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The use of Reference Points in Fisheries Management: A short review

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1. Introduction

The evaluation of a range of fixed-effort scenarios (undertaken as part of the recently completed project 'Development of an operating model and evaluation of harvest strategies for the Eastern Tuna and Billfish Fishery') provided guidance on identifying an appropriate initial Total Allowable Effort (*TAE)* for the longline fleet in the ETBF. However, ideally, any harvest strategy adopted for the ETBF should incorporate some form of feedback decision rule whereby the status of the fishery is regularly assessed, and the harvest strategy is updated and applied depending on the results. Without management feedback loops, high levels of combined effort may lead to overexploitation and/or overcapitalisation in the fishery. Alternatively, if effort levels can be adjusted in an appropriate manner, the risk of not achieving either the conservation and/or economic objectives should be diminished.

Decision rules used in fisheries management usually involve the use of reference points. Reference points act as benchmarks against which the performance of the fishery can be measured and are most widely used to achieve precautionary management objectives. Whilst the concept of Maximum Sustainable Yield (MSY) is a well known reference point which was widely adopted in the past, over the past decade a multitude of alternative reference points have been developed. This background paper briefly discusses the main issues involved in the adoption of performance measures and reference points in fisheries management.

2. Definitions

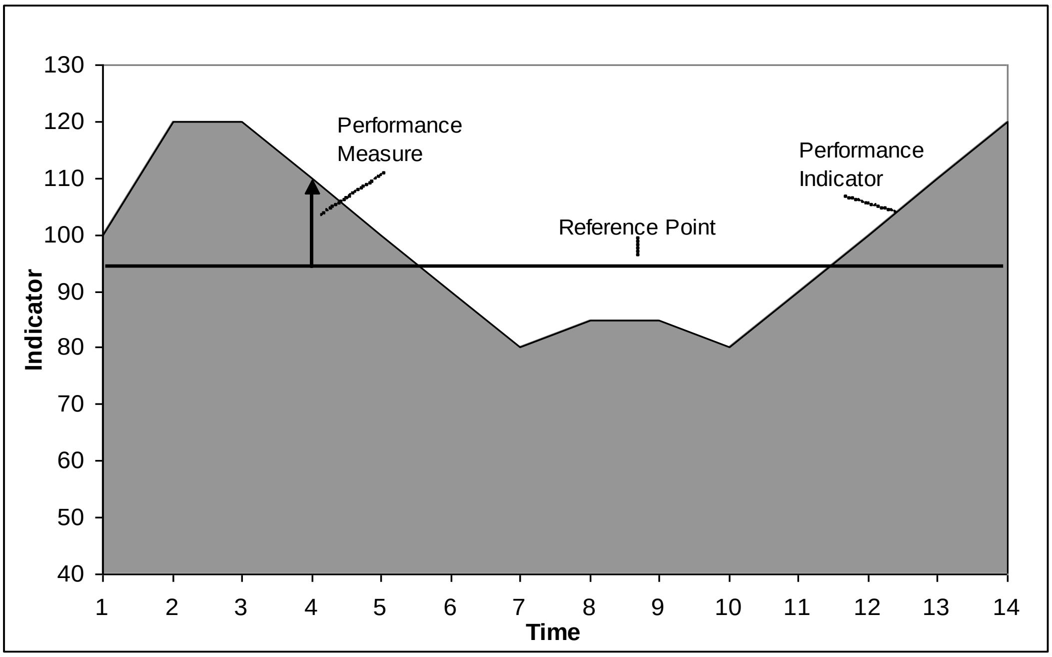
1) Performance Indicators and Measures:
   A performance indicator conveys information about some aspect of the system under study (eg. the biomass of the swordfish population in the SW Pacific) while a performance measure conveys information about how well the system is performing relative to some management objective (eg. it compares the performance indicator with some reference value or benchmark, say 30%B_o). Performance indicators are usually based on quantities estimated during the assessment and are generally useful only if a stock assessment method can estimate them reliably.

2) Target and Limit Reference Points
   The reference values or benchmarks against which fisheries performance is measured could be target values that identify desirable conditions at which management should aim (target reference points, TRP) and/or threshold or limit

values that identify critical levels which if exceeded result in potentially adverse fishery situations (limit reference points, LRP).

A schematic representation defining the relationship between a performance indicator, a performance measure and an associated reference point is shown in Figure 1. The Performance Indicator is shown by the height of the greyed area and is updated each year. An example may be the annual estimate of the spawning biomass of a given stock. The Reference Point is indicated by the horizontal line, while the value of the associated Performance Measure is the vertical distance between the Indicator and the Reference valve. For some years the Performance Measure is positive, indicating that the system is performing above the set Reference Point criteria, whilst in other years the Performance Measure is negative indicating that the system is under-performing.

Figure 1. Schematic representation of the relationship between a performance indicator and associated performance measures and reference point.

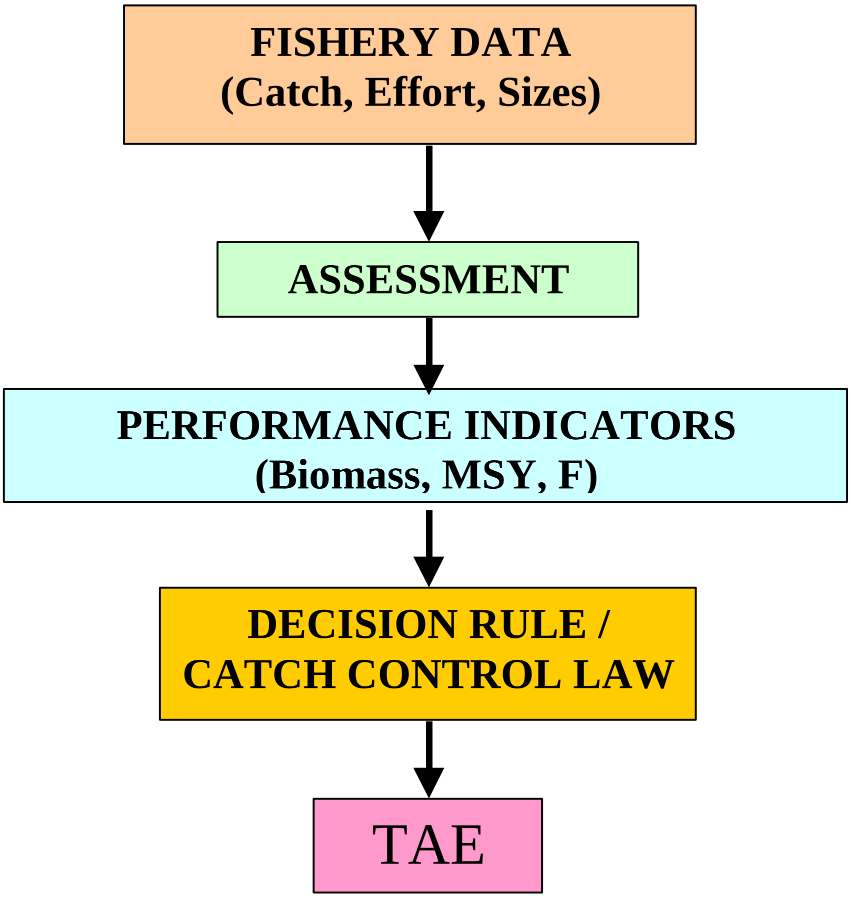


Traditionally, TRPs have been considered as indicators of a stock status which are desirable targets for management. It has been assumed that managing a fishery corresponds to adjusting the inputs to, or outputs from, a fishery until the relevant variables correspond to the chosen TRPs. TRP management requires active monitoring and continual readjustment of management measures on an appropriate (usually annual) time-scale. On the other hand, LRPs protect the resource and the associated industry against long-term damage, by defining and agreeing on a ‘danger’ zone where the continuity of resource production is in danger. A LRP may either correspond to some minimum condition (eg. a low spawning biomass) or some maximum condition (a high rate of decline in stock size, or a high mortality rate) at which a management response is triggered. Integral to the LRP approach is the concept that the fishery as a ‘system’ will react to the approach of the fishery to an LRP by adopting a pre-negotiated response to unfavourable events.

Historically, the reference point known as maximum sustainable yield (MSY) was often used as a target reference point, but today is often seen as a limit reference point (eg. FAO 1995).

3) Harvest Strategy
A harvest strategy is a set of rules that is used to determine a management action. The set of rules should define the data to be collected from the fishery, how those data are to be analysed, and how the results of the data analyses are to be used to determine actions. The components of a typical harvest strategy used to set a TAE are shown schematically in Figure 2.

Figure 2. Components of a 'typical' harvest strategy.

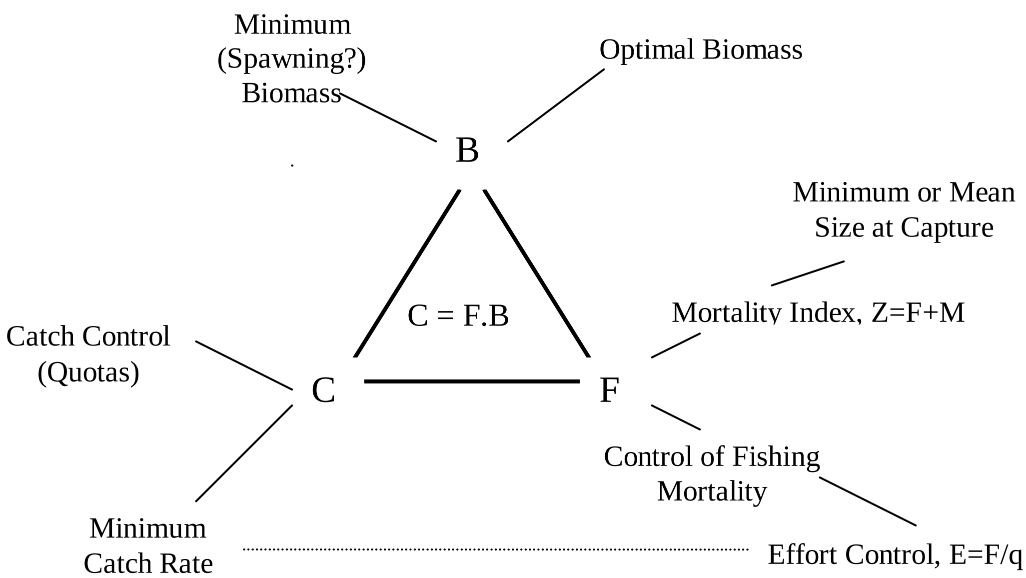


3. Reference Points and Harvest Strategies

Reference points usually begin as conceptual criteria which attempt to reflect in board terms the management objectives of the fishery (eg. prevent overfishing). However, for use in practice, conceptual reference points need to be converted into technical reference points which can be quantified on the basis of the characteristics of the fishery. For example, the concept of Maximum Sustainable Yield (MSY) has often been used as a reference point given the objective to maximize yield. However, the concept of MSY has been interpreted in several ways in an attempt to provide a technical definition. Another conceptual term for which there is not agreed technical definition is the point beyond which 'overfishing' is said to occur. Nevertheless, for implementation purposes, both the concepts of MSY and overfishing (which in the above context may be interpreted as target and limit reference points respectively) need to be technically defined. Indeed, the lack of clearly defined and quantifiable management objectives has been identified as one of the main impediments in establishing and adhering to reference points.

Caddy and Mahon argue that the relationship between fishing mortality (F), stock biomass (B) and catch (C) provide the basis for discussion of most performance measures and related reference points. The relationship between these three variables is shown in Figure 3. F and B are the most basic performance variables and most reference points are set in relation to these variables: e.g. the F which, if applied over a number of years, produces an average yield equivalent to MSY; the F which maximizes the average yield per recruit; the biomass which will produce a desired level of recruitment. Conventional fishery management seeks to control F or sustain B at levels which correspond to target values, using a variety of input and output controls.

Figure 3. The main population, reference and control variables used in defining biological reference points. In addition to the three primary measures of the state of an exploited population, fishing mortality rate (F), biomass (B) and catch (C), whose inter-relationship is specified by the catch equation, other secondary measures may also be used as performance variables. (Taken from Caddy and Mahon, 1995).



Despite this theoretical simplicity, Caddy (1998) notes that "previous management approaches based on target reference points alone had proved vulnerable to overfishing once a TRP had been overshot. This was partly because of the high degree of uncertainty in locating the current position of the fishery in relation to the TRP but also because of recovery times after effort overshoots were often long and because mechanisms for integrating the efforts of scientists, managers and fishermen into a single responsive fisheries management system had been neglected. Often adversarial positions were adopted in the course of management decision-making that required long negotiations and inconclusive management responses before the 'fishery system' could react to downturns in resource abundance due to fishing or natural causes. In the interim, the fishery continued to overfish the stock in absence of a pre-negotiated, precautionary approach to management which is integral to the new legal instruments."

Based on this experience, several issues need to be highlighted. First, reference points are only relevant if placed within a management context as part of a harvest strategy or decision rule that has been be agreed to by all stakeholders to be effective. Thus TRPs and LRPs alone do not lead to a responsible or precautionary management response. Second, reference points can only be effective if appropriate management responses are pre-negotiated and effectively implemented. Finally, a high degree of rigour is appropriate in setting LRPs only if the management response is designed to be rapid and effective in controlling potential overfishing (Caddy 1998).

5 Model –based Reference Points

The performance measures and reference points used in fishery management are largely based on biometric or econometric models of the fishery, and hence on mathematical conceptualizations of the underlying fish and fishery dynamics. Furthermore, reference points have generally focused on fishing mortality or biomass and are intended to maintain these at or below/above a level that will prevent recruitment overfishing. The basic process has the following steps (Hilborn 2002): (1) estimate the current and virgin stock size from some form of stock assessment, (2) calculate the target catch for the fishery by using accepted reference exploitation rates that depend on current and virgin stock size, (3) manage the fishery to try to achieve the target catch by using a variety of input and output controls. Several well-known and well-used target exploitation rates include the following:

1) Maximum Sustainable Yield, F_{MSY}

Maximum Sustainable Yield is a descriptive term for the highest point of the curve describing the relationship between the annual fishing effort applied by all fleets and the yield that should result if that effort level were maintained until equilibrium were reached. The effort level, E_{MSY}, at which MSY occurs can be converted to a fishing mortality, F_{MSY}, if the catchability coefficient q is known. It is important to note, that despite the name, management based on MSY as a TRP does not ensure a constant (sustainable) catch each year. In years with poor recruitment, a fishing mortality of F_{MSY} produces catches well below that indicated by the model. An attempt to harvest the statistically predicted MSY in these 'poor' years would require fishing above $F_{MSY.}$ Subsequent developments in the theory, and perhaps more so, practical experience in fishery management, have cast doubt on the usefulness of MSY as a safe TRP (eg. Larkin 1977). .

2) Maximum Constant Yield

An alternative interpretation of the MSY concept is the catch that could be removed in perpetuity from the resource with an accepted low probability of endangering it (Sissenwine 1978). A similar concept, known as Maximum Constant Yield MCY, has been used in New Zealand (Annala 1993) together with the concept called Current Annual Yield (CAY) which is based on applying a reference fishing mortality F_{REF} to the fishery each year which, if applied each year, would within an acceptable level of risk maximise the average catch from the fishery. Maximum Average Yield (MAY) is the long-term average of CAYs and is higher than MCY since the CAYs closely track the variation in fishable biomass.

3) Yield-per-Recruit, Fmax
This gives the level of fishing mortality for a given size at first capture which maximizes the average yield from each recruit entering the fishery. However, like MSY based fisheries management, it has also suffered from a number of failures as a TRP (eg. recruitment overfishing) and lead to the adoption of $F_{0.1}$ or $F_{0.2}$ as an alternative more precautionary fishing strategy.

4) The 40:10 Rule
This rule states that if the stock is above 40% of its virgin stock size, the target catch is the population size multiplied by a target reference exploitation rate, F_{ref}. If the stock is below 10% of its virgin stock size, no catch is permitted. If the stock is between 10% and 40% of its virgin stock size, the target exploitation rate increases linearly from 0 to F_{ref}. This approach has been adopted in a number of jurisdictions.

Although the use of reference points in harvest strategies, such as those outlined above, is generally accepted as a contemporary and effective way to approach the fisheries management, several problems nevertheless have been identified. Probably the most important criticism is that they rely too heavily on knowledge of stock abundance which is extremely prone to error (Essington 2001). Indeed, all the above strategies are predicated on some actual ability to measure abundance and an associated target mortality rate. However, it is often difficult to estimate any of these parameters very reliably (Hilborn 2002). Another criticism is that most limit reference points are arbitrary, or based on arbitrary assumptions (Gilbert et al. 2000; Essington 2001) Furthermore, accurate monitoring of the catch is essential for estimating current F-values. With under-reporting there is a high probability that target F-values will be exceeded. Given these concerns, attention needs to focus on alternative types of reference points, particularly those which do not rely on parameters which need to be estimated using complex stock assessment models.

6. Empirical-based Reference Points

The population model-based reference points are usually technically complex and require considerable quantities of data, usually collected over many years. Despite problems in the use of these model-based reference points due to poor estimation, for many fish stocks such data is not available and so defining precautionary reference points based on knowledge of fishing mortality or biomass becomes problematic. This is particularly so for new and developing fisheries. In such cases, one needs to be able to define less-technical reference points but which nevertheless still convey information related to some aspect concerning the condition of the stock. This is they should be based on variables which are themselves related to, or are influenced by, the basic reference variables F and B. For example, CPUE is usually taken as an indicator of population biomass.

Examples of possible empirical indicators are as follows:

Catch based RPs
Examples where uncorrected commercial catch or landings have been used as an indicator are sparse as it is difficult to identify appropriate reference points. However, Scandol (2003) examines the use and interpretation of landed catch as an indicator using a monitoring system based on cumulative sum (CUSUM) control charts.

CPUE based RPs
The quintessential low-cost index of abundance for monitoring resource abundance is commercial catch-per-unit-effort. This is based on the assumption that catch rates are proportional to the abundance of the underlying resource so that changes in catch rates reflect changes in abundance. However, the weakest component of CPUE data is the information about, and interpretation of, fishing effort. This is especially the situation in multi-species fisheries such as the ETBF.

Size based RPs
Various changes in the underlying population may be inferred from changes in the size-composition of the catch. Suggested performance indicators include:
a) Mean and upper-95 percentile fish weights in catch – the use of mean size as a TRP may be based on yield-per-recruit analysis or may consider the recruitment ogive in relation to the size at first maturity. For example, a target may be to aim for an exploitation rate such that the average size of fish caught is equal to, or greater than, the average size at maturity (so that at least 50% of individuals have an opportunity to reproduce).
b) Percentage of catch within various size classes
c) Percentage of mature fish in the catch
d) Ratio of mean size in the catch and size at 50% maturity.
Various methods have also been proposed for estimating total mortality from size composition data (eg. Sparre et al, 1989).

Spatially based RPs
It is assumed that following the start of a fishery, several stages may occur as progress is made from unfished to overfished conditions, and that this transition may be picked up by a simple spatial index of aggregation for i-1,2,3…N unit areas, such as that proposed by Gulland (1955):

$$I_g = [\mathrm{Sum}(C_i) / \mathrm{Sum}(E_i)] / [\mathrm{Sum}(CPUE_i) / N]$$

If this is the case, simple indices of concentration could be used to formulate LRPs designed to pick up unfavourable changes. The results of simulations might be used to specify situations where CPUE becomes low and uniform or where the area fished contracts in size with over-exploitation.

While the use of more-empirical based terms may be seen as being less rigorous, nevertheless, they may have the advantage of being based on more readily available data and calculated with minimal technical expertise and as such may be more readily understood and accepted. In other words, a highly technical reference point or control law may be difficult to explain but will still need to accumulate practical ‘hands-on’ experience, while a less precise ‘empirical’ based reference point may be more effective if it is understood and receives consensus from the industry and still leads to reproducible results.

The use of empirical indicators will need to be tested both in simulation and in practice in order to detect and overcome possible problems of practical implementation. However, while the empirical based approaches to identifying performance measures and related reference points may lack the theoretical rigour usually associated with the more familiar model-based reference points, initial results indicate the utility of this approach (Hilborn 2002). Furthermore, the use of such indicators may best be applied using a ‘basket’ of empirical measures, each derived from fundamentally different data sources in a “traffic-light” mode where the nature of the management response is based on the number of reference points which have turned from green to either yellow or red (Caddy 1998). Indeed, an ideal management strategy should include multiple indicators, derived from independent data, with trigger reference points at roughly the same level of exploitation or risk. Finally, as the history of their model-based counterparts indicates, such reference points will likely need to be subject to some ‘fine-tuning’ as part of a fishery management system, i.e. they will probably have to be modified in light of practical experience.

7. Other Approaches

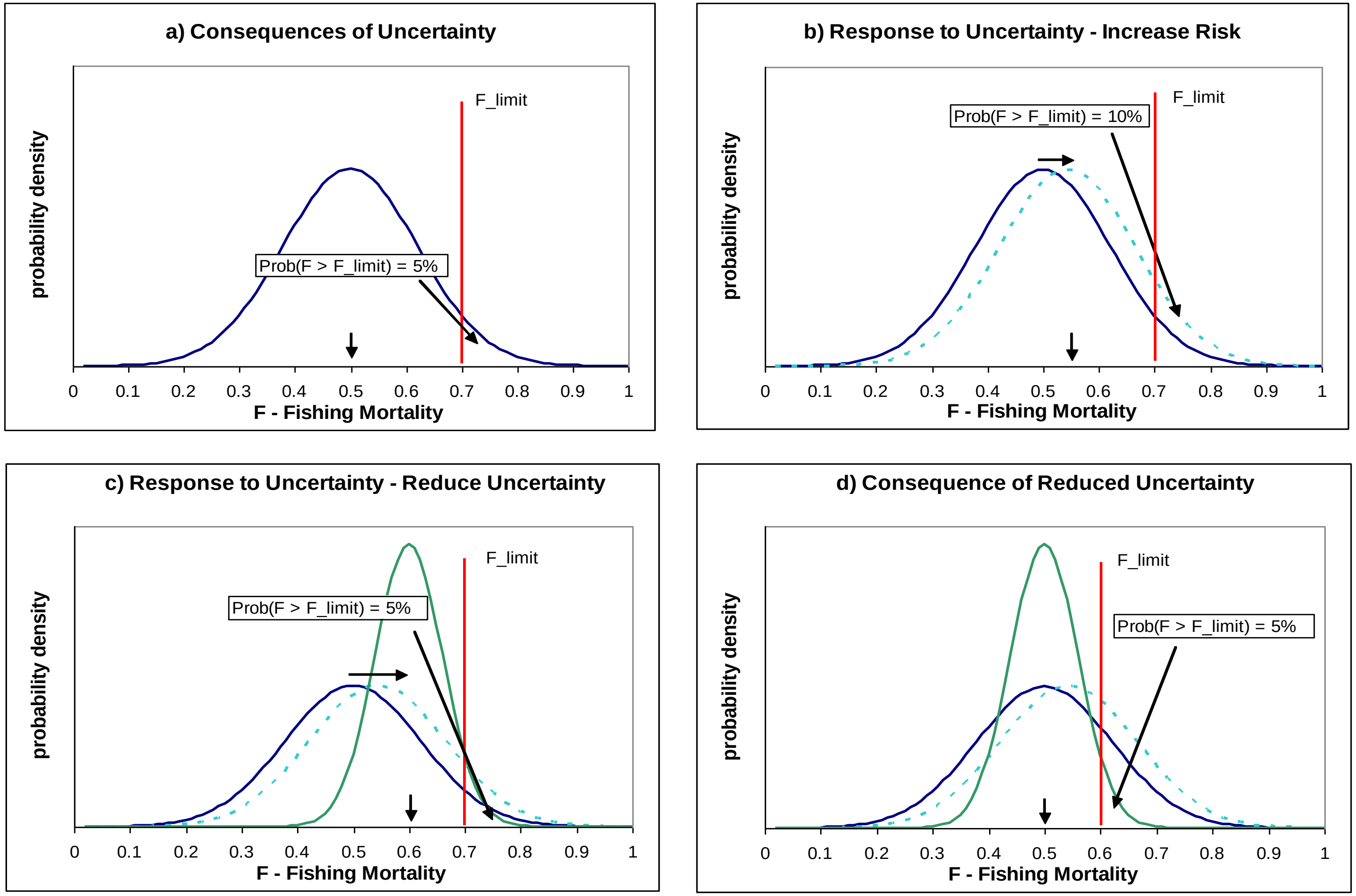
Finally, the concept of a reference point as a ‘conventional’ value that is agree to by all stakeholders may have to be considered if available data does not allow calculation of a ‘scientific’ or model based index. Such an approach is supported by the fact that acceptance of reference points is an important aspect of their utility.

8. Dealing with Uncertainty

The concept of reference points might imply to those unfamiliar with the practicalities of assessment science that managers know exactly where the fishery is in relation to them, and whether the fishery is in a ‘desired’ or ‘undesired’ condition. This is of course not so. What in effect will be required for ‘precaution’ is to translate reference points from deterministic values into likelihoods of the fishery finding itself in a more-or-less risk prone zone. For example, within ICES the precautionary basis for advice is that for a given stock “the probability of exceeding the limit reference point will not be greater than 5% in any given year (Serchuk et al 1997). However, given assessment coefficients of variation (the ratio of the standard error to the mean) of the order to 20-30%, the implication of this is that the TRP must be set at a conservative level, or one must have other controls in place to detect and respond to declines in stock levels before the LRP is reached.

A series of examples explaining the above relationship between estimation uncertainty and reference points is shown in Figure 4. To begin, consider the situation where the limit reference point for fishing mortality has been determined to be F_{lim}=0.7 and the standard error on the estimates of fishing mortality is 0.1215. Then, if one is to the restrict the probability of exceeding the limit reference point to 5% then the maximum fishing mortality that can be set is F=0.5. This situation is shown in Figure 4a. On the other hand, if we deploy an alternative precautionary criteria such that the probability of exceeding the limit reference point does not exceed 10% then

Figure 4. Dealing with assessment uncertainty in defining reference points. Refer to text for explanation.



the maximum fishing mortality that can be set is F=0.544 (around 9% higher). This situation is shown in Figure 4b.

An alternative to setting a less precautionary reference criterion is to try, where possible, to reduce the uncertainty in the assessment process. This can be achieved by a number of means such as collecting better data to conducting targeted research. If one were to reduce the uncertainty by a factor of two (ie. reduce the standard error on the fishing mortality rate from 0.1215 to 0.06075) then the maximum fishing mortality that could be set while still restricting the probability of exceeding the limit reference point to 5% increases by 20 percent from F=0.5 to F=0.6. This situation is shown in Figure 4c. It is possible, however, that the better data and research indicates that the limit reference point should in fact be lower at F_{lim}=0.6 instead of the original value of F_{lim}=0.7. In this situation, even though the limit reference point is more restrictive, the reduction in uncertainty allows fishing mortality to be monitored with greater certainty. Consequently, there need be no decrease in the maximum fishing mortality rate of F=0.5 while still restricting the probability of exceeding the limit reference point to 5%. This situation is shown in Figure 4d. If the reduction in uncertainty had not been achieved, then the probability of exceeding the limit reference point would have increased to around 20%.

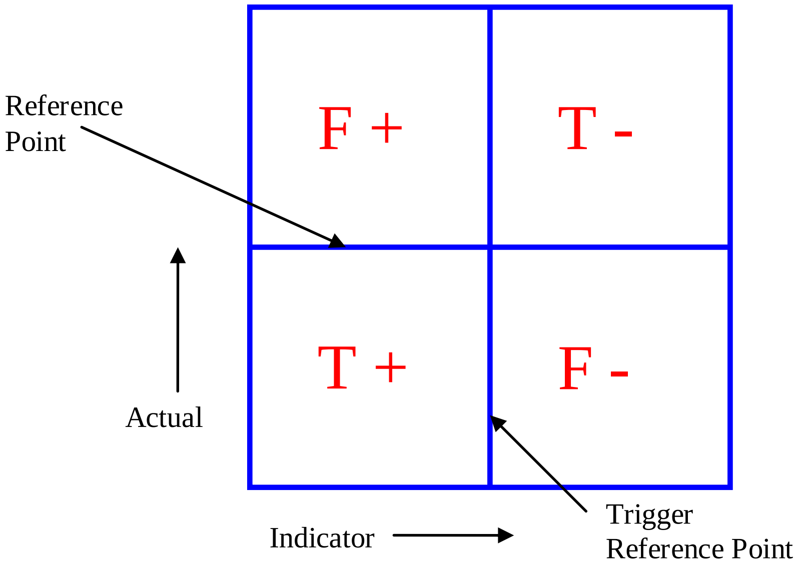
In simple terms, this example is intended to show that the collection of accurate and complete statistics, which allows the state of the system to be calculated with a higher degree of precision, permits a higher fishing mortality to be maintained with the same risk of overshoot than if data collection is given a low priority.

9. How "Good" is an Indicator?

An ideal indicator will have a linear relationship with that aspect of the system it is a measure of. For example, ideally we would like CPUE to be linearly related to the underlying abundance of the resource being fished. Hence, an X-percent decline in CPUE would then indicate a corresponding X-percent decline in the resource. In such a situation the indictor will always give a true reflection of the associated state of the system with the result that the indictor will be triggered only when the state of the system is below the associated reference value. Consequently, the relationship between the indictor and the actual state of the system can take on only two forms – a true positive (T+, the state is below the reference point and this was correctly detected) and a true-negative (T-, the state is above the reference point and this was correctly detected). However, in practice the above situation is never achieved. The non-linearity of the relationship between catch and effort, combined with the inherently stochastic nature of the marine system, means that the true nature of the relation between an indicator and that aspect of the fishery it is a measure of will likely remain unknown.

This uncertainty results in a number of consequences. First, an indicator may be triggered when the underlying aspect of the fishery is still above the corresponding reference value. This is known as a false-positive (F+, the state is above the reference point and this was incorrectly detected). Alternatively, an indicator may not be triggered when the underlying aspect of the fishery is actually below the corresponding reference value. This is known as a false-negative (F-, the state is

Figure 5. Diagrammatic representation of the 4-types of relationship between an indicator and the actual state of a system (From Scandol 2003).



below the reference point and this was incorrectly detected). Combining these with the two states identified previously therefore gives a total of four forms of the relation between an indicator and the actual state of a system. These are shown in Figure 5.

Understanding the nature of the false-positive and false-negative errors is fundamental to understanding the operation of any indicator and trigger point system. This is because any signaling system will generate errors in the form of false-positive as well as false-negative signals. However, one should attempt to identify those indictors which minimize the occurrence of both these types of errors (and consequently maximizes the likelihood of the indicator correctly indicating the true state of the system). Furthermore, for a given relationship between an indicator and the actual system state, false-positive outcomes are traded off directly against false-negative outcomes (i.e. as the likelihood of one type of outcome increases, the likelihood of the other decreases). Precautionary decision-making based upon such a relationship would entail making false-positive errors in preference to false-negative errors.

10. Ecosystem Related Reference Points

Given the increasing focus of management on assessing impacts on all components of the fishery related ecosystem, multispecies or ecosystem-related reference points will need to identified and agreed upon at some stage. However, this process is still in its early stages. Proposed reference points may include monitoring key-stone species or the use of a biomass-size spectrum of living resources.

11. Implementation

Given the use of both target and limit reference points there is an obvious choice in how a system of reference points can be implemented. Caddy (1998) suggests two approaches:

1. Targeted Approach: - A TRP is specified and the fishery managed so as to try and hit this target, with the proviso that, from precautionary considerations, statistical analyses and modeling are aimed at ensuring that the possibility of overshoots is minimized. The TRP itself could be specified based on first setting a LRP – the TRP is then estimated as a secondary quantity based on the degree of uncertainty in the position of the fishery and an acceptable probability of overshoot is agreed by all stakeholders (cf. section 7).

2. Non-Target Approach - No specific fisheries target is set. However, on triggering one of more LRPs the fishing effort is then reduced sufficiently to ensure that the resource has a chance to a level above that which applied before the management correction was imposed (otherwise the fishery risks becoming stuck at close to the LRP level (eg southern bluefin tuna)). When a basket of indicators are used, the severity of the management correction increases as the number of LRPs turn from ‘green’ to ‘red’.

12. Reference Points and the Precautionary Approach

Reference points have become closely identified with the precautionary approach to fisheries management. Based on views adopted by the FAO Expert Consultation on the precautionary approach, to be precautionary a fishery needed a management system that measured catches and abundance, rules about how catches would be changed in relation to the data collected, and the ability to enforce changes in catch. However, based on this view Hilborn argues that that most of the world’s fisheries are not precautionary – not because the reference exploitation rates are too high but rather because catch cannot be measured or catch limits enforce, because abundance cannot be estimated, or because rules do not state how catches will change in relation to stock size (Hilborn 2002). The key message is that it is the process that is precautionary, not the specific reference points.

Caddy and Mahon (1995) also conclude that despite an increasingly quantitative trend in the use of reference points for fisheries management, in most jurisdictions there has been a failure to conserve stocks. They identify the following reasons for this failure:

- Poorly defined management objectives
- Poorly defined conceptual bases for the reference points
- Problems of estimating reference points and stock status (variability)
- Failure to link the assessment of resources for the management objectives
- Difficulty of scientists in communicating these problems to managers and stakeholders
- The failure of management to constrain fisheries to agreed levels.

Given the experience of management based on MSY, two important lessons can be learnt. First, choosing any model-based performance measures and reference points implies that the underlying assessment model is agreed to be a reasonably accurate representation of the underlying dynamics of the fishery. Second, the more important question may be less one of picking reference points with the greater theoretical underpinnings, and more one of picking reference points that provide robust advice under conditions of uncertainty.

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