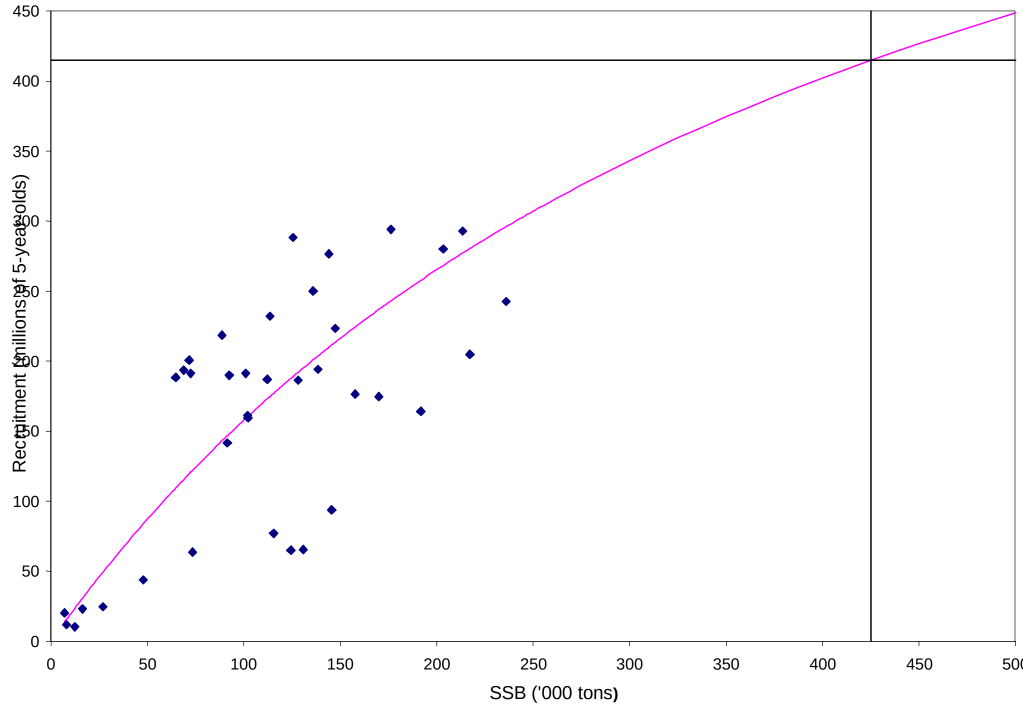

Fig. IV.2.2 American plaice in Div. 3LNO: stock-recruit scatter with fitted Beverton-Holt stock recruit curve. The horizontal line indicates 50% of maximum recruitment and the vertical line shows the SSB which gives this level of recruitment.

b) **Serebryakov Method (age 5 recruits)**

The stock-recruit scatter was also used to derive the SSB at $B_{50\%R90\%survival}$ (Fig. IV 2.3). This indicates that a limit reference point for this stock would be 70 000 tons of SSB. This is in close agreement with the visual inspection of the stock-recruit scatter given that there are no stock-recruit pairs between 50 000 and 65 000 tons. However, this may not be a good method at low stock size for reasons stated in Section III.5.

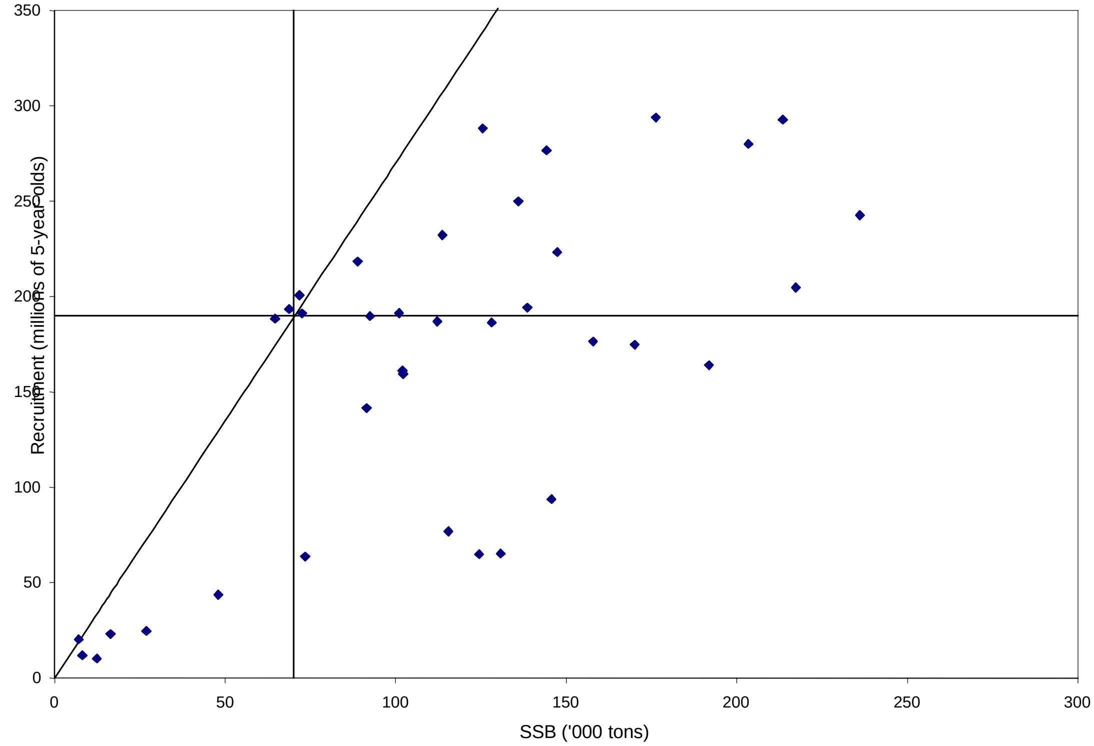

Fig. IV.2.3 American plaice in Div. 3LNO: stock-recruit scatter. The horizontal line represents the median level of recruitment. The line through the origin bisects the scatter so that 10% of the recruitments are above the line.

c) **YPR – SPR**

Yield-per-recruit (YPR) and spawner-per-recruit (SPR) analyses were run to estimate $F_{0.1}$ and F at 35% SPR using current values of average weights-at-age, maturities-at-age and partial recruitment-at-age. These values were the same as those used in the projections conducted in Morgan *et al.* (2002). These analyses indicated that $F_{0.1}$ is 0.2 and that F at 35% SPR is 0.25 (Fig. IV.2.4).

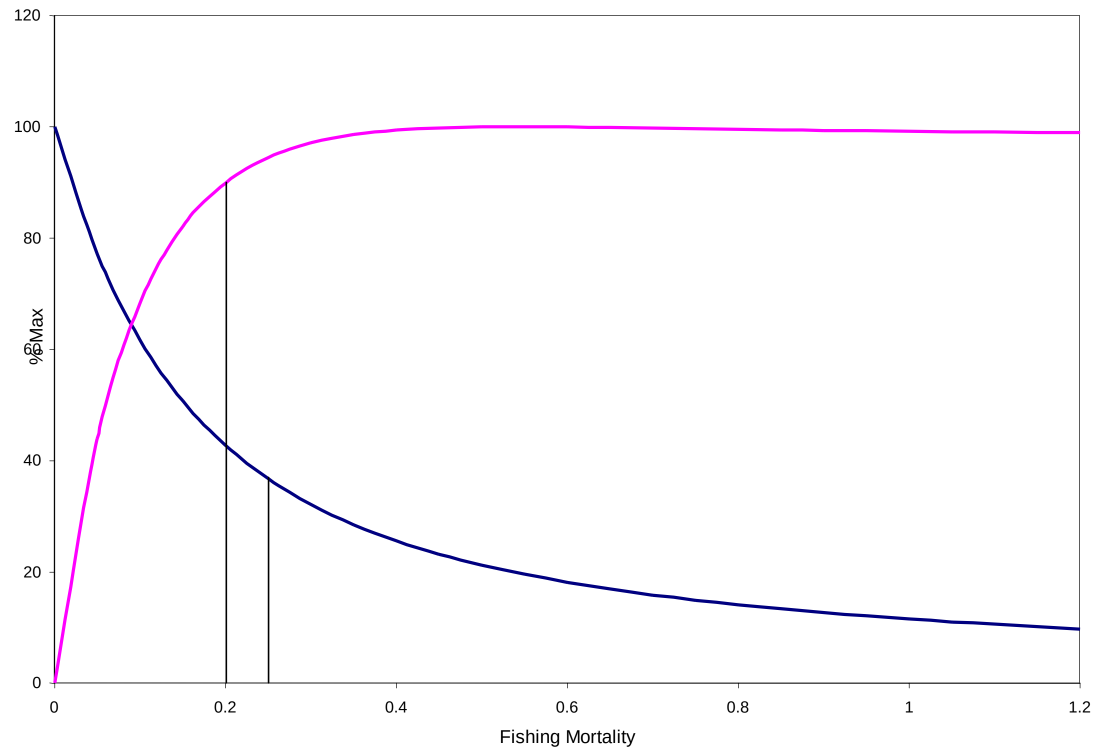

Fig. IV.2.4. American plaice in Div. 3LNO: yield-per-recruit and spawner-per-recruit. The vertical dotted line represents $F_{0.1}$ and the vertical solid line represents the F at 35% maximum spawner-per- recruit.

d) **Age-based Production Model (age 0 recruits)**

Stock-recruit observations for the 1960-1996 cohorts were obtained from Morgan *et al.* (2002). However, estimates of age-5 recruits (N_5) were adjusted to age-0 recruits (N_0) according to natural mortality (M = 0.2 for 1960-1988, M = 0.53 for 1989-1996):

$$N_{0+t} = N_{5,t+5}\, e^{(M_{t+1}+M_{t+2}+M_{t+3}+M_{t+4}+M_{t+5})}$$

The adjusted recruitment values provided a different perception of the stock-recruit relationship, particularly with respect to the 1989-1991 cohorts (Fig. IV.2.5). A Beverton-Holt relationship (see Section III.4) was fit to the observed data with lognormal error. Yield and spawning biomass-per-recruit were calculated using the mean weights at age, maturity and partial recruitment reported in Morgan *et al.* (2002) for medium-term projections.

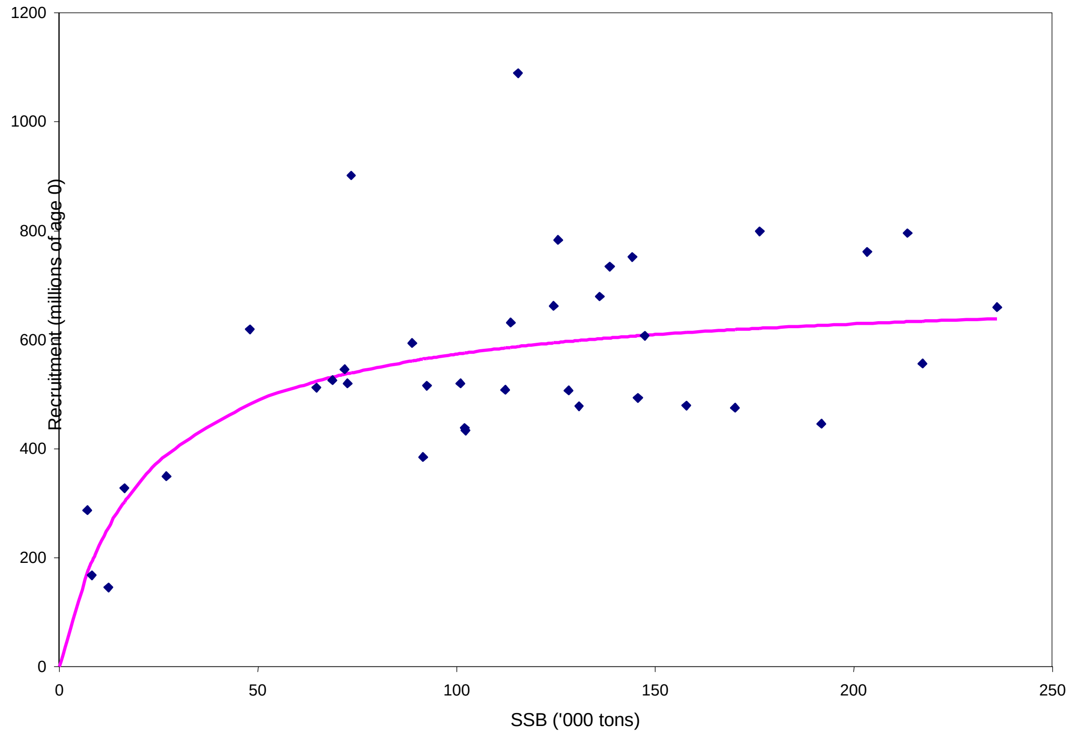

Fig. IV.2.5. American plaice in Div. 3LNO: stock-recruit observations and Beverton-Holt model predictions, 1960-1996 where recruitment is adjusted to age 0.

Equilibrium recruitment, yield and SSB were calculated for each value of F (see Section III.4). Production curves indicate that F_{msy} = 0.33 and SSB_{msy} =1 75 000 tons (Fig. IV.2.6). These reference points are consistent with historical productivity and other reference points for the stock (e.g. $F_{0.1}$ = 0.20, B_{lim} = 50 000 tons).

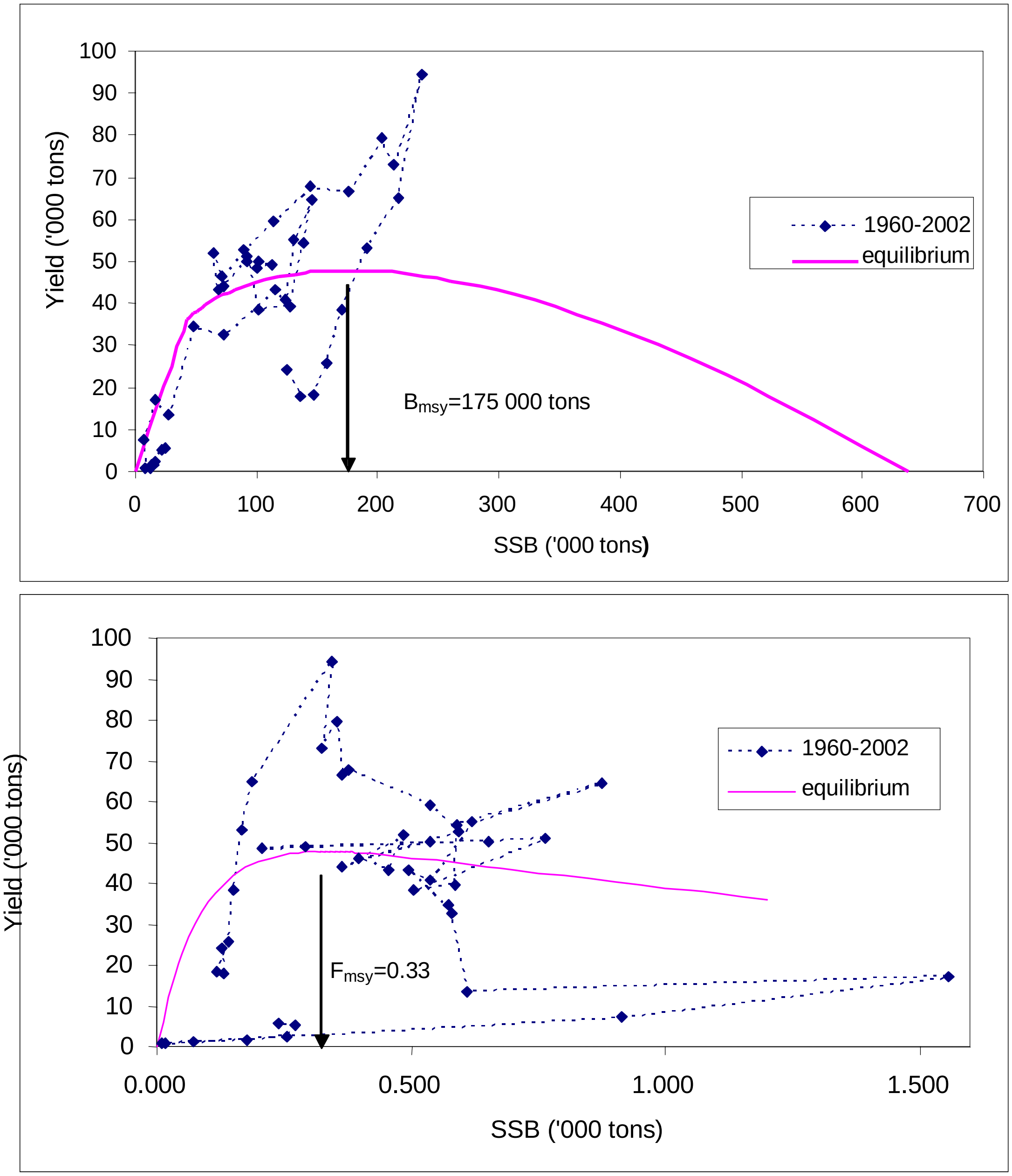

Fig. IV.2.6. American plaice in Div. 3LNO: equilibrium yield expectations from an age-based production model, with historic observations of catch, F and SSB, 1960-1996.

There was some concern about the accuracy of the level of M, its application to young ages and the resulting perception of strong recruitment from 1989 to 1991. Sensitivity analyses were completed to assess the effect of those cohorts on the age-based production model. The estimate of F_{msy} was not sensitive to the exclusion of those observations, and estimates of B_{msy} and MSY changed by five percent or less. Information on year-class strength from surveys was investigated to confirm the magnitude of calculated recruitment through graphical comparisons and correlations. Results indicated good agreement of survey indices and calculated abundance at ages 3 and 4, but less agreement at younger ages (with fall surveys agreeing with calculated recruitment more than spring indices).

Given the robustness of F_{msy} reference points to the observed recruitment from 1989 to 1991, the estimate (0.33 on ages 11+) as F_{lim} may be appropriate. However, further research is **recommended** to refine stock-recruit modeling, such as continued analysis on the estimation of M and exploration of trends in spawning potential (e.g. age structure and geographic distribution of the spawning stock) that may refute the perception of high reproductive potential (R/S) since the late-1980s.

The estimate of B_{msy} (175 000 tons SSB) may also serve as a provisional reference point. Given the current state of the resource (23 000 tons SSB in 2002, F = 0.24 in 2001), imprecision in the estimate will not affect short-term management. The provisional estimate can be re-evaluated as the stock rebuilds and provides more observations of recruitment at intermediate stock sizes.

e) **SSB at 50% Maximum Recruitment (age 0 recruits)**

Given the stock recruit series described above the SSB which would produce 50% of the maximum recruitment was recalculated using recruitment at age zero calculated as above. 50% R_{max} was estimated to be 360 million recruits at age 0 and the SSB giving this level of recruitment was 21 000 tons (Fig. IV 2.7).

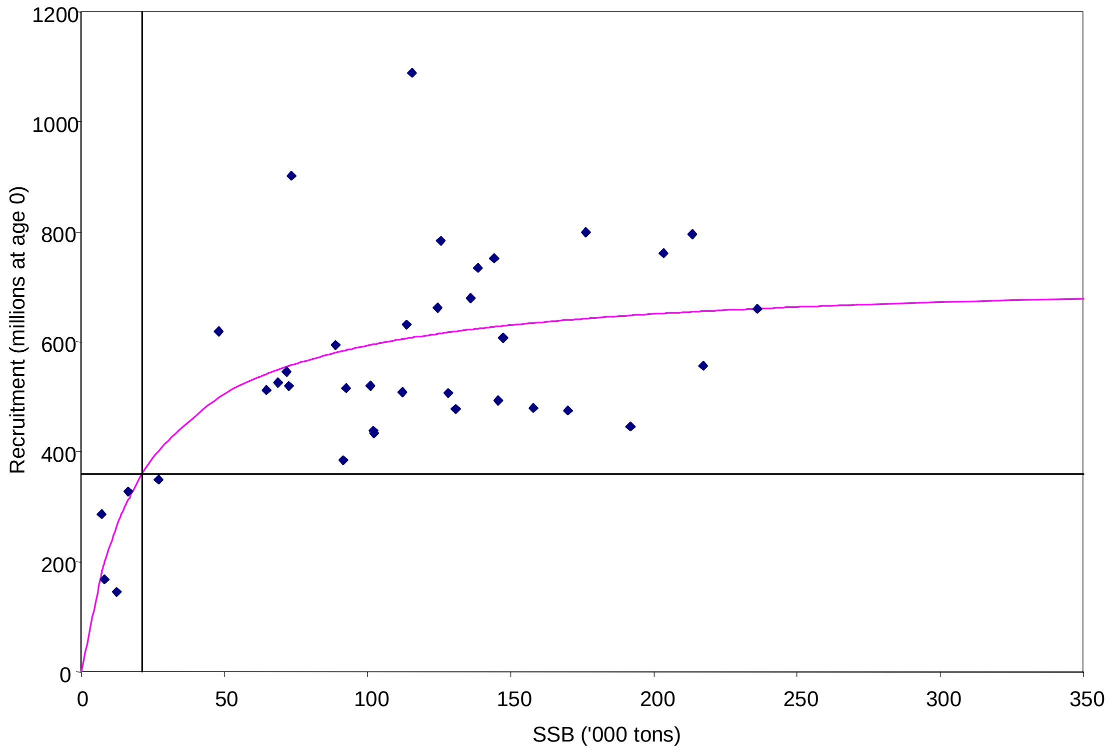

Fig. IV.2.7 American plaice in Div. 3LNO: stock-recruit scatter with fitted Beverton-Holt stock recruit curve. Recruits have been adjusted to age zero. The horizontal line indicates 50% of maximum recruitment and the vertical line shows the SSB which gives this level of recruitment.

f) **Serebryakov Method (age 0 recruits)**

The adjusted stock recruit scatter was also used to derive the SSB at $B_{50\%R90\%survival}$ (Fig. IV 2.8). This indicates that a limit reference point for this stock would be 40 000 tons of SSB.

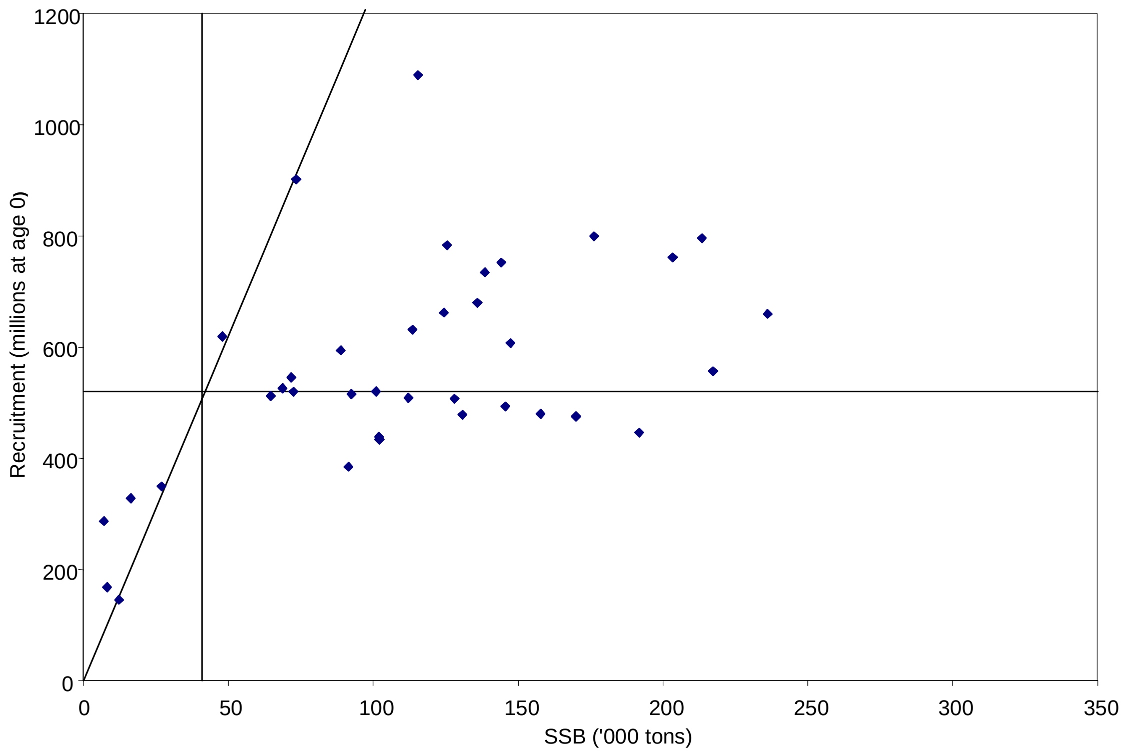

Fig. IV.2.8 American plaice in Div. 3LNO: stock-recruit scatter. Recruits have been adjusted to age 0. The horizontal line represents the median level of recruitment. The line through the origin bisects the scatter so that 10% of the recruitments are above the line.

g) **Segmented Regression**

A segmented regression was fit to the stock-recruit observations with recruits as millions of 5 year olds. However, the fit of the model was very poor. The estimated change point in this analysis was 121 000 tons.

A second segmented regression (see Section III.2) was fit to the stock-recruit data with the recruits adjusted to age 0 as above. The segmented regression fit is statistically significant at the 95% level of significance (p-value = 0), and the model explains 52% of variability in recruitment (coefficient of determination). Maximum likelihood estimate of the change point, the SSB at which recruitment is impaired, is 30 861 tons, and 80% profile likelihood confidence interval is given by 24 644 tons and 36 602 tons (Fig. IV.2.9).

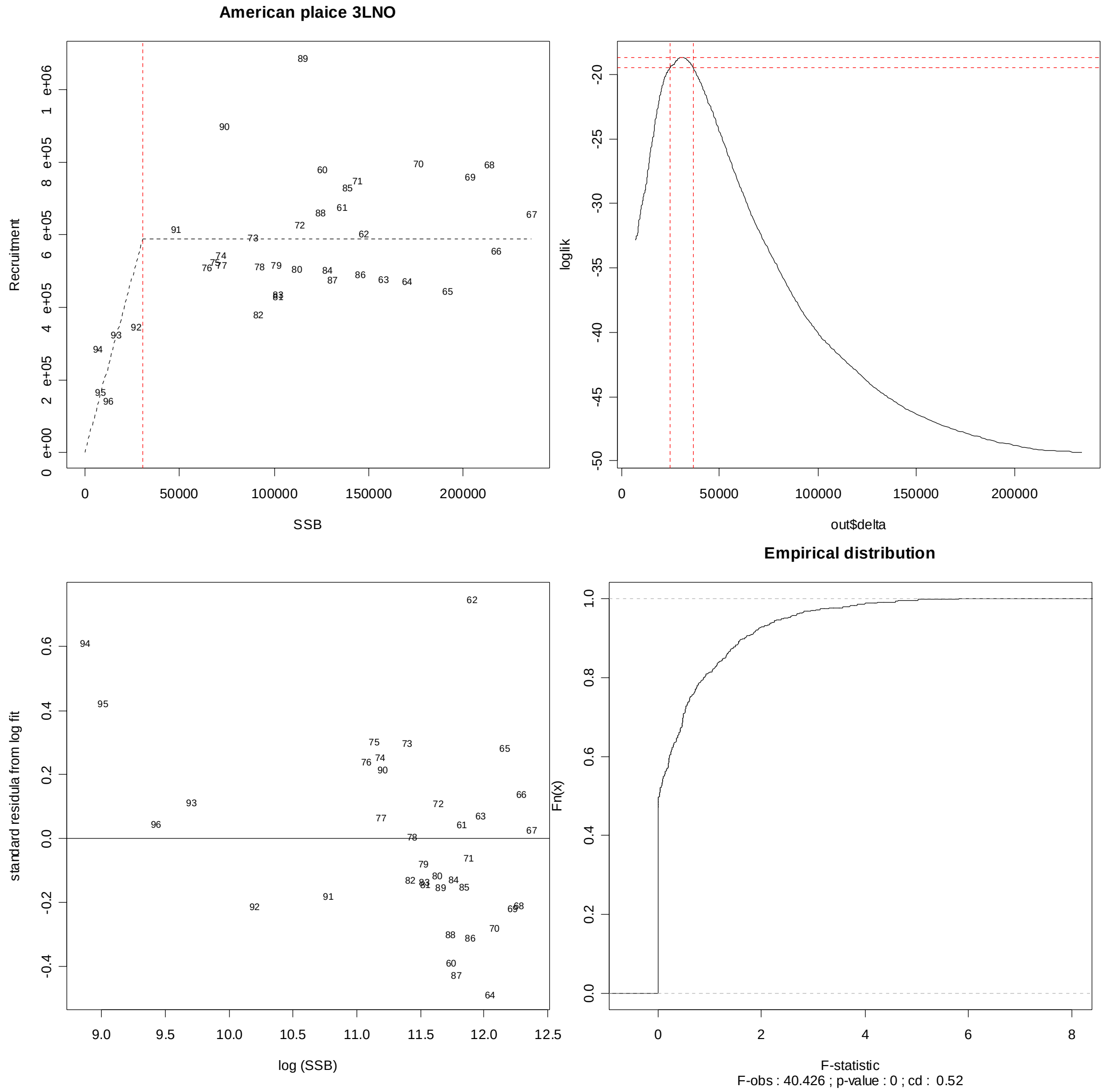

Fig. IV.2.9. American plaice in Div. 3LNO: Top left: stock-recruitment pairs identified by year-class, the segmented regression fitted model (dotted line) with the change point (vertical line). Top right: profile likelihood for changepoint (lower horizontal line – 80% likelihood ratio confidence interval for changepoint). Bottom left: standardized residuals *vs* SSB. Bottom right: bootstrapped empirical distribution of the F statistic *vs* the F observed. The corresponding p value and coefficient of determination are also given.

Sensitivity analyses of the segmented regression were also made to analyze the robustness and sensitivity of this method to the stock recruitment data analyzed (Fig. IV.2.10). This was performed to find out whether change points are stable and robust. This analysis was made eliminating a single year-class in turn and adding consecutively one year for the last years of the S-R time-series.

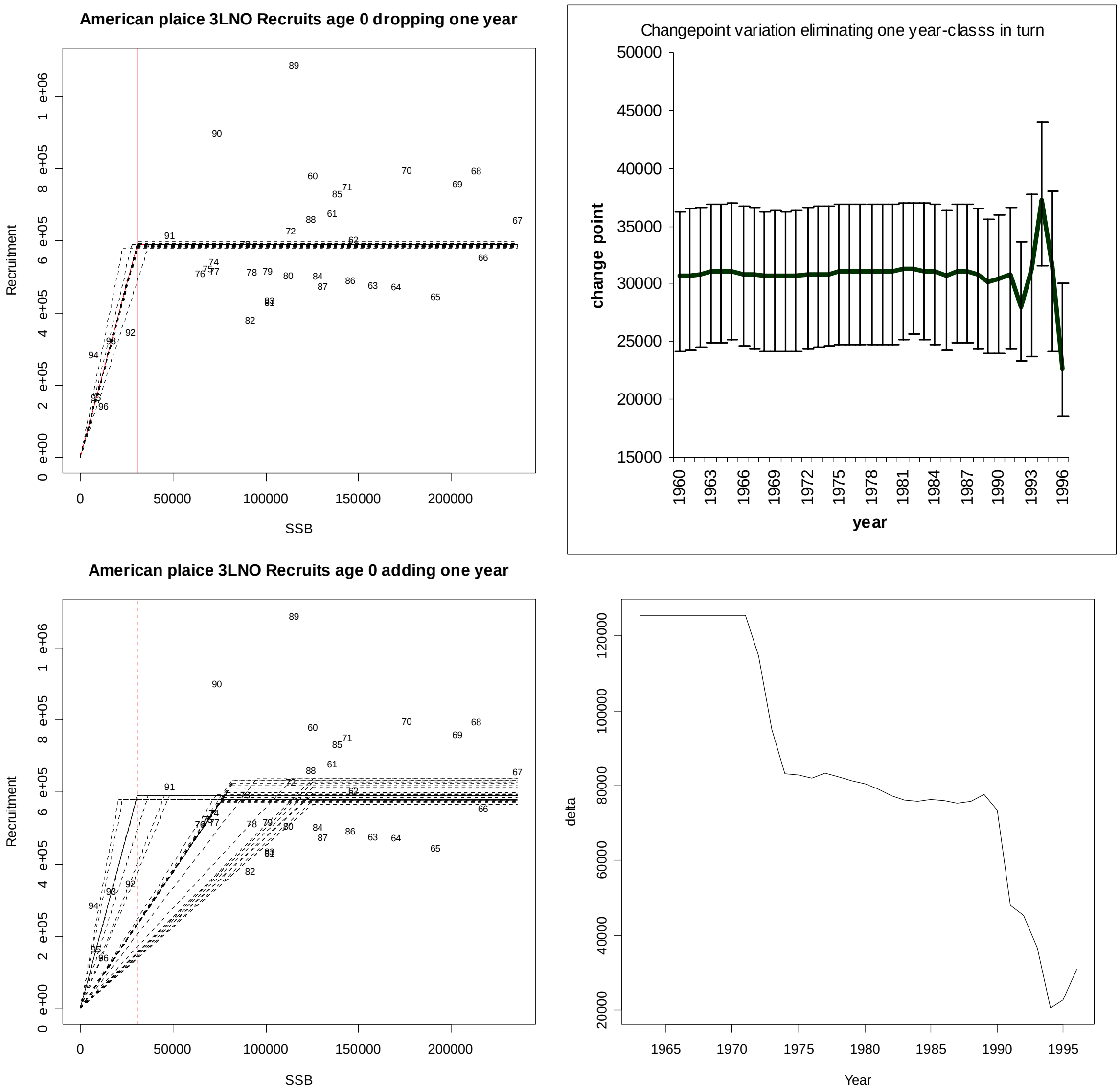

Fig. IV.2.10. American plaice in Div. 3LNO: Top left: stock-recruitment pairs identified by year-class; red solid line is the segmented regression model; and dotted lines are the changepoint models estimated by eliminating a single year-class in turn. Top right: changepoint *vs* eliminated year-class with 80% confidence interval. Bottom left: stock-recruitment pairs identified by year-class; solid line is the segmented regression model; and dotted lines are the changepoint models estimated by adding consecutively one year to the S-R time-series. Bottom right: changepoint *vs* added year-class

The analysis eliminating a single year-class in turn showed that the change point was rather stable, although change points vary when the 1994 and 1996 year-class are eliminated. The analysis of adding one year-class consecutively shows that there could be different productivity regimes in the time series. When the most recent year-classes are not used in the analysis the change point is greater than 70 000 tons indicating that these year-classes have a strong influence on the estimation of the change point.

h) Replacement Ratio Method

Catch and survey biomass reported in Morgan *et al.* (2002) were used to explore biomass dynamics of American plaice in Div. 3LNO. The data series is essentially a "one-way trip" with a recent period of slight rebuilding (Fig. IV.2.11). However, the effect of the recent increase in M for this stock is illustrated in the second panel on the left in which the survey biomass index is declining during a period of what appears to be a fairly constant relative F. This confounds the estimate of f_{rep}.

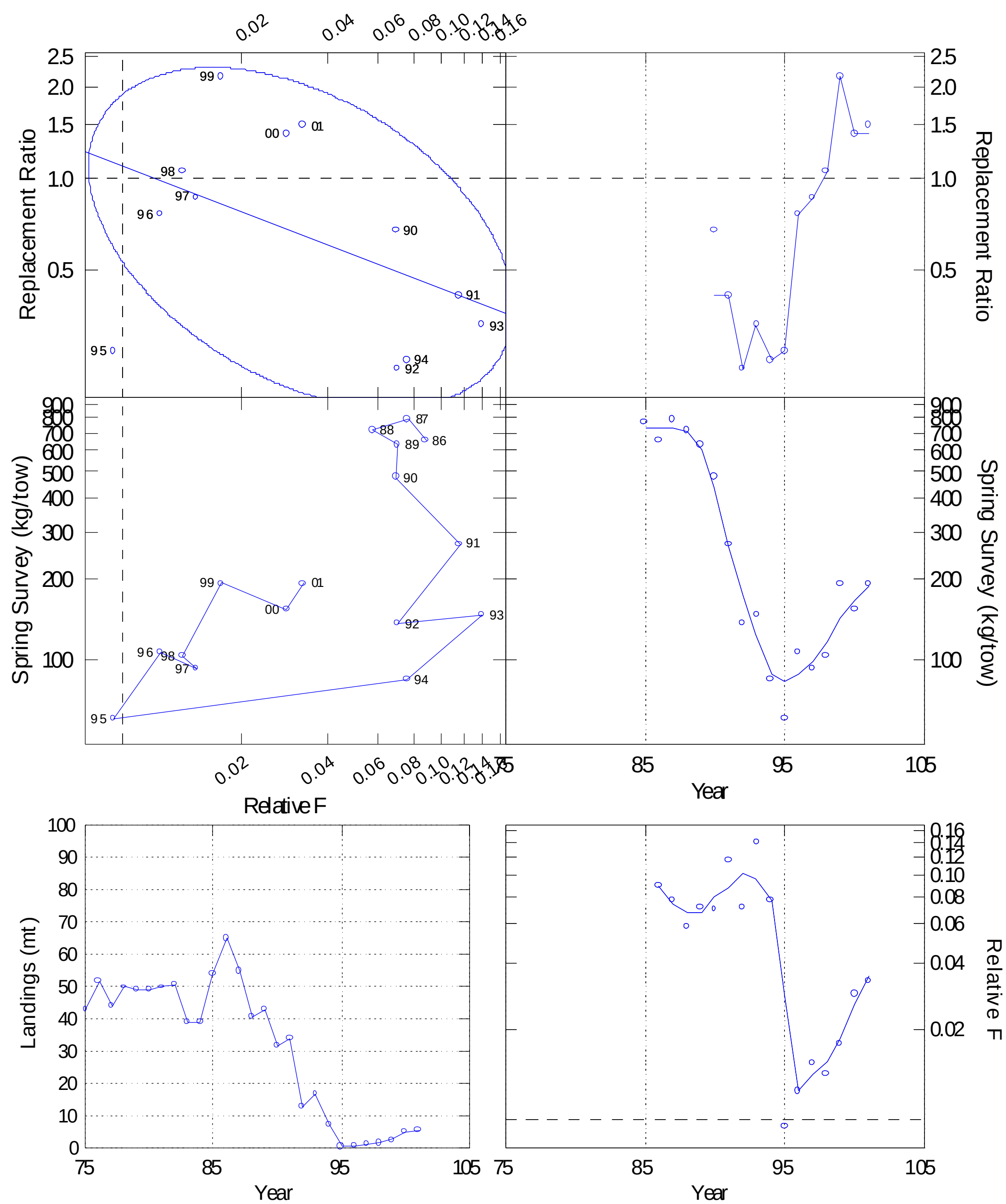

Fig. IV.2.11. American plaice in Div. 3LNO: trends in relative biomass, landings, relative fishing mortality rate (landings/index) and replacement ratios, using the spring survey and landings. Horizontal dashed lines represent replacement ratios = 1. The confidence ellipse has a nominal probability level of 0.68, and the diagonal line uses a robust regression estimator. (See section III.1 for full description).

Summary

The various analyses conducted here would indicate a B_{lim} in the range of 20 000 tons to 70 000 tons, bracketing the current B_{lim} of 50 000 tons. A possible candidate limit F reference point could be $F_{msy,}$ estimated at 0.33. The use of recruitment adjusted to age zero is not definitive and must be examined further.

References

Morgan, M. J., W. B. Brodie, B. P. Healey, D. Maddock Parsons, K. S. Dwyer and D. Power. 2002. An Assessment of American Plaice in NAFO Divisions 3LNO. *NAFO SCR Doc*., No. 70, Serial No. N4683, 68 p.

3. Cod in Div. 3NO

a) Serebryakov Method

The Serebryakov method (Serebryakov, 1991) was applied to the spawning stock-recruit data for the cod stock in Div. 3NO (Fig. IV.3.1). This method uses an intersection of two lines to determine B_{lim}. First, the median recruitment for the stock is computed. Then, a line is constructed through the origin having a slope equal to the 90^{th} percentile of recruits per spawner. Where these two lines intersect, a potential reference point is obtained. However, in a collapsed stock, all stock recruit points for the near future will likely be below both the median recruitment line, and less than the 90^{th} percentile of R/S. These effects may cause the limit reference point derived from the Serebryakov method to change substantially over time with the accumulation of stock-recruit pairs at low stock size and might make the method inappropriate for a collapsed stock.

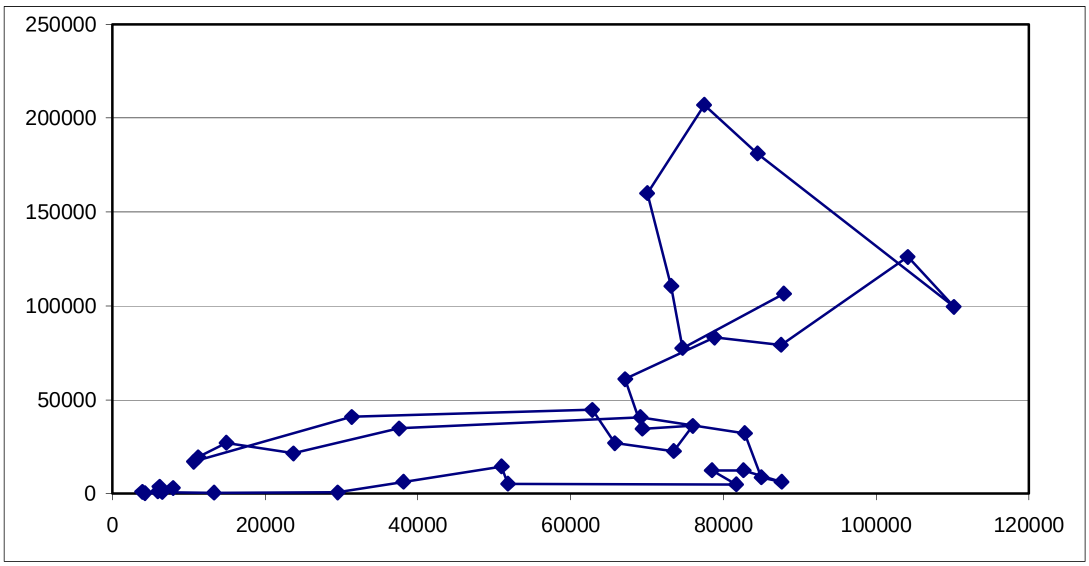

Fig. IV.3.1. Cod in Div. 3NO: stock-recruit scatter from the most recent assessment (Stansbury *et al*., 2001).

b) Replacement Ratio Method

The replacement ratio method was attempted for this stock, but the results were considered uninformative in deciding upon any reference points for the stock because biomass declined continuously during the period covered by the survey.

c) **Bayesian Production Model**

A version of the Bayesian production model (Hvingel and Kingsley, 2002) without a predation term was applied to this cod stock in Div. 3NO. Results indicated that the available input data contained little information with respect to model parameters e.g. MSY and K.

d) **Segmented Regression**

The segmented regression approach (O'Brien and Maxwell, 2002) using an implementation available in the R language (L. Ibaibarriaga, AZTI, Spain, pers. comm.) was explored as a parametric method of modeling the stock-recruit time series for cod in Div. 3NO (Stansbury *et al*., 2001). Using this methodology, the changepoint indicates an SSB level below which stock recruitment is impaired.

The resulting fit from this method is a straight line. It indicates that the changepoint occurs at the highest observed SSB, at about 110 000 tons (Fig. IV.3.2), however, the results are quite tenuous. Sensitivity analyses conducted suggest that using this method, the changepoint could be as low as 20 000 tons. Thus, application of the method to this stock-recruit scatter was considered uninformative for modification of B_{lim}.

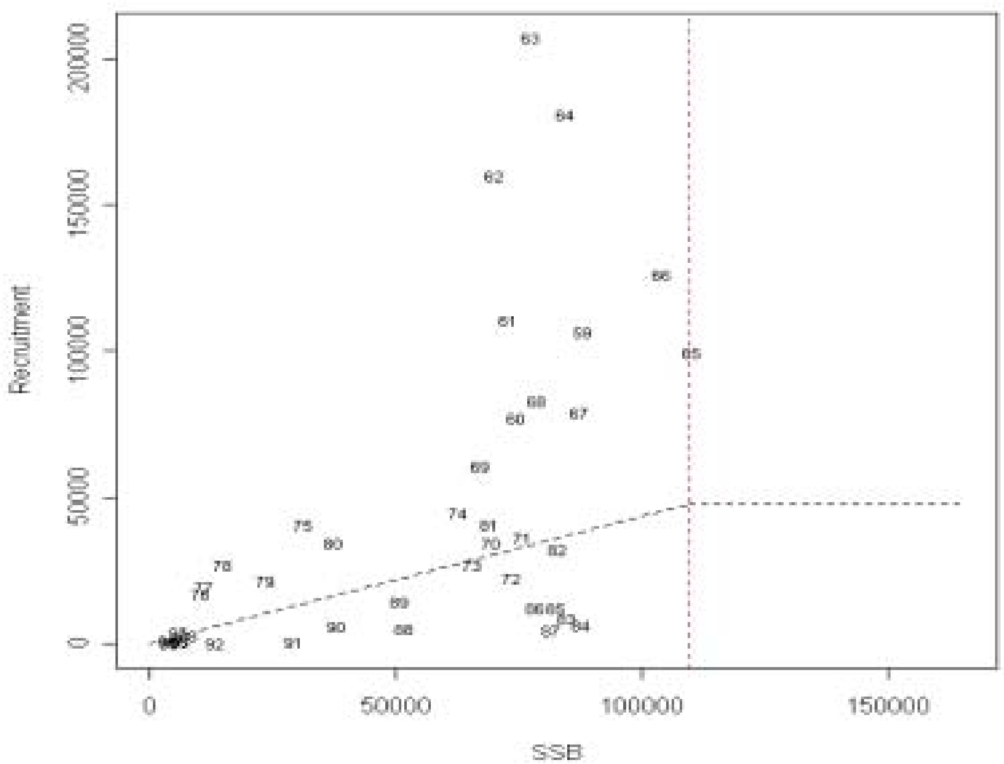

Fig. IV.3.2. Stock-recruit scatter for cod in Div. 3NO, with segmented regression fit. The estimated changepoint occurs at the highest observed Spawning Stock Biomass.

Other parametric stock-recruit models were also examined for this data set. However, the stock-recruit data for cod in Div. 3NO were not amenable to either the Beverton-Holt or Ricker curves, and both model fits were linear and uninformative with respect to amending B_{lim}.

e) **Non-Parametric Methods**

The Rice-Evans non-parametric kernel smoother approach described in Section III.7 was applied to S-R data for cod in Div. 3NO from the most recent assessment (Stansbury *et al.*, 2001). The stock-recruit scatter is shown in Fig. IV.3.1. A Cauchy kernel was selected and the shape parameter was estimated to be 12 800 tons SSB by minimizing the cross-validated prediction sums of squares using the kernel weighted mean as the predictor. The sums of squares surface is shown in Fig. IV.3.3. The resulting smoother is plotted together with the stock-recruit data in Fig. IV.3.4. The 10^{th} percentile of "observed" (SPA estimated) recruitment values was used to define "poor recruitment". This value is 1.074 x 10^6 recruits at age 3. The probability profile for recruitment being less than or equal to this value for the range of observed SSB values is shown in Fig. IV.3.5. The point at which the probability of poor recruitment increases markedly with decreasing SSB is approximately 60 000 tons, using the Cauchy kernel and the 10^{th} percentile of observed recruitments as a definition of "poor recruitment". It is suggested that this be considered as support for the existing B_{lim} of 60 000 tons identified for cod in Div. 3NO in NAFO (1999).

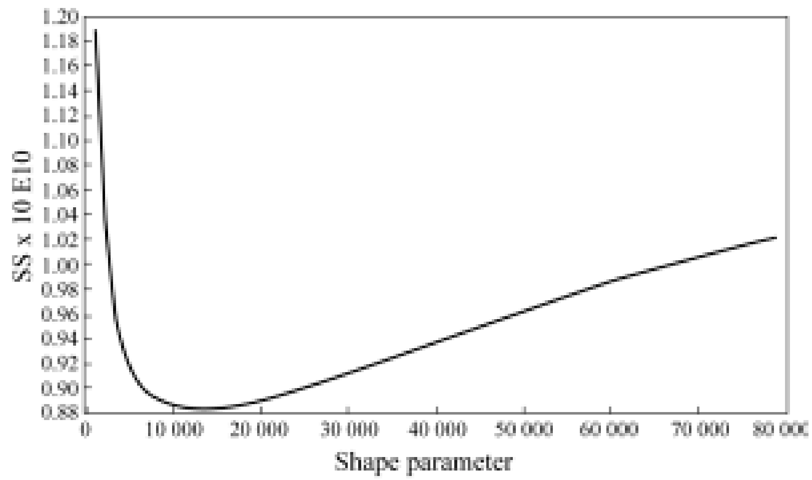

Fig. IV.3.3. Cod in Div. 3NO: the cross-validated prediction sums of squares for the Cauchy kernel weighted smoother in which the predictor is the kernel weighted mean.

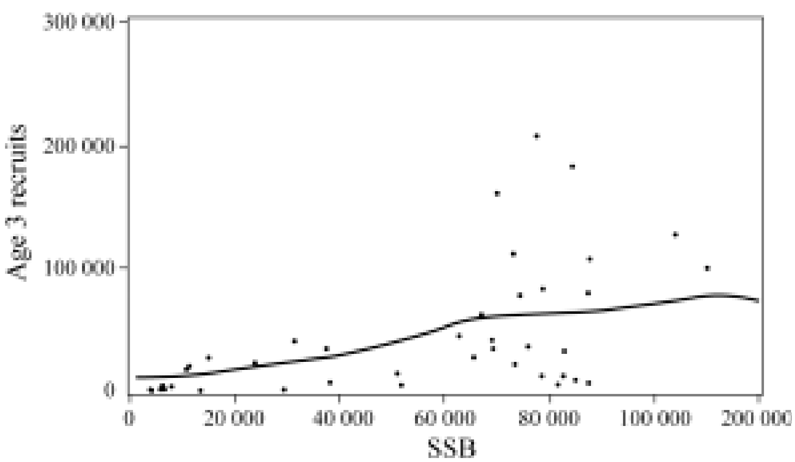

Fig. IV.3.4. Cod in Div. 3NO: the fitted non-parametric Cauchy kernel smoother together with the S-R data.

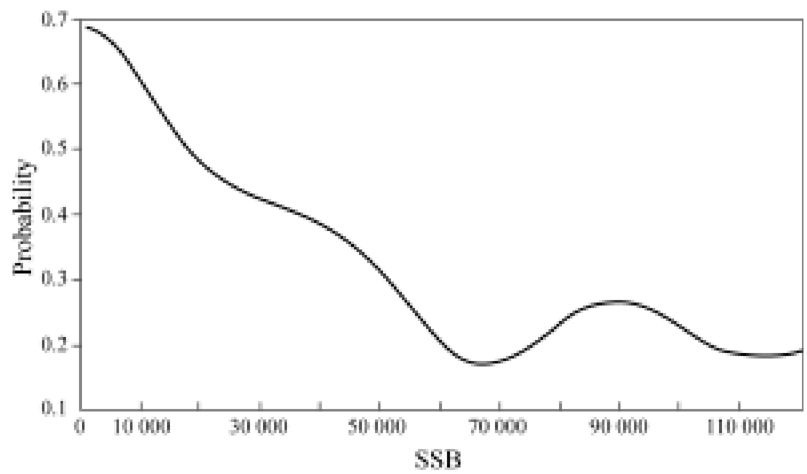

Fig. IV.3.5. Cod in Div. 3NO: the probability of poor recruitment ($<=1.074 \times 10^6$ recruits age 3) over the range of SSB. The point below which the probability of poor recruitment increases markedly is about 60 000 tons SSB, which is the current estimate of B_{lim}.

As a result of all these analyses, there is no basis upon which to amend the current Scientific Council PA B_{lim} reference point for the Div. 3NO cod stock. Therefore, 60 000 tons remains the current best estimate of B_{lim}.

References

Hvingel, C. and M. C. S. Kingsley. MS 2002. A Framework for the Development of Management Advice on a Shrimp Stock Using a Bayesian Approach. *NAFO SCR Doc*., 158, Serial No. N4787, 28 p.

NAFO. 1999. Scientific Council Reports, Part A. Scientific Council Meeting on Precautionary Approach, 27 April-1 May 1999. p. 5-26.

O'Brien, C. M. and D. L. Maxwell. MS 2002. Towards an operational implementation of the Precautionary Approach within ICES - biomass reference points. Working paper to the ICES Study Group on the Further Development of the Precautionary Approach to Fishery Management, Lisbon, Portugal, 4-8 March 2002.

Serebryakov, V. P. 1991. Predicting year-class strength under uncertainties related to the survival in the early life history of some North Atlantic commercial fish. *NAFO Sci. Coun. Studies*, **16**: 49-56.

Stansbury, D. E., P. A. Shelton , E. F. Murphy, B. P. Healey and J. Brattey. MS 2001. An assessment of the cod stock in NAFO Div. 3NO. *NAFO SCR Doc*., No. 72, Serial No. N4450, 64 p.

4. **Yellowtail flounder in Div. 3LNO**

Although indices of SSB and recruitment are available from survey data, no attempts were made at this workshop to use methodologies on the yellowtail flounder stock which employ SSB/recruitment relationships. Scientific Council noted that work on ageing of yellowtail flounder is progressing, and that development of age-structured models remains a priority for this stock.

A version of the Bayesian production model without a predation term was applied to yellowtail flounder in Div. 3LNO. The workshop recognized further work will be required to determine the applicability of this approach.

a) **ASPIC**

It is not possible to use age-structured methods with this stock at present, and the current stock assessment within Scientific Council is based on the ASPIC stock production model. Recent management advice for yellowtail flounder in Div. 3LNO has been based on an ASPIC biomass dynamics model (Walsh *et al.*, 2002). Results indicate that 2003 biomass = 121%B_{msy} and 2002F = 67%F_{msy}. Scientific Council considers the ASPIC estimate of relative F_{msy} to be an estimate of F_{lim}, and 2/3F_{msy} to be a target. Probability distributions of F_{msy} from a bootstrapped ASPIC model can also be used to calculate a buffer reference point for F. The relative biomass when the stock was closed to fishing in 1994, which is the lowest observed and corresponds to 20% of B_{msy}, could serve as a proxy for B_{lim} (NAFO, 2002). It was noted that the ASPIC-based reference points should be treated as interim values until age-based assessments and reference points are developed.

b) **Replacement Ratio Method**

The replacement ratio/index method was applied to the total commercial catches of yellowtail flounder in Div. 3LNO, and the Canadian spring survey series in the same area, from 1984-2002 (Fig. IV.4.1). Catch estimates and survey results for 2002 have not yet been reviewed by Scientific Council. Estimates of relative F were much higher prior to the mid-1990s, resulting initially from a rapid increase in catches in 1985-86, and subsequently from a decline in the survey index. With a moratorium on fishing, relative F declined to very low levels in 1995-97, then increased when the fishery reopened in 1998. The presence of several above-average year-classes during the 1990s, combined with a sharp decline in relative F during the moratorium, resulted in a rapid rate of increase in the stock during the late-1990s. From 1996-2001, the replacement ratio exceeded a value of 1.0 (which occurs whenever the fishing mortality rate is in balance with recruitment and growth).

The relationship between replacement ratio and relative F shows a correlation of -0.55. The randomization test for spurious correlation suggests an expected median correlation of -0.09 and a significance level = 0.04. In other words, the randomization test suggests that the association between the replacement ratio and the relative F is not simply an artifact of the data manipulations. Based on the results presented here, the model indicates that the relative F has been below the replacement F since 1993, but is approaching this level in recent years.

The same method was also tried with the fall survey data, but was not informative, likely because of the short time series of these data.

The utility of the replacement ratio (f_{rep}) as a proxy F_{msy} for yellowtail flounder in Div. 3LNO was evaluated by comparing reported estimates of f_{rep} to estimates of f_{msy} from ASPIC (in the same units as the replacement ratio, catch/survey biomass). Four pairs of estimates were available for three northwest Atlantic flatfish stocks. Yellowtail flounder in Div. 3LNO , yellowtail flounder in Div. 5Z and Winter flounder in Div. 5Z The comparisons show that f_{rep} was consistently similar to f_{msy}, and was 6% less on average (see Section III.1 for full details of this analysis).

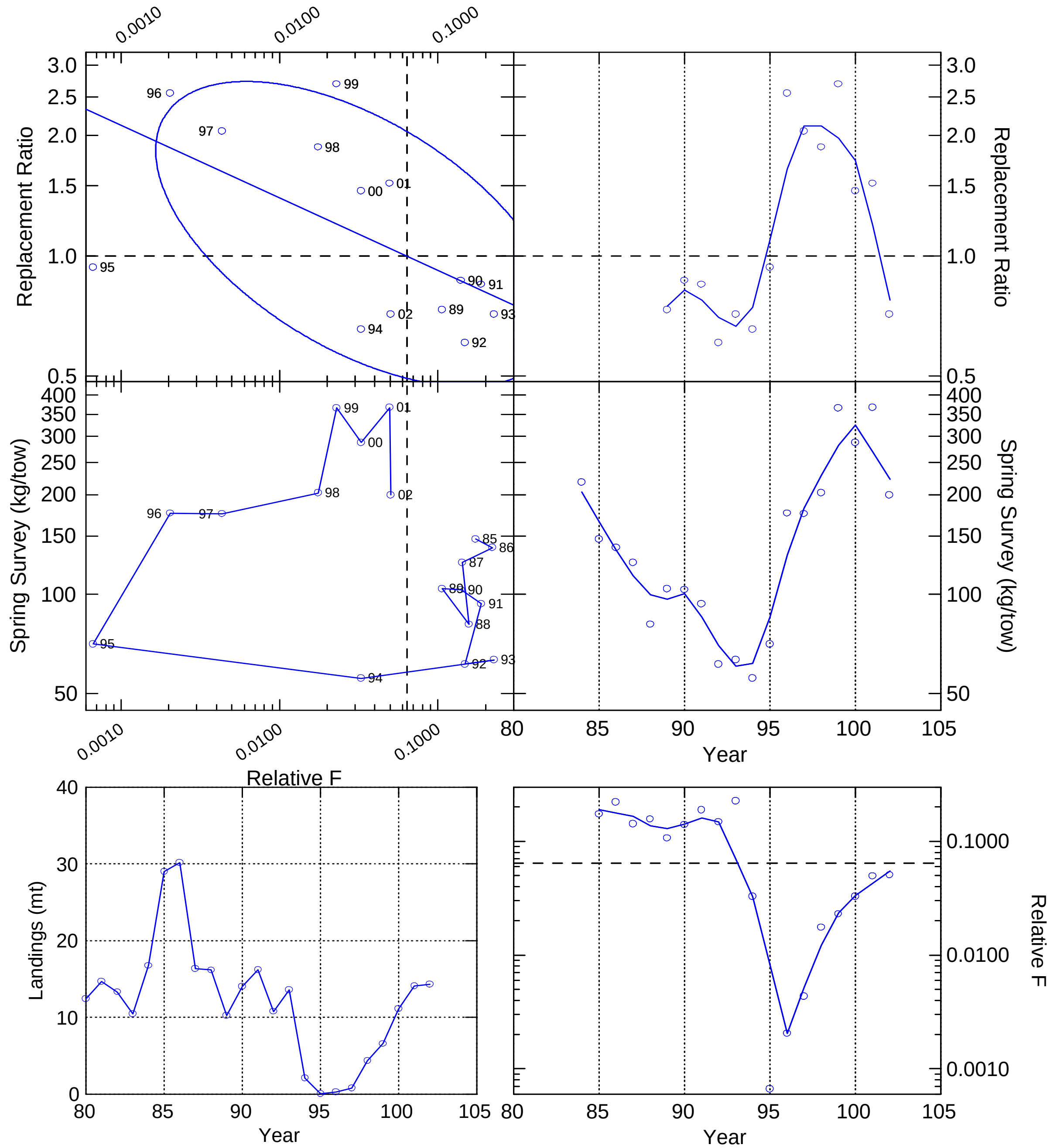

Fig. IV.4.1. Yellowtail flounder in Div. 3LNO: trends in relative biomass, landings, relative fishing mortality rate (landings/index) and replacement ratios, using the spring survey and total landings. Horizontal dashed lines represent replacement ratios = 1. The confidence ellipse has a nominal probability level of 0.68, and the diagonal line uses a robust regression estimator. Note that the survey data are actually biomass indices in '000 tons instead of kg/tow. (See section III.1 for full description).

References

NAFO. 2002. Scientific Council Reports, Part A. Scientific Council Meeting, 6-20 June 2002. p. 156.

5. **Redfish in Div. 3M**

Information was available to apply the Replacement Ratio method and the age-based MSY model (Sissenwine and Shepherd, 1987) to redfish in Div. 3M. Yield/SSB-per-recruit analysis was also applied to the average 1989-2001 XSA recruits extended to age 1. The Survey Proxy method did not provide any informative results because of a positive relationship between replacement ratio and relative fishing mortality. The results of the Age-Based MSY model provided an estimate of F_{msy} that was consistent with an ASPIC model from the most recent assessment of redfish in Div. 3M (Ávila de Melo *et al*., 2002) whereas the corresponding female spawning B_{msy} was at the level of virgin total biomass given both by ASPIC and yield-per-recruit analysis. The estimates of SSB and recruitment utilized in the age-based MSY model were derived from XSA, and yield and SSB-per-recruit were from the most recent assessment. It was acknowledged that the Scientific Council has only used the results of the XSA or ASPIC models for illustrative purposes to indicate trends in the resource over time. Therefore, there were no informative results from any of the analyses at this Workshop to provide reference points under a Precautionary Approach.

However, there may be some utility of the provisional F reference points from ASPIC and YPR analysis for providing management advice. For example, when F was greater than F_{msy} and $F_{0.1}$ the stock decreased, and when F was reduced to less than those reference points, the stock increased.

Reference

Ávila de Melo, A., R. Alpoim and F. Saborido-Rey. MS 2002. The present status of beaked redfish (*S. mentella* and *S. fasciatus*) in NAFO Division 3M and medium term projections under a low commercial catch/high shrimp fishery by-catch regime. *NAFO SCR Doc*., No. 54, Serial No. N4666, 60 p.

Sissenwine, M. P. and J. G. Shepherd. 1987. An alternative perspective on recruitment overfishing and biological reference points. *Can. J. Fish. Aquat. Sci*., **44**: 913-918.

6. **Cod in Div. 3M**

A preliminary estimate of B_{lim} at 14 000 tons was based on the analysis of the stock-recruitment relationship according results of the 1972 to 1999 XSA (Cerviño and Vázquez, 2000). This SSB level defines two different zones where the probability of getting good recruitments is different, being much lower when SSB was below 14 000 tons. This perception did not change in later analyses.

A replacement ratio analysis was carried out based on total catches from 1988-2001 and stock indices from the EU survey series 1988-2002. These data are considered the best and most representative series, but the 15-year time-series is at the limit of sensitivity of the method because the 5 year lag reduced the series to 10 points for the replacement ratio analysis. A regression of replacement ratio on relative fishing mortality was uninformative and the relative F equivalent to a replacement ratio of 1.0 was not determined. The stock has declined in most recent years in absence of fishing, illustrated by the declining trend in EU survey and low recent catches. Other external factors may need to be taken into account to explain the continued population decline as a consequence of poor recruitment since 1992. The trend in smoothed EU survey data is similar to trends in biomass from the XSA. The pattern in relative F, high throughout the 1990s and sharply declining in 1999, is similar to the pattern of fully recruited fishing mortality estimated by the XSA, and has been well below the replacement rate. Although results from this method are consistent with XSA, relative F reference points can not be developed from the current time series. However, the analysis indicates that replacement ratio has been below one for the entire time series.

A Segmented Regression Analysis was applied to the results of the last XSA, covering the 1972 to 2001 period. The analysis concluded that the SSB level was below the changepoint during the whole period, but this interpretation is considered unrealistic, and no further results were accepted.

An estimate of B_{lim} of 4 000 tons was estimated using the Serebryakov method (Serebryakov, 1991) for the period 1972-2000. The B_{lim} estimate is near the lowest observed value in the SSB time series. The same analysis was applied to the period before recruitment collapsed (1972-1991) and estimated a B_{lim} of 6 000 tons. Given the conclusions based on the analysis applied to the Div. 3NO cod stock, it is considered that these results are inconclusive for the Div. 3M cod stock.

In conclusion, 14 000 tons remains as a preliminary estimate of B_{lim}, although the Serebryakov method suggests a lower value.

Reference

Cerviño, S. and A. Vázquez. 2000. An assessment of the Cod stock in NAFO Division 3M. *NAFO SCR Doc*., No. 40, Serial No. N4269, 13 p.

Serebryakov, V. P. 1991. Predicting year-class strength under uncertainties related to the survival in the early life history of some North Atlantic commercial fish. *NAFO Sci. Coun. Studies*, **16**: 49-56.

7. Northern Shrimp in Subareas 0 and 1

a) Bayesian Production Model

The analysis indicates that the stock dynamics have responded to two different environmental regimes: one with high and the other with low cod abundance. The trajectory of the median estimate of 'biomass –ratio' (B_t/B_{msy}) plotted against 'mortality – ratio' (Z_t/Z_{msy}) (Fig. IV.7.1) starts in 1956 at half the optimum biomass ratio and at a mortality-ratio well above 1. The stock maintained itself in this region during the years when cod were abundant. When the cod stock declined in the late-1960s, and predation pressure was lifted, shrimp stock biomass increased and eventually began cycling in the left upper corner of the graph (Fig. IV.7.1) during the current regime of low cod abundance.

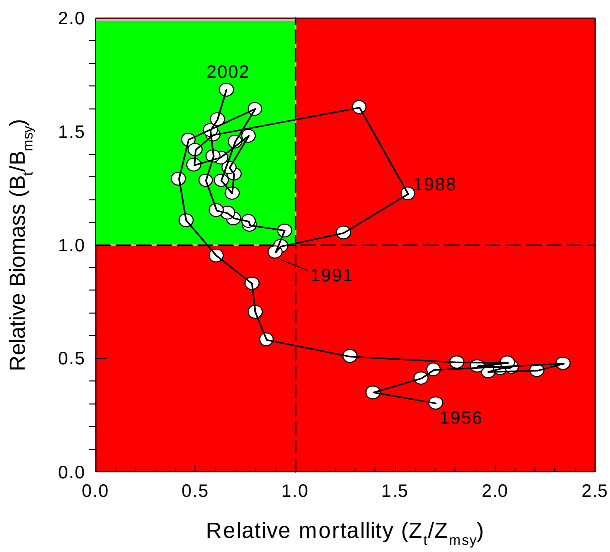

Fig. IV.7.1. Shrimp in Subareas 0 and 1: estimated annual median biomass-ratio (B/B_{msy}) and mortality-ratio (Z/Z_{msy}) 1956-2002.

Since the early-1970s the estimated median biomass-ratio ranged from about 0.96 to 1.67 (Fig. IV.7.1) and the probability that it had been below the optimum level was small for most years (Fig. IV.7.2), i.e. it seemed likely that the stock had been at or above its MSY level throughout the modern fishery. A steep decline in CPUE was noted in the late-1980s and early-1990s following a short-lived resurgence of the cod stock and the median estimate of biomass-ratio dipped just below the optimum in 1990-1991 (Fig. IV.7.1). The stock has increased since then and reached its highest level ever in 2002 with a median estimate of biomass-ratio of 1.67, corresponding to about 82% of estimated median carrying capacity. The estimated risk of stock biomass being below B_{msy} was less than 0.01 (Fig. IV.7.2).

The mortality ratio (Z ratio, which includes mortality by fishing and predation by cod) has been below 1 for most of the time since 1970, except for the period of high cod predation in the late-1980s (Fig. IV.7.1). Since 1997, annual median Z ratio has been stable at approximately 0.6, i.e. well below the optimum. The median of estimate for 2002 is 0.67 with a risk of only 0.04 of being above 1 (Fig. IV.7.2).

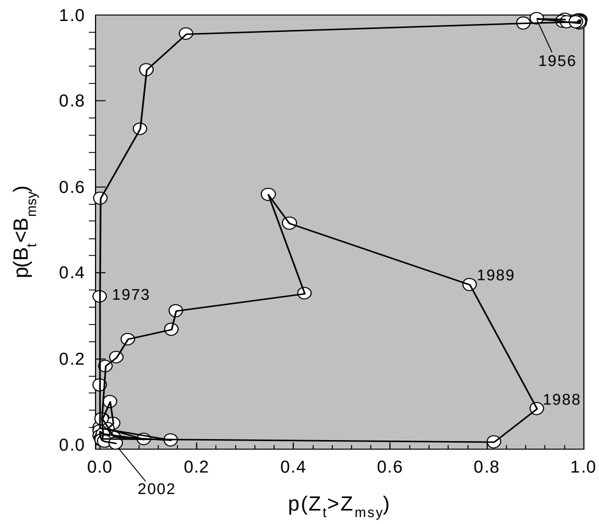

Fig IV.7.2. Shrimp in Subareas 0 and 1: risk of annual biomass being below B_{msy} and of mortality caused by fishing and cod predation being above Z_{msy} 1956-2002.

The median estimate of the maximum annual production surplus (MSY), available equally to the fishery and to the cod was estimated to 101 400 tons (Fig. IV.7.3). The risk function relating the probability of exceeding MSY to the combined removal by fishery and cod predation is given as the integral of this distribution (Fig. IV.7.3).

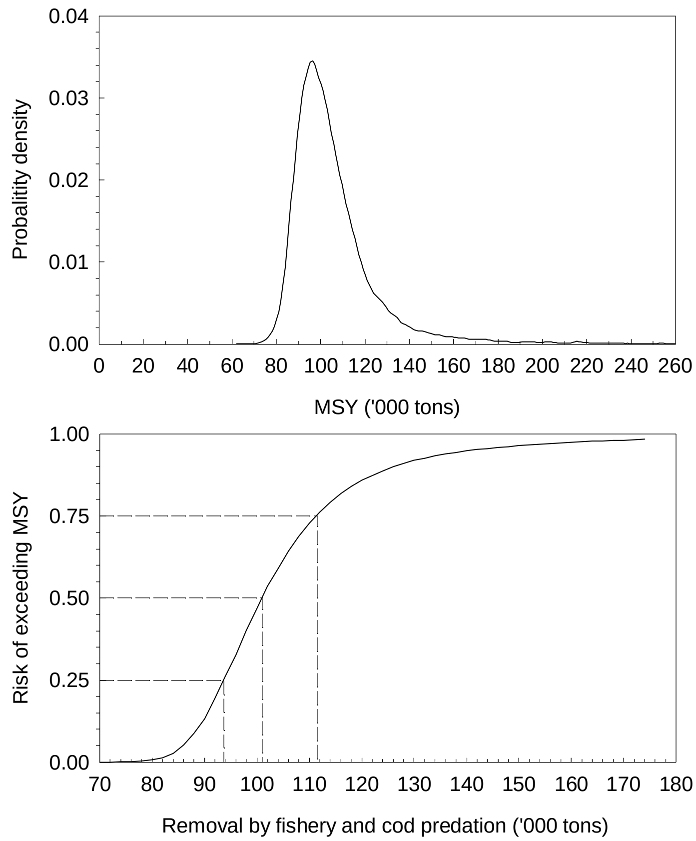

Fig. IV.7.3. Shrimp in Subareas 0 and 1: Posterior probability distribution of the maximum annual production surplus, available equally to the fishery the cod (MSY) (upper panel) and the cumulative probability of exceeding MSY.

Ten-year projections of stock development were made under the assumption that the cod stock will remain at its current low abundance. Five levels of annual catch: 80 000, 90 000, 100 000, 110 000 and 120 000 tons were investigated (Fig. IV.7.4).

The investigated catch options of 80 000 and 90 000 ton/yr have a small risk of being above MSY (Fig. IV.7.3) and the stock is therefore likely to remain above B_{msy} (Fig. IV.7.4) during the ten years of projection. The combined relative fishing and cod predation mortality, Z_t/Z_{msy}, has a high probability of being below 1 within this period (Fig. IV.7.5).

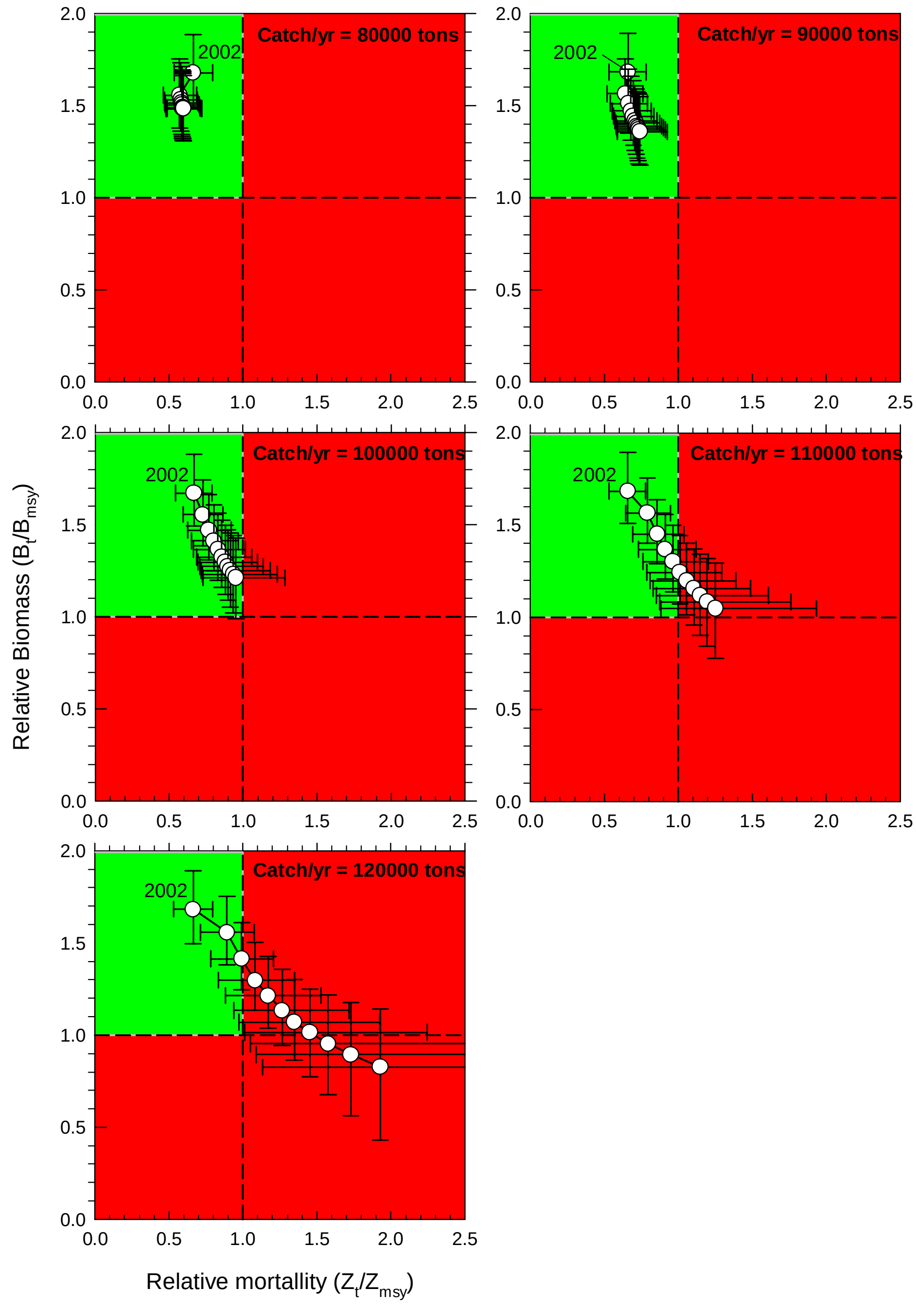

Fig. IV.7.4. Shrimp in Subareas 0 and 1: projections of stock development for the period 2002-2012 quantified in a biomass (B/B_{msy})-mortality (Z/Z_{msy}) continuum. Dynamics at 80 000, 90 000, 100 000, 110 000 and 120 000 tons of fixed annual catch levels are shown as medians with error-bars at the 25th and 75th percentiles. Dashed lines indicate level of biomass and mortality at MSY.

A catch option of 100 000 tons/yr will just about meet the estimated median MSY and is not likely to drive the stock below B_{msy} in the short to medium term (Fig. IV.7.4), i.e. the risk is less than 10% within the first five years and just above 25% after year 10 (Fig. IV.7.5). However, this level of exploitation might not be sustainable in the longer term, as risk of falling below B_{msy} continues to increase through time.

Fishing 110 000 tons/yr bears a 75% risk of being above MSY (Fig. IV.7.3), thus this catch level is not likely to be sustainable in the longer term. Owing to the current high stock level the risk of falling B_{msy} is still less than 20% after five years at this catch level, although after 10 years it is close to 50% (Fig. IV.7.5).

A catch of 120 000 tons/yr is associated with an 85% risk of exceeding MSY (Fig. IV.7.3) and the stock biomass will rapidly decline to below B_{msy} (Fig. IV.7.4). After just two years there is a 50% risk of exceeding Z_{msy} (Fig. IV.7.5).

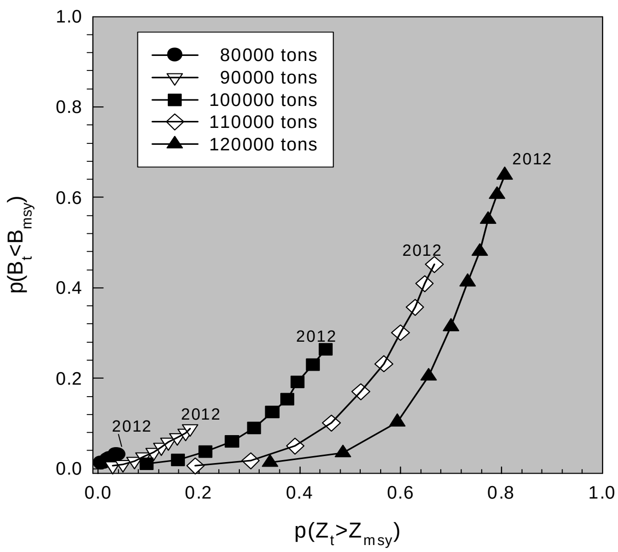

Fig. IV.7.5. Shrimp in Subareas 0 and 1: risk of exceeding Z_{msy} and of driving the stock below B_{msy} by maintaining optional annual catch levels of 80 000-120 000 tons/yr during the period 2003-2012.

The probabilities of transgressing chosen limits in response to different management options may readily be derived within this modeling framework. Hence explicit buffer reference points are not needed as the risk of exceeding the limit reference is quantified and uncertainty associated with the entire process is taken into account.

The limit reference mortality in the present example is Z_{msy}, i.e. Z-ratio=1. This applies in the current regime of low predation mortality where Z_{msy}~ F_{msy}. If predation becomes significant this reference has to be re-evaluated.

V. Recommendations

American plaice Div. 3LNO

- Further research is **recommended** on the adjustment of recruits to age 0 for American plaice in Div. 3LNO to refine stock-recruit modeling, such as continued analysis on the estimation of M and exploration of trends in spawning potential (e.g., age structure and geographic distribution of the spawning stock) that may refute the perception of high reproductive potential (R/S) since the late-1980s.

- A possible candidate limit F reference point could be $F_{MSY,}$ estimated at 0.33 for American plaice in Div. 3LNO American plaice.

Yellowtail flounder Div. 3LNO

- Continue work towards development of reference points based on age structured models.

Precautionary Approach Framework

- It is **recommended** that a study group be formed to evaluate methods for defining and deriving measures of B_{lim}.

VI. Other Business

There was no other business.

VII. Adoption of Report

The final draft of the report of this meeting was reviewed and **adopted**. It was noted that minor editorial details and the final formatting of the report will be done at the Secretariat in consultation with the Designated Experts and the Chair.

VIII. Adjournment

There being no other business, the Chair noted this report will be reviewed by the Scientific Council at its meeting of 5-19 June 2003, and subsequently submitted to the Fisheries Commission in September 2003.

The Chair thanked the participants for their long hours of very constructive and creative work, with special appreciation extended to the Designated Experts and subgroup leaders.

The Chair extended special thanks, on behalf of the participants, to the Canadian hosts from the Science, Oceans and Environments Branch, Department of Fisheries and Oceans, for the facilities and gracious hospitality. Thanks were extended to the Secretariat and the meeting was closed.

APPENDIX I

NAFO Scientific Council Workshop on the Precautionary Approach to Fisheries Management

Delta St. John's Hotel and Conference Centre
St. John's Newfoundland, Canada, 31 March-4 April 2003

AGENDA

I. Opening

1. Appointment of rapporteur
2. Adoption of agenda
3. Terms of reference

II. Review of Progress on Precautionary Approach

1. Basis for existing PA reference points for NAFO stocks
2. Evaluation of existing Scientific Council PA framework
3. Report of ICES SGPA meeting, 2-6 December 2002
4. Report of ICES PA meeting, 24-26 February 2003
5. Recent advances in other regional bodies
6. Recent advances in Coastal States
   III. Canada
   IV. United States of America

III. Review of Methods for Determining PA Reference Points

IV. Application to NAFO Stocks

1. Greenland halibut in Subarea 2 and Div. 3KLMNO
2. American plaice in Div. 3LNO
3. Cod in Div. 3NO
4. Yellowtail flounder in Div. 3LNO
5. Redfish in Div. 3M
6. Cod in Div. 3M
7. Northern shrimp in Subareas 0 and 1

V. Recommendations

VI. Other Business

VII. Adoption of Report

VIII. Adjournment

Terms of Reference

Terms of Reference for the Workshop agreed at the September 2002 Scientific Council meeting are:

- Review the basis for existing PA reference points.
- Determine appropriate methodology to calculate reference points for data-limited stocks.
- Develop or revise reference points for the following stocks:

  Greenland halibut in SA 2 and Div. 3LKMNO
  American plaice in Div. 3LNO
  Cod in Div. 3NO
  Yellowtail flounder in Div. 3LNO
  Redfish in Div. 3M
  Cod in Div. 3M
  Shrimp in SA 0 and 1

- Provide guidance to Designated Experts for calculating PA reference points for all remaining stocks for which sufficient data exist

An additional term of reference calls for a re-examination of the framework initially developed by the Scientific Council in 1997.

APPENDIX II

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