# Artículos de fondo

# Biological indicators and their use in stock assessment to achieve sustainable levels of fishing. Part 1

*John F. Caddy*[*]

The contexts within which fisheries indicators are used in marine fisheries management nowadays are described for non-specialists. Conventional fisheries management has made use of a relatively narrow range of input data, notably, catch, effort and size, and age composition of catches, often supplemented by research vessel surveys. Unfortunately, such assessments are performed for relatively few of the resources exploited globally, and it would be desirable to develop a supplementary approach that makes use of a broader range of informational inputs where specialized stock assessment expertise is absent. Prior to discussions on the possible role of the World Trade Organization with respect to fisheries subsidies, it was considered desirable to investigate the possibility of using supplementary information and expert opinion to guide fisheries decision-making, and to define the role of the different players in this process. Emphasis is placed on the need to display information to decision-makers and stakeholders in an ordered fashion, either using the "pressure- state- impact- response" (PSIR) format or the traffic light system, so that decision makers may be aware of the broad context of factors affecting the fishery.

**Key words**: Indicators, stock assessment, reference points, fisheries management, data limited decision-making, ecosystem approaches.

## Indicadores biológicos y su uso en la evaluación de poblaciones para lograr niveles sustentables en la pesca

El presente documento describe indicadores de manejo pesquero para no-especialistas. El manejo pesquero convencional utiliza datos limitados tales como son captura, esfuerzo, tamaño y composición de edad en las capturas, que son a veces complementados por información recopilada en cruceros de investigación. Desafortunadamente, tales evaluaciones se realizan tan sólo para algunos recursos explotados globalmente, por lo que sería deseable desarrollar mecanismos suplementarios que utilicen más información, donde no hay especialistas de evaluación de *stocks*. Antes de las discusiones sobre el posible papel de la Organización del Comercio Mundial en el tema de los subsidios a las industrias pesqueras, se consideraba necesario investigar la posibilidad de hacer uso de información suplementaria y opiniones técnicas de expertos, que guiaran a la toma de decisiones para definir el papel de los actores en este proceso. Se hace hincapié en la necesidad de proporcionar información de manera ordenada, ya sea usando el formato "presión- estado- impacto- respuesta" (PSIR) o el sistema de semáforo, con fin de que los administradores y usuarios del recurso pesquero tengan una idea clara del amplio contexto de los factores que afectan a la industria pesquera.

**Palabras clave**: Indicadores, evaluación de *stock*, puntos de referencia, manejo de pesquerías, decisiones con datos limitados, visión del ecosistema.

### Introduction

The 2002 issue of the FAO "State of World Fisheries and Aquaculture" (FAO, 2002) expressed concern as to the status of global marine resources as follows:

An estimated 25 percent of the major marine fish stocks or species groups for which information is available are underexploited or moderately exploited... about 47 percent of the main stocks or species groups are fully exploited... another 18 percent of stocks or species groups are reported as overexploited... the remaining 10 percent have become significantly depleted, or are recovering from depletion.

This division of world fisheries into four categories for those world fisheries for which at least some limited data are available as a basis for judgement, has been widely quoted, and will be commented on later in this paper. Many marine fish stocks have been declining in an alarming

* jfcaddy@yahoo.co.uk

fashion, and it is clear that there is an urgent need to reverse such declines. This was recognized by the 2002 United Nations' Johannesburg World Summit on Sustainable Development. Apart from overfishing, environmental deterioration and periodic changes in climatic regime as well as anthropogenically-caused global warming, all have an impact on fish stocks (see *e.g.,* Cushing, 1982; Kawasaki, 1983; Kelly, 1983; Glanz, 1990; Klyashtorin, 2001) especially, but not exclusively, for small pelagic fishes. The dominant effect on fisheries ecosystems is fishing itself, and it is not uncommon for exploitation rates to exceed 50% per year, given that for many stocks, the exploitation rate that would correspond to the maximum sustainable yield (MSY) is of the order of 15%-20% per annum. The UN Summit's Plan of Implementation (Article 30) stated that in order to achieve sustainable fisheries, despite progress with international fisheries agreements since UNCED such as the UN Fish Stock Agreement and FAO Code of Conduct for Responsible Fisheries (FAO, 1995), it is necessary to set concrete objectives, *viz*: "Maintain or restore stocks to levels that can produce the MSY with the aim of achieving these goals for depleted stocks on an urgent basis and where possible not later than 2015" (United Nations, 2002).

The 2002 FAO report went on to say: "Recovery usually implies drastic and long-lasting reductions in fishing pressure and/or the adoption of other management measures to remove conditions that contributed to the stock's overexploitation and depletion." A global review of stock recovery plans (Caddy & Agnew, 2004) found a number of cases in which a recovery effort had achieved some success –mainly in North American waters. Most recovery efforts have been recent, and recovery times were between four-eight years to 14-22 years or longer. While it seems likely that for shorter-lived (*e.g.* many tropical species) the recovery times may be shorter than this; sacrifices will need to be made in terms of a much reduced fishing pressure, as long as the environment has not been damaged by anthropogenic impacts such as nutrient runoff (*e.g*. Caddy, 2000a). Thus, achieving the UN Summit objective in the next nine years looks a formidable task!

**The problem of limited data**

The fact that fisheries resources are not usually directly available to census, and surveying requires highly expensive equipment (notably research vessels), means that the costs of management place serious constraints on the type and number of indicator series that can usually be collected, as well as the extent of infrastructure to make use of this data. The overall financial constraint for developing countries is not aided by a general inability to extract rent from the fishery from domestic users to use in fisheries management. This last constraint has led to the provision of access agreements to foreign fleets, but in some cases this strategy has led to a loss of control over the level of exploitation, and a flow of benefits abroad. Shortage of funding for data collectors in ports or at landing places, and for analysis of fisheries samples, or fisheries modelling, thus present major problems for developing fisheries. Finally, trained personnel in methods of population analysis are rarely available in many countries above the level of the fisheries biologist. All of these factors make annually-repeated stock assessments infrequent in most developing countries. A shortage of funds, and occasionally of political will, cast doubt on the ability of many countries to implement provisions of the FAO Code of Conduct, and a simpler questionnaire-based procedure has been suggested (Pitcher *et al*., 2006; FAO, 2007), or criteria based on ecosystem-based management (Ward *et al*., 2002).

For fisheries where multi-national fleets operate, problems of standardization and exchange of data are also impediments to reliable assessment work. International aid programs in fisheries assessment are no longer common, and although they collect useful data, their typical three year duration has rarely allowed adequate time series of data to be collected.

One other aspect of marine resource management that makes the use of data often problematical, and ensures that analyses remain low in precision, is the absence of controlled observations. Marine Protected Areas (MPAs, *e.g*., Russ & Alcala, 1996, 1998; Murawski *et al*., 2000; Jennings, 2001; White *et al*., 2002) have shown positive recoveries of fisheries ecosystems, and their use for comparison with exploited areas is in theory possible, as long as these areas are legislated free from fishing effort so as to provide controls for a program aimed at studying ecological impacts of fishing. Seeking indicators that integrate ecosystem impacts has received little attention to date however (Kabuta & Laane, 2003). Many existing closed areas (where they do exist) are usually too small to provide useful comparative data to fishing grounds. Analysing time series for the effect of fishing, when environmental and ecological changes are also occurring, makes for uncertainties in interpretation.

Recently, a realization has occurred in many world areas where skilled manpower is not available for standard assessment techniques to be applied, that alternative approaches are needed. These will also need to take into account a wider range of phenomena, and not just the dynamics of the species. Qualitative or semi-quantitative indicators may be used to support an approach which attempts to avoid the assumption that the key factors influencing the fishery are necessarily well understood (e.g. Caddy, 1999b; 2000b), and should try to establish what are the *inputs* to the management process, such as facilities (capital value and annual upkeep), personnel (numbers and salaries), and the cost of activities. Evidently expenses on management activities in their entirety should not form a high proportion of revenues flowing from the fishery, otherwise the fisheries sector becomes a burden on the rest of the economy. Monitoring the *outputs* from the management process (indicators of the successful application of inputs to ensure healthy populations) is perhaps even more important than inputs since it measures success rate, and has to be monitored. There are obvious problems of standardisation between different financial approaches adopted in different countries that make for difficulties in comparing the cost of management measures.

### *1. Fisheries indicators*

An indicator in the context discussed here, can be regarded as a measurement, direct or indirect, of the impact of a process on a resource. This paper mainly considers indicators that can be introduced into standard assessment models, or can be used in absence of such models to monitor ecosystem changes. Indirect indicators of resource health or degree of exploitation also exist, and will be discussed in the section on the traffic light approach. The classical indicators used in conventional stock assessment and management (Garcia, 2000; Garcia & Staples, 2000), are principally the next topic dealt with.

#### *Biomass*

The total weight of the stock on the grounds can in theory be established either by surveying or by estimating the catch and the exploitation rate from analysis of successive years of catch data sampled for size or age. Biomass can be monitored indirectly from the catch rate of a vessel (*e.g.* a research vessel or known commercial vessel category). Having information on the growth rate and rate of loss annually due to predation, allows estimates of sustainable yield to be made under a series of conventional assumptions as to the operation of fishing mortality and predation.

Trawl surveys (for demersals) and acoustic surveys (for pelagics) are "direct estimates of biomass", as opposed to deducing biomass from analysis of commercial landings. Attempts to manage shelf fisheries without annual surveys, based on analysing results of sampling schemes for age or size composition of the commercial catch, have proved less reliable. Estimates of the rate of decline in numbers of a year class in successive years can be established both from direct sampling and surveys, or the death rate due to fishing can be deduced from landing data and its size and age composition, using "cohort analysis" or its derivatives. (Although some of these methods also require data from annual surveys). At the same time, when drastic declines in fish populations occur, these two methods, if pursued independently, may give contrasting predictions. This appears to have happened in the case of the decline in Northern Cod stocks off Canada (Hutchings & Myers, 1994; Charles, 1998). The appropriate action when there is a divergent result between two methods of assessment is of course an intensified research programme, and precautionary reductions in fishing effort. Ideally, observers should be present on fishing boats to sample catches for recruitment, discards, and population biomass.

Maintaining two or more assessment procedures is costly and manpower intensive and such an approach is rarely used. However, it provides a necessary redundancy given that all methods commonly used have limited precision, and are subject to "surprises" caused by unusual factors that crop up in all long-term data series. In the absence of reliable catch sampling, repeating a regular survey with standard methods will provide a useful basis for establishing the overall trend in the fishery. Rarely however will it be possible to carry out an independent survey to establish the size of the incoming year class, and small fish may not be easily sampled with commercial gear (though survey trawls usually incorporate a smaller mesh to retain the incoming year class). In the case of acoustic surveys for small pelagic fish, the abundance of incoming year classes may be established by acoustic methods following calibration, but for large pelagic and other highly migratory stocks, there are few alternatives for monitoring than sampling the commercial stock.

### *Recruitment*

For multi-age species, annual estimates of incoming year class strength are vital to a management approach based on quotas, but obtaining convincing estimates of new recruitment poses sampling problems that for many species have not been resolved. Typically, wide population variability is a function of changing patterns of recruitment from year to year (*e.g.* Spencer & Collie, 1997), so that much of the fisheries yield comes from occasional very large year classes (Hennemuth & Autges, 1982; Fogarty *et al.*, 1991). Recruitment prediction would therefore be important for planned exploitation, but for most fisheries predicting year class strength a year or two ahead of exploitation is largely a matter of informed guesswork.

Based on an analysis of the age composition of the fishery landings, a measure of recruitment size may be possible for earlier years, as well as the parental biomass that gave rise to it, $t_c$ years earlier, where $t_c$ is the age at recruitment. These two data points, recruitment and parental biomass, may be used to fit a "Stock-Recruitment" (SRR) curve, which is a form of "control curve" that measures how recruitment has varied in the past as a function of parental stock size. Since there are other factors involved than parental stock size in recruitment success, for example environmental change also affects recruitment, these curves are rarely "clean" fits, and a wide scatter around the curve fitted to the annual data points is typical. Nonetheless, SRR's have been used to estimate at what biomass levels compensation gives way to depensation (see later section on these processes), and a SRR curve is currently used in some fisheries as an approach to finding a LRP for exploitation (see Reference Points).

### *Total and fishing mortality rates*

Because the human harvester is competing with the natural predators of the target species for their prey, the analytical assessment process has to find a way of subtracting the rate of death from predation from the overall rate of death Z, before the effect of a given fishing mortality rate on the next year's yield can be predicted. For "analytical assessments" therefore, we need to calculate the actual fishing rate – this is not directly available as an easily measured variable, but must be deduced indirectly.

The total mortality rate (Z) just mentioned is the annual rate at which deaths due to all causes occur within the fished population. If for example, the numbers added to the resource population by reproduction and recruitment increase the numbers of individuals of harvestable size annually by 20%, in theory, 20% of the resource may die due to all causes of mortality for the resource to still provide a "sustainable yield". As for any generalization, in some circumstances this is an oversimplification. The mortality rate due to fishing (F) is found by subtracting the rate of deaths due to natural causes (M) from the total death rate: F = Z-M using a variety of mathematical methods. Monitoring the total death rate (Z) is possible through annual fisheries surveys of stock biomass, or (indirectly) from calculations based on the size or age composition of catches. Standard calculation procedures and assumptions allow the number of recruited individuals remaining in the population by the end of a fishing season to be estimated, both by monitoring the age composition of the catch, and by regular at-sea surveys. As must be evident from the above, indirect estimates of the fishing mortality rate can only be approximations in most cases, and are subject to change from year to year, especially in a fishery under quota control.

It is difficult to estimate M, and in practice, certain "conventional" rates of natural mortality have been adopted for specific species: *M* is higher for short-lived species such as pelagic fishes than for longer-lived species such as large predators or long-lived bottom fishes. In other words, the actual rate of death due to fishing may be determined indirectly, by "Virtual Population Analysis" (VPA) or "Cohort Analysis" (CA) in those areas where the age composition of the stock is monitored annually. This is rarely possible in developing fisheries however, and where data are scarce, the assumption was made in the past that $F \equiv M$ (*i.e.,* the fishing mortality rate is approximately the same as mortality due to natural causes at close to the Maximum Sustainable Yield, MSY). As a generalization, this has proved over-optimistic for short-lived species whose populations are already under pressure from high predation. For long-lived top predators, harvest rates often considerably exceed the natural rate of death, and such rates are usually considered to be sustainable, and the assumption is often made that "compensation" by faster population growth occurs for fully exploited populations dominated by younger spawners.

### 2. Measurement of fishing effort exerted

Where an absolute estimate of the number of days fished is impossible, a sampling strategy may be feasible where there are several ports and limited personnel for port interviews or sampling. On random days, at a fixed frequency per week, personnel will spend a day in port and register the return to port of fishing vessels; noting the number of boxes/kilograms of fish landed. This may also be checked with the auctioneer or wholesaler operating out of the port. On this basis an estimate of total days fished/year of a boat and its contributions to the total catch from the stock area can be derived, based on the frequency of port visits.

#### Units of fishing effort

Several options exist that are given in *table 1*. It might seem obvious that the most detailed approach should be the one used, but this is not mandatory, since as emerges from the *table*, more precise measures impose serious difficulties of data collection. In relation to the last two categories for example, the horse power and tonnage of fishing vessels landing in a port regularly, should be relatively easy to establish. Sampling throughout the year of the number of vessels leaving port during a representative series of days when the port observer is present, and the typical number of hours out of port, are obtainable facts. The port captain may also keep data on the days fished by each registered boat. Evidently, the unit of measurement that can be put into effect, and is statistically reliable for all units, is the one to use. It may also become necessary that reporting of days fished, grounds fished, and weights landed, are obligatory as a condition of licensing.

Several sources of effort data can be identified; collected by:

a) Port interviews
b) At-sea observers
c) Log books or compulsory daily reporting by radio
d) Patrol vessels (occasional)
e) Shore-based radar or satellite monitoring

### 3. The definition and measurement of fishing effort and intensity

#### Effort units

Regulating fishing pressure by controlling fleet fishing power (Podesta, 1987; Robson, 1987; Millischer *et al*., 1999), or days fished, is often referred to as an 'Input control', while regulation by quotas is "Output control", and hence relies on the ability to detect changes in fishing pressure from an analysis of outputs such as catch per unit effort and size frequencies (Pope *et al*., 1988). Stock assessments in the NE Atlantic have been focussing almost exclusively on output control; (*i.e.,* stock assessments are based on catch quantity and composition; later analysed by VPA or length-based analyses). However, economic

**Table 1**
Some measures of fishing effort: ($\sum$ = sum)

| *Some possible measures of fishing effort* | *Comments** |
|---|---|
| $\sum$ Days fished/year | Here we need to calibrate between vessel/gear categories (– in theory, for ports closer to the grounds more time will be spent fishing in a day trip than for those further away). |
| $\sum$ Number of tows/year | It will not be possible to add the number of tows for different durations of tow and trawl width. |
| $\sum$ Time spent actually fishing/year | This may be estimated for a given inshore port knowing the time spent at sea on day trips after subtracting the travelling time. |
| $\sum$ (Horse power*days fished) | This approach may be appropriate for vessels of different dimensions using the same type of gear. |
| $\sum$ (Vessel tonnage*days fished) | As above, the assumption is that a larger vessel exerts a higher fishing intensity because of the increased size of net that is supposedly used. |

* Some effort definitions define searching time as opposed to actual fishing time (*i.e.,* when the gear is actually deployed) as an important component of fishing time at sea (for example, purse seiners).

analysis continues to rely on effort and capacity measures (Greboval, 1999), hence an unfortunate divergence between stock assessment and economic analysis occasionally results.

Two definitions of fishing effort are in common use:

a) "Nominal fishing effort" is measured in terms of the quantity/volume of resources devoted to fishing, either in monetary or physical units, and:
b) "Effective fishing effort" is a measure of fishing mortality, and is intended to be proportional to the fraction of population biomass extracted by fishing.

The distinction between a) and b) is reflected in the differing uses and formulation of the concept of *fishing effort* by (a) stock assessment workers, and (b) in the economic analysis of fleet capacity; (see section below). To our advantage, a direct regulation of allowable fishing effort (days at sea) may be more practical for fleets consisting of artisanal or day-boats, than it is for vessels that remain at sea for long periods. The number of boats leaving the harbour daily is more easily monitored, and a control on number and duration of fishing trips by (for example) restricting the days of the week when fishing is permitted, is at least feasible. For vessels that carry out longer trips, log-books will be required, but satellite monitoring or shore-based radar and obligatory daily reporting by radio, seem the few feasible options for controlling fishing effort directly, unless observers are used, or a MCS (Monitoring, Control and Surveillance) vessel continually patrols the fishing grounds.

## Non-uniform distributions of resources and effort

A frequent situation is one where the fleet expands its area of operation over a series of years to cover a progressively larger proportion of the stock area, and tend to develop by initially exploiting areas with highest concentrations before searching over a wider area Caddy (1975). Similar phenomena have been reported for groundfish from Taylor (1953) onwards. Fleets fishing scallops or aggregated finfish stocks direct their effort at the highest density patches, and are aided in doing this by experience, and nowadays by sophisticated sounders. Seijo *et al.* (1994, 2004) developed a suite of fisheries models to explore the consequences of non-uniform distributions of fish stock and fishing effort, and the existence of non-random or non-uniform distributions has now become well accepted.

## Availability and catchability

As just noted, the usual assumption that fishing effort is randomly distributed over the fishing grounds is unlikely to be correct, and it would be useful to clarify this issue. More recent information from telemetry or monitoring the activity of fishing vessels has shown that fishing is often intensely concentrated over limited areas of highly productive or easily fishable bottom (Fig. 1), and that fish may be attracted into this 'killing ground' from less easily fished areas around the trawling ground. This situation has been modelled by assuming that resource patches are targeted by fishing effort which is proportional to local density (Caddy, 1975). Again, this may seem theoretical, but some of the more negative effects of trawl effort can be where effort is concentrated on young fish concentrations, resulting in a high incidental mortality from discards, as well as damaging the critical habitat small fish may depend upon. Progressively, with accurate underwater sonar, rocky outcrops and sea grass beds are being damaged by trawl gear modified to work on rough bottoms.

Where fishing grounds are not uniformly fishable, the existence of areas of rough ground which are not easily exploited provides a conservation benefit, which may have to be aided by area closures. This illustrates the idea that there are two aspects to the estimate of catchability $q$, namely the fishing power of the (vessel + gear + technology + skipper skills) we have already discussed, and the *availability* of the stock which may differ throughout its range. Fish on rocky ground may be exploited if they migrate into fishable areas, perhaps attracted by the presence of food displaced from the bottom by the otter boards and trawl foot rope. An area where availability to trawling is naturally low due to rocky bottom may form a *refugium* for the species concerned. This difficulty of trawling on rocky bottom has evidently been overcome however, by the development of trawl gears that work over rough bottom, and Bellman *et al*. (2005) point to compulsory gear regulations banning such modifications to preserve these rocky refuges intact. The presence of high-risk areas can be reduced by the creation of *refugia*. This could be aided by gear regulations that make it difficult to use towed gear on rough bottom areas, or by introducing "sleeping policemen": obstacles placed in (sea grass beds) to prevent trawling.

## Zeroing in on the fishing effort that corresponds to MSY, or its analytical equivalents

*A biological foreword to discussions on MSY:*

The problem of excess fishing effort becomes evident for fish stocks that are *perennial* or multi-aged, in that the age structure of the population

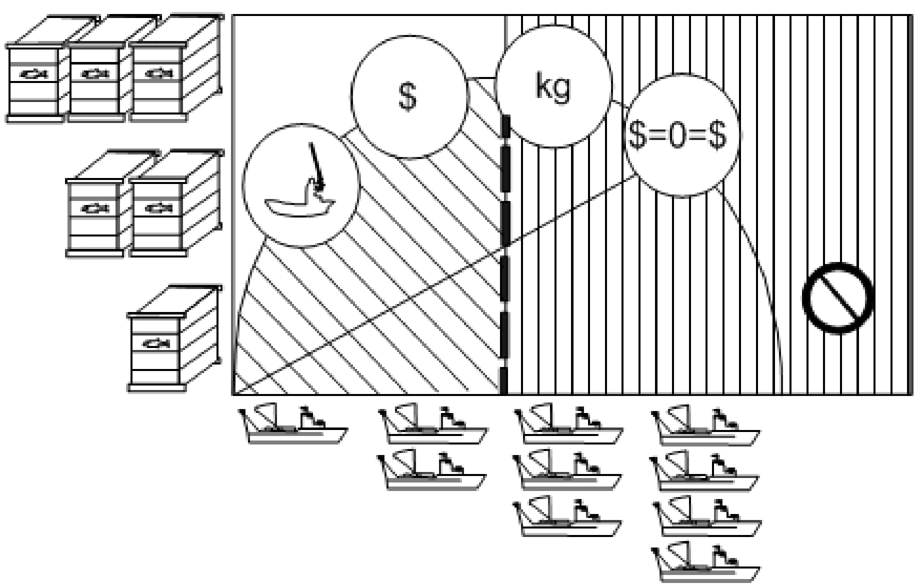



**Fig. 1.** Deterministic Schaefer model showing in the circles, the optima for different uses of a resource, displayed a simple production model of catch against fleet size. From left to right, symbols represent; an optimum for sports fishing; an overall economic optimum; maximum tonnage landed = MSY; zero profit; and fisheries collapse (from Caddy, 1999a).

is "truncated" by fishing. No more do we see those 20-30 lb cod caught by dory fishermen on the Grand Banks in the 1920's! Cod, haddock, groupers and most moderate-sized finfish, as well as large invertebrates such as spiny lobsters or scallops, have life spans of eight-ten years or more in the absence of fishing, while halibut, groupers and clawed lobsters may live longer than 30 years, and sturgeons are potentially centenarians. During at least half of their natural lifespan, most bottom fish and long-lived invertebrates reproduce each year, and mature females of some species may release as many as half a million eggs a year or more. Why do they need to produce so many eggs, given that a mature female will only need to produce a single spawning female of the next generation to replace the population? The simple answer is that the death rate by predation of larval and juvenile fish is very high, and evidence suggests that only in a few years do sufficient recruits survive to maturity to replace those lost from natural causes or from fishery harvests. Of course in these good years a considerable over-replacement by new recruits may occur (which is often followed by the cry from industry that the population has recovered, and the quota should be raised!). However, this occasional good recruitment has to support the fishery (and the reproductive needs of the population) over several years, even if fishing effort is moderate. The reason for the longevity of reproductive activity in multi-age species then becomes evident: perhaps in only one or two years in eight-ten is survival adequate to ensure population replacement.

We may ask then, what happens when fishing eliminates oldest age groups and only newly maturing females of age four-five are left in the population? The first consequence is that the biomass or standing stock of spawners is low and varies more widely since it depends on recent recruitment, and the likelihood of 'reproductive overfishing' or effort overshoots rises. Hence for both reasons fishery predictions become more unstable. The older paradigm of Beverton & Holt (1957) contributed to a false sense of security by suggesting that as long as a newly-mature year class could replace itself by spawning at least once before capture, population stability would be assured. Unfortunately, recent studies have shown that eggs from older females are not only much more abundant, but also more viable than those produced by first spawners. The upshot is that in some cases, what was a fairly stable production regime at a low fishing effort, has become progressively less stable. Add to this the unpredictable effects of climate change (Sharp, 2003), and our ability to predict population trends becomes unreliable. This is less of a problem if a strict effort control regime exists with adjustment for fishing power rises, but is a major problem where quotas are set annually based on not very precise estimates of stock size on the grounds.

**Compensation and depensation**

A simple explanation of the term *compensation* is that a stock fished for the first time (a "virgin" stock) tends to be dominated by large old fish. These are 'mined out' during the first years of the fishery when catch rates are high, and are not fully replaced while fishing pressure remains high (See: Smith *et al.*, 1998 for an estimate of "rebound potentials" of overfished shark populations). The early high catch rates and high initial catches usually lead to optimism, and promote further investment in fleet capacity, though later investments in the fishery often achieve markedly lower returns than vessels that entered the fishery early. Unlike the younger age groups that replace them, the large, old fish that dominated the unfished stock had a low growth rate, so that although the biomass drops significantly for several years after harvesting begins, stock productivity increases due to the higher mean growth rate of younger mature fish that replace them. Compensation is the mechanism underlying the theory of *production models* to be discussed later. The fact is that after the fishery has been underway for some years, productivity (net growth in weight/weight of stock) is higher than in the early years, and up to a certain level of exploitation, the stock reacts to depletion by faster recruitment and growth. This is why fisheries assessment workers and managers have come to rely on the population "compensating" for losses due to harvesting by increased growth. A higher growth is possible also because availability of food is high since competition for it has declined.

Unfortunately, once the population has been depleted below a usually undefined but low level, the opposite effect may intervene: so-called "depensatory effects" (Liermann & Hilborn, 2001). This term refers to the lower rate of population replenishment typical of a population which has dropped below a critical level. Reproduction is then less efficient, and often a depleted stock is partially replaced in the ecosystem by a competitor, and the competitor (which may or may not be a commercially valuable species) may occupy the ecological niche of the former target species, consume its food resources, and slow down its population recovery. An additional effect may also occur, namely that due to the mixed species nature of most trawl fisheries, even small by-catches of the former target species in the new fishery for its replacement species, may prevent it from recovering in stock size.

## The "power" of fishery indicators

There have been relatively few explicit tests of the power of fisheries indicators, but Trenkell & Rochet (2003) pointed out that until recently, most indicators have been based on theoretical considerations –*i.e.,* generated by mathematical models that represent preconceptions of unknown validity in specific cases, that are generated as outputs from models of exploited populations–. They took the approach of measuring indicators directly from field data collection and surveys, with minimal pre-treatment except to calculate mean values and variance. Examples they found of useful indicators for detecting the impact of progressively higher fishing intensity on finfish communities, were "the mean length of fish (all species) in the catch" (which declines with progressively higher fishing effort), "the proportion of non-commercial species in the catch" (which increases with fishing intensity), and the proportion of piscivores (which decreases with intensity). FAO has used some of these approaches to obtain indicators from reported national landings (FAO, 2006). The overall mortality rate (Z) was found to be more reliable than attempting to estimate the rate of fishing (F). As these authors point out, since no theory is put forward to support these indicators, using them to make inferences as to the state of the fishery has to be based on hypotheses, such as: "Mean age of fish declines as fishing intensity increases, hence mean sizes are lower", or: "Since piscivores are usually larger and older than the small forage fish they feed on, they will become rarer at higher fishing rates". These statements represent common sense, and the over-cautious use of such *empirical indicators,* represents perhaps the ascendancy mathematical modelling approaches have in the fisheries science community compared with field studies? What the Trenkell & Rochet (2003) study also illustrates, is that although field studies or data collection are expensive, changes in indicators coming from data collection procedures provide independent evidence, even prior to fitting theoretical models. They also provide a degree of redundancy and can confirm (or cast doubts upon) the results of one technique by comparing it with predictions from another.

Conventional single-species assessments based on surveys or commercial catches may collect more detailed data, or deduce secondary indicators from its analysis, such as on:

- Population biomass, and biomass/numbers of spawners (mature fish);
- Age or size structure of the population and mean sizes;
- Age or size at maturity;
- Indices of recruitment or year class strength;
- Condition factor and growth rate;
- Egg or larval surveys;
- Length-weight relationship or information on the condition factor;
- Abundance of main prey items;
- The reproductive potential of the adult population or its population fecundity.

## Data needs for the ecosystem approach

The ecosystem approach has suggested a wider range of indicators may need to be collected, and attempts have been made to integrate ecosystem approaches into management policy (Pope & Symes, 2000). Adding the multispecies dimension called for under ecosystem management can only be achieved by a further expenditure on monitoring. A detailed knowledge of linkages between all species in a food web is probably not needed nor is it practical, but it will be necessary to devise a series of indicators (Collie & Gislason, 2001) that give warning of unusual changes occurring in the ecosystem, even (if as is likely to be the case even for a full ecosystem model) the reasons for such changes are not obvious. Some variables that it would be wise to monitor have been suggested, *e.g.:*

- An index of abundance of the prey species of the predators being fished;
- Fishery production/shelf area – for small pelagics, demersal fish and commercial benthos;
- The ratio of demersal/pelagic production;
- The ratio of piscivore/planktivore production;
- The mean trophic level of catches.

**Reference points and precaution**

The fisheries models used for routine management have been used to estimate *reference points* (RPs) for the fishery. The first of these historically, was $f_{MSY}$; the effort that on average corresponds to MSY conditions. This is perhaps the oldest *target reference point* (TRP), but its deficiencies had become evident by 1995 when the Code of Conduct for Responsible Fishing and the UN Fish Stock Agreement were negotiated, which will be touched on later in this account. More "precautionary" target reference points have been suggested which correspond to lower, and more sustainable, rates of exploitation (Caddy & Mahon, 1995). These correspond to lower rates of harvest and also apply where less intensive uses of renewable resources such as sports fisheries occur, as shown in *figure 1* –since a lower rate of harvesting leads to higher catch rates of larger fish than at MSY–. If a commercial fishery operates on the same stock, the catch rates and sizes risk being generally lower in the sports fishery. Economic and ecosystem optima (Fig. 1) are different for each application, and will require that harvesting be carried out at a lower effort level than $f_{MSY}$, although this argument is not always taken into account where two fleets or nations compete for shares in a single resource.

Conventional reference points are often derived from one of a limited number of models of fishery yield, yield-per-recruit, or fecundity-per-recruit calculations, or from a stock-recruit relationship. In these cases, the rest of the ecosystem (and the environment, society, or economic context) is treated as "exogenous factors". As mentioned, the use of empirical indicators derived directly from data is emerging as a realistic alternative however, and Gilbert *et al*. (2000) urge this approach. They note for example, that stock-recruit relationships which imply a parental influence of the number of spawners on the number of progeny might equally realistically be replaced in many cases by functions driven by environmental variables. They also note that most fisheries models used to derive RPs assume that equilibrium conditions apply, an assumption that has been shown to be generally invalid (Caddy & Gulland, 1983; Hilborn & Walters, 1992). It might be more realistic to adopt a reference point which relates the current condition of an indicator to the observed values of that indicator during a well-studied reference period –for example when fisheries yields were favourable or unfavourable–.

By the 1970's-90's, FAO had assembled the conclusions of national assessment scientists around the world to the effect that significant numbers of fish stocks, especially of longer-lived species, were being fished harder than at $f_{MSY}$ and that some had become depleted. More explicitly, precautionary reference points had by then been proposed (Caddy & Mahon, 1995), including, a new category of reference points; the Limit Reference Points (LRPs). These were intended to be used in a different way from TRPs: the proposed strategy is that rather than aiming the fishery at an optimum which inevitably results in an appreciable risk of effort overshoot, a minimal condition for the fishery is defined, when important indicators show that there is a high statistical probability that dangerous or "red" conditions of the fishery are being approached. Action is then taken on an urgent basis to reverse the situation. To define LRPs, both the output of mathematical models, and criteria suggested by past experience with managing the resource, are used. Management is mandated to take the necessary measures to actively avoid these conditions, in order to reduce the chance of arriving at an LRP to a statistically low probability. This is an explicitly precautionary approach, and can be achieved by several strategies:

1) Derive reference points from the models used in past conventional management. The reference points $F_{0.1}$, $2/3f_{MSY}$ and $0.2 \cdot B_0$ are all basically arbitrary limits, but correspond to desirable results.
2) From past experience with this or similar fisheries, define a LRP for each indicator series that corresponds to the indicator values that applied *just before* the fishery reached a previous low or critical point. These values for the LRPs are the indicator values that lie just above (in the case of indicators of population biomass), or just below (in the case of mortality rates), what past experience suggested might bring the resource into jeopardy.
3) It may be possible for selected fisheries to obtain formal assessments. If not, using indicators based on FAOs Code of Conduct may be an alternative option, using a score derived from the questionnaire approach (FAO, 2007).

What should have emerged from the discussion so far, is that there has been a logical sequence in the development of indicators and reference points from those resulting from fitting models based on particular concepts of fisheries biology, to a broadening of applications to include reference points derived from time series of information obtained from field surveys and socio-economics, and that the formulation of these reference points correspond to particular values of these time series which are believed to represent the onset of dangerous or risky conditions. To be useful, indicators and reference points must be capable of integration across academic boundaries, and indicate the onset of overcapitalization and a resulting depletion of resources. It seems unlikely that a formal fisheries assessment will be vital to establishing if the resources are at risk; more easily available information, well-established criteria and procedures may provide an acceptable context for decision-making. Complicating the picture however are new perspectives which see fisheries management as a dynamic process, involving cooperation by several actors or participants, as in *table 2*.

Clearly the precautionary approach is more frequently evoked, as uncertainty (both in terms of data and of the appropriate models to use), becomes evident. Two particular consequences of applying the precautionary approach can be mentioned: firstly, the extensive use of the LRP

**Table 2**
Relative roles of different participants in the fisheries management process in defining reference points or a Fisheries Control Law

| *Scientists* | *Management* | *Industry* | *NGOs* |
|---|---|---|---|
| Measure or estimate the current size and reproductive potential of resources.<br>Suggest a number of reference points for management based on historical data. | Consider past changes in fishery yield as a function of expenditures on effort/capacity, and how indicators suggested by scientists have varied in relation to the various RPs suggested. | Use information on landings, area and time fished as a condition of licensing. Offer reactions to the current fisheries management regime in industry/ government meetings. | Point to data series, ecological situations, or analyses in this or similar fisheries, which have been ignored by management. |
| Define options for safe exploitation of the resources in relation to the reference points agreed to; expressed both in terms of fishing rates and biomasses. Suggest options for decision rules within which RPs will play a key role. | Develop a management plan for the fishery incorporating contingency plans for use if particular stock conditions arise.<br>Develop recovery plans in the case of stock collapse or depletion. Discuss these plans with the fishing industry and NGOs. | Suggest practical problems that are likely to arise in application of a management measure. | Suggest loopholes in the application of such options that could put at risk the species under conservation. |

concept, and secondly, the new concern within fisheries and ecosystem management, that a broader range of data series need to be monitored than the few series now used for formal single species assessments.

At the same time, most management bodies have established that the role of the fisheries scientist is not to suggest the harvesting strategy but to respond to management questions. They are supposed to state their best opinion of the consequences of a series of options being considered by management, and what is the risk by taking one of these decisions that it will lead to serious depletion below safe biomass levels. In a situation where most assessment workers are government employees working for national decision-makers, it takes courage to tell your employer that a fishery must be halted or seriously curtailed, since it does not fall within your terms of reference as described above. This is one reason why overview of fishery management decisions by a panel of independent experts has become common practice, at least for some international fisheries. In the absence of this safety valve, national and international NGOs (Non-Governmental Organizations) can play a key role, but only if the assessment data are available in the public domain. The need for technical overview of decision-making is even more important where the fishing industry is pushing through political channels for higher harvests.

It is also clear that despite their controlling role, managers should be restrained in their decisions by biological realities. Ideally, they should follow some pre-defined rules in deciding which management options are safe or when they may be approaching a dangerous condition; such as when the indicators chosen approach their pre-defined LRPs. Clearly, there is a need for a more specifically-defined interface between scientific advice and management action. Given the lack of ecosystem models that can take a wide range of management data into account, management rules need to be established which constrain what decisions should be taken if LRPs for the various indicators monitored are approached. This leads to management following a formal management rule incorporating indicators and their LRPs, as was originally proposed within the International Whaling Commission. This approach has also been adopted with some success, in southern hemisphere fisheries of Australia, New Zealand and South Africa (Hilborn & Walters, 1992; Butterworth *et al.,* 1997). These countries, together with some Northern hemisphere applications, appear to be at the forefront in the development of the *fisheries control rule* approach to *scientific management*.

**Displaying multiple indicator series**

Especially in the case of a group of non-experts evaluating the significance of indicator values, or where a formal assessment is missing, it is important that these values be presented in a non-technical way, and that the full range of past and present values of the indicator are available for inspection. A hypothetical example follows (Table 3) which suggests a set of indicator series that might be collected for a hypothetical fishery for a crustacean species A, but which also takes into account changes in abundance of its predators and competitors. In this case, the indicators are separated into 'Characteristics' which explain their practical significance, directly or indirectly:

In *table 3*, indicators monitor, directly or indirectly, the four *characteristics* of the population shown in the right hand column. The values for each can be displayed together in the form of a traffic light display (Fig. 2).

Taking a broader approach suggests that in addition to the 'Fisheries Indicators' discussed so far, indicators of environmental change, socio-economic and market factors, and the success of control and surveillance, may also require to be maintained by fisheries management, as in the following chart suggested for Black Sea fisheries (Table 4). Here, as for other enclosed seas, environmental change is a major factor affecting fisheries production, and cannot be neglected by fisheries managers.

In the case of fisheries where environmental change has reduced productivity, using the previous virgin biomass estimate would bias the indicator, as in the case of the Black Sea where the introduction of exotic species and eutrophication from land runoff has changed the productive capacity of the system. Referring subsequent trends in the fishery to conditions that applied (say) in the

**Table 3**

Four indicators for each of four characteristics of a possible traffic light monitoring system for a target crustacean species A, with predators 1 and 2, and a co-occurring species B (From Caddy, 2004)

| *Indicator* | *Characteristic* |
|---|---|
| 1. Mean survey catch per trap | Abundance |
| 2. Area with density >5·m$^{-2}$ | |
| 3. Early-season catch per trap haul | |
| 4. Bycatch species A on trawl fishery for species B | |
| 1. Number of recruits (carapace length <5 cm) | Production |
| 2. Area of recruit density >10·m$^{-2}$ | |
| 3. Mean size of mature females | |
| 4. condition factor (carapace length = 10-15 cm) | |
| 1. Mean $Z_t$ from survey data | Fishing pressure |
| 2. Fleet days fished per season | |
| 3. Immature individuals (%) | |
| 4. Annual number of trap hauls per area grounds | |
| 1. Abundance (predator 1/species A) | Ecosystem/environment |
| 2. Abundance (predator 2/species A) | |
| 3. Absolute value (bottom, temperature - optimum temperature) | |
| 4. Prey abundance·m$^{-2}$ | |

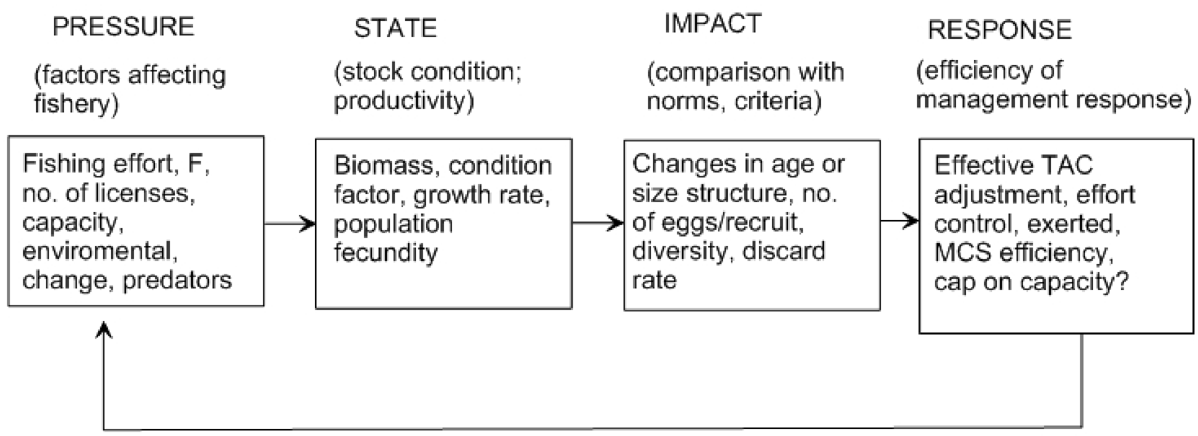


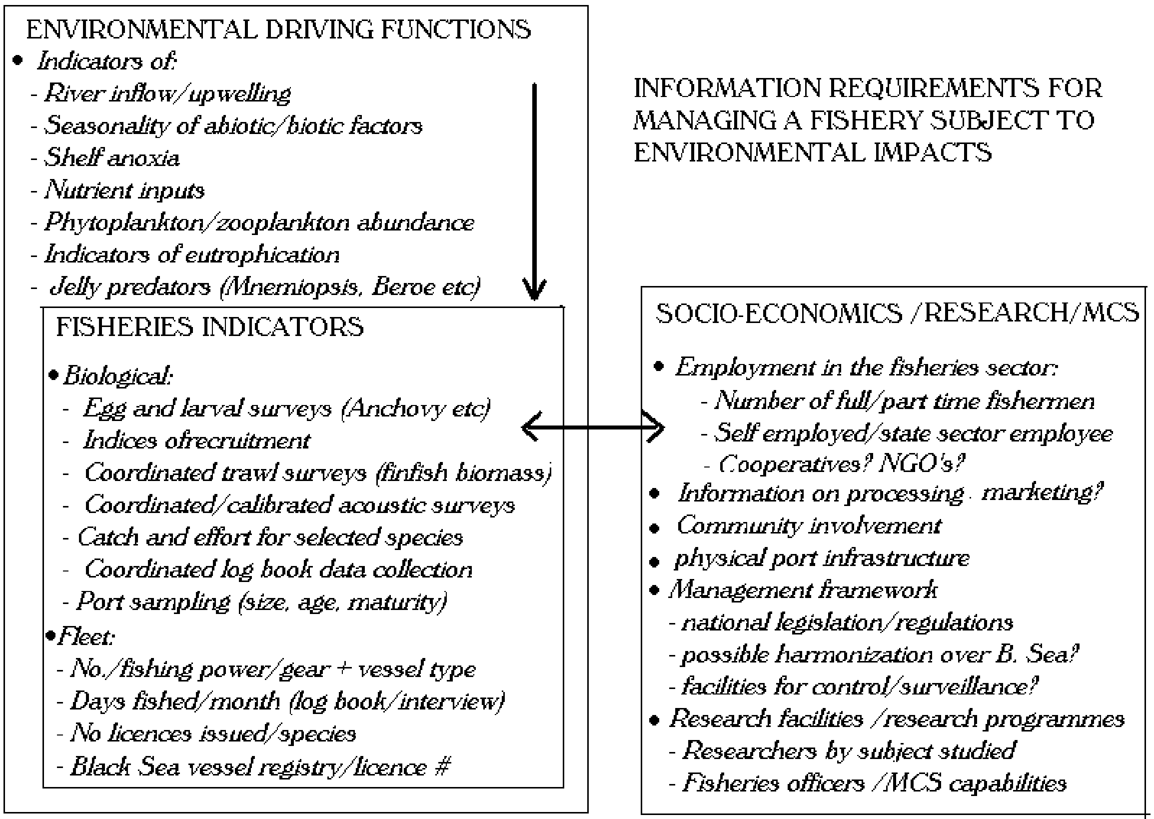

**Fig. 2.** Use of the PSIR approach as indicator display and use (from Caddy, 2004). Pressure, State, Impact and Response (PSIR) framework for fisheries research and management envisaged in the context of an annual research and management cycle. TAC, total allowable catch; MCS, monitoring control, and surveillance; F, fishing mortality.

three years of highest population biomass, or the when the profit margin was highest for example, would be one approach to formulating an indicator value relative to some desirable condition.

One approach for categorising and displaying indicators (Fig. 2) is the PSIR framework, which categorises indicators into four measures of the condition of a fishery and its management system: "Pressure" (on the stock); "State" (of the stock); "Impact" (measuring changes in the stock of concern to management); and "Response" (the effectiveness of management measures in restoring stock size or condition). Each characteristic is represented by different indicators. This approach, which is used in terrestrial systems of monitoring environmental quality, has also been discussed for application to fisheries (Gilbert *et al.,* 2000 and other papers in an

**Table 4**

How a range of indicators ideally cover changes in a variety of characteristics influencing fisheries success (from Caddy, 2002)




issue of *Australian Journal of Marine and Freshwater Research*, Vol. 51).

Gilbert *et al.* (2000) noted that a modified PSR (Pressure-State-Response) framework has officially been adopted in New Zealand for "state-of-environment" reporting by the government, and has led to an officially-accepted set of indicators. These only use direct pressure indicators rather than those that imply an indirect impact, (which in the author's opinion is unduly restrictive). Both the PSIR (I = Impact) or PSR frameworks, and the Traffic Light approach which classifies indicators into different characteristics (Caddy, 1999b; Koeller *et al.,* 2000; Halliday *et al*., 2001), provide managers with a simultaneous visual display of the state of the resource. This can be useful, even in the absence of an overall population model (which would be largely impossible to provide for the wide range of phenomena suggested in the above tables). Of course, achieving a monitoring framework incorporating such a wide range of variables would be costly, but many variables are already being collected outside the fisheries sector, such as sociological, economic and climatic data, and the issue here is how to assemble existing information into a readily understandable framework, rather than collecting new data.

**Some stock assessment basics**

Stock assessment is a practical application of population demographics to optimizing management decisions on the level and type of exploitation of a commercial fish or invertebrate stock. The main objectives are to establish the current status of the fish population, decide on a favourable exploitation strategy, and predict the behaviour of a stock in response to a given level of fishing effort or catch quota exerted on it by the fishing fleet(s) exploiting it. To do this, widely accepted mathematical procedures are applied to data series collected, reflecting simple models of population processes. The basic data comes from surveying the fishery (catch, effort and age and size composition of the catch), and more frequently nowadays, from regular surveys of the resource by research vessels (biomass, age and size composition). The distribution pattern, annual recruitment, and by special sampling possibly also the abundance of reproductive products or *planktonic larvae*, may provide the basis for estimating current stock size and optimal harvest levels. Because only a few variables are under human control (although these are often the most influential), the usual approach is to seek a means of adjusting fishing effort and/or catch to sustainable levels by analysing data trends collected, usually, over an annual cycle.

## Different schools of theory and practice in assessment science

More complex models have been developed with the aim of understanding population processes (for example, models of the marine ecosystem), and these may provide some insight into the ongoing processes. In practice, however, complex conceptual models have rarely proved very successful in providing concrete advice to fisheries managers. Hence, practical assessment advice is usually based on relatively simple models that use only a few types of data input, and necessarily assume that the principal factor influencing population changes is the intensity and selective pressures exerted by fishing. The practical constraint on using multiple indicators and complex models is also largely a function of the high level of uncertainty in our estimates as to the size of the fished population and of the mortality undergone by the target species. The high cost and low precision of much biological data on fishing operations, means that precise information both on the fish populations and the activities of harvesters is usually lacking, and the variance or bias associated with most indicator series used in assessment is fairly high, (the best estimates of population size from data analysis for example, are likely to be within 10%-30% of the true value). In these circumstances therefore, the possibility of overoptimistic decisions, even where the best estimate is used, are significant, and this is one reason why, in the post-UNCED era (United Nations Conference on Environment and Development); the *precautionary approach* has been introduced.

Ecosystem modelling approaches are now being actively promoted, but as noted, are still at an early stage of development and still not much used in providing advice to fisheries managers on what quotas or other regulations to set for commercial resources in the following year. On this point, it should be noted that the principal purpose of quota management is mainly to facilitate resource sharing between parties. If ecological objectives were predominant, a serious curtailment of areas/seasons fished and fleet numbers and capacities would be more appropriate. As before, most stock assessments deal with a target species and are referred to as single species assessments. Two approaches to single species assessment have generally been followed in the not so distant past, and are still used today in many areas. The first attempts to determine population structure by establishing rates of growth and mortality during the life history, through an analysis of the size or age composition of catches or survey data over time. These are generally referred to as analytical methods. The other school of practice seeks to fit more abstract mathematical or statistical models to the catch, effort, or catch rate data collected, without attempting to determine biologically meaningful biological rates such as growth or mortality. These “empirical” or statistical approaches are greatly facilitated by the powerful statistical packages now available on microcomputers. A common approach was referred to as “production modelling” in the past, but “biomass dynamic modelling” is a more current terminology.

There have also been changes in procedures to allow better fitting of these models to fishery data that can usefully be mentioned. The first is that uncertainty is specifically incorporated, by making the models “stochastic”, such that where the error around an estimate is known; variance can be incorporated into the model. A variant of this is the so-called Bayesian approach which adds a variance term to the formerly fixed values of population parameters, and generates output not as a single number, but as a statistical distribution allowing probabilistic statements to be made. One comment is that while adding information on individual processes increases model realism, it also adds more mathematical parameters to the assessment –or more "degrees of freedom"–. Adding more degrees of freedom by means of an ecosystem model with 20 interlinked species in the food web, for example, might seem a good idea, but of course adding more parameters means more sources of error, and rarely are there accurate estimates of the abundance for all species in the ecosystem. This appears to be one reason why relatively simple models are still commonly used to follow changes in a fishery.

Up until the 1980's, *production modelling* generally assumed that a fish population was either "at equilibrium" with the current level of fishing effort applied, or that a minor mathematical adjustment could lead to what was at the time called an "equilibrium production curve", which it was supposed could be used to predict the long term average yield for a given level of fishing effort. This approach has now largely been discarded in favour of "dynamic modelling". The practical implications of this changeover are a greater realism: negative events are generally predicted to occur at a lower effort level with more dynamic approaches. A variety of approaches to dealing with variance and optimal fitting have been developed, and quite often "schools of practice" have arisen in specific regions: thus outgrowths of production modelling are commonly used in the East Pacific and in tuna fisheries where age and size composition is difficult to obtain, but analytical methods tend to be predominant in Atlantic shelf fisheries.

The old terminology of "sustainable yield" is less often used by assessment workers nowadays, since it is understood that fish stocks and their environment and ecological interactions are inherently variable. Often the population biomass is unstable in its response to variable levels of fishing effort, and the stock shows chaotic processes associated with climatic fluctuations and ecosystem interactions with exploitation rate within the multispecies food web which are difficult to predict. Hence at the technical level, achieving "sustainable development" is not just a question of aiming for MSY (Larkin, 1997), or establishing a suitable fishing regime and "taking the management hand off the wheel" so to speak. This might have been possible, for example, if exploitation rates had remained moderate, at a level of fleet capacity corresponding to (say) 1/3 of the effort level ($1/3 \cdot f_{MSY}$) leading to what is called the "Maximum Sustainable Yield". $f_{MSY}$ was the conventional target reference point for fishing effort under the Law of the Sea (and the biomass corresponding to MSY is still the objective established by the UN Fish Stock Agreement for fisheries recovery plans). However, various management bodies have come to see that less ambitious targets would be wiser and safer, but the problem is seeking agreement for significant cuts in fishing effort and mortality. The population tends to instability under intense exploitation, and experience shows that attempting to extract the "last drop of productivity" from a stock, makes it progressively more unstable, and the fishery becomes more likely to unknowingly overshoot the effort level corresponding to MSY, with the risk of collapsing the fish population. Evidence suggests that if fishing effort is then reduced, the recovery time back to MSY conditions may be slow (Hutchings, 2000; Powers, 2003; Caddy & Agnew, 2004). Recovery may only be achieved by years of severe fishing effort restraint at below previous levels. The upshot is that in some cases, what was a fairly stable production regime at a low fishing effort, has become progressively less stable. Add to this the unpredictable effects of climate change (Southward *et al*., 1988; Lluch-Belda *et al*., 1989; Steele, 1996; MacCall, 2002), and our ability to predict population trends becomes less and less reliable. Nonetheless, a close control of fishing effort by effective fisheries policies is vital (Cunningham & Whitmarsh, 1980).

## A brief historical summary of the use of fishing effort in stock assessment

A geographical differentiation in the development of fisheries assessment techniques has been evident globally in the use of fishing effort data. This is seen when comparing the evolution of fisheries assessment and management approaches in the North Atlantic, with fisheries in the NE Pacific as well as tuna fisheries worldwide (De Leiva & Majkowski, 2005). The use of fishing effort in production modelling was proposed in Europe by Graham (1935), but has never been much used in the Eastern Atlantic, but Schaefer (1954) and later authors applied it to North American fisheries and tuna resources. In the 1970's-1990's there was a change in production modelling methodology, from the equilibrium-based approach promoted by John Gulland, to the non-equilibrium approaches described by Hilborn & Walters (1992) and Punt & Hilborn (1996), and production modelling is still widely used outside of Europe, especially in the management of tuna fisheries, or where biological data are limited.

The production modelling approach was not widely used in the NE Atlantic for reasons that related to the multinational and multispecies nature of fisheries there, in which a diversity of fishing gears and national regulations made separate calibration of fishing effort by species impractical, especially under quota control. For the same reason, in the Northeast Atlantic, fitting the MSY reference point from time series of catches and fishing effort was abandoned (a procedure still used in other parts of the world), and was substituted for by the development of RPs based on analytical and SRR models. Most of the assessments in the NE Atlantic depend on size and age compositions obtained by comprehensive catch sampling schemes and research vessel surveys. In the tropics, the use of analytical models was also promoted, employing length-based sampling of catches. This has led to a neglect of earlier attempts promoted by John Gulland and others to monitor the growth of fishing pressure directly. These length-based (and now trophic-based) sampling procedures permitted biologists to remain within their area of specialization, but often neglect the collection of relevant effort data. Hence, they have the major disadvantage that the main source of mortality on the stocks, *i.e.*, fishing pressure, is not always studied directly in any detail, but inferred from changes in the age composition of the stocks!

More recently Holden (1994) noted that despite quota control, several demersal stocks in the Northeast Atlantic have declined to historically low levels, while exploitation rates remain high. Shepherd (2003) has called for a return to some form of effort control, and a re-evaluation of effort assessment and management methods is now underway. Rijnsdorp *et al*. (2006) saw the lack of synchronous depletion of species quotas as leading to discarding and misreporting of fish species, especially those caught incidentally to other species and discarded dead after their quota had been filled. Despite the problems of sharing stocks and comparing the fishing power of different gears between national fleets and vessel classes (Martel & Walters, 2002), opinion in the ICES area seems to be swinging towards the feasibility of direct control of fishing effort (Ulrich *et al*., 2002; Shepherd, 2003). This last author suggested that under an effort allocation scheme, vessel entitlements be adjusted on the basis of past fishing performance, and enforced by satellite monitoring.

The situation portrayed in *table 5* is not fully exclusive, since hybrid methods have been developed that employ aspects of both approaches (*e.g.* production modelling with mortality rates). Nevertheless, regular annual sampling of commercial catches for biological data remains a problem in many areas, and attention may have to be focussed mainly on sampling survey catches for analytical information, as in the Mediterranean; sampling high-value commercial catches in port is impractical there. For many Mediterranean fisheries, and elsewhere, the multispecies multi-gear issues remain a major problem. However, as for many tropical fisheries, local small-scale fisheries operating within a given Management Unit are not difficult to monitor, since boats are generally fishing locally to port on a daily basis (Table 6).

The Response indicators are assumed to be largely the responsibility of the MCS arm, with appropriate consultation with stakeholders to ensure that the fishing industry is respecting the need to maintain effective effort levels in check. Specific committees considering fleet replacement plans and technological developments will presumably also be needed to keep an overall cap on fishing pressure, and hence on capacity, fishing power, and the number of fishing licences.

## Empirical approaches

When we discuss assessments in the developing world and the past work of FAO in this field, it will

**Table 5**
Some advantages and drawbacks of analytical and catch-effort modelling approaches

| | *Analytical methods using biological data* | *Methods using fishing effort data* |
|---|---|---|
| Some advantages: | - Data sets are more closely linked to the biological realities of the species and a monitoring of its potential productivity.<br>- Ecosystem and biodiversity issues, at least potentially, can be linked to analytical assessments.<br>- The net effects of a variety of gears are assumed to be integrated within the size/age composition of catch samples. | - Catch-effort modelling approaches and results are generally understandable to the industry and managers.<br>- Surprisingly, dynamic models using relatively simple "black box" concepts with minor data needs other than catch and effort, give results comparable to much more complex analytical procedures. In fact, the uncertainties in a model are predicted to increase with the number of variables and parameters that need to be fitted.<br>- More recent fisheries models based on catch/effort have been made spatially relevant; representing the real contagious distributions of resources and fishing effort over the grounds and stock distribution areas. |
| Some disadvantages: | - A high species diversity and the need for age/size sampling by species imposes impossible requirements for sampling to model analytically the entire suite of commercial species; (some 100's in tropical multispecies bottom fisheries).<br>- The cost of sampling and size/age analysis would be prohibitive for many small, local fisheries.<br>- Systematic errors can be introduced by exclusive reliance on VPA or its derivatives.<br>- VPA estimates are retrospective, and offer inaccurate information on the size of cohorts currently fished until they have completely passed through the fishery.<br>- An exclusive focus on biological data for analysis is opposed to the concerns of fisheries management and the fishing industry, which are primarily on catches and the activity of fleets.<br>- Economic models of fisheries performance are largely based on the Gordon-Schaefer production modelling approach. | - Major problems are caused by multinational, multi-gear and multispecies fisheries for both approaches.<br>- The steady growth in fishing power of fleets must take into account the effects of new technologies introduced.<br>- Issues such as recruitment failure, predation, growth and natural mortality are subsumed within the production model approach and must be sampled or studied by supplementary analytical approaches.<br>Biological sampling and surveys will be needed, but not necessarily annually. |

be evident that for only a relatively small proportion of world fisheries (though some of the more important quantitatively), are detailed data gathered, nor is there always access to the specialized personnel needed for assessment work on an annual basis. Generally, the data gathering capabilities to support assessments and the manpower and computer facilities for data storage and analysis, and research vessel survey capabilities, are lacking for many countries where marine fisheries have economic and dietary importance. Assessments and surveys may be only carried out occasionally –perhaps assisted by short-term aid programs–.

*Where data series are limited to overall catch.* Such indicators based on catch can be determined from the time series of catches, and the electronic equivalent that has replaced them. In some cases, the basic data set available to support an evaluation of the state of a resource is restricted to a series of annual catches by key species in which the landings from individual stocks may not be separated. As has been indicated in specific cases, these landing figures may be influenced by government plans calling for a particular level of production. Nonetheless, annual series of catch statistics are likely to be most reliable for fisheries subject to directed fisheries, but less so for rare or occasional species that may be

**Table 6**
A hypothetical division of labour using a PSIR framework for monitoring a fishery and its environment

| | *Pressure* | *State* | *Impact* | *Response* |
|---|---|---|---|---|
| Time frame | Annual & Longer term | Annual | Annual | Real time collection and responses |
| Personnel | Research, environmental & statistical officers | Research and assessment workers | Research and assessment workers | Monitoring, control and surveillance staff (MCS) |
| Roles | Collect + collate data sets, survey results, & develop indicators with measures of variance | Develop data sets into series of indicators using simple models where necessary | Collaboration between all sectors to decide on indicators, LRPs, and the current distance of an indicator from the agreed LRP. | Ensure a collective fishery law is equitably applied, and that responses to critical values of indicators are enforced |
| Performance measures of: | Appropriate data coverage; prompt collation of information | Cross calibration of indicator responses to ensure changing stock and environment status is correctly monitored. | Develop consensus around LRP values that are precautionary. Assess the probability that current values infringe pre-agreed LRP levels. | Good communication with industry to ensure that rationale for indicators, LRPs and appropriate responses are understood, and industry inputs are incorporated. |

incorporated into mixed fish categories. Analysis of trends in catch series may then be the only option for gaining some impression of the state of exploitation. Although the causes of trends may be ambiguous such that a low level of landings in recent years could either represent a low biomass, or as noted by Caddy & Surette (2005), low catches could reflect strict regulation of catches in order to allow stock recovery. Nonetheless, a basic assumption in analysing recent catch trends seems valid, namely, that there is a high and unsatisfied demand for fish globally by a well-developed trade network, and hence prices for fish are rising faster than for other food commodities (*e.g*. grain –see the 1995 FAO Conference in Kyoto, on the sustainable contribution of Fisheries to Food Security–). This means that in most cases, a low level of recent catch compared with previous years is almost certainly a result of a decline in stock size unless radical control measures have been introduced, and not due to a loss of commercial interest. Even superficial local information or sources of market data (*e.g., www.globefish.org*) can be used to confirm this supposition.

A recognition that time series of landings may be the only data set available has led to a series of methodologies based on analysis of landing time series. Some examples follow:

The problem of recognizing stock depletion for many marine resources has made for difficulties in establishing criteria for listing a species as "threatened" or "endangered" (Roberts & Hawkins, 1999; Abbitt & Scott, 2001; Hutchings, 2001; IUCN, 2002; Dulvy *et al*., 2006). CITES (Convention on International Trade in Endangered Species) with FAO (FAO/CITES, 2002), proposed several criteria which ideally could be applied to time series of survey biomass, but have also been applied to landing time series. They recommend considering several criteria, and following their suggestion, Garibaldi & Caddy (2004) used three "filters" to sort out depleted species, based on FAO landings time series where the following three criteria were valid:

*Criterion 1*: The slope of the catch trend over the last five years was negative;

*Criterion 2*: The average rate of the catch decline between the peak period and the mean catches of last three years was greater than 5% per year;

*Criterion 3*: Mean catches for the last three years had dropped below 20% of the peak value.

Obviously, a similar approach could be used to identify resources corresponding to a lesser degree of stock depletion, and Grainger & Garcia (1996) used cluster analysis to identify groups that correspond to the four categories mentioned earlier in the FAO diagnosis of global stock status.

The approach adopted by Garibaldi & Caddy (2004) is shown in *figure 3*, and attempts to identify seriously depleted fish resources which merit priority investigation as candidates for stock restoration. The occurrence of similar time series that meet all three criteria could be considered by regional fishery bodies as a valid reason to investigate the overcapacity of the exploiting fleets, or other anthropogenic stresses. In this case, the extent and rate of decline were measured with respect to the maximum value of a three year running average of catches registered in the FAO capture database since 1970. A match to all the criteria was considered an indicator that urgent attention is needed for this renewable resource on the part of fishery managers.

Grainger & Garcia (1996), Garibaldi & Limongelli (2003) and FAO (2006) provide a description of the approach now followed in establishing stock status for the regular series *Review of the State of the World Fisheries Resources: Marine Fisheries* issued by FIR/FAO and will be discussed under that section of the report.

**Empirical approaches based on time series of landings and other data sets**

Caddy & Surette (2005) reviewed landing time series for the NE and NW Atlantic for some 115 key commercial species since 1970, and came to the sobering conclusion that evidence for sustainability of these resources was hard to find. A traffic light approach was used to produce bar charts for each species which were placed in order of the year when 50% of the landings in the time series had been taken (Fig. 4). The maximum catch for each species in the time series was divided into quartiles. The range of observed landings of a species was divided into low (red), low-medium (yellow), medium to good (green), good-excellent (blue). Evidently the colour "red" in the earlier years does not mean overexploitation, but just low catches; whereas we may begin to suspect that when red (low catches) persists over a decade or more, stock depletion likely has occurred, although this conclusion may be erroneous where a fishery is under rebuilding and effort has been cut drastically. The left column shows that invertebrates (brown) have tended to peak recently, and pelagics (blue) and demersals (pink) have risen to high landings before dropping again. *X*'s show species considered depleted by Garibaldi & Caddy (2004). The asterisks in the chart mark the year by which 50% of total landings over the period were taken, and those in the left column mark deep water species. The typical series of colours for species that became exploited in the period 1970 to 2002, was a rapid rise from red to blue, followed by a slow decline to yellow and then red. For a significant proportion of species, especially finfish, landings have

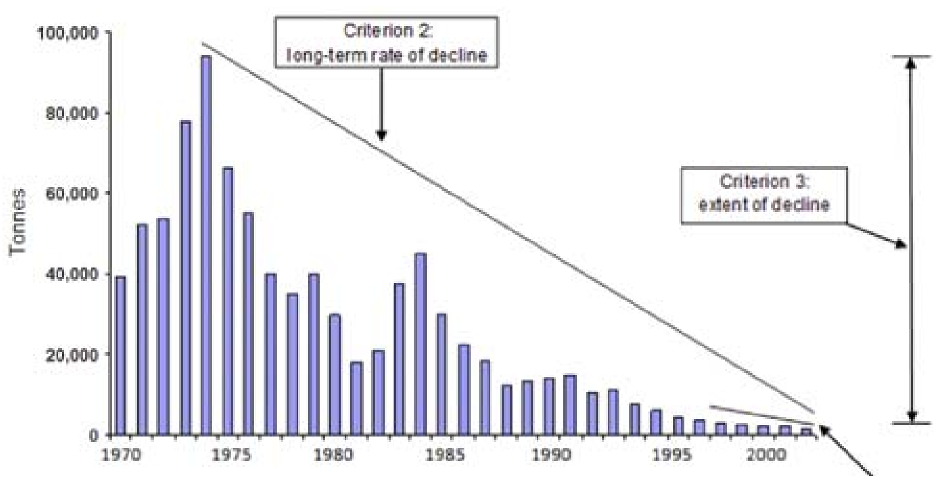



**Fig. 3.** Hypothetical example showing the three criteria used for classifying a resource as depleted based on historical FAO data (from Garibaldi & Caddy, 2004).
(N.B: Criterion 2 regression from peak year through 3-yr running averages is only represented diagrammatically here).

remained in the red category for a significant number of years. The only evidence that suggests "fishing down the food web" was in the NW Atlantic, where a progressive dominance of landings by invertebrate species possibly reflects a reduction in predation by finfish. "Fishing down the bathycline" seemed indicated however: *i.e*., the fishery has progressively targeted deeper water species, once shelf resources became depleted. Although there a variety of definitions of overfishing in common use (e.g. Regier *et al*., 1999; Murawski, 2000), this colour change could be a useful indicator of overfishing: the proportion of deep water species in the national catch seems to imply overexploitation of the (more productive) shelf resources. Evidently sequential depletion of resources has occurred, and the *figure* also shows that the recovery of stocks for the NW Atlantic as a whole is still at an early stage.

The trajectory of landings that appears typical was confirmed by fitting a series of mathematical functions to the landing time series. The best fitting function was the Hubbert curve; originally proposed for modelling a non-renewable resource –the predicted time series of petroleum extraction (ironically, an application where this function has *not* provided a good fit!)–. Nonetheless, it is sobering to consider that the best fitting model to fisheries landings is one aimed at explaining a production series for a non-renewable resource.

As noted, some partial successes have been obtained in the NW Atlantic with recovery plans, and a combination of past high fishing regimes and a current low productivity regime, with high natural mortality and poor growth conditions, seem to be responsible. The spectacular recovery of productivity of invertebrate species of commercial interest however, does not appear to be a function of improved management, and may represent an interspecies interaction. Such species interactions were not evident between finfish species, suggesting that a "pulse" of high fishing effort, possibly made more severe by a deteriorating environmental regime later in the time series (Zwanenberg *et al*., 2002), was the dominant factor leading to stock declines in the Northwest Atlantic, and to a lesser extent in the NE Atlantic (O'Brien *et al.*, 2000).

In general, the recent development of empirical approaches for following fisheries developments seems to reflect five main factors:

- A shortage of comprehensive data preventing full stock assessment procedures being applied to many species, and the realization that this shortage is likely to persist into the foreseeable future;
- The realization that a wider range of indicators may be available as a result of current fisheries survey efforts. While these might not directly measure biomass or mortality rates, they might help signal changes in the resource and environment, and provide "monitoring redundancy";
- The general acceptance of a "limit reference approach" has encouraged judgements as to which point in any indicator series corresponds to an ecologically abnormal situation or an unacceptable risk of stock collapse;
- A means of simultaneously displaying a larger number of indicators in either a "traffic light approach" (Caddy, 1999b, c; 2004; Halliday *et al*., 2001), or a PS(I)R approach (Malkina-Pykh, 2000; Caddy, 2004), facilitates visual identification of possible linkages of ecosystem change in a way that ideally should precede specific investigation or modelling;
- Based on values adopted by other indicators, in addition to the three used in conventional assessment, a "Harvest Control Rule" may be developed to provide guidance for management action, even if a classical fisheries assessment is unavailable. This will be especially useful if the indicator values preceding previous stock declines are known.

## Multispecies or ecosystem assessment and its data needs

A theoretical consideration of species interactions in the marine environment has a long history, and studies of predator-prey interactions have shown that separate single species assessments of predator and prey (cod and capelin, or Norway lobster and cod and whiting in the Irish Sea, Brander & Bennett, 1989), give quite different results when trophic interactions are specifically

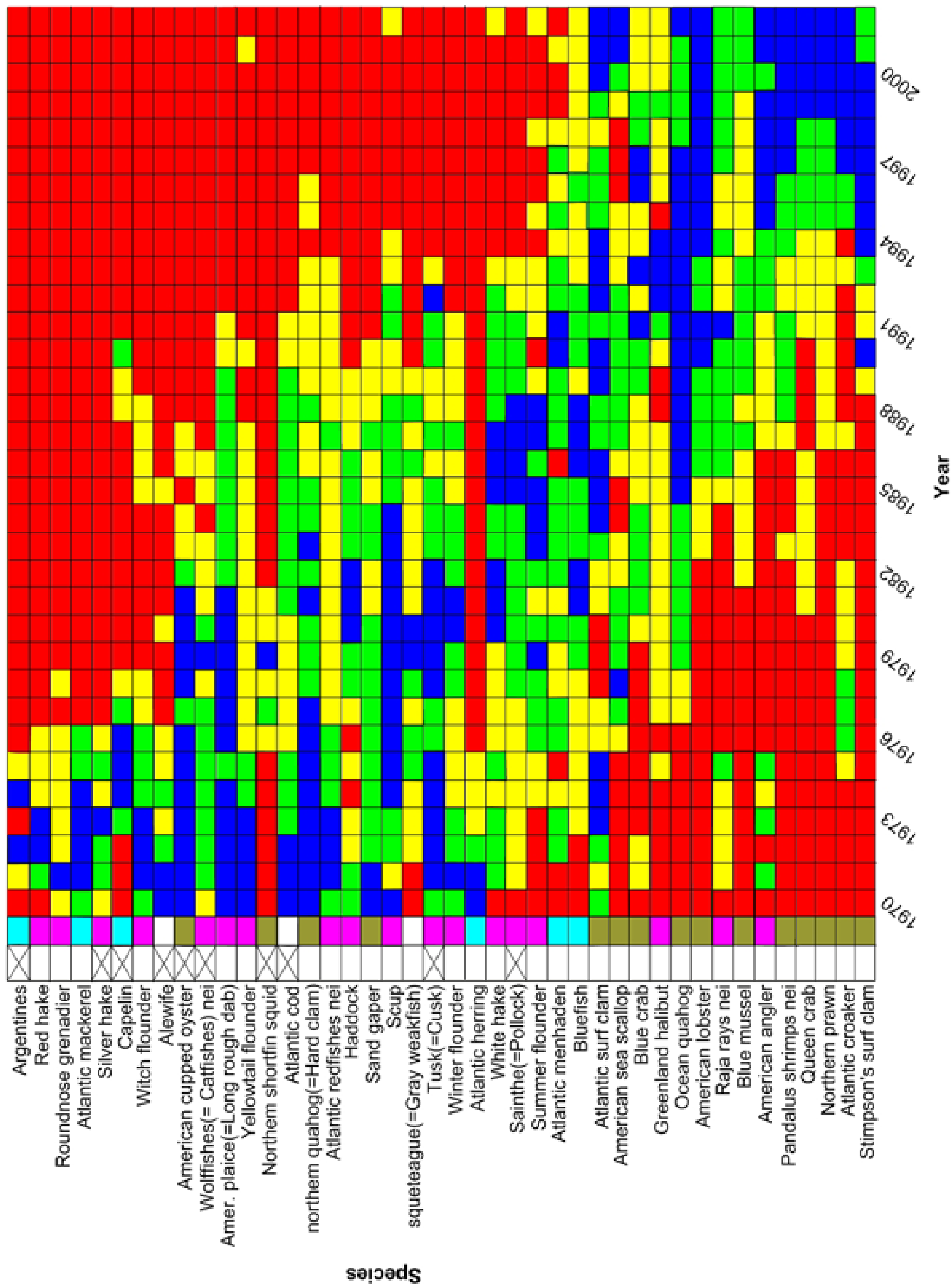



**Fig. 4.** Landing trends from 1970-2002 for 42 species or species groups from the Northwest Atlantic expressed in four colour bands, from bottom quartile (red) to top quartile (blue) of the observed range of species landings (from Caddy & Surette, 2005).

included. The Montpellier conference on Ecosystem effects of Fishing (Gislason *et al*., 2000) and the FAO conference in Reykjavik on managing marine ecosystems (www.fao.org), were two meetings that perhaps marked the onset of serious scientific and managerial preoccupation with ecosystem management. These conferences have only recently begun to define a new problem: how to optimise ecosystem outputs and conserve biodiversity? Other documents (*e.g*. the guidelines for ecosystem management in Ward *et al*., 2002 and FAO, 2003) attempt to spell out a new approach to fisheries management incorporating many ecological safeguards. What has become evident however is that we have few practical suggestions as to how "ecosystem management" should be applied without vastly increasing the requirements for data collection. A further issue, namely the long term effect of fishing on species genotype, is now also being raised (Law, 2000).

One comment from the oceanographer Alan Longhurst (2002) makes a case for conserving longevity of species as a criterion for sustainability. In his *Viewpoint* entitled: "The Sustainability Myth"; [*Fisheries Research* 81(2006): 107-112] he writes: "Fishery science … may be unique among the scientific disciplines: it produced a corpus of theory that was taught at universities and applied at sea, but which has since been proved to be wrong". While I would see this as somewhat of an exaggeration, it is nonetheless true that in application, stock assessment theory does not have a spotless record of success. The recent scrambling to add an ecosystem dimension to the techniques used so far has not yet provided a *practical and cost-effective* replacement for "single species assessment". Given that these kinds of expert opinions are becoming more common in the literature, we should not be embarrassed to use qualitative and empirical methods to judge the state of resources, and employ the precautionary approach (*e.g.,* FAO, 1995; Anon, 1997; Restrepo *et al*., 1998). Above all, we should be using more and more diverse, indicators than in classical assessment approaches, so as to provide some warning of ecological unsustainability.

Although considerable attention has been devoted to "mean trophic level" as an indicator of exploitation rate, Pauly *et al*. (1998) and Trenkell & Rochet (2003) point out its defects as an indicator of impacts of fishing on biological communities. These are that it is costly to determine (and like mean size) does not distinguish between the effects of nutrient enhancement in reducing the mean trophic level by increasing the abundance of planktivores, and fishing top predators in achieving a similar effect. This, to a certain degree, is a defect shared by all mean size indicators, and to a certain degree, many indicators share this property of responding both to the stresses of fishing and of environmental change.

A focus on management at the ecosystem level inevitably leads from defining indicators in terms of multispecies fisheries, to defining indicators in terms of the abundance of a wider range of ecosystem components, from the plankton, the benthos, and up through the food chain to marine mammals and birds (Kabuta & Laane, 2003). This seems to point to the need for more coordination in developing common systems of indicators between organizations involved in marine environmental quality issues (*e.g.* UNEP, United Nations Environment Programme), those concerned with biodiversity (IUCN, CITES) and those concerned primarily with fisheries (FAO).

### Indirect indicators of population health and exploitation rate

Biomass, recruitment, fishing mortality, and in some cases, fishing effort, are the variables that sampling effort has been mainly focussed upon as direct indicators, and which are routinely used as inputs to the simple modelling or analytical procedures mentioned earlier. Supplementary information may also be available, including anecdotal information from fishermen, which while not necessarily suited to feed into a quantitative model, provides a direct perception of the direction in which the fishery is moving. Actual impacts of bottom fishing gear on the habitat and grounds (Jennings & Kaiser, 1998) are however only now being taken seriously, and are not easily measured by a single indicator. Notwithstanding, one type of indicator is becoming more widely used: the number of times a year a given area of the fishing grounds is swept by bottom gear: figures upwards of 5x per year apply on heavily fished grounds: seriously impacting the epifauna needed for cover (Tupper & Boutilier, 1995; Rumohr & Kujawski, 2000).

This indirect approach, although less than rigorous mathematically, is easily understandable, and helps to formulate "precautionary measures" if the value of an ensemble of indicators suggests a serious situation is emerging. *Figure* 5 summarises "biological and environmental externalities" affecting a target species, which might be monitored by one or more indicator series if such data are available. An example is provided by sub-arctic Northern cod populations which are dependent for much of their food on a smaller fish, capelin, whose biomass typically fluctuates widely with environmental change. Here, the fishery quota for capelin must take into account both the direct fishery for capelin, and the food needs of the cod stock if the latter is not to suffer from food shortage. Similar examples are the North Sea sand eel population which is exploited by an industrial fishery, but is also a basic food source for fish and sea birds; and Antarctic krill, for which there is/was a limited fishery, but which also supports the food web of marine birds and mammals in the southern Ocean. Taking into account the food requirements of other species by a series of indicators is the most obvious and practical application of food web theory to fisheries management.

Other trends that may work in the opposite direction are evident in the Northwest Atlantic following the decline in groundfish predation: landings of shrimp, lobsters and mollusc shellfish seem to have increased over the last decade, and in fact the whole multispecies fishery is now dominated by high value invertebrate sea products, and seems now to operate at a higher economic landed value than when the fishery was largely dependent on groundfish and herring for revenues. As noted, this changeover possibly occurred in response to declines in predation by finfish, but possibly to some extent also, due to climate change. What is evident from these few examples is that multispecies management must follow an overriding rule that is in contrast with the idea of managing each species separately. It should not be assumed however, that a criterion aimed at maximizing the economic yield from all resources in the region will necessarily lead to restoration of the original ecosystem. Without controls, it seems likely that the fishery of a region will converge on harvests of species low in the food chain as higher food chain components become rare or commercially extinct. One logical endpoint possible then, is a cataclysmic scenario whereby a fishery is developed for surimi-like proteins from species low in the food chain that can be transformed into a wide range of products.

One role for fisheries management bodies and advisory NGO's in this particular context would be to monitor the ratios of abundance of predators versus prey in situations where the prey in question makes up a large proportion of the food resources of an exploited species (or a

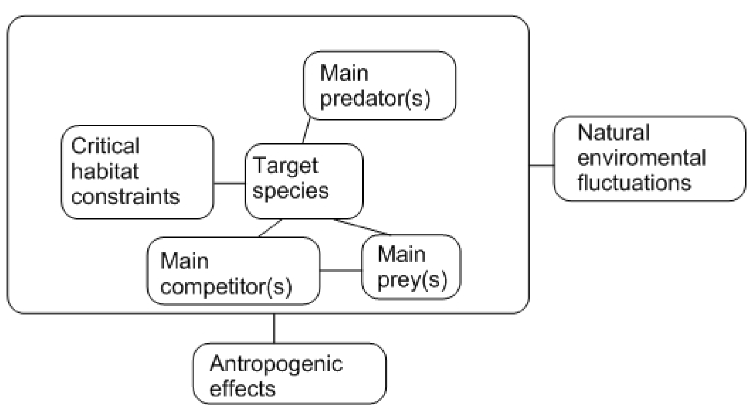



**Fig. 5.** Some first order biological interactions directly affecting the managed population that could usefully be monitored in a multispecies fishery. Taken from Caddy (1999a), showing key factors (inside the rectangle) affecting fisheries production, and some important "extrinsic" outside, that could be monitored by indicators.

protected species). To some extent, this type of indicator is already covered by the demersal/pelagic type of indicator already mentioned, or one based on mean trophic level.

**Who does the assessment and how?**

In developed countries and fisheries commissions, committees of scientists with qualifications and experience in population dynamics or other quantitative science disciplines, meet regularly to review the survey and commercial catch data, plus a range of biological information and information on the fishing effort exerted. In some cases, commissions also have a resident assessment expert who coordinates national activities and may carry out assessments in person. These data series are introduced into accepted mathematical procedures, and the results compared with reference points resulting from analysis of data for previous years. A range of options for TAC (total allowable catch) or fishing mortality rates are provided, ideally with an estimate of the risk such a TAC or mortality rate would infringe a LRP. Assessments are often based on a yield model, supplemented more frequently nowadays, by an estimate of the size of spawning biomass that would result and its possible impact on the reproductive success of the stock.

**Assessments presented at RFMOs**

My impression is that few regional fisheries management organizations (RFMOs) actually collect their own data –usually it is their member States that do this, although FAO (2001) seems to anticipate a larger role in this for RFMOs–, and suggests several indicators for measuring the performance of RFMOs and their members. RFMOs may however use their funds and limited staff (or support staff from developed countries) to sample or investigate data gaps from developing country areas. In Caddy (1998), I summarised the then budget and manpower for three fisheries Commissions: NAFO, at $0.7 million and two professionals, ICCAT, $1.1 million and three professionals, and ICES, $3.3 million and eight professionals (but much wider terms of reference): hence their capacity to directly implement monitoring and assessment activities for the fisheries under their responsibility is strictly limited. Other bodies, *e.g.* SPC and the FFA in the south Pacific may do more, but these are not exactly Commissions but groupings of producer States.

Analysing the data is another matter, but even here, it is usually member country scientists who present analyses at Commission Working Groups, even though some commissions have resident scientists to do some of this work. I would imagine data collection methods vary between commissions dealing with different resources - tuna commissions differing from those dealing with shelf resources, since monitoring, sampling, and collecting effort data, presents particular problems for high seas fisheries such as tunas –very few analytical approaches seem to be used for tuna assessments, since age composition data are rarely collected–.

Of course there are numerous institutes and universities with staff occasionally working in this area; the University of British Columbia and Dalhousie University in Canada are among those academic institutions who maintain publicly-available data bases, but university staff rarely has an institutional role, even if they may occasionally attend Commission meetings. An institutional role implies that a watching brief is maintained on a fishery, year in, year out this may be the case for example by several west coast US universities, with respect to salmon and other coastal fisheries; where university professors may be employed on long- or short-term contracts. Usually, national fisheries institutes carry out this role however, but only for their national fisheries, or for shared stocks. In other words, there is not to my knowledge an alternative source to FAO which provides global advice on resources (*FISHBASE is an international data base on fish biology that includes a wide range of information gleaned from the literature, but does not incorporate stock assessments per se).*

ICES has on occasions ventured to play a "global role", but I doubt if it has the funds to do this extensively. If the funding were available, some dozens of scientists either from "developing" countries or tropical developed countries with familiarity with tropical fisheries, could be available to take part in assessment missions if there were funding to pay for this function, and if they were given leave of absence from their current responsibilities.

Fisheries assessments carried out at RFMOs should in theory be subject to more adequate collegial criticism than purely national resources, but still depend on national reliability of data collection which may be mixed, especially for shared, migratory or straddling resources. Under-reporting or misreporting of landings between species and/or sub-areas is not uncommon, given that illegal fishing occurs in most areas to some extent and resulting catches are not reported. Self-serving national influences, even at the assessment level, with respect to parameter values and data used in analysis, cannot always be excluded.

Some reasons why the work of RFMOs is frequently hampered are given by FAO (2001), namely:

- Conservation measures are undermined by fishing of non-parties, illegal fishing and reflagged vessels;
- Members fail to provide adequate information on their fisheries;
- Political pressures related to sovereignty and national interests apply;
- Poor MCS capability exists;
- There are poor links between science and implementation;
- There is a lack of financial support;
- There is inadequate scheduling of activities to meet decision-making timetables.

Decisions arising from analysis of stock status at a Commission usually revert back to member States for implementation. This process is not always subject to external review (see however, Harris, 1990), and Fisheries Commissions are rarely delegated the power to implement management decisions made at their meetings. Such decisions often have to be arrived at by consensus, hence compromises may be made in selecting less painful management measures than those suggested by the scientific assessment; as a result, the required impact of a regulation may be blunted in application. Outside of EEZ waters, international accords from UNCLOS (United Nations Convention on the Law of the Sea) onwards may be lacking in application, and adequate supervision of fisheries harvests is unlikely distant from the coast. MCS functions are generally confined to monitoring national vessel performance within national EEZs, and may depend largely on inspection of landing or transhipment records and not necessarily on inspected catches, since transhipment of catches and processing at sea may make sampling of catches problematical.

FAO (2001) provides a list of criteria that parallels in many ways the WWF (World Wildlife Fund) approach specified in Ward *et al.* (2002). References are also made to two standard approaches towards ensuring an activity is sustainable:

- The 10 Bellagio Principles of Sustained Performance
- The International Organization for Standards (ISO), which through its ISO 14 000 (environmental management) series, seeks to establish: “documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines or definitions of characteristics, to ensure that materials, products, processes and services are fit for their purpose”.

Although further debate on this goes beyond the scope of this paper, there may be useful procedures outside of the fisheries field that can be adapted to the management of complex processes such as the management of ecosystems made up of wild living resources.

**How many fisheries are assessed?**

FAO (2006) suggested that for some 441 stocks, some estimate of the state of exploitation exists, presumably in addition to the indications provided by catch trend analysis. This leaves 143 stocks for which there was no assessment information, and some 20% of the remaining marine fish stocks (12.7% of landings), where no identification was possible, even at the taxonomic level of family. Even in developed country waters, the majority of ‘unconventional’ resources are probably not assessed. In the surveys carried out off Livorno, Italy in the western Mediterranean for example, some 200-300+ species of potential interest are regularly encountered in trawl surveys, but only a half dozen or so is assessed. The situation cannot be too different elsewhere, for example, the small tunas and tuna-like species of tropical areas are rarely looked at closely by Commissions dealing with tunas, even though these species may be taken incidentally by industrial vessels, and are often of key importance to inshore fleets.

### How many fisheries are "patently under-managed"?

If we look at the resource categories of commercial interest which are most difficult to assess, these include estuarine and lagoon species close to shore, many species of invertebrates, stocks shared between adjacent jurisdictions (where sharing of data is a precondition for any joint assessment), and straddling stocks (shared between an EEZ and high seas fleets, where sharing data is not always practiced, and for which assessments are relatively infrequent. Highly-migratory stocks are often addressed by tuna commissions, but shared small coastal tuna species or tuna-like species are rarely seriously addressed by tuna commissions.

With respect to shared stocks, Caddy (1998) reported on an estimate from a global GIS (Geographic Information System) data base showing 531 maritime boundaries between adjacent maritime States, excluding those running through inland water bodies or cutting island archipelagos. If we assume a modest figure of two or three commercially-important transboundary resources per boundary are shared by adjacent states, we are looking potentially at some 1 000 - 500 actual or potentially trans-boundary resources – setting aside those which are covered by regional fisheries commissions (which rarely deal with shared stocks confined to the EEZs of only two member countries however)–. Bilateral commissions or arrangements of course do exist, such as that for the River Plate, that between Trinidad and Tobago and Venezuela, and between the Falklands/Malvinas islands and Argentina, but equally, there are boundaries, such as several in the South China Seas where no formal mechanism, so far as one knows, has been set up. With respect to straddling stocks, the situation is not much different. Deep water resources and those of sea mounts are assuming higher importance now that coastal resources are often depleted, but are rarely assessed. Namibia has set up a commission to look at their deepsea resources, but unless there is an extended shelf area and valuable demersal resources (*e.g.* NAFO in the NW Atlantic), it is probably not typical that a commission or arrangement is set up to manage jointly straddling stocks between coastal and distant water fleets. The most valuable and easily exploited resources still tend to be within 200 miles of the coast, and this explains the importance still given by DWFVs (Distant Water Fishing Vessels) to access agreements (Martin *et al*., 2001).

Given these qualifications, despite the figures provided in FAO (2006), a significant proportion, almost certainly a majority by number (but not necessarily by catch proportion), of marine resources are not properly assessed. Possibly the most economically important marine resources are assessed regularly, but as we have seen, there are a fairly wide range of research activities that are occasionally counted as "assessments" that within the more rigorous jurisdictions would not be considered as such. However, one or more of the following modalities may be carried out:

- Analysis of landings by size or age;
- Analyses of fishing effort or mortality;
- Surveys of stock biomass by trawl or acoustic methods;
- (Rarely) egg and larval surveys to estimate spawning stock size;
- Monitoring of a set of indicators that measure directly or indirectly stock status and exploitation rate;
- (Rarely), monitoring indicators that measure diversity of the biological community as a whole.

In general, a fishery will not be considered assessed if frequent recourse to the precautionary approach is required due to a lack of necessary data

Although the following list is probably too exacting, a modern fishery may be defined as 'under-managed' and potentially unsustainable if its management system lacks one of the following components:

1) A system of monitoring the state of the resource, and the level of harvest;
2) A measure of the effective fishing effort exerted;
3) A regulatory framework that ensures that the fishing effort exerted is confined to vessels authorised to participate in the fishery;
4) A system of ensuring that capacity does not increase with vessel replacement;
5) A decision made on the limiting conditions beyond which the fishery and resource will be in risk of depletion or decline, translated into indicator values referred to as limit reference points;
6) A method of analysing indicator information so that the current position of the fishery in relation to reference points marks the onset of conditions and indicator values where experience and/or analysis suggests there is a high risk of stock collapse;
7) If the fishery is judged to be overfished in relation to established limit reference points, a recovery plan or other means of reducing effective effort must be incorporated in the regulatory framework, and should override short-term economic or social considerations;
8) There must be the capability of establishing on the fishing grounds that fishery regulations are respected by participants;
9) An independent review of management measures and their implementation should ideally be incorporated.

Even if some flexibility is allowed for in the method used to manage the fishery (quotas or effort control), the above list of *rules of thumb*, is potentially controllable by means of a questionnaire completed by those familiar with the fishery. Rules with a similar basic intention may have been established by countries and/or fisheries commissions, but rarely is such a system of management components *applied* in a rigorous fashion. Therefore, approaches to monitoring should ideally consider the following four questions:

1) Is the intention of the fisheries regulations in accord with sustainability as expressed by internationally-agreed rules and procedures?
2) Is data gathering and analysis adequate to track changes in resource status and fishing effort exerted?
3) Are the financial or manpower resources available to implement and monitor the efficiency of the above components of the management system?
4) Is the resource management system applied in a manner which makes these components effective in maintaining resources above dangerous levels?

**How does the quality of data vary?**

In general, national resource assessments of key resources are probably carried out by many European and North American countries, by developed countries in the Southern Hemisphere and Oceania, by some central, south American and Asian countries for key resources, by a number of countries in North and West Africa, and perhaps fewer in East Africa, again, for the same key resources. For many of the less important resources and smaller countries, a watching brief may be maintained using landing figures, or occasional studies may be sponsored, or there may be support from developed country mechanisms, perhaps acting through regional fisheries Commissions. Developed countries in the Southern hemisphere, and several in the northern hemisphere, probably merit mention as applying the most effective management regimes. Annual surveys by research vessel are probably carried out by a proportion of coastal states on their more important resources. For most developing countries, where assessments are carried out, these may be occasional, for only key resources, and may be implemented by foreign experts working for short-term projects.

In these circumstances, data quality will suffer, and fragmentation of data series (where these exist) is a serious problem, making the proper application of standard assessment procedures impossible. Reliance may have to be placed on analysis of occasional samples so that monitoring of developments in resource status is usually by “word-of-mouth” information from those most concerned; the fishermen. Under these circumstances, it is difficult to say that all assessments are "scientifically justified". "Standard assessment techniques or procedures" from developed country areas may be applied to situations and resources that are biologically unique or specific to a given region. On the other hand, the record of success in management of marine resources in countries where assessments are regularly carried out has not been spectacular judging from the status of many resources (see Caddy & Agnew, 2004).

Under these circumstances, currently available data does not always allow judgments on the health of a harvested stock, and where data are collected on landings and fleet size or capacity, these may be the only data series that allow some insight into fisheries impacts and ecological processes. At least maintaining an adequate and up-to-date registry of national vessels and their characteristics, and an adequate monitoring of landings by species, may be seen as a relatively positive achievement.

### A discussion of *Science-based* assessments: what would be the *best scientific* practice and do we fall short of this?

I think from the foregoing we can conclude that while *best scientific practice* can be fairly easily defined, it is not clear that the approaches suggested in this paper are being applied to many resources. Perhaps the issue is to know:

a) For which resources does current data allow judgements on the health of a stock, and:
b) When is a stock at risk of depletion?

The first issue is more difficult to answer objectively than the second if we reduce it down to the UNCLOS question: has the level of effort corresponding to MSY been passed? Given the strong economic implications of judgements on this issue, a hypothetical court of law might ask: can the evaluation show unambiguously that the stock is currently being fished beyond the $f_{MSY}$ level? A court of law in the US or other developed countries would require a full evaluation subscribed to by several internationally reputable scientists to accept this opinion. The more comparative approach applied by FAO in its periodic 'Review of the status of world marine resources' classifies stocks into 4 or 5 categories, using catch trends plus judgement and local experience, would I am afraid not be accepted as definitive in this legal context. (Also recognize that the FAO approach is not applied to single stocks, but to populations merged from much bigger FAO statistical areas.) At the same time, the new concern with ecosystem management does not look like it can produce sufficiently hard and fast results if the question were to be: "Is the ecosystem at risk from overfishing?" An analogy can be made here (perhaps in reverse?) with the criteria used by the Marine Stewardship Council for certifying a properly managed stock. Not many marine resources have fitted their criteria so far, and some positive certifications for specific resources have led to disagreements from some parties. This shows the problem faced in positively certifying a resource as "safely exploited".

The situation with respect to the second question may be more easily resolved where MSY conditions have been well passed, and there are numerous examples where catches have dropped to (say) one-third or one-fifth of the level corresponding to MSY. Either environmental conditions have deteriorated, and/or fishing effort has remained well above the level corresponding to a high 'sustainable yield'. The FAO Code of Conduct for responsible Fisheries (COC) does not allow a distinction between responses of stock declines to overfishing, and responses to negative environmental changes: in both cases, the COC states that effort has to be seriously reduced. Thus, a judgement that a resource is now at a (specified) fraction of the average stock size at which "sustainable" harvests were once extracted, could be made with some reliability if landing and fleet trends are known. A multi-criteria approach to analysing fisheries landing trends (such as suggested by FAO/CITES, 2002), and in Garibaldi & Caddy (2004), could be applied. A questionnaire incorporated information on fleet tonnage fishing, capacity control methods and procedures for license transfer now being implemented, the management regulations that apply, and the level of recent infringements observed by MCS staff, could be completed by experts who have no vested interests in the fishery. Such a questionnaire response should specify any problems in resource sharing between participants if the stock is shared, straddling or highly migratory. It seems unlikely that once such a standard approach has been established, that it would be seriously challenged. The need for such "low tech" approaches to stock evaluation has been emphasized during discussions on the potential role of the World Trade Organization (WTO) with respect to a control of the use of fisheries subsidies (Schorr & Caddy, 2007).

**A possible procedure which places the burden of doubt on the exploiting parties**

Although the reality of the situation is that formal annual stock assessments are still performed for a minority of resources, my opinion is that establishing which stocks are seriously depleted or "at risk", could be done fairly simply in a two or three stage process, in which the burden of proof is required from the parties fishing, and would not have to be provided at the expense of associated organizations. It could resemble the following.

1) A first listing of stocks that may be "at risk" could be made, using the procedures described for analysing data reported to FAO;
2) The second stage would be to post a list of these internationally, and ask for further information from parties exploiting these resources; not just on their status, but also a list of vessels by size/fishing power categories which are exploiting these stocks;
3) The third stage would be to find funding to send experts to make an evaluation.

Since this process is precautionary however, after posting a list of stocks and coastal states/ DWFNs (Distant Water Fishing Nations) exploiting them, and not receiving a reply from the relevant authorities, this would be reason enough to consider that there is a problem, even if other evidence is unavailable, *i.e.,* an evaluation panel established to identify fisheries at risk could begin with a relatively simple process, which gets more complex and costly, only if further more refined assessments are needed. The next step however should be taken at the expense of the country(ies)/industries exploiting the stock. If they do not respond adequately to a first appeal based on broad but imprecise evidence such as a drastic drop in catches and evidence of excessive demand, rising prices and excessive effort, then the stock is indeed at risk. At that point, a rough analysis based on some aspect of species vulnerability (such as biological characteristics stored in FISHBASE and the basic species biology which is usually known), may establish whether the life history is especially vulnerable.

The point here is that the onus is on exploiting States/communities/fishing industries to provide an analysis, and post a list based on key indicators, however imprecise. They should be encouraged to provide objective data at their own expense, perhaps as a condition of licensing.

In case this seems a rudimentary procedure, bear in mind that for most "well-managed" fisheries we either have quite good biological or fisheries landing data (outputs) or relatively reliable information on fishing effort or fleet capacities, but not so often are both types of information available. It is useful to have time series of size and age structure allowing a VPA analysis or size frequency analysis, but if you have no idea of the characteristics or effort exerted by the fishing fleets involved, or vice versa if you know the fleet size/capacity but have no data on recruitment, catch rates or mean sizes of the stock, the stock diagnosis will inevitably be provisional. The deficiency of most current assessment approaches is that they are unbalanced across this input/output divide.

The aspect emphasized here then, is that *both input and output data should be available*. For developing countries to satisfy a "science-based" assessment will be difficult, but clearly a questionnaire could establish what they are doing to ensure that:

- Infrastructure for data gathering and assessment exists;
- Management, control and surveillance infrastructure, and a system of fisheries regulations, are in place based on scientific principles;
- Data are collected on the effort/capacity operating on the stock, and the fleet capacity is controlled by licensing and vessel replacement criteria;
- Some biological and catch data are collected;

- Ideally, some closed areas protect critical habitats for demersal species;
- Some sort of stock assessments is attempted, if so for which species?
- Joint management is discussed with other parties sharing the resources;
- If management certifies operations by foreign fleets in their zone (or foreign fleets fish the same straddling or shared stock outside their zone), have they considered the impact of these "foreign" catches on their domestic fisheries/food security?

If they are able to answer most of these questions positively (even if they do not assess the resource, but do collect data, allowing an outside expert to do this for them), the criteria for responsible management are mainly satisfied.

## A preliminary fisheries diagnosis in the form of a traffic light questionnaire

As just noted, a variety of criteria have been suggested (*e.g.* in the COC and questionnaires based upon it, FAO, 2007), and a wide range of optima for judging fisheries performance is potentially available. These could be used in judging fisheries performance even with minimal assessment input or quantitative data. *Table 7* summarises a limited number of criteria for both inputs to the fishery and outputs. A high score to questions in the following table does not assure that the resource is being properly managed. However, by taking into account both inputs to the fishery and monitoring outputs, there is a reasonable chance that unsustainability will be detected in time to reverse current unsafe exploitation patterns if the relevant management body decides to do so.

Note that the proposed approach is to request an explanatory account for each line of the questionnaire, and supplementary information showing how the scoring was arrived at for the questions. To achieve an adequate compliance with sustainability, both inputs and outputs should receive a high positive score.

Completion of this kind of questionnaire should be understandable to a non-specialist organization, and unsatisfactory scorings could provide the basis for closer evaluation by an external review team. (Note: questions on subsidies are not included here, largely because answers on this issue would be difficult to confirm without detailed investigation).

A final score could be expressed in the form of a pie chart, which could be separately displayed for inputs and outputs (Fig. 6).

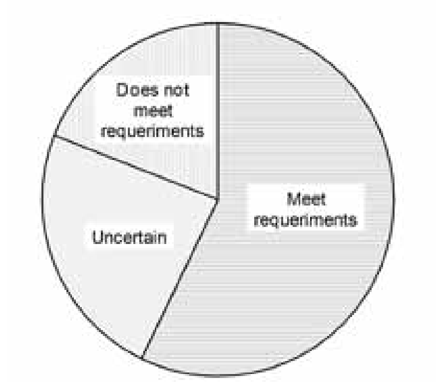



**Fig. 6.** Scoring to meet a hypothetical fisheries management guideline.

## Conclusions

- Fisheries are managed in a multidisciplinary way which should involve the skills and actions of a number of professional disciplines and teams.
- For scientific management of a stock, adequate monitoring is required, appropriate analysis of the indicator series, and decisions as to what values of indicators represent dangerous conditions, could be shown as a "red zone". A sequence of actions to take when these conditions occur should have been agreed upon in advance within a fisheries plan.
- An ecosystem can be monitored through a variety of indicators which represent different functions and measures of success of the fishery management system, or measure potential stresses on the resource. These indicators can take on critical values (LRPs) which, when reached, imply that remedial action should be taken.
- There is an optimal value (range of values) for a given indicator which represent(s) influences on resources and habitat/ecosystem

**Table 7**
A condensed questionnaire to establish the state of management and exploitation of marine resources (modified from Schorr & Caddy, 2007)

| *Characteristics of the fishery for resource A over the last decade* | *Yes* (*Green*) | *Maybe/ partially* (*Yellow*) | *No* (*Red*) |
|---|---|---|---|
| **OUTPUTS** | | | |
| 1) Landings are still *above* 50% of the average for the best three years landings on record (FAO Statistics)? | | | |
| 2) Landings *have not* continued to decline significantly over the last five years? | | | |
| 3) Catch rates *have not* declined significantly over the last five years (standard vessel category? | | | |
| 4) The fleet capacity utilizing the resource *has not* grown by more than 50% since the last of the best three years landings on record? | | | |
| 5) Prices for the product on the domestic market of the coastal state *have not* grown by more than 25% over the last five years? | | | |
| 6) Biological data *are* collected in port, *OR* "in-port interviews" *are* carried out, *OR* copies of catch log books *are* completed and collected by port officials? | | | |
| 7) The capture of protected species *is* actively discouraged? | | | |
| 8) The diversity of resources/habitats *is* being actively maintained? | | | |
| 9) Illegal or unreported fishing is being kept under strict control? | | | |
| **INPUTS** | | | |
| 10) Research vessel surveys *are* carried out at regular intervals? | | | |
| 11) There *is* a limited license system in operation that covers all vessels fishing the resource? | | | |
| 12) There *is* a system of licence transfers that ensures that fleet capacity is not increasing? | | | |
| 13) There *is* a system of at-sea surveillance of the fleet operation or on-board observers? | | | |
| 14) Biologists *are* employed to evaluate the fishery with at least Masters in Science education? | | | |
| 15) A management plan exists for the fishery? | | | |
| 16) Closed areas or MPAs are in effect? | | | |
| Some areas within the stock range are still unfished or form *refugia*? | | | |
| 17) For shared, straddling and highly migratory stocks, there are fisheries agreements or negotiations in course with other users of the same resources? | | | |
| 18) The government fisheries agency meets regularly with local community or fishing industry representatives? | | | |
| 19) The economic/social importance of the resources to the rural poor, or to sports fishing activities as revenue earners on the fishing grounds, are considered? | | | |
| 20) If there are foreign access agreements, do these specify avoidance of national fishing areas/resources, and are their provisions policed? | | | |
| 21) Are any specified provisions of ecosystem management/ biodiversity established by government outside the fisheries sector being applied? | | | |
| 22) Is there an integrated coastal area management plan in effect, protecting coastal resources from pollution/unwise developments? | | | |

health, and this can be referred to as a "green" range.

- It is likely however that given the low precision of most indicator systems, that an overriding principle of precaution will need to be invoked when there is a "yellow" or uncertain condition.
- In the case of ecosystems modified by human actions, these may differ from the indicator values that applied in the original or virgin

conditions, since inevitably, a system fished at close to MSY is modified, both in species and size composition. The optimal ecosystem state can be established by negotiation or consensus, but should help avoid major impacts on the biodiversity of the ecosystem.

- The safe range of conditions for an exploited ecosystem can be specified by those familiar with the system by appropriate observation and monitoring, but indicators may be semi-quantitative requiring judgement on the basis of past experience with this or similar fisheries.
- Beyond a certain value of a variable measuring stress on an ecosystem, it should play a seriously deterrent role in the ecosystem when the resource is at serious risk, and can then be said to have entered a "red zone". Identifying the onset of this involves specifying one or more "limit reference points", where the numerical value for the indicator is believed to represent the onset of actually or potentially bad conditions.
- These indicator values may be established by analysis or observation, and must be agreed to by system users. The critical indicator values or Limit Reference Points may modified in the light of experience, however, the management system must decide in advance what values of indicators approach dangerous conditions and act promptly when they occur, in an attempt to reverse them.
- 'Pre-negotiation of actions to take *before* red zones are entered is critical in order to avoid further deterioration during protracted negotiations when the variable is already "red".
- In a system where there are a number of different variables or indicators and their corresponding reference points, the relative importance of a variable may be modified relative to others, by incorporating a weighting factor.
- A lag effect may be allowed for in management if there are good grounds to expect a time delay before a management control impacts the resource/ecosystem, but the impact of management measures should be kept under continual review.

The management body may wish to avoid getting into too much detail on fisheries biological indicators as specified in this paper, where they are mainly of concern to the scientific management component, and are mainly included to explain the basis for assessments to those unfamiliar with fisheries science. In addition to the four questions listed above, some general but fundamental questions may also be asked however:

- a) What is the availability and quality of data and how does this influence the type of assessment possible?
- b) Have similar assessments shown trends or biases in reliability over time?
- c) Are protected species adequately looked after?
- c) Is there unnecessary wastage and incidental damage due to the fishing procedure?

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