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Limits to overfishing: reference points in the context of the Canadian perspective on the precautionary approach

Limites de surpêche : points de référence dans le contexte de la perspective du Canada en matière d'approche de précaution

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Abstract

Over the last 20 years Canada has subscribed to a philosophy that accepts limits to overfishing. However, there has been no effective framework for implementing a precautionary approach to prevent overfishing. A recent Canadian federal inter-departmental discussion paper provides a consolidation of thinking regarding the precautionary approach from a wide range of fields. It states that Canada applies the precautionary approach in situations when a decision must be made about a risk of serious or irreversible harm and when there is high scientific uncertainty. We evaluate potential fisheries limit reference points in the context of avoiding of serious or irreversible harm and in situations of high scientific uncertainty. Although it seems likely that the subset of reference points that should be considered as limit reference points are going to vary on a stock by stock basis, some guidance is provided on characteristics which may lead to useful limit reference points in the context of the federal framework. Once appropriate limit reference points are defined for a stock which set the boundary when further reduction in spawner biomass or increase in exploitation would constitute serious or irreversible harm, then implementation of the precautionary approach requires these limits to be avoided with a high probability. The process of incorporating the appropriate risk levels within a precautionary approach in the context of the federal framework is discussed. We argue that, while it would be useful to have the precautionary approach imbedded within a broader framework that considers optimising multiple objectives in fisheries management, the setting of limits, albeit preliminary in some cases, should proceed for each exploited stock as rapidly as possible.

Résumé

Depuis vingt ans, le Canada souscrit à une politique qui limite la pêche pour éviter la surpêche. Il n'y a cependant pas eu de cadre efficace pour la mise en œuvre d'une approche de précaution visant à prévenir la surpêche. Un récent document de travail interministériel du gouvernement fédéral présente une synthèse des idées provenant de diverses disciplines concernant l'approche de précaution. Selon le document, le Canada emploie cette approche lorsqu'une décision doit être prise à propos d'un risque de préjudice grave ou irréversible dans une situation de grande incertitude scientifique. Nous déterminons les points de référence de limites de pêche de façon à éviter un préjudice grave ou irréversible dans les situations très incertaines. Même s'il semble probable que les points de référence à retenir comme limites repères varieront en fonction des stocks, nous offrons des conseils sur la façon d'établir des limites repères utiles dans le contexte du cadre de travail fédéral. Une fois les limites repères établies pour un stock, lesquelles constituent le seuil au-delà duquel la réduction de la biomasse des géniteurs ou l'augmentation de l'exploitation causerait un préjudice grave ou irréversible, l'approche de précaution devra être appliquée de manière à ce que l'atteinte de ces limites soit très improbable. Nous discutons du processus d'intégration des niveaux de risque appropriés à l'approche de précaution dans le contexte du cadre de travail fédéral. Bien qu'il soit utile d'intégrer l'approche de précaution dans un cadre de travail plus large visant à optimiser les objectifs multiples en matière de gestion des pêches, nous estimons que l'établissement de limites, même préliminaire dans certains cas, devrait être effectué le plus rapidement possible pour chaque stock exploité.

Introduction

Through a succession of international agreements, declarations and undertakings, and nationally through legislation, Canada has, over the last 20 years, subscribed to a philosophy that accepts limits on overfishing. However, these limits are yet to be defined in operational terms. There is agreement that a line should be drawn, but there is no framework in place for determining where the line should be drawn or what constitutes tolerable risk of overstepping the line. The absence of a framework facilitates a situation where fish stocks continue to be pushed close to the edge by over-exploitation, despite the availability of data and analyses which would allow less risky approaches to be adopted. Recent developments with respect to the "precautionary approach" both nationally and internationally provide some optimism of a global intent to limit over-exploitation of fish stocks. This discussion of limit reference points was prepared for the DFO Workshop on Implementing the Precautionary Approach in Assessments and Advice held in Ottawa in December 2001 (Rice and Rivard 2002). In keeping with a recent Canadian governmental discussion paper, it pursues a particular definition of "limit" and considers which of the existing limit reference point approaches are consistent with this definition. We consider this a "first pass" prior to more rigorous evaluation on a stock by stock basis. In addition, we provide some thoughts on a number of issues related to implementing limits reference points under a precautionary approach. We conclude that limits for each exploited stock need to be defined as soon as possible, rather than waiting to embody them in a more complex framework for developing objectives to maximise societal benefits, which may take a number of years to develop and implement.

A precautionary framework that embodies limits

The conceptsof a "precautionary approach" and "limit reference points" in fisheries have been developed through a number of agreements, codes of conduct and declarations over the last decade to which Canada has subscribed. Richards and Maguire (1998) give a comprehensive account. These agreements comprise part of a philosophical foundation for the recent Canadian federal inter-departmental discussion paper on "A Canadian Perspective on the Precautionary Approach/Principle"(http://www.pco-bcp.gc.ca/raoics-srdc/docs/precaution/Discussion/discussion_e.pdf). The federal framework also encompasses the application of "precaution" in health and safety and international trade decisions, but those applications are not germane to this treatment of the role of precaution in conservation of renewable resources.

United Nations Fisheries Agreement 1982

The United Nations Agreement (UNFA) for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of December 10, 1982, Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks provided the initial impetus for developing limit reference points. Annex II of the Agreement defines limit reference points as boundaries which are intended to constrain harvesting within safe biological limits within which the stocks can produce maximum sustainable yield. The precautionary approach is embodied in the Agreement by the notion that "Fisheries management strategies shall ensure that the risk of exceeding limit reference points is very low". The Agreement states that "The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points". For stocks which are not over-fished, the Agreement requires that "fishery management strategies shall ensure that fishing mortality does not exceed that which corresponds to maximum sustainable yield and that biomass does not fall below a pre-defined threshold".

Rio Declaration on Environment and Development 1992

The Rio Declaration states that "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capability. Where there are threats of serious or irreversible damage, lack of scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

FAO Code of Conduct 1995

The 1995 FAO Code of Conduct for Responsible Fisheries provides a framework for national and international efforts to ensure sustainable exploitation. The Code is voluntary and thus not legally binding. General Principle 6.5 says that "States…should apply a precautionary approach widely to conservation, management and exploitation of living aquatic resources in order to protect and preserve the aquatic environment, taking into account of the best scientific evidence available". Under Fisheries Management, General Principle 7.5.3 says that "States…should, based on the basis of the best scientific advice available…determine: a) stock-specific reference points, and at the same time, the action to be taken if they are exceeded; and b) stock-specific limit reference points, and at the same time, the action to be taken if they are exceeded; when a limit reference point is approached, measures should be taken to ensure that it will not be exceeded.

Canada's Oceans Act 1997

A section of Canada's Oceans Act contains provisions for the Minister of Fisheries and Oceans to lead the development and implementation of a national strategy for oceans management based on the principles of sustainable development; integrated management of activities in estuaries, coastal and marine waters; and the precautionary approach which is interpreted as a commitment to err on the side of caution.

The Canadian Perspective 2001

The recent Canadian Perspective on the Precautionary Approach/Principle of September 2001 provides a framework which can be applied consistently across a wide spectrum of federal decision-making situations. It represents a consolidation of experience with precaution in protection of human health, environmental quality, and resource management, and fairness in international trade. It states that Canada applies the precautionary approach in situations when a decision must be made about a risk of serious or irreversible harm and when there is high scientific uncertainty. Under this framework, the precautionary approach is seen as a distinctive way of making decisions within science-based risk management, influencing how options are developed and how decisions are made.

Under general principles of application, the Canadian Perspective states that sound scientific information and its evaluation must be the basis for applying the precautionary approach. Before the precautionary approach can be applied, scientific data relevant to the risk must be evaluated through a sound, credible, transparent and inclusive mechanism leading to a conclusion that expresses the possibility of occurrence of harm and the magnitude of that harm (including the extent of possible damage, persistency, reversibility and delayed effect). The touchstone for a conservation concern is the point at which there is harm and that harm is considered to be serious or difficult to reverse. The PA kicks in when there is a true conservation concern and not just when it is thought that the management is sub-optimal.

The Canadian Perspective provides a philosophical framework which did not previously exist for such pieces of legislation as the Oceans Act (31 January 1997), which requires the government to promote a wide application of the precautionary approach to the conservation, management and exploitation of marine resources. This general invocation of precaution has been interpreted differently by various schools of thought within DFO. Some interpret the precautionary approach as being amorphous, without clear definition, to be legitimately invoked whenever convenient. Others feel it should mean protecting many properties of marine ecosystems from many different types of threats, not just the limitation of harvests to safe biological levels. We argue that when one wants to invoke "precaution" under the Oceans Act it requires that one get the "best possible" scientific advice, that the thing to be avoided has to be defensible as serious or difficult-to-reverse harm (not just something someone doesn't like), and that the decision is guided by being demonstrably risk averse given the uncertainty (which implies one has tried to quantify risk & uncertainty, and make a risk averse decision).

The federal perspective does several important things in bringing specificity to application of the PA. First, it clarifies that the Precautionary Approach is a subset of the application of “best practices” in risk management, an overarching policy commitment made by government in 1997. Second, it explicitly rejects an amorphous view of the PA, because of the threat this usage would pose to Canadian trade interests. Instead, the federal perspective provides a framework for developing a common and unambiguous approach across government. Third, the federal perspective explicitly endorses rule-based approaches to implementation of the PA for particular uses. This in turn makes the systematic use of biologically-based limit reference points a legitimate process for implementing the precautionary approach in fisheries, a step consistent with much other international practice (ICES 1998, FAO Code of Conduct, 1995).

Serious or irreversible harm

In developing the federal framework, specific cases were frequently cited to ground the discussions with regard to the implications for different activities of government. Fisheries was one of those cases. Although formal legal opinions were not issued, points of consensus were achieved among legal experts, trade negotiators, and scientists. Legal experts were confident that activities which simply reduced yield were economically inefficient, but would not comprise such "serious or irreversible harm". However, activities which jeopardized the future productivity of a stock could be argued to constitute such harm. Moving this into conventional fisheries models and terminology, growth overfishing, in which yield per recruit declines beyond some peak because the benefits accruing from fish growth are being negated by excessive fishing mortality, does not equate to serious or irreversible harm. Recruitment overfishing on the other hand does constitute harm and may be irreversible (or at least take decades to reverse). Recruitment overfishing can be defined as a level of fishing mortality that results in a sharp decrease in recruitment at equilibrium (Sissenwine and Shepherd 1987). It is understood to occur when spawning biomass is so low that recruitment decreases substantially and even precipitously. Sissenwine and Shepherd (1987) note that the definition is vague and does not lend itself to the exact specification of biological reference points. Some level of judgement must be applied to decide on when recruitment overfishing is taking place. Finding the boundary between growth overfishing and recruitment overfishing is central to establishing limit reference points in the context of the precautionary approach.

Deriving biological limits compatible with the federal framework

There are two questions we need to address in the context of applying the federal framework with respect to the precautionary approach and limit reference points to fish stock assessment and scientific advice:

What constitutes serious or irreversible harm in the context of a fish stock?
What is risk averse management action?

Using standard fisheries science model approaches described below, we will define a suite of potential biological limit reference points and discuss the extent to which these could fall within the federal framework guidelines of serious or irreversible harm. Further, we will briefly review the "operationability" and usefulness of some candidate limit reference points in terms of their ability to be applied in risk evaluation.

Sissenwine and Shepherd (1987) described three fishery modelling approaches which provide a basis for deriving reference points: dynamic pool, spawner-recruit and production models.

Dynamic pool models

These comprise yield per recruit and spawner biomass per recruit analyses. "Per recruit" analyses originated in the work of Thompson and Bell (1934) and Beverton and Holt

(1957). Age-specific mortality, body growth and sexual maturation are applied to modelled fish in a cohort and annual contributions in terms of yield or spawners are summed over the lifetime of the cohort. Yield and spawning biomass are usually normalised to the number of recruits. Spawner per recruit at a specific fishing mortality is usually compared as a percentage of the spawner per recruit at F=0.

Spawner-recruit models

Ricker (1954, 1975) provides the basis for understanding much of the dynamics of fish stocks. Density-dependent compensation in the stock-recruit relationship is thought to result in an increased per capita production of recruits when spawner stock biomass declines. As a consequence, recruitment reaches a peak at some intermediate level of spawner biomass and then declines at higher spawner stock biomass levels (Ricker model) or reaches an asymptote (Beverton-Holt model). The number of recruits required to replace the spawner biomass (replacement recruitment) is a function of age-specific mortality, body growth and sexual maturation. In spawner-recruit space, replacement recruitment can be represented by a line through the origin of the SR plot (assuming constant growth, mortality and maturation rates over time). Where this line intersects the stock-recruit curve an equilibrium spawner biomass theoretically exists.

Production models

Production models combine the theoretical underpinnings of both the dynamic pool and spawner-recruit models, either in an age-aggregated form (Schaefer 1953) or in an age-disaggregated form (SPA combined with a stock-recruit model). In age-aggregated production models, yield is, at equilibrium, a quadratic function of fishing effort, fishing mortality or biomass. Models have been formulated which do not require an equilibrium assumption (Rivard and Bledsoe 1978) and which can be fit to indices of stock size in addition to catch rates (e.g. Prager, 1994). Maximum sustainable yield occurs at an intermediate level of fishing effort, fishing mortality or biomass. In age-disaggregated form, the relationship between recruitment and spawner biomass dictates the shape of the yield curve. Yield is commonly evaluated against fishing mortality and the corresponding spawner biomass in both aggregated and disaggregated models.

Defining potential limit reference points

Limit reference points have been most commonly defined in terms of fishing mortality and spawning stock biomass. We provide some definitions of suggested reference points in these two categories as well as a third category which might apply when fishing mortality and stock size cannot be estimated. We comment on their utility with respect to potential limit reference points under the Canadian federal framework. Gabriel and Mace (1999) provide a very useful review of biological reference points and ICES (2001) provides an updated list and definitions of a number of reference points.

Fishing mortality based reference points

F_{crash} is the fishing mortality corresponding to the slope at the origin of the stock-recruit model fit to the stock-recruit data. Although this notion can be found within the body of theory developed by Ricker (1954, 1975), it was not named as such by him at the time. At fishing mortalities above this limit, there is no non-zero equilibrium and the stock collapses. F_{crash} may not represent serious or irreversible harm in the short term and when stock size is high. However, if the stock is at or near a spawner biomass limit reference point, or if F were maintained close to F_{crash} in the longer term then F_{crash} would constitute serious harm, and therefore it would qualify as a fishing mortality associated with harm that is serious and difficult to reverse. If collapse is assured at $F_{crash,}$ then fishing mortalities somewhat lower than F_{crash} would also be associated with serious harm. Therefore limit reference points for F cannot be higher than F_{crash} , and should be lower.

F_{msy}, based on the production model approach introduced by Schaefer (1953), is most usually thought of as a target fishing mortality reference level rather than a limit. However, as pointed out above, Annex II of UNFA suggests that this level of fishing mortality should be considered as a minimum standard for limit reference points. This point of view found support in the ICES COMFIE Working Group (ICES 1996) and has been elaborated on by Sinclair (1999) in a Canadian context, with the view being expressed that TACs should be set so that there is only a low probability that biomass might fall below B_{msy} and fishing mortality might rise above F_{msy}. While F_{msy} has been proposed by both NAFO and ICCAT as the maximum value for the limit fishing mortality value, ICES has not adopted it because of the difficulty in estimation due to density dependent and multispecies effects and the observation that several ICES stocks have persisted for decades at fishing mortalities which have exceeded F_{msy} (ICES 2001). As pointed out above, and elaborated further below, in the context of the Canadian federal framework definitions of serious or irreversible harm, B_{msy} and F_{msy} provide an often overly conservative basis for limit reference points. For many stocks transgressions will be associated with reduced yield below the maximum possible, which is in the domain of economic inefficiency but do not constitute serious harm to conservation of the resource.

F_{max} is the fully recruited fishing mortality that maximises yield per recruit. Fishing at F_{max} quite often leads to harvests that are too high and F_{max} is frequently greater than F_{msy} – the fishing mortality that produced MSY (Quinn and Deriso 1999). F_{max} does not have clear definition as a limit reference point under the federal framework.

$F_{0.1}$ was introduced (Gulland and Boerema 1972) as a more conservative fishing mortality than F_{max} in a dynamic pool model context. It was not thought of, at least initially, not as a limit, but rather as a target, or in the case of Atlantic groundfish stocks, as a long-term strategic goal, with fishing mortalities allowed to float above this level for some period of time (Rivard and Maguire 1993). However, for a stock such as northern cod it has been considered to be too high as a long-term optimum (Hilborn and Walters 1992, Walters and Maguire 1996), and in recent assessments of 3Ps cod off Newfoundland, $F_{0.1}$ has tentatively been though of as a limit and $0.5\text{x}F_{0.1}$ as a target (Brattey et al. 2000, 2001). Gabriel and Mace (1999) suggest that because dynamic pool models only reflect mortality and weight at age, F_{max} and $F_{0.1}$ should be considered as reference points in the context of growth overfishing and not recruitment overfishing.

While the heuristic basis for F_{max} and $F_{0.1}$ does not encompass recruitment overfishing *per se*, if a value of $F_{0.1}$ or F_{max} is sufficient to prevent growth overfishing, it will also prevent recruitment overfishing. However, within the federal framework these values may be too low to be supported as a source of *limit* reference points, because *F* at or somewhat above $F_{0.1}$ or even at F_{max} may not result in harm that is serious and difficult to reverse. Many of the concerns of Hilborn and Walters (1992) and Walters and Maguire (1996) are more with *F* historically not being kept at or below $F_{0.1}$, because of inaccuracies in the analytical assessments or the deliberate setting of TACs associated with higher *F*s in the trade off of social and economic goals against scientific uncertainty. Hence the evaluations of the performance of $F_{0.1}$ have not separated the consequences of ineffective management from the consequences of management around a value that was not sufficiently conservation-based, so their suitability as target or limit reference points in effectively managed fisheries remains unresolved. Within the federal framework such concerns are to be captured in the appropriate degree of risk aversion, and would not justify a conservatively biased selection of the limit reference point.

Criticism levelled at the past use of $F_{0.1}$ as a target for management of the northern cod stock (for example Walters and Maguire 1996) point to flaws in the way that the uncertainty was handled. Data and model uncertainty were underestimated with the methods of the day, and implementation uncertainty (impact of science advice on next year's management and impact of the management plan on what next year's fishery actually did) was greatly underestimated. These are serious problems, and successful management needs to confront them. With respect to science, improved quantification of the uncertainty in estimates of stock size, fishing mortality etc., leading to improved risk plots, can provide a more reliable guide to management decision making. However, taking a more conservative value than $F_{0.1,}$ as if it were the reference point associated with serious harm, biases the choice of the limit reference point rather than placing the appropriate emphasis on risk analysis and risk tolerance.

Biasing our selection of a limit reference point for *F* towards an overly conservative level, and claiming that this fishing mortality is associated with serious harm when in fact it would, if applied consistently, be sustainable, is the wrong approach. Rather, one should focus on getting a better estimation of uncertainty and, because we are uncertain about our uncertainty, to advise a catch associated with an even lower risk of exceeding the *F* that we truly believe differentiates sustainable from unsustainable exploitation. If, for example, there has been a recent problem with retrospective pattern (*F*s subsequently found to be higher than that estimated at the time of the assessment) in the assessment, we take this into account in our estimate of risk of accidentally exceeding the limit, not by biasing the limit itself.

The ICES Precautionary Approach Working Group has taken a view generally consistent with the Canadian framework. The Working Group found that $F_{0.1}$ results in %SPR of about 40% in many cases (see below for definition of %SPR); can nearly always be determined from available data; is one of the least variable of all reference points; does not rely on often difficult to compute stock-recruit relationships; allows more year classes to contribute to spawning stock biomass; results in stock sizes that should be above B_{lim}; and results in a yield-per-recruit that is close to the maximum net economic yield (ICES 2001). Because of these properties, the ICES WG suggested it as candidate for F_{pa}, a fishing mortality level above which management action would be taken to maintain the probability of exceeding F_{lim} at or below 0.05. That makes it function as a tool to ensure risk averse management relative to the limit reference point, and would trigger conservation action at any F higher than $F_{0.1.}$

$F_{35\%SPR}$ corresponds to the fishing mortality at which the percentage spawner biomass per recruit is 35% of that obtained in the absence of fishing in a dynamic pool model context. There is an empirical basis in that declines in productivity of stocks were observed in the range of 20-40% of the unfished level (Gabriel et al. 1984, Gabriel 1985, cited in Goodyear 1993). Clark (1991) found that $F_{35\%SPR}$ was close to F_{msy} for a range of life history parameters and spawner-recruit curves for demersal. Mace and Sissenwine (1993) posed the question “How much spawning per recruit is enough?” They found in a survey of 91 sets of stock-recruit data that they examined, the %SPR corresponding to F_{rep}=F_{med} averages slightly less than 20% overall. Some species, such as Atlantic cod and most flatfish exhibit consistently low levels of replacement %SPR which could be interpreted as meaning that they have a high resilience to fishing. They advocated $F_{20\%\mathrm{SPR}}$ as a recruitment overfishing threshold for well-known stocks with at least average resilience, and $F_{30\%\mathrm{SPR}}$ for less well known stocks thought to have low resilience. Clark (1993) found that $F_{40\%\mathrm{SPR}}$ was closer to optimum for cases with random and serially correlated recruitment variation. Mace (1994) recommended using $F_{40\%\mathrm{SPR}}$ as a default target fishing mortality rate. In the context of the Canadian federal framework, it is important to distinguish between %SPR levels that are suboptimum and those that define recruitment overfishing. It is the latter which are relevant here. It should also be noted that if the S-R relationship is known then %SPR would not be used *a priori* as a rule of thumb. However, it could still be useful as a heuristic to simplify the results of more detailed analysis.

F_{rep} is the fishing mortality at which the spawner biomass generates just sufficient recruits to replace itself, having allowed for growth, maturation and mortality. The context for this approach is both dynamic pool (spawner per recruit) and stock-recruit models and is derived directly from the work of Ricker (1954, 1975). It was proposed by Sissenwine and Shepherd (1986) and Mace and Sissenwine (1993) as a basis for defining recruitment overfishing, and hence as a limit reference point. F_{rep} can be drawn as a straight line through the origin in the spawner-recruit space with the slope proportional to the fishing mortality, under the assumption that weights, maturities and natural mortality at age are constant. At a given level of spawner biomass, recruit values that fall above the F_{rep} line will cause the stock to grow, whereas those that fall below the line will cause the stock to decline. Like F_{crash}, F_{rep} has an exact definition in terms of population dynamics theory. Also like F_{crash} , F_{rep} does not, in itself, constitute serious or irreversible harm in the short term and when stock size is high. However, if the stock is at or near a spawner biomass limit reference point, or if F were maintained close to F_{rep} in the longer term then F_{rep} would constitute serious harm, and therefore it could be considered a limit.

While replacement is undoubtedly an important concept in the context of the federal framework (in taking a longer term view and when combined with a measure of spawner stock size), variations in weight and maturity at age schedules can have very significant effects on the amount of recruitment required to meet replacement (Shelton and Morgan 1993, 1994). Further, weight itself is a proxy for reproductive potential and measures of actual egg production and prerecruit viability are also relevant in this context. The constant replacement heuristic depicted as a straight line though the origin in S-R space is misleading. Annual replacement based on annual measures of weight and maturity at age may be more appropriate (Shelton and Morgan 1993, 1994), but still does not capture the process of the cumulative annual lifetime contribution of a cohort to spawner production. Unfortunately, there does not appear to be a useful limit reference point heuristic for cohort replacement, short of a fully articulated population model.

P(F_{rep}) is the probability of failing to achieve replacement recruitment based on the probability distribution of recruitment at a specific spawner biomass level. Probabilities can be derived from a Beverton-Holt, Ricker or other parametric model or from a non-parametric model. Shelton and Morgan (1993, 1994) combined probabilities of failing to achieve replacement recruitment derived from the kernel smoother stock-recruit model of Rice and Evans (1986, 1988) and Evans and Rice (1988) with the concept of replacement recruitment. A similar approach has recently been independently advocated by Cook (2000). A strategy of achieving a low probability of failing to meet replacement recruitment when spawner stock biomass is below some limit, or as a longer term measure of overexploitation, is directly relevant to the Canadian federal framework.

F_{med} is the fishing mortality corresponding to a replacement line in stock-recruit space that has 50% of the recruit values above and 50% below. Thus it is based on both stock-recruit data (but does not require a model fit to the data) and spawner per recruit model contexts. It is assumed that the accumulated stock-recruit data points reflect the average productivity of the stock over the history of the fishery and that the fishing mortality corresponding to median line through the origin should thus be sustainable on average. However, as pointed out by Gabriel and Mace (1999), depending on which part of the of the stock size range is observed, F_{med} could vary and for some scenarios could be close to F_{crash} (a fishing mortality that is so excessive that it does not bisect the stock-recruit curve). Similarly, in ICES ACFM discussions, the past exploitation history of a stock has been found to strongly affect estimates of F_{med} in some cases, because overexploited stocks may have been kept at low states for a period of time and thus the data are not informative about the pattern of productivity of a stock overall. Although this may pose problems to varying extents for many possible limit metrics, with F_{med} completely determined as a bisector of the scatter of S-R points, past overfishing can be a particular problem for this estimator. In general, F_{med} cannot be considered as a prime candidate as a limit reference point under the federal framework.

$F_{loss} \approx G_{loss}$ is defined by Cook (1998) as the replacement (or F corresponding to the replacement line) from the origin through the recruitment value predicted by the stock-recruit model (either parametric or non-parametric model) at the lowest observed spawner biomass. The context is thus both the stock-recruit and the dynamic pool models. Cook

(1998) considered G_{loss} as a minimum estimate of G_{crash} ($=F_{crash}$). As a minimum estimate of F_{crash}, it is likely to be more conservative than would be appropriate for a limit reference point under the Canadian federal framework.

F_{lpg} is defined as the F corresponding to a 10% probability of giving a replacement line above F_{loss} (ICES 2001). Biological reference points that have built into them a particularly risk tolerance level are relatively rare in the fisheries literature and begs the question of what the appropriate stage is in the precautionary approach process to define risk levels for limit reference points. The context for this reference point is both the stock-recruit and the dynamic pool models, and requires a further analysis taking into account the uncertainty around the fitted recruitment model in order to generate the probability. The Canadian federal framework is more consistent with an approach that would capture the uncertainty in the risk management component, and not in the selection of the limit.

F_{high} corresponds to the fishing mortality for which 10% of the stock-recruit data points lie above the line (90th percentile survival ratio). It requires only the stock-recruit scatter to be computed, but requires spawner biomass per recruit to be quantified in terms of fishing mortality. Sissenwine and Shepherd (1987) note that Shepherd (1982) thought that this level of fishing mortality would be conservative because the population might be capable of more compensation at low stock levels than was evident in the data (i.e. F_{crash} may be at a higher value of F). Sissenwine and Shepherd (1987) however suggest that there is little evidence in available data to suggest that populations could support F values as high as F_{high} for any length of time, which strengthens support for using it as a limit reference point under the Canadian federal framework. They indicated that F_{high} may in fact be less conservative than F_{crash} in situations where high recruitment values are caused by anomalously favourable environmental conditions and in situations where there is little compensation and/or the stock-recruit data are collected at low stock sizes where the stock-recruit relationship can be approximated by a straight line through the origin. ICES experience has also found that F_{high} is both not conservative, relative to other reference points, and not stable as new SR data accumulate. It is thus not a strong contender as a limit in the context of the federal framework.

F_{comfie} is defined as the lowest of three other F reference points, F_{med}, F_{msy} and F_{crash}. It was developed within the Comprehensive Fishery Evaluation Working Group of ICES and provides a measure of robustness. However, it would be difficult to argue that it necessarily constitutes a limit reference point. Under many scenarios F_{med} and F_{msy} may be sustainable and F_{crash} may be poorly estimated (for example because only intermediate levels of SSB have been explored). Its appropriateness relative to the federal framework would depend on which reference point provided the lowest estimate and what the supporting S-R data are, on a case specific basis.

Spawner biomass based reference points

20%B_0 is an early definition of B_{lim} put forward by Beddington and Cooke (1983) in a production model context. They considered that an escapement level of 20% of the expected unexploited spawning stock biomass represented a lower limit where recruitment declines might be expected to be observable. The evidence linking the benchmark of 20% B_0 to recruitment decline has been reviewed several times since with varying conclusions. Using simulation analyses, Beddington and Cooke (1983) evaluated constant catch and constant fishing mortality strategies subject to the constraint that the probability that SSB falls below 20% of its unexploited level is less than 0.1 over a 20 year time horizon. This introduction of the notion of risk with respect to time was another important step forward in the development of a precautionary approach., Notwithstanding the mixed reviews of this measure that were mentioned above, this linkage of risk and productivity makes 20%B_0 directly relevant as a potential limit reference point in the Canadian framework.

B_{msy} is defined as the biomass at which maximum equilibrium yield occurs in a production model context. The ICES Comprehensive Fisheries Evaluation Working Group (COMFIE) interpreted the FAO Code of Conduct and UNFA to imply that in the absence of other information, reference points related to MSY would be limit reference points which set boundaries intended to constrain harvesting within safe biological limits. (ICES 1996, Sinclair 1999). They suggested that there should be only a low probability that biomass might fall below B_{msy}. However, Sinclair (1999) interprets B_{msy} as a stock rebuilding target rather than a limit, a notion that is more in keeping with the Canadian federal framework interpretation.

$B_{50\%\text{Rmax}}$ is defined as the level of SSB at which average recruitment is one half of the maximum of the underlying stock-recruit relationship. 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, $B_{50\%\text{Rmax}}$ 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 . Therefore this reference point would qualify as a possible candidate for a limit under the federal framework.

B_{loss} is defined as the lowest observed SSB. Clearly this reference would be very stock-dependent in its interpretation as a limit. For example, for a collapsed stock such as northern cod, the current spawner biomass of about 50,000 t should be considered far too low to be a viable candidate for a limit SSB. Usually B_{loss} is considered simultaneously with the level of fishing mortality which would give replacement at the predicted level of recruitment at B_{loss} (see F_{loss} above). Within ICES, where B_{loss} has been considered as a reference point, the language has been refined to now ensure that B_{loss} type biomass-based limit reference points are discussed as the lowest biomass from which a stock has been observed to have a "secure and rapid" recovery. Moreover, when ICES uses B_{loss} as a limit reference point, it is in cases where the stock-recruit scatter plots are particularly uninformative about an overall functional relationship. Thus defined, it would constitute a limit under the federal framework.

$B_{90\%R90\%Surv}$ 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 90th 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. This could be considered as a more profound definition of recruitment-overfishing than the common deterministic definition give above. It would also be arguable that it would not be conservative enough to be consistent with the Canadian federal framework's concept of serious harm. Allowing stocks to produce replacement (or better) recruitment only under uncommonly favourable conditions could be presented as a situation where harm has already been done to the stock that could only be reversed by an unlikely event. Hence a biomass limit would have to be somewhat higher than $B_{90\%R90\%Surv}$ to be precautionary in the context of limit reference point under the Canadian federal framework.

Limit reference points when fishing mortality and SSB cannot be estimated

"The absence of adequate scientific information should not be used as a reason for postponing or failing to take conservation or management measures" - Article 7.5 of the FAO Code of Conduct.

While clearly a mathematical model of a fish stock provides an explicit context in which to evaluate limit reference points and is thus highly desirable, there may be some situations in which data are lacking to achieve this objective. We consider briefly below two alternate approaches which may have some merit in data-poor situations. In these two approaches, limit references may be interpreted as "too many red lights" or "too high a probability of something bad happening" respectively.

Traffic lights approach - ICES (2001) suggests that the "traffic light" approach of Caddy (1998), may be the only alternative possibility for setting limit reference points when no analytical or index data are available. This approach uses whatever observations are available on the state of the stock, together with qualitative information on biology, life history and environmental signals to identify conditions of the stock that are undesirable. Information from diverse sources, including fishermen, can be incorporated into the process. Arbitrary weightings are given to the various sources of information in obtaining an overall perspective on the status of the stock.

Within the Canadian federal framework, the Traffic Light approach faces two challenges. The first is to identify unambiguously the boundary of regions that are associated with serious harm to the stock from regions which may be sub-optimal but do not constitute serious or lasting harm. When many indicators are used in such a qualitative approach, it may be hard to identify such boundaries in ways that are consistent across applications. The approach could result in situations where none of the individual "lights" were associated unambiguously with harm, requiring arguments to be made that some number of lights had to be "red" before harm is considered to have occurred, but that the particular combinations of "red lights" was not of primary importance. Such arguments would fall to external challenge on many grounds. The use of arbitrary weightings could further compound the vulnerability of this strategy to challenges that limits so produced are not reliable boundaries between conditions that constitute harm and those that do not. It is possible that such arguments would usually end up as discussions of the "weight of evidence" for and against various interpretations of stock condition. Such discussions have a place within the federal approach in the use of precaution in decision-making. However, that place is clearly outside the rule-based framework. Secondly, the nature of qualitative indicators also poses additional challenges in quantifying the risk of exceeding such boundaries. As noted in the Framework section, the PA is a special situation in risk management, so preferred implementation strategies have to incorporate "best practices" in quantifying and managing risk. When only qualitative information is available, the "best" risk management practices must be qualitative as well. However, when quantitative indicators are available, it must be demonstrable that relevant information is not lost converting such indices into qualitative state variables.

Subjective Bayesian rule-based inference - Many inference systems, such as the traffic light approach described above, are based on intuitive methods in the absence of adequate statistical samples and associated models required to apply a mathematically rigorous approach. Subjective Bayesian rule-based inference methods described, for example, in Duda et al. (1976), realises some of the advantages of both intuitive approaches and mathematically rigorous approaches. In particular it deals with the inconsistencies usually found in collections of subjective statements. It is considered to be a probabilistically exact procedure when not more than two mutually exclusive and exhaustive hypotheses are competing (e.g. is the population above or below B_{lim}?) The method distinguishes between the "strength" and the "uncertainty" in the evidence in ways which are reasonably intuitive and amenable to expression based on past experience.

In contrast, belief function approaches (e.g. Varis et al. 1993), use probability models that require less information than the Bayesian approach, but they appear to be less intuitive. The subjective Bayesian rule-based inference approach was evaluated using simulated data for a capelin and applied to real data from the Newfoundland capelin stock by Shelton and Carscadden (1995, and presented to the AFS meeting in Halifax in 1994) and used to develop TAC options by applying a decision rule to the probability outcomes regarding the state of the stock. The initial simulation trials suggested that the procedure might have some merit but it has not been investigated further. Simulation trials that actually demonstrate the effectiveness of the approach in a fisheries context (as opposed to agriculture etc. where it is widely used) would not be easy to carry out. Similar problems may exist in trying to evaluate the traffic light approach.

Review of some limit reference point evaluations

It seems likely that the subset of reference points that should be considered as limit reference points are going to vary on a stock by stock basis. A number of studies have suggested preferred limits or indicated which may be more robust under certain conditions. We agree with Myers et al. (1994) who concluded that no single method is best for every stock and that as many diagnostic measures as possible should be evaluated. On the other hand the Canadian federal framework has legitimately stressed the need for consistent practice in application of precaution in government decision-making. This makes it important that the actions of those examining possible reference points should be consistent across stocks, if the actions of DFO are to be deemed to be consistent. Hence there is a need to make meaningful progress on at least structuring the way that the stock-by-stock evaluations of reference points will be conducted. This should ensure that where limit reference points from different estimation procedures are adopted for different stocks, the reasons for the differences are well grounded in either the biology of the species or the data available. It can also guide the ability to generalize the detailed approach to setting limit reference points across stocks with similar properties and bases, so that the full spectrum of possibilities does not have to be examined *de novo* for every stock.

The ICES COMFIE WG used bootstrapping to evaluate the uncertainty in the estimates of biological reference points (ICES 1997). These were then compared with point estimates for the same reference points. In the bootstrap procedure, S-R pairs were resampled or the residuals from the original fit were resampled and the model fit repeated. Bootstrapped CV's on F_{crash}, F_{msy} and B_{msy} were in mostly in the range of 15-25%. In a comparable bootstrapping exercises CV's on $F_{0.1}$, F_{med}, F_{msy} and F_{crash} were found to be in the range of 10-25%. Weight, selectivity and maturity at age were also subject to resampling to investigate the sensitivity of the reference points to these sources of variation. The results indicated that there was little additional uncertainty in the estimates of the reference points when uncertainty in these inputs was considered. The greatest contribution was in selectivity at age. Nonetheless, time trends in life history parameters could have a profound effect on the ability of stocks to replace themselves at specific levels of fishing mortality (see for example Shelton and Morgan 1993, 1994 with respect to northern cod).

Overholtz (1999) also evaluated biological reference points using bootstrap procedures. He claimed that his results illustrated the potential benefits of using the spawning biomass that produces maximum sustainable yield as limit reference point rather than as a target. He concluded that statistics and estimates of precision from bootstrap results can be used to develop risk-averse management strategies, identify thresholds relating to recruitment overfishing, examine the utility of alternative limit and target reference points, develop robust target and limit reference points and investigate sustainable yield levels.

Patterson et al. (2000) recently evaluated the perceptions of uncertainty given by different methods with similar structural models in short term (1 year) projections. This EU study group found that the choice of stock assessment methods can have appreciable impact on perceptions of risk, even when the methods make essentially similar assumptions. The majority of current projection methods underestimate uncertainty. This implies that risk averse management actions are require based on model output to minimise the probability of falling on the wrong side of the limit. With respect to medium term forecasts (>2 years), they concluded that probability statements should be comparative only (e.g. action x is twice as risky as action y). In particular, they suggested that the use of probabilities in the tails of the distribution was unwise since these are the least well estimated. This poses a particular problem with respect to limit reference points (as opposed to targets) because under the precautionary approach, management is supposed to strive specifically for low probabilities of falling on the wrong side of the limits. This lends support to the notion of buffers or precautionary reference points which are somewhat removed from the limits and for which probabilities close to the median may be more appropriate.

The EU study group emphasised the need to test assessment methods, including those for estimating uncertainty, by carrying out extensive simulation analysis. They found that some existing methods provide biased estimates and underestimates of the uncertainty. Both failures would have significant effects on the implementation of limit reference points We strongly support their recommendation of extensive simulation testing of candidate limit reference points as well as the estimation and inference methods on which they are based. The designing of a comprehensive evaluation procedure for candidate methods should be given a high priority in terms of implementing the federal framework within DFO.

Although beyond the scope of the this presentation, it should be noted that precautionary or buffer reference points are considered to be more conservative than limit reference points by a distance that reflects both the uncertainty in the estimates of the reference points and the degree of risk-averse behaviour of the decision maker. A rule of thumb for the relationship between a B_{pa} or F_{pa} and a $B_{\lim}$ or $F_{\lim}$ proposed within ICES is of the form $B_{pa} = B_{\lim} \exp^{(1.645 * \sigma)}$ where σ is the coefficient of variation of the estimated reference point. The equivalent equation would hold for F_{pa}. This rule of thumb was used by ICES in estimating many candidate precautionary (buffer) reference points in the late 1990s. Several years of experience, and the simulation work of Patterson et al. (2000), seems to be indicating that the exponent parameter of 1.645σ does not allow sufficiently for uncertainty in the annual estimates of stock status relative to the reference points. This may be because the estimates of σ underestimate the true uncertainty of the population estimates used as a basis for annual scientific advice. This issue is scheduled for more systematic consideration as a part of an overall review of ICES reference points in 2003.

Additional considerations

What is risk averse?

Under the federal framework, conservation limits are set at the boundary when further reduction in stock status or increase in exploitation would constitute serious harm to the stock. This harm to the stock is to be avoided with a high probability, although that probability is not specified in the framework. Moreover, precedents are inconsistent, even among case histories used in the supporting documents for the federal framework.

In applications of precaution to human health, public tolerance for risk of involuntary exposure to health risks is very low. This as led to extremely stringent controls on the nation's blood system. For example individuals who have spent six months or more in the UK are forbidden from donating blood, and a single positive result on tests with false positives as high as 98% permanently excludes potential donors (see Krever 1997). On the other hand, where the risks are voluntary, the public is allowed to engage in very high risk activities, such as smoking. In recent years, however, there has been increasing acceptance of measures to protect bystanders from exposure to second-hand cigarette smoke. Here the risks are lower than the direct risk to the smoker, but are involuntary. In the area of genetically modified foods, Canada's standards appear to be less stringent than those in the EU, despite the same science information being available in both jurisdictions.

Lacking clear precedents in the field of health, DFO is seeking consensus on what comprises "risk aversion" in resource management contexts. As noted in the preceding section, the conceptual implementation of "limit" and "precautionary" (in the labelling sense used by ICES) reference points appears largely consistent with the Canadian federal framework. The basic idea is that because of error of estimation and inherent inability to predict future states of nature, management action should be taken before the limits are approached if the limit is to be avoided with high probability. In ICES, the goal is to ensure that the probability of spawner biomass falling below, or fishing mortality rising above, the limit is no greater than 5%. ICES attempts to achieve this by basing management advice on "Precautionary" reference points. These Precautionary reference points are defined, with what are thought to be the best risk quantification tools available (see Patterson et al. 2000), as the biomass or fishing mortality that, given all sources of uncertainty, should ensure no more than a 5% probability that *B* or *F* is actually outside its respective limit reference point. The distance between the limit and the precautionary reference in part reflects the risk tolerance of managers and in part the precision in estimating the reference points (ICES 2001). The actual tools that ICES uses to position precautionary reference points relative to the respective limits have varied among stocks. These difference have caused problems with the credibility of ICES advice to clients, and created opportunities for the advice to be challenged. Several initiatives are underway (for example Lassen and Sparholt 2001) to bring greater consistency to this aspect of implementing the precautionary approach. NAFO applies a similar conceptual approach with its "buffer" reference points, but the parallel between the NAFO limits and the Canadian federal framework is less direct in that the buffer does not directly incorporate a specified level of risk tolerance with respect to the limit reference point nor does it incorporate an estimate of precision of the estimated reference point.

With these precedents, it would seem that scientific advice on management that assured not more than a 5% chance would certainly be consistent with the goal of being risk averse relative to serious harm to the resource. Given a risk profile from a process considered "best practice" among professionals, the 5% position on the profile would be the basis for advice. When a stock is healthy, management actions to achieve fisheries management objectives and targets (OBFM references) should keep the stock well above the 5% probability of falling outside a limit reference point. As stock status deteriorates, however, maintaining a 5% risk of falling below limit reference points would require increasingly stringent management advice and actions. Both the ICES and NAFO approaches function in this manner. If the probability that a stock's biomass or fishing mortality violated its limit reference point exceeded 5%, the most stringent possible conservation means would have to be implemented, including closure of all directed fisheries and aggressive measures to limit by-catch of the depleted species in other fisheries to an absolute minimum.

Although the federal framework does allow "society's choice" to determine the risk tolerance, this wording is primarily to allow a VERY high degree of risk aversion in things like human health. In health applications, as few as 5 fatalities a year among 28 million Canadians due to side effects of a drug can be considered unacceptable. By contrast a 1% or 5% risk in resource management decision-making, is considered overly stringent in some discussions with industry and management sectors. Acknowledging society's right to choose its desired level of risk protection, historic experience, the technical results summarised throughout this paper, and the basic concept of what it means to be "risk averse", all argue that risk tolerances greater than 5% are not consistent the federal framework on precaution in decision-making. Were a 5% risk tolerance adopted in fisheries contexts, then if the risk of falling below B_{lim} were 0.05, ALL fisheries taking that species as directed catch would closed, and any fisheries taking it as bycatch, would be required to implement technical measures to reduce bycatch to lowest possible levels. Even those levels would have to looked at, discussed among experts, and an explicit decision made that the bycatch was tolerable. The same approach would be required with regard to decisions about harvests for scientific information.

The framework incorporating limit reference points and pre-identified risk tolerance also would give consistent and clear structure for the reporting of assessment results. If the stock is estimated to be above B_{lim} with no catch, then the assessment would produce risk plots where the y-axis is P ($B < B_{\mathrm{lim}}$) and the x-axis is catch. A vertical bar would designate the point on the catch axis where P reached the pre-identified tolerance, and no catch higher than this would be considered under a precautionary approach.

Under the federal framework, the limit reference points associated with serious harm are not going to be as conservation-oriented as some experts have argued they should be. But in exchange for working with a lower limit biomass and a higher limit exploitation rate, there is strong empowerment for risk aversion. Any harvest associated with a pre-identified risk tolerance of violating a limit can be labelled as inconsistent with a precautionary approach in a public document such as an SSR (stock status report). Decisions for TACs that exceed the risk tolerance level would clearly not be precautionary and the Minister would have to publicly defend his or her rationale for deciding to act in a non-precautionary manner. Likewise, use of risk tolerances greater than 5% would have to be debated in the context of whether or not society does accept a categorical increase in risk of serious or irreversible harm to living marine resources. This would be a very different debate than current ones about the need for particular coastal communities to continue to fish, despite the poor but uncertain state of a particular stock under discussion..

What other biological properties are pertinent?

Nothing in the Canadian federal framework restricts selection of reference points to only the biological currencies of spawner biomass and fishing mortality. What is does require is sound scientific evidence that the properties used to set precautionary rules are associated with harm that is serious and difficult to reverse.

Operationally, such evidence may not be difficult to acquire. For example, if age-specific fecundity or subsequent survival of early life history stages is documented for a stock, harvesting in ways that shift the age composition to include few mature individuals would clearly reduce future productivity and comprise harm to the stock. The problem is identifying a specific limit reference point for such properties. For example, it is not straightforward to find the age composition for a stock above which productivity, although not maximized, is adequate to maintain the stock, but below which the expected recruitment is insufficient to meet replacement. Such tasks are not impossible, but they usually involve a sequence of computations which journey back through the stock-recruit relationships themselves. It may still be preferred to base limits on a property such as age composition, if it is being monitored with greater accuracy and precision than spawner biomass itself, or exploitation rate. However, the evidence for harm associated with a particular age composition needs to be adequately demonstrated to form the basis for management under a precautionary approach. It rarely has been in the past.

The problem of over-simplified models

Standard methods in fisheries stock assessment assume a single stable equilibrium population, a monotonic change in recruitment with stock size, random recruitment residuals around the stock-recruit relationship, time-invariant age vectors of weight, proportion mature and selectivity in projections, time-invariant natural mortality, etc. In many cases these simplifying assumptions have to be made because data are either lacking or too noisy to build more complicated models. When more complicated models are built, they often do not provide better predictions. We consider three issues of over-simplification with direct bearing on the estimation and application of limit reference points: non-stationarity in the stock-recruit relationship, depensation in the stock-recruit relationship and time-varying biological properties of the population.

Stationarity occurs when the distribution of model predictions based on the estimated parameters does not change over time. The assumption of stationarity is implicit in any analysis that purports to estimate parameters from historical data to use in prediction of future states (Hilborn and Walters 1992). When productivity regimes change over time, the amount of recruits expected at a particular spawner stock size may also change. Unless these causative factors are included in the model, recruitment will vary around the spawner stock biomass in a time-dependent manner. Non-stationarity can also occur if the productivity of the spawner biomass is changing over time, for example because of an increase in the proportion of first time spawners which may, for example, mature less batches of eggs per body weight of mature females. This could be included in the stock-recruit model by developing a more appropriate measure of egg production. Spawner-recruit models typically show some degree of non-stationarity. In the absence of an understanding of the causative factors, the model may still be improved in some cases by including autocorrelation.

When "regime-shifts" occur, it is tempting to consider "moving the goal posts" – setting lower SSB limits than would be envisaged under a high recruitment regime. The problem with changing the SSB limits is that when the regime changes to one of high productivity again, the SSB could be too low take advantage of the improved regime conditions. If long-term stock dynamics and persistence have been based on occasional periods of exceptional recruitment (e.g. Beamish et al. 2000), allowing SSB to be reduced to a size that cannot produce the exceptional recruitments when conditions are favourable constitutes serious harm indeed. Note that this thinking is encompassed in part in the B_{lim} proposed by Serebryakov (1991).

Although biomass-based limit reference points should not be reduced with changes in stock productivity, reference points in terms of fishing mortality could be varied. The estimation of fishing mortality associated with various equilibrium SSBs would require separate productivity data for each regime. However, one would have to have little uncertainty about detecting regime shifts and knowing what productivity regime applied during the advisory period in order to apply the appropriate productivity data. If this can be done, then, limit reference points based on fishing mortality could be altered with regime changes. If those conditions could not be fulfilled, then it would be necessary to determine the fishing mortality associated with an equilibrium biomass above B_{lim} for reasonable assumptions about expected recruitment. In practice, this may be an unnecessary complication, as long as biomass reference points were kept high during periods of low productivity, for the reasons given in the preceding paragraph. During a period of low productivity, a given biomass can only be maintained with a much lower exploitation rate than is possible during a period of high productivity. Hence managing to maintain the proper biomass reference point necessarily requires the proper adjustments to fishing mortality, even if the appropriate regime-specific fishing mortality rates are difficult to estimate and implement in management.

For a set of stock and recruit data well represented by smooth and continuous functions (Ricker, Beverton-Holt, etc.), it can argued that expected productivity is being reduced for every decrease in SSB below the peak of the dome or the asymptote. Reasoning close to this, in fact, is the basis for the NASCO approach to setting reference points (NASCO 2000). However, such choices leads to internal contradictions in practice, because the same reference point will have some properties of a limit (to be avoided with high probability) and a target (to be achieved in a risk neutral approach) (Rice and O'Maleighdeigh 2001). Analyses in terms of spawner per recruit can circumvent these arguments, and provide an unambiguous way of identifying the SSB below which expected productivity can only lead to further reductions in stock size.

When the S-R relationship is not smooth and continuous, the definition of spawner biomass limits below which productivity is impaired becomes more complicated. In situations where depensation occurs at low stock size (e.g. Shelton and Healey 1999), there will be a threshold spawner biomass at a particular value of *F* below which the stock will collapse to a lower equilibrium state from which recovery is not necessarily assured – the so called "predator pit" effect. Falling into a predator-pit region would qualify as serious and potentially irreversible harm in terms of the federal framework. Depensation may be able to be detected using a modified form of the traditional S-R model (see Myers et al.1995) but in most cases it seems likely that the statistical power will be low (Shelton and Healy 1999). Where there are multiple inflection points, recruitment can be modelled using kernel approaches where the probability density function of recruitment is modelled as a function of SSB (Rice and Evans 1986, 1988, Evans and Rice 1988). The inflection points of these pdfs, when moderately smoothed, will show the SSB where a small further decrease in SSB is expected to result in a large decrease in probability of producing a good recruitment (or large increase in probability of producing poor recruitment). Simulations have not tested this approach fully, but it may offer a way to identify reference points when S-R data are particularly scattered, or where patterns are dominated by high or low outliers.

When the S-R data are poorly represented by a smooth functional relationship, an alternative approach to setting limit reference points is suggested by the dual properties of limit reference points stressed by ICES (ICES 2001). ICES notes that reducing an SSB to an extent that *either* impairs the ability of a stock to produce good cohorts *or* enhances the likelihood that a stock will produce poor cohorts comprises serious harm to the stock. These two types of harm do not necessarily start to occur at the same SSB, so the limit reference point is the higher of the two biomasses that meet the two criteria. So far strictly empirical methods for identifying "good" and "poor" cohorts have not been proposed although Serebryakov's 90^{th} percentile rule and the kernel methods are possibilities.

When weights and maturities at age change over time, this can have a significant effect on the ability of the population to replace itself, and alter perceptions regarding the level of fishing mortality than is considered to be precautionary. Replacement is routinely computed as a straight line through the origin in stock-recruit space. In situations where weights at age and/or maturity at age are changing over time, replacement cannot be represented by a single straight line. The concept of "annual replacement" introduced by Shelton and Morgan (1993, 1994) allows historical changes in biological parameters to be taken into account. Changes in historical replacement levels indicated that for several Atlantic cod stocks, annual replacement levels became difficult to achieve even if fishing mortality were to have been removed in the late 1980s (e.g. Shelton and Sinclair 1995). The precautionary attributes of future TAC options are routinely evaluated in stock projections that assume the biological processes such as growth and maturation (and fisheries processes such as selection at age) will remain constant over time. Some simulations may assume that these vary randomly, modelled for example by randomly selecting past vectors of parameters. Almost never are time dependent changes in biological parameters affecting population productivity included in projections. This may lead to a substantial under-estimation of the risk associated with a particular TAC option.

From rhetoric to implementation

Although the Canadian federal framework provides a good foundation, there is little tangible evidence of progress in the implementation of the precautionary approach in a Canadian context. Fisheries have reopened on collapsed groundfish stocks that have shown no evidence of recovery. In some cases these stocks are declining even further under unsustainable levels of directed fishing mortality. In other cases stocks are declining under bycatch mortality. Concern is growing about their status in terms of "species at risk". Species at risk legislation should be a last resort – something that kicks in when, despite best efforts, the precautionary approach has failed to safeguard the productivity of the stock. To knowingly and systematically choose to continue to fish at levels outside safe biological limits suggests that there is much work to be done in moving from the rhetoric on the precautionary approach, to actual implementation. In some cases fisheries are being pursued at commercial levels of intensity in the absence of a scientific evaluation of the limits of stock productivity. Such fisheries cannot be deemed as being consistent with a precautionary approach without appropriate data and analysis. The onus is to show that they are biologically safe in a precautionary context, rather than to prove beyond doubt that they are not safe.

While it would be useful to have the precautionary approach imbedded within a functional Objectives Based Fisheries Management Approach, the issue of setting of limits to exploitation cannot wait interminably for solutions to be found to the problems of optimising fisheries management in the face of multiple and often conflicting objectives. Limits to overfishing, however tentative, need to be defined for each exploited stock as soon as possible. They can be improved when better data and more sophisticated analyses become available in the future. DFO Science has the capacity to provide responsible advice on limits to overfishing for most stocks, but there needs to be an acceptance at all levels that the setting of limits is a necessary prerequisite to wise stewardship of sustainable fisheries.

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