A Review of Biological Reference Points in the Context of the Precautionary Approach

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Abstract.- Draft guidelines for National Standards under the Magnuson-Stevens Act state that Councils should adopt a precautionary approach to specification of Optimum Yield (*OY*), and list three features which characterize this approach: 1.) target reference points such as *OY* should be set safely below limit reference points (such as the Maximum Sustainable Yield, *MSY*); 2.) stocks at sizes below the level that produces *MSY* should be harvested at lower rates than stocks at sizes above the level that produces *MSY;* 3.) as uncertainty about stock status or productive capacity increases, target catch levels should be more cautious. The guidelines indicate limit reference points which include a maximum fishing mortality rate which produces *MSY* and minimum stock size thresholds from which a stock could be rebuilt to *MSY* within ten years. Reference points can be direct estimates or proxies for direct estimates, depending on adequacy of available data. In this paper, we review desirable properties of directly-estimated and potential proxy biological reference points, in the contexts of the National Standards, guidelines, approaches adopted by international management bodies, and other more generic contexts of the precautionary approach. We compare alternative candidate reference points in terms of their utility and potential performance as limit or target reference points in risk-averse management frameworks.

Introduction

The objective of this paper is to review model-based approaches to the estimation of biological reference points, review precautionary reference points as a component of the precautionary approach, and describe the relevant subset of biological reference points which are consistent with the *MSY*-related focus of the UN Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks (1995) and the revised Magnuson-Stevens Fisheries Conservation and Management Act (MSFCMA).

Biological Reference Points: A Brief Review

A biological reference point (BRP) in its most generic form is a metric of stock status from a biological perspective. The biological reference point often reflects the combination of several components of stock dynamics (growth, recruitment and mortality, usually including fishing mortality) into a single index. The index is usually expressed as an associated fishing mortality rate or a biomass level. The procedure for estimating the reference point and the underlying model is agreed within the scientific community.

The three most common models that underlie biological reference points have been summarized by Sissenwine and Shepherd (1987): (1) spawner-recruit, (2) dynamic pool and (3) production models. The choice of model is predicated on life history and availability of catch, relative abundance, stock-recruitment, and age-specific mortality, growth, and maturity data (Table 1).

<u>Spawner-Recruit Reference Points (Semelparous Populations)</u>

Ricker (1975) describes multiple features of the spawner-recruit relationship which may serve as biological reference points for semelparous populations such as Pacific salmon. In these models, spawners and recruits are both represented in terms of numbers. Age-structure is not incorporated, because spawners are assumed to spawn once and then die; and because recruits produced by spawners are all assumed to return to spawn at the same time. The underlying dynamic mechanism is density-dependent compensation in the stock-recruitment relationship, which results in an increased production of recruits per capita at lower spawner abundances and reduced per capita production at high stock sizes. This may arise when the survival of eggs and/or larvae is affected by density-dependent competition for food or space, compensatory predation, or cannibalism of young by adults (Ricker, 1975). Those reference points are derived from continuous spawner-recruit functions and include spawners needed for maximum recruitment (P_m in Ricker's notation), the replacement spawner abundance at which recruitment equals parent stock (P_r); spawners needed for maximum sustainable yield (*MSY*)(P_s) and rate of exploitation at *MSY* (u_s).

<u>Dynamic Pool (Per-Recruit) Reference Points</u>

Dynamic pool models were initially described by Thompson and Bell (1934) and Beverton and Holt (1957). These models serve as the basis for biological

 The views expressed herein are those of the authors, not necessarily NMFS'

Table 1. Summary of principal models that underlie biological reference points, and associated specification of age-structured and stock-recruitment data.

Age structure in population	S-R data required	S-R function required	Model type	Example citation	Reference points	Comments
Unknown	No	No	Surplus production	Schaefer, 1957 Prager, 1993	F_{MSY}, B_{MSY}	Very risk-prone without auxiliary data on recent relative recruitment
No (semelparous)	Yes	Yes	Spawner-recruit	Ricker, 1975	P_s, u_s	
Yes (iteroparous)	No	No	Dynamic pool, Y/R	Thompson and Bell, 1934	F_{max}, $F_{0.1}$	No information about reproductive dynamics
	By analogy	By analogy	Dynamic pool, SSB/R		$F_{20\%SPR}$, $F_{35\%SPR}$	No stock-recruitment relationship, except by analogy
	Yes	No	Dynamic pool, SSB/R	Shepherd, 1982	F_{med}	
	Yes	Yes	Dynamic pool, SSB/R	Mace, 1994	F_τ	
	Yes	Yes	Production	Sissenwine and Shepherd, 1987	F_{MSY}, B_{MSY}	

reference points on a cohort or year class basis, standardized to the number recruited to the cohort, and so are also referred to as yield-per-recruit, egg-per-recruit and spawning-stock-biomass-per-recruit models. Age structure is incorporated in terms of age-specific schedules of mortality, growth, and sexual maturity. Age-specific fishing mortality rates reflect the effects of a fishery selection (or exploitation) pattern, in which the vulnerability of a cohort changes as it ages. This could reflect changing patterns in availability to the fishery or vulnerability to the gear. "Knife-edge" exploitation patterns are approximations that assume that below the age at first capture, fishing mortality = 0, but at or above the age at first capture, the cohort is fully vulnerable to the same rate of fishing mortality. Age-specific schedules of weights in the spawning stock or weights in the catches (as landings or discards) are specified, as are age-specific maturity rates. The models enable an evaluation of the effects of alternative exploitation patterns and fully-recruited fishing mortality rates on the amount of yield or spawning stock biomass per recruit, over the lifetime of the cohort, independent of the initial size of the cohort at recruitment. The models do not usually incorporate density-dependent compensation: the same age-specific mortality, maturity, and growth schedules are assumed to apply regardless of year class size initially or at subsequent ages. The models do not incorporate density-independent effects: the age-specific rates are assumed to apply regardless of any changing environmental conditions, fishery behavior, predation levels, or prey availability over the life of the cohort. The schedules must be obtained over the entire lifespan of the cohort in order for the calculated yield per recruit or spawning stock biomass per recruit to be realized. In the case of spawning-stock-biomass-per-recruit analyses, all kilograms of spawning stock biomass are assumed to be equally productive in terms of recruitment, i.e., the production of viable eggs per kilogram of spawning stock biomass is assumed to be equal regardless of age composition, size composition, and number of previous spawning seasons of spawners contributing to the spawning stock biomass. For this reason, metrics other than spawning biomass are sometimes used (e.g., egg production). Length-based estimates of yield per recruit and spawning stock biomass per recruit are possible when growth, maturity at length and length-composition data are available (e.g., Gallucci *et al*., 1996).

Reference points derived from yield-per-recruit analyses include F_{max}, the (fully-recruited) fishing mortality rate which produces the maximum yield per recruit; and $F_{0.1}$, the fishing mortality rate corresponding to 10% of the slope of the yield-per-recruit curve at the origin (Gulland and Boerema, 1973). The $F_{0.1}$ reference point was conceptualized as a biologically precautionary target relative to F_{max}: at $F_{0.1}$, catch per unit effort is not reduced substantially, but the fishing mortality rate is lower than F_{max}. Because the yield-per-recruit analyses only reflect schedules of mortality and weight at age in the catch, both F_{max} and $F_{0.1}$ are reference points in the context of growth overfishing, not recruitment overfishing.

A wide variety of reference points have been derived from spawning-stock-biomass-per-recruit models. In isolation, spawning-stock-biomass-per-recruit analyses reflect schedules of mortality, maturity, and spawning weight at age for a cohort. Under conditions of no fishing mortality, 100% of a stock's spawning potential is obtained. As fishing mortality rates increase, spawning stock biomass per recruit decreases, as more spawning opportunities are lost over the lifetime of the cohort. The reduction in spawning stock biomass per recruit relative to the unfished level can be reflected as a percentage of the maximum spawning potential (*MSP*), e.g., a fishing mortality rate denoted $F_{35\%MSP}$ would allow a stock to attain only 35% of the maximum spawning potential which would have been obtained under conditions of no fishing mortality. It is thus possible to calculate spawning stock biomass per recruit as a function of fishing mortality rate, in terms of either kilograms of spawning stock biomass per number of recruits or in terms of percentage of the maximum spawning potential (the ratio of kilograms of spawning stock biomass per recruit under a specific *F* compared to kilograms of spawning stock biomass per recruit under no *F*). These give rise to reference points of the form of e.g., $F_{20\%SPR}$ or $F_{35\%SPR}$, where SPR stands for spawning (products) per recruit, and "products" are biomass, egg production, or related metrics, and x% SPR has exactly the same meaning as x% MSP.

Results of spawning-stock-biomass-per-recruit analyses can be combined with stock-recruitment data to provide reference points in the context of recruitment overfishing. If a stock-recruitment model can be fitted, then the fishing mortality rate which corresponds to the slope of the function at the origin can be estimated, F_{τ} (Mace and Sissenwine, 1993). This is possible because the slope of the stock-recruitment function has units of *R/SSB* and if this value is inverted to units of *SSB/R*, a corresponding fishing mortality rate can be found from the relationship between *SSB/R* and *F* as described above.

It may not be possible to fit a stock-recruitment relationship because the range of observed stock sizes is narrow, data are dominated by environmental variability, or stock or recruitment estimates are imprecise or inaccurate, for example. In that case, it still may be possible to define fishing mortality reference points based on the distribution of observed *R/SSB*, from a ratio of observed *SSB* and subsequent recruitment. Such reference points include those introduced by Shepherd (1982) and ICES (Anon., 1984), F_{low}, F_{med}, and F_{high}, corresponding to the lower 10-percentile, 50-percentile, and upper 90-percentile of the observed R/SSB ratios, respectively. These reference points represent fishing mortality rates which can be supported by observed survival rates from spawning to recruitment in 90%, 50%, and 10% of the years, respectively. The same shortcomings in the data which would prevent fitting a stock-recruitment relationship make other reference points based on different forms of the same data less reliable, however. Depending on which part of the stock size range is observed, F_{med} may be close to *F* at the slope at the origin, F_{msy}, or close to zero. F_{med} may also be unsustainable depending on the age structure of the stock and degree of temporal correlation in survival ratios: although high recruitment rates may balance low recruitment rates over the long term, if age structure in a stock is severely truncated, (e.g., to four age classes) there is a higher probability the stock may collapse under exploitation at F_{med} (e.g., if four consecutive years of poor *R/SSB* were obtained). G_{loss} (Cook, 1998) is a more elaborately formulated reference point which includes uncertainty in the estimation of the stock-recruitment data and the *R/SSB* calculations using simulation procedures, and a smoothed trend rather than a fitted stock-recruitment relationship: the distribution of *R/SSB* at the lowest observed stock size is simulated, and compared with the distribution of *R/SSB* at the current fishing mortality rates.

Surplus Production Reference Points I

The surplus production model is among the simplest of the models used for stock assessment: it does not reflect any age structure in a population, and the dynamics of natural mortality, growth, and recruitment are aggregated into a single intrinsic rate of population biomass increase, modified by fishing mortality. Model dynamics are also affected by the size of the population with respect to its carrying capacity. Data requirements are modest: the model can be fitted based on an abundance (catch per unit effort) index and catch. Models have been formulated which do not require an equilibrium assumption (e.g., Prager, 1994). However, both observation and process errors occur (random variation in the observed abundance index and catch of the stock; and in the population dynamics of the stock, respectively). Although observation error estimators have been fairly well developed, if process error is large, then parameter estimation may be poor (Prager, 1994; Chen and Andrew, 1998). Thus, if there is a trend or cycle to natural or fishing mortality, growth, or recruitment, for example, this type of model will perform poorly or separate fits would be required for each period in the stock's history. Although surplus production models produce relatively precise estimates of *MSY* and f_{MSY}, absolute values of F_{MSY} and B_{MSY} are usually not precise and require good estimates of q (the parameter that scales abundance indices into biomass estimates)(Prager, 1994).

Surplus Production Reference Points II

The production model described in Sissenwine and Shepherd (1987), in contrast, is one of the more data-intensive and complex models. It requires a functional stock-recruitment relationship, a spawning-stock-biomass-per-recruit analysis, and a yield-per-recruit analysis. For any specified rate of fishing mortality, an associated value of *SSB/R* is defined, incorporating the assumptions detailed in the previous section on dynamic pool models. When this value of *SSB/R* is inverted and superimposed on the stock-recruitment function as a slope (*R/SSB*), the intersection of this slope with the stock-recruitment function defines an equilibrium level of recruitment. When this value of recruitment is multiplied by the yield per recruit calculated for the same fishing mortality rate, the equilibrium yield associated with the fishing mortality rate emerges. F_{MSY}, the fishing mortality rate which maximizes the yield from the system (conditional on selection pattern, schedules of growth and maturity, accuracy of stock-recruitment function, etc. as detailed in the preceding section on dynamic pool models) can be found; and B_{MSY}, the associated stock biomass which produces that yield can also be found.

Biological Reference Points and Fishery Management Reference Points

In a management context, a biological reference point can serve as a performance standard or a landmark for a fishery management regime. Other types of performance standards are also available in the domain of economics (e.g., the fishing mortality rate which produces maximum economic yield). Some performance standards are not quantitative but only directional (e.g., some social anthropological elements such as the social stability of local fishing villages). Others are not articulated (e.g., minimum sustainable whinge, *sensu* Pope)

The biological reference point itself is not equivalent to a management regime or the management objectives. If the management objective were to maximize economic efficiency, for example, the effect of any proposed measures would presumably be evaluated in terms of economic impact. Those proposed measures would also be evaluated with respect to the impact on stock status in terms of growth overfishing, recruitment overfishing, or the sustainability of yields from the stock, however. Appropriate biological reference points would provide standards by which to judge the performance of that management regime in a biological context, even though the ultimate aim of the management regime might be to achieve some specific economic end. As noted above, F_{max} or $F_{0.1}$ are biological reference points commonly used to index growth overfishing; $F_{35\%SPR}$, F_{med}, or F_{τ} have been used to index recruitment overfishing; and F_{MSY} and B_{MSY} index stock conditions which produce surplus production as maximum sustainable yield (*MSY*). In the context of this paper, *MSY* or *OY* are considered emergent properties of other reference points or harvest control policies.

Precautionary Reference Points

Two types of precautionary reference points, limits and targets, and their management contexts are described in Annex II of the UN Straddling Stocks Agreement (1995): *Limit reference points set boundaries which are intended to constrain harvesting within safe biological limits within which the stocks can produce maximum sustainable yield.... Fishery management strategies shall ensure that the risk of exceeding limit reference points is very low. If a stock falls below a limit reference point or is at risk of falling below such a reference point, conservation and management action should be initiated to facilitate stock recovery... 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 overfished, fishery management strategies shall ensure that fishing mortality does not exceed that which corresponds to maximum sustainable yield, and that the biomass does not fall below a predefined threshold.*

In Annex II, *Target reference points are intended to meet management objectives...Fishery management strategies shall ensure that target reference points are not exceeded on average. For overfished stocks, the biomass which would produce maximum sustainable yield can serve as a rebuilding target.*

Thus, the UN Straddling Stocks Agreement defines two fishery management reference points to achieve precautionary objectives: limit reference points and target reference points. These reference points are cast entirely in terms of biological reference points related to maximum sustainable yield, B_{MSY} and F_{MSY}.

The FAO guidelines on the precautionary approach (1995a) discuss operational targets and constraints, and treat biological reference points as measurable terms to express those targets and constraints. The guidelines recognize that what is measurable will vary, depending on species and fishery. Operational targets are associated with desirable outcomes to be attained, such as particular abundance levels or fishing mortality rates. Operational constraints are associated with undesirable outcomes to be avoided, such as risk of declining recruitment. The constraint is directly comparable to the limit: "it is highly desirable... to maintain acceptable low levels of probability that the constraints are violated." Under the precautionary approach, operational targets may require adjustment to be consistent with constraints, e.g., so that target fishing mortality rates are lower than F_{MSY}. Constraints have precedence over targets: if B_{MSY} (target) were lower than the biomass where there is a high probability of reduced recruitment (constraint), then the probability of violating the constraint while meeting the target would be too large. If targets can be approached rapidly, then there may be a possibility of overshooting the target and violating the constraints, which should be avoided.

The critical reference point within the precautionary context is the limit reference point. Within Annex II, paragraph 7 states that: *The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points.* Within the revised MSFCMA, Section 3(29)

Table 2. Summary of limit, threshold and target reference points as defined by U.S. advisory documents and legislation, and international management institutions. Initial definition of limit, threshold and target reference points are by Garcia (1995).

	Rosenberg *et al*., 1996	**National SAW SC/NSG, 1998**	**Revised MFCMA**	**ICES**	**NAFO**	**NASCO**	**ICCAT**
Term: Limit	Absolute threshold	Threshold	Limit	Limit: B_{lim}, F_{lim}	Limit: B_{lim}, F_{lim}	Conservation limit	Overfishing BRPs
Term: Threshold	Precautionary threshold	Precautionary target		Precautionary value: B_{pa}, F_{pa}	Buffer: $B_{buf,}$ F_{buf}		
Term: Target	Target	Target	Target	Target: B_{target}, F_{target}	Target: B_{tr}, F_{tr}	Management target	
BRP: *F* Limit	F where E(R)=0.5 $E(R_{max})$	F = Min(F_{MSY}, or proxies $F_{\%SPR}$, $F_{0.1}$, F=M)= MFMT	F_{MSY}	F_{lim}=F_{crash}, F_{loss} or F_{med} (left limb)	F_{lim}=F_{MSY}, F_{max}, F_{med} or $F_{30\%SPR}$	Escapement producing B_{MSY}	F = F_{MSY}, $F_{0.1}$ or F_{max}
BRP: *F* Threshold		F = 0.75 MFMT		F_{pa} = $F_{lim}e^{-2s}$ or F_{lpg} or F_{med}	F_{buf} = $F_{lim}e^{-2s}$, M, or $F_{MSY}/2$		
BRP: *F* Target		$F_{OY} < F_{MSY}$	$F_{OY} < F_{MSY}$				
BRP: SSB Limit	SSB where E(R)=0.5 $E(R_{max})$	B = Max(B_{MSY}/2, B to B_{MSY} in 10 years) = MSST	B_{MSY} (for rebuilding)	B_{lim} = B_{loss} or MBAL	B_{lim} = B_{loss}, MBAL, or 0.2*B_{max} (survey)	Escapement producing B_{MSY}	B = B_{MSY}
BRP: SSB Threshold				B_{pa} = B_{loss} or $B_{lim}e^{-2s}$	B_{buf} = $B_{lim}e^{-2s}$, 2/3B_{MSY}, or 0.5*B_{max} (survey)		
BRP: SSB Target		B_{OY}	B_{OY}		B_{MSY}		

states that : *The terms 'overfishing' and 'overfished' mean a rate or level of fishing mortality that jeopardizes the capacity of a fishery to produce the maximum sustainable yield on a continuing basis.* There thus is indirect correspondence between limit reference points recommended under the UN Straddling Stocks Agreement and overfishing definitions under the revised MSFCMA: in both cases, F_{MSY} represents an upper bound to fishing mortality rates. Similarly, there is correspondence between target reference points intended to meet management objectives under the Straddling Stocks Agreement and *OY* under the revised MSFCMA.

Garcia (1995) distinguishes among limit, target, and threshold reference points in the precautionary context: limit points should never be reached, and if they were to be reached, severe and corrective management actions should be implemented. He indicates that limits should be minimum rebuilding targets to be reached before any rebuilding measures are relaxed. The threshold reference point is defined as an "early warning" reference point, to reduce the probability that a target or limit point would be exceeded due to estimation or observation uncertainty or due to slow management reaction. Thresholds are advisable when there is an especially high probability of a negative outcome when the limit is crossed, e.g., in a highly variable environment, when species are at the edge of their geographic range or are relatively unresilient; or other circumstances when the cost of exceeding the limit is high (Garcia, 1995).

A relatively wide variety of precautionary reference points has been proposed by various different national and international working groups and fishery management organizations. While biological reference points are based on scientifically agreed models, precautionary reference points reflect individual organizations' interpretations and implementations of precautionary management. Using Garcia's distinctions between limit, threshold, and target reference points as a basis for organization, we summarize a range of precautionary reference points currently or recently under consideration by various working and management groups (Table 2). Additional information on different organizations' applications of the precautionary approach is summarized in Mace and Gabriel, this volume. It is important to note that in the U. S. National Standard Guidelines, Technical Guidance on the Use of Precautionary Approaches to Implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act (Restrepo *et al*., 1998), and Scientific Review of Definitions of Overfishing in U.S. Fishery Management Plans (Rosenberg et al., 1994), the use of the term "threshold" corresponds to the "limit" reference point as defined in FAO guidelines rather than to the "early warning" reference point indicated by Garcia (1995).

Precautionary Management: Harvest Control Rules, Uncertainty and Precautionary Reference Points

The FAO Code of Conduct for Responsible Fisheries (FAO 1995b) summarizes the relationship between precautionary reference points and harvest control rules: *When precautionary or limit reference points are approached, measures should be taken to ensure that they will not be exceeded. These measures should where possible be pre-negotiated. If such reference points are exceeded, recovery plans should be implemented immediately to restore the stocks.* The biological reference points which serve as limits, thresholds, or targets are triggers for management actions or are parameters in harvest control rules. The harvest control rule is a pre-agreed course of management action as a function of stock status and other economic or environmental conditions. A recovery plan may be considered a specialized control rule which applies when the stock is outside safe biological limits. Harvest control rules (including their component biological reference points) should be developed in the management planning stage with the involvement of all stakeholders, and then evaluated for robustness to uncertainties in statistical estimates of stock status, environmental conditions, harvester behavior, and managers' ability to change harvest levels (FAO, 1995b). If harvest control rules are based on large amounts of uncertainty in terms of model, observation, process, or implementation errors (including estimation of reference points), then the formulation of the control rule should be more precautionary. If, on the other hand, inputs to harvest control rules are based on little uncertainty and/or if resulting controls more stringent, then a less precautionary formulation of the control rule should be successful.

In a different approach to the development of harvest control rules, the management community could specify performance criteria for harvest rules (including robustness) at the outset, and then alternative harvest control rules would be developed which meet those performance criteria. This different approach is implemented in the International Whaling Commission's revised management procedure, and focusses pre-agreement on the performance criteria rather than on any particular control rule or component reference points.

The need for simultaneous consideration of reference points and actions to be taken if they are exceeded is made in both the FAO Code of Conduct for Responsible Fisheries (1995b) and Article 6 of the United Nations agreement relating to the conservation and management of straddling fish stocks and highly migratory fish stocks (1995). In the FAO Code of Conduct,

7.5.2 In implementing the precautionary approach, States should take into account, inter alia, uncertainties relating to the size and productivity of the stocks, reference points, stock condition in relation to such reference points, levels and distribution of fishing mortality and the impact of fishing activities, including discards, on non-target and associated or dependent species as well as environmental and socio-economic conditions.

7.5.3 States and subregional or regional fisheries management organizations and arrangements should, on the basis of the best scientific evidence available, inter alia, determine:

a. stock specific target 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.

In Article 6 of the Straddling Stocks Agreement (1995):

3. In implementing the precautionary approach, States shall:

(a) improve decision-making for fishery resource conservation and management by obtaining and sharing the best scientific information available and implementing techniques for dealing with risk and uncertainty;

(b) apply the guidelines set out in Annex II and determine, on the basis of the best scientific

information available, stock-specific reference points and the action to be taken if they are exceeded;

(c) take into account, inter alia, uncertainties relating to the size and productivity of the stocks, reference points, stock condition in relation to such reference points, levels and distribution of fishing mortality and the impact of fishing activities on non-target and associated and socio-economic conditions...

4. States shall take measures to ensure that, when reference points are approached, they will not be exceeded. In the event that they are exceeded, States shall, without delay, take the action determined under paragraph (3) to restore the stocks.

Implementation of the precautionary approach requires consideration of uncertainty in stock size and productivity. Unless stock sizes are known with perfect certainty, the estimation of uncertainty associated with a reference point is only part of the precautionary process, and the uncertainty associated with the current estimate of stock size or stock status is a critical part of the evaluation. The probability that the currently observed fishing mortality rate, for example, exceeds the limit reference point then would become conditional on the estimate of the limit reference point (e.g., Conser and Gabriel, 1992).

The harvest control rule has two components: the specification of the reference points (and other relevent parameters), and a functional form relating current stock status and reference points to management reaction (e.g., catch). The two components act together to determine the degree of precaution afforded by the rule. Rosenberg and Restrepo (1996) discuss the interaction among the acceptable probability of overfishing, the consequences of exceeding limit reference points, and the action to be taken when the stock is overfished. For example, an acceptable probability of overfishing could be higher if the action to be taken when the limit is exceeded is immediate and drastic. An acceptable probability of overfishing could be higher if stock conditions were exceptionally favorable, or if the result is simply that the probability of poor recruitment increases slightly in only one year, rather than resulting in a significant increase in the probability of repeated recruitment failure.

Parameterizing Limit Control Rules under National Standard Guidelines

As noted previously, within the precautionary context, the limit reference point is the critical reference point. Both the UN Straddling Stocks Agreement and the revised MSFCMA focus on *MSY*-related reference points as limits. This constrains the range of relevent biological reference points to a subset of those described earlier.

A default limit control rule is outlined in the Technical Guidance on the Use of Precautionary Approaches to Implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act, which defines limits to fishing mortality rate as a function of stock biomass (Restrepo *et al*., 1998). The rule is based on three parameters, F_{MSY}, B_{MSY} and c, a factor which reflects the expectation that a stock fished at F_{MSY} would naturally fluctuate around B_{MSY}:

$$F(B) = \frac{F_{MSY}\,B}{c\,B_{MSY}} \qquad \text{for all } B \le c\,B_{MSY}$$

$$F(B) = F_{MSY} \qquad \text{for all } B > c\,B_{MSY}.$$

The extent of that fluctuation is likely related to the natural mortality rate, and so c is defined as the maximum of (1-*M*, 1/2). The fishing mortality rate cannot exceed F_{MSY} , regardless of stock size, and must be reduced below F_{MSY} to zero as biomass declines below cB_{MSY} to zero. A minimum stock size threshold (MSST) is also specified: in no case should MSST be less than half the level which produces *MSY* (i.e., MSST >1/2 B_{MSY}), and MSST may be approximated as cB_{MSY} . The rule provides an approximate estimate of the maximum fishing mortality rate (MFMT).

The NMFS National Standard Guidelines for Standard 1 define *MSY* as "the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological and environmental conditions" with *MSY* stock size defined as "the long-term average size of the stock or stock complex, measured in terms of spawning biomass or other appropriate units, that would be achieved under an *MSY* control rule in which fishing mortality rate is constant." The *MSY* control rule is defined as "a harvest strategy which, if implemented, would be expected to result in a long-term average catch approximating *MSY*." In this context, the *MSY* stock size would be reflected by the biological reference point B_{MSY}, and the *MSY* fishing mortality rate would correspond to the biological reference point F_{MSY}.

Situations Requiring the Use of Proxies for F_{MSY} and B_{MSY}

The MSFCMA allows for the use of proxies in situations where there is insufficient knowledge to implement approaches outlined above. In general, proxies would be needed when *MSY*-related parameters cannot be estimated at all from available data, or when their estimated values are deemed to be unreliable for various reasons (e.g., extremely low precision, insufficient contrast in the data, or inadequate models). We refer to these situations as "data-poor" and "data-moderate", respectively. However, it should also be noted that there may also be circumstances under which proxies would also be useful in "data-rich" situations (e.g., when they are believed to be more robust or reliable than the estimates of *MSY*-related parameters). Thus, our use of the term "data-moderate" can be more generally interpreted as meaning "information-moderate".

In this report, proxies are substitutes for key biological reference points, which are used in place of those key reference points because they are easier to calculate, or require fewer data, or are more robust. *MSY*-based reference points are often difficult to estimate, particularly when the calculations involve estimation of the parameters of a stock-recruitment relationship. However, *MSY* has been the central focus of management objectives for several decades in many national and international agreements, and many proxies have been developed and applied. In addition, empirical studies and computer models have suggested which proxies can generally be considered reasonable for use as "default" substitutes (point estimates or ranges corresponding to life history strategies) for *MSY*-related parameters.

The list of proxies presented in the following sections is not all-inclusive and fisheries scientists are encouraged to develop and examine alternatives.

<u>Data-Moderate Situations</u>

In general, reference points from yield-per-recruit (YPR) and spawning-stock-biomass-per-recruit (SPR) analyses are easy to calculate because relatively few data are required; in particular, it is not necessary to obtain stock-recruitment data. For this reason, YPR and SPR reference points are often used as proxies for other reference points that do require stock and recruitment data.

Proxies for F_{MSY}

F_{max} was one of the earliest measures used as a proxy for F_{MSY}. However, it was often believed to be an overestimate of F_{MSY}, because it does not account for the fact that recruitment must decline at low spawning stock sizes. Computer models have also demonstrated that F_{max} invariably overestimates F_{MSY} if a Beverton-Holt (1957) stock-recruitment relationship applies, although F_{MSY} can sometimes exceed F_{max} with a Ricker (1958) curve. For this reason, and taking into account economic considerations, $F_{0.1}$ was developed and promoted as a more prudent alternative (Gulland and Boerema, 1973). Although $F_{0.1}$ is commonly interpreted as a conservative or cautious estimate of F_{MSY}, this is not always the case (Mace, 1994; Mace and Sissenwine, 1993). And even when $F_{0.1}$ does underestimate F_{MSY}, the equilibrium yields associated with the two reference points may be relatively very close (based on the argument that the difference between the equilibrium yields associated with F_{max} and $F_{0.1}$ are usually small, and F_{MSY} is usually less than F_{max}).

Another class of reference points that has gained prominence as proxies or independent measures of targets and limits are those based on $F_{\%SPR}$. In particular, values in the range $F_{20\%}$ to $F_{30\%}$ have frequently been used to characterize recruitment overfishing thresholds (Rosenberg *et al*., 1994), while values in the range $F_{30\%}$ to $F_{40\%}$ have been used as proxies for F_{MSY}. These defaults are supported by Mace and Sissenwine (1993) who advocated $F_{20\%}$ as a recruitment overfishing threshold for well-known stocks with at least average resilience and $F_{30\%}$ as a recruitment overfishing threshold for less well-known stocks or those believed to have low resilience, by Clark (1991, 1993) who advocated $F_{35\%}$ as a robust estimator of F_{MSY} applicable over a wide range of life histories, or $F_{40\%}$ if there is strong serial correlation in recruitment, and by Goodyear (1993) who advocated at least 20% SPR unless there were evidence of exceptionally strong density dependence.

Finally, in the uncommon situation where stocks have been maintained near B_{MSY}, F_{med} may be considered a reasonable proxy for F_{MSY}.

Proxies for B_{MSY}

The equilibrium biomass corresponding to the above-mentioned fishing mortality reference points can be used as proxies for B_{MSY}. In addition, B_{MSY} has been approximated by various percentages of the unfished biomass, usually in the range 30-60% B_0 (higher percentages being used for less resilient species, and lower percentages for more resilient species). B_{MSY} can also be approximated by the mean recruitment (R_{mean}) multiplied by either (a) the level of spawning per recruit at F_{MSY}; namely SPR(F_{MSY}), or some proxy thereof, or (b) 30-60% $SPR_{F=0}$. Note that if F_{MSY} is overestimated, then SPR(F_{MSY}) and B_{MSY} will both be underestimated, thus compounding the riskiness of control rules that use estimates of F_{MSY} and B_{MSY} in combination.

If catch and CPUE data are available, production models may provide useful proxies such as $CPUE_{MSY}$ which can be used as a relative index of B_{MSY} (in addition, the nominal effort (e.g., in boat-months) corresponding to F_{MSY} can be used as a relative index of F_{MSY}).

The risks of using CPUE as an index of or proxy for stock size with associated assumptions of constant catchability over all stock sizes and time may be sizeable and have been well-described (e.g., Hilborn and Walters, 1992).

Proxies for B_0

Where B_0 is unknown, it can be approximated by the product of average recruitment and $SPR_{F=0}$ (Myers *et al.*, 1994); however, this approximation assumes that there have been no density-dependent changes in growth, survival, or age at maturity during the "fishing down" period.

Proxies for MSY

The equilibrium yield corresponding to the above-mentioned *F* and/or *B* reference points can be used as a proxy for *MSY*, although of course such estimates of *MSY* must be considered long-term averages, and not treated as constant annual catches. For a fishery where annual quotas remain constant over a prolonged period (perhaps because there are insufficient data to update stock assessments), such quotas should be set at a level of 60-90% of the equilibrium or static estimate of *MSY*, with the high end of the scale applying to species with low natural variability or low *M*, and the low end applying to species with high natural variability or high *M* (Mace and Sissenwine, 1989).

Constraints on Acceptable Proxies

In addition, there are a number of estimators of, or approximations to, the limit reference F_t points based on the slope at the origin of stock-recruitment relationships (variously called $F_{extinction}$, F_{ext}, F_τ (Mace, 1994), F_{crash} (ICES 1997a)). These estimators include F_{med} (if calculated from data collected during a period when the stock was at low biomass), F_{high} (the fishing mortality corresponding to the 90th percentile of survival ratios), $F_{20\%}$, F_{loss} (the fishing mortality corresponding to the lowest observed spawning stock and associated recruitment — Cook, 1998), and F_{COMFIE} (the minimum of F_{MSY}, F_{med} and F_{crash}). Suggested biomass limits that have been considered dangerously close to the origin include MBAL (the minimum biologically acceptable level of spawning biomass; Serchuk and Grainger, 1992), $B_{50\%R}$ (the spawning biomass corresponding to 50% of the maximum recruitment in a stock recruitment relationship; Mace, 1994; Myers *et al.;* 1994), $B_{90\%R,90\%R/S}$ (the biomass corresponding to the intersection of the 90th percentile of observed recruitment and the 90th percentile of survival; Serebryakov, 1991; Shepherd, 1991), and B_{loss} (the biomass corresponding to the lowest observed spawning stock; ICES, 1997a). Any proxies used for F_{MSY} or B_{MSY} should be more conservative than these extremes.

Recommended Data-Moderate Defaults

The recommended data-moderate default limit control rule is the limit control rule described above as in Restrepo *et al*., 1998, using proxies for F_{MSY} and B_{MSY} as described below.

We recommend that fishing mortality rates in the range $F_{30\%SPR}$ to $F_{40\%SPR}$ be used as general default proxies for F_{MSY}, in cases where the latter cannot be reliably estimated. In the absence of data and analyses that can be used to justify alternative approaches, it is recommended that $F_{30\%SPR}$ be used for stocks believed to have relatively high resilience, $F_{40\%SPR}$ for stocks believed to have low to moderate resilience, and $F_{35\%SPR}$ for stocks with "average" resilience. Less-preferred alternatives (in order of decreasing preference) are to use $F_{0.1}$, *M*, F_{max}, or F_{med} (when F_{med} is calculated from data collected when the stock was believed to be fluctuating around B_{MSY}) as the proxies for F_{MSY}. The equilibrium or average biomass levels corresponding to these fishing mortality rates should then be used as proxies for B_{MSY}, in the same order of preference. The default limit control rule would then be defined with fishing mortality set to this default level when biomass exceeds $(1-M)*B_{MSY}$ or 1/2 B_{MSY}, whichever is greater, and would decline linearly to zero for biomass levels below this threshold.. The recommended default MSST corresponds to 1/2 B_{MSY} (the absolute lowest limit triggering the need for a rebuilding plan) for species with $M \geq 0.5$; but occurs at a larger biomass for species with smaller *M*.

<u>Data-Poor Situations</u>

If data are insufficient data to conduct YPR and SPR analyses, or if estimates of *F* and *B* cannot be obtained for comparison with YPR and SPR reference points, there are far fewer options for defining meaningful targets and limits. Priority should be given to bringing the knowledge base at least up to "data-moderate" standards.

Proxies for F_{MSY}

The natural mortality rate *M* has often been considered to be a conservative estimate of F_{MSY}; however, it is becoming more and more frequently advocated as a target or limit for fisheries with a modest amount of information. In fact, in several fisheries, $F=0.8*M$ and $F=0.75*M$ have been suggested as default targets for data-poor cases (Thompson, 1993; NMFS, 1996). In data-poor situations, M may not be reliably estimated either, however.

Proxies for B_{MSY}

The equilibrium biomass corresponding to $F=M$ or $F=0.8*M$ can be used as a proxy for B_{MSY}. However, in most data-poor situations, it will not be possible to calculate this quantity.

Proxies for B_0

If there are no data on recruitment, some function of CPUE might conceivably be used as a relative index of initial biomass. If information (perhaps anecdotal) exists on resource conditions prior to or shortly after the onset of fishing, some inferences of initial biomass (B_0) may be possible. Because the geographic area occupied by a stock may contract with declines in abundance, the contrast between present and early geographic distributions of the resource may be used to obtain a rough approximation of pre-fishery abundance. Early sport fishing records may provide useful information on resource conditions prior to intense exploitation (MacCall 1996). Estimates of early CPUE may relate to B_0, but care must be taken to correct for the general tendency for CPUE to underestimate declines in resource abundance. For example, this may require geographic stratification, correction for temporal changes in fleet composition (e.g., loss of less efficient vessels as catch rate declines) and a variety of behavioral and biological interactions. Nonequilibrium production modeling (Hilborn and Walters, 1992; Prager, 1994) also may provide an inference of initial CPUE for the fishery.

Proxies for MSY

If there is absolutely no information available to estimate fishing mortality or biomass reference points, it may be reasonable to use the historical average catch as a proxy for MSY, taking care to select a period when there is no evidence that abundance was declining. In recognition of the danger of continually setting annual quotas at a constant level equal to the historical average catch (a common situation in data-poor fisheries), it might be best to scale down the historical average catch by multiplying by a factor in the range 0.6-0.9 where smaller multipliers would be used for highly variable stocks and larger numbers for less variable stocks (Mace and Sissenwine 1989).

Recommended Data-Poor Defaults

In the absence of data and analyses that can be used to justify alternative approaches, it is recommended that the default limit control rule be implemented by multiplying the average catch from a time period when there is no quantitative or qualitative evidence of declining abundance ("Recent Catch") by a factor depending on a qualitative estimate of relative stock size:

Above B_{MSY}:
Limit catch = 1.0*(Recent catch)
Above MSST but below B_{MSY}:
Limit catch = 0.67*(Recent catch)
Below MSST (i.e., overfished):
Limit catch = 0.33*(Recent catch).

The multipliers 1.0, 0.67 and 0.33 were derived by dividing the default precautionary target multipliers in Section 3.3.2 of Restrepo *et al*. (1998) by 0.75, in order to maintain the 0.75 ratio recommended as the default distance between the limit and target reference points for stocks above (1-*M*)*B_{MSY}. Since it probably will not be possible to determine stock status relative to B_{MSY} analytically, an approach based on "informed judgement" (e.g., a Delphi approach) may be necessary.

Concluding Observations

The *MSY*-related reference points in the MSCFMA National Standard Guidelines and the FAO guidelines appear stringent in the context of current fishing mortality rates observed in open-access fisheries. Yet, historically, the risk associated with *MSY*-related reference points has been well detailed from a qualitative perspective: Larkin's (1977) famous summary cites the relative instability of stocks harvested at *MSY* which may arise from a relatively high proportion of young and first-time spawners (which may reduce the viability of eggs which are deposited) and the reduction in the number of spawning age classes; the risk to local subpopulations or substocks with lower productivities than the stock as a whole; the risk to less productive co-occurring species when highly productive species are fished at *MSY* levels; and the risk to productivity of competitors and predators when all stocks cannot be fished simultaneously at their respective *MSY*-related levels. Typical single-species reference points still treat all units of spawning stock biomass as equivalent, regardless of age structure or spawning history; and rarely include diversity of age structure as a component of the reference point. Maintenance of genetic diversity and problems of technological and biological interactions must be dealt with through compromises, and so there continue to be elements in the fishery system which are at risk under this approach.

For many of the model-based estimates of biological reference points, uncertainty has been evaluated using Monte Carlo or bootstrap procedures (e.g., surplus production models: Prager, 1994; Polacheck *et al*., 1993; yield-per-recruit models: Restrepo and Fox, 1988; Pelletier and Gros, 1991; spawning-stock-biomass-per recruit models: Cook, 1998). As more and more information about uncertainty becomes available or is included in the estimation process, the estimate of uncertainty related to the reference point increases. This may occur as more sources of observation error are included, or if process error is also included. The method used to fit a model may also affect the the estimate of uncertainty, as a function of the types of errors included in the model (e.g., Chen and Andrews, 1997). Consequently, although procedures for estimating the reference point and the underlying model may be agreed within the scientific community, the procedures for estimating uncertainty in those reference points are less standardized. In the most information-poor situations, quantification of uncertainty associated with the reference point may not even be possible. Thus, paradoxically, statistical uncertainty may appear to increase while the quality of information is increasing. The evaluation of alternative reference points as proxies for *MSY*-related reference points becomes problematic, because each reference point may be estimated with a different degree of certainty, some of which may be due to statistical artifact but which may affect its performance as a proxy in a precautionary context.

There is a fast-burgeoning body of literature which reviews various biological reference points as candidates for limit and target reference points in the precautionary contexts of various management institutions. Those papers almost universally endorse the evaluation of the performance of those reference points and associated harvest control rules using simulation modelling. We propose that for many management systems, the results of these simulations may show that the effect of the choice of a particular estimate of F_{MSY} or B_{MSY} (or its respective proxy) as a limit reference point may be tangential to the success of a precautionary managment regime when compared to the effects of the form of the associated harvest control rules, and historically observed implementation errors (the difference between the intended effect of management action and the realized result; e.g., the difference between total allowable catch and actual catch in a year). There have been cases where biological reference points and stock status have been defined with reasonable quality data and with reasonable certainty, but associated management regimes have led to significant and undesirable stock declines. Although the specification of *MSY*-related limit reference points based on poor-quality data may be daunting, for many fishery systems it is likely to be the easiest component of the precautionary process to implement.

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