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Design of operational management strategies for achieving fishery ecosystem objectives

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Ecosystem objectives in fisheries management usually flow from high-level national policies or strategies and international agreements. Consequently they are often broadly stated and hence are difficult to incorporate directly in management plans. Predicting the results of any management action is very uncertain because the dynamics of ecosystems are complex and poorly understood. Methods to design and evaluate operational management strategies have advanced considerably in the past decade. These management-strategy-evaluation (MSE) methods rely on simulation testing of the whole management process using performance measures derived from operational objectives. The MSE approach involves selecting (operational) management objectives, specifying performance measures, specifying alternative management strategies, and evaluating these using simulation. The MSE framework emphasizes the identification and modelling of uncertainties, and propagates these through to their effects on the performance measures. The framework is outlined and illustrated by three ecosystem-related applications: management of benthic habitats and broad fish community composition; by-catch of species of high conservation value; and food-chain interactions and dependencies. Challenges to be overcome before broader ecosystem-related objectives can be fully handled are discussed briefly.

Key words: ecosystem indicators, ecosystem objectives, fisheries management, management strategy evaluation (MSE), operational management strategies (design and evaluation), uncertainty.

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Introduction

Fisheries management has historically focused on achieving objectives that relate to the well-being of commercially harvested species and the associated fishing industry, but there is now an increasing trend to consider broader, ecosystem-orientated objectives as well. There is a long list of issues related to the broad marine ecosystem. These include recovery of endangered species, effects of fishing on species and habitats impacted incidentally by fishing or as by-catch, preserving the food supply for other marine predators, maintaining biodiversity at all biological levels (e.g., genetic, species, habitat, community), and maintaining ecosystem integrity and resilience.

The broad ecosystem objectives stem mainly from high-level agreements, treaties, and policies that set out principles and objectives for human use of biological resources. For example, objectives from the Law of the Sea Convention (LOSC), the UN Convention on the Environment and Development (UNCED) and the Convention on Biological Diversity (CBD) include:

- Manage marine living resources sustainably for human nutritional, economic, and social goals (LOSC and UNCED);
- Protect and conserve the marine environment (LOSC);
- Protect rare or fragile ecosystems, habitats, and species (UNCED);
- Use preventative, precautionary, and anticipatory planning and management implementation (UNCED);
- Protect and maintain the relationships and dependencies among species (UNCED);
- Conserve genetic, species and ecosystem biodiversity (CBD).

National policies and legislation, often designed at least in part to give national effect to the international

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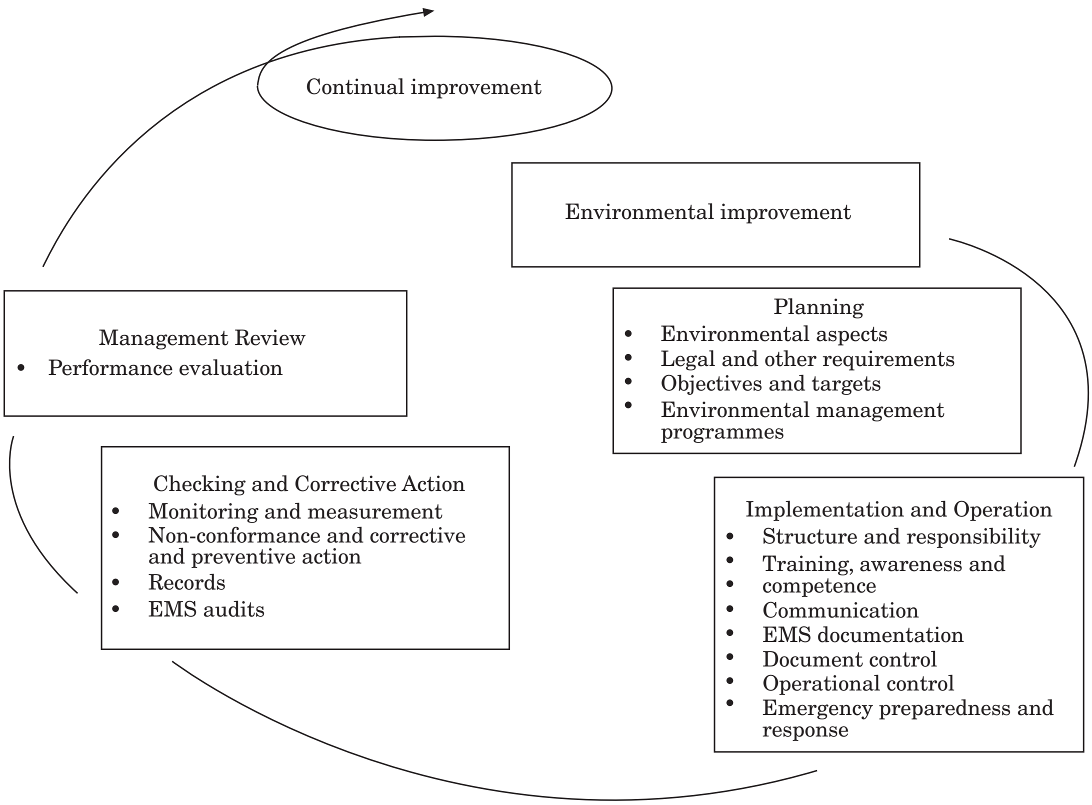

Figure 1. The management strategy framework contained in the International Standards Organization (ISO 14000) standards for environmental management.

agreements, are starting to include ecosystem objectives and principles. For example, Australian Federal fisheries legislation includes an objective of ecologically sustainable development (ESD), and the Australian National Strategies for ESD and biodiversity conservation specify that management of resource use must include precautionary decision making and protection of ecological dependencies.

Fishery management is implemented at the operational level through management plans, administrative regulations, and the decisions of individual managers or management bodies. Often, choices need to be made about which of several alternative management actions provides the best compromise amongst conflicting objectives. It is therefore necessary to be able to relate the likely consequences of prospective management actions to the objectives, and answer questions such as: what specific outcomes are intended by the management action?; what information is needed to support management decisions?; and how would success or failure be measured and detected?

It is at the operational level, and through operational management strategies, that broad policy goals are linked to individual management actions. The general framework for operational management strategies is described in many guidelines and standards, such as the International Standards Organization 14000 standards for environmental management (Fig. 1). The ISO 14000 and other such frameworks emphasize the combination of:

- evaluating the performance of the management system as a whole (not just isolated parts),
- specifying measurable targets and performance measures that relate to the objectives,
- monitoring the managed system,
- iterative and "feed-back" decision-making based on monitoring data,
- developing a procedure for implementing management decisions, and
- evaluating peformance.

Development and evaluation of operational management strategies to achieve broadly stated management objectives is neither easy nor straightforward, although considerable progress has been achieved during the last two decades, at least for target species. The scientific methods for evaluating fishery-management strategies were advanced through two parallel initiatives: "adaptive management" developed by Walters, Hilborn, and others (e.g., Walters and Hilborn, 1976; Hilborn, 1979;

Smith and Walters, 1981; Walters, 1986; Fournier and Warburton, 1989; Ludwig and Walters, 1989), and "comprehensive assessment and management procedure evaluation" developed by the International Whaling Commission (Donovan, 1989; Magnusson and Stefánsson, 1989; Kirkwood, 1993; de la Mare, 1996).

In the 1970s and 1980s, both groups recognized the need to evaluate the performance of management strategies in their entirety, and not just to focus on isolated issues of scientific resource assessment. For example, by taking this approach the IWC showed that a key failure of its previous method for setting catch limits for baleen whales was the inadequacy of the estimators of key parameters used in a decision rule. It is important to note that the role of inadequate estimation in the failure to achieve management objectives could not be seen from consideration of the estimators alone: the properties of the estimators needed to be evaluated in the context of their use in decision-making. The Scientific Committee of IWC has since developed a management strategy for setting catch limits that meets all conservation-related objectives and is robust to a wide range of uncertainties.

The "adaptive management" and "management procedure evaluation" approaches are conceptually the same, and are termed management strategy evaluation (MSE) here. Use of this methodology is now widely recognized as providing a successful and appropriate framework for scientific input to fishery management (Cooke, 1999; Sainsbury, 1998) – notwithstanding that successful fisheries management requires more than appropriate scientific input. Management strategies have been developed for many specific fisheries (Punt, 1992; Butterworth and Bergh, 1993; Butterworth *et al.*, 1993; Baldursson *et al.*, 1996; de la Mare, 1996; Smith *et al.*, 1996; Punt and Smith, 1999).

After outlining the general MSE framework we illustrate its application in three examples: (1) management of by-catch of high-conservation-value species, (2) management of food-chain interactions and dependencies, and (3) management of benthic habitats and associated fish community composition. Although they are all based on the same general framework, differ in emphasis thereof. For instance, the second example does not place as much emphasis on alternative hypotheses as the other two, and only the third explicitly considers the details of an assessment model. We conclude with some comments on the strengths and challenges of the MSE framework in providing scientific support for management toward ecosystem objectives.

The management-strategy-evaluation framework

A management strategy consists of specifications for:

- the monitoring programme;
- the measurements that will be made;
- how these measurements will be analysed and used in the scientific assessment;
- how the results of the assessment will be used in management (usually through a "decision rule"); and
- how any decisions will be implemented.

The goals of MSE are to support informed selection of a management strategy by means of quantitative analysis, to make clear the trade-offs among the management objectives for any given strategy, and to identify the requirements for successful management. MSE uses simulation modelling to examine the performance of alternative strategies, and therefore requires that all five of the above elements be specified in a way that allows quantitative analysis.

Key features of the general MSE framework (Fig. 2) are:

(1) Simulation of the managed system as a whole. For management toward ecological objectives, this means simulating both the management decision and the ecological systems, and the connections between them made through monitoring and through the implementation of management decisions. If economic objectives are considered, then a linked economic system is also needed.

(2) Alternative strategies are compared using quantitative performance measures derived from the objectives, usually through the specification of quantifiable targets or limits (analogous to target and limit reference points in fisheries assessment). All MSE applications must have stated management objectives and performance measures, irrespective of the amount of background information available.

(3) The model of the ecological system (the operating model) represents hypotheses about how that system might work. There are often many models to capture alternative hypotheses about, for example, resource dynamics, monitoring processes, and the success of implementing management decisions.

(4) The methods and procedures specified in the management decision system comprise the strategy being evaluated. Simulation of a management strategy includes:

- Simulating the observation or monitoring process. For example, this may include collection of catch and effort data from fisheries or resource abundance data from scientific surveys;
- Simulating the scientific assessment or data analysis. The assessment model specifies how the monitoring data are to be analysed to calculate indicators and performance measures (Fig. 3), and to provide the input to the management decision rules. For example, exploitation levels might be reduced substantially if the indicator is below the target level and (particularly) if it is less than the limit level. The assessment

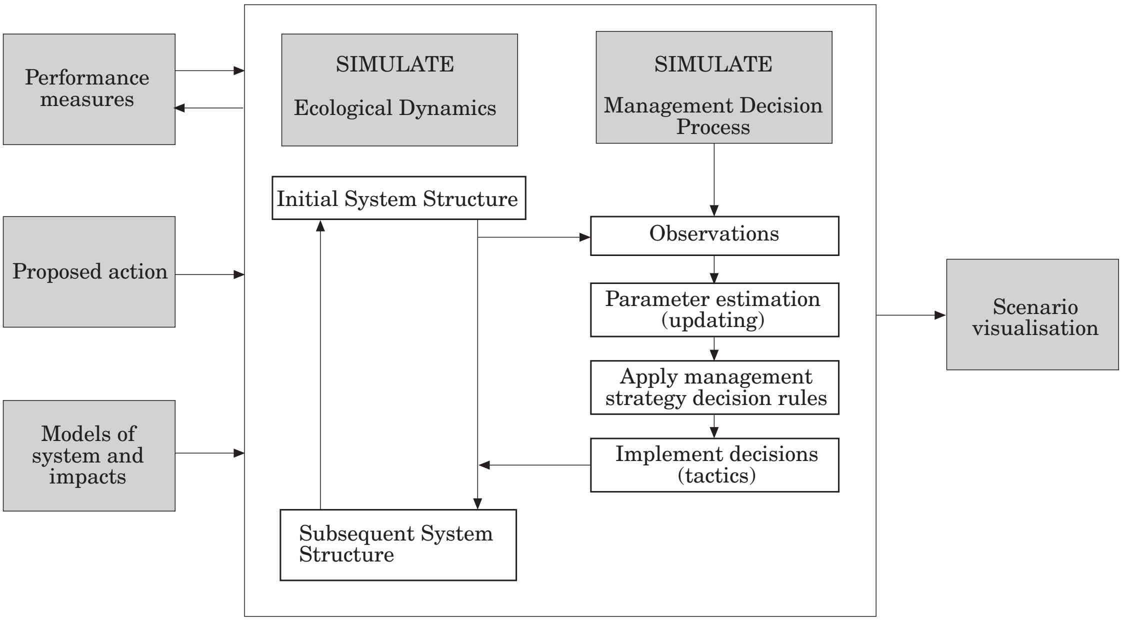

Figure 2. A general framework for management-strategy evaluation (MSE).

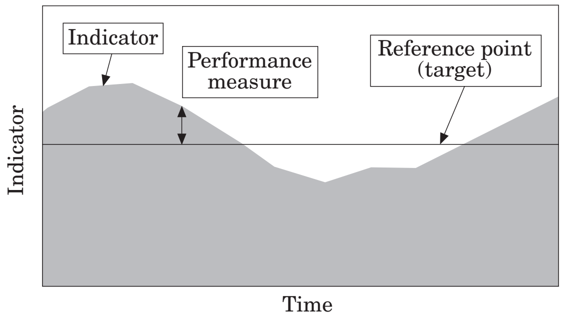

Figure 3. Example use of indicators, performance measures and reference points. An indicator is determined from measurements obtained by monitoring the system. Reference points for the indicators are derived from broader management objectives. They may be targets (to be achieved) or limits (to be avoided).

model will generally not be the same as the operating model. A distinction can be made between estimates of performance measures and the true state within the simulated system. The estimated performance measures indicate what a real-world decision-maker might see via the monitoring process. Several studies (Hilborn and Walters, 1992; Smith, 1993; Patterson and Kirkwood, 1995; de la Mare, 1998) have used the MSE approach to assess how good these estimated performance measures are likely to be for specific cases and monitoring strategies;

- Simulating how the results of the data analysis will be used for management purposes (the "decision rule"). MSE requires that the connection between data analysis and decision-making be specified clearly. For target species, the decision rule often determines a catch limit given the results of a stock assessment (Fig. 4). However, the results of the data analysis can be used in a wide variety of ways. Monitoring or analysis that is not used in decision-making cannot affect the performance measures;
- Simulating implementation of management decisions. The properties of the management control process, such as the speed and accuracy of achieving the changes in catch limits specified by the decision rule, are a critical element in determining the performance of a strategy.

The MSE framework can be used to compare alternative aspects of any part of a strategy – from monitoring options, through the scientific assessment and its use in decision making and implementation – in the "common currency" of the performance measures. For example, it may be asked whether a stock assessment model has the "right" level of complexity, is it complex enough to represent the managed system adequately, or is it too complex and so vulnerable to mis-specification and inadequate parameterization? Similarly, alternative monitoring programmes can be compared.

The MSE framework is explicitly designed for management that is adaptive, i.e., management that monitors the system and uses that information to modify management actions. However, a distinction can be made between two forms: passively and actively adaptive management. Passively adaptive management strategies use the information collected from the monitoring programme to update resource assessments and

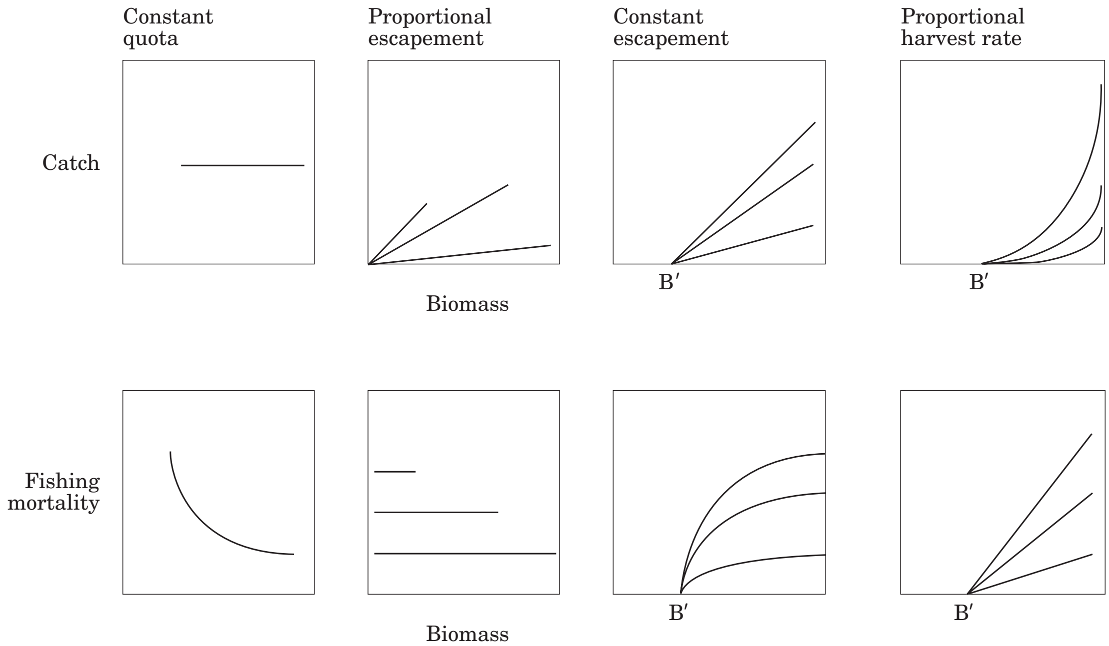

Figure 4. Common decision rules used in fisheries management. The results from the data analysis (in this case biomass from stock assessment) are related to the catch limit. B′ is a biomass threshold.

management measures, but do not intentionally alter management arrangements (other than the monitoring programme) to improve the assessments. Most fishery management arrangements use a passively adaptive strategy, although its details usually have not been explicitly designed or evaluated. Passively adaptive management will result in some empirical learning about resource dynamics. Sometimes, however, a fishery provides a weak experimental design for discriminating between important alternative hypotheses about population regulation, so the rate of learning can be very slow. In actively adaptive (experimental) management strategies, fishery controls such as the catch level are altered specifically to improve the rate of learning about some important alternative hypotheses about the fishery. The MSE framework is the same for evaluation of both types.

Example applications for ecosystem objectives

Management of sustainable incidental catch

Fishing operations usually kill some species other than the target species, and the broader ecosystem objectives of fisheries management often relate to this impact of fishing. For example, the FAO (1994a) Code of Conduct and use of the precautionary approach in capture fisheries (FAO, 1995b) both include emphasis on consideration of the biological and ecological implications of incidental by-catch during fishing operations. In principle, an impact and sustainability assessment could be conducted for each species caught. In practice, however, inadequate data and ecological understanding about non-target species greatly limits this approach.

One type of by-catch relates to the incidental capture of long-lived, slow-growing species during fishing for shorter-lived, faster-growing species. Wade (1998) used an MSE-like framework to develop a method to support operational implementation of the United States of America Marine Mammals Protection Act (MMPA). The method calculates the potential biological removal (PBR), a by-catch level that would robustly allow the objectives of the MMPA to be achieved despite limited data being available on the species concerned. The method includes default precautionary parameter values for use when the biology of the species is poorly known.

The broad objectives of the MMPA are to maintain populations above the level giving maximum net productivity and to allow markedly reduced populations to recover at close to the fastest possible rate (Wade, 1998). Operational objectives, derived from these broad objectives, were used to develop two performance measures that were then used to compare different methods for determining *PBR*. These performance measures were (1) that populations starting at the level of maximum net productivity were still at or above that level after 20 years, and (2) that populations starting at 30% carrying capacity reached at least the maximum net productivity level after 100 years.

The simulation trials used were similar to those used to evaluate the performance of candidate management strategies for commercial whaling (Donovan, 1989; IWC, 1992). Key uncertainties in these trials were the bias and precision of by-catch estimates, precision of population abundance estimates, the production dynamics of the population, variable implementation of the *PBR* catch limit, and the time between surveys of the population. MSE analysis was used to identify appropriate default values for parameters that may be poorly known in some applications. All performance measures were found to be met if *PBR* is estimated from (Wade, 1998):

$$\mathrm{PBR} = 0.5\ N_{min}\ R_{max}\ F_r$$

where N_{min} is the "minimum population size" (the lower 20th percentile of the distribution of the most recent estimate of absolute abundance, assuming that this estimate is lognormally distributed), R_{max} is the maximum rate of population increase at small population size (default values for pinnipeds and cetaceans are 0.12 and 0.04 respectively), and F_r is a "recovery factor" between 0.1 and 1.0 (values <1 provide a "safety factor" to account for unknown bias or estimation problems; default value 0.5, and made smaller for endangered or threatened species).

The default parameter values were based on achievement of conservation objectives only. This is because the evaluation was made to support implementation of an Act that provides only conservation objectives. In New Zealand, a similar approach is used to manage the impact of by-catch of Hooker's sea lions (*Phocarctos hookeri*) in the fishery for arrow squid (*Nototodarus sloanii*). The fishery is closed for the remainder of a quota season if the estimated kill of sea lion exceeds the maximum allowable fishing-related mortality (MALFRM, the New Zealand equivalent to PBR). Maunder *et al.* (2000) use an MSE-type approach to evaluate a variety of methods for estimating MALFRM based on variants of the PBR formula. However, in addition to considering the marine mammal recovery objectives from New Zealand legislation, and population levels and parameters specific to the Hooker's sea lion, they also modelled the loss to yield from closure of the fishery. In this case, the MSE methodology allowed explicit consideration of the trade-off between loss in catch and achieving conservation objectives. Fishery performance is very sensitive to whether the fishery is closed when the threshold by-catch is exceeded, but the sea lion recovery is relatively insensitive to this (Fig. 5).

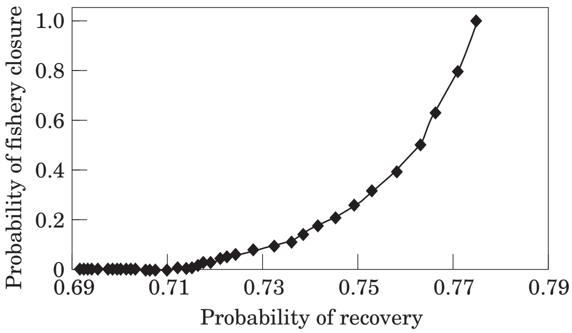

Figure 5. Expected annual (relative) loss in squid catch as a function of the probability of the Hooker's sea lion population recovering to 90% of its pre-exploitation level. The calculations span the range F_r=0 to F_r=1. The probability of sea lion recovery if the fishery is not managed using a MALFRM is 0.69. (From Maunder *et al.*, 2000.)

Food-chain dependencies and interactions

The broad management objectives concerning food-chain dependencies are to protect and maintain the relationships that sustain species. These relationships are thought to be important in maintaining the stability and diversity of ecosystems. The objectives include protecting trophically dependent species (predator species when their prey are fishery targets), the indirect effects of removing top predators ("trophic cascade"), and replacement of the upper part of the natural food chain by human predators ("fishing down the food chain"). While these objectives and their related concerns have been articulated for many years, and the issues are potentially very important, there has been little progress in developing operational interpretations.

Many food-web models have been developed, ranging from complex networks of predator-prey population dynamics to compartment models of the flow of energy or matter (reviewed by Bax, 1998). It is possible to develop complicated models that incorporate many species and have high temporal and spatial resolution (e.g., MULTSPEC of Bogstad *et al.*, 1997; Tjelmeland and Bogstad, 1998). Trophic interactions can be also incorporated into fishery-assessment models to account for the effect of past variations in predator or prey populations on the dynamics of target species (Stokes, 1991; Livingston and Methot, 1998).

Food-web models could be used as operating or assessment models in an MSE context. In principle, models that incorporate predation dynamics could also be used to identify limit reference points for the abundance of predator or prey species, by predicting, for example, that an undesirable impact might occur if the biomass drops below a certain threshold. However, food-chain models do not appear to have been used for this purpose nor have the methods of MSE been applied using them. There are current attempts at including food-chain models explicitly in MSE analyses (Thomson *et al.*, 2000). However, it remains to be seen whether these will be successful. Their main use is likely to be in forming part of the operating models used to evaluate prospective management strategies. For example, Schweder *et al.* (1998) use MULTSPEC as an operating model in their examination of the performance of (single-species) management strategies for all species included in the model.

The utility of complicated multispecies operating models in the evaluation of the performance of management strategies for the ecosystem is, however, unclear. This is because (1) these models have enormous data requirements that cannot be met in many applications, (2) there is considerable difficulty in correctly identifying functional relationships to describe feeding, and (3) it is difficult to select the species or groups of species to include in the model (Schaffer, 1981; Yodzis, 1994).

The first point is a matter of practicality; the other two points are matters of principle. For example, feeding studies may provide baseline information about predation and, given information on abundance, this information can be used to establish baseline predation rates. However, it may be far from clear how these rates change when the abundance of the prey/predator species change.

Highly complex operating models are vulnerable to model mis-specification. This problem may be avoided to some extent by using several alternative operating models with different specifications to represent the uncertainties, and by searching for management strategies that are robust across them. However, this becomes an enormous task for complex models. Simple models are also vulnerable to model mis-specification, but many alternative models can be developed and used in an MSE framework to test robustness of a management strategy. For example, Punt and Butterworth (1995) consider the implications of a cull of the Cape fur seal (*Arctocephalus pusillus pusillus*) on the catch of the two Cape hakes *Merluccius capensis* and *M. paradoxus*, using different operating models that included different numbers of hake species. The results depended strongly on the species selected for inclusion. For example, the number of hake species included in the model was selected such that 90% of the intra- and interspecific predation mortality (i.e., hake consuming hake of any species) could be assigned within the model to a specific hake species. Criteria for selection can be established and reported for any given application. But ultimately the consequences of the selection can be explored or understood only in comparison with a more complete selection.

It is probably more sensible and practical to consider several operating models of intermediate complexity than to consider only a single highly complex operating model. However, while MSE can be used to identify management strategies that are robust to the uncertainties and alternative model structures considered, there is no guarantee that they will be robust to a wider set of uncertainties and models. If a single complex food-web model is used as the operating model, the strong assumption is being made that model structure and parameterization correctly reflect all the important features of the real food web.

Probably the most progress in developing management strategies for food-chain dependencies has been made through the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) for the krill fishery. As krill are a primary food source for many whale, seal, fish, and bird species, there was concern that the krill fishery could reduce these populations or impede their recovery from previous fishing. The approach taken by CCAMLR is described in detail by de la Mare (1996). The salient points, from an operational MSE viewpoint, are:

- The broad objective, flowing from the Convention, was maintenance of the relationships between harvested and dependent species.
- The approach taken did not use predator-prey models to determine an appropriate operational target level for the krill population because these models were judged to be too uncertain. Instead a pragmatic approach was taken: 75% of the pristine spawner biomass was adopted as a precautionary reference point. This value was arrived at from general considerations, being midway between the population level without fishing (100%) and the level of reduction often associated with fishing to provide the maximum sustainable yield (50%).
- Performance measures based on this and other agreed reference points were used to examine the performance of candidate strategies for specifying the constant annual catch based on a survey estimate of the unfished population size. The operating model included uncertainty in the recruitment, growth, and natural mortality of krill, and in the estimates of population abundance.

The management strategy chosen by CCAMLR involves calculating the fixed proportion of the initial, unfished, population that can be caught each year. This fixed proportion is multiplied by a survey estimate of the unfished population to give the constant annual catch level. The procedure to determine the fixed proportion involves first calculating two candidate values. The first candidate proportion meets the condition that, over a 20 yr period, the spawner biomass has less than a 10% chance of being below 20% of its median pre-exploitation level. The second candidate proportion meets the condition that the median spawner biomass is greater than or equal to 75% of its median pre-exploitation level at the end of the 20 yr period. The lower of the two candidate proportions is then used to calculate the constant annual catch level under the strategy. A similar strategy has now also been applied to some fish stocks, both within and outside CCAMLR. A reduction to 75% of the median pre-exploitation spawner biomass is used for designated key prey species, while 50% is used for all other species.

This management strategy, and its method of development, provides a constructive attempt to account for predator-prey dynamics without engaging the full complexity of the real marine food web and hence requiring extensive information on the actual interactions. The adoption of a precautionary reference level of stock reduction, in the absence of quantitative guidance from predator-prey studies, was a critical step in allowing MSE methods to be applied. As with all its applications, however, the performance of the strategy is with respect to the range of uncertainties included in the operating model. The strategy may have different, and possibly less precautionary, performance across a broader range of uncertainties. This is likely to become an important issue if the CCAMLR strategy is applied uncritically to species other than krill, for which it was designed.

Benthic habitats and fish community composition

In this example, an actively adaptive management strategy that uses management actions to meet the dual objectives of resolving key uncertainties about resource dynamics and of sustainable resource use was evaluated and applied. Details are provided in Sainsbury (1991) and Sainsbury *et al.* (1997). Key features of this application are:

- There was a marked change in the composition of the fish community on Australia's north-west shelf after introduction of fishing, with a decrease in high-valued species and an increase in low-valued species. The central questions were: could this be reversed?; was it worth trying to reverse?; and if so, just what strategy should be used in the attempt?
- Four different hypotheses were identified that could reasonably explain the observed change, and that had quite different implications for the best long-term management strategy. The hypotheses included no inter-specific interaction (i.e. a multiple single-species model), two variations of competitive interaction among species, and trawl-induced alteration of seabed habitats. These alternative hypotheses were incorporated in an operating model. Account was also taken of two fishing methods (trap and trawl), which differed in their selectivity on fish species and their impact on benthic habitats.
- Non-adaptive, passively adaptive, and actively adaptive strategies were evaluated. The non-adaptive strategy specified the catch and capture method based on existing data and did not include further monitoring or decisions. The passively adaptive strategy involved monitoring the resource while a fixed catch and capture method was applied during a "learning period". At the end of this period the monitoring data are used to update the probability initially placed on each resource dynamics model and a decision rule is used to select catch and capture methods for the future. The actively adaptive strategy had the same structure as the former except that different experimental management regimes could be applied in different areas during the learning period. The experimental management regimes were combinations of catch and capture method applied in an area, and included closing areas to all fishing or to fishing with some gears. In both adaptive strategies, the type and intensity of monitoring could be varied, and the possibility of failed management implementation was included.
- Performance was measured by the expected net present value of the catch, i.e., the sum of the discounted annual net revenue from the fishery (the annual first sale value of the catch less capture and monitoring costs). A good management strategy would therefore give cheap recognition of each alternative model if it were true so as to allow selection of the appropriate long-term catch level and fishing method. Some actively adaptive strategies performed better than the non-adaptive and passively adaptive strategies, but only for a (roughly) 5–15-year learning period duration. Shorter experiments did not provide enough discrimination among alternative hypotheses to improve selection of the appropriate management regime. Longer experiments gave very good hypothesis discrimination, but the cost of that discrimination was greater than the future value derived from improved decision-making.

An adaptive strategy involving sequential closure of areas to trawl fishing was adopted in 1985. By 1991, the experiment had successfully discriminated among the competing hypotheses and provided a greater than expected economic return (Sainsbury *et al.*, 1997). The fishery managers of the region now use a complex of areas that are open and closed to trawl fishing.

Discussion

The MSE approach has been used to help develop management strategies to achieve objectives relating both to target species and to the ecosystem. It has been applied successfully in both information-rich and information-poor situations. Some applications are based on large amounts of background research and monitoring data. Others are based on relatively little background information. The MSE approach has been applied, also successfully, to fisheries problems involving spatially based management and should, therefore, be applicable to the design and monitoring of marine protected areas to achieve conservation objectives.

The approach forces the clarification of objectives, the evaluation of trade-offs, and the balancing of different views about the dynamics of resources and ecological dependencies and interactions. It has helped reach agreement on management and monitoring measures in the face of uncertainties that sometimes appeared bewildering at first. It has also helped clarify what is meant by being precautionary in specific cases, and allowed different degrees of precaution to be examined as well as the ultimate selection of a particular one. The approach extends the traditional focus of fisheries science by forcing the analyst to give explicit consideration to the management objectives, any future monitoring/assessment schemes, implementation, etc. These aspects were missing from risk assessments that involved simply assessing the implications of a future sequence of catches. Such risk assessments do fall within the scope of the MSE approach, but only as a special case.

While the use of MSE to date has been successful, there are some serious challenges in dealing with complex ecosystem issues and objectives. So far, ecosystem applications have been relatively simple. They have included only a limited number of uncertainties and just a few of the more clearly defined ecosystem objectives. In contrast, real ecosystems are complex and poorly understood. Scientific learning about ecosystem processes is difficult and slow, and empirical conclusions do not generalize well. If ecosystems really are highly interconnected and highly non-linear, then ultimately everything would depend on the exact state of everything else, and ecosystem dynamics could be essentially inaccessible to finite levels of scientific investigation.

The application of MSE to examine a wider range of ecosystem- and resource-use objectives will involve dealing with much greater levels of uncertainty and complexity than has been attempted to date. It is not clear at this stage whether scientifically defensible and practically useful conclusions can still be reached as the level of uncertainty addressed is significantly increased. Two particular issues are:

- The operating models are likely to be highly complex and to contain many parameters. Although substantial progress has been made in developing methods to handle large models in the last decade (Gelman *et al.*, 1995), computational constraints will limit the range of uncertainities that can be considered in a particular application for many years to come.
- The selection, and weighting of, hypotheses to include in the analysis can have an important effect on the results, but there are no adequate criteria and objective methods for making these critical choices. In particular, the usual scientific hypothesis-testing criteria, based on type I error rates and Occam's razor, are inadequate in a decision-making context (Sainsbury, 1998; Butterworth *et al.*, 1996).

The MSE approach emphasizes broad input from managers, stakeholders, and scientists. Apart from ensuring a high level of peer review, this process allows the non-technical parties to have significant input into the evaluation process. For example, hypotheses, performance measures, and candidate management strategies can be developed conceptually by these parties. However, the most important interaction between the technical analysts and the stakeholders occurs when explaining the results and their implications. There are a variety of ways of conveying the often-complicated results of an MSE evaluation, which may contain many hypotheses, prospective management strategies, and performance measures. Although final decisions should be based on the results of many carefully designed simulations, there is considerable benefit from developing a computer program that allows stakeholders to "pull the management levers" and act as the managers themselves (Butterworth *et al.*, 1997; Walters, 1994). A better understanding of the underlying trade-offs among the management objectives and of types of behaviour and quality of observation to be expected from the system will facilitate reaching agreement.

MSE ensures that the impact of uncertainty on achieving management objectives remains a focus of attention. This focus is useful in itself because overconfidence in our understanding of ecosystems and the effectiveness of our management controls has led to unwelcome surprises. In addition, it provides a clear basis to examine precaution and robustness in decision-making; strategies that work for only a small set of available hypotheses about the resource dynamics are quickly identified. The framework, with its focus on the use of clearly specified performance measures and visually accessible simulation trials, also provides a good mechanism for improving the accessibility of scientific results to stakeholders and decision-makers.

While there are major challenges to overcome, it remains useful to test prospective management strategies using operating models that incorporate some ecosystem features, even if these are highly simplified. These tests will at least identify strategies that will not work even when the dynamics are assumed to be relatively simple. If a strategy doesn't work on a simple model, what justification is there for assuming that it will work in the real world?

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