“Risk” in fisheries management: a review

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Abstract: “Risk” has appeared more frequently in the fisheries management literature in recent years. The reasons for this are partly internal (scientists seeking better ways to advise fishery managers) and partly external (e.g., adoption of the precautionary approach). Though terminology varies, there is consensus that there are two stages in dealing with risk. The first (here called risk assessment) is the formulation of advice for fisheries managers in a way that conveys the possible consequences of uncertainty. This advice is in the form of an evaluation of the expected effects of alternative management options, rather than recommendations. Risk assessment has been undertaken in many fisheries, and there is general agreement as to how it should be done (although technical details differ). The second stage (risk management) is the way fishery managers take uncertainty into account in making decisions. Much fisheries risk management is informal, i.e., nonquantitative, undocumented, and loosely linked (if at all) with a risk assessment. The major reason for this is that the objectives of fisheries management are often conflicting and are rarely stated in a way that provides explicit direction to managers or scientists.

Résumé : Le mot risque est employé plus fréquemment dans la documentation sur la gestion des pêches au cours des dernières années. S’il en est ainsi, c’est en partie pour des raisons internes (les scientifiques cherchent de meilleures façons de conseiller les gestionnaires des pêches) et en partie pour des raisons externes (p. ex., l’adoption d’une approche prudente). Bien que la terminologie varie, il y a consensus sur le fait qu’il existe deux niveaux lorsqu’on parle de risque. Le premier niveau (appelé ici évaluation du risque) est la formulation d’un conseil à l’intention des gestionnaires des pêches d’une manière qui met en lumière les conséquences possibles de l’incertitude. Ce conseil prend la forme d’une évaluation des effets prévus de différentes options de gestion, plutôt que de recommandations. L’évaluation du risque a été entreprise dans le cas de nombreuses pêcheries et, de façon générale, on s’entend sur la façon dont elle doit être effectuée (bien que les détails techniques varient). Le deuxième niveau (gestion du risque) est la façon dont les gestionnaires des pêches tiennent compte de l’incertitude lorsqu’ils prennent des décisions. Une grande partie de la gestion du risque dans le domaine des pêches est informelle, c’est-à-dire, non quantitative, non documentée et liée vaguement à une évaluation du risque (si jamais elle l’est). La principale raison qui justifie cette situation, c’est que les objectifs en matière de gestion des pêches sont souvent contradictoires et qu’ils sont rarement formulés d’une manière qui donne des instructions explicites aux gestionnaires ou aux scientifiques.
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Introduction

Since the beginning of the 1990s there has been increasing use of the word “risk” in documents concerned with the management of fisheries. Although many uses have been nontechnical (i.e., the word has been used in one of its normal English meanings) increasing numbers of authors have used the word in a technical sense. That is, they have assigned a specific, sometimes quantitative, meaning to their use of the word (sometimes in compound forms such as “risk analysis,” “risk assessment,” or “risk management”).

There has also been an increased institutional interest in risk in relationship to fisheries management. Several conferences have focussed, in whole or in part, on this topic (SEFSC 1991 (cited in Caddy and Mahon 1995); NAFO 1991; Smith et al. 1993; International Counicil on the Exploration of the Sea (ICES) theme session on risk, Dublin, 1993), and some analysis of risk has become an important tool in many major fisheries forums, e.g., in ICES (Serchuck and Grainger 1992; Kirkegaard et al. 1995), the International Whaling Commission (IWC) (Kirkwood 1993), and the National Marine Fisheries Service (NMFS) (Rosenberg and Restrepo 1994).

Three recent papers have commented on aspects of this growing literature. Shotton (1993) discussed the use of the concepts of risk, uncertainty, and utility; Rosenberg and Restrepo (1994) summarized applications in U.S. marine fisheries; and Caddy and Mahon (1995) discussed risk and uncertainty in relation to reference points in fisheries management. The present paper is intended to extend these commentaries in a broader review. Its aim is to discover how the concept of risk is being used in the fisheries management literature, to show where consensus occurs, and, where it does not, to describe the debate. This paper is intended for a broad audience and so does not delve into mathematical or statistical details.

Much of the literature reviewed here might be considered to fall under the heading of fisheries science, rather than fisheries management, and so it might be asked why we have used the latter term in our title. The answer is that a major reason for the increasing use of “risk” in this literature appears to have been a desire on the part of fisheries scientists to improve their advice to those who manage fisheries.

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Why risk?

Before examining how the concept of risk has been applied in fisheries management it is worth asking why it has been applied. There appear to be three main reasons: the perceived failure of fisheries management in recent decades, changing public attitudes to risk, and increased computing power.

The failure of fisheries management

It is widely felt that modern fisheries management has seen many more failures than successes (Stephenson and Lane 1995, and references therein). Thompson (1993) listed 13 stocks that have "collapsed" recently (in the sense that they have experienced a severe decline in biomass and have subsequently failed to recover, despite a reduction in the fishing mortality rate). Horwood (1993), speaking of European fisheries, stated that "many of our most important stocks are at historically low levels." (In these cases, failure is evident; we shall see below that it is not always easy to determine whether management has failed because the objectives of management are often not stated.)

This perceived failure has focussed attention on how institutions involved in fisheries management operate. In particular, it has caused fisheries scientists to examine both the form of their advice to fishery managers, and how, or whether, that advice has been used. One consequence has been the realization of the importance of incorporating into advice some expression of the uncertainty associated with it:

> "Understanding the risk or uncertainty associated with choices could help fishery managers select management strategies, decide which types of risks and uncertainties inhibit the effectiveness of management techniques, and finally, recognize which types of uncertainty must inevitably remain as a part of the fishing business." (Peterson and Smith 1982);

> "With an appropriate understanding of the risk of severe decline of the fishery relative to the biological productivity of fish stocks, managers can integrate socioeconomic and political information to make final decisions." (Linder et al. 1987);

> "The managers' task may be made easier if uncertainty in a fishery assessment were expressed in terms of risk to the fishery..." (Francis 1992);

> "Scientific advice to fishery managers needs to be expressed in probabilistic terms to convey uncertainty about the consequences of alternative harvesting policies." (McAllister et al. 1994);

> "Clearly, when management decisions are to be based on quantitative estimates from fishery assessment models, it is desirable that the uncertainty be quantified, and used to calculate the probability of achieving the desired target and/or risk of incurring undesirable events." (Caddy and Mahon 1995).

Rosenberg and Restrepo (1994) also noted that, for some fisheries, stock assessments are highly controversial and political, with a number of nations and (or) interest groups being involved. In such situations, some form of risk analysis or assessment may be useful to allay possible concerns about the scientific advice "by confronting uncertainty directly."

Changing public attitudes to risk

The general public are becoming increasingly aware of the extent to which industrial activities can have major impacts on the environment and human health. As a consequence, they are demanding greater regulatory controls over these activities. Major events such as the Exxon Valdez oil spill, the Chernobyl and Three Mile Island nuclear power generation accidents, and the proliferation of the zebra mussel (*Dreissena polymorpha*) in the Great Lakes of North America have caused the public to demand more caution on the part of regulators. A recent editorial in *Nature* (7 March 1996) highlights the increasing role of "science-based risk analysis" in environmental legislation in the United States.

Walters and Pearce (1996) believe that these trends will lead to greater public influence in fisheries management decisions, and that "this influence will pressure fisheries agencies to adopt low-risk policies." Two manifestations of the public desire for more caution in fisheries management are the *602 Guidelines* in the United States and the promotion of the precautionary approach. Both have had the effect of focussing the attention of fisheries scientists and managers on questions of risk.

The 602 guidelines

These guidelines were published by the United States Department of Commerce in 1989 and require fishery management agencies to "specify, to the maximum extent possible, an objective and measurable definition of overfishing for each stock or stock complex" (quoted in Mace and Sissenwine 1993). Further, they require that recovery plans be formulated for all stocks that, according to these definitions, are found to be overfished (Rosenberg and Restrepo 1994).

The precautionary approach

The precautionary approach has been embodied in national laws and regulations for many years, particularly in matters relating to human health and, more recently, the environment (Garcia 1994*b*). For example, in the regulation of pharmaceuticals, this approach requires that new products may not be sold until they have been shown to pose no unacceptable risk. More recently, following its adoption in Principle 15 of the Rio Declaration of the UN Conference on Environment and Development in 1992, interest has been renewed in applying the precautionary approach to fisheries management (Garcia 1994*a*, 1994*b*).

A precautionary approach to fisheries management was first advocated as early as 1955 (Kesteven and Holt 1955) and interest in the concept has developed internationally, spurred on by initiatives on the part of FAO (the Food and Agriculture Organization of the United Nations). The precautionary approach played a part in the UN Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks (Garcia 1994*a*); it has been adopted as one of the general principles to be followed in a code of conduct for responsible fisheries (FAO 1995*a*), and guidelines on its application have been drawn up (FAO 1995*b*). These guidelines note that "Management according to the precautionary approach exercises prudent foresight to avoid unacceptable or undesirable situations, taking into account that changes in fisheries systems are slowly reversible, difficult to control, not well understood, and subject to change in the environment and human values."

Given the precedent of the UN Convention on the Law of the Sea, it seems likely that the precautionary approach will soon become part of the national laws and international treaties governing the management of fisheries in many parts of the world.

Increased computing power

The techniques described below for quantifying risk are conceptually simple but require very large numbers of calculations. Until recently, computers sufficiently powerful to perform these calculations were not available to many fisheries scientists. As Efron (1979) has noted (in reference to the development of computer-intensive statistics) the increase of computing power has allowed analysts to "think the unthinkable." However, as Caddy and Mahon (1995) point out, it is still true that "the cost and availability of information and expertise required may preclude the use of these techniques for many small or low value stocks and for most stocks in developing countries."

Uncertainty

There is a general consensus in the literature on risk in fisheries management that risk, however it is defined, arises from uncertainty. The most useful definition of uncertainty, in this context, seems to be "The incompleteness of knowledge about the state or processes (past, present, and future) of nature" (after FAO 1995*b*). Thus, it is agreed that it is a lack of knowledge that causes risk.

Some authors have used more specific or technical definitions of uncertainty. Peterson and Smith (1982) distinguished between risk, which they viewed as a "measurable probability..." and uncertainty "which is subjective". Shotton (1993) also referred to this distinction (which he said is one used by economists) and noted (citing Lindley 1985) that, in decision theory, "uncertainty" refers only to unknown events in the future. However, these distinctions do not appear to have been found useful by many authors in the fisheries literature.

Error and uncertainty

Before discussing categories of uncertainty, we will comment on the relationship between "error" and "uncertainty." These are allied concepts but are not, as some authors have treated them, equivalent. Although error implies uncertainty (e.g., error in measurement leads to uncertainty about the measured quantity) the reverse is not true. Another important source of uncertainty is natural variation. This is often confused with error, as the following example illustrates.

Consider a scatterplot of body mass versus body length for some species of fish. It is useful to summarize the relationship between these two quantities by some curve that passes through the middle (in some sense) of the scatter of points. In using regression to derive an equation for this curve we commonly refer to the deviation between any individual point and the line as "error." This may be convenient, but it is misleading. It implies that the deviation may be partitioned into error in length and error in mass, whereas the natural between-individual variation that causes the great majority of the scatter in this plot (we assume measurement error is minor) cannot be subdivided in this way. That is, it is not sensible to ask whether a point that lies above the curve does so because the associated fish is heavy for its length, or short for its mass. If we use the scatterplot to infer the mass of an individual (not represented in the plot) from its length, there will be uncertainty in our inference. This uncertainty derives from natural variation, not error.

Six types of uncertainty

A number of authors have categorized the types of uncertainty (sometimes called error) that are important as sources of risk in a fisheries setting (A.D.M. Smith 1993; Megrey et al. 1994; Rosenberg and Restrepo 1994; Caddy and Mahon 1995; Hilborn and Peterman 1996; Fogarty et al. 1996). Six types have emerged: those associated with process, observation, model, estimation, implementation, and institutions. We will discuss these in turn.

Process uncertainty has been defined as "the underlying stochasticity in the population dynamics such as the variability in recruitment" (Caddy and Mahon 1995, following Rosenberg and Restrepo 1994) or "random variation in demographic rates and processes" (Fogarty et al. 1996). This type of uncertainty arises from natural variability, not error. For that reason it seems desirable to avoid the term "process error." Although this term is readily understood amongst specialists, it may be confusing, and misleading, in communications with fishery managers and stakeholders. The most common example of process uncertainty in the fisheries risk literature is interannual variability in recruitment. Beddington and Cooke (1983) tabulated estimates of the extent of this variability for a large number of fish stocks.

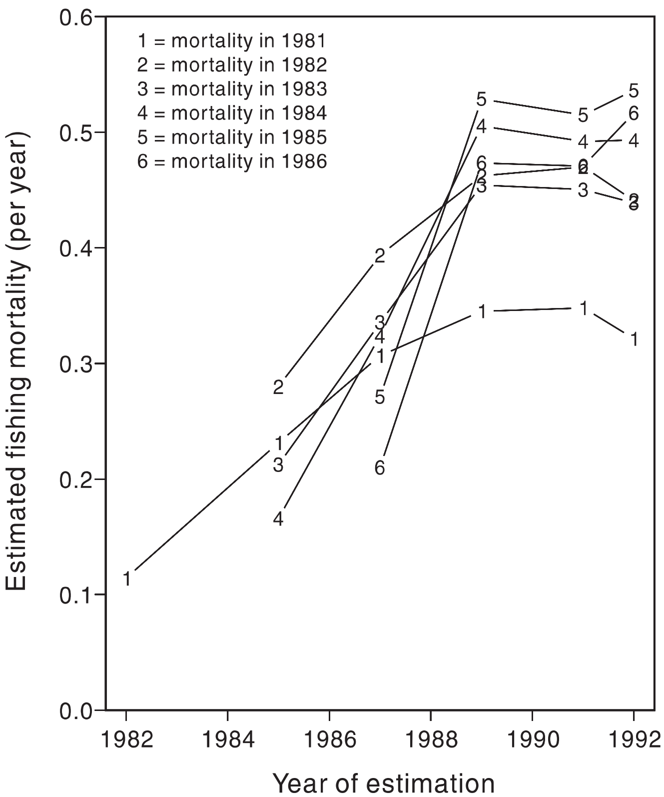
Observation uncertainty arises in the process of data collection, through measurement and sampling error (the latter deriving from the fact that we observe only a sample from a population, not its entirety). For data on commercial and recreational fisheries, inadequate data collection systems and deliberate misreporting may also be significant sources of observational uncertainty.

Model uncertainty arises from the "lack of complete information on the population and community dynamics of the system" (Fogarty et al. 1996). The term "model" refers to the conceptual model that fisheries scientists and managers use as an aid in making inferences and decisions about fish populations and fisheries. Sometimes the models are qualitative and the uncertainties are unquantified (e.g., uncertainties about the location of stock boundaries and whether fish prices will rise or fall). More commonly, the models are mathematical, i.e., a set of equations describing (a simplified version of) how populations and fisheries change over time. For this type of model the uncertainty includes lack of information about the correct structure (e.g., is the stock–recruit relationship asymptotic or domed?) and parameter values (is natural mortality 0.2 or 0.3?). Note that the distinction between structure and parameter values is arbitrary. The structural question of whether to use an asymptotic (e.g., Beverton and Holt) or domed (e.g., Ricker) stock–recruit relationship may be made into a parametric question simply by using a more complicated stock–recruit function which can take either shape.

An important, and easily overlooked, type of model uncertainty is that to do with what is commonly called the "error structure" (a structure that often includes both error from observations and natural variability!). Inferences drawn from modelling exercises may be profoundly affected by the choice of error structure (see Schnute (1991) and Polacheck et al. (1993) for examples).

Estimation uncertainty relates to the process of parameter

Fig. 1. Illustration of the retrospective problem in the analysis of catch-at-age data. Sequences of successive estimates of instantaneous fishing mortality for 7-to 9-year-old cod in Labrador and northeastern Newfoundland (NAFO region 2J3KL). Note that each sequence shows a trend in the same direction (upward). More information about these data is given by Myers et al. (1997).



estimation. It is a secondary type of uncertainty in that it derives from some or all of the three above types. Estimation requires data and a formula, or algorithm, which implies a model. The former are subject to observation uncertainty and possibly process uncertainty (e.g., if the data are numbers of recruits), the latter to model uncertainty. A striking, and important, example of the possible effects of estimation uncertainty is the so-called "retrospective problem" in the analysis of catch-at-age data (Fig. 1; Sinclair et al. 1991; Parma 1993).

Rosenberg and Brault (1993) drew attention to implementation uncertainty, by which they meant uncertainty about "the extent to which management policies will be successfully implemented." For example, a target harvest rate (the management policy) may not be achieved. They noted that the risk associated with alternative management policies depends in part on how effectively they are likely to be implemented. Rice and Richards (1996) suggested that management actions were likely to be ineffective when the objectives of management and industry differ substantially. Angel et al. (1994) concluded that the primary cause of the failure to conserve groundfish stocks on the Scotian Shelf off eastern Canada between 1977 and 1993 was a failure in implementation: "In sum, the tactical approach chosen to control fishing mortality generated illegal [fishing] behaviour which was not curbed by the available enforcement regime."

O'Boyle (1993) defined institutional uncertainty as arising from "... problems associated with the interaction of the individuals and groups (scientist, economist, fisherman, etc.) that compose the management process" and suggested that this could exceed "quantifiable" sources of uncertainty in stock assessments. One type of institutional uncertainty is associated with the lack of well-defined social, economic, and political objectives in fisheries management. Participants in a recent workshop identified this as a major source of uncertainty (S.J. Smith 1993). Serchuck and Grainger (1992) and Francis (1994) describe institutional settings in which, because clear management objectives have not been stated, scientists have had to try to infer them. Megrey et al. (1994) stated that "the communication of risk to fisheries management by scientists is hindered by a lack of well-defined objectives for fisheries management." Stephenson and Lane (1995) claim that part of the reason for many fisheries failures in recent decades is that "objectives have been broad, ill-defined, and in many cases not operationally feasible."

Reducible and irreducible uncertainty

Fogarty et al. (1996) made an important distinction. They noted that uncertainties derived from observations and models (and thus from estimation) are, in principle, "reducible" by, for example, more intensive sampling and increased research effort. Institutional and implementation uncertainties are also, with appropriate effort, reducible. However, process uncertainty is inherent and thus "irreducible." For example, with increased effort one may measure recruitment more precisely, and learn more about why it fluctuates, but whatever is done (short of extinguishing the population) will not stop it fluctuating.

The terminology of risk

There has been some debate in the literature about appropriate technical definitions of terms like "risk" and "risk analysis." In commenting on this debate we will follow the suggestion of Shotton (1993) that an important criterion is "how well do such terms help managers to make the 'best' decision?"

Risk

There are two schools of thought on how "risk" should be defined and used in the fisheries management literature. The great majority of authors have, whether explicitly or implicitly, taken it to mean something like "the probability of something undesirable happening" (e.g., Peterson and Smith 1982; Brown and Patil 1986; Bergh and Butterworth 1987; Linder et al. 1987; Swartzman et al. 1987; Hall et al. 1988; Francis 1991; Punt and Butterworth 1991; Fogarty et al. 1992; Restrepo et al. 1992; Hilborn et al. 1993; FAO 1995*b*; Fogarty et al. 1996). Others have preferred "decision-theoretic" definitions; i.e., those that treat risk as an expected loss and thus incorporate both the probability and the severity of the undesirable event(s) (Shotton 1993; Horwood 1993; Rosenberg and Restrepo 1994). This is the interpretation of risk used in some formulations of decision theory (Ferguson 1967; Berger 1985).

We cannot turn to common English usage to resolve this debate because both meanings occur. For example, most people, in interpreting the phrase "the risks associated with smoking are high," would consider both the severity and probability of consequences (a severe consequence that has a very low probability, e.g., death in an airplane crash, does not constitute a high risk). However, in the phrase "the risk of death is high," "risk" would be taken as synonomous with "probability."

A major reason that most authors have not used decision-theoretic definitions may be the great difficulty involved in quantifying the severity of certain "undesirable" events (Horwood 1993; Mohn 1993). For example, although it is widely believed that a low level of spawning biomass is undesirable (because it may lead to stock collapse), we are aware of no attempt to estimate the severity (in the form of potential losses) of this event (see The Risk of Collapse, below).

Because of this difficulty it seems sensible to follow FAO (1995*b*) in treating risk as "the probability of something undesirable happening," and reserving the terms "expected loss" or "average forecasted loss" for quantities encompassed by decision-theoretic definitions. Note that this is simply a matter of terminology. It is not to say that we should ignore the issue of severity; this should be quantified wherever possible. Of course, to make the above definition operational we must be more specific (see Choice of Performance Measures, below).

Two stages in dealing with risk

Although their terminology varies, many authors appear to accept the view that the process of dealing with risk in fisheries management has two distinct stages. The first deals with the formulation of advice for fisheries managers; the second deals with the ways in which managers use that advice to make decisions. We will follow Pearse and Walters (1992) and Lane and Stephenson (1997) in calling these "risk assessment" and "risk management," respectively.

Lane and Stephenson (1997) quote from the decision analysis literature to support their contention that the term "risk analysis" should be used to describe the combination of these two stages. This broad use of "risk analysis" has also been advocated in the area of animal health (Ahl et al. 1993; they add a third stage: risk communication). However, many authors in the fisheries literature use this term to refer to what is here called risk assessment.

Risk assessment

The aims of risk assessment may be encapsulated in two quotes. Peterson and Smith (1982) commented that it is useful "to evaluate possible management techniques as they may increase or decrease risk and uncertainty for the fishing industry and for achieving stated objectives of management." Fogarty et al. (1996) said that "Formal risk assessment provides a mechanism for explicitly accounting for uncertainty in framing fishery management advice."

The following quotations illustrate the range of ways in which the first stage in dealing with risk has been defined:

> Risk analysis is "the evaluation of the probability of an end event or events happening which result from a combination of events" (Brown and Patil 1986);

> Risk assessment "deals with methods of assessing the probability of possible outcomes of decisions" (Pearse and Walters 1992);

> "Risk assessment or analysis..., as seen from the fisheries scientists' point of view, most often focuses on ways of quantifying probabilities of outcomes, and on ways of fixing acceptable levels for these probabilities." (Basson 1993);

> "Risk analysis may be thought of as being comprised of two components. The first is the propogation of uncertainties for a given course of action and the second is a metric of consequences." (Mohn 1993);

> Risk assessment "... has been used to mean estimating the probability that a given management decision or strategy will exceed some defined management threshold." (A.D.M. Smith 1993);

> Risk evaluation is ways "to pass on the interpretation of [the effects of uncertainty] in a constructive manner to the fisheries managers and fishing industry" (S.J. Smith 1993);

> "Risk analysis is the evaluation of benefit streams under uncertainty produced in a risk assessment using a specified loss or utility function." (Rosenberg and Restrepo 1994);

> "Risk assessment is the process that evaluates possible outcomes or consequences and estimates their likelihood of occurrence as a function of a decision taken and the probabilistic realization of uncontrollable state dynamics of the system.... [it] assigns probabilities to the multidimensional simulation outcomes for each decision alternative" (Lane and Stephenson 1997).

Although the authors variously use the terms "risk analysis," "risk evaluation," and "risk assessment," they are all, with one exception, defining more or less the same activity. That is, "using information on the status and dynamics of the fishery to present fishery managers with probabilistic descriptions of the likely effects of alternative future management options." The one exception is that part of the definition by Basson (1993) that refers to "fixing acceptable levels"; most authors would place that activity in the second stage, as part of risk management. Note that the distinction made by A.D.M. Smith (1993) between risk assessment and management strategy evaluation is avoided by this definition.

Risk management

In the fisheries context, risk management has been defined as the following:

> "[dealing] with ways of responding to uncertainty about outcomes" (Pearse and Walters 1992);

> "the process of making of decisions concerning risks and the subsequent implementation of those decisions" (Basson 1993);

> "Application of decision-making criteria embodied in management utility functions that measure the expected value of each decision alternative in terms of the multiple criteria and their tradeoffs, and thereby evaluates and ranks alternative decisions for presentation to decision makers" (Lane and Stephenson 1997).

We feel that none of these definitions is sufficient and thus satisfactory. The first two are general, providing no direction for those concerned with the application of a methodology. The last is an improvement in at least dealing with expected values of uncertain outcomes but fails to say that the response of decision makers will depend on their attitude to risk (aversion to, or propensity for).

Of course, any decision process that may result in an undesirable outcome and that takes uncertainty into account, in some way or other, may be termed risk management. However, there

Table 1. Key components in fisheries management applications of risk assessment.

Inputs	(1) Data on the fishery and the fish population (including estimates derived from such data)
	(2) A model describing the dynamics of the fishery
	(3) Quantitative descriptions of uncertainty about the data and (or) the model
	(4) Several alternative future management options
Outputs	One or more performance measures describing the future performance of the fishery under each of the alternative management options.
Method	Monte Carlo projection

Note: See text for details.

is a broad spectrum of possible approaches to risk management, ranging from the informal to the formal. On this spectrum, the great majority of risk management in fisheries would lie close to the informal end. This sort of management is characteristically nonquantitative, undocumented (in terms of decision criteria and process), and only loosely linked (if at all) with a risk assessment. It may be imagined as taking the form of negotiations in a smoke-filled room.

Formal risk management entails a description of the decision criteria (i.e., those to be used in choosing amongst alternative management options) that is sufficiently complete and specific to define the quantities that should be calculated in the risk assessment and to make the decision, given the results of the risk assessment, clear cut. The key point here is that the decision criteria should be stated, very specifically, before the risk assessment takes place.

Note that, even with the most formal of risk management, it will often be unclear in advance what range of alternative management options to include in the risk assessment. There will always need to be scope for the risk assessment to be repeated with different management options until an acceptable one is found. In addition, as Morgan and Henrion (1990) note, rarely is a problem solved once and for all. However, once an acceptable management option is found, it should be, according to the decision criteria, preferable to all other options considered. (We take the view that the occurrence of two or more equally acceptable options is unlikely in practice, no matter how diverting it may be in theory).

Risk assessment in practice

Although there is no agreement in the fisheries literature about how we should define risk assessment, and what we should call it, there appears to be broad agreement on the type of analysis that should be done. In this section we first present a schema that describes this area of agreement and then discuss some issues that arise from an examination of recent practice.

Common components

Almost all fisheries management applications of risk assessment have certain components in common (Table 1), which we will discuss in turn.

The inputs

Examples of data inputs include catch and effort (either of which may be broken down by area, time, vessel type, etc.); survey estimates of population abundance; estimates of rates of growth and natural mortality; etc.

The descriptions of uncertainty will include at least one of the six types described above and will contain uncertainty about both the current and future status of the fishery. Two types of descriptions are used. The first is probabilistic, taking the form of statistical distributions (e.g., giving the range of values a parameter might take and the probability associated with each value). The second type consists of a set of alternative hypotheses to which no probabilities are attached. For example, there may be two different explanations for recruitment fluctuations (Parma and Deriso 1990) or several alternative data sets (Punt and Butterworth 1991).

The management options are typically to do with the annual decisions which affect the level of catch in the fishery, through controls on either catch or effort. They may be only for the next year (i.e., the first year in the future), or may extend many years into the future (in which case the word "strategy" may be preferable to "option"). We will refer to the period covered by these management options as the "management period." Two distinct classes of management options are described below.

The model is usually in the form of a computer program that describes, in a simplified way, the dynamics of the fishery (i.e., how the population changes over time with different levels of fishing).

The method

Monte Carlo projection is a way of dealing with uncertainty in evaluating management options. If there were no uncertainty the model could produce, for each alternative management option, a single exact description of the future of the fishery (Fig. 2A). Because there is uncertainty, the method of Monte Carlo projection produces a large number (usually at least 100, often 1000 or more) of alternative possible futures for the fishery for each management option (Fig. 2B). Each of these possible futures (often referred to as "realizations") is a description of how the fishery might develop as a result of that option.

Note that what constitutes a realization depends on how complex the model is. For a simple model, a single realization would consist of just the population biomass and the catch for each year of the management period. With a more complex model, the biomass and catch might be specified for each age-class, and the catch may be further broken down by area and (or) vessel type. In some assessments, each realization will also extend into the past and thus describe a possible past for the fishery. However, because we are evaluating future management options, our focus will be on the future part of each realization.

The word "projection" refers to the fact that the method projects the fishery into the future. The label "Monte Carlo" signals that there is a random element in the way the realizations are constructed. For example, suppose that, in the situation illustrated in Fig. 2B, the only uncertainties are (*i*) the present biomass and (*ii*) the recruitment to the fishery (which may or may not depend on spawning biomass) in each of the 5 years of the management period. Each of these uncertainties would be described by a probability distribution (i.e., a function describing the probability of each of the possible values of biomass or recruitment). To generate one realization the computer program must first pick six random numbers, one from each of the six probability distributions. This set of six numbers describes a possible reality. For this possible reality the model will produce, for each management option, one realization.

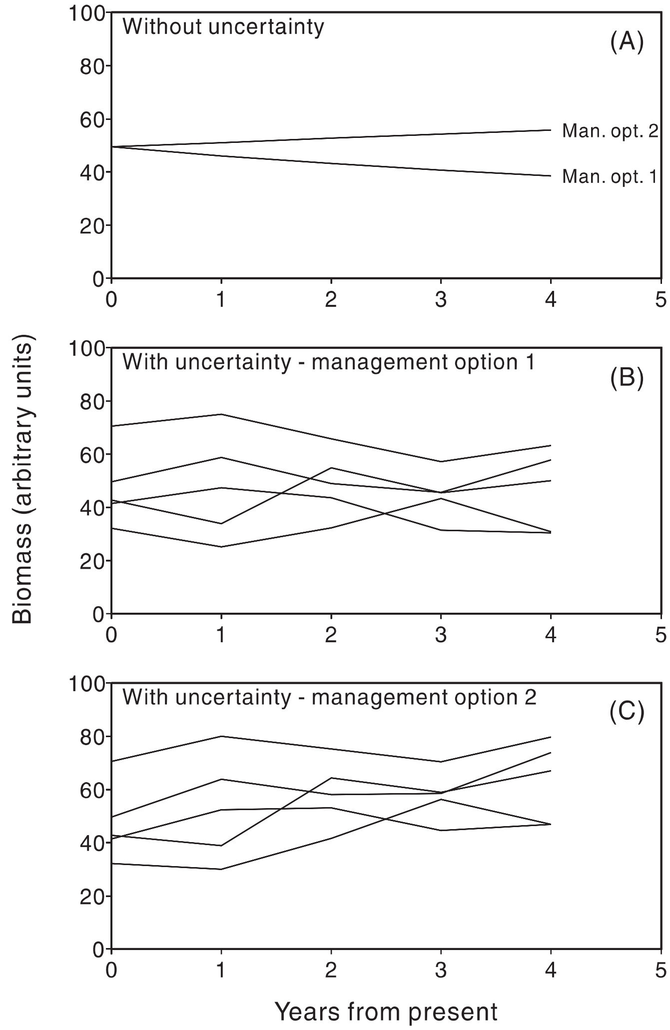
Note that the uncertainty is expressed by the difference between alternative realizations; there is no uncertainty in a particular realization (but see below the distinction between quantifiable and unquantifiable uncertainty). The greater the uncertainty, the greater the range of possible futures described by the realizations. Note that in Fig. 2B most of the biomass trajectories increase. Thus, we could say that, under option O_1, the biomass will probably increase. If the projections are done in such a way that each of the realizations is considered equally likely, and if the biomass increases in 80 of 100 realizations, we would say that there is a probability of 0.8 that the biomass will increase. In some risk assessments there will be a different probability associated with each realization.

The outputs

The performance measures are numerical descriptions of the likely future effects of the alternative management options, taking into account uncertainty about the current status of the fishery and its future behaviour. Typical examples are the probability that the biomass will fall below some threshold level during the management period, the expected catch over that period, and the expected net present value of the catch. Performance measures are often thought of as expressions of "risk" in one or another of the senses defined above.

Note that all we know about the possible future effect of a particular management option is contained in the set of realizations (possible futures) calculated for that option in the projections. Thus, the performance measures may be seen as summaries of this information. A key point about them is that they are typically statistical in nature, e.g., probabilities, expected values, standard deviations, etc. They summarize the range of possible futures for each alternative management option.

Fig. 2. Illustration of the method of Monte Carlo projection for two alternative management options over a 4-year management period. Plots of biomass against time: (A) without uncertainty, one curve for each option, and (B and C) with uncertainty, five realizations (alternative possible futures) under management options 1 and 2, respectively.



Two types of risk assessment

Risk assessment has been applied to fisheries management in two distinct situations, which we might label "stock assessment" and "harvest strategy evaluation." What distinguishes these applications is whether they take into account the current status of a particular fish stock. The former type of application does take this into account and is aimed at helping managers to decide what actions to take in the immediate future in managing that stock. In this situation it is of great importance to know whether the stock is currently depleted or not, and whether recruitment in the next few years is likely to be high or low. Examples of this type of risk assessment are given by Brown and Patil (1986), Mohn (1991), Francis (1992), Mesnil (1993), and McAllister et al. (1994).

In stock assessment applications the management period (as defined above) is generally short (1–5 years). It is important to realize that the management period is not the same as what we might call the "decision period," the time period covered by the decision that managers have to make (the decision for which the stock assessment is intended to provide supporting information). Most fisheries management is done on an annual cycle so the decision period is generally only 1 year. Francis (1994) used the phrase "Think five years, act one year" to make an analogy with the environmental dictum "Think global, act local" in explaining the philosophy behind making the management period longer than the decision period. Most people, institutions, or goverments can act only on a local level, but the environmental dictum reminds them of the importance of considering the global implications of their actions. Similarly, there are a number of constraints (chiefly a lack of information) that require fishery management actions to be annual, but it is often prudent to consider the longer term implications of making particular annual decisions. For this reason the management period may be longer than the decision period.

Harvest-strategy evaluations ignore the current status of a fish stock and are not concerned with immediate management decisions. They are aimed at answering the question “What would happen in the long term if we used a specific rule (harvest strategy) to make our annual management decisions?” Here the management period is longer, typically 10–50 years. The harvest rules may be simple (e.g., take the same catch, or the same proportion of the biomass, each year) or more complicated (e.g., strategies that change when the biomass falls below a specified threshold). Examples of harvest-strategy evaluations are given by Ruppert et al. (1985), Swartzman et al. (1987), Hall et al. (1988), Francis (1993), Sigler and Fujioka (1993), Megrey et al. (1994), and Kirkwood (1997).

Within harvest-strategy evaluations, two types of questions are considered: “What are the pros and cons of different types of strategy?” and “What are the effects of different levels of fishing intensity for a given strategy?” For example, how do the consequences of catching the same amount of fish each year (constant catch strategy) compare with those from taking the same proportion of the population each year (constant fishing mortality)? For the latter strategy, what are the effects of different levels of fishing mortality?

There is a technical difficulty with this sort of risk assessment in that the fishery must be given some sort of initial state for the stochastic projections, but it is desired that the results should not depend on that intial state. A common solution to this problem is to make the period covered by future projections somewhat longer than that used in calculating the performance measures. For example, Megrey et al. (1994) projected 70 years into the future but used only the last 50 years in calculating their performance measures.

Some authors have used the term “management procedure” to encompass both a harvest strategy and descriptions of the data that should be collected each year and the methods used to analyse these data to calculate the harvest level. Risk assessments that evaluate management procedures (e.g., Butterworth and Bergh 1993; Punt 1995; Kirkwood 1997) must simulate not only the fish population, but also the collection and analysis of data. Kirkwood and Smith (1996) discuss how such analyses may be used to assess how precautionary a proposed management procedure is likely to be.

The problem of presentation

Although the general approach to risk assessment in fisheries (Table 1) is commonly accepted, Rosenberg and Restrepo (1994) noted that “there is, as yet, no standard approach in the presentation of advice [to fishery managers] with respect to uncertainty and risk.” Further, the development of effective methods of presentation “presents substantial challenges to both fishery technicians and managers” (Caddy and Mahon 1995). Two issues to be decided are which performance measures to use, and how complex should the presentation be for each performance measure.

Choice of performance measures

There is little agreement as to the what are the “best” performance measures. To some extent this is inevitable in that the choice of measure should depend on the objectives of the managers of the fishery in question and their attitude to risk. Also, for stock assessments, it may depend on the current status of the fishery; performance measures appropriate for a developing fishery may not make sense for one that is overexploited. However, in considering the very wide range of performance measures that have been used it is hard to escape from the conclusion that it would be useful to narrow this range.

A bewildering variety of performance measures have been used. We counted approximately 39 different performance measures in a sample of about 20 published risk assessments. (These numbers are approximate because it was sometimes debatable as to how many separate risk assessments are contained in one paper, and some performance measures were not sufficiently well described to indicate whether they were distinct from others.) To give some idea of how it is possible to generate so many different measures it is useful to present a formal description of the choices involved (Table 2).

In step 4 of Table 2, some authors, rather than presenting a single number, chose to present the whole distribution (Fig. 3). (Note that Fig. 3B is equivalent to calculating $P(B < B_{\mathrm{targ}})$, where P is the probability and B is the biomass, for all possible values of the target biomass, B_{targ}.)

The description in Table 2 is sufficiently general to cover most performance measures in the fisheries literature. One example not covered is that of net present value (NPV). Calculating this type of performance measure involves determining the monetary value of the catch and then applying an appropriate discount rate (discount rates are considered further below).

One of the most common performance measures is of the form $P(B < B_{\mathrm{thr}})$, where B_{thr} is the threshold biomass (see Table 2). However, opinions differ as to the appropriate level for B_{thr}. The most popular value is probably $0.2B_0$ (which seems to originate from Beddington and Cooke (1983), where B_0 is the virgin biomass), but a range of other values have been used: $0.1B_0$ (Berg and Butterworth 1987), $0.25B_0$ (Hall et al. 1988), $0.5B_{\mathrm{MESY}}$ (Getz et al. 1987; B_{MESY} is the biomass associated with the maximum estimated sustainable yield), the minimum historic value (Sigler and Fujioka 1993), and the biomass for which the mean recruitment is estimated to be half the maximum mean recruitment (Restrepo and Rosenberg 1994) (also, see Myers et al. 1994). Nor is there any consensus as to whether this probability should be be calculated as a proportion of years or of realizations (some authors do not even clearly specify which is used). (In the formalization of Table 2 this is equivalent to deciding whether, at step 2, the five values of B for each realization should be summarized by their minimum value.)

There are three criteria that should be considered in choosing a performance measure. First, it should be readily intelligible to managers and other stakeholders. In our experience, standard deviations and coefficients of variation are not easily understood by nonspecialists (despite their importance in statistical inference) and are best avoided. For describing variability in catch, the average absolute change in catch from year to year is probably more intelligible. (We note though that many papers using standard deviations or coefficients of variation are aimed at scientists, who may be more able to interpret these quantities than fishery managers or other stakeholders.) Second, a performance measure should show contrast between alternative management options. If it takes almost the same value for all management options it is of little use in decision making. Third, it must be related to management objectives. This should, of course, be the first criterion. We have given it

Table 2. Description of four choices that must be made in constructing a single performance measure. To clarify the presentation we assume that the risk assessment has involved calculating 100 "possible futures" (realizations), each projecting 5 years into the future.

1. Which "attribute"?	Most examples use catch, C; biomass, B; fishing mortality, F; or recruitment, R. For each choice this results in a set of 500 numbers (5 years times 100 realizations). Some performance measures have used the change in catch from year to year, ΔC.
2. Summarize within realizations?	For example, rather than using all five catches for each realization, it might be better just to use the mean, minimum, or total or to use only the catch in the final year. If this summary is made, the set of 500 numbers reduces to 100.
3. What units?	For example, rather than dealing with a biomass in tonnes it might be preferable to divide by the virgin biomass, B_0, or some target biomass, B_{targ}, and thus deal with biomass as a fraction of B_0 or B_{targ}.
4. Which summary statistic?	Generally the performance measure is a single number summarizing the set of 500 (or 100) numbers. For example, the mean, standard deviation, coefficient of variation, median, or some other percentile (e.g., 5th or 95th). Alternatively, it may be expressed as a probability, e.g., the probability that the biomass will fall below some threshold level, written $P(B < B_{thr})$.

Note: More complicated performance measures require additional choices (see text).

last because it is probably the most difficult; management objectives are usually not stated explicitly, and when they are, the statements are often too vague to be useful in constructing a performance measure.

Complexity of presentation

The complexity of the presentation will depend to some extent on the nature of the uncertainties. The simplest presentation is of the type shown in Table 3A. For each management option, a single number is presented for each performance measure. However, such a simple presentation will only be possible if all the uncertainty can be expressed probabilistically.

When some of the uncertainty is expressed in the form of alternative hypotheses a presentation like Table 3B may be appropriate. Sometimes one of these alternatives will be preferred (or considered most likely) and may be referred to as the "base case" assessment. The other assessments are then considered as sensitivity analyses. Suppose, for example, that the alternative hypothesis differs from the base case by changing one model assumption. Then the sensitivity of the assessment to this assumption is measured by how much the calculated values of the performance measures change between the two analyses. In some assessments there will be no base case, i.e., none of the alternative hypotheses will be considered "most likely."

Note that, in presentations like that in Table 3B, uncertainty has been dealt with in two ways. The "quantifiable uncertainty" (i.e., all that to which probabilities can be assigned) has been incorporated into the stochastic projections. It is expressed as the difference between realizations and is summarized by the performance measures. The "unquantifiable uncertainty" is that incorporated in the alternative hypotheses. This is expressed, for each management option, by the amount of variation between the calculated values of each performance measure.

Some authors have advocated presentations like that in Table 3C (e.g., Hilborn et al. 1993, Table 2; McAllister et al. 1994, Table 6; Hilborn and Peterman 1996, Table 2). Here, part of the quantifiable uncertainty has been disaggregated and expressed as a set of alternative "states of nature" with probabilities

Fig. 3. Example of two ways of presenting a performance measure (from the risk assessment in Fig. 2) as a distribution, rather than a single number. Each graph describes the uncertainty the biomass 4 years from the present for each of two management strategies: (A) as a probability density and (B) as a cumulative distribution function.

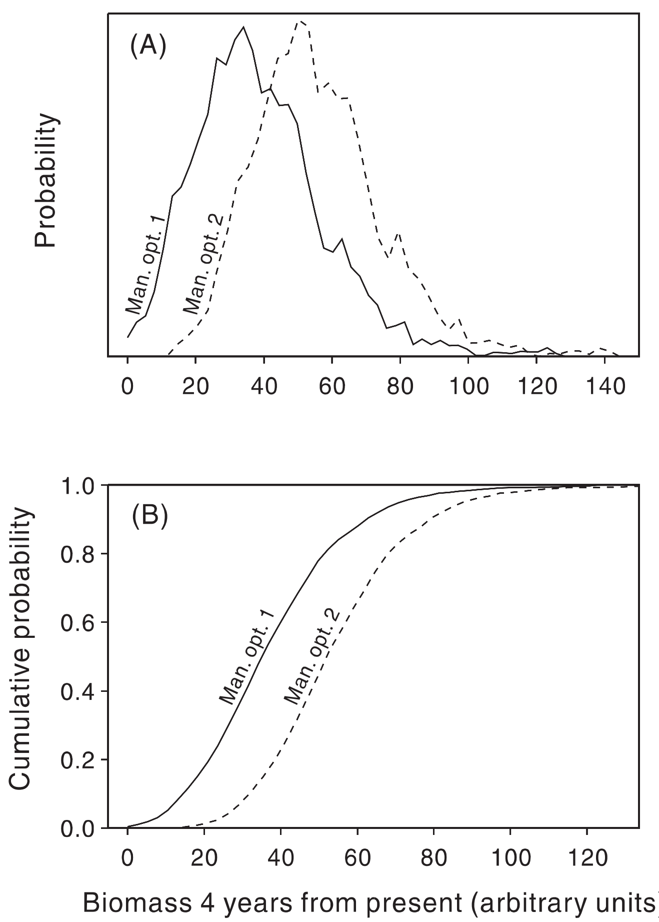


Table 3. Example of three levels of complexity in the presentation of results from a risk assessment.

(A) Simplest case

Management option	Performance measure: $P(B < B_{thr})$	Performance measure: Mean C
Option 1	0.1	1000
Option 2	0.2	1200
Option 3	0.3	1500

(B) With two alternative hypotheses

Management option and hypothesis	Performance measure: $P(B < B_{thr})$	Performance measure: Mean C
Option 1		
Base case	0.10	1000
Alternative hypothesis 1	0.05	900
Alternative hypothesis 2	0.02	700
Option 2		
Base case	0.20	1200
Alternative hypothesis 1	0.15	1150
Alternative hypothesis 2	0.12	950
Option 3		
Base case	0.30	1400
Alternative hypothesis 1	0.25	1200
Alternative hypothesis 2	0.23	1000

(C) With alternative states of nature

	$P(B < B_{thr})$				Mean C			
Recruitment: Probability:	Poor (0.3)	Medium (0.4)	Good (0.3)	Expected value	Poor (0.3)	Medium (0.4)	Good (0.3)	Expected value
Management option								
Option 1	0.35	0.15	0.01	0.17	600	900	1500	1000
Option 2	0.50	0.25	0.05	0.27	700	1200	1700	1200
Option 3	0.70	0.33	0.15	0.39	900	1600	2000	1500

assigned to each alternative. Note that the expected value columns in Table 3C are equivalent to the columns in Table 3A. Of course, if there are also alternative hypotheses, Table 3C will become more complicated again.

This type of presentation involves some difficult choices for the analyst. First, which portion of the quantifiable uncertainty should be disaggregated? In the two examples quoted above it was uncertainty about B_0. It could just as easily have been uncertainty about the natural mortality, M. Second, if the range of possible values for the variable concerned is inherently continuous (as it is for B_0 and M), how is it best divided into discrete alternative sets of values? For example, what should be the boundaries between "low," "medium," and "high" B_0, and would it be better to have only two categories or perhaps four?

In choosing between methods of presentation like those in Table 3 the main question that must be answered is "Which will be most likely to lead to the best decision?" Table 3A would seem ideal: a single compact table that, if the performance measures are well chosen, clearly summarizes the likely performance of the fishery under alternative management options. Unfortunately, there are often unquantifiable uncertainties so the next level of complexity (Table 3B) is often unavoidable. A challenge for analysts is to restrict the number of alternative hypotheses so as to adequately express the uncertainty without providing an overwhelming number of alternatives. It is unclear whether the complexity added by the disaggregation in Table 3C will lead to better decisions, especially if there are unquantifiable uncertainties to be dealt with so that a combination of Tables 3B and 3C is necessary. Clearly there needs to be close collaboration between those who carry out risk assessments and those who use them to ensure that the form of presentation used aids the decision-making process to the greatest extent possible.

True versus perceived states

A number of authors have stressed the importance in risk-assessment models of distinguishing between the "true" and perceived states of the fishery (Punt and Butterworth 1991; Hollowed and Megrey 1993; Rosenberg and Restrepo 1993; Kirkwood 1997). This may involve having a single model and two sets of parameters or two different models. In either case, one model (or parameter set) is taken as describing the "true" state of the fishery, and the other, how it is perceived by scientists and managers.

We have written "true," rather than true, here because no model can precisely describe the actual fishery. This is taken for granted. However, it is important to realize that, even if the fishery were described exactly by some model, there would still be an important difference between the actual state of the fishery and its perceived state. This arises because of observation and model uncertainty.

Some examples will illustrate the value of this distinction. Hollowed and Megrey (1993) described an assessment in which the proportion of the time that the biomass, B, is greater than some threshold, B_{thr}, (i.e., $P(B > B_{thr})$) is an important performance measure. They showed how it could happen that the perceived value of $P(B > B_{thr})$ may be consistently lower than the "true" value. (Note that B and B_{thr} are parameters that have both "true" and perceived values, the latter being estimates of the former). Rosenberg and Restrepo (1993) examined a similar situation in more detail. They calculated what they called (*i*) "power" and (*ii*) "type I error." These are the probabilities that it will be perceived that B is below B_{thr}, (*i*) given that it actually is, and (*ii*) given that it is not. Punt and Butterworth (1991) discussed a fishery for which there were a number of alternative descriptions (combinations of model and data set). They then showed, for each pair of descriptions, what would be the effect of managing the fishery if one description was assumed to be true while the other was actually true. As a result, they were able to eliminate some descriptions on the basis that they performed so poorly if one or more of the other descriptions were "true."

The value of simple models

There is a natural tendency, as our knowledge of fish and fisheries increases, to incorporate this knowledge in our models and thus make them more and more complex. This would appear to be a positive trend. It seems obvious that the more closely our models imitate reality, the more useful they will be to us. However, recent work has shown that this is not necessarily true (Punt 1993; Steinshamn 1993; Kirkwood 1997). The point is that, in a fisheries management setting, our objective is to manage the fishery well, not to model it well. The above references provide examples where simpler models support fishery management better than more realistic ones.

The risk of collapse

Probably the most extreme "undesirable event" that fisheries managers wish to avoid is the collapse of the fishery. By "collapse" we mean a severe decline in biomass and subsequent failure to recover, despite a reduction in the fishing mortality rate (following Thompson 1993, who gave a table of 13 stocks to which this has happened). Such an event implies a long-term severe drop in production and thus revenue.

It would seem obvious that we should guard against such a catastrophe by making the probability of collapse one of our performance measures in all risk assessments. This way, any management option that produced an unacceptably high probability of collapse could be avoided. Unfortunately this is not possible because we don't understand enough about how fisheries collapse to model this event. This is not to say there are no theories on this subject. The problem is that, for a particular fish stock, we often don't know how to choose between the theories and usually have scant knowledge about model parameter values.

A common response to this lack of knowledge is to use $P(B < B_{thr})$ as a performance measure, rather than P(collapse). The rationale behind this is the belief that the probability of collapse in the near future is inversely related to biomass, with the probability becoming significant as the biomass falls below B_{thr}. Note that this does not mean that the stock will definitely collapse if $B < B_{thr}$, only that the probability of collapse is thought to be significant. However, we are unable to say how high this probability is or how fast it increases with decreasing biomass. In other words, although our Monte Carlo projections allow us to estimate the probability of the undesirable event ($B < B_{thr}$), we cannot estimate its severity. This is in contrast to the undesirable event of fishery collapse, for which we can estimate severity but not probability.

Risk management in theory

Although some form of risk assessment has become routine in the management of many fisheries, there appear to be very few examples where formal risk management (as defined above) has been applied in fisheries. However, there is a growing literature about how it ought to be, or could be, applied. In this section we will discuss first some issues that arise from this literature and then two attempts at formal risk management.

Objective or loss functions

The simplest way to formalize risk management is to devise a single performance measure for the fishery and then choose the management option that maximizes (or minimizes) this measure. The function that calculates this performance measure from a set of realizations is called an "objective function" (if it is to be maximized) or a "loss function" (if it is to be minimized). (In what follows we will refer only to objective functions because a loss function can always be turned into an objective function by taking its negative.)

A slightly more complicated approach would be to maximize one performance measure subject to some constraint on a second measure. Thus, for example, Francis (1993) used mean catch (C) as an objective function and searched for the management option that maximized this subject to the condition that $P(B < 0.2B_0) < 0.1$.

Objective functions have been calculated for various fishery management problems (e.g., Ruppert et al. 1985; Quinn et al. 1990; Hollowed and Megrey 1993; Megrey et al. 1994). However, these have typically been by way of example, rather than operational functions that have been used to make fishery management decisions. Before considering why this is so, we will briefly discuss two technical issues that are of importance in constructing objective functions: utility and future discounting.

Utility

In a fisheries context, some obvious units in which to measure gains (or losses) are tonnes for catch or dollars (or other monetary unit) for income or profit. However, the problem is that these are not necessarily the best units for use in objective functions because they may not measure well the strength of people's preferences. For example, the possibility of obtaining an additional 1 t of catch is generally more attractive to the fisher who already has access to 20 t, than it is to one with 100 t. A second example deals with peoples' attitudes to uncertainty. Suppose we are given the choice between receiving \$1000 or tossing a coin and accepting \$2000 if it comes down heads and nothing if it comes down tails. In terms of expected outcome, measured in dollars, it would appear that the two options are equally attractive. The fact that many people would prefer the certainty of the first option shows us that, at least in this case, dollars are not a good measure of preference.

The concept of utility was devised to deal with this problem. A utility function is a means of expressing outcomes in units that measure preference. When there is uncertainty, it is also a means of expressing the attitude of people (e.g., decision makers) to risk. In the above example, people who prefer the coin toss are termed risk preferrers; those who prefer the $1000 are risk averse. It is clearly important to ensure that the attitudes to risk of decision makers (and (or) stakeholders) are incorporated in whatever objective function is used in a fisheries risk assessment.

It is beyond the scope of this paper to delve further into this complex topic. Readers are referred to Shotton (1993) and Lane and Stephenson (1997) for further discussion in a fisheries context (and references in both these papers for wider applications). Examples of applications of utility functions to fisheries problems are given by Powers and Lackey (1976), Keeney (1977), Mendelssohn (1982), Die et al. (1988), Quinn et al. (1990), Kope (1992), and Horwood (1993).

Future discounting

It is commonly observed that the perceived value of some future benefit depends on how long it is before that benefit is to be obtained (with the value generally declining with increasing time). This is what is called "future discounting," which Shotton (1994) defined as "the concept of time preference in relation to future benefits." The conventional way to deal with this is to express all values in present terms, using a discount rate. For example, the present value of $1000 that is available in 5 years' time is $\$1000/(1 + x/100)^5$, where x is the discount rate (expressed as a percentage). The bigger x is, the more the future is discounted (i.e., the less is the present value of a given future benefit).

The relevance of future discounting to fisheries management in general was clearly illustrated by Clark (1976) and Silvert (1977) who showed that, under certain conditions, if the discount rate of decision makers with regard to future benefits from a fish stock is high enough, there is no economic reason to conserve the stock. In the construction of objective functions for fishery management, discount rates will clearly be relevant for any management options that cover more than 1 year. However, although they have been used and discussed in many theoretical fisheries papers (e.g., Charles 1983; Plourde and Bodell 1984; Hannesson 1986; Horwood 1987; Welch and Noakes 1991; Megrey et al. 1994; Ianelli and Heifetz 1995) their explicit use in fisheries management decisions appears to be rare.

Where the precautionary approach to fisheries management is adopted it would seem that discount rates would have application only in short-term management decisions. For decisions with long-term consequences (e.g., those referred to in the above references to Clark (1976) and Silvert (1977)) the issue of intergenerational equity, which is so central to the precautionary approach (Garcia 1996), would seem to preclude the use of discount rates. For example, even a relatively low discount rate of 2.5% implies that the importance of each successive generation declines by a factor of almost 2 ($=1.025^{25}$, assuming a human generation time of 25 years).

It is important to be sure what is being discounted. Suppose, for example, you are offered a choice between receiving either $750 today and $750 tomorrow, or just $1000 today. If you choose the latter you are likely to be judged as having a high rate of future discounting. However, it could be that the reason for your choice is that you consider money offered today to be certain but that you have doubts as to whether that promised for tomorrow will actually materialize. In other words what you are discounting is not the future value of money, it is the likelihood of receiving it. Now, consider a common situation in which fishers voice a preference for a management option that gives them a high catch in the next year followed by a period of lower catches, over an option that provides medium catches over the whole period. Does this preference stem from their discounting the future value of catches (or money), or are they actually discounting the stock assessment (i.e., the prediction that a high catch next year will need to be followed by a period of low catches)? One might deal with the former type of discounting by incorporating a discount rate in the objective function; this would not be appropriate with the latter type.

Multiple objectives

The objectives of fisheries management are usually multiple and often conflicting. Shotton (1994) noted that "One example FAO often encounters is the desire of countries to earn foreign exchange through exports of fish and at the same time to promote national food consumption of domestic supplies of cheaper fish... Other common mutually-exclusive objectives that are simultaneously sought by Departments of Fisheries are those of economic efficiency and regional development, or equity of income distribution."

Hollowed and Megrey (1993) provide a good example of how conflicting objectives can be combined into a single objective function. Their objective function may be written as

$$\frac{\text{mean}\,(C)}{\text{MSY}} - \text{P}(B < B_{thr})$$

i.e., it is the mean catch, divided by the maximum sustainable yield (MSY), minus the probability that the biomass falls below a threshold biomass. This function implies two potentially conflicting objectives: to maximize mean catch and to minimize the probability of low biomass. The difficult task in combining these objectives is to decide what is an appropriate trade-off between these objectives. This requires obtaining from fishery managers an answer to the question "How much would you be prepared to allow $P(B < B_{\text{thr}})$ to increase in return for an increase in mean catch of 1% MSY?" Hollowed and Megrey have implicitly, and arbitrarily, assumed that the answer to this question is 1%. There is no reason to believe that fishery managers would agree that this was the appropriate trade-off. This objective function could also fail to meet the requirements of fishery managers if there was some level of $P(B < B_{\text{thr}})$ that they were unwilling to exceed, regardless of any short-term gain in catch.

There is a formal theory of decision making with multiple objectives (e.g., Keeney and Raiffa 1976), and there have been some theoretical fisheries applications (e.g., Walker et al. 1983; Sylvia and Enriquez 1994). However, it seems that this theory "still remains untried in operational divisions of departments responsible for fisheries management" (Shotton 1993). Pearse and Walters (1992), while admitting the appeal of these techniques as a way of clarifying objectives and attitudes to risk, suggest that "... [they] are not so well developed and standardized that they can be routinely applied and readily understood. Nor are the results easily interpreted and evaluated in the usual arenas of political debate."

Eliciting objectives

It has been said above that a major barrier to effective fisheries management is the lack of explicit objectives. This affects both the advice that is offered to support management decisions and the decision-making process. Scientists providing management advice are often forced to infer management objectives so as to formulate their advice appropriately and then may have great difficulty in determining how their advice has been used. Without explicit objectives it is not possible to make rational decisions or evaluate past decisions.

However, the difficulty of eliciting objectives that are sufficiently explicit to be usable in assessing and managing risk should not be underestimated. We use the word "elicit" here to emphasize that this task necessarily involves (lengthy) dialogue between those charged with formulating policy and objectives and those with the skills to express these objectives in an operational form. This is a difficult and time-consuming process. The following quotes identify two related problems.

> "For different fisheries or jurisdictions the decision maker might be a council of ministers, treaty commissioners, the minister of fisheries, a management council or advisory committee, or a fishery manager. The accessibility of the decision maker for questioning about specific management objectives will vary greatly across this range." (A.D.M. Smith 1993);

> "... it is often difficult to identify the decision maker whose attitude towards risk should be the basis for assessing the utility function...Ministers of fisheries come and go, threatening inconsistency over time; external advisers and bureaucrats raise questions about representativeness and accountability; resource users cannot always be relied upon to represent the broader public interest in long-term conservation." (Pearse and Walters 1992)

In jurisdictions where fisheries are managed by councils whose members represent a range of interest groups, individual councillors may not feel it in their interest to be frank about their objectives (because, for example, this could reduce their flexibility in negotiations).

Two attempts at formal risk management

A good example of an attempt at formal risk management is provided by the management procedure for South African anchovy *Engraulis capensis* (Bergh and Butterworth 1987; Butterworth and Bergh 1993; Butterworth et al. 1993). This procedure specifies precisely what data will be gathered each year and the algorithm that will be used to calculate catch limits from these data. In other words, it automates the annual harvest rate decision. The risk management consisted of finding the best values for the parameters of this algorithm. This decision was made after consideration, by managers and fishers, of the results of an extensive series of simulations based on various alternative parameter values. (Thus, this was a harvest-strategy evaluation, as defined above.) The main consideration appeared to be to find an acceptable trade-off between having a high mean catch and not having too much year-to-year variability in catch (anchovy, like most other small pelagic species, fluctuates considerably in abundance from year to year).

This management procedure has been applied in only 4 of the 9 years since it was introduced, despite having been modified twice. In the other 5 years, the catch limit produced by the procedure was deemed unacceptable. Thus, it would appear that the risk management was not very successful. It appears to us to be a good example of how difficult it is to accurately elicit objectives from decision makers. For example, in the original risk assessment it was made quite clear to decision makers that, in a small proportion of years, the procedure would set a zero catch limit because of low stock size. This appeared to be accepted. Yet the first time this occurred the procedure was rejected. It would seem that what appears acceptable on paper, or a computer screen, may not be when it actually occurs.

Kirkwood (1997) provided a very interesting account of another attempt at formal risk management: the development of the Revised Management Procedure (RMP) for the International Whaling Commission. This involved a long (7 years) and exhaustive series of simulation exercises in which a strong emphasis was placed on constructing "robust" procedures. That is, the procedures were expected to perform reasonably well even when the assumptions on which they were based were false. For example, simulations were carried out in which abundance estimates (assumed by the management procedure to be unbiased) were actually biased, either upwards or downwards or with a trend in the bias. The main performance measures used in evaluating candidate management procedures were concerned with interannual variability in catch, minimum population size over the simulation period, total catch, and catch at the end of the management period. No attempt was made to combine these performance measures into a single objective (or utility) function, it being judged "unlikely that such a utility function could be derived."

It remains to be seen how successful this risk management will be, because, although it led to agreement on the form of the RMP, the procedure has yet to be applied because the IWC moratorium on commercial whaling is still in force.

The division of responsibilities

Throughout this review we have repeatedly referred to two groups of people: (fisheries) scientists, and decision makers (or managers). A number of authors have commented on the roles for these two groups, either as these have evolved over time, or as it is felt they ought to be to facilitate effective fisheries management.

There is a broad consensus that it is the job of scientists to carry out risk assessments (i.e., to evaluate alternative management options) and of decision makers to do risk management (i.e., to make decisions based on the assessed risks) (Pearse and Walters 1992; Hilborn et al. 1993; Morrissey 1993; A.D.M. Smith 1993; Fogarty et al. 1996). This may seem too obvious to be worth stating, but a glance backwards in time shows that roles have not always been so distinct. In this context Serchuck and Grainger (1992) and Kirkegaard et al. (1995) present a very useful description of how the activities of ICES have evolved since 1976. ICES is an exclusively scientific body, founded in 1902, that provides scientific information and advice on environmental and fisheries management to a range of management bodies. It was not until 1991 that it specifically recognized that it was not its role to define management objectives, but rather it should "present options as to how management objectives can be reached and... clearly describe the implications and consequences of these options and their associated risks" (Serchuck and Grainger 1992).

A.D.M. Smith (1993) drew a clear distinction, stating that the role of scientists is to (*i*) elicit and clarify objectives, (*ii*) turn objectives into specific attributes and criteria, (*iii*) identify a range of strategy choices, (*iv*) evaluate outcomes, and (*v*) communicate the results to the decision maker; and that of the decision makers is to (*i*) specify the objectives of the management, (*ii*) evaluate the results and weight the objectives, and (*iii*) make the decision.

Hilborn et al. (1993) made a similar distinction but suggested two specific limits on the role of scientists (the "stock assessment group"). The first is that they should make no recommendations. This is consistent with the trend for scientific bodies to evaluate alternatives rather than make recommendations. However, ICES still reserves the right to recommend management actions for stocks that are "at or below the 'minimum biologically acceptable level' (MBAL) or expected to become so in the near future at current levels of fishing mortality rate" (Kirkegaard et al. 1995). Second, scientists should not attempt to make "best" estimates of biological parameters such as MSY or current stock size.

Rosenberg and Restrepo (1994) disagreed with this, stating that it often requires scientists' special knowledge about species, stocks and models to determine what the best estimate is. However, this may be a misunderstanding. What Hilborn et al. (1993) appeared to be saying was that scientists should not hide uncertainty by presenting only a best estimate. For example, the uncertainty inherent in conflicting data should be clearly presented in the form of alternative estimates. Sometimes it would be appropriate to label one of these estimates as best (i.e., most likely).

Caddy and Mahon (1995) expanded on the above role of the decision makers saying that they "must develop means of objectively evaluating the potential costs of undesirable events and define acceptable levels of risk and of short-term yield which can be foregone to reduce these risks."

The need for extensive dialogue between the two groups is emphasized. In the first place, this is necessary to clarify objectives. This will be an ongoing process because objectives will change as new situations emerge and the membership of decision-making bodies, and governments, change. The trend to increase the participation of the fishing industry and other stakeholders (recreational fishers, environmental groups, indigenous peoples) in the decision-making process makes this an increasingly challenging task. Second, decision makers will often want to consider management options not included in an initial risk assessment. Hilborn et al. (1993) and Walters (1994) favour providing them with the means, in the form of computer programs, to evaluate alternative strategies themselves.

Lane and Stephenson (1995) take a somewhat different view from those stated above. They contrast fisheries science, which they say has "established a large literature and a strong scientific methodology" with fisheries management, which, "in contrast to fisheries science, has not developed a standardized methodology.... [it] has not formally considered the full suite of implications that its policies engender, and as a result it has failed to live up to its broad mandate." They propose the development of a new science, "fisheries management science," which combines the disciplines of fisheries management, fisheries science, and management science. The effect of this, in terms of the division of labour described above, seems to be to expand the role of the group we have called scientists and diminish that of the decision makers. (Very similar views are expressed by Stephenson and Lane 1995.)

Whatever institutional structures are used, and roles assigned, there is clear scope for discussion about what might be called risk management policy. Basson (1993) provides a good example of this by discussing four opposing pairs of attitudes to the role and practice of risk management. The process of deciding which of these attitudes are acceptable in a particular fisheries management forum would clearly be useful in clarifying issues, structures, and procedures. Although scientists have a role in this debate, it is primarily in the realm of decision makers.

Discussion

A common way for scientists to present their advice to fishery managers is as a single number, or sometimes a number with some confidence interval about it. This number is their estimate of the level of catch (or fishing mortality) that is, in some sense, optimal. This form of advice presents difficulties for fishery managers. There is often pressure from other parties to set the catch at a different level, and the advice provides no measure of the consequences of succumbing to that pressure. In principle, the fisheries risk assessment overcomes these difficulties. Rather than presenting a "best" option, it evaluates a range of options by showing the likely consequences of following each of them. Also, it acknowledges and incorporates uncertainty by presenting results in the form of probabilities, or expected values, etc. Further, it attempts to give to those who are charged with the responsibility of making decisions the information they need.

The examples discussed above have focussed on just one of the many types of fisheries management decisions, that concerned with setting the annual harvest rate. However, the same techniques can be applied to other types of decisions, e.g., the value of additional research (Cochrane and Starfield 1992; Powers and Restrepo 1993).

There is some scope to improve fisheries risk assessments. We have discussed the need for some standardization of performance measures and the problem of complexity in presentation. There are also many technical issues concerning model structure, the relative merits of Bayesian and frequentist approaches, etc., that are beyond the scope of this paper. Cordue and Francis (1994) pointed out that little consideration has been given to the accuracy (sometimes alarmingly low) with which performance measures are estimated. However, the greatest need in many fisheries jurisdictions is for an explicit statement of management objectives so that the risk assessment can better support management decisions.

There is great scope to improve the practice of fisheries risk management by making it more formal and less in the category of "negotiations in smoke-filled rooms." This change could produce many benefits. Fisheries would be better managed because the available data would be better used, decision-making would be more transparent and better documented, and there would be more strategic planning and fewer ad hoc decisions. The debate on the management of individual stocks would be more constructive (and perhaps less heated) because the focus would shift from annual harvest rate decisions to the criteria on which those decisions should be made. This should give stakeholders a better idea of where the fishery is going. More formal risk management also allows (and even encourages) the construction of standards against which to evaluate, and thus improve, the effectiveness of fisheries management.

We do not wish to minimize the formidable difficulties involved in formalizing the treatment of risk in fisheries management. The greatest of these are the problems of eliciting specific management objectives and establishing acceptable trade-offs between conflicting objectives. As the experience with South African anchovy has shown, these are challenging tasks. They involve decision processes that, while established in the methodological literature, have not yet been used operationally. To us these tasks appear much less tractable, and of much greater importance, than relatively minor issues like establishing appropriate discount rates and the degree of risk aversion of decision makers. It is perhaps important to be realistic about what might be achieved. Decision makers will be not be able to articulate all their trade-offs, and we cannot expect all management objectives to be summarized in a single objective function in all fisheries. However, we do not know of any fisheries where the management could not be improved by being made more formal.

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