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Coping with Uncertainty: Evolution of the Relationship between Science and Management

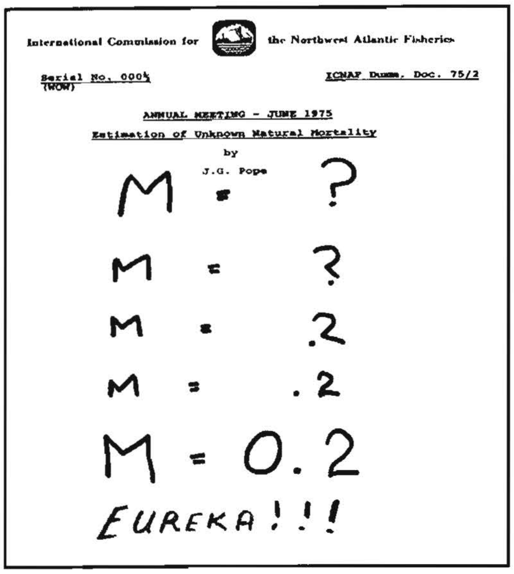
PAMELA M. MACE AND MICHAEL P. SISSENWINE
National Marine Fisheries Service, National Oceanic and Atmospheric Administration
166 Water Street, Woods Hole, Massachusetts 02543, USA

Abstract.—Scientists, managers and fishers have always known that uncertainty is an integral part of nature. Early assessment models dealt with uncertainty as a signal-noise problem, developing deterministic, equilibrium relationships to explain cause and effect. Other models coped with uncertainty by normalizing model outputs against inputs that were known to be highly variable (for example, yield per recruit analysis, which avoids consideration of recruitment variability by performing calculations on a per recruit basis). Although deterministic approaches are still widely used, it is also true that methods for quantifying and presenting uncertainty have been taught, developed, and applied for several decades. The question has been less one of how to present uncertainty, rather than whether to present it. What purpose would it serve? Experience showed that managers or politicians presented with a range of estimates frequently chose to set quotas from the risk-prone end of the range. In short, uncertainty was used as a reason for avoiding conservation measures. Development of the precautionary approach to fisheries management has initiated a transition in the perception of uncertainty from that of a reason to avoid action to that of a reason to exercise caution. Increased public awareness of the limits to the productivity of natural marine resources and increasing numbers of economically devastating stock collapses have been instrumental in initiating the transition, more so than scientific advances in the modeling and representation of uncertainty. This transition is, however, more active on paper than in actual implementation. Today, one challenge is to integrate science and management into a rigorous, risk-averse, decision analysis framework, and another is to further promote responsible management and the application of the precautionary approach in the face of uncertainty. Presentation of uncertainty as risk profiles or Bayesian posterior distributions rather than confidence intervals around point estimates has provided a more objective basis for evaluating the consequences of alternative management decisions, but there is a need for better comprehension of the full consequences of the large risks managers, fishers and other stakeholders (which includes the public in general) often appear to be willing to take.

Introduction

In the late 19th and early 20th centuries, fisheries scientists were primarily concerned with sorting the "signal" from the "noise" by creating rules or laws in the form of deterministic relationships between variables. In other words, they tried to create order in a world of enormous variability and uncertainty. Although the limitations of deterministic, equilibrium approaches are widely recognized, they still provide useful benchmarks in that they are essentially approximations to the mean response of a variable. In addition, they probably represent an essential step towards an understanding of complex biological and fishery interactions, without which there may never have been much progress in the relatively new discipline of fisheries science. It may have been necessary to assume constancy in certain processes in order to be able to investigate the nature and consequences of other processes. One tongue-in-cheek example of trying to create order (in this case, constancy) out of uncertainty is given by John Pope's portrayal of the evolution of the specification of natural mortality, M, which starts with $M = ?$ and gradually transforms the question mark to become $M = 0.2$, the value commonly assumed in stock assessments for temperate water finfish (Figure 1; Pope 1975).

In this paper, we first categorize the various types and sources of uncertainty and provide a brief overview of early responses to each type. Next, we discuss how uncertainty has in the past been misused to forestall effective management decisions. We then describe the paradigms under which fisheries have operated until recently and the transition in paradigms that is currently in progress. Such paradigm shifts include changes in the perception of maximum sustainable yield (MSY), development of precautionary approaches to fisheries management, and development of target and limit reference points and harvest control rules. Finally, we provide examples of modern methods for presenting uncertainty, and discuss current developments that will make the treatment of uncertainty more comprehensive, although they may also complicate its interpretation.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Estimation of Unknown Natural Mortality

by

J.G. Pope

M = ?

M = ?

M = .2

M = .2

M = 0.2

EUREKA!!!

FIGURE 1. The evolution of the specification of natural mortality by Pope (1975).

Types of Uncertainty

Many papers and books have discussed the uncertain environment in which fishery scientists and managers operate, and have attempted to categorize the various sources of uncertainty (e.g., Sissenwine 1984; Hilborn 1987; Hilborn and Walters 1992; Fogarty et al. 1996; Quinn and Deriso 1999), including some chapters in the current book (Helser, Parma, Shepherd, and Vaughan). In this paper, we consider five categories of uncertainty of relevance to fisheries science and management:

(1) Natural variation, which to a large degree is irreducible,
(2) Observation errors in input data,
(3) Model misspecification,
(4) Translation of scientific advice into management actions designed to achieve stated objectives, and
(5) Imperfect implementation of management strategies.

There is no perfect or uniquely correct classification of the sources of uncertainty. However, the particular classification given here follows a logical sequence in terms of chronology: uncertainties are generated by nature and by fishing activities as natural variability, these are then augmented in the form of observation errors made by field biologists, further amplified in models constructed by mathematical biologists, possibly misconstrued or compromised by being combined with political considerations by decision makers, and exacerbated by imperfect implementation of management decisions. Early responses to each of these sources of uncertainty are briefly summarized in the next section.

Early Responses to Uncertainty

(1) Natural variation, which to a large degree is irreducible

Natural variation includes variation in the physical, chemical and biological environment, as well as variation associated with human activities. Examples of the former include variations in water temperature, salinity and currents, and variation in growth, survival and reproductive rates. Examples of the latter include changes in the distribution of fishing effort and changes in catchability.

One of the most fundamental sources of natural variability in marine resources is in the relationship between spawning stock size and recruitment. The magnitude of the variation is often large enough to obscure any underlying relationship, even though the nature of the relationship is obvious at the extremes (no spawners, no recruits). Because variability and other factors obscure the relationship, there was historically a tendency to treat recruitment as independent of stock size, and instead to focus on yield per recruit analyses and predictions, with F_{max}, and to a lesser extent $F_{0.1}$, being the most commonly used biological reference points. However, using F_{max} as the basis for management is essentially equivalent to assuming infinitely strong compensatory density dependence such that recruitment is constant, even at low stock size. It has subsequently been pointed out that this is the wrong null model, with the more appropriate one being a straight line through the origin implying no density–dependence (Sissenwine and Shepherd 1987; Sissenwine et al. 1988; Fogarty et al. 1991). In fact, this is an example where fisheries scientists made a risk-prone choice in their response to uncertainty (Holt 1990).

Due to the ease of application of yield per recruit analysis, its utility for indexing growth overfishing, and the complexity of stock–recruitment data, stock–recruitment relationships were largely ignored for several decades. Nowadays, recruitment overfishing is widely recognized as a reality based on studies that have developed the underlying theory (e.g., Sissenwine and Shepherd 1987), and from empirical demonstrations of the phenomenon such as the meta-analyses conducted by Myers et al. (1994). Consequently, stock–recruitment relationships are now a primary focus of uncertainty modeling. Advances in population dynamics theory and improved computer capabilities have also made it possible to model other sources of natural variation, including density–dependent growth, survival and maturity, multispecies interactions and environmental effects on demographic parameters.

(2) Observation errors in input data

The term, "observation error" incorporates both measurement error (e.g., errors in counts, length measurements or temperature readings) and sampling error (errors associated with sampling from unknown or unobserved distributions). In most fisheries applications, sampling errors are likely to be of greater magnitude than measurement errors. Of all the uncertainties in fisheries science and management, techniques for dealing with observation errors have the longest history of development both in the fisheries literature and in the statistical literature. Overall, fisheries scientists (who generally have at least basic training in mathematical statistics) have fairly routinely dealt with uncertainty in the form of observation errors in their assessments, at least for selected variables. Standard statistical techniques such as data fitting procedures and residual analysis are employed in the majority of assessments. There are many review papers and books that address observation errors in input data; for example, Doubleday and Rivard (1983) and FAO (1999) for sampling catches; and Alverson (1971), Mackett (1973), Saville (1977), Doubleday and Rivard (1981), Sissenwine et al. (1983) and Barnard et al. (1985) for resource abundance surveys.

The foregoing is not meant to imply that observation errors are always easy to deal with. To the contrary, the (common) case where both the independent and dependent variables are measured with error (the errors-in-variables problem) has historically not been paid due regard, even though it can be sufficiently serious that it masks the true relationship (Walters and Ludwig 1981). When the independent variables are measured with error, the estimates will be biased. Various methods for correcting the bias have been developed (e.g., Kendall and Stuart 1979; Ludwig and Walters 1981), but in general, these have not had widespread utility (Hilborn and Walters 1992). In some cases, sophisticated statistical methods such as Kalman filters can be used to separate the signal from the noise (Collie and Sissenwine 1983; Peterman et al. 2000). Kalman filters are particularly useful tools for parameter estimation in systems with time-varying (nonstationary) productivity parameters.

Despite the availability of techniques for representing and analyzing the consequences of observation error, until recently, fisheries scientists tended to present only "best estimates" of management reference points such as "the projected quota for next year based on an $F_{0.1}$ harvest strategy."

(3) Model misspecification

In essence, all models are misspecified in the sense that they are abstractions of reality. There are two basic ways in which this misspecification can occur. First, the assumed structural relationships between variables may be incorrect or oversimplified. An example is the common assumption that catch per unit effort is proportional to stock abundance. Second, potentially influential relationships and dynamics may have been totally excluded from the model. An example is single-species models that assume natural mortality (M) is constant over time when in fact it may vary substantially depending on the relative sizes of predator populations and alternative prey available to them. The distinction between the two forms of misspecification may or may not be important, but both represent trade-offs between simple (tractable) representations of reality and complex (potentially more realistic) representations. Although simple models may be biased, they tend to be more statistically stable than more complex models. And even in complex models, there is a possibility that some important aspect of the dynamics of the system will be excluded or misrepresented.

In terms of early representations of the uncertainty associated with model misspecification, the response was much the same as that to observation error. Although assessments might be conducted using alternative models and parameterizations of models in a sensitivity analysis framework, there was a general belief that fisheries managers should be presented with only a single "base case." In fact, even though uncertainties about model specifications were rarely presented in an operational format, they may often represent one of the most important sources of uncertainty overall in stock assessment models (Punt and Hilborn 1997). For example, Sissenwine et al. (1998) describe the implications of model misspecification (specifically for the spawner–recruit function) on rebuilding strategies for western

Atlantic bluefin tuna *Thunnus thynnus*. Growing evidence that ecological and/or climate regime shifts may fundamentally alter the production function of the species being assessed (Kawasaki 1992; Francis and Hare 1994) adds to the magnitude of the uncertainty associated with model misspecification.

(4) Translation of scientific advice into management actions designed to achieve stated objectives

Why did fisheries scientists model uncertainty but not present it? The primary reason is because of the difficulty of translating scientific advice into management action when the objectives of management are not stated explicitly, or unambiguously, or operationally. The first author of this paper recalls an instance in the mid-1980s when fisheries scientists presented 95% confidence intervals around the best estimate of next year's quota based on an $F_{0.1}$ harvest strategy. The managers asked the scientists to give a good reason as to why the upper limit of the quota range should not be used. Apparently, the scientists were unable to do so, because the quota was set near the upper end of the range. The form of the advice quickly reverted to "best estimates" without confidence limits.

In fact, until recently it might have been reasonable to generalize that in most situations, fisheries managers didn't ask for estimates of uncertainty, didn't want them, and probably wouldn't have known what to do with them. When stock assessments were presented, but managers chose to listen to fishing industry representatives who did not believe the stock assessments, risk prone decisions were often made. Such decisions generally led to overfishing. New England groundfish is one of the best known examples of protracted overfishing, for which the National Research Council (1997) concluded that "valid scientific warnings of imminent stock collapse were not acted on" due to political pressure. In this case, both of the authors witnessed how the misuse of information about uncertainty (as well as unsupported assertions) led to the collapse.

(5) Imperfect implementation of management strategies

Finally, one source of uncertainty that has largely been ignored until very recently is the errors or uncertainties in implementing agreed management actions. Following the collapse of the northern cod stock off Newfoundland, there were assertions that one of the causes of the collapse was illegal, unreported catch outside of the Canadian fishing zone by non-Canadian vessels. Conjecture about unreported catch resulted in considerable tension between Canada and other countries that were fishing off Newfoundland. This situation provided impetus for the negotiation of a new international treaty for the management of straddling and highly migratory fish stocks (United Nations 1995). Continuing concern about imperfect implementation of management strategies has led to FAO agreeing to prepare an International Plan of Action to address illegal, unreported, and unregulated (IUU) fishing.

Imperfect implementation of management strategies has received considerable international attention lately, but it is very much a national problem too. Concerns about misreporting of catches are frequently noted in stock assessment reports and can be extremely high. For example, it was estimated that the Bay of Fundy herring purse seine fishery exceeded its quota by 77% in 1984, a year of augmented enforcement (Mace 1985). Discarding is also problematic. Sometimes management measures are implemented without considering the effect they will have on the amount of mortality that will be caused by discarding. For example, the fishery management plan for cod in the Gulf of Maine set the limit on the amount that could be landed per fishing trip at a very low level in order to achieve the objective of the fishery management plan. However, the objective would only have been achieved if the trip limits did not cause an increase in the amount of mortality caused by discarding. The fishing industry itself, as well as scientific observers placed on a sample of vessels, reported levels of discarding so high that the objectives of the plan were almost certainly undermined.

The main way in which imperfect implementation of management strategies has (sometimes) been incorporated into stock assessments is to add estimates of misreporting rates and discards to the official landings for assessment purposes. However, the extent of misreporting and discarding is often unknown and may not be incorporated into the assessment process due to the lack of a scientific basis for estimation.

Implementation problems are even more acute in multispecies fisheries where switching between stocks can occur rapidly depending on relative stock abundance, management regulations, and market conditions. In such cases, it is important that management strategies take account of the likely behavior of fishing fleets and the likely response to new regulations (Rosenberg and Brault 1993).

Alternative Classifications of Uncertainty

Most classification schemes for uncertainty in the fisheries and statistics literature distinguish between observation error and process error in the estimation process (e.g., Walters 1986; Hilborn and Walters 1992; Meyer and Millar 1999; Polacheck et al. 1993; Quinn and Deriso 1999). The term observation error appears to have a relatively consistent and unambiguous interpretation in the literature, more or less equivalent to that described in item (2) above. The only discrepancy is that the term, measurement error is sometimes thought of as synonymous with observation error, and sometimes as a sub-category within the more inclusive observation error category that includes both measurement error and sampling error. Process error, on the other hand, is a term used to represent the variation in the dynamics of a system that is a property of the system itself as distinguished from errors incurred by sampling or measurement of the system dynamics. In this respect, process error is most closely related to item (1) in the above list. More broadly, process error has also been used to refer to any situation in which a process is not represented exactly in a model. Using this broad interpretation, process error could include both categories 1 (natural variability) and 3 (model misspecification). In this regard, the utility of the term "process error" may be limited unless it is clear which process is being referenced. In the current paper, we prefer to explicitly distinguish natural variation and model misspecification and therefore will not use the term further.

Another way of categorizing sources of uncertainty is in terms of the frequencies at which they occur. For example, Hilborn (1987) suggested the following three categories: frequently observed uncertainties, referred to as "noise"; rarely observed uncertainties, referred to as "uncertain states of nature"; and uncertainties beyond the range of prior experience, referred to as "surprise." Although it would result in a very complex system, a temporal classification of this nature could potentially be nested in each of the five categories used above.

Uncertainty and the Burden of Proof

To date, the existence of uncertainty has often been used to forestall implementation of restrictive management measures. Debates about whether it was overfishing, or environmental effects, or habitat destruction that caused stock declines exist throughout the world. Pollution and consumption by marine mammals are also commonly claimed to have larger effects than fishing. Even when fishing is acknowledged as at least a partial culprit, there may be arguments about the relative destructiveness of large vessels versus small, or one gear segment versus another, or recreational versus commercial vessels. To stock assessment scientists and fisheries managers, however, the most important question that carries the burden of proof goes something like: "are you sure enough of your results to destroy the economic base of several communities and the livelihoods of hundreds of individuals?"

The burden of proof has usually been directed towards scientists and regulators rather than users of fisheries resources. Thus, the common response to uncertainty has been management inaction unless it can be proven beyond reasonable doubt that fish stocks have become depleted. John Gulland, one of the pioneers of fisheries science, described the history of fishery management as "interminable debate about the condition of fish stocks until all doubt is removed." Such was the case for New England groundfish fisheries where effective management was largely delayed until the condition of the stocks was "beyond denial" (Collins 1994).

There are several reasons why society has allowed the burden of proof to be placed on scientists and regulators. The effects of overfishing in marine systems are usually reversible, even at the extreme, and overfishing is generally not hazardous to human health and safety. In addition, until recently, there has been a widely held belief that economic constraints would restrain fishing effort prior to recruitment overfishing. Thus, biological resilience and economic constraints have been widely used as reasons to delay restrictive management action (e.g., in Atlantic Canada; Angel et al. 1994). Subsequently, it has been discovered that some marine resources (e.g., northern cod) may not be as resilient as once believed and that "recruitment overfishing is possible prior to economic overfishing." (Angel et al. 1994).

The argument of biological resilience may be valid for most species in most situations, but dramatic stock collapses can result when overfishing is combined with other factors. For example, it may be possible to fish stocks at unsustainably high fishing mortality rates for long periods of favorable environmental conditions, but when the environment reverts to normal or unfavorable conditions, the combined effect of high fishing mortality and reduced survival, growth, or fecundity may result in sudden stock declines. If additional factors such as overly optimistic stock assessments, misreporting, and discarding are operative, the joint effect may be even greater. A combination of such factors is likely to have resulted in the demise of the northern cod fishery, one of the most dramatic and devastating stock collapses in recent years (Hutchings and Myers 1994; Hutchings 1996).

With respect to the belief that economic constraints will likely restrain fishing effort before overfishing becomes severe, this may have been generally true at one time when the technology to catch fish was limited and the value of fish was lower. Today, however, seafood is in high demand and the technology to produce it has advanced greatly. The diminished ability of economic constraints to restrain fishing effort is compounded by the reality that many of the stakeholders in fisheries tend to have very high discount rates (i.e., they value the more certain returns from the near future much more highly than the uncertain returns from the distant future). Aside from the uncertainties in stock assessments about current stock status, fishers have to contend with uncertainties about future abundance and distribution of the resource, future stock assessment findings, future allocation decisions and competition from other sectors of the fishery, potential changes in government law or policy, concern about continued physical ability to participate in fishing, and potential downturns in market demand or prices (Mace 1993, 1997). Even politicians, and to some extent managers, may have high discount rates due to the limited time they are likely to be in office.

One of the most disturbing consequences of allowing short-term gains to take precedence over long-term sustainability is that once begun, it becomes progressively more difficult to make amends. The greater the degree of overfishing, the greater the short-term sacrifices that need to be made to ensure long-term sustainability, and as a result, fishers may become progressively more entrenched in maintaining a progressively worsening status quo.

Recent Responses to Uncertainty: Shifting Paradigms

The burden of proof and the precautionary approach

One reason that the burden of proof has been placed on the science rather than fisheries activities per se is the continued belief in the inexhaustibility paradigm, as articulated by Thomas Huxley in 1884 (cited in Smith 1994) and repeated with many variations since:

> . . . the cod fishery, the herring fishery, the pilchard fishery, the mackerel fishery, and probably all the great sea-fisheries, are inexhaustible; that is to say nothing we do seriously affects the number of fish. And any attempt to regulate these fisheries seems consequently . . . to be useless.

There has been a gradual move away from viewing the bounty of the oceans as essentially infinite to managing "on the edge," where fishers, scientists and managers have been gaining a more realistic appreciation of the potentially disastrous consequences of uncertainty. As a result, there has been a rapid evolution of paradigms primarily in the last decade – from "it is not possible to overexploit natural marine resources" to "it is not acceptable to overexploit natural marine resources" to "it is both possible and acceptable to under-exploit natural marine ecosystems [to ensure that they] are preserved in perpetuity while still contributing substantially to the food, recreational and livelihood requirements of the world's human population" (Mace 1999). Here the term "under-exploit" is not meant to imply an ultraconservative harvest strategy; rather it is meant to imply that "optimal" is not necessarily equivalent to "maximum." In other words, in order to optimally exploit marine resources, it may not be a good strategy to aim for the maximum exploitation rate due to the pitfalls of attempting to "manage at the edge." Attempts to squeeze out the last possible ton often result in overruns due to a combination of assessment errors, lags in reporting landings, misreporting, discarding, and other factors. Such attempts may also ignore species interdependencies and other ecological relationships.

The problem of the burden of proof being placed on fishery scientists and managers has long been recognized. Thompson (1919) wrote, ". . proof that seeks to change the way of commerce and sport must be overwhelming." More recently, several authors have argued to change the burden of proof (Sissenwine 1987; Mangel et al. 1996; and Dayton 1998). In fact, in 1991 the intent to make the change was clearly stated in the strategic plan of the National Marine Fisheries Service (NMFS 1991), which explicitly called for risk-averse decisions to help maintain productive fisheries. Internationally, the burden of proof was being discussed in conjunction with concerns about the applicability of the "precautionary principle" to fisheries. The precautionary principle was originally conceptualized as a means of managing highly polluting activities by controlling pollution at source even in the absence of "proof" of a causal link between emissions and environmental effects. There was concern that application of the precautionary principle, which was designed to guard against the possibility of making irreversible mistakes, might be too extreme in fisheries where most mistakes have a high probability of being reversed. This debate led to the evolution of the "precautionary approach," a "gentler" version of the precautionary principle, which was adopted as a key element of the United Nations Implementing Agreement for Straddling Fish Stocks and Highly Migratory Fish Stocks (United Nations 1995) and the FAO Code of Conduct for Responsible Fisheries (FAO 1995). Subsequently, FAO (1996) published technical guidelines on the application of the precautionary approach to capture fisheries. Serchuk et al. (1997), Restrepo et al. (1998), and Mace and Gabriel (1999) have summarized the development and key features of the precautionary approach to fisheries management.

Although the precautionary approach is an adaptation of the "precautionary principle," the difference is more than subtle. An example might serve to make the distinction. It is well known that certain fishing gears affect marine habitats by disturbing them, but the long-term effects on productivity and species composition are generally not well understood. Application of the precautionary principle might result in a complete prohibition of such gears or technologies (as was the case with large-scale high seas drift nets), whereas application of the precautionary approach could lead to the conclusion that fishing should continue but with additional cautionary measures such as area closures and limitations on fleet size. In fact, the precautionary approach is multifaceted and broad in scope. According to the Code of Conduct (FAO 1995), precaution is required in development planning, management, research, technology development and transfer, legal and institutional frameworks, fish capture and processing, fisheries enhancement, and aquaculture. Even when applied to fisheries management specifically, there are many facets and it is difficult to define succinctly. The following is one such attempt (Restrepo et al. 1999):

> the precautionary approach is about applying judicious and responsible fisheries management practices, based on sound scientific research and analysis, proactively (to avoid or reverse overexploitation) rather than reactively (once all doubt has been removed and the resource is severely overexploited) to ensure the sustainability of fishery resources and associated ecosystems for the benefit of future as well as current generations.

This definition emphasizes the need to be proactive with respect to uncertainty rather than awaiting the certainty that comes when the stock can no longer support a viable fishery. The precautionary approach is particularly significant to the issues being dealt with herein because it explicitly addresses uncertainty and states that greater uncertainty should result in greater caution in fishing activities.

FAO's (1996) technical guidelines on the precautionary approach state that fisheries should be developed cautiously pending scientific evidence that fishing activities are sustainable. In addition to the maxim that the greater the uncertainty, the greater the degree of caution that must be exercised, FAO suggests that all fishing activities must have prior management authorization and be subject to periodic review, and that those who exploit public resources have the responsibility of accountability for their actions, and to report their activities (where, when, how, and how much caught) to the public. The guidelines do not explicitly call for a reversal in the burden of proof (thus distinguishing the precautionary approach from the precautionary principle); rather they conclude that if the precautionary approach is properly applied, then the burden of proof will be appropriately placed. In essence, the distinction lies with the standard of proof to be applied, analogous to the difference between criminal and civil court cases in terms of the level of certainty required. The precautionary principle implies that activities should not proceed unless it can be shown beyond a reasonable doubt that the activity is safe; the precautionary approach implies that the preponderance of evidence should indicate that the activity is sustainable. While rebuilding of depleted stocks and reduction of overexploitation is the main priority of precautionary management, if there are options for achieving these objectives that enable a viable fishery to continue, these should be favored provided, of course, that the current fishing capacity can be supported by the resource in the long term.

The MSY transition

These paradigm shifts, along with a better understanding of how uncertainty should be treated, are reflected in several transitions in the perception of the concept of Maximum Sustainable Yield (MSY) (Mace 2001). MSY has gone in and out of vogue since its inception about 70 years ago and has been periodically subject to harsh criticism (e.g., Larkin 1997; Sissenwine 1978). However, MSY is the foundation of numerous international and national fisheries laws, it is intuitively appealing and logical to nontechnical audiences, and no better operational management goal has been found to be as widely applicable (Punt and Smith 2001). Lately, it has experienced a resurgence in application within the United States and elsewhere, due in part to the most recent step in the evolution of its interpretation, as described below.

A literal or *static* interpretation of MSY is that MSY is the maximum *constant* yield (MCY) that can be taken year after year (Mace and Sissenwine 1989). However, the maximum constant yield that can be taken from a naturally fluctuating resource is low because any constant catch will represent a relatively large fraction of the stock at the low points of the natural fluctuations. Thus, a constant catch will often drive a low population even lower, and therefore carries a high risk of stock collapse (Sissenwine 1978). It is much safer for the resource and also produces higher average yields if catches are more or less proportional to stock size. For this reason, the more modern *dynamic* interpretation of MSY is that it is the maximum *average* yield (MAY) that can be achieved by varying annual yields in response to fluctuations in stock size. One common, straightforward way to approximate MAY is to apply a constant fishing mortality rate (F_{MSY}). However, this will not necessarily achieve the "global" (highest possible) MAY. Even higher average yields can sometimes be obtained by applying a variable fishing mortality strategy (e.g., constant or proportional escapement), although these strategies tend to also have the disadvantage of high interannual variability in catch. Fishing mortality reference points can also be made to vary with some relevant environmental factors to account for phenomena such as environmental regime shifts that may substantially impact productivity. For example, the NMFS Pacific coastal pelagics FMP treats F_{MSY} as a function of sea surface temperature (Jacobson and MacCall 1995; PFMC 1999).

The most recent transition regarding the perception of MSY is to think of it (or associated reference points) in terms of limits rather than targets. This was first recommended in an international context in Annex II of the United Nations Implementing Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks (United Nations 1995). Paragraph 7 of Annex II states that "the fishing mortality rate which generates maximum sustainable yield [F_{MSY}] shall be regarded as a minimum standard for limit reference points." Subsequently, in 1996, the U.S. Sustainable Fisheries Act changed the definition of optimum yield (OY) from "... MSY as *modified* by [relevant factors]" to "... MSY as *reduced* by [relevant factors]," implying that MSY should be thought of as an upper bound on OY.

There are several reasons why it makes sense to treat F_{MSY} as a limit rather than a target (Mace 2001). Among these is that it is a more risk-averse way of dealing with uncertainty. If the true F_{MSY} is repeatedly overshot (due to assessment errors, implementation errors, or other factors), the cumulative effect is that eventually yields will fall below the associated long-term maximum average yield and the stock will become depleted relative to B_{MSY}, ultimately requiring implementation of economically and socially disruptive restrictive management measures in order to rebuild the stock. On the other hand, the cumulative effect of habitually undershooting the true F_{MSY} (e.g., by treating it as a limit to be avoided), is that the risk of future economic and social disruption is minimized and there may even be future opportunities for temporary increases in catches. In addition, foregone yields may be small or negligible because reductions in fishing mortality are compensated to some extent by increases in biomass (at least for cases where the yield curve is relatively flat near F_{MSY}).

The transition from a static to a dynamic interpretation of MSY stems largely from the scientific community. However, the transition from MSY-based reference points as targets to limits is more a result of increased public awareness and concern. Fisheries environmentalists have noted that while MSY has been embodied in several important international and national agreements since the mid-1970s, overfishing has increased in terms of both the number of fisheries and the magnitude of overfishing. This has resulted in periodic calls to abandon the concept but since no one seems to have been able to come up with a better substitute (e.g., one that is more conceptually appealing, operational and widely applicable), one alternative is to treat it as an upper limit and also to focus on other aspects of precautionary approaches to fisheries. Thus, this aspect of the evolution of the relationship between science and management has largely been spurred by increased public outcry about overexploitation of natural resources. However, it should be emphasized that the cases of overfishing that have raised concern are not the result of shortcomings in MSY as a management strategy; rather, they are a result of risk-prone management strategies that failed to achieve MSY.

Targets, limits, and control rules

Attempts to implement the precautionary approach have resulted in the development of harvest control rules that incorporate fishing targets and limits, with the difference between the two reflecting the degree of uncertainty. A harvest control rule should have the following two elements: (1) a limiting fishing mortality rate that may or may not be related to biomass over some or all of its range, and (2) a target fishing mortality rate that may or may not be related to biomass over some or all of its range, but must always be less than the limit fishing mortality over all parts of the range. The distance between the target and the limit should be sufficiently great that attempts to achieve the target on average will have low probability of exceeding the limit. One of the simplest control rules satisfying these criteria is the example provided by ICCAT (2000), in which the limit control rule specifies fishing mortality as independent of biomass over the entire range of biomass, and the target control rule specifies fishing mortality as being independent of biomass at high biomass, but tending towards zero with declining biomass in order to provide an additional margin of safety for severely depleted stocks (Figure 2).

In general, fishing mortality rates above the limit control rule correspond to the act of overfishing, while biomass levels below some threshold or limit denote an overfished or depleted stock.

Some paradoxes

Even though the precautionary approach dictates that management actions should be more conservative in situations where there is a paucity of data or great uncertainty about stock status, in reality the reverse may occur. For example, in theory, if there was no information about a particular fish stock other than some rough measure of annual landings, the fishery should be curtailed until adequate data can be collected to determine the status of the stock; in reality, it would be extremely difficult for the fisheries management authorities of most countries to implement any quota that was less than recent landings. In theory, the more the data, the greater the accuracy and precision of estimates of biological reference points such as fishing mortality targets, and therefore the lower the probability of exceeding the target on average; in reality, more data allow use of more complex models with more parameters and therefore more potential sources of uncertainty, so that estimated (not actual) confidence intervals around targets and limits may increase.

In most instances, fisheries management is still about preserving the status quo, and the transitions that have taken place are more evident on paper than in practice. In addition, the legacy of the inexhaustibility paradigm remains with us. Although there are increasingly many examples of

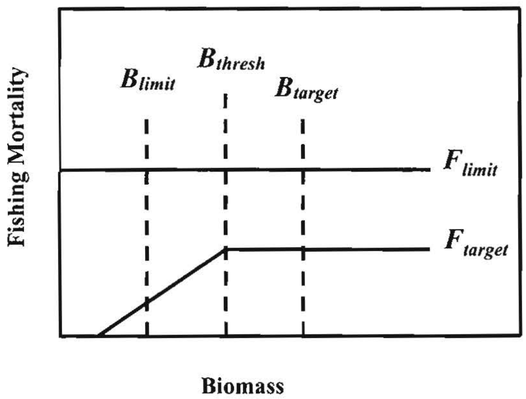

FIGURE 2. Simple example harvest control rule illustrating potential biomass targets, thresholds, and limits and fishing mortality targets and limits. After ICCAT (2000).

economically devastating stock collapses, there are no known examples where entire marine species have been fished to extinction (such is certainly not the case for freshwater species or for individual stocks of marine or anadromous species such as salmonids). For these reasons, risk prone decisions are still made today, especially in those cases where management objectives are still not fully and operationally defined. However, this practice is increasingly being judged to be unacceptable by the public and by the courts in the United States and elsewhere.

Modern Approaches to Portraying and Confronting Uncertainty

Even a cursory review of the fisheries science literature on risk and uncertainty is sufficient to reveal the wide diversity of ways of presenting and dealing with uncertainty (see, for example, the papers in Smith et al. (1993) on "Risk evaluation and biological reference points for fisheries management," and Volume 56, Issue 6 (1999) of the ICES Journal of Marine Science, which is devoted to papers from the symposium, "Confronting uncertainty in the evaluation and implementation of fisheries management systems"). In fact, techniques for presenting and dealing with uncertainty have existed for several decades and a number of papers from the 1970s and 1980s were already claiming that a revolution in the approach to uncertainty was taking place. This revolution has, however, been slow to catch fire. Even up until about 10 years ago, the most common ways that fisheries scientists would present uncertainty in stock assessment results to fisheries managers and stakeholders were to provide a range of quotas or other relevant metric, or a point estimate with confidence intervals. Many of the techniques being developed and advocated in the 1970s and 1980s (e.g., Monte Carlo techniques, Beddington and Cooke 1983; Multi-Attribute Utility Analysis, Healey 1984) have only begun to achieve widespread application within the last 5–10 years.

One of the more significant revolutions in the response to uncertainty and inadequate data has been to develop techniques for including data from as many sources as possible and involving stakeholders in the analysis of alternative hypotheses and management strategies. Rather than stakeholders using uncertainty as a lever to advance a particular course of action or inaction, it is preferable if all players work together to develop and evaluate alternative hypotheses and actions, so that they share a sense of involvement as well as gaining a better understanding of the complexities and trade-offs of the alternatives.

The potential pitfalls of attempting to produce a single best estimate of an assessment output have been pointed out by a number of authors including Hilborn et al. (1993) and Schnute and Hilborn (1993). Of particular concern are situations involving contradictory data (Richards 1991; Schnute and Hilborn 1993). The uncertainty in the divergent data will be masked, rather than being presented as two alternative hypotheses that decision makers and stakeholders should be cognizant of throughout the entire decision process. Hilborn et al. (1993) suggest that for the northern cod stock assessments conducted just prior to the collapse of that stock, it may have been better to present two alternative hypotheses about stock size rather than averaging the contradictory signals from the commercial CPUE (which suggested an increasing stock) and research survey data (which suggested a decreasing stock). Alternatively, contradictory results can be consolidated under a single analysis that allows varying degrees of credibility for each data set (Schnute and Hilborn 1993).

Rather than attempting to produce a "best" estimate of some management attribute such as a quota, a simple way to explicitly deal with uncertainty and risk is to construct a decision table (Walters and Hilborn 1976; Hilborn et al. 1993, 1994). Decision tables can take many forms, but one basic approach is to specify a number of alternative system states based on biological and/or economic and/or social criteria as columns, then a range of possible management actions (e.g., harvest levels) as rows, with entries in the cells of the table being expected consequences (in terms of, for example, catch, risk of stock collapse, or employment levels) of each management action if each of the alternative system states is true (Hilborn et al. 1993). Decision makers and stakeholders can then develop a process for weighting the risks and reaching agreement on the best management action(s) given all of the inherent uncertainties in the analysis.

Multi-Attribute Utility Theory (MAUT) analysis is a related but more formal approach. Healey (1984) outlined the six steps involved in the application of this theory to the resolution of multiobjective problems, using estimations of optimum yields based on biological, economic and social considerations as examples. The six steps include bounding the problem, determining the range of feasible yields, establishing the criteria against which the yields will be judged, weighting the criteria, scoring the yields, and applying the decision rule. Healey (1984) pointed out that the methodology was already well-developed by the mid-1970s and wondered why it was not more widely used in fisheries given its intuitive appeal, its ability to incorporate a wide range of types and qualities of data, and its adaptability to a variety of decision rules.

The decision analysis approach that seems to have gained the largest foothold in recent years is Bayesian analysis (Punt and Hilborn 1997; McAllister and Kirkwood 1998; Deriso, and Parma, both this volume). Bayesian methods have been widely promoted as approaches for representing and taking account of a wide range of uncertainties and incorporating existing knowledge and expert judgment. Bayesian decision analysis has proved particularly useful in data-poor situations where prior distributions based on incomplete data or data from ecologically similar species can be used to assist in differentiating between alternative hypotheses about stock status.

Overall, there has been widespread adoption of more informative approaches to portraying uncertainty. These often utilize some form of risk analysis format for portraying the consequences of decisions about current and future catches or fishing mortalities. Generally, these consequences are presented in terms of the risk that something bad may occur (e.g., $\Pr(B < B_{\text{limit}})$) or the probability of something good (e.g., $\Pr[B > B_{\text{MSY}}$ within 20 years]).

Three recent examples of graphic portrayals of the uncertainty associated with assessments of current and future stock status are provided below. These examples were chosen as "typical" of recent methods of depicting uncertainty, rather than as "ideal" methods that should be advocated.

In the northeastern United States, the NMFS Northeast Fisheries Science Center has developed a standard output for results from Virtual Population Analysis (VPA), which provides graphs of probability distributions around the most recent estimates of fishing mortality and biomass. Cumulative distributions enable determination of the probability that fishing mortality exceeds some specified rate or that spawning stock biomass is below a given level. For Gulf of Maine cod, it appears that there is about a 50% probability that the fishing mortality in 1997 exceeded 0.75 and about a 50% probability that spawning biomass was below 9,000 mt (Figure 3; Mayo et al. 1998). Projections of stock status under various scenarios are portrayed as the median and 80th percentile bootstrapped confidence limits. These methods of presenting uncertainty have been routine for about 5–6 years.

On the other side of the United States, at the NMFS Alaska Fisheries Science Center and elsewhere, there is much less use of VPA and increased recent emphasis on assessment methods based on Bayesian approaches. However, similar methods can be used to present uncertainty in current estimates and probabilities of future stock conditions, as illustrated for eastern Bering Sea walleye pollock *Theragra chalcogramma* (Figures 4 and 5; Ianelli et al. 1999). Figure 4 depicts the probability that yields in 1999 would have been less than some specified value if fishing occurred at one of three reference levels of fishing mortality. Figure 5 shows the probability that spawning biomass will be less than a given level in the year 2003 if fishing proceeds at a rate of $F_{40\%}$. It appears that the probability of spawning biomass being below $B_{40\%}$ is less than 50% and the probability of being below B_{MSY} is even lower.

The last example is from the Scientific Committee on Research and Statistics (SCRS) of the International Commission for the Conservation of Atlantic Tunas (ICCAT 1999), which uses a wide range of assessment techniques but almost always projects stock and fishery status in terms of constant quota scenarios rather than the constant fishing mortality scenarios that are more common elsewhere. At ICCAT, great emphasis is placed on stock projections using alternative quotas, as well as the uncertainty around those projections. The example provided is for the 1998 western Atlantic bluefin tuna assessment using bootstrapped VPA results (Figures 6 and 7; ICCAT 1999). The results indicate that the stock has high probability of rebuilding at a quota of 1500 mt, but depending on the stock–recruitment hypothesis used, it may or may not rebuild at the current quota level of 2500 mt.

There are still several unresolved questions related to presentations of uncertainty. For example, most calculations of uncertainty are known or believed to underestimate true levels of uncertainty because they do not consider the entire spectrum of possible models or model parameterizations. Another concern is the determination of appropriate time horizons for stock projections. Although it may be useful to know the long-term consequences of particular management strategies, projections become increasingly uncertain as the time horizon increases. Some stock assessment scientists feel that the credibility of the science may be adversely affected

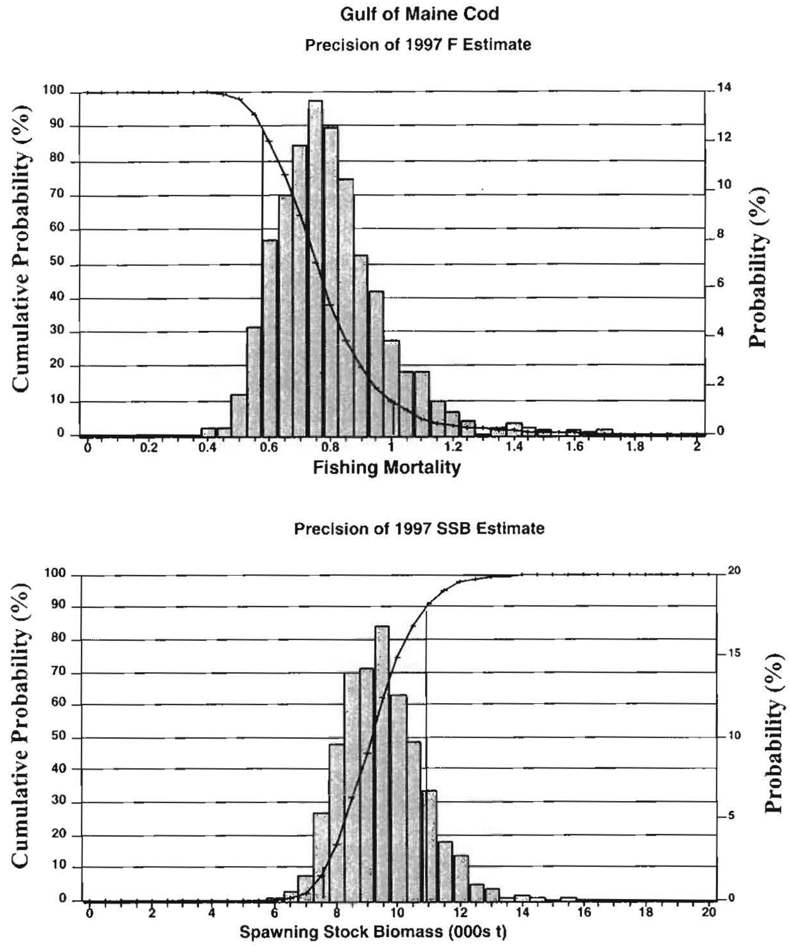

FIGURE 3. Presentations of uncertainty in estimates of current biomass and current fishing mortality. From Mayo et al. (1998).

by extrapolating more than a few years into the future. At the other extreme, projections that are too short may be of limited utility; for example, calculations of the probability of rebuilding to some target biomass within a single year.

As mentioned previously, the three examples presented above simply demonstrate current rather than "ideal" methods for portraying uncertainty and/or the results of risk analyses. None of the examples can be considered comprehensive examinations of the sources and implications of uncertainty and the most appropriate responses to them. One reason that such comprehensive analyses are not conducted on a routine basis is that they would require considerably more time and human resources, particularly if the full suite of biological, economic and social consequences of a wide range of different management actions were to be thoroughly examined in a forum involving representatives of all affected stakeholders. In addition, for key species, stock assessments are usually conducted every 1–2 years, thus allowing for frequent, if not comprehensive, evaluation of previous responses to uncertainty.

Beyond Simple Single Species Stock Assessments

So far this paper has focused on uncertainties arising from "simple" single species stock assessments, and how fisheries scientists and managers have dealt with uncertainty at this level. The situation becomes considerably more complex when one considers a broader spectrum of uncertainties. Currently, there are two distinct avenues of investigation that extend the realm of uncertainties. First is the

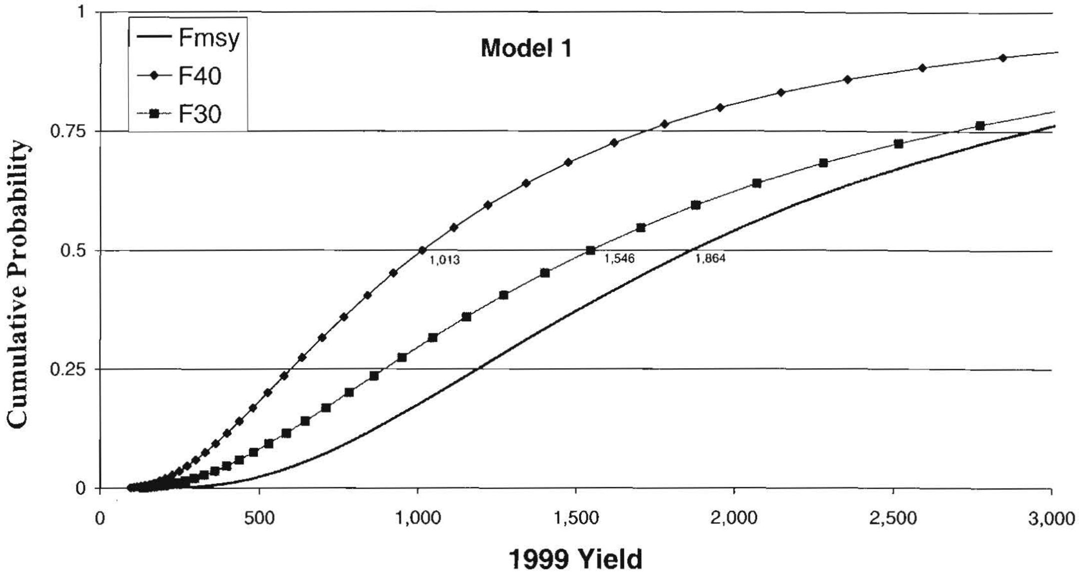

FIGURE 4. Measures of uncertainty in 1999 (unadjusted) yield for Eastern Bering Sea walleye pollock as a cumulative distribution. Values along the curve represent the estimated probability (vertical axis) that the 1999 yield will be lower than the corresponding value on the horizontal axis when fishing at three reference levels of fishing mortality: $F_{30\%}$, $F_{40\%}$ and F_{MSY}. From Ianelli et al. (1999).

continued development of feedback control policies over the past 2–3 decades. The name and acronym given to the procedure varies; for example it was called a fisheries control system by Hilborn (1979), a revised management procedure or RMP by the International Whaling Commission (IWC 1993 1994), a system for evaluating management strategies by ICES (1994), a management procedures simulation model approach by ICCAT (2000), a management strategy evaluation or MSE by Smith et al.

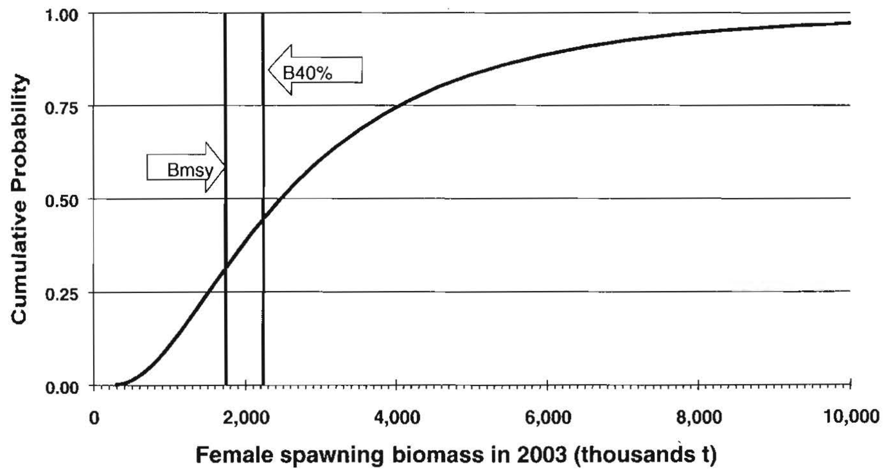

FIGURE 5. Approximate cumulative probability distribution of future female Eastern Bering Sea pollock spawning biomass relative to B_{MSY} and $B_{40\%}$ based on projections assuming future fishing mortality rates are set to adjusted $F_{40\%}$ values. Points along the curve represent the estimated probability (vertical axis) that the female spawning biomass in 2003 will be lower than the corresponding value on the horizontal axis. From Ianelli et al. (1999).

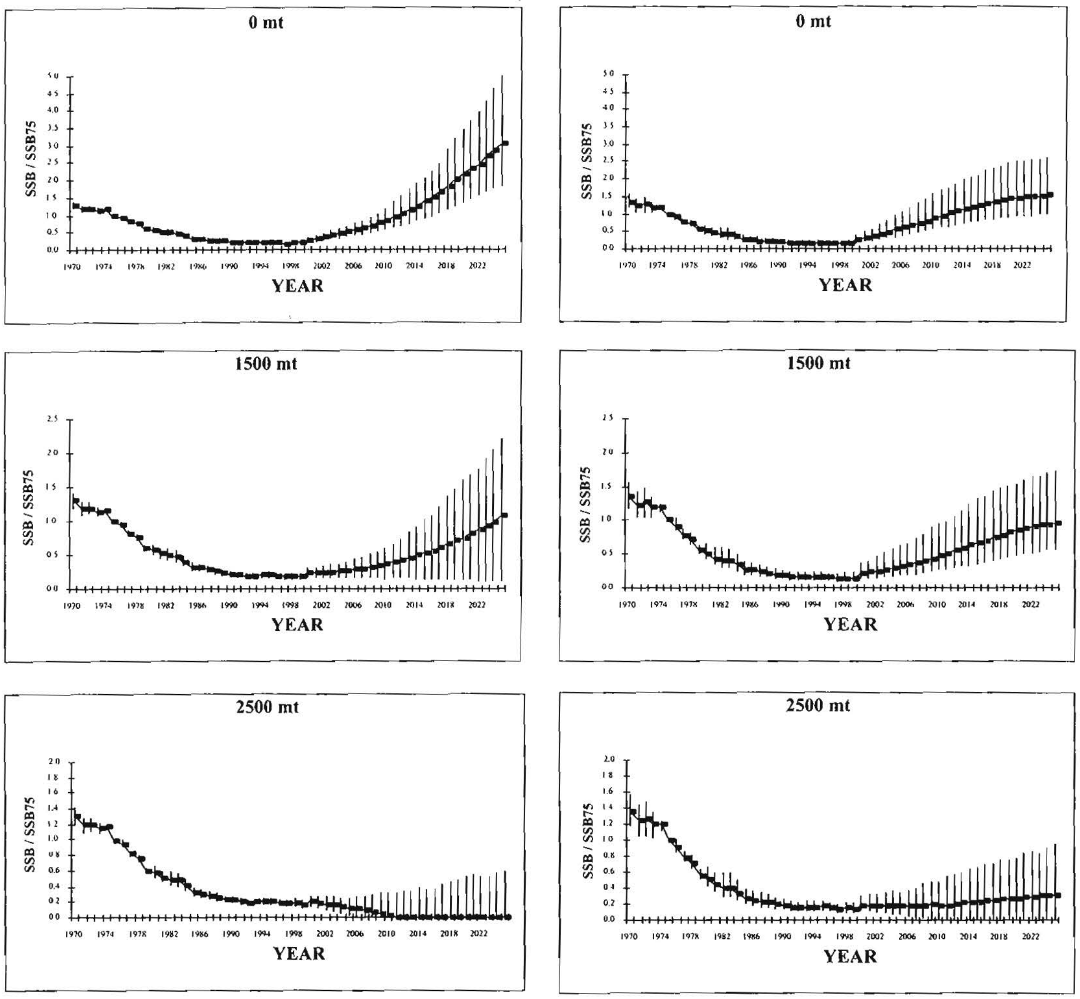

FIGURE 6. Stochastic projections of spawning stock biomass (SSB) relative to the 1975 level for western Atlantic bluefin tuna using two alternative stock recruitment relationships: a Beverton–Holt relationship (left panels) and a two line model (right panels). Error bars represent 80% bootstrapped confidence intervals. From ICCAT (1999).

(1996) and Polacheck et al. (1999), and an operational management procedure or OPM by Barnes (1999) and others in South Africa. However, the structure is generally similar, consisting of an operating model that provides a simulation of a "true" population, a procedure for sampling the true population, an assessment model that uses the sampled data to produce a "perceived" population, a management model that implements specific harvest rules, and performance statistics and feedback associated with each of these components (Figure 8). Although this type of model tends to be oriented to single species, it goes beyond uncertainties in stock assessments alone by also considering uncertainties in other aspects of the assessment and management system such as process errors and implementation errors, and feedback between the real system, the perceived (assessed) system, and the management system. It is a particularly useful framework for investigating the robustness of various types of biological reference points and management actions.

The second distinct avenue for adding complexity is to adopt an ecosystem approach by including multispecies interactions and environmental effects. Common examples of multispecies or ecosystem approaches include multispecies virtual population analysis (MSVPA; Sparre 1991) and the EcoPath, EcoSim, and EcoSpace models developed from the original EcoPath formulation (Polovina 1984) by scientists at the University of British

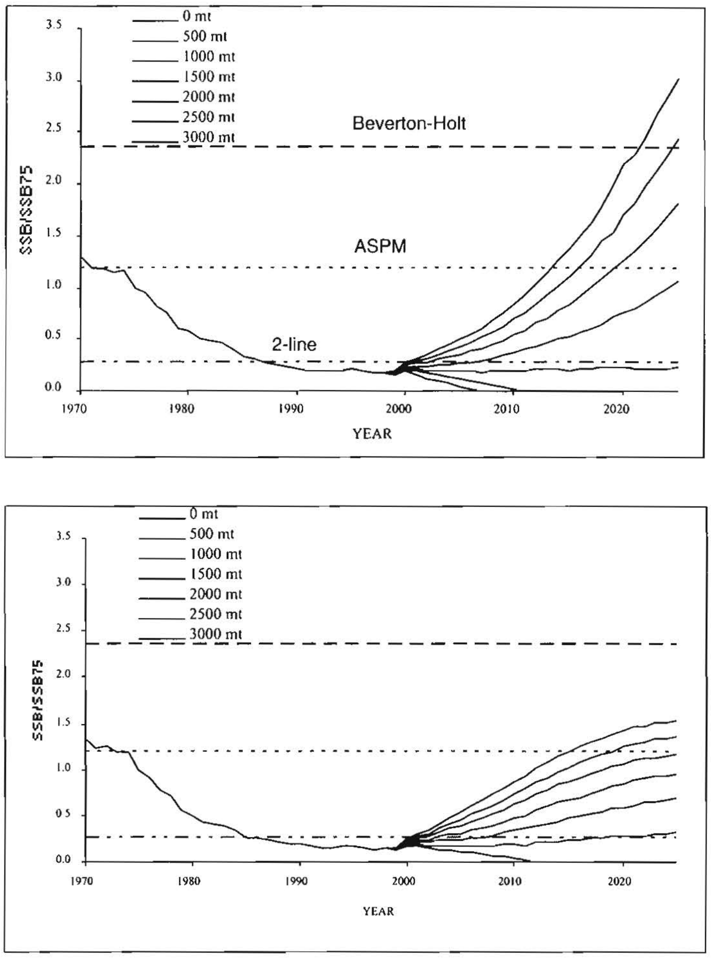

FIGURE 7. Median projections of spawning stock biomass (SSB) relative to the 1975 level for western Atlantic bluefin tuna assuming a Beverton–Holt stock recruitment relationship (upper diagram) and a two line stock recruitment relationship (lower diagram) for constant catches in the range 0–3000 mt. Horizontal lines represent three different estimates of the SSB at MSY relative to the 1975 SSB, one based on a Beverton–Holt relationship fit to stock and recruitment estimates from virtual population analysis, another on a piecewise linear (2 line) relationship fit to a subset of the same estimates, and a third one based on stock and recruitment estimates from an age-structured production model (ASPM). From ICCAT (1999).

Columbia Fisheries Center and elsewhere (Pauly et al. 2000). The complexity of ecosystems and the large number of alternative plausible formulations of ecosystem structure and function makes representation of uncertainty particularly difficult. As a result, the utility of multispecies and ecosystem models for providing operational objectives, performance measures, and management advice has, to date, been very limited. In recognition of this difficulty, a committee of the National Research Council and a congressionally mandated panel formed by the National Marine Fisheries Service both concluded that applying the precautionary approach to single species management was a necessary step toward an ecosystem approach (Ecosystem Principles Advisory Panel 1999; National Research Council 1999). An alternative, or perhaps a complementary approach, is to develop adaptive management strategies as mechanisms for dealing with uncertainty. The focus of adaptive management is to treat fisheries as experiments that are designed to provide information as they proceed (Walters 1986). For example, fisheries can be experimentally manipulated in ways

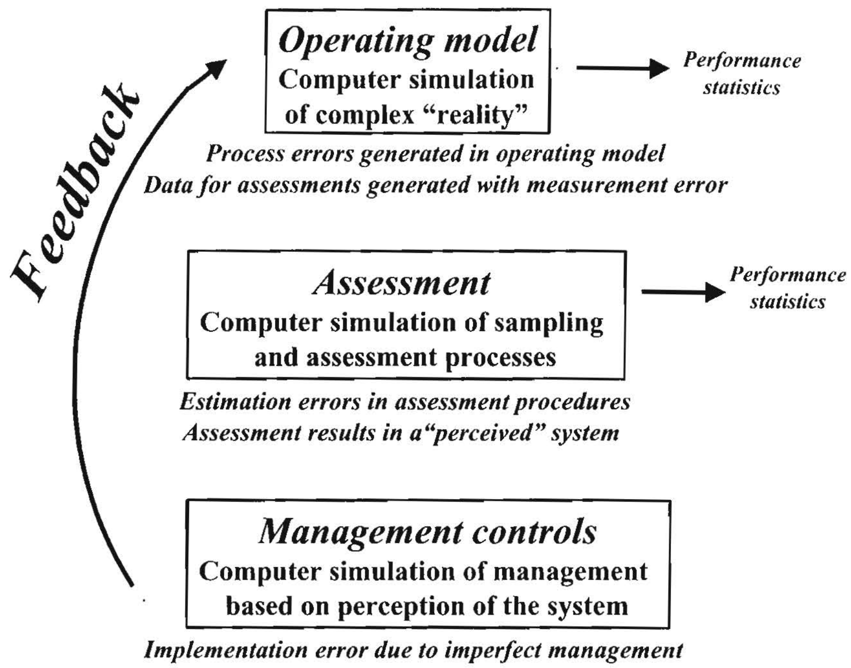

FIGURE 8. Schematic diagram of a management procedures simulation model. From ICCAT (2000).

that will enable evaluation of competing hypotheses about system function (Sainsbury et al. 1997).

Concluding Remarks

Scientists, managers, and fishers have always known that uncertainty is an integral part of nature. In addition, most fisheries scientists have strong quantitative backgrounds and have received training in methods of presenting uncertainty. Therefore, why isn't the presentation of uncertainty more routine in fisheries? One of the primary reasons suggested in this paper is that it has generally been used as a reason for continuing the status quo, rather than as a reason for exercising restraint. Recently, however, increased public awareness of, and concern about, the limits to the productivity of natural marine resources has resulted in a transition in paradigms from one of "it is not possible to overexploit" to one of "it is not acceptable to overexploit." Overall, in most cases, the practice has yet to catch up with the theory in terms of this paradigm shift.

One of the most important keys to the future elimination and/or prevention of overfishing is to shift from risk-prone to risk-averse decision making as called for by the precautionary approach. There are two general ways to accomplish this. One is to devise strict, unambiguous, enforceable laws (as exemplified by the U.S. Marine Mammal Protection Act). The other is to develop and foster a strong conservation ethic to which all or most stakeholders subscribe (as exemplified by the Pacific halibut fishery; McCaughran 1997). The latter option is to be preferred because it is likely to be less controversial, and therefore less costly to the nation, and more likely to succeed. However, there are considerable challenges inherent in developing a strong conservation ethic in fisheries where generations of fishers have operated on the premise that fisheries resources should be capable of providing livelihoods for all who wish to pursue this way of life.

Another difficult challenge is to determine whether it was overfishing or environment that caused a stock to become depleted. The actual cause of depletion may be largely irrelevant in terms of the subsequent management actions required, in that a depleted stock is likely less productive and harvest levels will need to be reduced to either maintain the stock at its depleted level or to rebuild it. However, the one respect in which the overfishing/environment dichotomy may matter regards the choice between an active and a passive rebuilding strategy (Sissenwine et al. 1998). Passive rebuilding strategies are potentially the most pragmatic approach to use in instances where environmental regime shifts are suspected. If a regime shift to lower productivity has occurred, and the target rebuilding biomass is based on the period of higher productivity, it will be impossible to reach. Alternatively, if the stock is in a phase of high productivity, and an estimate of target biomass from a low productivity phase is used, it will be very easy to achieve but may well be far from optimal. When, as is generally the case, it is not known whether the stock has experienced a regime shift or has actually been depleted by fishing and other factors, it may be particularly difficult to estimate an appropriate target biomass for rebuilding. In such cases, the most pragmatic management strategy may be one that ensures steady progress, including milestones along the way to an initial target (e.g., the level of biomass based on a low productivity phase). Once the initial target is achieved, the situation can be reevaluated to determine whether the target biomass should be even higher. A passive rebuilding strategy would require that fishing mortality be kept within reasonable bounds (e.g., those appropriate to reaching the low productivity target), while not requiring drastic reductions in fishing mortality (e.g., those appropriate to reaching the high productivity target), but would also operate by capitalizing on years of good recruitment and "banking" them for future stock rebuilding rather than cropping them off as soon as they become available to the fishery.

Now and into the future, it is essential that scientists, managers, the industry and the public be cognizant of the risks and the benefits associated with fisheries management decisions, and that such risks and benefits therefore be presented in a rigorous, risk-averse decision analysis framework that is readily interpretable.

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