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Reference points for fisheries management

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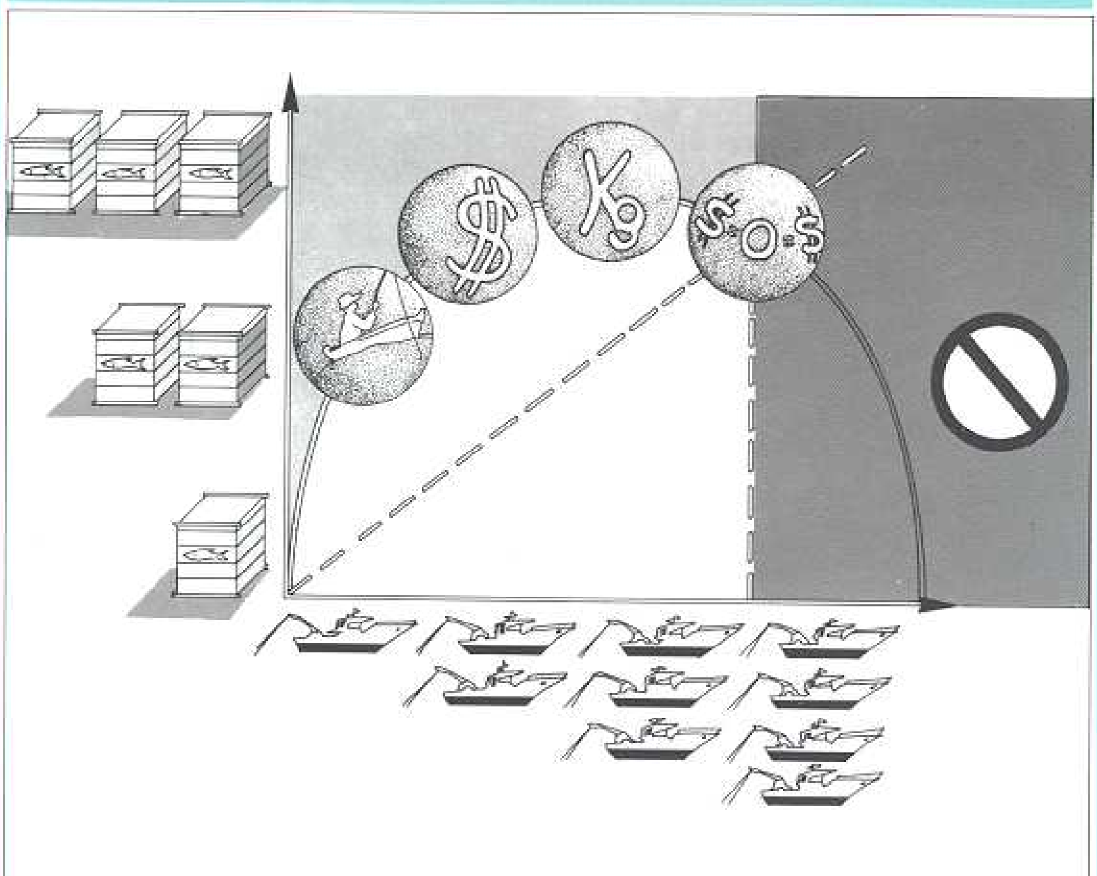

Food and Agriculture Organization of the United Nations

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Reference points for fisheries management

by
J.F. Caddy
FAO Fisheries Department
and
R. Mahon
Fisheries and Environmental Consulting
Saint James, Barbados

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PREPARATION OF THIS DOCUMENT

This document is based on a background paper on fishery management reference points prepared following a request from the Secretary of the United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks after its first session in New York in June 1993, and on FAO Fisheries Circular No. 864. This document attempts to place the various reference points used, or potentially useful, for management purposes, in a broader less technical content, suitable for both assessment workers and fisheries managers.

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Distribution:

FAO Fisheries Department
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Authors
Marine Science (General)
Directors of Fisheries

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ABSTRACT

This paper reviews the conceptual background and application of technical reference points in fishery management. Despite considerable investment in stock assessment methodology and expertise, fisheries worldwide are overexploited. This appears to be due to a mismatch between the precision of assessment and the precision of management. Two types of reference points are recognized: target reference points (TRPs) and limit reference points (LRPs). The use of MSY as a target reference point is considered in the light of past performance of fishery management, and it is suggested that MSY and other reference points formerly used as targets, may be more appropriately applied as LRPs. The recent trend towards the quantification of uncertainty and estimation of risk in the provision of advice is considered to be good, but the cost and availability of information and expertise required may preclude the use of these techniques for many small or low value stocks and for most stocks in developing countries. The recent trend towards inclusion of 'ecosystem concepts' in setting fishery management objectives is also seen as good, and overdue. Although still in their formative stages, ecosystem concepts can still provide LRPs. Effective management will require a 'set of rules' comprising both TRPs and LRPs. In most national and international fishery management situations, the current institutional structure will probably require some modification in order to successfully apply these sets of rules. Fisheries management organizations will continue to assess and manage fisheries routinely, but management may need to develop an independent review which comes into play when resource production limits are approached. The action to be taken at such limits should be discussed and agreed in advance.

CONTENTS

SUMMARY AND CONCLUSIONS

1. Despite an increasingly quantitative trend in the use of reference points for fisheries management, in practice, in most jurisdictions there has been failure to conserve stocks for sustainable use. There have been several reasons for this, including:
   - 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 to the management objectives,
   - difficulty of scientists in communicating these problems to managers and stakeholders,
   - the failure of management to constrain fisheries to agreed levels.

2. There has been a trend in the reference points used from those which maximise yield (F_{max}, F_{msy}, F_{Msr}) to lower rates of target exploitation which recognise the need to be conservative ($F_{0.1}$, $2/3F_{msy}$) to those which set limits or thresholds to protect the stock against collapse (F_{med}).

3. The earlier reference points proposed by fishery scientists have been used primarily as Target Reference Points (TRPs), but owing to problems caused by overshooting TRPs, there has been a perceived need for reference points that help to avoid situations which are dangerous to the resource. These have been referred to as Limit Reference Points (LRPs), or threshold reference points.

4. The shift away from Reference Points based on mathematical optima, to conservative, or protective ones that mark the boundary between rational and non-sustainable exploitation, requires decisions about what is an appropriate level of risk in the face of uncertainty due to measurement error, model error, and process error. These decisions on the acceptable risk and on the LRPs are inevitably arbitrary, but it is essential for managers to make them.

5. The need for arbitrary, albeit technically informed, decisions has affected fishery management in two ways. The first affects the technical aspects of stock assessment, which has recently begun to focus on quantifying the effects of uncertainty on management. The second aspect affected is the decision-making process, which must develop means of evaluating and deciding upon an appropriate, or acceptable level of risk, then agreeing upon informed, even if occasionally arbitrary, target and limit reference points.

6. The mathematical complexity of models incorporating risk, and the research costs associated with quantifying uncertainty will probably preclude this approach for most of the world's smaller fish stocks in the near future. For the managers of those stocks, the focus must be on developing the second of the options in paragraph 5, as well as focusing on procedures for agreeing upon precautionary reference points, adopting them as a convention, and taking management action in a timely and adequate fashion.

7. There is a growing trend towards inclusion of ecosystem concepts as a basis for establishing limits to exploitation. While still immature relative to concepts based on single species considerations, these can already provide guidance as to safe limits for fishing.

8. For limit or threshold points, the emphasis must be upon establishing agreement among participants as to the limiting conditions corresponding to the reference point(s) used and the actions to take when these are believed to have been reached. The management action should be automatic; ideally agreed to in advance by the resource users and their representatives.

9. Most national fisheries ministries and international fishery management organizations appear to be structured and to function in a way which would permit them to adopt the approach discussed above. Hitherto, these organizations may have overemphasised the role of technical inputs in making management decisions. In some cases, action has been deferred due to a lack of an adequate scientific consensus for decision.

10. The major change which will be required by most organizations will be to incorporate a body or committee with a broader responsibility for fishery sustainability, which will be responsible for defining objectives and Reference Points, and to which management responsibility will pass when limits are approached.

11. Given the current state of the world's fish stocks, the recent history of collapse of major fish stocks, and the continuing declining trend of many resources, there is a need to refocus effort on the agreement/decision making process, and to respect the provisions of the United Nations 1982 Convention on the Law of the Sea in taking management action based on the best available information.

1. INTRODUCTION

The conclusion that many marine fish stocks within and outside EEZs are currently subject to ineffective management measures, applies not just to the little known resources off developing countries, or the difficult to assess highly migratory species of the high seas, but also to well-studied demersal resources of northern continental shelves where recent dramatic stock declines have been registered for some important species (FAO 1994). Several highly migratory resources (notably the depleted bluefin tuna stocks) also offer dramatic histories of stock decline, despite an international management history of several decades.

Due to dramatic improvements in fishing and communications technology, fleet fishing power can be exerted ever more rapidly and moved from one fishery to another within short time periods. Good statistics for the early years of the fishery when effort is low may later be extremely valuable in obtaining reliable estimates of the current status, and may even be essential (Hilborn 1979). Unfortunately, a fishing effort level for a stock, which in the 1950s could have taken half a decade to reach, can now be achieved in the first year of a new fishery.

The 1982 United Nations Convention on the Law of the Sea (UN 1983) is a key reference point for discussion on national and international fisheries management. The logical points of entry for this discussion are Articles 61-64, which provide criteria for managing a stock within a single exclusive economic zone (Hayashi 1993). In Article 61, this responsibility is given to the coastal State, which is directed to take account of the best scientific evidence available, to ensure that the living resources within the EEZ are not endangered by over-exploitation, and "to maintain or restore populations of harvested species at levels which can produce the maximum sustainable yield, as qualified by relevant environmental and economic factors". Among the qualifying factors mentioned is the interdependence of different stocks on the same fishing ground, with its implicit reference to multi-species considerations. A primary responsibility is given for protecting stocks from overexploitation, and a secondary one, referred to as 'optimal utilisation', which simply requires that the stock is large enough that when harvested, it can produce the maximum sustainable yield (MSY). Although initially intended to encourage management for MSY, it should be noted that, from a population dynamics perspective, this includes all fishing effort levels below that which provides the MSY.

> *STATES SHALL, "...TAKING INTO ACCOUNT THE BEST SCIENTIFIC EVIDENCE AVAILABLE [...] ENSURE THROUGH PROPER CONSERVATION AND MANAGEMENT MEASURES THAT THE MAINTENANCE OF THE LIVING RESOURCES IN THE EXCLUSIVE ECONOMIC ZONE IS NOT ENDANGERED BY OVER-EXPLOITATION.*
>
> The 1982 Convention on the Law of the Sea

Under Article 63, shared and straddling stocks are treated together. In both cases, the States concerned, whether coastal or distant water fishing nations, should seek: "either directly or through appropriate regional or subregional organizations", to agree upon the measures necessary for their conservation and development. Article 64 deals with highly migratory species, where again, "the coastal State and other States whose nationals fish in the region" are urged to "cooperate directly or through appropriate international organizations with a view to ensuring conservation and promoting the objective of optimal utilization of such species...both within and beyond the exclusive economic zone". Under both of these last mentioned articles, the overall objective of conserving for optimal utilization remains by implication that specified under Article 63.

There has recently been a recent trend in fisheries management towards the inclusion of all users in the management process. Broadly defined, users in developed fishery regimes includes fishermen, the fishing industry, all those who rely on fishery habitats for a living, and those interested in conservation of fishery resources and habitats. Formal mechanisms for the input of users are now included in the management process in many countries, e.g. the Fishery Management Councils of the USA, the newly established Fisheries Resources Conservation Commission (FRCC) of Atlantic Canada, and Fisheries Advisory Committees required by legislation in Caribbean Community States. In many instances this trend extends to the point of vesting the responsibility for management in the users (community based management). The continued successful evolution of these trends requires that the process of assessing fisheries and providing management advice based on management reference points be made more understandable to non-technical users, so that they can participate meaningfully in the decision-making process.

More recently there has been a global movement towards integrated management of marine ecosystems. This has resulted largely from the 1992 United Nations Conference on Environment and Development (UNCED) which produced Agenda 21, the manifesto of follow-on actions adopted by a majority of coastal nations. Specifically, Chapter 17 on the oceans, recommended that nations:

- Reduce and control degradation of the marine environment so as to maintain and improve its life support and productive capacities;

- Develop and increase the potential of marine living resources to meet human nutritional needs, as well as social economic and development goals; and

- Promote the integrated management and sustainable development of coastal areas and the marine environment.

There have been several fishery specific and fishing-related follow-up activities since UNCED. Issues of concern to small island developing States (SIDS) were recently addressed at the Global Conference for Sustainable Development of Small Island Developing States (Barbados, 1994). Among coastal States, SIDS have a particularly high stake in marine management, as their ratio of EEZ to land area or population is significantly higher than for mainland States. Two areas of focus for FAO became the development of a Code of Conduct for Responsible Fisheries (FAO Technical Consultation on the Code of Conduct on Responsible Fishing, Rome, 1994), and the development of criteria for the management of straddling stocks and highly migratory stocks (United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks, New York, 1993/1994 and still under way); both of which envisage adoption of the precautionary approach to fisheries (Garcia 1994).

As discussed at the FAO Technical Consultation on High Seas Fisheries (FAO 1992c), a more effective approach to setting and enforcing management targets is needed. The approach must be respected by all fishery participants, and this is an important component of the International Code of Conduct for Responsible Fishing currently being developed by FAO (COFI 1993). While discussing the various reference points that have been proposed for management of fisheries in national and international waters, our paper also tries to place them in a management context.

> *"DECISION-MAKERS NEED TO HAVE OPTIONS THAT PERMIT SUSTAINABILITY, AND REWARDS FOR CHOOSING THEM".*
>
> Norse 1993

The unsatisfactory performance of fishery science and management procedures to date calls for a significant change in the management of fisheries. The newly ratified United Nations Convention on the Law of the Sea provides the framework for change, and the trends described above indicate an increased receptivity by the political directorate to new ideas about fisheries management. In this light we review the use of reference points in fisheries management, recommend that limit or threshold reference points be incorporated into management wherever possible and suggest ways in which they may be applied.

2. THE DEVELOPMENT AND DIVERSITY OF REFERENCE POINTS

2.1 MANAGEMENT OBJECTIVES AND THE CONCEPT OF A 'REFERENCE POINT'

Reference points begin as conceptual criteria which capture in broad terms the management objective for the fishery. To implement fishery management it must be possible to convert the conceptual Reference Point into a Technical Reference point, which can be calculated or quantified on the basis of biological or economic characteristics of the fishery (Fig. 1). For example, when the objective is to maximise yield, MSY has frequently been used as a conceptual reference point. The concept of MSY has been interpreted in various ways, ranging from its strict technical meaning as the peak of the surplus production curve, or the point of maximum surplus reproduction on a stock recruitment curve, to its more literal interpretation as the maximum constant yield that can be taken year after year, as described by Sissenwine (1978) and Annala (1993).

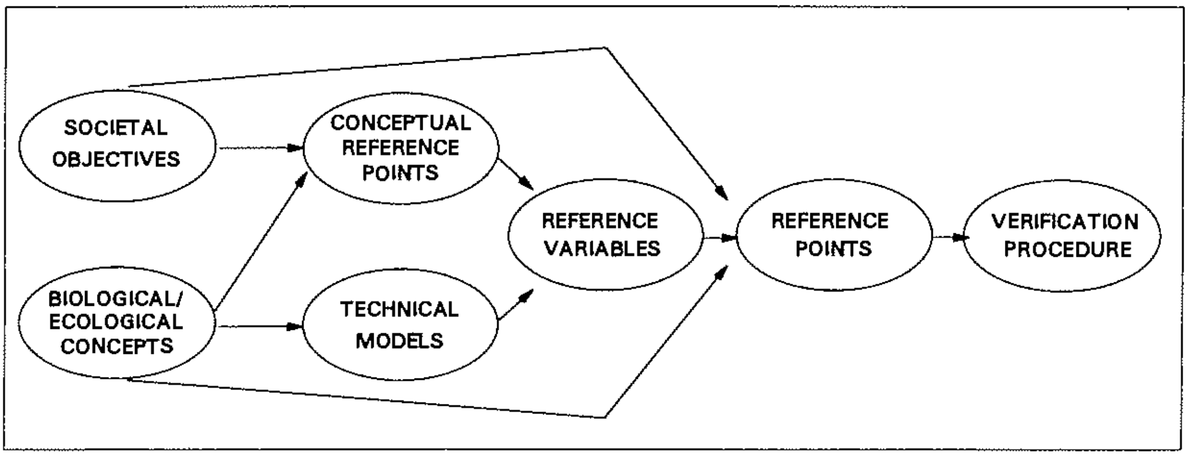

Figure 1: **The sequence of development of conceptual and technical reference points incorporating scientific models and societal goals for fisheries management.**

The objectives of fishery management are generally more diverse than a simple maximisation of yield. They often include considerations of foreign exchange, employment, contribution to disadvantaged rural areas, profit, *inter alia.* The concept of an overall objective that incorporates all important factors for a fishery was reflected in the 1958 United Nations Oceans Convention in Geneva, where the term "Optimal Sustainable Yield" emerged. Optimal Yield (OY) has since been variously defined as allowing for inputs of "...economic, social and biological values [...] rather than being limited to maximizing net profits or maximizing sustainable yield" (Wallace 1975). Since it has no single technical definition, we do not consider OY to be a technical reference point, but a state which may result when a series of criteria are satisfied which effectively ensure that the fishery remains within a safe and productive area.

Smith *et al.* (1993) identify the lack of clearly defined management objectives as one of the main impediments to establishing and adhering to Reference Points. As described above there may be many societal objectives in managing a fishery, and each may correspond to the interests of a particular user group. Thus the stakeholders in a fishery need to agree on the management objectives for the fishery. In order to reach agreement on a conceptual reference point users must understand the relationships between the objectives, and the characteristics of the fishery: they must be able to appreciate the trade-offs among the various possible reference points in real, even if only relative, terms: whether expressed as fishing mortality rates, catch rates, mean fish sizes, etc. Various means of simplifying these relationships must be explored, in order to facilitate the participation of all users (e.g. Fig. 2).

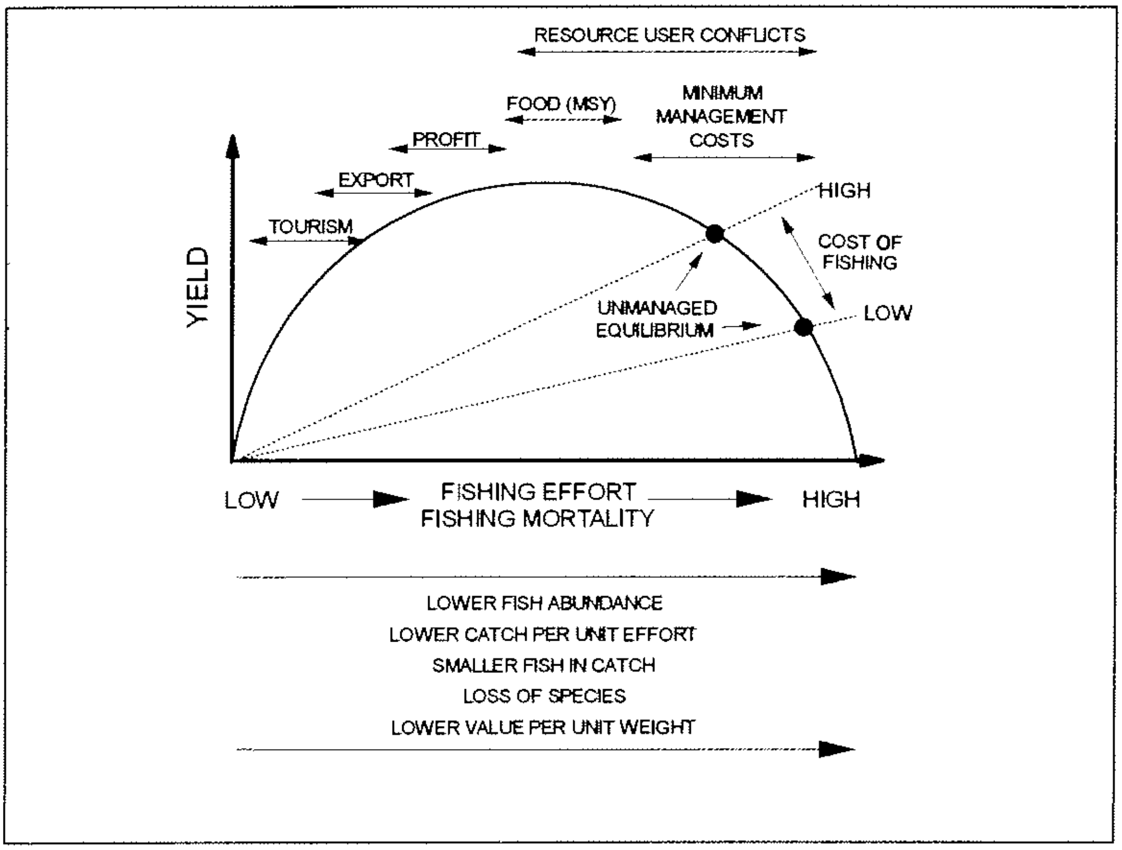

Figure 2: Some relative ranges for the fishing mortality rates corresponding to different societal objectives for marine resource use in the context of a multispecies surplus production model for reef fisheries (after Mahon 1992)

Thus far, there are very few instances in which multiple objectives have been formally incorporated into a management strategy, much less related to a single technical reference point. Healey (1984) proposed an analytical approach to determining optimum yield based on multi-attribute utility analysis. The methodology, which quantifies and weights the objectives of the users appears to be a reasonable way of making agreed upon decisions when there are multiple objectives. However, there are few instances in which we know of a multi-criterion approach to decision making being formally applied in fisheries management: two of these are the Yucatan Shelf octopus fishery (Diaz-de Leon and Seijo 1992), and a chinook salmon fishery in Alaska (Merrit and Criddle 1993).

Another conceptual reference point is the point beyond which 'overfishing' is said to occur. In the USA, plans require that a definition, or technical reference point be provided for overfishing for each stock. In the ICES area, this conceptual point is referred to as the Minimum Biologically Acceptable Level, MBAL, for the fishery. For implementation purposes 'overfishing' and MBALs must be technically defined, and this has been done in several ways as will be described later.

For the purposes of this paper, a Reference Point will be defined as a conventional value, derived from technical analysis, which represents a state of the fishery or population, and whose characteristics are believed to be useful for the management of the unit stock. Defining a reference point as a conventional value reflects that in practical terms they may frequently assume arbitrary values and are often specified without variance terms. It is worth noting here that all of the model-based reference points, and the parameters they are derived from, are only known approximately, often with a poorly-defined level of error.

2.2 THE UNDERLYING POPULATION MODELS

The technical reference points used in fishery management are largely based on biometric or econometric models, and hence on mathematical conceptualization of fish populations, and can be difficult to assimilate for the non-technical reader. Consequently, throughout this paper we will try to support our arguments with graphical summaries where possible. Annex I presents a few key concepts. Fuller treatment of the basic methods can be found in standard texts on biological and economic assessment of fisheries (e.g. Ricker 1975, Gulland 1983, Clarke 1985, Hilborn and Walters 1992).

The relationship between fishing mortality (F), stock biomass (B) and yield can provide the basis for discussion of most reference points (Fig. 3). F and B are the most basic Reference Variables. Reference Points on these variables are set using various criteria to be discussed later, 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 methods (Fig. 3). Fishing mortality and natural mortality (M) due to predation, disease, etc., combine to equal the total mortality rate ($Z = F + M$) for the population.

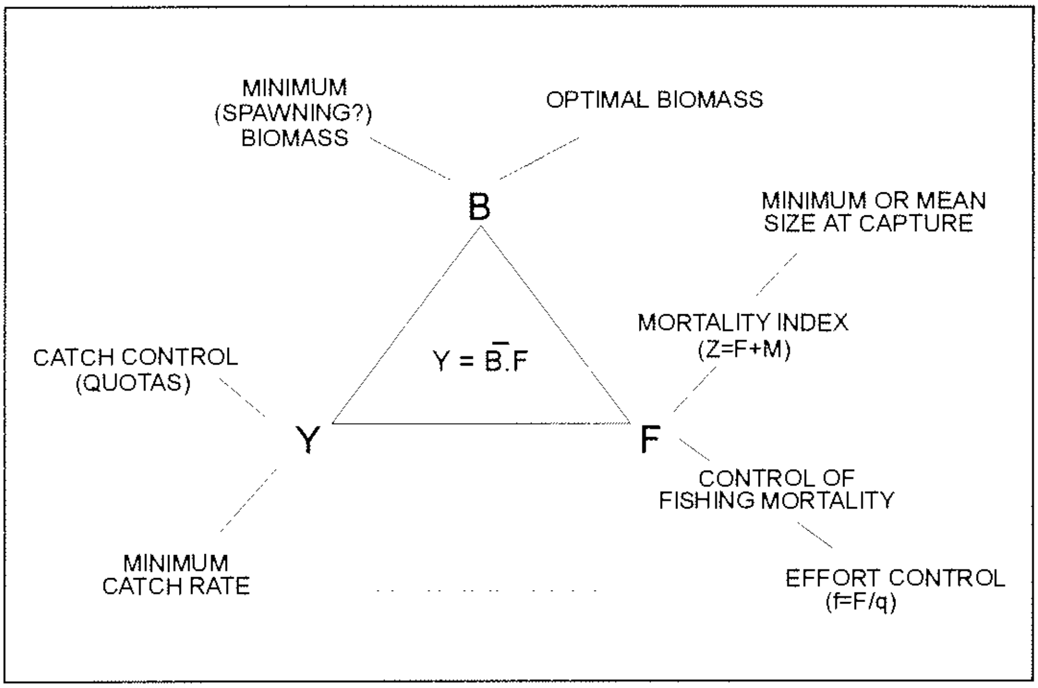

Figure 3: **The main population, reference and control variables used in defining biological reference points. In addition to the three primary measures of the state of an exploited population, fishing mortality rate (F), biomass, (B) and yield (Y), whose interrelationship is specified in a catch equation, other secondary measures shown may also be used as reference variables.**

Other variables which directly influence, are related to, or are indicators of the basic Reference Variables, can also be used as Reference Variables. For example, fishing mortality and fishing effort (f) are related by the catchability coefficient (q), which is usually assumed to be constant, such that F = q.f. If this assumption is true, the catch rate, or catch per unit effort (CPUE) is an indicator of the population biomass (Fig. 3). In this paper all reference points will be expressed in terms of the primary variables. The current status of the stock according to any reference variable is designated by the subscript now, e.g. F_{now}, B_{now}, Y_{now}.

The models underlying MSY (and many of the other reference points described later) were originally equilibrium models, which implied that the yield represented by the production curve is that resulting when the corresponding standard effort has been applied for the years necessary for equilibrium to be reached, the 'return time' (Beddington and May 1977). However, it is erroneous to assume that a given level of fishing effort/mortality allows a certain surplus yield to be maintained indefinitely, irrespective of environmental conditions (Hilborn 1979).

Although analytical models incorporating growth and mortality rates, age at first capture, etc., are widely used in 'developed' country fisheries, the data required to estimate current age-structure of the fish population are not available for many small, or tropical stocks, or are labour and technology intensive. Where assessments have been performed, many of them still depend on low precision approaches using sparse or inaccurate data, making management by target reference points problematical, and precautionary approaches to avoiding stock collapse mandatory, even if this apparently involves forgoing some immediate benefits in terms of yield.

In summary, to manage the fishery, it is necessary to ensure that all Conceptual Reference Points to be used are represented by one or more Technical Reference Points, for which the methodology of derivation and measurement is clearly specified (Fig. 1). To borrow terminology from logical framework analysis (CEC 1993), these reference points must also have a means of verification (MOV), and an objectively verifiable indicator (OVI). These must be clearly defined and agreed upon in advance, so that they can be acted upon without the necessity for negotiation. If we have learned anything from the historical performance of fisheries management it is that it is more important that the basis for fishery management action be clear and indisputable than that it should claim to be precise and accurate.

2.3 REFERENCE POINTS AS TARGETS OR LIMITS

The many technical reference points which have been proposed for rational exploitation of fishery resources can, in terms of their use, be placed in two categories: Target Reference Points (TRPs) and Limit Reference Points (LRPs). Traditionally, Target Reference Points have been considered as indicators of a stock status which is a desirable targets for management. It has been assumed that managing a fishery corresponds to adjusting the inputs to, or outputs from, a fishery until one or more of the primary or secondary variables correspond to the TRP chosen (which is, of course, TRP). As previously mentioned, MSY has most often been used in this sense. TRP management requires active monitoring and continual readjustment of management measures on an appropriate (usually annual) time-scale. It also requires attention to the effect of a variety of sources of uncertainty on the estimates of the TRP and of the stock status.

In 1987, the ICES Advisory Committee on Fishery Management (ACFM) report noted that "biological reference points are intended to provide guidance concerning management, and that no biological reference point can serve as a universal target". In order to protect the resource and the fishing industry against long-term damage, it is important to define and agree on a 'red area' where the continuity of resource production is in danger, and immediate action is needed, such as a substantial reduction in fishing effort/mortality, or in the extreme case, closure of the fishery for a period of time (ICES 1988). Reference points which indicate when such a danger area is about to be entered can be referred to as threshold reference points (e.g. Quinn *et al.* 1990) or (to avoid confusion with the acronym Target RP), as limit reference points (LRPs).

In the United States, fisheries are managed through management plans which are "... required to specify, to the maximum extent possible, an objective and measurable definition of overfishing for each stock or stock complex covered by that FMP, and to provide an analysis of how the definition was determined and how it relates to reproductive potential" (Mace and Sissenwine 1993).

An LRP may either correspond to some minimum condition (e.g. a dangerously low spawning biomass) or some maximum condition (a high rate of decline in stock size, or a high mortality rate) at which point a management response which has been negotiated earlier with the participants in the fishery, is automatically triggered. For new fisheries, or those in developing countries where the information required to use the mathematical fisheries models if often not available, qualitative or semi-quantitative criteria also can be used directly as LRPs. Even when there is adequate information for the definition of sophisticated LRPs, but there are broader ecological concerns about the sustainability of benefits due to the possible impacts of exploitation on the ecosystem, it may be desirable to set LRPs using a precautionary approach (Garcia 1994).

Definitions:

A Target Reference Point indicates to a state of a fishing and/or resource which is considered to be desirable and at which management action, whether during development or stock rebuilding, should aim.

A Limit Reference Point indicates a state of a fishery and/or a resource which is considered to be undesirable and which management action should avoid.

2.4 TARGET REFERENCE POINTS (TRPs)

2.4.1 Maximum Sustainable Yield Criteria: F_{msy} and 2/3 F_{msy}

The 1982 Convention specifies only one technical Reference Point, notably the Maximum Sustainable Yield (MSY), a descriptive term for the highest point of the curve describing the relationship between the annual standard fishing effort applied by all fleets, and the yield that should result if that effort level were maintained until equilibrium were reached. This is, at first sight, an obvious target for management of a single species fishery and was widely used for this purpose by fishery commissions in the 1960s and 19770s. Subsequent developments in the theory, and perhaps more so, practical experience in fishery management, have cast doubts on the usefulness of MSY as a safe TRP (e.g. Larkin 1977). This sparked the search for alternative Reference Points, as summarised below.

Maximum Sustainable Yield as the underlying Reference Point for fisheries considerations in the 1982 Convention is the basis for defining 'surplus yield' as that part of the MSY not currently being taken by a coastal State. According to the 1982 Convention, any shortfall of national harvests below MSY within an EEZ, may be considered 'surplus to the needs' of the coastal State. This consideration has contributed to the continued use by many countries of MSY as a target. However, viewed in the wider context of management objectives, the inappropriateness of this interpretation of 'surplus yield' has been noted by many coastal States, since catching this surplus by other fishing states would negatively impact catch rates in fisheries of the coastal State. Several States have concluded that Reference Points based on fishing rates significantly below F_{msy} levels are more favourable economically and ecologically to their fishing industry and resources. A more appropriate interpretation sees the removal of the MSY as an option which may rarely be used: the stock is held at a level of biomass such that the MSY could but not necessarily should, be harvested, without endangering the stock, implying that stock levels are kept adequately high to permit the MSY to be harvested 'at least once' (although as noted by Doubleday 1976, there is no guarantee that, as conventionally defined, it can be harvested year after year).

> *COASTAL STATES SHALL "...MAINTAIN OR RESTORE POPULATIONS OF HARVESTED SPECIES AT LEVELS WHICH CAN PRODUCE THE MAXIMUM SUSTAINABLE YIELD, AS QUALIFIED BY RELEVANT ENVIRONMENTAL AND ECONOMIC FACTORS [...] TAKING INTO ACCOUNT [...] THE INTERDEPENDENCE OF STOCKS AND ANY GENERALLY RECOMMENDED INTERNATIONAL MINIMUM STANDARDS."*
>
> The 1982 Convention on the Law of the Sea

The MSY, and its equivalent levels of standard fishing effort/fishing mortality (f_{msy}/F_{msy}), was first formulated for the symmetrical Schaefer or logistic model, (e.g. Fig. 4). The reference point is 'model based', depending on one of the several published production model formulations (e.g. Fox 1970; Pella and Tomlinson 1969), and requires statistical fitting of historical catch and standard effort data on which a considerable literature exists (see Hilborn and Walters 1992, Polachek *et al.* 1993). The effort level, F_{msy} at which MSY occurs, can be converted to a fishing mortality, F_{msy}, if the catchability coefficient q is known.

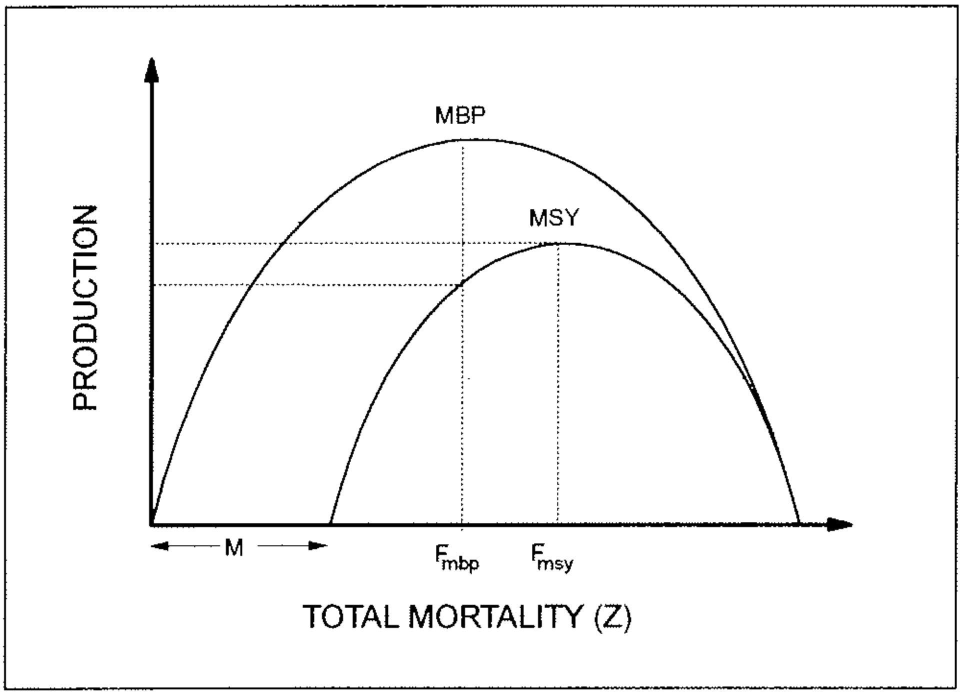

Figure 4: The equilibrium Schaefer model, showing the relationship between MSY, Z, and the fishing rate corresponding to the Maximum Biological Production (MBP). Note that $F_{mbp} < F_{msy}$, and that there is no yield when $Z \leq M$.

Choosing any model-based Reference Point, implies that the underlying mathematical model that reflects most faithfully the fish population dynamics is agreed upon. The question may, however, be less one of picking the Reference Point with the most robust theoretical underpinnings, and more one of picking an Reference Point that provides conservative advice under conditions of uncertainty. From this perspective, MSY has not performed well as a TRP (see e.g. Doubleday 1976, Larkin 1977, Sissenwine 1978, Garcia 1984). High initial catch rates inevitably result in a substantial overshoot of equilibrium F_{msy} conditions. There are then serious economic problems in reducing effort and/or fleet size or access downwards to a much lower equilibrium MSY level in later years. This has led to serious criticism of production models which assume equilibrium in forecasting short-term yield (Hilborn and Walters 1992).

There have been few explicit estimates of the accuracy with which MSY conditions have been achieved, but inspection of many production models suggests that an accuracy of better than ± 20% of the standard effort yielding MSY would be unusual. The estimation of MSY by statistical fitting of the model to historical data assumes that past conditions have a similar probability of recurring in the future. However, in a series of years with poor recruitment, a fishing mortality of F_{msy} produces a yield well below that indicated by the model which is assumed to have been fitted from data for years with more 'normal' levels of recruitment. An attempt to harvest the statistically predicted MSY in these 'poor' years would require fishing above, and possibly well above, F_{msy}. Thus the use of the word 'sustainable' for an MSY obtained in the conventional way is inappropriate, since "in the presence of fluctuations in production, attempts to remove the MSY yield each year from a stock leads to disaster" (Doubleday 1976).

Owing to uncertainty as to the actual status of the stock with respect to this TRP, it is obvious that a fishery believed to be operating in the region of F_{msy} is always either overfishing or underfishing with respect to this benchmark, and often significantly so, but the biological production responses of the resource to overfishing and underfishing are not necessarily symmetrical. Overfishing leads to fewer age groups in the fishery, hence increasing the dependence of overall yield on occasional good year classes, as well as leading to declining mean sizes and catch rates. Relatively constant year-to-year recruitment is the exception rather than the rule (Hennemuth *et al.* 1980), and reduced or more variable recruitment with reduced spawning stock size is accompanied by increased dependence of the fishery on newly-maturing age-classes. This in turn will result in an increase in environmentally-induced variation in stock biomass. From theoretical considerations, Beddington and May (1977) noted that once F_{msy} has been exceeded, stocks will fluctuate more severely, and their return time to equilibrium will increase markedly.

The appropriate type of production model for a particular fishery can only be known after overfishing has occurred, and the total effort that provides MSY has been exceeded, thus revealing the form of the relationship. Total yield may then drop (implying a dome shaped model), or reach a plateau (as is often the case in tropical shrimp fisheries). Controlled overfishing strategies have even been proposed as one way of better locating MSY conditions and, as noted above, these often occur despite a stated objective of MSY management. Because the type of model to use, and the level of effort or fishing mortality which approximately corresponds to MSY may be only roughly known under the best of circumstances, other more conservative production model based TRPs have been defined.

Following the Marginal Yield concept of Gulland, Doubleday (1976) postulated that fishing at the effort level that corresponded to 2/3 of the effort needed to produce MSY would allow a very large fraction (about 80%) of the MSY to be harvested with a significantly reduced risk of stock collapse. This target, although safer than F_{msy} , has been criticised, in our view unfairly, as arbitrary, empirical and insensitive to changes in recruitment. It may be useful to note that this approach to setting reference levels for F may be generalized for other commonly used population models (Table 1) and can be regarded as a precautionary approach to using the results of production modelling. This table illustrates that reducing effort levels below those yielding MSY does not result in a correspondingly large reduction in the long-term equilibrium yield once the stock has recovered from the previously heavier exploitation rate.

Sissenwine (1978) has pointed out that for little-studied stocks, MSY has often erroneously been equated with the Maximum Average Yield (MAY). This latter quantity has occasionally been used as a TRP, but gives dangerous weight to the early years of the fishery when catches were high as the virgin stock was being fished down. Again, the use of MAY-based reference points would seem to call for a suitable degree of precaution, as described in the previous paragraph.

A more rational interpretation of MSY for a stock subject to wide variations in recruitment, would be the yield which could be removed in perpetuity from the resource with an accepted low probability of endangering it (Sissenwine 1978). ICES (1993a) has recently been considering this interpretation as an approach to stable long-term management of fisheries. Similar interpretations of MSY are in current use in management of New Zealand fisheries (Annala 1993). The first is a static interpretation called Maximum Constant Yield (MCY) which is defined as "The maximum constant catch that is estimated to be sustainable, with an acceptable level of risk, at all future levels of biomass". This interpretation is radically different from MSY as normally derived, since it implies much lower levels of fishing mortality (F_{mcy}) and catch than at F_{msy}. The second interpretation is a dynamic one called Current Annual Yield (CAY), which is defined as the one year catch calculated by applying a reference fishing mortality, F_{ref}, to an estimate of the fishable biomass present during the next fishing year. F_{ref} is the level of instantaneous fishing mortality that, if applied every year, would, within an acceptable level of risk, maximise the average catch from the fishery (F_{ref} is often set equal to $F_{0.1}$) In the New Zealand fishery assessment process, 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 (Annala 1993).

In conclusion, it is now evident from the variety of technical, conceptual, and practical difficulties associated with the use of F_{msy} as a TRP, that it should be used more as an LRP as discussed in the following Section.

2.4.2 Yield per recruit criteria: e.g. F_{max}, $F_{0.1}$.

The fact that production models combine all aspects of population productivity, recruitment, growth and mortality and ignore details such as age/size at recruitment, has led to the use of analytical, age-structured, models based on detailed population dynamics. These are particularly useful when there are several fleet components exploiting different age groups, and when gear regulations affecting age/size at first capture may be an important management tool.

The early theory of population dynamics of exploited fishing stocks emphasised the calculation of F_{max}, the level of fishing mortality for a given size at first capture, which maximizes the average yield from each recruit entering the fishery. The yield-per-recruit analysis uses information on average individual growth, natural mortality and vulnerability to fishing. This was one of the earliest benchmarks for fisheries management, and as for MSY, suffered from a number of failures as a TRP.

The use of yield-per-recruit as a reference variable does not take into account the effect of fishing mortality on the proportion of mature fish left in the population and hence its reproductive potential. Although generalizing about the relative performance of Reference Points developed from production models and analytical models can be hazardous, there seems little doubt that F_{max} is usually greater than F_{msy}, and that fishing at this rate over an extended period of time is liable to deplete the spawning stock and reduce future recruitment (e.g. Clarke 1991). Although there may be good reasons for eliminating the use of F_{max} as a TRP, it could be considered as an upper limit for F, i.e. as an LRP for the stock

For many species there is no clear maximum to the curve of yield-per-recruit against F. The fishing mortality level $F_{0.1}$ proposed as a conservative TRP by Gulland and Boerema (1973) does not require that there be a maximum, being an arbitrary criterion based on the slope of the yield per recruit curve at the origin. $F_{0.1}$ is the fishing mortality rate at which the slope of the yield per recruit curve as a function of fishing mortality is 10% of its value at the origin (Fig. 5). In South Africa, an even more restrictive criterion is used, notably $F_{0.2}$.

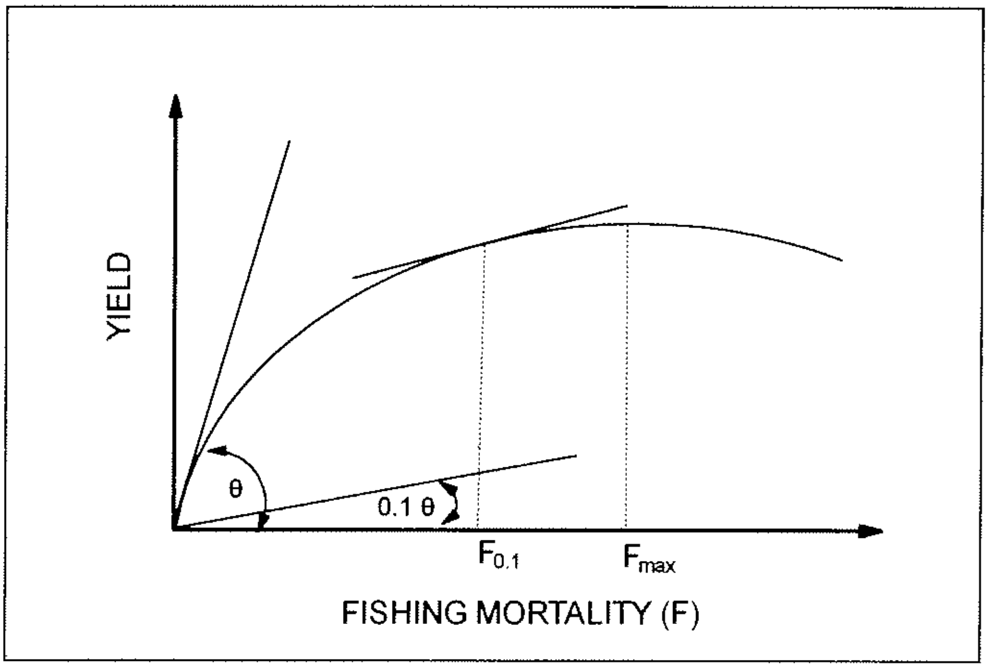

Figure 5: Illustrating the method of defining $F_{0.1}$, given a known relationship between fishing mortality rate and yield per recruit, as the point on the Y/R curve at which the slope of (a line tangential to) the curve is 1/10th the slope of (a line tangential to) the curve at the origin.

The $F_{0.1}$ measure, although arbitrary, is in a sense a bioeconomic criterion, in that a marginal yield of less than 10% was felt to be close to the point at which most fisheries administrators would consider further increases in fishing mortality or effort to be no longer economically worthwhile. This measure has been widely used in many fisheries of the

Northwest Atlantic (e.g. Rivard and Maguire 1993, Hildén 1993). F-based strategies have been followed off eastern Canada for more than a decade, and $F_{0.1}$ is often used in establishing catch quotas.

Knowledge of the correct catch is essential to estimating current F-values under quota control, but there are known to be substantial problems with the accuracy of commercial catch reporting. This has affected stock assessments and has been especially pronounced where there is fleet overcapacity. With under-reporting there is a high probability that target F values will be exceeded. This, and not just the changes in $F_{0.1}$ that occur with changing fishing pattern and input values for M (Jakobsen 1992), may be the main explanation for declines in several stocks managed under $F_{0.1}$ criteria.

2.4.3 TRPs based on the size of fish caught

Yield-per-recruit analysis indicates the mean age/size of fish in the catch that provides the maximum yield-per-recruit for a given set of population parameters and given fishing mortality level. When the data required to estimate an optimal level of fishing mortality are not available, the mean size of fish in the catch can be used in conjunction with other data as a 'proxy' TRP.

The use of mean size of fish as a TRP may be based on yield-per-recruit analysis or may consider the recruitment ogive (partial recruitment) in relation to the size at first maturity. A rational target would 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. Thus, at least 50% of individuals would have an opportunity to reproduce. For iteroparous species the relationship of this target to a target %SSB (see below) would depend on M, which determines the average number of years a mature fish can be expected to spawn in an unfished population before dying of natural causes. Caddy and Die (in press) substitute the average length at maturity into Beverton and Holt's equation relating Z to mean size in the catch to estimate a corresponding reference value for total mortality Z^*. This may be useful when survey data from which to estimate Z are available, but catch data from which to estimate the mean size are not.

2.4.4 Reference points based on the natural mortality rate, M.

New fisheries usually develop in the absence of adequate assessment information, and management has to proceed on the basis of available information. A cautious approach may result in underexploitation, but will not necessarily lead to a long-term loss of yield. In the 1960s and 1970s, many new fisheries developed in different parts of the world for which the only data on stock status were one or more exploratory survey estimates of biomass. In an attempt to provide some basis for fleet and fishery development, Gulland (1973) proposed a simple empirical formula for the MSY in terms of the virgin biomass B_0 and the natural mortality rate, M: notably, MSY = $0.5MB_0$ (a reformulation of the second yield equation in Annex I). This follows the symmetrical Schaefer yield model in assuming that MSY will occur at half the virgin stock size B_0, and that at MSY, the fishing mortality and natural mortality rates will be equal. Later, the equation was generalized to MSY = $x.M.B_0$ with the value of x being related to the stock characteristics, and variations were proposed to accommodate situations in which there was already some fishing mortality (Gulland 1983). Garcia *et al.* (1989) proposed several estimators for MSY when historical data series are not available.

There is little empirical evidence that $F_{msy} = M$ for many stocks. Beddington and Cooke (1983) suggested that x is generally smaller than 0.5, whereas for tropical penaeids Garcia and LeReste (1981) suggested that values x = 0.32 to 0.44 are appropriate. From a set of 11 stocks, Caddy and Csirke (1983) found x values ranging from by 0.33 to at least 4. The lowest values were for short-lived shrimp and sardine populations, and the highest were for two northern demersal finfish; apical predators with low natural mortality rates. From an analysis of several stocks of small pelagic fishes, Patterson (1992) found that only low exploitation rates, corresponding to no more than x = 0.33, are sustainable. For new fisheries in New Zealand, a conservative approach is used, where $MCY = 0.25F_{0.1}B_0$ (Annala 1993). These benchmarks, though very approximate, may be the only ones immediately available for setting 'Precautionary' Reference Points for many stocks off developing coastal countries.

2.4.5 Reference points based on the total mortality rate, Z_{mbp}, Z^*

Since partitioning the overall mortality into components due to fishing, predation, etc., is often problematical, there may be advantages in expressing Reference Points in terms of the overall mortality Z experienced by the stock due to all causes of death. Virgin populations are dominated by large, old individuals, whose contribution to biological production (growth, yield, plus deaths due to predation) is lower than that of younger individuals which gradually dominate population as exploitation intensifies. Thus we can postulate that there is a mortality level, Z_{mbp}, at which the Maximal Biological Production is obtained from the stock (Caddy and Csirke 1983).

For the Schaefer model, Z_{mbp} and F_{mbp} correspond to a fishing mortality which is consistently below F_{msy}, being progressively more so for species low in the food chain with high natural mortality rates (Fig. 4). Simulations show that it is difficult to produce excessively high fishing mortalities using this TRP (Caddy and Die in press). There should be little risk of environmentally induced collapse when the stock is at its maximum productive capacity.

2.4.6 TRPs derived from recruitment considerations

In addition to size-based reproductive TRPs (Section 2.4.3) due to the frequently demonstrated dependence of recruitment on the spawning stock size, there is a potential role for TRPs which ensure that the spawning capacity of the stocks to reproduce will be conserved. TRPs based on recruitment considerations may be derived from stock-recruitment (S-R) relationships, or from an extension of yield per recruit analysis which incorporates age/size at maturity in calculating the spawning biomass per recruit (SPR) at various levels of F. Recently, these two types of analysis have been linked to calculate the stock biomass levels associated with various SPR levels. The targets may be stated in terms of a stock biomass or spawning stock biomass that is expected to yield the desired recruits, or in terms of the fishing mortality level which is expected to result in these biomass or SPR levels.

Early approaches to stock-recruitment analysis involved fitting various types of curves to time series of data on stock and recruitment. In all S-R relationships, the spawning biomass corresponding to the Maximum Surplus Reproduction, B_{msr}, occurs at some level intermediate between a high and a very low stock size (Ricker 1975) (Fig. 6). In theory, for any stock size greater than B_{msr}, there is a level of fishing mortality, F_{msr}, that would allow the B_{msr} to survive and reproduce in that year. In practice, given natural variation in stock sizes from year to year, this level of fishing mortality would have to be changed annually to achieve a 'constant escapement' of B_{msr}. Thus, the fishing rate that would allow constant escapement must be calculated annually. This may be a useful strategy for managing salmon which can be counted during their upriver spawning migration, but is likely to exceed the information levels for most widely dispersed stocks in open sea systems. A further problem with direct use of the S-R relationship is in determining the correct stock recruitment model to use under conditions of high recruitment variability.

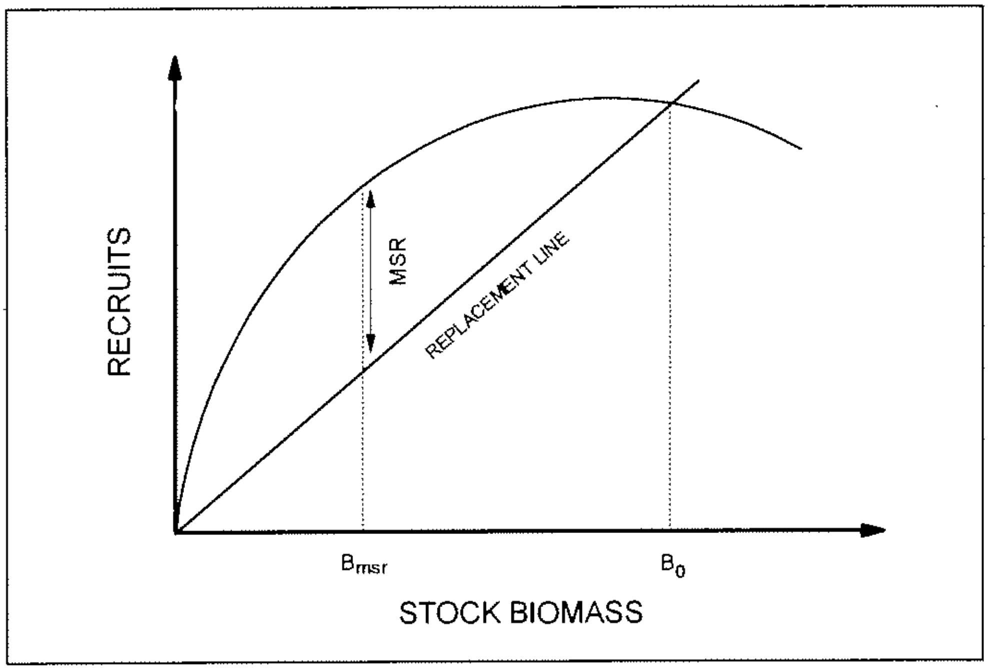

Figure 6: **Illustrating (after Ricker 1975) a generalized relationship between spawning stock size and the number of recruits (progeny). The line A-B corresponds to the stock size or biomass of spawners for this specific relationship where the surplus of progeny over parental stock size is at a maximum: the point at Maximum Surplus Reproduction.**

The considerable variability in recruitment data, and other methodological problems (Walters and Ludwig 1981) has made it difficult to describe statistically significant, and biologically meaningful relationships between spawning stock size and number of recruits for many stocks. This problem has led to other approaches to the use of S-R data to generate Reference Points. Evans and Rice (1988) propose methods of predicting recruitment directly from observations on stock and recruitment without the mediation of a functional relationship. Getz and Swartzman (1981) propose an approach in which the S-R scattergram would be divided into stock biomass and recruitment ranges. A transition matrix indicating the probability of each recruitment range resulting from each stock biomass range, can be used as a guide to setting a target biomass range for fishery management, and the extent to which it may be necessary to avoid low biomass levels. A major problem with S-R analysis is that a relatively long time-series spanning a range of stock sizes (e.g. Myers *et al.* 1994) is needed to produce a reliable stock-recruit curve. This is rarely available for setting TRPs for newly exploited or little studied stocks.

The calculation of 'spawning biomass per recruit' (SPR) is an extension to yield-per-recruit analysis which can be carried out in the absence of historical data, if information on maturity/fecundity at size/age is available (Gabriel *et al.* 1989). Mace and Sissenwine (1993) explain the derivation and application of Reference Points based on SPR calculations. Unlike yield-per-recruit which shows a maximum with increasing F, SPR decreases monotonically. SPR is usually expressed as a percentage of the SPR under unfished conditions (i.e. at virgin spawning biomass, B_0) and is variously designated as (%SSBR or %SPR). The F which produces any particular %SPR is designated $F_{\%spr}$ or just $F_{\%}$.

Reference Points based on SPR or %SPR have only recently been defined based on the relationship between SPR and the survival ratios (R/S) obtained from pairs of stock-recruitment observations (Fig. 7). For any F level there is a corresponding straight line through the origin of the S-R scatterplot. The slope of this line is the inverse of the SPR which corresponds to the F level. The S-R values and plot can then be used to select a survival ratio for use as a Reference Point. This can be translated back into SPR values and projected onto the F scale to determine the corresponding F level. The reference level F_{rep} (Sissenwine and Shepherd 1987), also referred to as F_{med} by ICES (1993b), corresponds to the line representing an average survival ratio, S/R = 1, at which the stock replaces itself. At this level of F, SR would be expected to be > 1 in 50% of the years, i.e. corresponds to the F where recruitment in half of the years more than balances losses due to mortality.

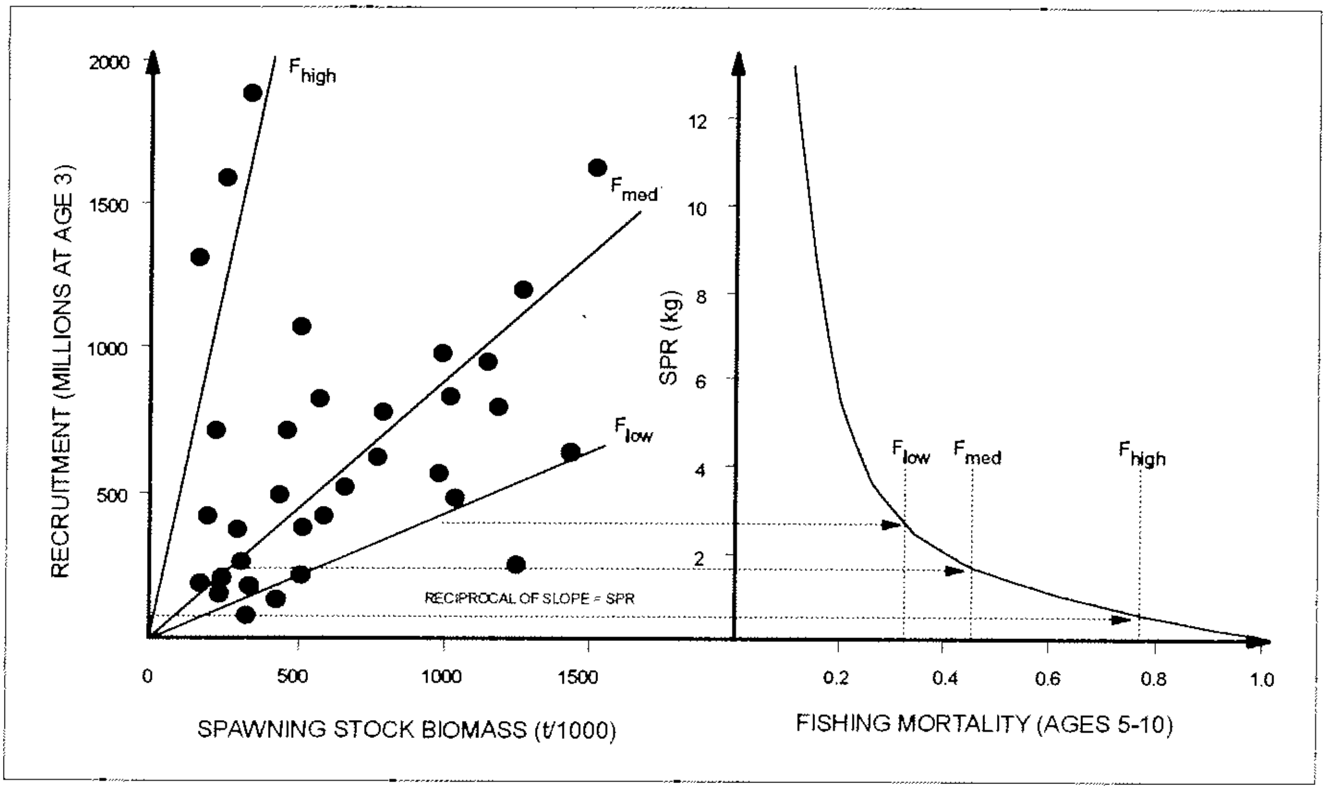

Figure 7: Illustrating the definition of F_{low}, F_{med} and F_{high} and their relationship to spawning stock biomass per recruit (SPR) (redrawn from Jakobsen 1992)

Heavy fishing and depressed stocks in the North Atlantic in recent years have led fishery scientists to emphasize spawning stock considerations in advice to management bodies. Thus the use of recruitment-based TRPs derived from SPR and S-R data has been pioneered in the ICES area (ICES 1984). ICES routinely estimates three reference levels of F in this way, F_{high}, F_{med} and F_{low}. F_{low} and F_{high} bracket F_{med}, and are similarly defined to leave 90% and 10% of the data points for recruitment above the line through the origin corresponding to that level of fishing mortality (Fig 7). Assuming that S-R relationships continue as in the past, they have the following properties (ICES 1991; Jakobsen 1992):

F_{low} - low probability of stock decline, and some likelihood of stock increase,
F_{med} - likely that current stock levels will be sustained,
F_{high} - likely that fishing at this level will result in stock declines.

More recently, ICES has tended to view F_{med} as a limit Reference Point since at F levels higher than F_{med} stocks can be expected to decline (see Section 5.6).

These measures appear less vulnerable to the consequences of assuming an incorrect value of M than F_{max} and $F_{0.1}$ levels (Jakobsen 1992). F_{med} fell close to F_{max} and F_{msy} for Georges Bank haddock (Gabriel *et al.* 1989).

Simulations showed that for northern demersal stocks a yield of at least 75% of MSY is possible as long as the spawning biomass is maintained in the range 20-60% of the unfished level; irrespective of the spawner-recruit relationship (Clarke 1991). Relative spawning biomass can be maintained in this range by choosing an F value that will reduce spawning biomass per recruit to about 35% of the unfished level. This F value is usually very close to $F_{0.1}$ (Clarke 1991). Variation in recruitment calls for a slightly higher target level of SBR, around 40%, particularly if there is serial correlation in recruitment (Clark 1993). Thompson's (1992) analysis of uncertainty in the stock recruitment relationship supports this finding, and suggests the intuitive conclusion that F should be constrained when the S-R relationship is uncertain.

In a recent comparative study, %SPR was found to be positively correlated with natural mortality and negatively correlated with various indices of size: thus cod and most flatfish require low levels of %SPR, but some pelagics require values as high as 40-60% for consistent stock replacement. Although these conclusions agree with those in the earlier section on M based Reference Points, it is probably dangerous to use them outside their geographic region of origin, since the data upon which this generalization is based are mainly for fishery resources in higher latitudes. Nonetheless, the use of %SPR criteria is not as information-demanding as other reproductive criteria, and has broad potential in the developing fisheries context.

Mace (1994) observed that TRPs and LRPs are highly dependent on the degree of density dependence in the S-R relationship. She recommended that when the S-R relationship is unknown, $F_{40\%}$ be adopted as a target fishing mortality, but that it be adjusted to accommodate any known or assumed degree of density dependence in the S-R relationship. This corresponds to a recruitment of about 50% of that expected from a virgin stock. For recruitment-based TRPs where biomass is stated in relation to virgin biomass, the latter is estimated from the intersection of the S-R curve or mean recruitment with the replacement line corresponding to F=0, the unfished condition.

2.4.7 TRPs derived from economic considerations - the optimal fishing effort, F_{mey}

Normal market forces are believed to maximize economic benefits to participants (Gordon 1954), but in open access fisheries, the individual efforts of private agents (fishermen), each working to improve their individual economic situation, does not 'guide the net sum of private activities towards the common good'. In fact, recent analyses of global fishery trends have revealed that the high level of over-investment in fleets is the major causal factor for overfishing within and outside EEZs (FAO 1992a, b). Combined with restrictions on fisheries within EEZs, this has motivated movement into largely unrestricted fisheries beyond 200 miles. The global sum of fishing subsidies was estimated at about US $54,000 million per year (FAO 1992b). The development of effective management criteria therefore would potentially release substantial global financial resources, as well as reducing adverse impacts on stocks.

There is an extensive literature on fisheries economic theory in which the Gordon-Schaefer equilibrium production model is central (Gordon 1954, Schaefer 1957, Clark 1983). This theory holds that there is an economic TRP, the Maximum Economic Yield (MEY), which occurs at the effort level yielding the greatest margin of revenue over cost from the resource (Fig. 8). For a linear cost curve, this inevitably occurs to the left of MSY on the fishing effort axis. Since F_{mey} occurs at lower levels of effort than F_{msy}, the use of this economic Target Reference Point is less likely to result in biological overfishing than the use of F_{msy}.

As a TRP, F_{mey} is responsive to any changes in the economic environment which affect either the value of fish, or the cost of fishing. It may also be dependent on changes in fish abundance, if market price increases with declining abundance and is independent of the availability of similar resources elsewhere. . Subsidies or external economic considerations such as fuel taxes will also affect the location of an economic Reference Point (e.g. Panayotou 1988).

The effect of supply on fish prices may, under certain circumstances, result in higher total profit, or profit per unit catch, when total catch is reduced. This characteristic may be a consideration in setting target fishing levels or catches but is least likely to be effective in situations where fish prices are set by global markets, e.g. the tuna fishery for the canning industry.

The value of a unit weight of the landed catch may vary with the size of individual fish, and in multispecies fisheries with species composition. Both fish size and species composition are functions of fishing mortality, and based on purely economic criteria, may be used as target reference points. Even if the actual target F cannot be estimated, in theory, F could be adjusted in increments until the desirable target catch characteristics are achieved.

In considering TRPs based on economic criteria, it is important to be aware of the effect which the practice of discounting could have on reference points. In evaluating investment projects, including resource management, economists discount the future value of any commodity. Discount rates may be in the order of 10%. In the case of a fishery where the population growth rate does not exceed the discount rate, then a strict application of economic theory would suggest that in the absence of other considerations (such as an economic value placed on recreational use of resources) the whole stock should be harvested now, and the proceeds of their sale invested. Long-lived species with slow growth rates, such as whales, clearly fall into this category. The blatant contradiction between this common economic approach, and the concept of sustainability, constitutes an unresolved paradox (Hilborn and Walters 1992).

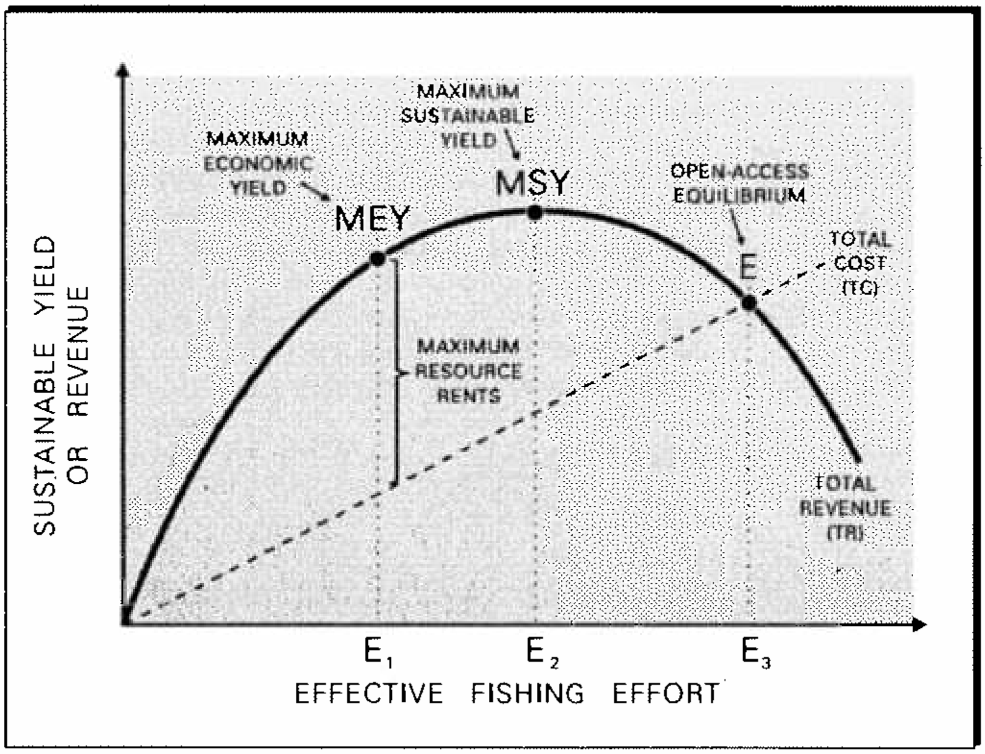

Figure 8: The Graham-Schaefer equilibrium production curve relating yield or revenue to effective fishing effort, showing three Reference Points: MEY, MSY and the bioeconomic equilibrium point E. These occur at progressively higher levels of fishing effort.

2.5 LIMIT OR THRESHOLD REFERENCE POINTS (LRPs)

STATES SHALL TAKE MEASURES TO ENSURE THAT, WHEN REFERENCE POINTS ARE APPROACHED, THEY WILL NOT BE EXCEEDED. IN THE EVENT THAT SUCH REFERENCE POINTS ARE EXCEEDED, STATES SHALL, WITHOUT DELAY, TAKE THE ADDITIONAL CONSERVATION AND MANAGEMENT ACTION DETERMINED UNDER PARAGRAPH 3(B) TO RESTORE STOCK(S)."

Article 6, United Nations, 1995

2.5.1 F_{msy} as an LRP

The use of F_{msy} as a LRP rather than a TRP could provide flexibility in choosing a more cautious F-based TRP that has useful management characteristics (McGarvey and Caddy in press). This is illustrated in Fig. 9. It is necessary to have information on the variability associated with the estimate of current fishing mortality, F_{now}. While such information is infrequently reported in the literature, it seems unlikely for well studied fisheries that the coefficient of variation for F will be less than 15-30%. For poorly studied fisheries it will probably be much higher. In the hypothetical example shown in Fig. 9, FMSY = 0.6 is assumed to be a LRP. The actual fishing mortality rate FNOW that will be exerted in the current season is not precisely known, but two cumulative probability distributions are shown, one corresponding to a high level of precision? (c.v. = variance/mean = 20%); the other to a low level (c.v. = 40%). The means of both distributions are positioned relative to each other along the X-axis such that the points for which there is a 10% probability that FNOW> =FMSY=0.6, coincide. It is clear that for this situation to prevail, the centre or mean of the distribution of FNOW which is imprecisely known, must be located at a lower fishing mortality rate than when more accurate statistical information is available.

In simple terms, this example is intended to show that the collection of accurate and complete statistics which allows the death rate due to fishing to be calculated with a higher precision, permits a higher fishing rate to be maintained with the same risk of overshoot, than if data collection is given a low priority. This illustrates clearly the economic value of a good system of data collection in a precautionary management system.

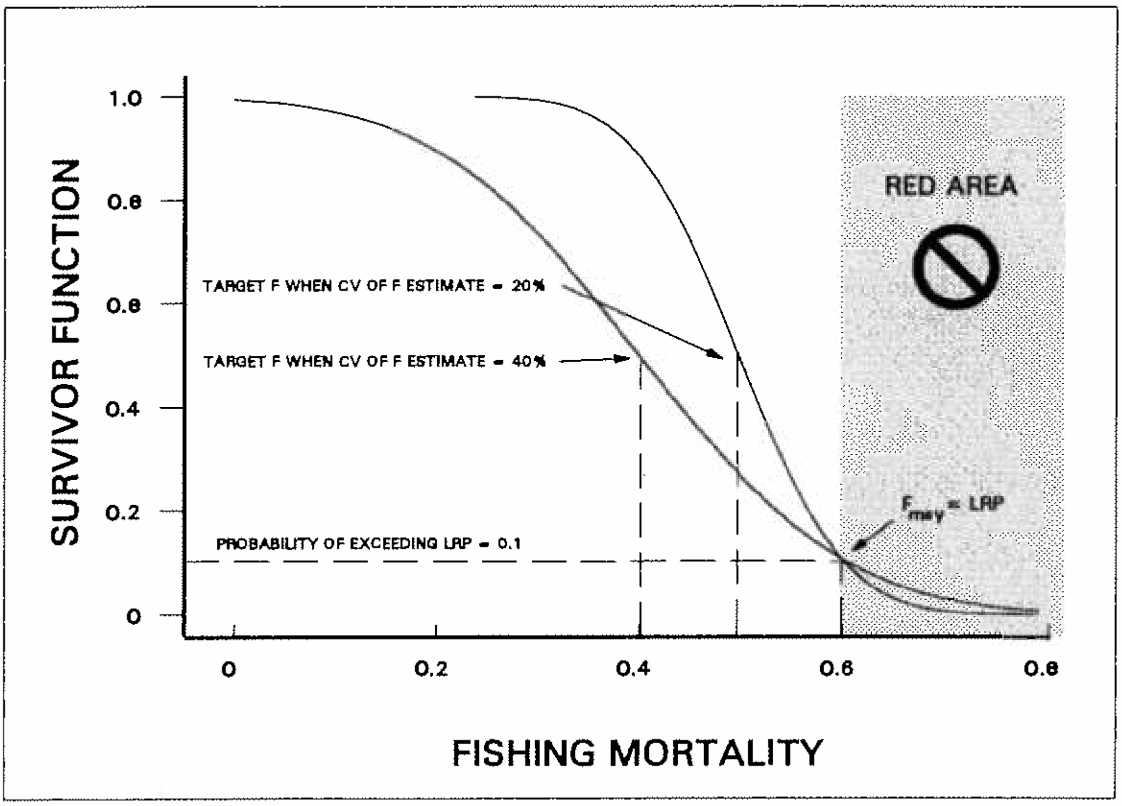

Figure 9: (caption) illustrating two situations: one (the upper curve) where the precision of forecasting the current fishing mortality rate is relatively high, compared with that for a low precision (lower curve). If both have an equal 10% probability of exceeding FMSY at FNOW = 0.6, and entering the RED AREA, the target fishing mortality with the lower precision must be set more cautiously than if, due to improved statistics, the current fishing mortality is better known.

A more elaborate use of MSY as a LRP was incorporated in the New Management Procedure developed by the International Whaling Commission (Garrod and Horwood 1979), where a maximum harvest of 90% of MSY (set at 60% of the unexploited stock level) was agreed to. This was to be reduced progressively by 10% for each 1% shortfall of the stock below the level required to produce MSY. Thus, as soon as stock size dropped below 90% of the MSY level, there was a threshold at which the stock entered a fully protected category. This example also illustrates one other essential feature of a LRP-based management system: the pre-negotiation of future automatic management responses once the system enters an agreed endangered state.

2.5.2 LRPs derived from stock recruitment considerations

The guidelines for US fishery management plans state that although some types of overfishing (growth, localised and pulse) may be permissible, management must guard against recruitment overfishing. Mace and Sissenwine (1993) noted that 60% of the definitions of overfishing to date had been based on spawning stock biomass/recruit (SSB/R) analysis, with typical values ranging from 20-35% of virgin stock levels. In response to the above guidelines and for MBALS in ICES assessments, there has been considerable recent activity aimed at developing various methods of calculating recruitment based LRPs and at evaluating their relationships to various TRPs (Mace and Sissenwine 1993, Clark 1993, Goodyear 1993, ICES 1993b, Mace 1994, Myers *et al.* 1994). Most of these LRPs are variations of the TRPs discussed in the previous section, and are derived in a similar fashion.

> *STATES SHALL BE MORE CAUTIOUS WHEN INFORMATION IS UNCERTAIN, UNRELIABLE OR INADEQUATE. THE ABSENCE OF ADEQUATE SCIENTIFIC INFORMATION SHALL NOT BE USED AS A REASON FOR POSTPONING OR FAILING TO TAKE CONSERVATION AND MANAGEMENT MEASURES.*
> Article 6, United Nations, 1995

An extreme LRP for spawning stock biomass is F_τ, which is based on the slope of the S-R relationship at the origin (Mace and Sissenwine 1993). When $F > F_\tau$, effective stock extinction is assured. One proposed way of estimating F_τ is to use the 90th percentile of observed survival ratios (S/R); the same as the F_{high} of ICES. However, the authors noted that if recruitment is highly variable, and the majority of S-R observations are at a low stock size, this approach will probably overestimate F_τ. In fact, if the S-R scattergram consists only of points on the ascending linear part of the curve, F_τ will be more closely approximated by the 50th percentile of observed survival ratios, which is the same as F_{med} of ICES. Even for a stock in which stock recruitment data cover the full range of stock sizes, given that stock decline would be expected at sustained F levels in excess of F_{med}, it appears that F_{med} may the most rational recruitment-based LRP for most stocks.

From a theoretical analysis of biological reference points for stocks with a wide range of life history characteristics, Mace (1994) recommends that when the S-R relationship is known, TRPs should be estimated directly. She points out that neither the slope at the origin of the S-R relationship nor the SSB which would be expected to provide 50% of the maximum recruitment (R_{max}) are likely to be conservative LRPs, and "...should probably be treated as absolute boundaries not to be crossed". In view of this she recommends a target F which should be as close as possible to F_{msy} subject to the constraint that the probability that stock biomass will fall below $100.\tau.B_0$ should be no greater than 0.05.

Myers *et al.* (1994) pursued the issue of defining LRPs based on conservation of spawning stock biomass using S-R data from 74 stocks for which there were >20 years of data. They evaluated eight methods for estimating the critical spawning stock biomass (%SSB). Of six methods which relied on fitted S-R relationships, two estimated the point where expected recruitment would be 50% of its maximum value. The remaining four estimated the critical point as 20% of estimated virgin biomass. They concluded that there was no one single method for estimating critical spawning levels for all stocks. However, they proposed a number of simple criteria to determine if an LRP estimated from S-R data using any of the above criteria is sensible. These are based on the relative slopes of the log-transformed S-R points above and below the estimated LRP:

- If both slopes are positive, and the slope above the LRP is less than that below it, the LRP is sensible,
- If both slopes are positive, and the slope above the LRP is greater than that below it, the LRP is probably set at too low a biomass,
- If both slopes are negative, the LRP is probably conservative,
- If the slope above the LRP is positive and that below it is negative, the data should be considered uninterpretable.

Another simple rule is that recruitment below the LRP should be on average lower than above the LRP (ICES 1993b).

The above methods depend on the availability of S-R data. In the absence of information on stock and recruitment, practical management advice has been based on generalisations from examination of a large number of exploited stocks. A survey of 91 stock and recruitment data sets for Europe and North America suggest that for stocks considered to have average resilience, a biomass level of 20% of the unfished level should be considered a recruitment-based LRP. In the case of little known stocks, the LRP should be set at 30% of the unfished biomass level. The theoretical analysis by Mace (1994) supported these recommendations and suggested that these results may be applicable to stocks outside the North Atlantic.

2.5.3 Other biological LRPs

If the age at first capture falls below the age at first maturity there is a risk of recruitment overfishing. If control of fishing effort is unreliable, one Reference Point that could be used would be to require fishing to take only individuals at and above the size of first maturity, without discarding or damaging undersized individuals.

Die and Caddy (in press) suggested other possible warning signals which could be adopted as LRPs in the absence of adequate information or more precise analyses, as is often the case with fisheries in developing countries. These include: (a) when total mortality Z rises above some agreed value, such as that corresponding to Z_{mbp} or Z^* for the stock (see section 2.4); (b) when the proportion of mature individuals in the stock falls below some agreed percentage of that for the virgin stock; and (c) when annual recruitment remains poor for a predetermined number of years in a row. Other robust indices which are often associated with low stock size and hence reduced intraspecific competition, are increases in weight-at-age and reduced size at maturity, but by the time these biological indicators have changed significantly, overfishing may already be severe. Figure 10 illustrates the use of survey data to monitor stock status in relation to an agreed LRP. This may be particularly useful when it is difficult to obtain representative samples from the fishery.

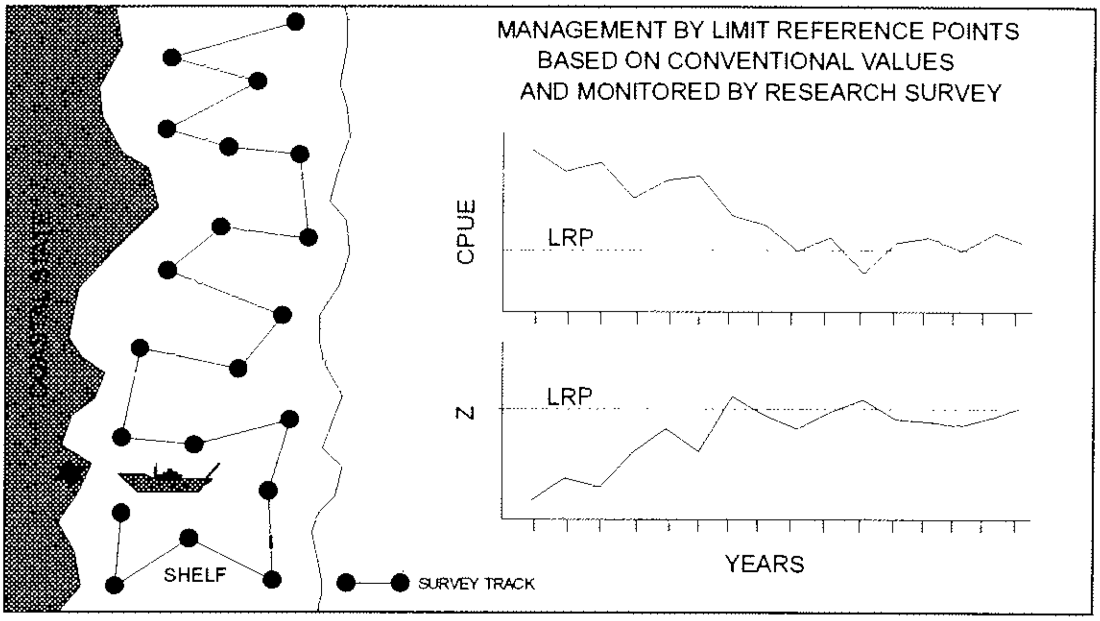

Figure 10: Illustrating the use of a survey CPUE or Z value as an agreed upon LRP. Surveys may be the only approach to monitoring fishery status relative to and RP when little or no fishery data are available.

Zheng *et al.* (1993) compare and evaluate threshold estimation methods for pollock and herring in the Bering Sea. Most are variations of the LRPs dealt with above, but their treatment includes some different approaches to estimating the TRP, including the incorporation of zero production thresholds and depensatory production into the traditional surplus production model.

2.5.4 LRPs derived from economic considerations

It is generally acknowledged (e.g. Panayotou 1988) that on the curve of revenue versus fishing effort, the point of 'economic equilibrium' is an 'attractor', albeit extremely undesirable, for an open access fishery in which net earnings from the fishery equal the costs of fishing (Gordon 1954). Beyond this level of effort the whole fishery is operating at a loss. This is also the point at which the cost of managing the fishery for mortality rate will theoretically be zero.The effort level corresponding to this point (E in Fig. 8), is artificially increased when subsidies reduce the cost of fishing (see FAO 1992b).

In situations where management is impossible, or where the State(s) in question cannot afford any form of management, the unsubsidised point of economic equilibrium could be adopted as an LRP. It would be achieved by the removal of any subsidies supporting the fishery sector.

Since catch per unit effort is often assumed to be proportional to biomass (CPUE = q.B), and revenue is proportional to CPUE, the revenue per unit effort (RPUE) is a potential economic reference variable. This may be particularly useful in some fisheries for highly migratory resources where survey methods are difficult to implement. The point at which RPUE is equal to the cost per unit effort of fishing is a variation of the LRP suggested above. It is presumably axiomatic that a fishing operation that does not generate rent but contributes to dangerously depleting the stock is difficult to justify. However, it will be necessary to separate low CPUE due to availability (e.g. at the beginning and end of the local fishing season for a migratory resource) from that due to low stock size.

2.6 REFERENCE POINTS FOR NEW OR DEVELOPING FISHERIES

Establishing Reference Points for new or developing fisheries requires special consideration if overcapitalisation is to be avoided. Reference points will usually be derived from exploratory or survey biomass estimates, as described in section 2.4.4 above, with considerable uncertainty as to the appropriate values of x to use. Precautionary or probing strategies are suggested, but which restrict fisheries to fishing intensities well below the likely MSY levels revealed by exploratory fishing (e.g. Annala 1993). Intensive data gathering should be an objective in a developing fishery and provision of data should be a requirement for licensing any 'pilot scale' fishery. Although there is the need to acquire good information from the fishery at low stock sizes for future fitting of fishery models, it must be recognized that as exploitation intensifies, the behaviour of the population, including the S-R relationship, may not be adequately described by data from the period when the exploitation rate was low.

2.7 REFERENCE POINTS FOR STOCK REBUILDING

Considering the overexploited condition of many marine fish stocks (FAO 1994), stock rebuilding towards long-term TRPs must be a priority for management. Rebuilding requires that effort be reduced to permit the accumulation of surplus production. This means that the fishing industry must accept a short-term loss in revenue in return for the expectation of higher yields-per-unit effort in the long term (e.g. Overholtz *et al.* 1993). Appropriate targets levels of F for rebuilding will depend on the extent of overexploitation and on the economic impacts of the action, but may need to be considerably lower than those which can be sustained at long-term target stock sizes.

Since stock rebuilding generally requires several years, fishing intensity need to be reduced continuously for the required period. For relatively long-lived species such as cod and haddock, Rosenberg and Brault (1991) showed that rebuilding over moderate time spans (say 5 years) is less economically destructive than short, sharp reductions in fishing mortality (2-year rebuilding scenarios), but that longer rebuilding periods are likely to be too long to see signs of effective recovery. In the case of short-lived stocks, the rebuilding time is likely to be correspondingly shorter, however. For many stocks which are currently heavily exploited, larger-than-normal cohorts make up a progressively larger part of the annual yield, but may not occur very frequently. Keying in on the protection of these larger-than-normal cohorts may be the most rapid way to rebuild a stock.

For stock rebuilding, F must be below F_{med}, the level at which the stock replaces itself (Mace and Sissenwine 1993). For extremely depressed stocks, F_{low}, the level at which recruitment is expected to exceed replacement level in 90% of the years, may be the most appropriate strategy. In any case, the rebuilding target level of F will be an arbitrary level which depends on the desired rate of rebuilding. As with other reference points, it must be agreed upon prior to implementation and sustained in the face of short-term market requirements. In rebuilding it may be reasonable to allow F to progressively approach the target F as stock biomass increases. Owing to the inevitable pressure from the fishing industry to increase effort at high catch rates and to the dependence of most current management systems on short-term decision making, the schedule for increasing F towards the long-term target level in relation to the reference points chosen, must also be agreed to in advance by participants.

Reference points can be envisioned for recovering stocks that would signal various stages in the recovery process and indicate that the recovery or enhancement plan is working. These recovery reference points can be in terms of various states of the population. For example: biomass could be indicated as a percentage of the rebuilt target biomass; for multi-age stocks, an age structure that includes an increased number of age classes; expansion of the area of or number of, localities occupied by the species; the point at which the requirements of predators species have been satisfied.

2.8 PRECAUTIONARY REFERENCE POINTS

In some fora there has been reference to "Precautionary Reference Points", where the intention appears to indicate that such reference points, whether Limit or Target Reference Points, are to be used in a precautionary fashion.

ARTICLE 6: THE APPLICATION OF THE PRECAUTIONARY APPROACH

STATES SHALL APPLY THE PRECAUTIONARY APPROACH WIDELY TO CONSERVATION, MANAGEMENT AND EXPLOITATION OF STRADDLING FISH STOCKS AND HIGHLY MIGRATORY FISH STOCKS IN ORDER TO PROTECT THE LIVING MARINE RESOURCES AND PRESERVE THE MARINE ENVIRONMENT.

United Nations, 1995

Garcia (1994) provides a discussion of the issues involved in applying the Precautionary Principle to fisheries. His definition of this Principle is:

> "Accepting that, in order to protect a marine area from possibly damaging effects of the most dangerous fishing practices and gears, a precautionary approach is necessary which may require action to control fishing activities even before a causal link has been established by absolutely clear scientific evidence.
>
> States accept the principle of safeguarding the marine ecosystem by reducing dangerous fishing practices, by the use of the best technology available and other appropriate means. This applies especially when there is reason to assume that certain damage or harmful effects on the living resources are likely to be caused by such fishing practices and technologies, even where there is no scientific evidence to prove a causal link between practices and effects (the principle of precautionary action)."

These concepts and guidelines for their implementation have been further developed in the Technical Consultation on the Precautionary Approach to Capture Fisheries (FAO/Govt. of Sweden 1995). Their deliberations were predicated on the definition of precaution as: "Caution exercised beforehand to provide against mischief and secure good results - prudent foresight."

The term precautionary reference points does not refer to how the reference point was developed, or its technical basis, but to how it is used as a component for precautionary management strategy. This seems to be how the term is being used in the 'United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks' (United Nations 1995).

IN APPLYING 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 IMPROVED TECHNIQUES FOR DEALING WITH RISK AND UNCERTAINTY;

(B) APPLY THE GUIDELINES SET OUT IN ANNEX 2 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(S), REFERENCE POINTS, STOCK CONDITION IN RELATION TO SUCH REFERENCE POINTS, LEVELS AND DISTRIBUTIONS OF FISHING MORTALITY AND THE IMPACT OF FISHING ACTIVITIES ON NON-TARGET AND ASSOCIATED OR DEPENDENT SPECIES, AS WELL AS OCEANIC, ENVIRONMENTAL AND SOCIO-ECONOMIC CONDITIONS; AND

(D) DEVELOP DATA COLLECTION AND RESEARCH PROGRAMMES TO ASSESS THE IMPACT OF FISHING ON NON-TARGET AND ASSOCIATED OR DEPENDENT SPECIES AND THEIR ENVIRONMENT, ADOPT PLANS AS NECESSARY TO ENSURE THE CONSERVATION OF SUCH SPECIES AND PROTECT HABITATS OF SPECIAL CONCERN.

Article 6, United Nations, 1995

Annex 2 of this last-cited report "*Guidelines for Application of Precautionary Reference Points in Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks*" is of particular relevance, and is reproduced in full below:

ANNEX 2

1. A PRECAUTIONARY REFERENCE POINT IS AN ESTIMATED VALUE DERIVED THROUGH AN AGREED SCIENTIFIC PROCEDURE, WHICH CORRESPONDS TO THE STATE OF THE RESOURCE AND OF THE FISHERY, AND WHICH CAN BE USED AS A GUIDE FOR FISHERIES MANAGEMENT.

2. TWO TYPES OF PRECAUTIONARY REFERENCE POINTS SHOULD BE USED: CONSERVATION, OR LIMIT, REFERENCE POINTS AND MANAGEMENT, OR TARGET, REFERENCE POINTS. LIMIT REFERENCE POINTS SET BOUNDARIES WHICH ARE INTENDED TO CONSTRAIN HARVESTING WITHIN SAFE BIOLOGICAL LIMITS WITHIN WHICH THE STOCK(S) CAN PRODUCE MAXIMUM SUSTAINABLE YIELD (MSY). TARGET REFERENCE POINTS ARE INTENDED TO MEET MANAGEMENT OBJECTIVES.

3. PRECAUTIONARY REFERENCE POINTS SHOULD BE STOCK-SPECIFIC TO ACCOUNT, INTER ALIA, FOR THE REPRODUCTIVE CAPACITY, THE RESILIENCE OF EACH STOCK, AND THE CHARACTERISTICS OF FISHERIES EXPLOITING THE STOCK, AS WELL AS OTHER SOURCES OF MORTALITY AND MAJOR SOURCES OF UNCERTAINTY.

4. MANAGEMENT STRATEGIES SHALL SEEK TO MAINTAIN OR RESTOR POPULATIONS OF HARVESTED STOCKS, AND WHERE NECESSARY ASSOCIATED OR DEPENDENT SPECIES, AT LEVELS CONSISTENT WITH PREVIOUSLY AGREED PRECAUTIONARY REFERENCE POINTS. SUCH REFERENCE POINTS SHALL BE USED TO TRIGGER PRE-AGREED CONSERVATION AND MANAGEMENT ACTION. MANAGEMENT STRATEGIES SHALL INCLUDE MEASURES WHICH CAN BE IMPLEMENTED WHEN PRECAUTIONARY REFERENCE POINTS ARE APPROACHED.

5. 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. FISHERY MANAGEMENT STRATEGIES SHALL ENSURE THAT TARGET REFERENCE POINTS ARE NOT EXCEEDED ON AVERAGE.

6. WHEN INFORMATION FOR DETERMINING REFERENCE POINTS FOR A FISHERY IS POOR OR ABSENT, PROVISIONS REFERENCE POINTS SHALL BE SET. PROVISIONAL REFERENCE POINTS MAY BE ESTABLISHED BY ANALOGY TO SIMILAR AND BETTER-KNOWN STOCKS. IN SUCH SITUATIONS, THE FISHERY SHALL BE SUBJECT TO ENHANCED MONITORING SO AS TO ENABLE REVISION OF PROVISIONAL REFERENCE POINTS AS IMPROVED INFORMATION BECOMES AVAILABLE.

7. THE FISHING MORTALITY RATE WHICH GENERATES MSY SHOULD BE REGARDED AS A MINIMUM STANDARD FOR LIMIT REFERENCE POINTS. FOR STOCKS WHICH ARE NOT OVER-FISHED, FISHERY MANAGEMENT STRATEGIES SHALL ENSURE THAT FISHING MORTALITY DOES NOT EXCEED THAT WHICH CORRESPONDS TO MSY, AND THAT THE BIOMASS DOES NOT FALL BELOW A PRE-DEFINED THRESHOLD. FOR OVER-FISHED STOCKS, THE BIOMASS WHICH WOULD PRODUCE MSY CAN SERVE AS A REBUILDING TARGET.

United Nations, 1995

2.9 REFERENCE POINTS FOR HIGHLY MIGRATORY RESOURCES

From a technical point of view, reference points for straddling and highly migratory stocks do not differ from those for shared stocks (Gulland 1980, Caddy 1982), or for those occurring entirely within an EEZ. However, the feasibility of application of individual reference points may differ, due to the multijurisdictional nature of the resources, rather than their biological characteristics. The variety of types of shared/migratory resources is described by Caddy (1982). Here, we consider the most difficult situation, that of sequential exploitation along a migratory route.

This particular case has been the subject of intense international negotiation at the United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks in 1994-95. An excerpt from Article 7 of the Chairman's report is given in the following box:

ARTICLE 7

COMPATIBILITY OF CONSERVATION AND MANAGEMENT MEASURES

(B) WITH RESPECT TO HIGHLY MIGRATORY FISH STOCKS, THE RELEVANT COASTAL STATE(S) AND THE OTHER STATE(S) WHOSE NATIONALS FISH IN THE REGION FOR THESE COOPERATION PROVIDED FOR IN PART III WITH A VIEW TO ENSURING CONSERVATION AND PROMOTING THE OBJECTIVE OF OPTIMUM UTILIZATION OF SUCH STOCKS THROUGHOUT THE REGION, BOTH WITHIN AND BEYOND THE AREAS UNDER NATIONAL JURISDICTION.

2. CONSERVATION AND MANAGEMENT MEASURES TAKEN ON THE HIGH SEAS AND THOSE TAKEN WITHIN AREAS UNDER NATIONAL JURISDICTION SHALL BE COMPATIBLE IN ORDER TO ENSURE CONSERVATION AND MANAGEMENT OF THE STOCKS OVERALL. TO THIS END COASTAL STATES AND STATES FISHING ON THE HIGH SEAS HAVE A DUTY TO COOPERATE FOR THE PURPOSE OF ACHIEVING COMPATIBLE MEASURES IN RESPECT OF STRADDLING FISH STOCKS AND HIGHLY MIGRATORY FISH STOCKS. IN DETERMINING COMPATIBLE CONSERVATION AND MANAGEMENT MEASURES, STATES SHALL:

(A) TAKE INTO ACCOUNT THE CONSERVATION AND MANAGEMENT MEASURES ESTABLISHED IN ACCORDANCE WITH ARTICLE 61 OF THE CONVENTION IN RESPECT OF THE SAME STOCK(S) BY COASTAL STATES WITHIN AREAS UNDER NATIONAL JURISDICTION AND ENSURE THAT MEASURES ESTABLISHED IN RESPECT OF THE HIGH SEAS DO NOT UNDERMINE THE EFFECTIVENESS OF THOSE MEASURES ESTABLISHED IN RESPECT OF THE SAME STOCKS(S) BY COASTAL STATES IN AREAS UNDER NATIONAL JURISDICTION;

(B) TAKE INTO ACCOUNT PREVIOUSLY AGREED MEASURES ESTABLISHED IN ACCORDANCE WITH THE CONVENTION FOR THE SAME STOCK(S) BY RELEVANT COASTAL STATES AND STATES FISHING ON THE HIGH SEAS IN RESPECT OF THE HIGH SEAS;

(C) TAKE INTO ACCOUNT THE BIOLOGICAL UNITY AND OTHER CHARACTERISTICS OF THE STOCK(S) AND THE RELATIONSHIPS BETWEEN THE DISTRIBUTION OF THE STOCK(S), THE FISHERIES AND THE GEOGRAPHICAL PARTICULARITIES OF THE REGION, INCLUDING THE EXTENT TO WHICH THE STOCK(S) OCCUR AND ARE FISHED IN AREAS UNDER NATIONAL JURISDICTION;

(D) TAKE INTO ACCOUNT THE RESPECTIVE DEPENDENCE OF THE COASTAL STATE(S) AND THE STATE(S) FISHING ON THE HIGH SEAS ON THE STOCK(S) CONCERNED: AND

(E) ENSURE THAT THE MEASURES TAKEN DO NOT RESULT IN HARMFUL IMPACT ON THE LIVING MARINE RESOURCES AS A WHOLE. Excerpt from United Nations, 1995

COASTAL STATES "...SHALL CO-OPERATE DIRECTLY OR THROUGH APPROPRIATE INTERNATIONAL ORGANIZATIONS WITH A VIEW TO ENSURING CONSERVATION AND PROMOTING THE OBJECTIVE OF OPTIMUM UTILIZATION OF [HIGHLY MIGRATORY] SPECIES THROUGHOUT THE REGION, BOTH WITHIN AND BEYOND THE EXCLUSIVE ECONOMIC ZONE.

"...SHALL CO-OPERATE [...] IN THE CONSERVATION AND MANAGEMENT OF LIVING RESOURCES IN THE AREAS OF THE HIGH SEAS, [...] SHALL ENTER INTO NEGOTIATIONS WITH A VIEW TO TAKING THE MEASURES NECESSARY FOR THE CONSERVATION OF THE LIVING RESOURCES CONCERNED, [AND] SHALL CO-OPERATE TO ESTABLISH SUBREGIONAL OR REGIONAL FISHERIES ORGANIZATIONS TO THIS END".

The 1982 Convention on the Law of the Sea

Complex management arrangements may be needed to deal with highly migratory resources in which multiple fisheries occur sequentially at different locations on the overall migratory route (Fig. 11). Such local fisheries are usually seasonal, and often too short to allow declines in catch rate and/or size to be unambiguously attributed to fishing as opposed to changing regional availability or migration. At each locality, availability to fishing and age composition of the catch may differ. Under these circumstances, there is no ready alternative to pooling catch data and performing a global assessment. One possibility is to use an escapement or gauntlet model for management (Paulik and Greenough 1966).

A practical consideration for sequential fisheries on a common stock, is that fishing locations may differ in suitability in relation to a size-based Reference Point such as the optimal size at first capture l_c based on yield-per-recruit or spawning biomass-per-recruit analyses for the whole stock (Fig. 11). Consequently, the sacrifices needed to either achieve an optimal yield-per-recruit, or to protect the spawning stock or juveniles from overfishing, are not shared equally for all participants. They often depend for their success on the actions of one or a few coastal States where these critical life history stages occur. Under these circumstances, the overall yield from the population will be suboptimal if all participating States are obliged to harvest the stock exclusively within their EEZs, and if only a few (e.g. juvenile) age classes are available in any given EEZ (Caddy 1982). The optimal solution from a yield-per-recruit perspective would be to agree to limit harvesting to seasons/areas where the size frequency, catch rates and market prices are optimal. This would require access to these areas for all parties, or compensation for those parties prepared to forego fishing for suboptimal sizes within their own EEZs.

In a sequential fishery for a highly migratory species, the best overall Reference Point is one which ensures that a target spawning biomass survives all fisheries to replace the stock. From a simple example, it is clear that this can be achieved by many different combinations of national allocations, which all result in the same cumulative risk of death prior to spawning (Table 2). If the mechanism proposed in the last paragraph is rejected in favour of sub-optimal harvesting within each jurisdiction, the vector of mortalities-at-age, and the corresponding allocations, should still be negotiated by participants in relation to one or more of the overall stock reference points discussed earlier.

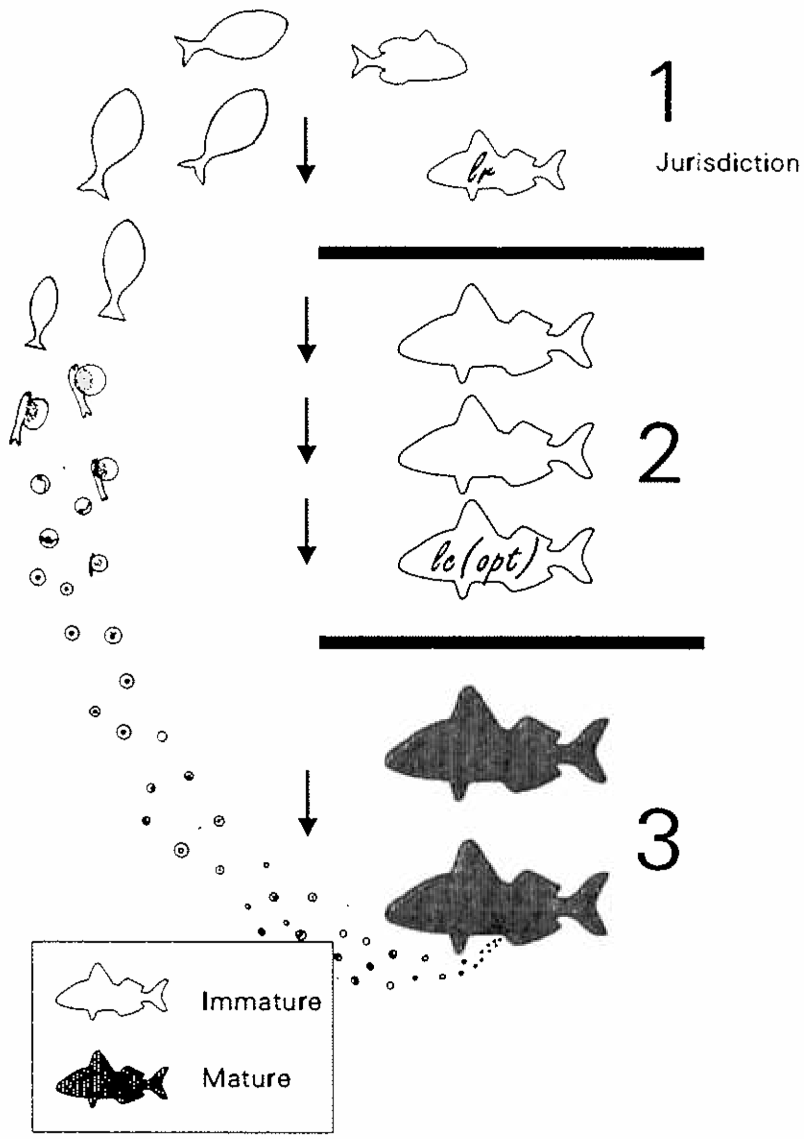

Figure 11: **An idealized gauntlet fishery for a highly migratory species crossing 3 jurisdictions during its life history. The size at first recruitment to the fishery l_r, occurs in jurisdiction 1; the optimum size at first capture (lc_{opt}) which gives maximum Y/R occurs in jurisdiction 2, and spawning occurs in jurisdiction 3.**

Economic reference points may not always be practical as reference points for management of straddling stocks, and even less so for highly migratory resources, because each national fleet may have a different economic optimum, depending on its costs, earnings and national market prices. In general, F_{mey} is not easily defined in fisheries involving several fleet components with different gears and fishing practices.

Similarly, for straddling and highly migratory stocks, it can be extremely difficult to estimate a yield-per-recruit based TRP if fleet-specific vectors of F-at-age for an exploited resource differ among jurisdictions, and the relative effort of the fleets changes from year to year.

2.10 MULTISPECIES AND ECOSYSTEM CONSIDERATIONS IN SETTING REFERENCE POINTS

The need for multispecies and ecosystem perspectives in fisheries management has been frequently noted (Mercer 1982, Sugihara *et al.* 1984). For fisheries management, these considerations may be seen as comprising the following categories:

Technical interactions -- The technical problem of managing sets of species which are harvested together, regardless to whether there are any biological interactions among them;

Species interactions -- Primarily the effects of predation and competition on the population responses of the species for which management advice is being provided;

Ecosystem interactions[1] -- The effect which the reduction of biomass of exploited species may have on other organisms in the ecosystem of which they are part.

Fisheries scientists have recognized the potential impacts of all of these relationships on the probability of success of management based on single species models, and have devoted considerable effort over the past two decades to developing practicable solutions to these problems. Formal incorporation of these considerations into management advice has, however, been difficult to achieve.

> *COASTAL STATES SHALL "...TAKE INTO CONSIDERATION THE EFFECTS ON SPECIES ASSOCIATED WITH OR DEPENDENT UPON HARVESTED SPECIES WITH A VIEW TO MAINTAINING OR RESTORING POPULATIONS OF SUCH ASSOCIATED OR DEPENDENT SPECIES ABOVE LEVELS AT WHICH THEIR REPRODUCTION MAY BECOME SERIOUSLY THREATENED."*
>
> The 1982 Convention for the Law of the Sea

2.10.1 Technical interactions

The major problem with harvesting several species from an assemblage using a single unselective gear, such as trawl or fish trap, is that each species will have different life-history characteristics, and consequently different responses to exploitation. Thus an overall F-based Reference Point will overexploit some species and underexploit others. Scaling species-specific values of F-based LRPs for different trophic levels according to their relative rates of natural mortality, remains a theoretical possibility (Caddy and Sharp 1986), but would be

[1] Clearly, species interactions play a leading role in ecosystem responses to exploitation. Nonetheless, the latter two categories are intended to distinguish between population level and ecosystem level phenomena.

difficult to implement for fishing gears such as bottom trawls or fish traps that are relatively unselective by species. For such unselective types of gears, a precautionary approach for all species being exploited risks ecosystem exploitation being defined in terms of the species with the least resistance to harvesting. Thus if harvesting is to be optimized for the individual species of an ecosystem, developing more selective modes of harvesting is a high priority. This can be approached through the use of more selective gear, or through knowledge of the spatial distribution of the resource and deployment of effort accordingly.

When there are separate assessments for individual species, as in demersal trawl fisheries in the north Atlantic, the species TACs are rarely in proportion to the relative catch rates in the trawl. Optimization of the concurrent harvesting by trawl fisheries on jointly-occurring groundfish species, has been approached using information on the spatial variability in composition of the catch to deploy fishing effort among species assemblage areas, in such a way as to optimize harvesting of the combined quotas (Murawski *et al.* 1983, Murawski and Finn 1988). In this case, this target reference point is the sum of quotas of all species. In theory, the target can only be achieved if all quotas are met at exactly the same time, otherwise the fishery closes when the first quota is met, and the remainder of the other quotas remain unharvested. In reality, the fishery compensates for this by discarding, and one major objective of quota management is aimed primarily at reducing this undesirable feature of multispecies fisheries.

There is increasing concern about the direct physical effect of fishing activities on marine habitats (ICES 1993b, EEC 1994). As these physical effects become better understood, these concerns could give rise to further fishery reference points which may define and limit the permissible extent of physical damage. For example, trawling and dredging directly affect benthic habitats and communities. Thus fishing may be limited to a level in which the total area trawled in any year does not exceed some proportion of the total trawlable area based perhaps on the observed rate of regeneration of the habitat or community. At present there are extreme examples in which the use of fishing gear and practices which damage habitats such as coral reefs are prohibited, i.e. are part of a set of management rules.

Direct effects of fishing on non-target species are also of concern (EEC 1994). Sea birds, turtles and mammals are primary examples which are leading to the imposition of limits on fishing. In the case of turtle by-catch in shrimp trawlers, it is recommended to use turtle excluder devices (TEDs) which increase fishing costs, and reduce shrimp catches (Gibbons-Fly *et al.* 1994) but may provide the only ecologically acceptable option. The most notable example is the tuna purse seine-dolphin interaction in the east-central Pacific in which catches are limited by an allowable number of dolphin kills annually. This has dramatically affected tuna fishing practices and management procedures (see Annex 3).

2.10.2 Species interactions

The 1982 Convention (UN 1983) considers the potential impact that fishing one resource may have on others. These kinds of impacts are likely to be most pronounced for species that are competitors, predators, or prey of the target species, or are taken as bycatch. Reference points that explicitly recognize and quantify these specific types of interactions, have not been routinely applied in many fisheries. The information requirements generally go beyond the level of knowledge presently available for most marine ecosystems. However, there are various instances in which interaction of coexisting species are considered in setting TRPs.

Predator prey situations have long been of concern to fishery scientists (Clepper 1979). Pauly (1979) emphasises the trade-offs in attempting to exploit both predator and prey. In some situations management has provided for the food requirements of a predator when the prey is harvested. For capelin off eastern Canada a catch LRP of no more than 10% of the spawning biomass has been used. This relatively low rate was selected arbitrarily based on capelin's position in the food chain as a prey species, assuming that there was a relatively high M due to predation by marine mammals and cod. In particular, there was concern that excessive harvesting could negatively impact the production of cod (Shelton *et al.* 1993). Capelin management in Norway explicitly uses an estimate of the amount of capelin required by cod (Anon 1993). Even in apparently simple two-species systems, the complexities of species interactions may diminish the effectiveness of multispecies approaches. For example, management may provide for a high prey biomass of a small pelagic fish, sprat, for cod, but not allow for the fact that large sprat prey on cod eggs! Nonetheless, it is clear that setting Reference Points for exploitation of prey species should, where possible, consider predators, whether they are exploited or not.

More formal, model-based approaches to taking species interactions into account have included attempts to link single species models together by including terms for the interactions, notably predation. The multispecies model for the North Sea, and subsequent multispecies VPAs for that area are notable examples. A multispecies VPA models the trade-offs between exploiters of different ecosystem components, but is extremely data intensive. At this time there are few systems for which the data for this potential management approach are available. Even for the Northwest Atlantic (a well studied area), participants at a workshop on 'Inclusion of fishery interactions in management advice' agreed that "Large multispecies models...were beyond the scope of the resources and manpower of...[fishery] laboratories" (Mahon 1985). There is no evidence that this situation has changed, and most attempts to incorporate multispecies approaches into fisheries assessment have focused on interactions between two or more components of an ecosystem, and the fleets exploiting them.

An alternative approach to dealing with the effect of species interactions on yield from an assemblage of coexisting species is to combine them into a single analysis which assumes that the behaviour of the combined biomass will be similar to that of a single species. This approach has been used to estimate MSY for coral reef fisheries, in which there are too many species to attempt single species analyses (Medley *et al.* 1993). It has also been used as a second, limiting, tier to single species management, because when the exploited assemblage includes both prey and predator species, there is reason to expect that the sum of yields from single species assessments will overestimate the combined yield. Therefore, a combined analysis was also used by ICNAF in a two-tiered approach to management, in which the sum of single species quotas was constrained by the yield estimated from the combined stocks (see Mahon 1985).

2.10.3 Ecosystem interactions

A further area of concern regarding sustainability of fishery production is that the significant reduction of biomass of several, possibly keystone, species from an ecosystem will bring about changes in the system which may be precipitous and possibly irreversible. Many ecosystems have exhibited significant changes in response to exploitation, although this has often been confounded with environmental changes and with pollution. Notable examples are the demersal assemblages off the north eastern USA and in the Gulf of Thailand (Saila 1993). Similarly, several studies have noted the effects of fishing on the species composition of coral reef fish assemblages (Medley *et al.* 1993). The observation that species composition in exploited assemblages tends to shift towards a predominance of smaller, more resilient, but often less valuable species could provide the basis of a diversity-based target reference point for management of multispecies fisheries.

Quantitative descriptors of fishery induced trends in exploited assemblages could be used as reference variables. Saila (1993) suggests multivariate trend analysis methods which can be used to detect trends. Participants could agree upon a desired mix of species based on their size and value, and adjust fishing effort in an attempt to achieve the desired mix. This would constitute a multispecies TRP. The proportion of one or more desirable or undesirable species in the catch could be used to set limit reference points in terms of their minimum proportion in the catch.

The question of precipitous (sometimes referred to as catastrophic) changes in ecosystems has frequently been raised. A major question is whether there are multiple stable states in ecosystems, such that when exploited, the system would move from one stable state to another, but would not move back when exploitation ceased. One such example for northern warm-water lakes is the transition from assemblages dominated by percids to those dominated by smaller, less desirable species, as a function of lake productivity and exploitation (Kerr 1976). On the basis of the information provided by Kerr, it should be possible to propose an LRP for exploitation of such lakes. The large number of northern lakes provided the sample size required to identify this transition point. The marine environment does not usually provide similar opportunities for sample replication. Thus one must either infer from other systems, or learn from experience, by which time it may be too late. However, if there is the expectation that the system to be managed may exhibit a change in states, precautionary LRPs should be adopted.

Another approach to incorporating ecological principles into fishery management involves use of the biomass size-spectrum of living organisms as an indicator of the effect of exploitation (Dickie *et al.* 1987, Platt and Denman 1978, Caddy and Sharp 1986). Ecosystem characteristics of immediate interest to fishery managers are directly related to the size-spectrum due to inter and intra-specific scaling of physiological processes. Reference points could be based on this ecosystem characteristic, and though less precise than conventional F based reference points, would be more easily monitored.

> *"THAT AUSTRALIAN FISHERIES MANAGEMENT BE UNDERTAKEN WITHIN AN ECOSYSTEM MANAGEMENT FRAMEWORK."*
>
> Anon 1991

From a practical management perspective, there is limited management experience with deliberate manipulation of the relative biomass of ecosystem components. Such changes affect the equity of fleets fishing different resources, and requires negotiation between users of different components of the food web (see e.g. Brander and Bennett 1989) prior to selecting species-specific Reference Points for the ecosystem component in question. A current example of an unresolved contention of this type is the tuna purse seine-dolphin interaction in the east-central Pacific where there is disagreement between the 'users' of these two interacting resources as to the ideal overall harvest rates (see Annex III).

Concern about ecosystem responses to exploitation extends beyond the effects on fisheries outputs, to include aspects of overall ecosystem health, stability and biodiversity (United Nations 1992, Chapter 17, Norse 1993, Gimbel 1994). In attempting to encompass these concerns, Sherman (1994) takes a broad ecological view of sustainability of biomass yields from marine ecosystems. He promotes the use of the Large Marine Ecosystem (LME) concept as a context for management of renewable resources. In this context, management decisions would have to be viewed in the light of their expected impacts on the entire ecosystem. He cites several LMEs in which an holistic approach to management is being attempted (Yellow Sea, Benguela Current, Great Barrier Reef, NW Australian Shelf and Antarctic marine ecosystems) or is being developed (Black Sea, Barents Sea, North Sea and North California Current ecosystems) (see Sherman *et al.* 1993 for basic descriptions of these systems). One praiseworthy attempt at whole ecosystem management is found in the Convention on the Conservation of Antarctic Marine Living Resources (see CCAMLR 1993), but despite the clauses in the Convention, many Antarctic finfish resources are severely depleted, largely due to a lack of means to control access.

The CCAMLR convention (Article IIc) explicitly requires a management response to 'potentially irreversible changes to the ecosystem as a whole' due to a wide range of possible causal factors. This leads to discussion on what actions are irreversible how to tell, how to tell when an irreversible change has occurred, what elements of the ecosystem are controllable, and to what extent.

For the most part, initiatives towards ecosystem level management are at the stage of developing conceptual reference points or guidelines, and/or defining the research and monitoring needed to address the major questions (e.g. Holling 1993, Apollonio 1994, Sherman 1994). Indeed, there are significant challenges in providing descriptions of ecosystem health, even without reference to the impacts of exploitation (GESAMP 1994). Converting these conceptual approaches to target or limit management reference points which can be routinely used in management decisions will take time and negotiation (e.g. Norse 1993). There are also a number of institutional issues which must be addressed. At both national and international levels, many of the important components of ecosystems cut across issues of health, trade, tourism, transportation, *inter alia* and are beyond the current terms of reference of institutions solely charged with marine resource management. Nonetheless, as these concepts evolve towards applicability, they can still provide a context within which fishery managers can attempt to understand the effects of their decisions on the systems they are managing (Apollonio 1994).

2.11 AN OVERVIEW OF REFERENCE POINTS

At the time when they proposed $F_{0.1}$ as a TRP, Gulland and Boerema (1973) noted that there was no theoretical model for setting annual catch quotas that combines the desirable features of being readily understandable to decision makers; describing and realistically predicting to an acceptable degree of precision the events within the fish stock; and being applicable to a specific fishery without great demands in data and analysis. It is not clear that the situation is greatly improved today.

The population model-derived reference points are technically complex and require considerable quantities of data, usually collected over many years (Table 3). Other less complex Reference Points have also been considered. Many of these are based on population models, or on generalisations from the application of models to many different types of populations. Some, such as mean sizes in the catch relative to size at maturity, can be easily observed with minimal technical expertise and cost. Others must be based on the best available information borrowed from similar fish stocks in other areas. In the absence of more data and sophisticated analyses, such Precautionary Reference Points should be adopted, at least as interim measures, until the necessary assessments have been carried out which allow more precise reference points to be developed.

Limit or threshold reference points indicate that an undesirable stock status is unacceptably close, and that immediate management action is urgently needed. The incorporation of an LRP into a management strategy requires that its responses be pre-established by negotiation among the participants in the fishery and to be acted upon immediately the agreed-upon indices or assessments indicate that the LRP has been reached.

Reference Points related to multispecies or ecosystem considerations are still in their formative stages, but can still provide a valuable basis for management. The challenge is to formulate some of these concepts in terms of Reference Points which can be widely agreed upon and adopted as conventions.

3. UNCERTAINTY AND RISK

Uncertainty, as defined by the Technical Consultation on the Precautionary Approach to Capture Fisheries (TCPA), is "The incompleteness of knowledge about the state or process of nature" (FAO/Govt. of Sweden 1995). Statistical uncertainty is "stochasticity or error from various sources as described using statistical methodology." The TCPA defines risk as "the probability of something bad happening." Note that in decision theoretic terms, risk is defined as the average loss or forecasted loss when something bad happens.

Clearly, when management decisions are to be based on quantitative estimates from fishery assessment models, it is desirable that the uncertainty be quantified, and used to calculate the probability of achieving the desired target and/or risk of incurring undesirable events. The process of communicating this risk to decision-makers is in its early developmental stages and presents substantial challenges to both fishery technicians and managers. In turn, fishery managers and participants must develop means of objectively evaluating the potential costs of undesirable events and define acceptable levels of risk and of risk and of short-term yield which can be foregone to reduce these risks.

Evaluation of and the expected cost of undesirable events which may result from a particular course of action is desirable when proposing management measures (e.g. Beddington 1978; Francis 1991). While this practice has been rare in the past, some failures in the management of well-studied stocks in recent years have brought this issue to the scientific forefront. There have been several recent workshops which have focused on the evaluation of risk in fisheries management (SEFSC 1991, NAFO 1991, Anon. 1992, Smith *et al.* 1993, Kruze *et al.* 1993, FAO/Govt. of Sweden 1995).

3.1 TYPES OF UNCERTAINTY

There are several sources of uncertainty in the calculation of reference points, and in the evaluation of stock status relative to these reference points. Five types of uncertainty arising from an imprecise knowledge of the state of nature are (Rosenberg and Restrepo 1992):

- Measurement uncertainty is the error in the observed quantities such as the catch or biological parameters;

- Process uncertainty is the underlying stochasticity in the population dynamics such as the variability in recruitment;

- Model uncertainty is the misspecification of model structure;

- Estimation uncertainty can result from any, or a combination of the above uncertainties and is the inaccuracy and imprecision in abundance or fishing mortality rate;

- Implementation uncertainty results from variability in the resulting implementation of a management policy, i.e. inability to exactly achieve a target harvest strategy.

Note that sources of uncertainty include not only statistical error in detecting stock status and environmental trends or errors in population analysis, but also wrong decisions and an inefficient management framework; issues dealt with later in this paper.

3.1.1 Uncertainty due to measurement error and bias

The potential sources of variability in commonly available data from commercial fisheries -- catch, fishing effort, and biological samples of the catch for length, age and maturity determination -- have been a focus of fishery statisticians and assessment scientists for several decades (e.g. Doubleday and Rivard 1983, ICES Assessment Working Group Reports). These sources are now relatively well known and quantified. Where sample surveys are used, there are standard statistical problems of sample size and representativeness. Difficulty in accounting for discarding continues to bias landing statistics in many fisheries however (Alverson *et al.* 1994). In logbook and reporting systems there is often misreporting, and in quantifying effort, there are often hidden increases in the fishing power of boats due to fishermen learning and technological change.

While a fishing surveys with a standard boat and randomized design can provide objective estimates or indices of stock size which are less liable to biases than catch data, the resulting survey estimates also have a significant variance (e.g. Doubleday and Rivard 1981). The variance associated with acoustic surveys is usually also considerable (Simmonds *et al.* 1992). Table 4 includes some estimates of the likely range of errors in various population variables for well-studied offshore fish stocks.

3.1.2 Process uncertainty

The natural variability associated with fish production systems can be enormous. Environmental variability, the largest source of process errors, usually manifests itself as recruitment variability (e.g. Hennemuth *et al.* 1980). In short-lived populations this can result in dramatic fluctuations in adult biomass (Lluch-Belda *et al.* 1989).

Although there may be relationships and patterns which can be statistically modelled to provide some explanation of past events, there has been little success in predicting environmental conditions or the responses of fish populations sufficiently far in the future to be useful to management (Walters and Collie 1988). Thus environmental variability is often treated as entirely stochastic, and the most appropriate approach is usually to measure its effects on the fish population directly with surveys of pre-recruits (Bradford 1992).

In addition to variability on an inter-annual time scale there are also environmental changes on decadal and longer time-scales, which affect population abundance, distribution and location in ways which are difficult to measure, much less predict (e.g. Murawski 1993).

It is generally accepted that fish stocks become more susceptible to environmental variability as exploitation increases. Thus there is a direct effect of management on uncertainty, and the reduction of uncertainty may itself be a management objective.

3.1.3 Model uncertainty

Model errors are seldom evaluated, because the data required to distinguish among different models are not available. Studies on the relative performance of various model formulations, e.g. Schaeffer and Fox production models, suggest that they may provide substantially different answers using the same data. In fact, the same model may give quite different results depending on the error structure assumed (Polancheck *et al.* 1993). Other examples of potential model errors in stock assessment include the models used to calibrate indices of abundance (e.g. VPA tuning), the use of conventional constant values for natural mortality, and the setting of F values for the young fish as a function of that for older individuals.

Model error can be examined to some extent by using several models to evaluate the same resource although, in practice, the data and expertise required for a multi-model approach are seldom available. However, in those instances where it has been attempted, substantial differences are often found, for example in the case of bluefin tuna in the west Atlantic three methods gave MSY estimates of 3,942, 5,530 and 6,755 mt/yr (ICCAT 1994).

3.1.4 Estimation uncertainty

Owing to the sequential nature of assessment, estimation errors occur at several stages, and are propagated through the process. They can be seen as the combined result of the three types of error outlined above. Although in the past, explicit estimates of accuracy or precision were rare, they are now becoming more common in the literature. Some estimates of the likely order of the error for quantities commonly used in assessing stock status are presented in Table 4 for shelf fisheries. The generality of these examples is open to question, but they are likely to be underestimates for pelagic and large pelagic fish stocks.

Attempts to quantify estimation error use the estimated variability in measured parameters measured. However, it is important to note that several procedures use assumed or unmeasured inputs, for which there is no information on variability. The most significant among these assumed input parameters is natural mortality, which is seldom measured or readily measurable. A recent analysis of haddock in three subareas of the North Sea provided estimates of M ranging from 0.37 to 0.53, considerably higher than the conventional value of 0.2 which is used for North Atlantic groundfish stocks (Jones and Shanks 1990).

Most stock assessments and calculations of target reference points involve a sequence of complex analyses. Inevitably, at each stage there are decisions to be made which may significantly affect the outcome of the analysis. In the absence of a methodology which can provide a unique solution, many management systems adopt a committee approach, in which the result is often arrived at by consensus. For some types of assessment, notably VPA-based assessments, this problem has been dealt with by automating the procedure (Gavaris 1988, Conser and Powers 1990).

Estimation errors which result from biases or trends in input variables may be very difficult to detect or describe. One dramatic example is the systematic error in estimation of stock abundance using sequential population analysis methods (virtual population analysis and cohort analysis). These were only detected when scientists undertook retrospective analyses several years after the population estimates had been used to provide management advice. This could only be done by comparing population estimates for cohorts which had passed almost entirely through the fishery (cohorts for which the SPA has converged and for which estimates are little affected by the input values of F for the most recent year), with the estimates of those cohorts at the time when they had recently entered the fishery. Substantial differences between the two estimates, sometimes an order of magnitude or more, were detected.

Owing to the complexity of the assessment process, the causes of the differences found by the retrospective analyses were exceedingly difficult to evaluate, and are still not well understood. They have been variously attributed to misreporting of catch, trends in catchability, the assumption of constant natural mortality across all age groups, and assumptions regarding partial recruitment (the susceptibility to exploitation) at various ages (e.g. Sinclair *et al.* 1990, Parma 1993). Sinclair *et al.* (1990) concluded that "estimates of population size from the converged part of the SPA do not necessarily represent the true population size for those years", thus leaving considerable doubt as to the validity of a methodology which has been the cornerstone of stock assessment in many developed parts of the world.

The values in Table 4 make it clear that the current stock size and fishing mortality are known with relatively low accuracy for most fisheries, although with retrospective analysis, particularly VPA, the above estimates may improve somewhat. Total yield may appear to be known with a higher precision than other variables, but often suffer from high or unknown biases due to discarding and misreporting, particularly if management is by quotas. Survey estimates of biomass typically have a higher variance, but may be less biased, and improve with research investment. In all cases, the relative magnitude of change from year to year will be known with more precision than the absolute value.

"IN THE ABSENCE OF PRECISE INFORMATION, JUDGMENTALLY PRUDENT TARGETS MAY NEED TO BE ESTABLISHED"

Anon 1991

To date, the focus has been on quantifying the uncertainty associated with estimates of stock status. Reference Points are frequently viewed as point values. The problem is likely to be most severe when the status and target values are estimated using different models and/or data. Ultimately, fishery scientists will need to expand their approaches to take into account the conjoint uncertainty in estimates of stock status and of reference points and, if possible, interactions in the estimation process.

3.1.5 Implementation uncertainty

Implementation error is usually regarded as falling outside the scientific component of fisheries management and although very much in evidence, has been little studied (O'Boyle 1993). It is largely the failure to control exploitation by whatever MCS (monitoring, control and surveillance) measures have been adopted. The reasons are many and interrelated, for example, poor surveillance and enforcement, lack of concern by the judiciary when cases are heard, failure of participants to support measures due to lack of opportunity for input during their development or simply disagreement with the measures enforced.

In management systems which a rebased primarily on advice from biological assessments, failure to incorporate, or incorrect incorporation of non-biological information, also contributes to implementation error. These problems may frequently be known to the managers and their technical advisers, but it may be impossible to quantify the uncertainty, except in retrospect.

A workshop to review management of groundfish stocks on the Scotian Shelf off eastern Canada from 1977 to 1993 concluded that implementation error was the primary cause of the failure to conserve stocks (Angel *et al.* 1994). The workshop noted that "In sum, the tactical approach chosen to control fishing mortality generated illegal behaviour which was not curbed by the available enforcement regime."

The institutional aspects of implementation error will be considered in greater detail in Section 4.

3.2 ESTIMATING UNCERTAINTY AND RISK

The most common approach to estimating the effect of variability on the outputs of models which use a variety of input parameters is a 'propagation of errors' simulation in which the input parameters are allowed to vary and the variability of the model output is described in probabilistic terms. The two most commonly used methodological approaches to the propagation of errors are Monte Carlo simulations, and resampling techniques such as 'bootstrapping'. Monte Carlo simulation is the replication of a procedure with input data or parameters drawn randomly from a parametric distribution (sometimes referred to as parametric bootstrapping). Resampling techniques involve the replication of a procedure using input data obtained by sampling from empirical observations (Manly 1991). Smith *et al.* (1993) provide an overview of 'bootstrapping' approaches to identifying and quantifying uncertainties associated with reference points. These procedures provide estimates of the probability density function (PDF) for the outputs, which may be displayed in several ways (Fig. 12)

Monte Carlo simulation is statistically more demanding than 'bootstrapping' in that it requires that the error distribution of the input parameters be known. Rice (1993) suggests that nonparametric density estimation methods (Silverman 1986) may also be applicable, partioularly in instances where there is doubt as to the extent to which the models misspecify the functional relationships between pairs of historical variables, e.g. spawning stock biomass and recruitment.

Information on variability in model input has been used to assess risk in two ways. First, it has been used to simulate the response of the population to various harvesting strategies with the aim of comparing long-term management approaches (e.g. Ruppert *et al.* 1985). Second, it has been used to estimate the probability of being at or close to a target point in a given year, and in that light, the probability of exceeding some undesirable limit or threshold (e.g. Mohn 1993). The latter use has been the main recent focus of attention in fisheries management.

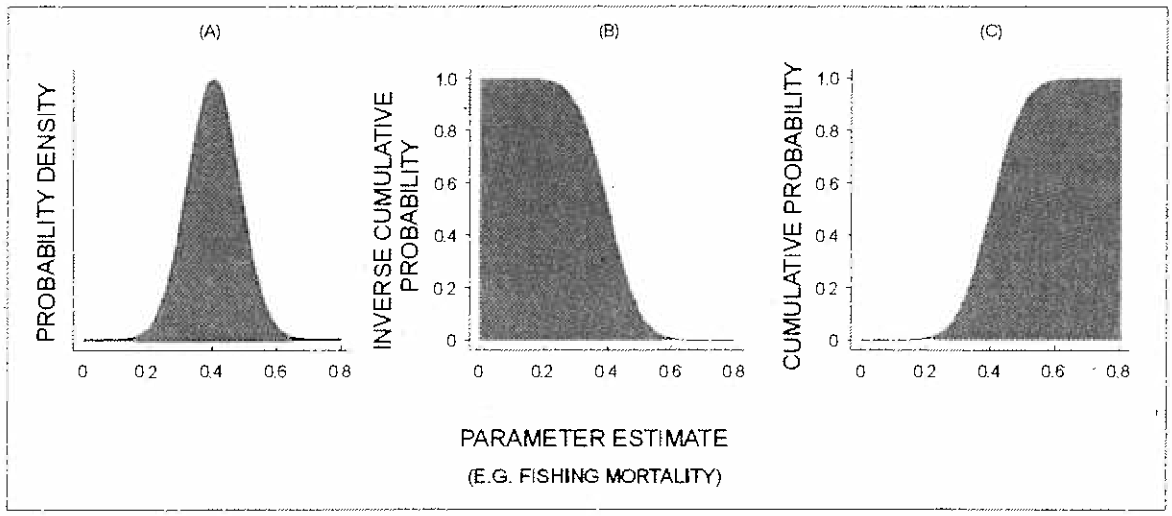

Figure 12: Three ways of displaying the information on uncertainty using a probability distribution: (a) the Probability Density Function is most appropriate when the probability of hitting a target is the primary concern; (b, c) the Survivor Probability and Cumulative Probability Distributions are most appropriate when avoidance of a ceiling and floor LRP respectively are the primary concern.

To advise on risk, it is necessary to go beyond the probability of occurrence of particular events, and to quantify the degree to which the events are undesirable; that is, the cost or impact of the event. This requires that the relationship between specific outcomes and the consequent loss of benefits be specified (Anon. 1992). Increasing yield is accompanied by reduced biomass in fisheries, and has associated risks of variability and stock collapse. The simplest risk issue is usually, "How much catch can be taken without reducing the stock to the point where it may fluctuate unacceptably, and/or be unable to replenish itself below 10% (or even higher)". There are as many other questions regarding risk, as there are management objectives, or combinations of management objectives. As the quantification of risk and the application of decision theory based on risks becomes more formally incorporated into fisheries management, the concept will inevitably be applied to more complex social and economic issues.

At present, one of the main impediments to the evaluation and use of risk in the provision of management advice has been the formal definition of 'safe' (acceptable risk). Clearly this should be fishery specific. However, some precautionary generalisations are desirable. For example, although risk is included in the conceptual basis of management of New Zealand Fisheries it has not been formally defined. Francis (1993) proposes a definition in which the level of harvesting should be considered safe if it maintains the spawning stock biomass above 20% of the virgin stock level at least 90% of the time. Definitions of acceptable risk will generally be stated in similar terms has been discussed so far, that levels of risk below 10% (or even higher) will be justified by the available data.

Two categories of risk can be identified: the risk of not achieving a TRP, and the risk of exceeding an LRP (Mace 1994). The costs of not achieving a TRP are usually defined in terms of the short-term reduction or interruption of the flow of benefits to participants in the fishery and consumers, even though this may result in a net gain in the long term. This may also be partly offset by a rise in market prices resulting from a reduction in supply. For species with low natural mortality, most of the yield foregone in one year should be available the following year. For species with high natural mortality, the unharvested biomass will make a contribution through predation to other, possibly commercially valuable, components of the food web.

The costs of exceeding an LRP are much more serious, and have been discussed earlier, and range from stock decline to collapse, impacts on associated species and ecosystem destabilization, long term loss of earnings, including intergenerational impacts. If the conditions for safe harvesting can only be met by expenditures on research, management and enforcement that exceed the net rent likely to be provided by the resource, other less costly approaches to management, such as intermittent harvesting (pulse fishing or culling) under close supervision, or rotation of fishing among fishing areas should be considered.

Consistent with the two categories of risk described above are two types of management error which may arise due to uncertainty about the current status of the stock (Rosenberg and Restrepo 1995). The terms Type I and Type II error are adopted from standard statistical usage. Type I error occurs when the scientist erroneously advises the manager that overfishing is taking place. Type II error occurs when the scientist erroneously concludes that the stock is underfished. As indicated above, the consequences of a bias towards Type II errors are more serious than those of Type I error.

A management framework that invokes preset actions when one or more (whether qualitative or quantitative) LRPs have been exceeded is in effect a precautionary approach.

One context for this approach is analogous to a thermostat (Die and Caddy in press): the fishery operating under strict access control, is not subject to a catch target or limitation, but once one, or a series of LRPs, show evidence of overexploitation, a pre-established management action is triggered which reduces the fleet effort. This is maintained or reinforced until the resource recovers to a pre-agreed level, when exploitation rate may be increased slightly.

There can also be risks due to unforseen biological interactions which are beyond the scope of management control, but nonetheless affect the fishery. For example, the invasion of Norwegian waters by harp seals which in 1987 and 1988 were estimated to have consumed 325,000 $\pm$ 75,000 t of cod and saithe, produced a sudden decline in three year classes (Ugland *et al.* 1993). Such environmental and biological events, even though not necessarily caused by fishing, will need to be predicted where possible, monitored, and taken into account in relation to any biomass-based LRP.

3.3 ADVISING MANAGERS ON UNCERTAINTY AND RISK

There are no standard methods for communicating uncertainty and risk to fishery decision-makers (Rosenberg and Restrepo in press). Basic statistics provide a variety of means of communicating variability which can be used to indicate the uncertainty associated with a particular estimate, or the probability of occurrence of an undesirable event. Probability density functions are most frequently used to communicate the variability associated with a mean when the observations are normally distributed. For fishery management purposes, cumulative probability or cumulative survivor distributions may be more useful when the aim is to estimate the probability of avoiding and upper or lower limit (Fig. 12). Nonparametric methods based on percentiles or quartiles, and the use of box plots may be more appropriate when distributions are skewed.

The method for communicating uncertainty and risk to managers will depend on their level of technical sophistication. In most developing country situations, it will be important to relate the uncertainty to characteristics of the fishery which are well known, e.g. an amount of catch, rather than an F level. A simple graphical presentation was used for flyingfish in the eastern Caribbean as a means of communicating trends in yield, catch rates, their variability and the increased probability of undesirable events with increasing F (Fig. 13).

For many valuable stocks, attempts to quantify uncertainty and risk will be justified. For the northern cod fishery of Newfoundland and Labrador, Restrepo *et al.* (1992) used the Monte Carlo approach to investigate risks associated with quota management. Using 1000 simulation runs they found that, if at the end of 1990 we wish to achieve $F_{1991} = F_{1990}$, quota estimates for 1991 could be in the range 170,000-260,000 when all known elements of uncertainty were introduced into the model. Such a simulation provides the basis for evaluating of the risk of any quota. Thus they noted that increasing the quota from 210,000t by 5000t, doubles the risk of exceeding F_{1990}. (Incidentally, there is a considerable interest in revisiting this particular risk evaluation following the collapse and closure of this cod fishery over the last few years).

Hilborn and Peterman, 1995, recommended that scientists avoid simply presenting a range of values. They state that advice should deal with alternative consequences of alternative hypotheses as well as alternative actions. They suggest that instead of saying that "the sustainable yield may be between 5 and 100 mt, with our best guess being 75 mt", more fully informed discussions would result if the advice were presented in the form that "there is a 40% chance of being able to take 50 mt/yr for the next 20 years, a 50% chance of being able to take 75 mt/yr and a 10% chance of being able to take 100 mt/yr."

The current focus on the quantification of uncertainty and risk requires a considerable amount of information and expertise. It is important for fishery advisers and managers to note that subjective views of risk based on the experience of participants, can also be applied in management. Most informed fishers and managers would agree that there is an unacceptably high risk that uncontrolled fishing on grouper spawning aggregations will lead to extinction of the aggregation, and that access to aggregations should be controlled. No assessment of the particular stock is required for management action. The data to estimate an optimal escapement may not be available, nor, due to discounting, may it be perceived as economically feasible to acquire and analyse the data, but sustainability can be achieved by limiting access.

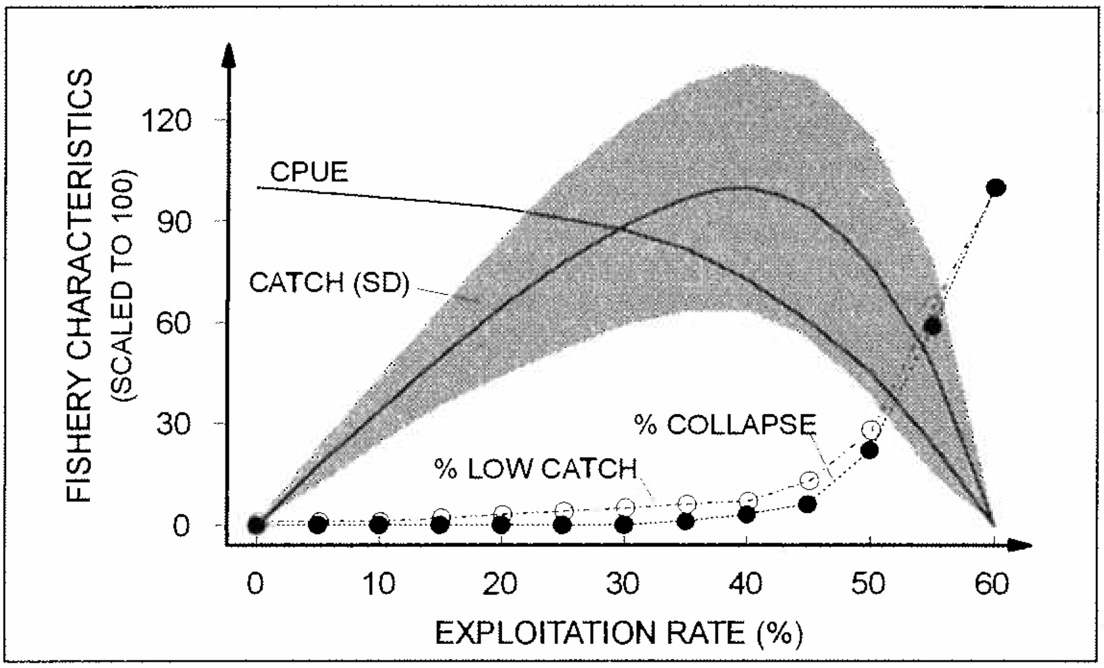

Figure 13: A summary of fishery characteristics based on a stock-recruitment simulation for eastern Caribbean flyingfish, indicating the risk of undesirable occurrences associated with increasing levels of exploitation. These include variability in catch, and by inference, catch rate, and probability of years with 'critically low catch' defined as annual catch < 30% of current average catch, and 'collapse', defined as critically low catch for four or more consecutive years (Mahon 1989).

4. THE PRACTICAL APPLICATION OF REFERENCE POINTS IN FISHERY MANAGEMENT

4.1 INCORPORATING REFERENCE POINTS IN MANAGEMENT

4.1.1 TRPs and LRPs as 'Sets of Rules'

A decision rule which, as defined by the TCPA, "specifies how preagreed management actions will respond to estimated or perceived states of nature" (FAO Govt. of Sweden 1995) is fundamental to the effective application of reference points, particularly Limit Reference Points.

There are two substantially different approaches to the application of LRPs. The first is the simpler. Fishing is unregulated until the LRP is reached, then it is stopped (e.g. Hall *et al.* 1988, Quinn *et al.* 1990). When the ecosystem recovers, fishing can begin again. This is also referred to as pulse fishing. A spatial version is the rotation of fishing effort through a series of fishing subareas in which fishing is either 'on' or 'off'. The pulse fishing approach has significant implications for economic outputs of the fisheries, because production may be erratic, except in the case of spatial rotation. Furthermore, unless the 'on' switch is activated only at significantly higher levels of biomass than the 'off' switch, the fishery will hover in the vicinity of the LRP.

Alternatively, the LRP can be used as an 'undesirable event' whose risk of occurrence should be minimized by setting targets which are well clear of the limit. If there is an estimate of the variability associated with the reference variable used to set the LRP, then the target value for the reference variable can be defined as the value at which there is an acceptably small probability that the LRP will be reached. Used in this way, the LRP is an emergency control point, with a low (and known) probability of being invoked, rather than a means of ongoing control. An example of this situation was shown in Figure 9 using F_{msy} as the limit to be avoided. The relationship between target F and limit F_{msy}, in the simplest context, is defined by the variability of the F estimate. With this latter approach there is no need for an arbitrary conservative value for target fishing mortality such as $2/3F_{msy}$, although of course, the value for the limiting probability (0.1, 0.02) may be arbitrarily chosen.

In establishing the decision rule or control law for implementation of an LRP, it may be most effective to reduce F to a level that is inversely proportional to the extent to which the TRP has been exceeded.

In addition to TRPs defined so as to avoid LRPs, there may be other desirable attributes of the fishery which can be targeted within the constraints of the LRP. Thus any well managed fishery will use a combination of TRPs and LRPs. In well studied fisheries with good historical data it is likely that there will be at least one model based TRP, and possibly several LRPs; some model-based, others empirical. For little studied fisheries, it may be necessary to adopt TRPs and LRPs, which will be simple criteria based on experience derived from other similar fisheries or from generalisations about many fisheries, such as the %SPR values suggested by Mace (1994) or Hall *et al.* (1988).

Reference points which are qualitative or semi-quantitative in nature can also be incorporated within a "Set of Rules" which determine how the fishery is to be managed. These may specify the management response to (e.g.), a high discard rate of protected species. Again, if one or more of these rules are broken, a pre-negotiated management response should automatically be initiated. One example might be the temporary ban on fishing by a given fleet in a prespecified area when discards or by-catch limits have been exceeded. Another example of a trigger might be when the proportion of immature fish in the catch exceeds a preset percentage.

The TRPs and LRPs can be incorporated into a set of management criteria (e.g. Table 5). The development of such sets of rules will be most effective if it is based on a sequence of questions and actions such as is shown in Figure 14. If one or more of the latter criteria are infringed, a preset management response is triggered. One such set of criteria has apparently been developed for the Eastern Bering Sea/Gulf of Alaska groundfish fishery and includes: a threshold biomass set at 20% of the virgin stock biomass; a maximum fishing mortality rate set at 30% of the relative SSB/R; and a maximum fishing mortality rate set at 80% of the M value for the species concerned.

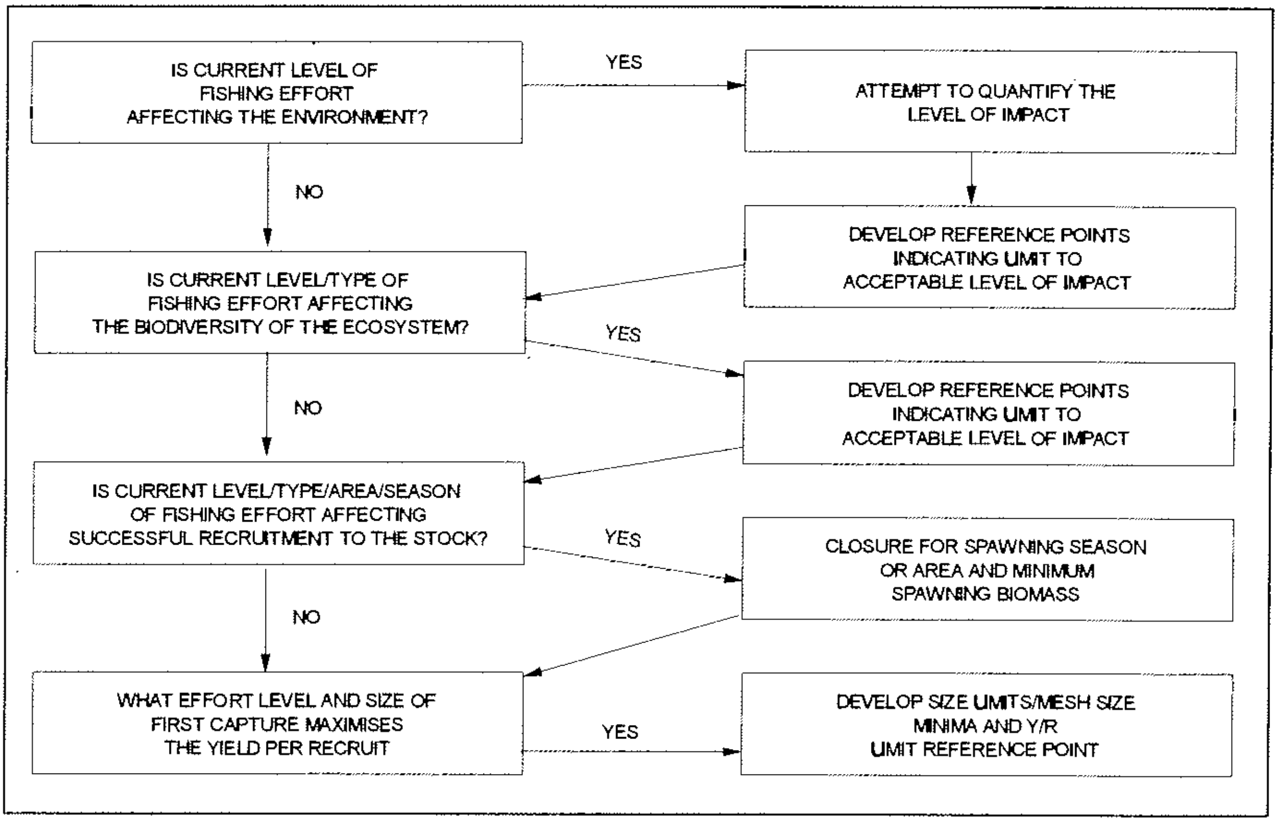

Figure 14. **Sequencing of fishery management questions with a priority on sustainability gives habitat and ecosystem conservation highest priority, puts resource conservation next, and ends with issues of yield optimisation.**

For short-lived species, e.g. some squid or anchovy resources, for which stock size may only become known during the fishing season, a set of rules may have to be invoked in sequence during the same season (Caddy 1994, Basson and Beddington 1993, Butterworth *et al.* 1993). For squid, effort (number of licences) or TAC may be set at the beginning of the season to aim for a target level of 'proportional escapement to spawning', an agreed percentage of that surviving for the same number of recruits with no fishing, which would provide a safe level of absolute escapement, provided that recruitment is in the normal range. The artisanal effort can be fine-tuned later in the season through a variable date of closure of the fishery, if real-time measures of accumulated catches and/or surveys of abundance, indicate that either changes in fishing patterns or very low recruitment may result in escapement to spawning dropping below the preset threshold level.

4.1.2 Updating Reference Points and establishing the current status of the fishery relative to the reference point chosen

The means of verification (MOV) and objectively verifiable indicators (OVIs) for establishing the current status of the fishery must be clearly specified. The MOV will generally be based on the same models and methods used to derive the reference points. The frequency with which the status of a fishery must be checked will be dependent on the life history of the species. For most stocks in which the age range of fish in the catch is 3-10 years, an annual time-frame will be appropriate. For long-lived species such as whales, redfish in the North Atlantic and orange roughy in the area of Australia and New Zealand, where the mean age of exploited individuals may be > 10 or even 20 years, it should only be necessary to review stock status at intervals of several years. In contrast, for short-lived, or annual species, such as small pelagic fishes, or squids, real-time evaluation of stock status may be required (Basson and Beddington 1993, Butterworth *et al.* 1993).

The review and revision of reference points may be desirable or necessary for various reasons:

- Management objectives may change (e.g. the need to conserve reef fish for tourism instead of for commercial fishing only, as formerly);
- A more precautionary approach may be needed, judged from the results of management or stock size trends.
- There may be conceptual advances regarding appropriate management of resources (e.g. inclusion of ecosystem criteria, or measures of ecosystem 'health');
- There may be methodological improvements relating to existing Reference Points (e.g. maximum likelihood estimators of S-R relationships) which change our perception of the RP being used; and
- New data may become available for incorporation (e.g. more data points for a S-R relationship);

The first three require renegotiation of the "Set of rules" for management. The fourth requires renegotiation of the MOV and possibly the OVI, the last is automatic whenever new data become available.

The growing emphasis on non-harvest uses of the resource may be one reason for modifying the management objectives of fishing. This is increasing in frequency as a result of the interests of constituencies outside the fishery sector. For multi-user resources there is a considerable danger of frequent changes in objectives, which can lead to time-consuming negotiations, and in the event of disagreement between the parties concerned, a management vacuum and the danger of overexploitation. If negotiations are protracted, management should provide for the use of a precautionary approach in the interim.

To know where the stock is in relation to a Reference Point requires regular monitoring of the relevant reference variables (OVIs) and also a realistic appreciation of the precision with which these variables can be estimated. The current value of the chosen reference variable(s), such as the fishing mortality rate, stock biomass, and yield (Fig. 3) can be referred to as F_{now}, B_{now}, and Y_{now}. These estimates should be accompanied by at least a rough estimate of the likely magnitude and direction of the error of estimation.

Systems for collecting and storing fishery information from all participants and carrying out fisheries surveys and research, are integral parts of establishing whether management targets are being met, and of evaluating the effectiveness and impact of management measures. As a condition for receiving a commercial fishing licence, fishermen should be obliged to provide accurate information on their location, type and time of catches, and fishing effort. This information can be gathered through log book systems, by port interviews with fishery officers, by on-board observers, radio reporting and at-sea inspection. and possibly in the future, through black box monitoring via satellite of the position of fishing vessels and the operation of their mechanical equipment. Likely biases, errors and misreporting of catches will need to be estimated under a precautionary management framework.

4.1.3 Components of a Reference Point-based management system

Management actions for a new fishery should ideally follow the sequence:

a. Exploratory fishing and research;
b. Provision for the routine collection of statistics and samples;
c. The assessment of the state of the resource;
e. The formulation of management objectives and reference points;
f. The negotiation of effort or catch allocations by countries and fleets;
g. The framing of (national or international) management agreements and their approval by governments or administrations;
h. The translation of national legislation into fisheries regulations for the resource;
i. International or coordinated national provisions for control and surveillance of all participants;
j. The setting of annual targets for the fishery;
k. The monitoring of the stock, the fishery, and the enforcement of fishery regulations;

Some items in the above sequence (e.g. e, f, and g) should be under regular review, but renegotiations to revise them will be difficult to achieve for a multi-participatory fishery. Others (e.g. b, h and i) will need to be reviewed at intervals of several years as conditions change, and items a, c, j, and k will need to be reviewed yearly if benefit from a resource is to be optimal, and the probabilities of overshooting the chosen TRP, or entering a dangerous zone as indicated by a LRP, are to be minimized.

There will rarely be new fisheries that do not affect existing marine harvests, where the sequence a-k above can be applied uninfluenced by an existing or associated fishery. New objectives in a fishery are almost always superimposed on or replace old ones. Thus the relative emphasis on the elements in the above sequence may vary depending on what is already in place.

Regardless of what sequence of actions is considered to be most appropriate for the fishery in question, the process should be documented in a way which will facilitate input and review by all interested parties. The macro-decisions should also be addressed within a framework, such as shown in Fig. 15, which requires that management decisions be taken by agreement even when there is a need to acquire more information for long-term management.

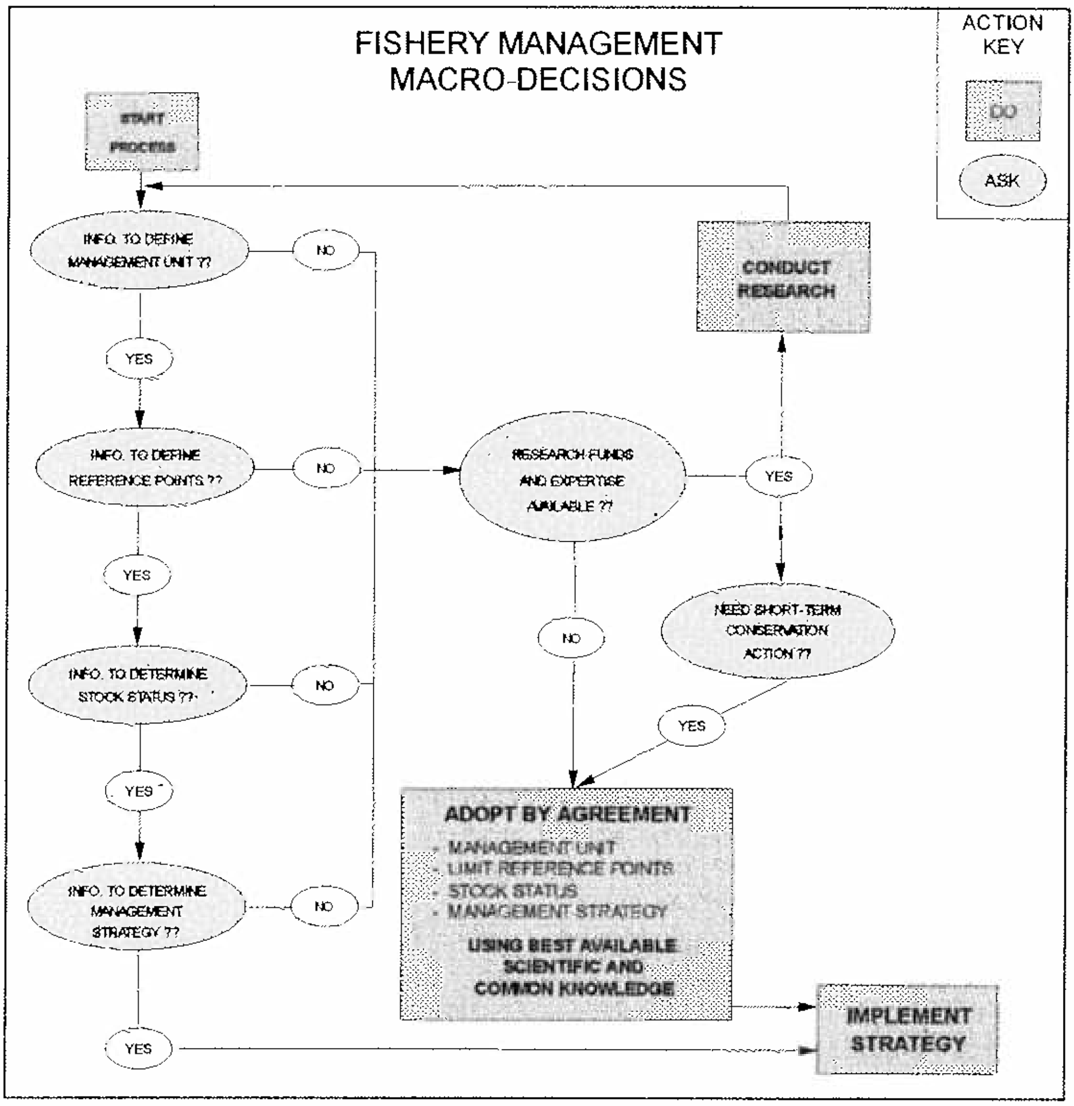

Figure 15. **A macro-decision sequence for fishery management which emphasises the need for agreement, even when the fullest desirable information may not yet be available. Lack of information may be a short-term condition, while data collection and analysis is in progress, or a long-term condition due to lack of funds and expertise. In either case management must proceed using the best available knowledge.**

As specified under the 1982 Convention, the above activities need to be carried out in cooperation by all parties, with exchange and pooling of data as preconditions for any scientific management of a shared, straddling or highly migratory stock.

> *COASTAL STATES "...SHALL SEEK, EITHER DIRECTLY OR THROUGH APPROPRIATE SUBREGIONAL OR REGIONAL ORGANIZATIONS, TO AGREE UPON THE MEASURES NECESSARY TO CO-ORDINATE AND ENSURE THE CONSERVATION AND DEVELOPMENT OF [SHARED] STOCKS..."*
>
> The 1982 Convention on the Law of the Sea

4.1.4 The role of scientific advice in Reference Point-based management

Traditionally, the assessment and management of fish stocks has been a two-tier process: scientists present assessments in the form of one or more catch or fishing mortality levels aimed at maintaining or rebuilding stocks, and the managers (Commissioners or representatives of the Ministers of Fisheries of the countries concerned) make the final decisions on the level of harvesting to be followed. While fishery scientists are best qualified to provide quantitative advice on the risk associated with any management strategy, they cannot be expected to advise on the acceptability of a particular risk (Hilborn *et al.* 1993); similarly, managers should have a clear understanding of the risks of particular management actions.

In some fishery management systems scientists have noted that if they adopt the statistically correct procedure of providing a range of possible values for any TRP, the managers usually select a value towards the upper, more risk-prone, level of the range. This generalization, and the high degree of uncertainty inherent in the assessment process, has often led to scientific advice being presented to decision-makers as one, or several, explicit values, without reference to the uncertainty of the estimates. This practice of providing estimates without reference to their uncertainty means that scientists have preempted the responsibility of managers for deciding upon an acceptable level of risk. It has thus given management a false sense of the precision of the assessment process, and underplayed the risks of stock decline due to uncertainty in the advice. It has probably also reduced the imperative for managers and decision makers to confront uncertainty, and to take the necessary steps to address it with industry, participants and fishers.

The role of the stock assessment expert in the fishery management system should be to provide options based on the best available information, with associated estimates of uncertainty, and where possible risk. They should avoid 'second guessing' the management process, or adjusting their advice to compensate for perceived inadequacies in management.

4.1.5 The use of Reference Points with different management strategies

The choice of a control system or management strategy for fishery management will depend largely upon the set of reference points selected. There are usually several ways, however, of regulating the fishery towards a desired Reference Point (Beddington and Rettig 1984). The open access nature of most marine fisheries has been the main cause of stock depletion, loss of biodiversity and loss of economic earnings, which together have adversely impacted fishing communities.

Management measures may be envisaged as either, a) Input controls, such as limitations on size and fishing power of vessels and gear, restrictions on credit, limited licence or limited access schemes, or b) Output controls, such as restrictions on the characteristics of the catch (size, species composition), the total amount of fish harvested annually by the fleet (Total Allowable Catches), by individual vessels (Individual Quota Schemes), or controls by taxes on landings. In some managements systems, individual vessel or fishermen's quotas may be transferable (ITQs) through the creation of a market for access rights. As for landing taxes this market in rights may be used by management or the State to extract revenue from the fishery.

Three distinct management strategies have been proposed that explicitly or implicitly use target reference points: constant catch, constant effort and constant escapement. These strategies can be combined with threshold values to drastically reduce exploitation when stocks are believed to be in danger of overexploitation (Fig. 16).

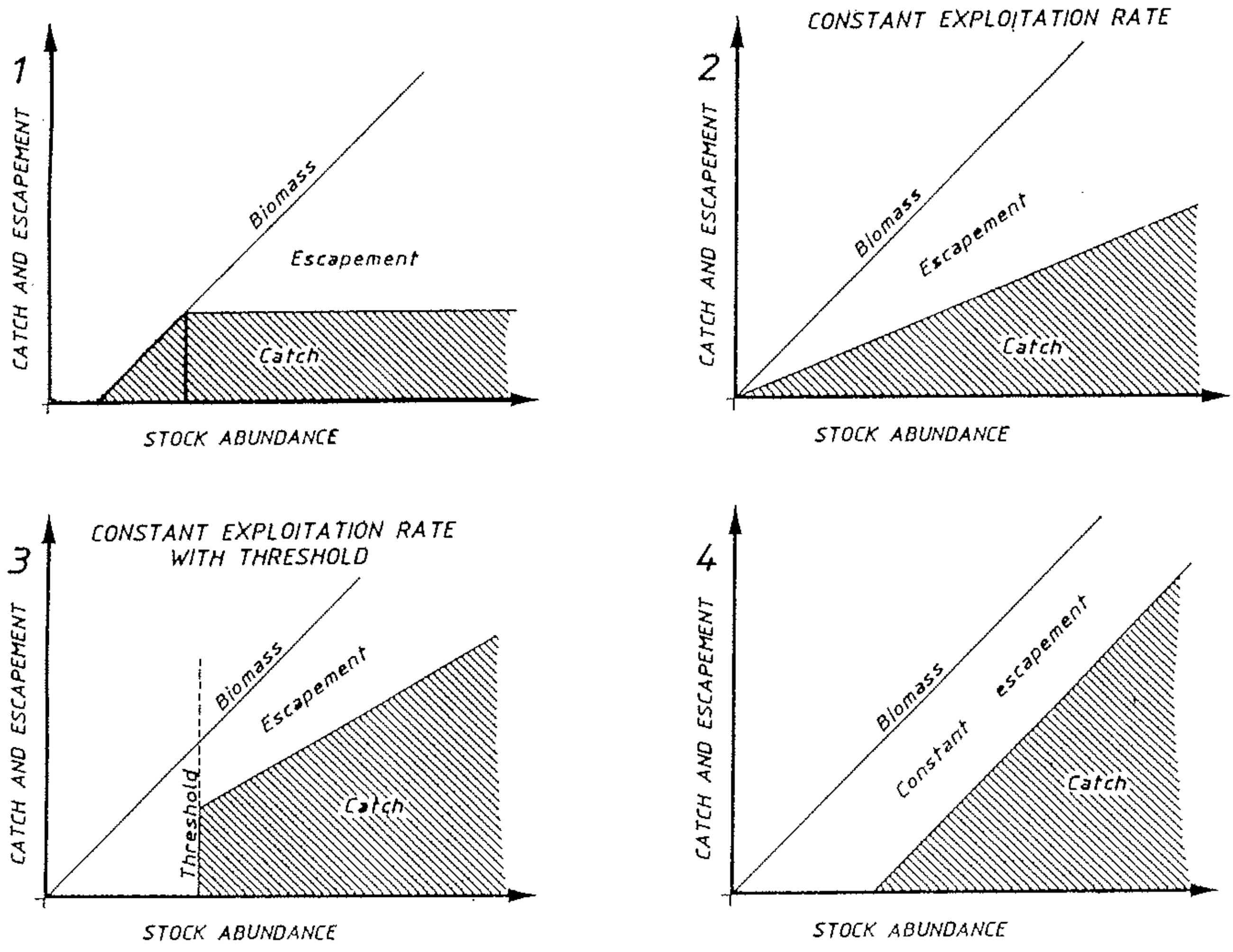

Figure 16: Showing the idealized relationship between catch and escapement under wide variations of stock abundance for four management strategies: 1) a constant annual quota with threshold at low abundance when fishing is not allowed; 2) management under a constant exploitation rate; 3) again, a constant effort control scenario with a threshold if natural variation results in very low stock sizes, 4) A constant escapement strategy as attempted for some salmonid and squid stocks.

Catch quotas may be used to achieve a TRP and may be variable or constant. For stocks with wide fluctuations in abundance (as for many pelagic resources), a constant catch quota referred to here as MCY will result in constantly varying rates of exploitation (Sissenwine 1978). Unless it is set at a very low level, a significant probability of overexploitation always exists in low abundance years (Fig. 17). If information is scarce or uncertain, then a very low, fixed quota, using TRP criteria developed with reference to a preset probability of F_{msy} being exceeded, could be followed as discussed above. One alternative here could be to definitively allocate this low MCY as ITQs, agreeing on supplementary and temporary allocations only in very favourable years.

Allocating a low MCY could also be useful in situations where maintaining a moderately high stock size is essential, as for stocks also important to sports fishing, tourism, subsistence fishermen, or for straddling stocks which provide a livelihood to communities of the rural poor. Here management could adopt a constant, low, annual quota and a cutoff point dictated by one or a series of LRPs which measure when stock size is critical. At that point the fishery should be temporarily interrupted until unambiguous signs of recovery are seen (Fig. 16). Management with such a cutoff point was successfully applied to herring stocks on the West Coast of Canada (which are highly vulnerable to overfishing or pre-spawning congregations) following a moratorium for stock rebuilding after earlier depletion by an open access fishery.

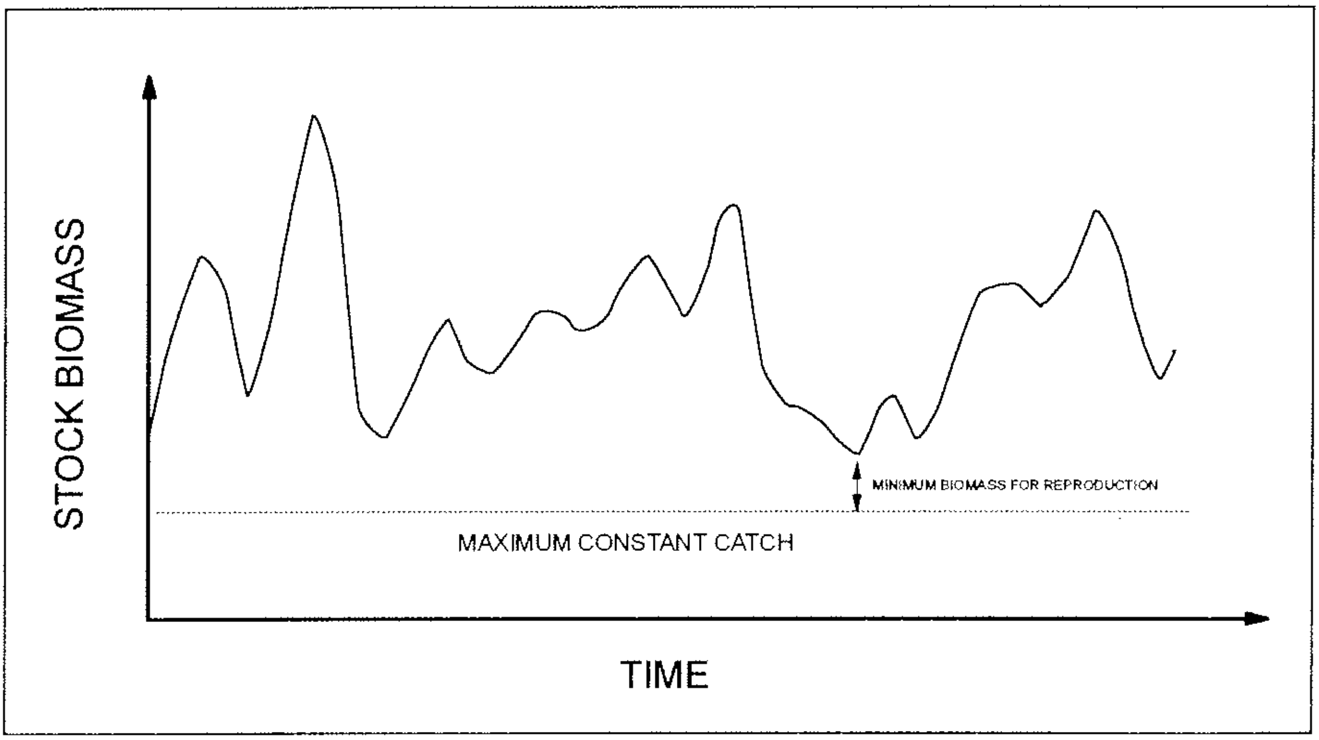

Figure 17: **Illustration of the constant catch fishery management strategy for a stock which fluctuates. Constant catch must leave enough spawning stock biomass at the lowest stock biomass level.**

Variable quotas tend to lag behind the actual variations in recruitment (and still later, stock size) by one or several years. Particularly as good year classes are being fished up, a quota that would have corresponded to $F_{0.1}$ or even lower levels when the peak year class was entering the fishery, now corresponds to F_{msy} or even higher levels. There is a marked reluctance by industry to accept a sudden drop in supply under these circumstances. In the North Atlantic, management to date has been largely based on TACs, but there is growing evidence that advice on desirable catch levels has become less reliable due to unrecorded catch and high discards (FAO 1992a). The TAC advised by scientists, that TAC finally agreed after political decision making, and the actual catches taken, have tended to increase in sequence (Angel *et al.* 1993).

One of the mandatory requirements for quota management under open access, even at apparently reasonable F levels such as $F_{0.1}$, is the need to ensure accurate, real-time estimates of catch, age composition and standardized fishing effort. The fact that many conservatively-targeted quota management systems have failed, even for proprietary resources of EEZs, should prompt a re-examination of all facets of the management procedure. This review should begin from considerations of statistical validity of the sampling scheme, the possibility of misreporting, the appropriate population models used, and should involve sensitivity analysis of the parameter values entered in them. The degree to which quotas chosen correspond to the projected fishing mortality rate has been questioned for some developed country fisheries. Even more serious in their effect is the degree to which subsequent catches can be maintained within the quotas allocated, or whether politico-economic considerations will be allowed to 'stretch' the quotas proposed by fishery scientists.

A number of authors have shown the advantages of fixing the level of fishing effort as opposed to fixing catch quotas (e.g. Hannesson 1993) (Fig. 16). Beddington and May (1977) noted that with a constant catch management strategy, environmental perturbations will cause more serious departures from equilibrium conditions than when a constant effort strategy is followed. This was also the conclusion of Reeves (1974), who found by simulation, that under recruitment variation, an effort limit produces higher catch rates than a fixed catch quota, even if the latter corresponds to the same Reference Point defined in terms of fishing effort.

A constant effort strategy requires that fishing effort be controlled to that corresponding to a target F value; usually by limited entry. Early criticisms of this approach were that increases in catchability due to learning by skippers and due to technological improvements to boats and gear, both lead to 'creeping' increases in fleet fishing power. Another disadvantage, seen in the early optimistic days of quota control, was that under effort control, catches would vary more from year to year than with TAC management, but we should note that this is still more desirable than stock collapse. Other more valid objections relate to pelagic stocks such as herring where vulnerability to fishing goes up at low stock sizes, so that the fishery can enter an unstable area at low stock sizes unless some limiting LRP is applied, as for the constant escapement strategy mentioned above.

The objections to effort control as a management procedure need to be reassessed in the light of recent failures of quota control. Effort control measures have the following virtue, especially for poorly documented straddling stocks: they provide a more stable rate of exploitation and do not require real-time enumeration of all catches. Thus there is less need for drastic year-to-year renegotiation of management targets, than is the case under quota control.

A constant escapement or spawning biomass-based policy has generally been shown to provide the highest sustainable yields. Salmon management has classically been based on attempting to achieve a minimum escapement to spawning, and many such fisheries in western North America aim for fixed escapement objectives. This type of management approach has also been used for squid fishery management in the south Atlantic within exclusive management control. Such a management approach is compatible with the spawning biomass Reference Points described earlier, but is likely to require too high a level of information input, and real time monitoring and control, for most of the open sea resources considered here.

4.2 INSTITUTIONAL REQUIREMENTS

In many instances, despite the availability of useful and safe reference points, management has failed to achieve sustainability owing to problems with the institutional arrangements for reviewing, and/or modifying advice in the context of other considerations. Although many of these institutional considerations are not as well quantified as the assessment advice, they can nonetheless be formally stated and accommodated in deriving the final set of TRPs and LRPs from which management will be implemented.

> *"... FISHERIES DEVELOPMENT PROJECTS NEED TO EMPHASIZE ORGANIZATIONAL RATHER THAN TECHNICAL FACTORS IN PROMOTING SOCIALLY AND BIOLOGICALLY SUSTAINABLE DEVELOPMENT"*
> Bailey and Jentoft 1990

The mechanism by which the above process is achieved must have an institutional framework. It must include a means of consultation with the stakeholders and other interested parties, and a decision-making forum. However, once an approach has been adopted and a set of rules agreed upon, *ad hoc* short-term decision-making should be kept to a minimum. Short-term expediency should not, except in extreme circumstances, be allowed to interfere with the long-term management objectives which have been established by consensus, within the framework of a medium to long-term consensus fisheries management plan. The routine management and surveillance capability, and the statistical sampling needed to generate objective ongoing information on stock status, must operate largely autonomously from socio-economic pressures. As previously stressed, the response to an infringement of an LRP must also be automatic. Once the consensus of industry has been achieved, implementation of management measures agreed to should be immune, to the fullest extent possible, from 'interference' by the resource users and their representatives.

A transition from a largely 'biological approach' to a 'bioeconomic approach' is desirable, and will draw in fishery system components formerly considered extrinsic to the technical advisory process (e.g., fishery enforcement, fishery associations, the private sector, etc.) to the arena of technical analysis (Anderson 1987). In section 2 we referred to some analytical approaches to reconciling inputs from various sources. This inevitably changes the focus from '... open-access equilibrium and a narrowly defined efficiency point, to a comparison of a regulated equilibrium and a more broadly defined efficiency point' (Anderson 1987).

A review of several examples of how, in practice, information flows, advice is structured, and decisions are taken in fishery management systems, suggests that there has been a 'Standard Management Format' for fisheries bodies but that the current trend is away from that format (Appendix III). In the Standard Format there are at least two bodies arranged in a hierarchical fashion. One is a group of resource scientists developing technical advice and providing it, possibly via a technical review body, to a dominant Management Authority or Body (e.g. the Minister or a group of senior civil servants) which draws its authority to act from the State or States involved which have set up the management system. This Authority negotiates with the fishing industry and decides if and how the resource shares advised by the technical body should be modified in the light of current requirements of the stakeholders in the fishery. It usually has the power to overturn advice from the resource advisors, based on perceived, often short-term considerations, in which the current well-being of the stockholders plays a major role.

> *THE INABILITY TO MEET THE CONSERVATION OBJECTIVES, IN PART DUE TO SHORT TERM TRADE-OFFS IN SUPPORT OF SOCIAL AND ECONOMIC OBJECTIVES, HAS IN THE LONGER TERM UNDERMINED THE SUSTAINABILITY OF THE COMMERCIAL FISHERY AND THE FISHING COMMUNITIES.*
>
> Angel *et al.* 1994

With the Standard Management Format, the resource assessment group operates under terms of reference provided by the dominant management body. These, if formulated, are usually defined in terms of one, or several, alternative targets for exploitation. Under this format, decisions are often left to the resource assessment group as to:

- The type and quality of relevant or admissible data,
- The mathematical models to use,
- The mode of fitting the models and the statistical limits acceptable,
- The interpretation of the current status of the stock and its future potential for replenishment.

The assessment group may be requested to suggest management targets and new target reference points for the approval of the dominant management body. Broad issues such as ecological considerations extrinsic to the (usually single) species being assessed may be addressed by this group, but until recently have generally been considered outside the formal management advisory process. This vacuum of concern is currently becoming a preoccupation of society at large, outside the fisheries sector.

The Dominant Management Body is appointed by the State or States, and its member(s) often have a different mix of professional competence from the assessment group. They are usually government employees; often senior civil servants, economists, and directors of resource institutes. They receive inputs from representatives of fishers and the fishing industry, often via a formal consultative procedure. Very occasionally, non-exploitative interests are represented, e.g. fish consumers, academics, and conservationists. Given that this group has the duty of responding to pressures from fishers and the fishing industry, who inevitably have legitimate concerns with negative socio-economic impacts of effort restrictions on coastal communities, it is influenced by the desire to at least maintain allocations for fishing at current levels, and are likely to resist cuts in exploitation rate.

4.2.1 Checks and balances from outside the fishery sector

An argument can be made, which is consistent with the ideas presented in this paper, that the Standard Format is an appropriate one at low to moderate levels of fishing, but is less effective in dealing with situations where formal limits to exploitation need to be erected and restrictions or reductions in the level of exploitation justified.

Other management frameworks may be required to ensure that day-to-day decisions on management by the management body which has been given authority, are constrained by a "Management Plan or Procedure" or by a Fishery Convention (see for example that of CCAMLR). These documents should provide criteria for allowable action, but usually lack an independent review body that sets up LRPs and ensures that they are not infringed. Such a hypothetical review body is referred to here as the 'Committee for Limits and Standards' (CLS). The CLS would not replace the Standard Fisheries Management Authority (SFMA) and its resource assessment advisory group, but would provide a review mechanism, with experts from outside the government organization responsible for fisheries, to ensure that the overall limits for continued resource productivity are not overstepped (Table 6). Such a mechanism has recently been instituted in Atlantic Canada, where the Commission for Conservation of Fishery Resources (CCFR) performs such a role: a body with members also drawn from outside the federal fisheries department reporting directly to the Minister of Fisheries.

It is useful to note that other successful governmental mechanisms of government with a hierarchical structure for decision-making also perform similar independent review and appeal functions involving a system of checks and balances (often referred to as a 'watchdog' function). The role of the Supreme Court in some democracies checks the legitimacy of government action against the system of laws in place or against a formal constitution. In some countries, the Central Bank is expected to set interest rates and control money supply, largely independent of immediate government policies, in order, amongst other roles, to control inflation. Both of these mechanisms are staffed by top expertise, and operate 'at the limits', without becoming involved in the routine operations of the courts, or the day-to-day running of the government or economy, respectively. Fisheries management is currently coming to be viewed as a high risk activity. Interestingly enough, following massive financial losses to commercial banks engaged in high risk 'futures' trading (where the investor attempts to predict future prices of a commodity), 'watchdog' functions are being recommended for merchant banks.

It is in this context that the hypothetical CLS is viewed as operating: establishing the limits to safe exploitation, overseeing short-term management measures, and offering advice, on request, on technical issues related to management, but not replacing the role of the SFMA and its assessment advisory group in routine management (Table 7).

The division of responsibility between the CLS and SFMA is suggested in Table 8. The technical and operational roles inherent in the 'Standard Management Model' being are divided the different bodies: for the CLS, the objective is to define dangerous stock conditions and protect the stock from the results of human error; and for the SFMA, it is to develop practical management measures that do not infringe limits set by the CLS. Both groups would include a wide and different, though overlapping, range of technical competence, and may each have their technical working groups or advisory experts.

There is usually considerable reluctance to establish new structures and committees, particularly at the national level, and especially in developing countries with limited resources. Thus it is important to examine ways in which the above structure can be accommodated within existing organizations. Most coastal States have legislative provision for the SFMA. A Fisheries Department usually serves both as the SFMA and its technical group, while a Fishery Advisory Committee from outside the Fisheries Department often serves to advise the Minister based on independent technical inputs from its own representatives or from non-governmental institutions.

The recent emphasis on sustainable development and environment has led several coastal States to consider the establishment of transdisciplinary bodies for integrated coastal zone management (e.g. Towle *et al.* 1991). Such a body might also function as a Committee on Limits and Standards, since fisheries would inevitably fall within its broader ambit. Therefore, in planning for the broader environmental needs of sustainable development and resource use, in the coastal environment, it should be possible to also provide for the function of the proposed CLS.

5. DISCUSSION

The largely F-based reference points discussed in this paper reflect almost a century of development of the ideas pertaining to the dynamics and management of fishery resources. They are now technically complex (in relation to the skills of most managers), require considerable quantities of data, usually collected systematically over many years, are fraught with uncertainty, and need good judgement to apply. Due to their cost of application, they are probably unavailable as tools for managers of most small stocks, and outside the reach of managers in most developing countries, due to their technical complexity. Furthermore, even in those areas where there is abundant data, and the best technical expertise, they have not always provided an adequate basis for sustainable harvesting of fishery resources, although this may be largely because, in the final analysis, strict rules for their application have not been followed.

There are many sources of uncertainty in the estimation and application of references points in fisheries management. The estimation and communication of this uncertainty is increasingly a focus in stock assessment. The methods used in developed countries are usually complex and require extensive data. Given the wide variety of sources of uncertainty, it appears unlikely that all factors which may contribute to the probability of an undesirable event can be accounted for in estimating its probability.

For those stocks where the data and expertise are available, and where the value of the resource can support the associated costs, the current trend should lead to significant improvements in management. However, for the thousands of small/and little studied stocks, mostly in the developing world, these methods will not be applicable in the foreseeable future, and it will be necessary to take a conservative or precautionary approach in a situation of poor stock data in order to account for uncertainty and mitigate risk.

In practical terms, this will mean that many users and managers must accept that they will not have good formal estimates of risk in the near future. Consequently, in order to manage sustainably and responsibly they will have to use the best available information to define, albeit arbitrarily, an acceptable level of risk, and to agree upon often empirical target and limit reference points consistent with the reduction of risk to acceptable levels.

The common perception has been that the failure of management has been due to errors and uncertainties in models: a failure that can be remedied by more investment in technical advice. If this is true, it poses major problems for managing small resources, and for management bodies with limited funds and trained manpower. We may question, however, if the lack of technical advice is the real problem. The lack of inadequacy of the institutional framework for implementation may be as significant a contributory factor in the failure of fisheries management as it appears to be in the case of fisheries development (O'Boyle 1993, Bailey and Jentoft 1990).

What we are proposing here is that within the framework of management, some specific attempts be made to set limits to exploitation, and arrange the flow of advice and decision-making in such a way that 'precaution' is the key word for management action, and the setting of practical limits to exploitation, management actions should be based on information, not be decoupled from the fishery it is intended to serve.

There appears to be a variety of straightforward reference points which could be adopted in a participatory manner as conventions, were which might serve to limit exploitation to population sizes which can support sustainable yields. Many of these are based, albeit loosely, on the models which are used to derive the Reference Points in Table 4. However, the emphasis in applying them is different; it is on establishing mechanisms by which management can be implemented almost automatically, on the basis of prior agreement, once there is evidence that a limiting resource condition is in danger of arising.

From the preceding review, it is evident that fishery management reference points are ultimately set by convention. As such, where data and expertise are available and cost effective, they may be technically based, and may be considered in the context of a formal evaluation of risk and uncertainty. However, they may also be based on intuition, traditional knowledge, or just plain common sense. They must be responsible, and where necessary precautionary. Regardless of their basis, to be successfully applied, they must have a public justification and be agreed upon in advance by the participants in the fishery.

> *"WHATEVER APPROACH IS ADOPTED, THERE SHOULD BE AVAILABLE TO THE PUBLIC CLEAR AND AGREED LONG-TERM OBJECTIVES AGAINST WHICH PERFORMANCE CAN BE ASSESSED IN TERMS OF WHAT THE BROADER COMMUNITY EXPECTS FROM ITS FISHERIES MANAGERS"*
>
> Anon 1991

To some extent, the perception that fishery management must be based entirely on technically derived reference points has provided decision makers with an excuse to avoid difficult decisions, and has excluded knowledgeable non-technical inputs to the management process. For fisheries management to move beyond its current *impasse* in industrialised fishing regions, and to make its rightful contribution to economic enfranchisement in developing countries, there must be a new focus on the fishery management process, at national and international levels, with the technical inputs placed correctly in a supporting role, and the flow of advice consultation, and decision-making clearly identified.

The process of applying Target and Limit Reference Points requires a formal institutional mechanism in which they are discussed, agreed upon, and which their implementation overseen. Implementation, in turn must be formally vested in the appropriate national and international agency which can apply the management tools and monitoring systems required to reach a TRP, and ensure that pre-established LRPs and their unfortunate consequences, are avoided.

The required change in advisory and decision-making mechanisms for fisheries management must not just focus on desirable targets, but must meet requirements for action based on Limit Reference Points and precautionary principles. The suggestions provided here are not intended to be peremptory, but simply to promote debate on possible structures and to bring the problem more fully into focus. The problem does not just fall within the ambit of fisheries science under classical 'biological and bioeconomic approaches' (Anderson 1987):

a proper evaluation of risk and decision-making under a precautionary approach, cannot avoid assessing the efficiency of the management system as a whole.

Absolute dominance in decision making by a non-technical senior committee is not necessarily compatible with precautionary management especially when the resource is in danger. A system of checks and balances involving two groups with different membership, and specific, complementary skills and powers offers the possibility of a flexible precautionary response to unplanned technological changes and other 'surprises' that fisheries are subject to. It also offers the possibility of placing fisheries within the broader context of coastal zone management. The dominance might even be allowed to shift between the two groups depending on the state of the stock.

It thus seems advisable for the State(s) concerned to provide for not only a body responsible for routine assessment and management, but also a review body whose role is specifically to limit or override management measures or errors that may lead to resource collapse and/or associated negative effects on national ecosystems. This function could be incorporated within national structures which are already in place for reviewing the health of aquatic ecosystems and their their living resources. Such a system of mutual constraints by government bodies should help ensure that long-term natural resource constraints are not subordinate to short-term economic expediency.

Table 1: Assuming a Schaefer model at equilibrium, the table provides yield values (as percentages of MSY), for different percentages of the fishing effort (mortality) rate, F_{msy} (CPUE = equilibrium catch rate).

% of F_{msy}	10	20	30	40	50	60	70	80	90
% of MSY	19	36	51	64	75	84	91	96	99
% of CPUE at MSY (+ ve values)	190	180	170	160	150	140	130	120	110

Table 2: An illustration that two alternative sets of F values at age and their equivalent age/site-specific quotas can result in the same RP for survival to maturity. This is relevant where fish migrate through different EEZs in which different levels of exploitation occur.

AGE CLASS	MATURITY	SET I		SET II	
		F	Quota (t)	F	Quota (t)
1	Immature	0.2	780	0.45	1,131
2	Immature	0.2	960	0.21	763
3	Immature	0.2	861	0.14	580
4	Immature	0.2	685	0.10	441
5	Mature	0.2	513	0.10	365
Survival to maturity at Age 5		13.5%		13.5%	

Table 3: The main reference points mentioned in this paper, their data needs, and bibliographic reference. Also listed are the advantages and disadvantages of the mortality-based reference points for fishing management mentioned in this paper and their potential application: (Y = Yes; YY = favoured; N = No; LRP = limited reference point; TRP = target reference point; SR = stock rebuilding - see text).

RP	THEORETICAL BASIS	DATA NEEDS	ADVANTAGES	DISADVANTAGES	USE AS: TRP	USE AS: LRP	USE AS: SR	REFERENCE
F_{msy}	Production model	Annual series for Y & calibrated f for all removals	Estimates and historical Y,f series often available	High danger of overfishing as TRP	N	Y Y	N	Hilborn & Walters (1992)
F_{mcy}	Simulation from Annual recruitment series	Popn. parameters and probability distribution of annual recruitment	In theory, allows constant low quota	Data-intensive (info on recruitment variability)	Y	N	Y	Sissenwine (1978)
$2/3F_{msy}$	Production model	A production model is assumed fitted	Simply calculated if production model exists	Empirical; needs historical data (Y; f/F)	Y	N	Y ?	Doubleday (1976)
F_{max}	Y/R calculations	Y/R model fitted	Simply calculated	Needs growth/mortality info	N	Y	N	Beverton & Holt (1957)
$F_{0.1}$	Y/R calculation and current state of popn.	Popn. parameters (M size at age, size at first recruitment	well studied: simple to calculate from popn. parameters	Varies with fishing strategy: sensitive to recruitment level	Y	N	Y ?	Gulland & Boerema (1973)
Z_{mbp}	Production model	Annual data series of standard catch rate and Z	Incorporates predation; requires simple historical data on CPUE; Z	In present form assumes Schaefer model	Y	N	Y ?	Caddy and Csirke (1983)
Z^{*}	Simulate overall Z and mean size caught	Popn. parameters; mean death rate/size in popn. & catch	Simply calculated from basic parameters	Needs unbiased data on size frequency of catch	N	Y	N	Die & Caddy (in press)
F_{med}			Theoretically attractive if stock/recruit data exist	Both best Y and F will vary annually	Y	N	Y	
F_{low}	Estimate F giving 90% of years with stock replacement	Assumes data for fitting stock recruitment (usually from cohort analysis)	Reflects past probability of recruitment	Needs historical data on stock/recruitment	Y ?	N	Y	ICES (1984); Jakobsen (1992)

F_{med}	Estimate F giving 50% replacement	Assumes data for fitting stock recruitment (usually from cohort analysis)	Reflects past probability of recruitment	Needs historical data on stock/recruitment	Y	N	N	ICES (1984); Jakobsen (1992)
F_{high}	Estimate F giving 10% replacement	Assumes data for fitting stock recruitment (usually from cohort analysis)	Reflects past probability of recruitment	Needs historical data on stock/recruitment	N	Y	N	ICES (1984); Jakobsen (1992)
$F_{\% SPR}$	Analytic model of Biomass/recruit	Popn. parameters and maturity-at-age data	Simple to calculate and flexible (depends on O/O)	Sensitive to life-history parameters, must be generalised cautiously	Y	Y	Y	e.g. Clark (1991)
$F > \approx M$	Empirical (for top predators)	M and sustainable Fs for similar resources	Top predators Low data needs (estimate of M)	M often guessed. An empirical approach	Y	N	N	Fisheries literature
$F < M$	As above (for small pelagics)	M and sustainable Fs for similar resources	Small pelagics. Low data needs (estimate of M)	M often guessed. An empirical approach	Y	N	N	Patterson (1992)
F_{mey}	Econometric modelling	Historical data on Yield/effort/cost and earnings	Can use production model fit plus cost/revenue data	Hard to define for multiple fleets & varying economic systems/indicators	Y	N	N	Clarke (1976) Panayotou (1988) Gordon (1954)

Table 4: **Some likely magnitudes of errors for quantities used in assessing the status of shelf fisheries (CV = coefficient of variation = 1 standard deviation/mean value*).**

VARIABLE	DATA SOURCE	CV VALUES (ROUGH RANGE)	REMARKS
Annual catch	Commercial statistics	> 10%	Significant bias (discards/misreporting)
Commercial Catch rate	"	around 10%	" "
Catch-at-age	"	around 10%	Subject to ageing errors
Survey for biomass	trawling	35 - 40%	Improves with repetition (more stations sampled)
" "	acoustic (small pelagic fish)	25 - 35%	" " "
Fishing mortality rate (F)	cohort analysis etc.	10 - 30%	
Natural mortality rate (M)	catch curves etc.	(Usually indefinite)	Most assessments employ values developed for other stocks

* There is an 85% chance that the variable lies within 1 standard deviation of its mean value. Thus, if the CV = 30%, and the mean is 100 t, there is an 85% chance that the mean lies between 70 and 130 t.

Table 5: **Illustration of how different criteria result in a wide range of possible fishing mortality and catch values for a stock (From Gulland and Boerema 1972). For each criterion, the value recommended by scientists in the 1970s was normally presented without an estimate of risk and uncertainty.**

OBJECTIVE AND DEPENDENCE OF RECRUITMENT ON STOCK SIZE	OPTIMUM F	CATCH (t)
Maximum physical yield		
- Constant	1.2	110,000
- Moderately density-dependent	0.9	84,000
- Strongly density dependent	0.6	59,000
Maximum Economic Yield (for given costs and prices)		
- Constant	0.8	76,000
- Moderately density-dependent	0.7	68,000
- Strongly density dependent	0.5	50,000

Table 6: A purely hypothetical example of a set of rules combining TRPs and LRPs for fishery management.

Variable	TRP	LRP
Habitat		a rate of destruction of habitat $\leq$ rate of regeneration
Biodiversity		a rate of harvesting allowing sustainable reproduction of all (including by catch) species
Associated prey species	stock size expressed as (e.g. 70%) virgin biomass	stock size expressed as (e.g. 50%) of virgin biomass
Bycatch sp.	e.g. less than 5% of annual catch	less than 10% of annual catch
Size of target sp. Mean L	> size of 1st maturity plus 10%	> size at 1st maturity
F of target sp.	$F_{now} < 0.3$	$F_{now} = F_{msy} = 0.6$
Catch rates of target sp.	$\geq$ 60% of catch rates from virgin stock	$\geq$ 40% of catch rates from virgin stock

Table 7: The possible membership of the two main groups in the proposed management system.

Committee on Limits and Standards (CLS)	Standard Fisheries Management Authority (SFMA)
Resource biologists and ecologists from government, NGOs and universities.	National or regional resource managers and socioeconomists
Representatives of the public	Fisher's representatives
Economists	Control and surveillance officers
Quantitative experts including analysts*	Fish stock assessment experts*
*in an advisory capacity	

Table 8: The roles of the two main groups in the proposed management structure.

The Committee on Limits and Standards (CLS)	The Standard Fisheries Management Authority (SFMA)
AUTHORITY: Overrides or constrains decisions of SFMA when LRPs are in danger of being exceeded.	Decides exploitation in relation to established TRPs when the stock is in a healthy condition, and LRPs are not exceeded.
FREQUENCY: May meet annually, or at intervals of several years, unless there is an unexpected problem.	Meets frequently as required.
TERMS OF REFERENCE: Sets limits to exploitation such that both a productive ecosystem, ecosystem diversity, and intergenerational equity are conserved.	Establishes targets for fishing in the current year that comply with the constraints set by the CLS
OBJECTIVES: 1) Sets levels and modalities of catch sampling for a given stock, and standards for control and surveillance. Sees that these standards are being met in practice.	1) Reports to CLS on attainment of agreed levels of sampling, surveys, and control and surveillance of the fishery.
2) Reviews performance of the fishery in relation to the measures set by the SFMA. Sets and periodically revises acceptable limits to the rate of fishery exploitation based on acceptable risks.	2) Analyses fishery and survey data to estimate current stock size, recruitment and fishing mortality, and forecasts the values for the coming year within catch/fleet constraints.
3) Considers the historical effects of exploitation in relation to the attainment of long-term management objectives	3) Sets targets (for catches/effort/area/ season of fishing) for the coming year such that the annual F and/or residual biomass remain within the limits specified by the CLS.
4) Seeks improved institutional and management measures, and suggests limits and criteria for the control of catches/ access	4) Allocates TACs and/or access rights among the different stakeholders
5) Evaluates the impact of different gears, of by-catch and of discards.	5) Suggests practical means of dealing with fishery and species interactions.
6) Considers impacts of ecosystem and environment changes, and of other fisheries, on the resource and its long-term sustainability	6) Adjusts seasons, areas fished and technological criteria to minimize incidental catches that lead to catch overruns and discarding.
7) Takes into account the impact of the fishery on by-catch species; sets limits for bycatch and discarding	7) Develops practical measures to attain discarding and bycatch targets.
8) Makes recommendations for fundamental research in support of fishery assessment	8) Develops plans for, and coordinates research on, issues raised by the CLS.
9) Suggests targets and time frames for stock rebuilding	9) Develops and implements stock rebuilding strategies that meet CLS requirements.

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ANNEX I: THE FISHERY MODELS

The Unit Stock

Stock assessment calculations begin at the Unit Stock level; i.e., they consider distinct and separate population units of a single species from which the fisheries yield is, or could be, extracted. A unit stock is more correctly viewed as a self-reproducing population, with limited emigration/immigration to/from other unit stocks. In the case of mobile and migratory stocks which may diffuse or migrate across maritime boundaries, we must include removals from the stock taken from inside all jurisdictions in the initial assessment, since the estimation from the fishery statistics of any single country, of whether an overall RP for fishery yield or standard fishing effort/mortality has been met, is likely to be seriously biased if it is based on incomplete coverage. Also, if a significant component of the catch and effort is not included due to misreporting or non-reporting, this also will result in a high probability that the perceived position of the fishery in relation to the reference point chosen, will be seriously in error.

Global and analytical models and stock-recruit relationships

It is necessary to make a distinction between production models, where we only have two trains of annual information; fishing effort and total yield, and where generalizations can be made as to the overall behaviour of the population, but all biological processes going on within it are unknown; and so-called Analytical models, where processes of growth, reproduction and death, subscripted by age, are assumed to be understood and the relevant rates at which they occur are known. The many variants of yield/recruit analyses belong here. Combinations of these two types of models have emerged in recent years, but few applications in practical fishery management have emerged so far. A further type of model that is largely empirical, relates the number of recruits that occur in a year to the spawning stock size (Fig. 4). All of these methodological approaches have generated their own model-based management reference points.

The catch equations

The single species theory of fish population dynamics is based on the so-called "catch equations", which postulate mathematical relationships between:

a) the stock (represented as total numbers of individuals in those age groups available to fishing (the recruited age groups),

b) the fishing effort (f) and corresponding fishing mortality (F) it causes, and:

c) the yield in numbers and/or weight resulting from this operation, given that

d) in addition to fishing, a natural death rate (M) applies, which is the rate at which the stock is being diminished by deaths caused by factors other than fishing; (notably predation).

e) Various aspects of the natural history of the species are also pertinent to its capacity to support exploitation.

Two of the most commonly used catch equations are those below, respectively used where the age composition is known (and the subscript t refers to the age of a group of fish), and for the mean population biomass undifferentiated by age, as following the second = sign:

$$Y_t=\sum N_t . w_t . (F/Z_t) . (1-\exp(-Z_t) =\overline{B} . F$$

Both equations contain three interdependent variables (see fig 1) which are the primary variables available for consideration as possible Reference Points for fisheries management. These are the fishing mortality F (related to the total (usually annual) fishing effort as F = qf, (where q is the catchability coefficient); the Biomass B, and the fishery yield (usually annual) Y. Since fish stock assessment assigns a primary role to fishing as a cause of mortality, the primary 'control variable' is of course the control of fishing effort and/or fishing mortality, while catch, catch rate and biomass may under specified conditions of stability and equilibrium, be used as measures of the effects of fishing, and/or measures used to indirectly control fishing mortality.

Control of fishing intensity may imply control of the number of vessels of a given type or power allowed in the fishery, and even of the maximum number of standard days fishing allowed. However, for reasons described below, access rights in terms of fleet size and total annual fishing effort have in the past been rarely used directly in negotiations, and has been assumed to be less easily monitored than a fixed catch or quota. Control of the annual yield (despite technical disadvantages at least equal in magnitude), has been the most widely used management practice; perhaps also because it reflects more directly the benefits to be gained by different participants in the fishery. In some fisheries, equivalent benchmarks of economic performance have been calculated; particularly for national fisheries where common measures of economic performance apply. In other circumstances where the levels of total removals, total fishing effort and net economic benefits are difficult to determine, but direct survey of the stock is possible, measures based on controlling the biomass of the stock may be more feasible and not liable to biases due to misreporting.

ANNEX II: USING AN LRP TO SET A RISK-AVERSE TARGET FOR EXPLOITATION - THE F_{MSY} EXAMPLE

There may be circumstances when fisheries managers are able to specify an upper limit to fishing intensity, beyond which an extremely undesirable state of the fishery is agreed to exist. As noted, this may be referred to as a Limit Reference Point (LRP). For mathematical simplicity we assume in the following, that F_{MSY} is a conventionally-accepted value, known without error. In the following example we further assume that the LRP used in this case is a pre-established value for the fishing mortality corresponding to MSY conditions.

The managers acknowledge that they are operating in an uncertain environment and that the current 'status quo' for the fishery, and the F-value during the last season ($= F_{NOW}$), was not precisely known, but that some rough estimates of its standard deviation can be made. In the hypothetical case in question, there is strong evidence that the fishing intensity last year was below F_{MSY} , and it is assumed that if the same effort were to be exerted in the next season, we could expect the probability distribution of fishing mortality rates to remain the same. The managers feel however that it would be useful to define a target reference point in such a way that this results in a small, prespecified risk that F_{MSY} is not exceeded.

Given this situation, the following illustrates one procedure for calculating appropriate target values for F_{NOW} which result in a pre-specified probability of an agreed LRP being respected. In this example, the LRP is assumed to be a pre-established value for $F_{MSY} = 0.6$. Although thera is no unambiguous evidence in the literature as to the most appropriate distribution function to use for F, it is believed that the uncertainty in the relative position of $F_{NOW} < F_{MSY}$ can reasonably be expressed by a normal distribution (see Fig18 below), although similar calculations could readily be performed for other distribution functions.

Let us assume that the current level of the fishing mortality, F, is less than the target reference point, F_{MSY}. For mathematical simplicity we assume that F_{MSY} is known without uncertainty. We further assume that the uncertainty of F, is described by a lognormal distribution where, with equal probability, i.e. with equal levels of confidence, the actual value of F in the fishery may be twice or half the estimated parameter, F_{NOW}. We seek to find a value for this limit reference point, F_{NOW}, that lies safely below F_{MSY}, leaving only an acceptably small probability that the 'true' value of the current F is, in fact, greater than F_{MSY}.

Mathematically the suggested procedure is the following: The level of risk the fishery can safely tolerate, (quantified in the appendix figure as the shaded area on the right hand tail of the normal distribution), is equivalent to the integral of the probability that the current F exceeds our limit reference point. Referring to this chosen level of acceptable risk as P ($F > F_{MSY}$), we must solve for the value of F_{NOW} that corresponds to the target reference point that provides this margin of safety. The cumulative probability for the right hand tail of the normal distribution may then be written as:

$$P(F > F_{MSY}) = \int_{F_{MSY}}^{\infty} \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left\{ -\frac{(F - F_{NOW})^2}{2\sigma^2} \right\}$$

From this we can obtain F_{NOW} using a mathematical package (e.g. MAPLE, MATHEMATICA) designed for equation solving.

The standard deviation of **F** could then, in theory, be estimated from the historical record by comparing the predicted **F**'s and the 'true' values obtained retrospectively from VPA, or by agreeing on a 'likely' margin of error given estimates of the variance in population size estimates. Furthermore, this type of historical comparison could enable fishery managers to describe more accurately the nature of the distribution in uncertainty of **F**.

Appendix table: Assuming F_{MSY} = 0.6, the following gives indicative values of F_{NOW} that could be used as TRPs for combinations of (Columns): - The acceptable proportion of the time that $F_{NOW} > F_{MSY}$, and (Rows):- standard deviations of F_{NOW}.

	[P(x)]	STANDARD	DEVIATION:	
		σ = 0.25	= 0.5	= 1.0
$P(F_{NOW} > F_{MSY})$	30%	0.53	0.475	0.39
	20%	0.50	0.42	0.33
	10%	0.45	0.365	0.26

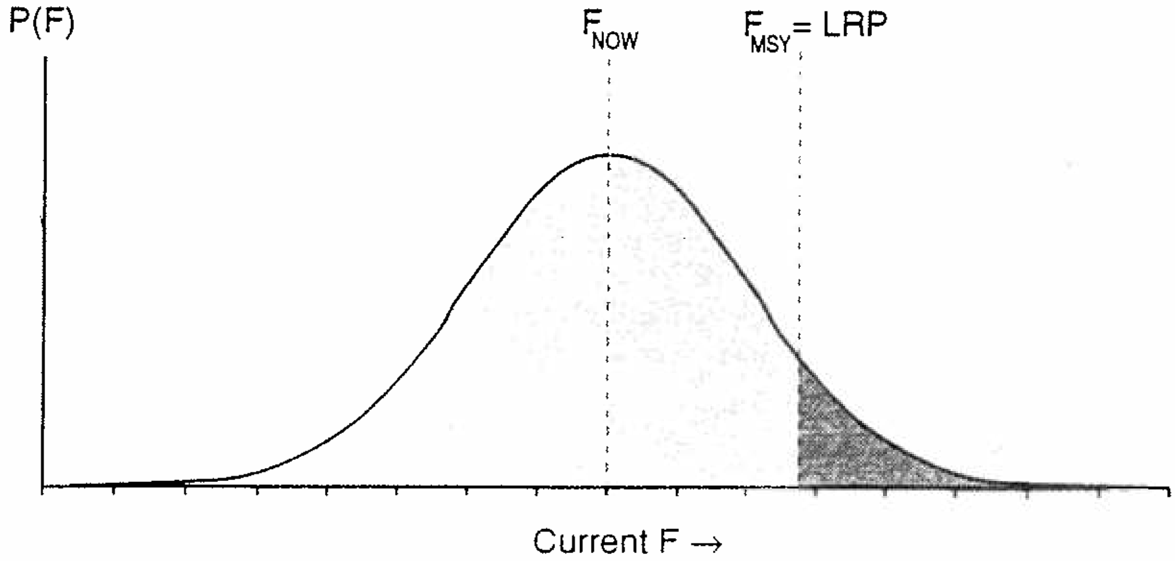

Figure 18: Illustrating the uncertainty as to the present rate of fishing, F_{NOW} in relation to a Limit Reference Point (in this case, assumed to be F_{MSY}). A finite probability P(F) of F > F_{MSY} is represented by the shaded right hand limb of the normal distribution.

ANNEX III: SOME EXAMPLES OF FISHERY MANAGEMENT FRAMEWORKS

Some examples are given below which draw freely on reports on the mode of operation of a number of management bodies, as given in Anon (1992), Horwood and Griffith (1992), and from personal experience. No attempt is made to suggest that their modality of operation is always that briefly summarized here, no evaluation of the performance of these bodies is offered. The only objective evaluation of the performance of a management body must rest on the evidence of the state of resources under their jurisdiction.

Fisheries Management in northern European Community waters

An outline of the procedure followed by the European Community (EC) for resources within its Common Fishing Zone in the North Atlantic is given in Anon (1992), in which advice from ICES is incorporated. This, subject to correction, appears to incorporate the following flow of advice and decision-making:

Assessments made by national staff are reconciled in ICES working groups, and later in the Advisory Committee on Fishery Management (ACFM); both made up of resource scientists where EC staff sit as observers. A range of options for TACs is then presented to the Scientific and Technical Committee for Fisheries (STCF) made up of EC staff and national resource advisors. Here the debate widens to consider other technical (e.g. fishing gear) and economic issues. The reports of the ACFM and STCF are reviewed by EC staff, and initial proposals for TACs are discussed with senior representatives on member country administrations. At the Council of Ministers, national shares are agreed on, preferential treatment may be accorded for socioeconomic reasons, and some quota swapping may occur. The national shares agreed to are subsequently allocated to stakeholders in the national fisheries concerned. In a sense, although more complex, the above sequence follows the Standard Management Format with, however, the possibility of multiple reviews at different levels in the management decision tree.

Evolution of the management framework for domestic Canadian east coast fisheries.

In the 1970s, the management process began with the regular re-analysis of the current state of the stocks by individual scientists in federal fisheries laboratories, who used commercial statistics, biological samples and survey data to assess the state of stocks. Scientists were assigned responsibilities for assessment of the resource in question, and came under the supervision of the Regional Directors of fisheries research. A panel of government scientists (The Canadian Atlantic Fisheries Scientific and Advisory Committee) provided the first review process of these assessments of individual stocks. CAFSAC was structured as a series of sub-committees dealing with specific resources or problem areas, and met at least once annually to review assessments prepared by scientists. These were further reviewed and approved by a CAFSAC steering committee made up of the chairmen of individual sub-committees in the Regional Directors and others.

Government-industry groups, such as the east-west groundfish committee with membership of industry and participation of government fishery scientists, economists and fishery protection officers was responsible for reviewing the assessment recommendations, and advised on allocation of catches/access rights to the various fleets. The Minister of Fisheries had the responsibility for the final proposals emerging from this process. On occasions when problems arose, it had sometimes been the practice of a Minister to appoint a special Board of Enquiry or ad hoc Governmental Commission to review a particular area of controversy; this ad hoc group usually consisted of one or more distinguished individuals from outside the Federal Fisheries Service. More recently, CAFSAC has been terminated and the Minister has set up a Fishery Resource Conservation Council (Anon 1993) to take on a special role in overviewing the assessment process. This appears to be a move away from the Standard Format in the direction hypothesised in section 4.2.1.

The Regional Management Councils in the United States

Here the Fishery Conservation and Management Act of 1976 (The Magnuson Act), lays out a procedure for managing fish stocks within the US Fishery Conservation Zone. Regional Management Councils, dominated by representatives from the fishing industry and fishermen, with government technical assistance, take management decisions under the guidance of an agreed management plan for the fishery. The Plan which includes an Environmental Import Statement (EIS) is drafted by experts, specifies who are the stakeholders in the fishery, and is supposed to cover all important aspects required for long-range fishery management, such as biological, fishery, sociological, legal and economic information, and is agreed to in advance by stakeholders (Costello and Pulos 1979). The Plan provides a clear definition of overfishing (e.g. a target harvest rate or stock level) and rebuilding programmes for stocks that are currently overfished. One must suppose that the Plan, once approved, is in some sense, a dominant document, in deference to which the Council voluntarily constrains the management options available to it (Fig 3).

In some cases, the success of this management procedure has been hampered in the past (see e.g. Gimbel 1994), by open access conditions, although some management plans (e.g. those for Atlantic Surf Clams) are now employing closed lists of fishermen or vessels to limit access. As noted, the management plan is intended to constrain short-term management measures taken by the Fishery Management Authority; in this case the Council, so that long term management goals are not compromised. The fact that this management procedure has not always worked, e.g. for groundfish resources in the Northwest Atlantic (FAO 1992a; 1993), may be in part due to a lack of an essential tool, notably measures to control or regulate fishing effort or access.

The International Whaling Commission (IWC) Revised Management Procedure

Scientific advice within the IWC had early on proceeded beyond simply passing updated assessments of stock status to decision makers. The Commission had realized that in order to evaluate the performance of the fishery under conditions of uncertainty, not only the stock status but the management procedure itself must be included in the model of the 'fishery'. This was embodied in the 'Revised Management Procedure' (RMP). The Commission reformulated its main objectives as follows (Kirkwood 1993, Donovon 1993):

- The highest continuing yield from the stock,
- Stability of catch limits, for the orderly development of the whaling industry,
- An acceptable risk that a stock not be depleted below some chosen level so that the risk of extinction is not seriously increased by exploitation.

To meet these objectives in a risk-averse manner, the Commission adopted a procedure, the catch limit algorithm (CLA), which specifies the way in which catch limits are set from the required information. The CLA recognises that there may a wide range of estimates for stock status, and seeks to assess the likelihood of the various values. The stability of catches is addressed by setting catch levels for five-year periods. As new information is acquired, in particular sight or visual surveys of abundance (given that the harvesting of most whole stocks is under moratorium), population estimates are revised. The CLA, plus several other rules, e.g. regarding stock boundary delimitation, allocation of catches, timing of reviews, form the Revised Management Procedure (RMP), which the Scientific Committee recommended to the IWC in 1993.

The philosophy underlying this approach appears to be that the net performance of an assessment model, a set of management measures, the efficiency of surveillance and enforcement, and (presumably) the management structure, can be determined in combination by Bayesian trials. The RMP is also aimed at reducing the subjectivity, and thus the potential for political interference, in the management procedure.

This example is used to make the point that the 'rules' embedded within an obligatory resource and management procedure, if applied in a real world situation, would presumably constrain managers to ecologically acceptable responses that are compatible with a predetermined level of risk. The RMP acts as an overall constraint on year to year, short-term management measures.

The RMP historically anticipates the use of risk-averse strategies elsewhere, but still retained the 'deterministic' structure of management advice (Kirkwood 1993). What were in effect, Limit Reference Points (LRPs) were specified, and an attempt was made to generate a single numerical value for allowable catch that was 'precautionary'. Kirkwood also notes that although this semi-automatic procedure for computing allowable catches worked for a few years, there were problems in achieving agreement on the MSY and on current and initial stock levels. A significant disadvantage of such a procedure, is that it does not accommodate unexpected events. Clearly, when there are 'surprises' due to unusual environmental or fishery-driven events, a simulation-based, 'automatic management procedure', or set of rules, cannot be effective without a review committee to oversee its function.

The Inter-American Tropical Tuna Commission (IATTC) system for dolphin by-catch in the purse seine fishery of the Eastern Pacific Ocean

The IATTC Secretariat regularly assesses the tuna stocks of the Eastern Central Pacific, but the total tuna quota is no longer a function of potential yield estimates, but is now largely an indirect consequence of a global quota on incidental dolphins kills during 'dolphin sets' on tuna schools associated with these mammals.

An Intergovernmental Agreement was established by the Signatory Nations of IATTC who meet annually to decide on global dolphin bycatch quotas, and on infractions and sanctions to be taken against those exceeding these quotas; and to appoint members of an International Review Panel (IRP). Member nations send the IATTC Secretariat and the IRP, a list of vessels which require dolphin quotas. . The IRP is drawn from non-member nations of IATTC, and is made up of a specified mix of national directors of marine institutes, fishing industry and environmental community representatives. The IRP meets 3-4 times a year, and from a list of qualified skippers, decides which boats qualify for a specified individual limit to dolphin kills as a by-catch to surface tuna sets. A dolphin kill record is reported to the respective fishing nations by on-board observers. Sanctions are applied against boats infringing these quotas after legal/administrative process.

The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR)

The CCAMLR Convention acts as the controlling or dominant structure, limiting those options legally available to the Commission. Article II of the Convention spells out a number of criteria that must be respected in setting fisheries regulations, as seen in the following excerpts:

" Any harvesting and associated activities in the area to which this Convention applies shall be conducted in accordance with..... the following principles of conservation:

a) prevention of the decrease in the size of any harvested population to levels below those which ensure its stable recruitment. For this purpose its size should not be allowed to fall below a level close to that which ensures the greatest net annual recruitment;

b) maintenance of the ecological relationships between harvested, dependent and related populations.......and the restoration of depleted populations to the levels defined in sub-paragraph (a) above; and

c) prevention of changes or minimization of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades, taking into account the state of available knowledge of the direct and indirect impact of harvesting.....with the aim of making possible the sustained conservation of Antarctic marine living resources".

In the case of krill, the intention is to keep the biomass at a higher level than would be the case if safe single species harvesting of krill alone were the objective, in order to provide for the needs of predators with restricted forage ranges, and to focus on avoiding the lower end of the range of likely future biomasses (CCAMLR 1993). We see here therefore, the Convention spelling out limits to management action. Again, unexpected 'surprises' may occur which were not anticipated in formulating the Convention, and these could only be allowed for at the risk of making the Convention rather restrictive on resource harvesting.

This paper reviews the conceptual background and application of technical reference points in fisheries management. Despite considerable investment in stock assessment methodology and expertise, fisheries worldwide are overexploited, apparently because of a mismatch between the precision of assessment and the precision of management. Two types of reference points are recognized: target reference points (TRPs) and limit reference points (LRPs). The use of maximum sustainable yield (MSY) as a target reference point is considered in the light of past performance of fisheries management, and it is suggested that MSY and other reference points formerly used as targets may be more appropriately applied as LRPs. The recent trend towards the quantification of uncertainty and estimation of risk is considered to be good, but the cost and availability of information and expertise required may preclude the use of these techniques for many small or low-value stocks and for most stocks in developing countries. The recent trend towards inclusion of "ecosystem concepts" in setting fishery management objectives is also seen as good, as well as overdue. Although still in their formative stages, ecosystem concepts can still provide LRPs. Effective management requires a set of rules comprising both TRPs and LRPs. In most national and international fisheries management situations, the current institutional structure will probably require some modification in order to apply these sets of rules successfully. Fisheries management organizations will continue to assess and manage fisheries routinely, but an independent review may be needed when resource production limits are approached. The action to be taken at such limits should be discussed and agreed upon in advance.

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