

Proceedings of the Fifth National NMFS Stock Assessment Workshop

**Providing Scientific Advice to Implement
the Precautionary Approach Under
the Magnuson-Stevens Fishery
Conservation and Management Act**

February 24-26, 1998, Key Largo, Florida

Prepared by the National Marine Fisheries Service

Victor R. Restrepo (Editor)



U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

NOAA Technical Memorandum NMFS-F/SPO-40
July 1999



This document is a compendium of the presentations and discussions of the Fifth National NMFS Stock Assessment Workshop. The main theme of the Workshop was scientific advice for the implementation of a precautionary approach to managing U.S. fishery resources.

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1

INTRODUCTION

Since 1991, the National Marine Fisheries Service (NMFS) has held five national workshops devoted to examining issues of contemporary interest in stock assessment. These workshops have become an important venue for NMFS scientists to exchange ideas of direct relevance to NOAA's mission and, more importantly, to focus efforts on problems of national interest such as bycatch or uncertainty and risk estimation in stock assessments.

Objectives

The fifth National Stock Assessment Workshop (NSAW) focused primarily on the theme "Providing Scientific Advice to Implement the Precautionary Approach Under the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA)¹." In order to convey the importance of this theme in the context of issues of national interest, a brief recap of key points from U.S. fisheries management is given below.

The MSFCMA contains a set of ten National Standards for fishery conservation and management. National Standard 1 states,

"Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield [OY] from each fishery for the United States fishing industry."

The MSFCMA also requires the Secretary of Commerce to prepare guidelines for assisting in the development of fishery management plans that adhere to the National Standards (the National Standard Guidelines, NSG²). As the current status of many U.S. fisheries is either overfished³, approaching an overfished condition, or unknown, there is a widely perceived need to adopt a precautionary approach to the management of these fisheries. In this context, and in reference to National Standard 1, §600.310(f)(5) of the NSGs states,

"OY and the precautionary approach. In general, Councils should adopt a precautionary approach to specification of OY."

And, in the Preamble, the NSGs state,

"Because specification of a precautionary approach can be a complicated exercise, NMFS plans to supplement these guidelines in the near future with technical guidance for use in implementing such an approach."

Thus, the workshop served as a forum to facilitate discussions and presentations of ideas by many NMFS scientists, managers, and colleagues from outside the agency, many of whom had considerable experience from similar efforts to formulate a precautionary approach in national and international fora.

Concurrent with the planning and execution of the workshop, a team of scientists was asked to draft a document providing the detailed technical guidance for implementing the precautionary approach, in accordance to the need expressed by the NSGs. In preparing that document⁴, the drafting team made use of information given during workshop presentations and of the general discussions held throughout the workshop. As such, these workshop Proceedings are complementary to the technical guidance document.

Organization of the Workshop

The workshop was held at the Holiday Inn hotel in Key Largo, Florida. It was organized by a Steering Committee comprised by Wendy Gabriel, Loh-Lee Low, Alec MacCall, Richard Methot, Joseph Powers, Victor Restrepo (co-Convenor), and John Witzig (co-Convenor). Eighty-two participants (listed in Annex A) included individuals from all Fisheries Science Centers, two Regional Offices, two Headquarters Offices, one Management Council, and scientists from several external organizations who attended by invitation.

Twenty-four presentations were made at the workshop (see the Agenda in Annex B). The remainder of the workshop, or about 40% of its duration, was used for working group meetings and plenary discussions.

¹ The MSFCMA, U.S. Public Law 94-265, as amended through October 11, 1996, establishes the legislation upon which the management of all fisheries in U.S. EEZ waters is based. The MSFCMA is available as NOAA Technical Memorandum NMFS-F/SPO-23, 1996.

² The NSGs were published in the Federal Register as proposed rule on August 4, 1997; the final rule was published after the NSAW on May 1, 1998.

³ The MSFCMA requires the Secretary of Commerce to report to Congress annually on the status of stocks. In the 1997 report (NMFS 1997, Status of Fisheries of the United States), 31% of the species whose status was known were listed as being overfished, and 62% of the species examined were listed as having unknown status.

⁴ Restrepo, V.R., G.G. Thompson, P.M. Mace, W.L. Gabriel, L.L. Low, A.D. MacCall, R.D. Methot, J.E. Powers, B.L. Taylor, P.R. Wade, and J.F. Witzig. 1998. Technical guidance on the use of precautionary approaches to implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act. NOAA Technical Memorandum NMFS-F/SPO-31, 54p.

Organization of this Document⁵

The remainder of this document is organized into two sections: Section 2 contains abstracts and papers corresponding to the presentations made at the workshop. Section 3 contains reports from four working groups that met to discuss aspects of the precautionary approach from the point of view of four different tiers of information (data) richness or complexity.

Other Issues

During the last plenary session, NSAW participants discussed several issues that are not captured in the remainder of this report. Three of these were:

Toolbox: Several presentations were made about software “toolboxes” for analyses in support of stock assessment (see Annex B). Participants noted that a standard toolbox could bring several benefits, from providing a minimum standard platform, to facilitating software development. Ideally, a minimum standards toolbox should have redundant built-in diagnostics procedures to help the user evaluate model performance.

Communication/Education: The scientific advice on how to interpret and implement the NSGs should be communicated to Council staff and other interested persons as clearly as possible. Some participants proposed a structured seminar series, originated in headquarters, to be given in all regions. Other participants felt that scientists from each Center ought to give such presentations as needed, tailored to each particular region’s needs.

Next Workshop: Participants agreed that the next SAW should be held approximately 18-24 months after this one. At least two-thirds of the workshop should be devoted to a theme that is NOAA-NMFS mission-relevant.

Acknowledgments

This workshop was hosted by the Southeast Fisheries Science Center and the participants thank its Director, Brad Brown, and his staff for all the help provided. Special thanks to Rick Brown of the Office of Science and Technology in Silver Spring, MD, for providing all of the critical logistical support, and to Pamela Mace, of the same Office, for her thorough comments on the entire volume. A number of other reviewers provided critical comments on the papers published here and their efforts are also appreciated.

⁵ Most of the papers and group reports contained in this publication have not been updated to reflect the many NSG-related activities that have taken place since February of 1998. These documents have not been subjected to full peer-review and do not necessarily reflect NOAA-NMFS policy.

2

**ABSTRACTS AND
SCIENTIFIC PAPERS**

Incorporating No-Take Marine Reserves into Precautionary Management and Stock Assessment

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Abstract.— No-take marine reserves, areas protected from all fishing and other extractive activities, offer a conservative, ecologically and habitat based, tool for fishery management. They can support sustainable fisheries by providing significant protection of species composition, abundance, size and age structure, fecundity and spawning potential. They offer particular potential for protecting stock genetics from detrimental selective effects of fishing and are ideal for species with few available data or that have little economic importance. In many cases marine reserves may have less detrimental impacts on fisheries and provide better resource protection than more traditional measures, such as quotas, and size and bag limits. Marine reserves also provide essential reference areas to assess fishing effects, interspecies interactions, and environmental effects on stocks. Although few exist, they are being created at an accelerated rate worldwide. Increased use of no-take marine reserves poses some problems for stock assessment because portions of the stock will not be subject to traditional fishery-dependent data collection. This problem can be treated by greater use of spatially explicit models, fishery-independent length-frequency data, 'mean size in the exploitable phase', and stereo video technology.

Introduction

"The serious problems we have can't be solved at the same level of the thinking we were at when we created them."

Albert Einstein.

Overfishing problems are receiving increased worldwide public and scientific attention, resulting in increased calls by scientists and conservationists to establish no-take marine reserves (Roberts, 1997a). The journal *Science* alone published at least eight relevant articles within the past year. Malakoff (1997) examined the possibility of extinction on the high seas from fishing, while Schmidt (1997), Williams (1998), Roberts (1997b) and Ogden (1997) examined no-take zones in fisheries management. Reznick et al. (1997) examined impacts of predation on the genetics of fish populations, a process quite analogous to fishing. The two most recent articles concerned fishing impacts on marine ecosystems. Dayton (1998) called for reversal of proof in fisheries management to show that fishing does not harm marine ecosystems and Pauley et al. (1998) measured fishing effects on top carnivores in marine food webs.

Fishery management must develop a social policy to protect resources in the face of increased demands for exploitation. Due to a variety of biological, economic, and social factors, traditional fishery management has often failed to maintain sustainable fisheries while protecting biodiversity and ecosystem function (Ludwig, et al., 1993; Dayton et al., 1995; Bohnsack

and Ault, 1996; Pauly et al., 1998). Overexploitation, stock collapse, and loss of biodiversity are growing problems because of open access fisheries, increased fishing power, habitat damage from fishing, loss of natural refuges, and an inability of traditional methods to effectively control fishing effort and mortality (Boelert, 1996; Bohnsack and Ault 1996).

Since Beverton and Holt (1957), fisheries management has attempted to regulate fisheries by providing stocks a refuge in numbers, either by limiting the size of capture or reducing fishing mortality by controlling fishing effort. Unfortunately in many cases controlling harvest size and effort have not been effective or possible. Although largely overlooked (Pauly, 1997), Beverton and Holt (1957) noted that providing a refuge in space could also be used. In many cases, protecting areas from harvest potentially could be more effective than other management approaches. Despite this potential and support from hundreds of peer reviewed papers, fishery management is only beginning to seriously examine the use of marine reserves in fisheries management (Schmidt, 1997).

Here I discuss how marine reserves fit in a precautionary management strategy with emphasis on design principles and the potential of reserves to protect stock genetics from detrimental selective effects of fishing. Some obstacles to using reserves are examined and compared to use of size limits. Finally, I examine potential problems marine reserves pose for stock assessments. Approaches are suggested to solve these problems.

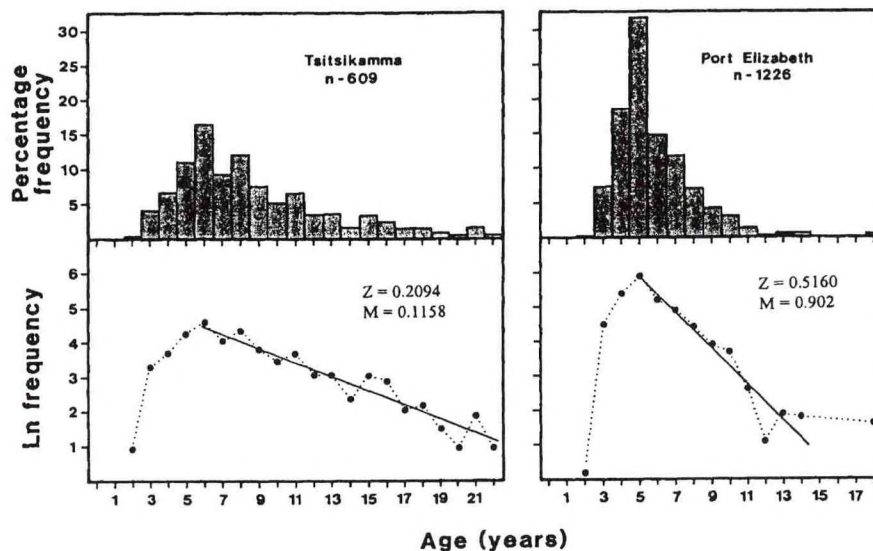


Figure 1. Distribution of age classes (top) and catch curves (bottom) of *Chrysoblephus cristiceps* sampled in areas protected from fishing for 25 yr, Tsitsikamma marine reserve (left), and fished, Port Elizabeth (right), South Africa. The slope of the descending limb of the catch curves is the estimate of total mortality. After: Buxton, 1993 (Fig. 9, pg 59), with kind permission from Kluwer Academic Publishers.

Marine Reserves: Attributes and Potential Benefits

Marine reserves are defined here as areas protected from all extractive activities. Many scientists have called for establishing networks of 'no-take' marine reserves to reduce fishing mortality, maintain sustainable fisheries, and protect biodiversity (Lauck et al, 1998). Spatial protection is a precautionary approach consistent with habitat and ecosystem management and is ideally suited to the ecology of most marine organisms that disperse as eggs and larvae but are relative sedentary or philopatric as adults. Besides providing fishery benefits, marine reserves can protect marine ecosystems, improve non-consumptive recreational opportunities, diversify the coastal economy, increase scientific understanding of resource dynamics, and facilitate public appreciation and protection of marine resources (Sobel, 1996).

Compared to having all areas open to exploitation, marine reserves offer major direct fishery benefits: (1) more fish from increased production and dispersal of eggs and larvae from larger size classes, greater abundances, and increased spawning potentials in unexploited reserves; (2) export of biomass from juvenile and adult fish moving across reserve boundaries to fishing grounds; (3) protection of genetic quality from detrimental effects of fisheries selection; (4) insurance against stock collapse from fishing or natural recruitment failure; (5) more rapid rebuilding in case stocks do collapse; (6) reduced annual variability in landings from fisheries by providing more consistent recruitment

potential; and (7) sustained fisheries for vulnerable species that are rare, change sex (e.g. protogynous hermaphrodites), or that have strong Allee' effects in which any reduced adult density has non-linear negative effects on fecundity (e.g. sea urchins and other broadcast spawners). Sobel (1996) and Bohnsack (1998) discuss additional fishery benefits. For example, with a sufficient network of protective marine reserves, overfishing is more difficult and recreational fisheries with reasonable bag or size limits could continue to operate year around with little fear of exceeding their quota and being closed. Reserves also could buffer detrimental effects of natural environmental variation by protecting a portion of older age classes from harvest until extreme environmental conditions change.

Marine reserves also offer important indirect fishery benefits by providing: (1) reference sites for determining fishery impacts on marine ecosystems; (2) monitoring sites for determining natural versus anthropogenic influences on stocks; (3) experimental sites with minimum human disturbance for fishery investigations on behavior, environmental factors, species interactions, and natural mortality; and (4) easier enforcement. Compared with traditional regulations, fishery violations are easier to detect because boardings are not required and only the act of fishing is the violation. Also, limited enforcement resources can be more effectively deployed over a limited area instead of the entire fishing grounds. The eventual ability to directly measure natural mortality in reserves is especially important because it is a key parameter in VPA and most stock assessment models.

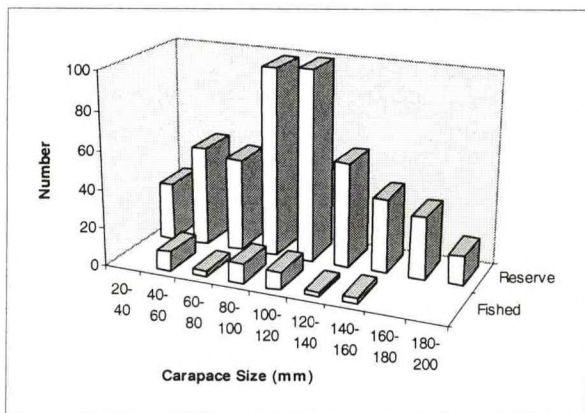


Figure 2. Population abundance and size structure of spiny crayfish, *Jasus*, from similar habitat inside and outside Leigh Marine Reserve, New Zealand. Data replotted from MacDiarmid and Breen (1992).

When all areas are exploited, natural mortality must be indirectly estimated. Given time, marine reserves could provide direct estimates of natural mortality (Fig. 1).

Scientific reviews, done almost annually this decade (e.g. PDT, 1990; Roberts and Polunin, 1991; Dugan and Davis, 1993; Rowley, 1994; Roberts et al., 1995; Bohnsack, 1996; Ruckelshause, in press), support most predicted benefits of marine reserves. When protected from fishing, most stocks can recover in terms of increased abundance, density, biomass, size and age classes, and fecundity (Figs. 2 - 4). In some cases, observed abundance, density, and spawning potential can be orders of magnitude higher in reserves than surrounding fished areas with similar habitat. Although their primary contribution to fisheries is likely to be production of new recruits from export of larvae, they can also contribute significantly to direct export of adults and exploitable biomass to local fishing grounds (Fig. 3). Biomass export has been documented for tropical reef fishes (Russ and Alcala, 1996a), temperate reef fishes (Attwood and Bennet, 1994), estuarine fishes (Johnson et al., in press), and spiny lobster *Panulirus argus* (Davis and Dodrill, 1989). The importance of larval dispersal from marine reserves to surrounding fisheries is the most difficult hypothesis to test but has some support from studies of fishes (Tilney et al., 1996) and conch, *Strombus gigas* (Stoner and Ray, 1996). While closed areas were thought to benefit mostly sedentary species, some species considered highly mobile have been shown to benefit, including carangids, *Caranx melampygus*, (Holland et al., 1996), spiny lobster, *P. argus* (Davis and Dodrill, 1980) and rock lobster, *Jasus* (MacDiarmid and Breen, 1992).

In essence, marine reserves offer a bet-hedging strategy in case of miscalculation or failure of more traditional management approaches. With marine reserves,

all species receive some level of protection, including species for which there are little data. Data needed to do a full stock assessment are inadequate for most species under present funding and this situation is likely to continue based on projected level or declining NOAA funding through 2003 (Lawler 1998). Also virtually no data are collected on non-commercial species incidentally taken as bycatch or that are impacted by habitat alterations associated with fishing (Dayton, et al. 1995; Dayton 1998). Clearly, marine reserves offer precautionary protection in these situations.

Genetic Protection

Fishing can lead to changes in life-history (Buxton, 1993) and genetics of exploited species (PDT, 1990). Because fisheries harvest wild populations, they present unique genetic problems for management. An assumption that stocks can be intensively fished or over exploited with no long-term harm to stock genetics is questionable and should be a particular concern of fishery management (PDT, 1990). Size-selective fishing, in particular, can be a directional selective force on population life-history characters such as growth rates, age at maturity, maximum size, total fecundity, and behavior.

The theoretical basis for genetic effects of fishery selection is well established (Bergh and Getz, 1989). Natural populations are vulnerable to loss of genetic variability with severe reduction in population size (Da Cunha and Dobzhansky, 1954) or though directional selection effects. Loss of genetic variability can reduce stock persistence under high environmental variability. Directional selection from fishing can change population genetics and life history characters related to age at first reproduction, fecundity, age and size structure, and behavior. Goodyear (1996) modeled how large minimum sizes for red grouper cause the fishery to harvest the faster-growing members of each size class and this could induce strong genetic selection for slow growth that may significantly reduce future stock productivity.

Detrimental genetic changes from fishing are difficult to show (Nelson and Soule, 1987) but have been demonstrated for important fishery species including pink (*Oncorhynchus gorboscha*) and chinook salmon (*O. tshawytscha*) (Ricker 1981), and orange roughy, *Hoplostethus atlanticus* (Smith et al., 1991). Empirical studies have demonstrated impacts of fishing on growth, size at maturity, maximum age (Drake et al., 1997) and behavioral characters, such as aggressiveness and shyness (Wilson and Clark, 1996). Fishing is a form of predation. Reznick et al. (1997) measured evolutionary rates based on genetic changes in artificial predation experiments on natural fish populations. They observed evolutionary rates ranging from 3,700 to 45,000 darwins,

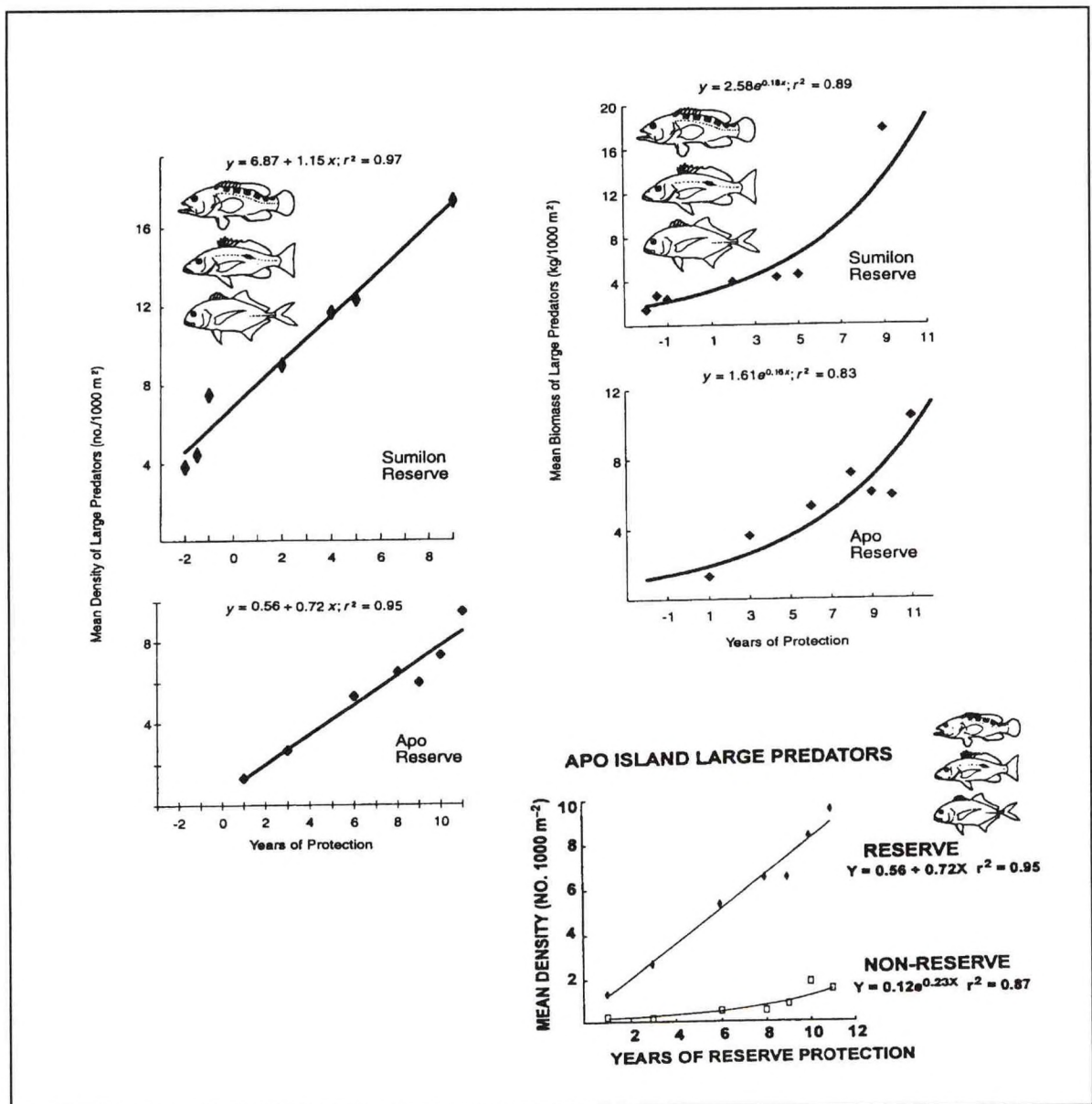


Figure 3. Changes in mean density (left) and biomass (right, top) of large predators (serranids, lutjanids, lethrinids, and carangids) inside Sumilon and Apo marine reserves, Philippines. Negative years were open to fishing. (Right, bottom) changes in density of large predators inside and outside Apo reserve. After: Russ and Alcala, 1996a, 1996b; with permission.

as compared to the evolutionary rates of 0.7 - 3.7 darwins typically observed in the fossil record and a geometric mean of 58,000 (range 12,000 to 200,000) darwins observed in animal and plant breeding efforts. These experiments suggest that the evolutionary effects of fishing could be closer to animal husbandry than natural selection (Svensson, 1997). By providing a refuge, marine reserves offer perhaps the only way to protect stock quality in terms of detrimental selective effects of fishing on genetics.

Design Criteria.

Ballantine (1997a,b) provided general design guidelines for designing marine reserves (Table 1). Most

important, reserves should be no-take, permanent, and include representative replicates of all habitats. Public access is essential as a passive enforcement mechanism and for building continued support (i.e. the public must see benefits). Periodically opening reserves to fishing has been shown to be ineffective, especially for long-lived species, because the protected resources may take decades to build up and the benefits often can be dissipated quickly (Bohnsack, 1994).

The size of individual reserves and the total amount of habitat that should be protected in no-take zones is more controversial, although clearly substantial areas are required, especially to be self-sustaining. In his earlier papers, Ballantine (1991) argued for a minimum of

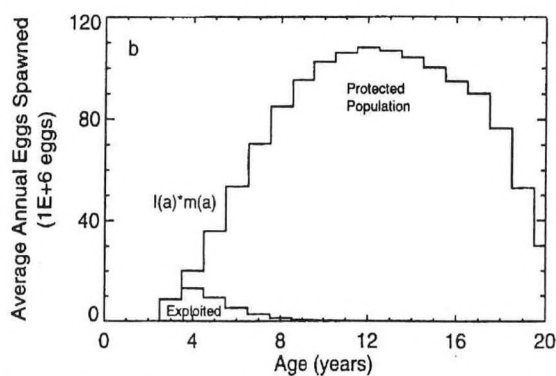


Figure 4. Reproductive potential (eggs spawned) by a typical scallop recruited at age two in an exploited and protected population as a function of age, mortality probability, and fecundity. Areas under each curve represent the lifetime eggs produced by an average individual in exploited and protected populations. After: McGarvey and Willison, 1995, with permission.

Table 1. Design Principles for Marine Reserves (After Ballantine 1997a,b).

- Include All Representative Habitats
- Permanent Reserves
- No-Take
- Network Design of Replicated Sites
- Geographically Dispersed
- Goal: Self-Sustaining
- Encourage Public Access
- Establish on Principle

10% coverage of all habitats, but more recently, he increased the recommended size to 20 to 30% (Ballantine, 1997b). Some scientists have suggested that 20% would be necessary based on minimum protection of spawning potential ratios (PDT, 1990) while some models have indicated that 30% or higher may be possible and still maintain maximum sustainable landings (Sladek-Nowlis, 1997). Some conservation groups are calling for protection of 20% of all marine habitats by the year 2020.

Ballantine (1997a,b) emphasized common sense and establishing marine reserves on principle in the same way that we build schools and educate children. His guiding principles are summarized in Table 2. The precautionary approach is particularly important for fisheries: without complete understanding of resources and processes, some resources should be withheld from exploitation. Even with good understanding, some areas should be left undisturbed from human impact. Also, if science is to have any importance in resource management, no-take reserves are absolutely essential as reference areas and controls to evaluate fishing impacts on natural systems.

Table 2. Principles used in establishing marine reserves (Ballantine 1997a, b).

- Precautionary Management (if you don't have complete understanding, withhold some resources from exploitation)
- Essential for Scientific Understanding as Control or Reference Areas
- Not Designed to Solve Species-Specific Problems (created independently of regulations required by exploitive activities)
- Some Areas should be Left in a Natural, Undisturbed State
- Protect all Species

Despite common sense and the fact that large areas are protected from exploitation on land, marine reserves remain controversial and only beginning to be incorporated into policy for most countries. In the Florida Keys National Marine Sanctuary, for example, the establishment of 19 no-take zones in 1997 included less than 1% of Sanctuary waters (U.S. Department of Commerce, 1996). Likewise, California, despite having 104 marine protected areas, currently has only a few hectares under no-take protection (McArdle, 1997).

Obstacles to Establishing Marine Reserves

The biggest obstacles preventing widespread use of marine reserves for fisheries purposes are concerns over: (1) short-term impacts to yield, (2) lack of direct experience, (3) lack of precise models predicting optimum locations and design features, and (4) crowding among anglers. Obviously marine reserves are subject to all other obstacles common to all fishery management actions, including apathy, ignorance, disproportionate political or economic influence, lack of enforcement, and general distrust of science and management among users. Phasing in closures over time helps avoid short-term detrimental impacts to fisheries by allowing accrued benefits to compensate decreased fishing area (Sladek-Nowlis and Roberts, 1997). The second two issues deal with specific local conditions and can only be effectively treated with an adaptive management approach of actually establishing reserves and modifying them accordingly as new information becomes available on local conditions. Marine reserve theory currently is general and real, but not precise.

Increased crowding is often used as the fatal argument to kill marine reserve proposals, but it is often more an issue of perception than substance, especially for small reserves. In fact, even large reserves may have less negative impacts on fishery landings than other conservation measures often used. Using gag grouper (*Myctoperca microlepis*) from the Gulf of Mexico as a model, I compared catch curves and crowding effects of a marine reserve that protects 20% of the total fishing

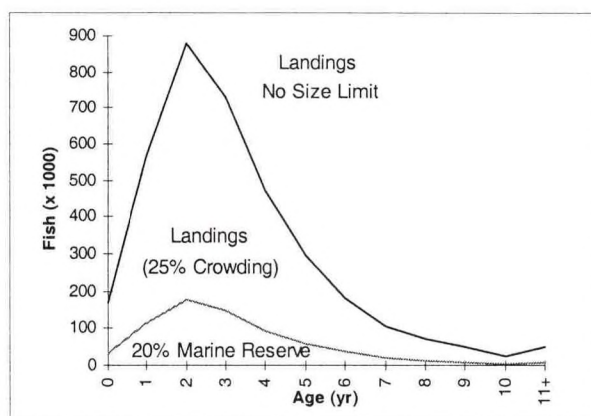


Figure 5. Projected catch curve for gag grouper, *Myctoperca microlepis*, in the Gulf of Mexico for 1992-1996 without size limits. A marine reserves covering 20% of fishing grounds would have protected 20% of the stock in all age classes and reduced the catch of all age classes by 20%. The resulting crowding, measured as the number of available fish per angler, for anglers displaced by reserves would have been 25%.

grounds with impacts of establishing a minimum 20" size restriction (Fig. 5). Closing 20% of fishing grounds as marine reserves results in 25% increased crowding in terms of angler density and available fish per angler, since 80% of the fishing grounds and fish must be shared by 100% of the anglers. With reasonable compliance and limited fish movements, nearly 20% of the stock and habitat is protected from fishing.

Figure 6 shows the same catch curve with and without a 20" minimum size limit. When measured in numbers of legally available fish per angler, the size limit leads to 68% crowding because of the large number of small individuals in the population that are now "protected". Although a popular management measure, minimum size limits may provide relative little stock protection unless there is a substantial change in how fishing is prosecuted. Since fish less than 20" will still be caught as bycatch, the conservation benefit of the size limit depends on the level of release mortality. Unless anglers can avoid catching legally undersized fish, Figure 6 underestimates the actual bycatch with a size limit. 'High grading' by recreational anglers under bag limits can become a problem which reduces conservation benefits. Although numbers of fish caught can be an important consideration for recreational anglers, commercial anglers rely on total weight and must now process more fish (or target other species) in order to obtain the same revenue. This increased fishing effort increases the bycatch of undersized fish while increasing the mortality of the larger legal-sized individuals with a disproportionate negative effect on spawning potential.

Thus, when "crowding" is compared on the basis of available fish per angler, the marine reserve is pref-

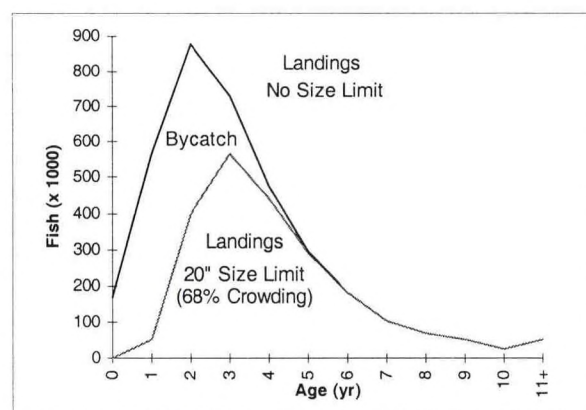


Figure 6. Catch curves for Gulf of Mexico gag grouper, *Myctoperca microlepis*, (1992-1996) with and without 20" minimum size limits. Ages at 20" vary around the 3 yr age class depending on individual growth rates. The minimum size limit results in 68% crowding in terms of available fish per angler. Undersized fishes caught must be discarded and are subject to bycatch mortality. Replotted from Schirripa and Legault (1997).

erable in that it provides more secure protection of the stock and has less detrimental impacts on anglers. There is no bycatch for fish in the reserve. In addition, the conservation value of a 20" size limit is questionable since gag grouper change sex and are often caught in deep water where release survival is reduced. For any level of stock protection, marine reserves may be less obtrusive for anglers than other traditional management measures.

Challenges for Stock Assessment

As fishery regulations increase and no-take marine reserves become more widespread, new approaches to stock assessment will be required because traditional assessments that rely mainly on fishery-dependent (FD) data will be inadequate. Even without using reserves, fishery-dependent data are becoming less useful with increased regulation. For example, fewer data are available as size and bag limits are imposed, seasons are shortened, and fisheries are closed for rebuilding. With larger size limits, younger age classes are less represented or absent from the data. As fishing effort switches to larger individuals, older age classes become truncated. Also, as recreational fisheries expand and become more important, fishery sampling becomes more expensive, difficult, and less precise. Finally, with increased regulation, many anglers are less cooperative in supplying 'voluntary' data and may have increased incentive to deceive samplers.

Assessments based primarily on fishery-dependent data may be misleading when marine reserves are used because significant portions of the stock may be unavailable to fishing. Another problem is that present length-

or age-based assessment methods rely on the assumption that a stock is homogeneous and reflects fishing pressure uniformly. With reserves, emigration from protected to fished areas potentially distorts the catch composition relative to the dynamics assumed in the standard models. Finally, increased fish abundance, density, and size in marine reserves can potentially contribute significantly to conservation targets such as SPR and prevention of over fishing. Fishery independent sampling that uses destructive fishing techniques are unlikely to offer much help because only on rare and exceptional cases, are reserve managers likely to allow destructive sampling for fishery purposes (Fig. 1). Solutions to these problems will require development of spatially explicit stock assessment models and increased reliance on non-destructive, fishery-independent (FI) data collection and length-based assessment methods (Gallucci et al., 1996). Unfortunately, age for most fishes can not be directly determined from length data so that assessment methods will have to be appropriately adapted. Ault et al. (1998) provide an example of an assessment based on 'mean size in the exploitable phase' for 35 reef fish species in the Florida Keys using diver visual estimates of length frequency combined with headboat data.

New technology may facilitate length-frequency data collection in a cost effective manner. Development and application of underwater, stereo-video technology offers particular promise (Bohnsack, 1995). With modification of off-the-shelf technology, it is potentially possible to greatly increase the quantity, precision, and accuracy of FI data. Many more fishes could be observed than are landed in the fishery. Also, more size classes and greater depths could be sampled than is feasible using divers. Data collection can be controlled in terms of standardizing distances and sampling time. Accurate habitat information could be provided, including topography, benthic species composition, and presence of foraging resources. In waters with moderate turbidity, stereo images are superior to single images. However, electronic processing of images could potentially double the actual visibility by substituting pixels from unobstructed portions of each image. Video systems can be used directly by divers or remotely operated vehicles (ROVs), as well as independent passive gear (i.e. video traps). Not having to rely on divers would greatly expand the sampling potential in terms of depth, sea conditions, and lighting conditions. This could be especially useful where crepuscular or nocturnal sampling is desirable. Finally, by providing accurate distance estimates, the statistical basis for calculating density is greatly improved.

Conclusions

No-take marine reserves are an essential, but

underutilized tool in precautionary fishery management. They are perhaps the only way to protect stock genetics from detrimental selective effects of fishing. General guidelines for establishing reserves exist but will have to be adapted to local conditions. Some of the concerns about using marine reserves compared to more traditional management measures appear to be based more on perception than substance. Use of marine reserves will require new approaches to stock assessments that use spatially-explicit models, fishery-independent length-frequency data, 'mean size in the exploitable phase', and stereo video technology for data collection.

Acknowledgments

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A Precautionary Approach to Fishery Control Rules Based on Surplus Production Modeling

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Abstract.— A risk-averse control rule, derived from surplus production model parameters and associated uncertainty, was developed to manage fisheries for maximum sustainable yield (MSY) and rapid rebuilding of overfished stocks. The proposed control rule consists of an overfishing threshold of F_{MSY} (the fishing mortality which produces MSY on a continuing basis, equal to half the intrinsic population growth rate, r) when biomass is greater than B_{MSY} (the biomass which can produce MSY). When biomass is less than B_{MSY} , the threshold F is derived as the maximum F which allows rebuilding to B_{MSY} in a specified period. Assuming logistic population growth, threshold F is a function of biomass relative to B_{MSY} and r . Precautionary levels of target F are derived from uncertainty in the estimate of r . Target F for a healthy stock is less than F_{MSY} , because it is derived from a lower quantile of the conditional probability distribution of r (designated as r'). At low stock size, target F is the maximum F which allows rebuilding to B_{MSY} in the specified period, assuming that r' is the intrinsic growth rate. The proposed control rule was applied to results of a nonequilibrium production model (ASPIC) of the Georges Bank yellowtail flounder stock, which is currently rebuilding from a collapsed state. Four years appears to be an appropriate rebuilding period for this stock, because r was estimated to be relatively rapid (0.60). Target F is derived from the 10th bootstrap percentile of r ($r'=0.53$; $F_{MSY}'=r'/2=0.26$). Conditional stochastic projection of ASPIC results suggests that, after four years of a rebuilding target determined by the control rule, there is high probability that the stock will grow to exceed B_{MSY} , and then produce 95% of MSY at the long-term target F . However, the cumulative risk of not achieving B_{MSY} in the specified period substantially increases if the rebuilding period is increased. The proposed control rule may be applied to other stocks which can be reliably modeled by logistic growth. Target F will be slightly less than the overfishing limit if r is well estimated, and substantially less than the limit if r is poorly estimated. However, the appropriate rebuilding time may be longer for slower-growing stocks ($r<0.6$) and shorter for faster-growing stocks ($r>0.6$) to conserve similar levels of relative biomass.

Introduction

The Sustainable Fisheries Act emphasizes the need to conserve U.S. fishery resources for long-term maximum sustainable yield (MSY) through precautionary management. Proposed guidelines on managing sustainable fisheries include several components: 1) preventing overfishing while producing MSY on a continuing basis; 2) defining overfishing as a rate of fishing mortality (F) that exceeds the threshold rate associated with producing MSY (F_{MSY}); 3) defining an overfished state as a stock size that is less than a minimum stock size threshold, which is the stock biomass that will allow rebuilding to the MSY stock biomass (B_{MSY}) in ten years; and 4) adopting fishery control rules that incorporate uncertainty of MSY reference point estimates, so that fishing targets are risk averse (DOC 1997). The proposed guidelines recommend that management be based on a 'precautionary approach' which has been endorsed by several international fishery management agencies (FAO 1995, UN 1995, ICES 1997, Serchuk et al. 1997). Although agencies have different specific guidelines for implementing a precautionary approach, a common feature is that target fishing levels should have low risk of exceeding MSY reference points. This study was conducted to derive a fishery control rule that conforms to the proposed national guidelines on sustainable fisheries. The control rule was designed to pro-

vide guidance on appropriate target and threshold levels of F conditioned on levels of stock biomass with the objectives of quickly rebuilding depleted stocks to levels that can produce MSY.

Surplus production models can provide guidance on stock status, MSY reference points, and associated uncertainties. Results from a nonequilibrium production model (ASPIC, Prager 1994, 1995) played a central role in the most recent stock assessment of Georges Bank yellowtail flounder (Cadrin et al. 1997, Neilson et al. 1997). Estimates of biomass and F from ASPIC agreed closely with estimates from an age-structured model and were considered reliable for management advice (DFO 1997, NEFSC 1997, NRC 1998). Stock assessment results show that F exceeded the level of maximum yield-per-recruit (F_{max}) from the late 1950s to the early 1990s. During this period, the fishery was managed using several strategies (e.g., national quotas, minimum size limits, minimum mesh sizes, spawning area closures, and trip limits). By 1994, the stock was considered to have collapsed (NEFSC 1994). Subsequently, amendments to the Northeast Multispecies Fishery Management Plan were designed to rebuild yellowtail flounder and other principal groundfish stocks to threshold levels of spawning stock biomass (SSB; for

Georges Bank yellowtail flounder, the threshold was 10,000 mt) by limiting days at sea, closing large areas year-round, increasing minimum mesh size, and imposing trip limits for some sectors of the fishery. In 1995, Canada also began to impose restrictive catch quotas. The most recent assessment of the Georges Bank yellowtail flounder stock indicated that biomass had increased to above the rebuilding threshold, but was well below B_{MSY} (Cadrin et al. 1997, Neilson et al. 1997). Precautionary management measures are needed to allow continued rebuilding of the Georges Bank yellowtail flounder stock.

Surplus Production Modeling

A nonequilibrium surplus production model incorporating covariates (ASPIC; Prager 1994, 1995) was applied to total catch and survey biomass indices for the Georges Bank yellowtail flounder stock. A previous application of ASPIC to the Georges Bank yellowtail flounder stock (Cadrin et al. 1997, Neilson et al. 1997) was revised by including discard estimates from U.S. fisheries (1963-1972 from M. Parrack, unpublished¹; 1973-1990 from Conser et al. 1991, 1991-1993 from NEFSC 1994, 1994-1996 from Cadrin et al. 1997). Total catch averaged more than 18,000 mt during 1963-1976, decreased to approximately 7,000 mt from 1978-1981, increased temporarily to more than 11,000 mt in 1982 and 1983, but declined to less than 7,000 mt after 1984. Biomass indices from NEFSC groundfish surveys generally declined at a rate of 10% per year since 1963, with a temporary increase in the early 1980s (Figure 1). Declines in average weight per tow suggest that current biomass levels are about 10% of levels observed in the 1960s. However, there are indications of increasing stock biomass levels in the last two years. The weight per tow index from the Canadian survey increased to a peak in 1996. Correlations among survey biomass indices were moderate to strong ($r=0.5, 0.7$, and 0.8).

The production model assumes logistic population growth, in which the change in stock biomass over time (dB/dt) is a quadratic function of biomass (B):

$$dB/dt = rB_t - (r/K)B_t^2 \quad (1)$$

where r is the intrinsic rate of population growth, and K is carrying capacity. For a fished stock, the rate of change is also a function of catch (C):

$$dB/dt = rB_t - (r/K)B_t^2 - C_t \quad (2)$$

Biological reference points can be calculated from the production model parameters:

$$MSY = Kr/4 \quad (3)$$

$$B_{MSY} = K/2 \quad (4)$$

$$F_{MSY} = r/2 \quad (5)$$

Initial biomass (expressed as a ratio to B_{MSY} : BIR), r , and MSY were estimated using nonlinear least squares of survey residuals. Catch per unit effort (CPUE) from the NEFSC fall survey contributed to the total sum of squares as a series of observed effort ($E=1/CPUE/C$). The NEFSC spring survey and the Canadian survey contributed as independent biomass indices. Survey residuals were randomly resampled 500 times to approximate precision and model bias.

Most of the variance in survey indices was explained by the model ($R^2=0.78, 0.56$, and 0.84). Model results indicate that a maximum sustainable yield of 14,500 mt can be produced when stock biomass is approximately 48,600 mt (B_{MSY}) and F is 0.30 (F_{MSY}). The MSY estimate is slightly lower than a previous MSY estimate (16,000 mt, NEFSC 1995). The B_{MSY} estimate is not directly comparable to published estimates of SSB_{MSY} , because it pertains to total stock biomass rather than mature biomass, but the estimate is between the current

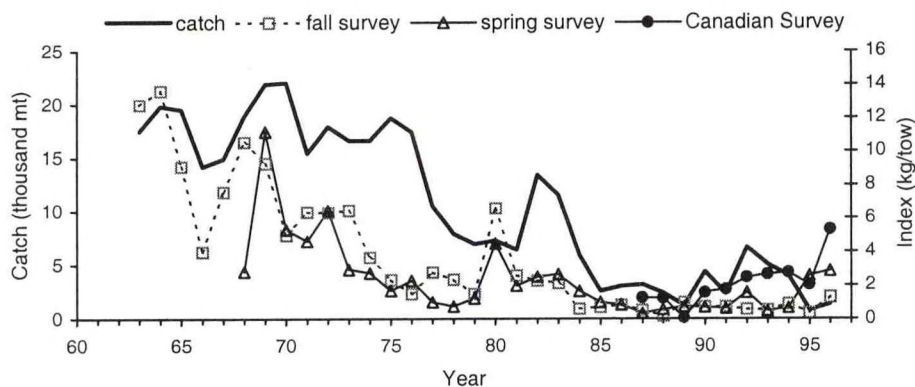


Figure 1. Input data for surplus production analysis of Georges Bank yellowtail flounder.

¹Parrack, M.L. A catch analysis of the Georges Bank yellowtail flounder stock. Northeast Fisheries Center, Woods Hole, MA.

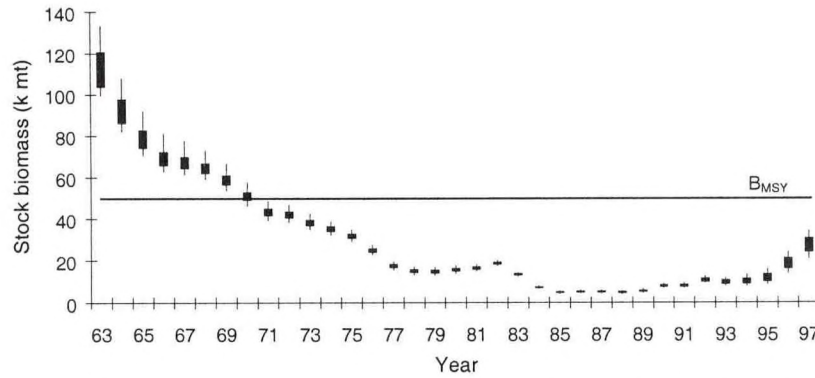


Figure 2. Biomass estimates from surplus production analysis of Georges Bank yellowtail flounder. Box plots indicate 50% and 80% confidence intervals.

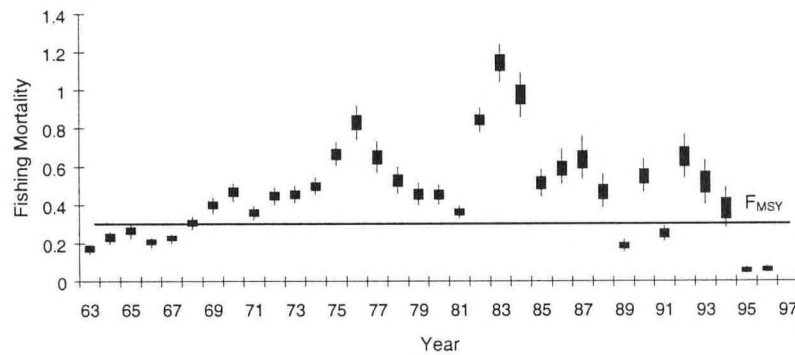


Figure 3. Fishing mortality estimates from surplus production analysis of Georges Bank yellowtail flounder. Box plots indicate 50% and 80% confidence intervals.

rebuilding target (10,000 mt SSB) and a previous estimate of SSB_{MSY} (65,000 mt, NEFSC 1995). The MSY reference points from ASPIC are similar to those estimated from stock-recruit data (Overholtz 1999).

Estimated stock biomass was greater than 50,000 mt in the 1960s (Figure 2). However, after 1967, F exceeded F_{MSY} , and biomass declined further. F continued to exceed F_{MSY} until 1995 (Figure 3). Biomass was reduced to less than B_{MSY} beginning in 1971, and continued declining to approximately 5,000 mt in the 1980s. In 1995, F sharply decreased, and biomass increased to 40% of B_{MSY} in 1996. Estimates of stock biomass and F from the surplus production model were similar to those from virtual population analysis (Cadrin et al. 1997, Neilson et al. 1997). Bootstrap analysis showed that MSY , r , K , B_{MSY} , and F_{MSY} were well estimated (relative interquartile range, $IQR < 10\%$), BIR and survey catchability coefficients (q) were slightly more variable ($IQR = 11\%$ to 31%), and ratios of current conditions to MSY conditions were less precise ($IQR = 28$ to 32%).

Exploratory ASPIC analyses were performed which included historical catch and landings-per-unit-effort as an index of biomass from 1943-1966 (Lux 1964, 1969a),

but the model did not fit the data well (Cadrin et al. 1997). Estimates of MSY , r , K , and q were not sensitive to extending the time series, including the LPUE series, or removing the penalty function for $BIR > K$ (Prager 1994).

Rebuilding Trajectories

The stock's capacity to rebuild from low biomass levels can be assessed by simulating population growth using parameter estimates from the production model. Assuming logistic growth, minimum stock size required to achieve B_{MSY} in ten years depends on the current level of biomass, F , and the stock's intrinsic growth rate (r). There is a threshold stock size, below which B_{MSY} cannot be attained in 10 years, even at $F=0$. Threshold combinations of maximum F and minimum biomass required to achieve B_{MSY} in ten years can be projected using an annual difference equation:

$$B_{t+1} = B_t + (r - F_t)B_t - (r/K)B_t^2 \quad (6)$$

Therefore, at any fixed F , a minimum biomass (B_0), which is less than B_{MSY} , can be solved so that $B_{10} = B_{MSY}$. If biomass is expressed as a ratio to B_{MSY} ($B = B/B_{MSY}$),

the equation becomes a function of r , F , and the current level of relative biomass, because $K=2B_{MSY}$:

$$B'_{t+1} = B'_t + (r - F_t)B'_t - (r/2)B'^2_t \quad (7)$$

Solving for several values of relative F (F/F_{MSY}) shows that slow growing stocks (e.g., $r=0.2$) cannot grow to B_{MSY} within ten years if the stock is reduced to approximately 25% of B_{MSY} (even with no fishing, Figure 4). Logistic growth with faster growth rates (i.e., greater values of r) implies that stocks can be depleted to extremely low levels and still grow to B_{MSY} in ten years. However, stocks at extremely low biomass levels are likely to have unstable age structures that may reduce the stock's general growth capacity. Therefore, managing fast-growing stocks based on ten-year rebuilding horizons would be risky, and it would not be prudent to base minimum stock size thresholds on ten-year rebuilding horizons for fast-growing stocks (DOC 1997).

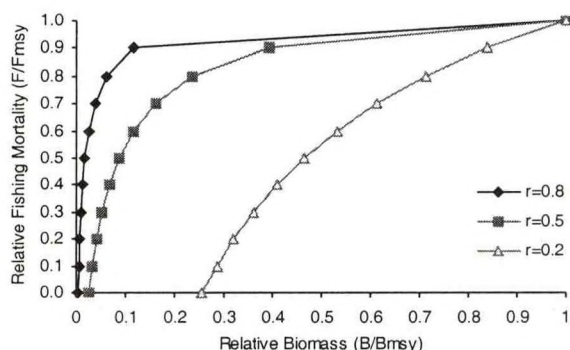


Figure 4. Maximum F and minimum biomass required to achieve B_{MSY} in ten years at several intrinsic rates of increase (r).

More appropriate rebuilding horizons for fast-growing stocks can be determined by inspecting rebuilding isopleths (curves of paired maximum F and minimum biomass to achieve B_{MSY}) over one to ten-years. For example, rebuilding isopleths for Georges Bank yellowtail flounder ($r=0.60$) are shown in Figure 5.

Control Rule

Production model results provide several limit reference points for managing sustainable yield. For example, when stock biomass of Georges Bank yellowtail flounder is greater than B_{MSY} (48,600 mt), F should be limited to less than F_{MSY} , which is 0.30. This corresponds to the fixed- F MSY control rule described by Thompson (1999). A precautionary long-term target can be derived from the conditional bootstrap distribution of r . For the yellowtail flounder example, the 10th bootstrap percentile of bootstrap r estimates (r') was 0.53 and the

associated target F would be 0.26 ($F_{MSY}' = r'/2$). A target F of 0.26 should have approximately a 90% chance of being below F_{MSY} .

Rebuilding times and limit F 's for low stock sizes of Georges Bank yellowtail flounder can be derived from the rebuilding isopleths in Figure 5. Requiring the stock to rebuild within four years suggests that fishing should stop when the stock is reduced to approximately 11,000 mt ($1/4B_{MSY}$). At the 1996 level of mean biomass (23,000 mt), an F of less than 0.18 should allow the stock biomass to rebuild to B_{MSY} within four years. Target rebuilding F 's for low stock sizes can be also derived from r' . For example, a target F of 0.11 would allow rebuilding from current biomass to B_{MSY} in four years if r' is assumed to be the intrinsic growth rate. An example of the proposed control rule is illustrated in Figure 6.

Stochastic projection, incorporating uncertainty in

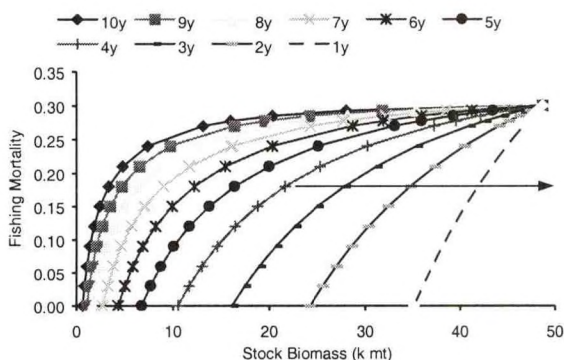


Figure 5. Rebuilding isopleths of maximum F and minimum stock biomass that allow rebuilding to B_{MSY} over several time horizons (1-10 y) for Georges Bank yellowtail flounder. Arrow indicates a 4-year rebuilding scenario from the current biomass level.

current biomass and model parameters for Georges Bank yellowtail flounder, with $F=0.11$ for the next four years (1997-2000) suggests that there is approximately a 60% probability that the stock will rebuild to B_{MSY} by the year 2001 (Figure 7). Extended projection at the long term target ($F=0.26$) suggests that the stock will be maintained at levels above B_{MSY} and yield 95% of MSY. Stochastic projection of control rules based on longer rebuilding periods indicates that the proportion of simulated projections that achieve B_{MSY} in the desired time period substantially decreases. For example, only 40% of simulations of a rebuilding target $F=0.16$ (based on a five year rebuilding period) attained B_{MSY} by the year 2002.

Discussion

The rebuilding simulations and control rule described here can be applied to any stock with reliable estimates of r and K . Most production models require a

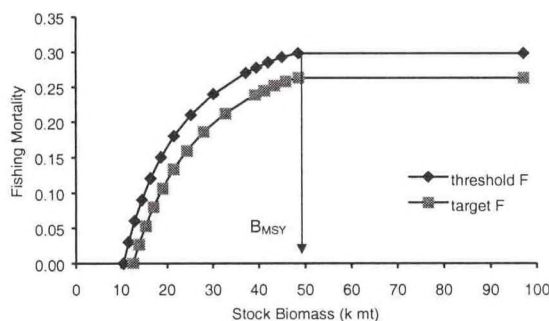


Figure 6. Proposed control rule for Georges Bank yellowtail flounder.

time series which encompasses a broad range of stock biomass and yield to provide dependable parameter estimates (Prager et al. 1996). In cases where the data series is not informative enough to reliably estimate all parameters, independent data can be used to fix certain parameters. For example, Prager (1993) fixed the value of r to provide guidance on MSY, but fixing r will determine the level of F_{MSY} . Application of ASPIC to other stocks in the northeast U.S. demonstrates that values of q can be fixed according to VPA estimates of stock biomass, or BIR values can be fixed according to ancillary information to provide reliable estimates of MSY conditions². However, targets that are based on bootstrap distributions from such strongly constrained models may be risk prone, because the probability distributions are conditional on the accuracy and precision of the fixed parameter values.

The shape of the control rule will change according to the estimate of r (see Figure 3) or the specified rebuilding period (see Figure 5), and target F 's will be closer to threshold F 's as uncertainty decreases. Appropriate rebuilding periods may be determined from

estimates of cumulative risk of not attaining B_{MSY} in the specified period. For the Georges Bank yellowtail flounder stock, the cumulative risk of not reaching B_{MSY} in four years using target F from the control rule is approximately 40% for the current stock conditions. Allowing a longer rebuilding period and a higher target F substantially increases the risk of not attaining B_{MSY} on schedule.

Alternatively, rebuilding times can be chosen based on the biomass at which rebuilding isopleths intersect the abscissa ($F=0$). For example, rebuilding periods may be based on maintaining a minimum biomass of $\frac{1}{4}B_{MSY}$, below which target F is zero². In comparison to the control rule for Georges Bank yellowtail flounder, rebuilding periods must be longer than four years for slower-growing stocks ($r < 0.6$) and shorter than four years for faster-growing stocks ($r > 0.6$) in order to maintain $\frac{1}{4}B_{MSY}$. Advocating a target F of zero when stock biomass falls below $\frac{1}{4}B_{MSY}$ may appear overly restrictive, but similar management advice was offered for the example stock without an explicit control rule: In 1993, when stock biomass was approximately 10,000 mt, the 18th Northeast Regional Stock Assessment Review Committee concluded that the stock had 'collapsed' and recommended that, 'Fishing mortality on the Georges Bank yellowtail stock should be reduced to levels approaching zero' (NEFSC 1994).

The proposed targets incorporate a constant probability level of exceeding F thresholds (approximately 10%). However, a more conservative approach would entail lower risk at low stock sizes, and perhaps more risk at high stock sizes². Many alternative control rules can be derived using the same rebuilding isopleths and bootstrap distributions reported here.

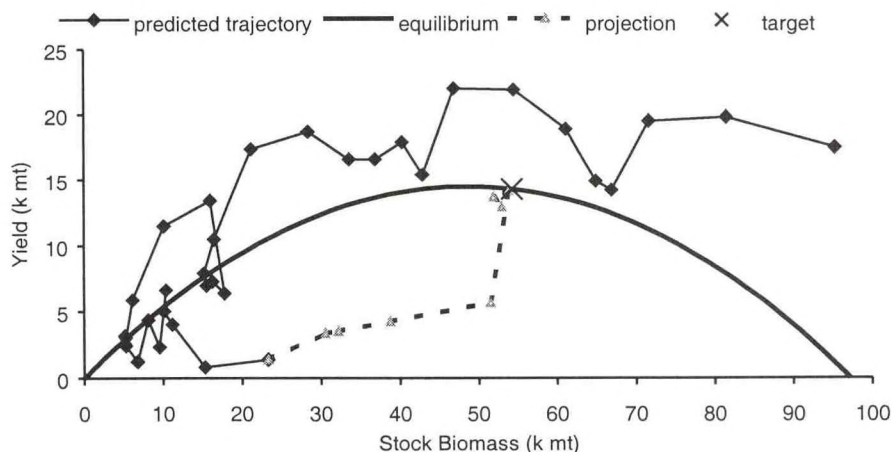


Figure 7. Projection of yield and biomass for Georges Bank yellowtail flounder with four years at the rebuilding target ($F=0.11$) and three years at the long-term target ($F=0.26$).

² Overfishing Definition Review Panel. 1998. Evaluation of existing overfishing definitions and recommendations for new overfishing definitions to comply with the Sustainable Fisheries Act. New England Fishery management Council Report.

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The Application of Precautionary Principles to the Northwestern Hawaiian Island Lobster Fishery: Life in the Trenches

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The Northwestern Hawaiian Island (NWHI) lobster fishery is managed based on a constant harvest rate strategy that allows only a 10% risk of overfishing in a given year and the retention of all lobsters caught. Implementation of the constant harvest rate strategy results from a 1994 Expert Review Panel recommendation to investigate alternative harvesting strategies and develop a revised quota setting procedure that explicitly allows for uncertainty in stock assessments, while assuring minimal risk of overfishing. Monte Carlo projections of an age-based simulation model which allows for systematic, process, and measurement error, as well as autocorrelation in recruitment innovations, was used to compare harvesting strategies and assess their effects relative to the risk of overfishing over a range of discard mortality and retention scenarios. The expected effects of alternative strategies and consequences of uncertainty were presented to the Western Pacific Region Fishery Management Council for evaluation and a 10% risk of overfishing in a given year was accepted. Because of a high perceived rate of discard mortality, which has been verified, a retain-all catch policy was also adopted. In this talk I will elaborate on the process to incorporate precautionary principles in the management of NWHI lobsters and recent developments in their assessment and management.

Using the Precautionary Approach to Control Deleterious Effects of Artificial Propagation on Natural Populations

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Artificial propagation has long been a controversial aspect of salmonid conservation and management in the Pacific Northwest. A large part of this controversy stems from considerable scientific uncertainty regarding the deleterious effects that artificial propagation has on natural populations, and the degree to which these effects can be controlled or prevented through management actions. Some effects, for example genetic introgression due to stock transfers, are both relatively well understood and relatively easy to prevent in a cost effective manner. Other effects, such as predation of natural fish by artificially propagated fish, can be effectively monitored and controlled to some degree by adaptive management actions. Finally, some effects, such as genetic change due to domestication, may be of uncertain magnitude, as well as being difficult to prevent in a cost effective manner and difficult to detect before substantial harm has already occurred. Focusing on Pacific salmon and steelhead, this presentation will provide some examples of the deleterious effects that artificial propagation can have on natural populations, as well as recommendations of how the precautionary approach can be used to reduce the risk of those effects.

Nature's Monte Carlo Experiments in Sustainability

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Abstract.- It has been made clear in the literature that management must simultaneously 1) apply consistently to individual species, ecosystems, and the biosphere; 2) account for complexity, stochasticity, processes, mechanics, dynamics, uncertainty, unknowns, and all scales of time and space; 3) maintain components of each level of biological organization within their normal ranges of natural variation; 4) exercise precaution by considering risk in achieving sustainability; 5) be information-based and interdisciplinary in approach; 6) include monitoring, assessment, and objectives; 7) recognize that control is limited primarily to human action; and 8) include humans as components of inclusive living systems.

These requirements for management may seem impossible, especially when combined. But there is a way to proceed. Management action could be guided by frequency distributions of empirical examples of sustainability, to ensure that human presence and influence in living systems fall within the normal ranges of natural variation. In regard to fisheries management, this applies to such things as resource utilization rates. For example, frequency distributions among species according to the rates that they consume a particular prey species demonstrate both variation and limits. Similar distributions occur for other ways of measuring a species. These include biomass consumption within particular ecosystems and numbers of resource species consumed. The central tendencies of such distributions for consumption rates serve as estimates of ecologically sustainable yields (ESY) or rates (ESYR), that can be used in place of methodologies currently in place (e.g., the "Fs" of conventional approaches in fisheries management).

Species frequency distributions reflect the results of the trial-and-error processes of natural selection, including selective extinction and speciation. They emerge from the complexity of reality and exposure to it. This reality includes all processes, mechanics, and materials. Species, and the individuals that comprise them, may be seen as physical Monte Carlo models in a kind of natural Bayesian integration process. These models are tested empirically against the risks and limitations of the realities of their environment. Extinction and associated risks are accounted for because existing species, as represented in frequency distributions, have not succumbed to risks leading to extinction that has removed billions of species as failures in the grand natural experiment. Collective risks prevent the accumulation of species in the tails of species frequency distributions and especially beyond the normal ranges of natural variation.

Sample applications of this approach at ecosystem and single-species levels use marine mammals as empirical examples of sustainable resource consumption rates. These same species may also serve as resource species for human consumption exemplified by the subsistence taking of northern fur seals. In this approach, science, monitoring and assessment are involved in 1) documenting the normal ranges of natural variation among species and ecosystems, 2) monitoring human progress in finding a position within the normal range of natural variation, and 3) observing other species and ecosystems as they respond, presumably to regain positions within normal ranges of natural variation in reaction to human change, the change over which we have some control.

Introduction

There is a voluminous accumulation of literature on management and the ways it would apply in consideration of, or application to, ecosystems (e.g., Grumbine 1994, Christensen et al. 1996, Mangel et al. 1996, Czech and Krausman 1997, Grumbine 1997, Fowler in prep.). It is clear that management must meet a number of criteria to be acceptable. In particular, any form of management adopted must successfully apply in the realm of natural resources such as management of commercial fisheries, the primary focus of this paper. The criteria which must be met by management are numerous but can be distilled into 8 essential elements, all of which must apply simultaneously (Table 1).

On the surface, it would seem impossible to find a form of management that meets the combination of these requirements by adhering to all of the underlying principles. Nevertheless, it can be done. At least one way of accomplishing this task is by using other species as empirical examples of sustainability. Consider, for example, the take ("harvest" or consumption) of biomass from either an ecosystem or a resource species. Rates of consumption by heterotrophic consumers can be used to form distributions that provide information regarding empirically observed sustainability. Action is then guided by the information (Criterion 5, Table 1) found in such frequency distributions each of which exhibits natural variation and limits.

Table 1. A list of criteria that must be met by any form of management that applies to the management of human use of natural resources (see, e.g., Grumbine 1994, Christensen et al. 1996, Mangel et al. 1996, Czech and Krausman 1997, Grumbine 1997, Fowler in prep.).

- 1) Any form of management must apply simultaneously at the various levels of biological organization, and it must do so consistently, without conflict. In other words, management applied in the management of the harvest of biomass from individual resource species must be compatible with the harvest of biomass from the ecosystems in which the harvested species occur. Similarly, biomass consumption by humans from the biosphere must be guided by principles that are not in conflict with those guiding the harvest of biomass from either an individual resource species or any particular ecosystem.
- 2) Management action must be based on a process that accounts for reality in its complexity over the various scales of time, space, and biological organization. The context of environmental factors must be accounted for along with the elements of stochasticity and the diversity of processes, mechanics, and dynamics. It must be possible to consider the complexity of organizational structure, elements, compounds, organs, chemicals, and physical and chemical processes. Furthermore, we must be able to consider uncertainty and the unknowns within the complexity of things. Some of these are truly unknowable, but there must be a way for them to be taken into account.
- 3) A core principle of management is that of maintaining individuals, species, and ecosystems within their respective normal ranges of natural variation as components of the more aggregated levels of biological organization (Rapport et al. 1981, Rapport, Regier, and Hutchinson 1985, Christensen et al. 1996, Holling and Meffe 1996, Mangel et al. 1996). Any form of management must apply this principle.
- 4) Management must be risk-averse in exercising precaution to achieve sustainability. Sustainability is, by definition, not achieved by any form of management that generates risk rather than minimizing it.
- 5) Guidance must be available to management in the form of information that provides goals and objectives. This information must be based on interdisciplinary approaches in the sense of meeting Criterion 2 above.
- 6) Management must include monitoring, assessment, and objectives, not only to produce the information that is used for guidance (Criterion 5), but also for evaluation of progress in achieving established goals and objectives.
- 7) It must be recognized that control over other species and ecosystems is impossible (Christensen et al. 1996, Holling and Meffe 1996, Mangel et al. 1996). The only option for control is the control of human action. We can control fishing effort but not the resource population. We can influence the resource population, but not control it or the indirect changes brought about by our influence. The guidance that we need for management is guidance regarding the level of influence (e.g., harvest rate) that meets the other criteria of this list.
- 8) Humans must be allowed to be components of at least some ecosystems to avoid unrealistically precluding human existence.

All heterotrophic species, including humans, consume biomass. This consumption influences other species and ecosystems. Management actions, in the approach described here, would ensure that human presence (Criterion 8, Table 1) and influence in living systems would fall within the normal ranges of natural variation (Criterion 3). More specifically, the goals and objectives (Criteria 5 and 6) would be provided by the central tendencies of frequency distributions of consumption rates among other species. This is management guided by using other species as empirical examples of sustainability and is concerned with controlling human influence (Criterion 7) rather than controlling population levels of resource species or the composition of the ecosystems.

Examples of the ways this approach works are presented below in more detail. Preliminary elements of the application of this process are presented for application at two levels of biological organization: the ecosystem and single species.

Ecosystem Application

This section treats one part of the first criterion of Table 1: application of management at the level of the ecosystem. Management at any level must be able to address a number of important questions. With an ecosystem in mind, one important question is: "What is the most sustainable level of biomass consumption from this ecosystem?" Figure 1 shows the frequency distribution for one set of estimated rates of consumption for a set of individual species from a single ecosystem. This distribution is for 24 species of marine mammals and birds that consume from the Georges Bank ecosystem according to their rates of consumption (measured as the \log_{10} of biomass consumed in thousands of metric tons annually). These species thus serve as examples of sustainability, only a small part of which is their role as competitors with humans and other species.

In concept, the application of information such as shown in Figure 1 is simple. Using non-human species

as examples of sustainability becomes a matter of confining human consumption (commercial harvest) of biomass to catch rates within the bounds of the range shown in Figure 1 (Criteria 3 and 7, Table 1). To be risk-averse and precautionary (Criterion 4, Table 1), commercial harvests would be conducted at levels near the central tendencies of such distributions. This would avoid the risks and constraints posed by the overall system (including ecosystem) to prevent the accumulation of species in the tails of such distributions.

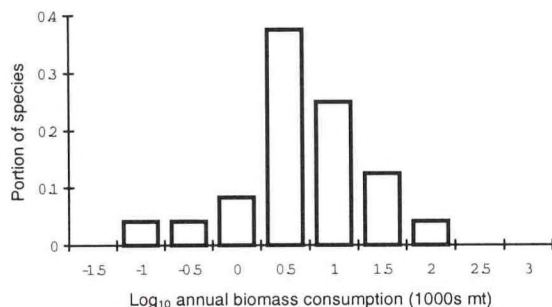


Figure 1. A species frequency distribution representing the Georges Bank ecosystem, showing variability among 24 species of marine mammals and birds as distributed according to estimated annual biomass consumption (log thousands of metric tons) within this region (from Backus and Bourne 1986). Each bar represents the fraction of the 24 species found in the category corresponding to the labeled rate of resource consumption.

Maximizing sustainability is largely a matter of minimizing risk. The “harvest rates” near the central tendencies (such as the mode of distributions like those shown in Fig. 1) are given greater emphasis in being represented by more numerous examples of sustainability (a kind of statistical weighting) than are the examples in the tails of the distributions. These central tendencies provide specific measures that define goals or objectives for management (Criteria 5 and 6, Table 1). Long time scales are accounted for (Criterion 2, Table 1) by virtue of the evolutionary dynamics behind the development of characteristics that contribute to the occurrence of such rates. Thus, frequency distributions among species account for the collective risks on various temporal and spatial scales (Criterion 2, Table 1). These risks include the dynamics of selective extinction and speciation (Lewontin 1970, Slatkin 1981, Arnold and Fristrup 1982, Fowler and MacMahon 1982, Levinton 1988, Eldredge 1989, Williams 1992, Fowler in prep), with extinction as one of the risks that prevent the accumulation of species in the tails of such distributions.

In practice, however, there are a number of factors

to take into account that complicate application of management based on empirical examples of sustainability. For example, the specific data in Figure 1 may be subject to bias. We would want to account for any recent human influence through the effects of commercial fishing in the Georges Bank ecosystem. This influence may have altered the frequency distribution shown in Figure 1 to result in broader ranges of variation, shifted position of the mean, or an altered shape compared to what would be expected under circumstances wherein human influence would be within the normal ranges of natural variation.

Other factors also come into play. For example, at this point it is not known how stable a distribution like that of Figure 1 is over time. To be better prepared to apply the proposed approach, it is important to have a frequency distribution that provides averages to account for temporal variation. Ideally, we would emphasize mean consumption rates for species that have been part of the ecosystem over evolutionary time scales (e.g., evolved as part of the ecosystem) and place less importance on species that are recent arrivals to the system (e.g., translocated species). Finally, distributions such as that of Figure 1 are subject to variation owing to the procedures used to estimate consumption rates. Other factors will be treated below.

Single-species Application

A second part of the first criterion in Table 1 requires that any form of management adopted must also apply at the single-species level. In an example parallel to that above for ecosystems, it must apply to the harvest of any single species used for human consumption. Here, we must be able to address a different set of important questions. Among them is: “What is the most sustainable level of biomass consumption from the species being considered as a resource?” We must proceed beyond the conventional treatment of this question to find answers that consider more than population dynamics. We must be able to claim to have met Criterion 2 (Table 1), including consideration of evolutionary dynamics and genetic effects of harvesting (see Law et al. 1993, and the references therein plus: Policansky 1993, Rijnsdorp 1993).

Figure 2 depicts frequency distributions showing variability for estimated total annual consumption among consumers from four individual resource species. Each distribution represents a variety of marine mammals, birds, and fishes as consumers of biomass from each one of the resource species. Each consumer species is represented in one of the bars according to its estimated level of consumption. If we knew the total standing stock biomass of each resource species, these consumption rates could be expressed as a portion of the stand-

ing stock biomass (or its log conversion). This would be a specific or relative rate compared to the crude rates of both Figs. 1 and 2.

Adhering to the principles of management behind the criteria of Table 1 is the same as it was for ecosystems. The concept is simply a matter of confining human consumption of biomass (i.e., commercial harvest of biomass) to rates within the normal range of variation shown for each species of those shown in Figure 2 that we choose to use as a resource. Risk-averse and precautionary measures would be accomplished by regulating commercial harvests (biomass consumption) from each resource species so that these harvests would fall near the central tendencies of such distributions. This avoids the risks that prevent species from accumulating in the tails of such distributions. Long-term optimal sustainability, which can be referred to as ecologically sustainable yield (ESY for the yield, ESYR for the rate), would be achieved in takes corresponding to the central tendencies of such distributions. As with ecosystems, temporal scales much longer than currently considered are accounted for through the evolutionary dynamics that influence the development of characteristic rates of consumption especially those represented by the most numerous examples of empirically observed sustainability.

In parallel with the ecosystem example above, there are factors that must be considered in regard to their influence on these sets of data. The potential biases of the data in Figure 2 may again include human influence. These should be accounted for to avoid misleading advice derived from any abnormal variation, modified mean, or other unnatural shape of the probability distributions represented by Figure 2. Changes in such distributions over time, as well as their differences among various types of resource species are factors to take into account. Patterns related to features such as life history strategy, environmental conditions, body size, or metabolic rates would be of importance.

Thus, in both the ecosystem application, and the single-species application, it is important to avoid any of several ways of misinterpreting such data. For example, homeothermic species similar in body size to humans are likely to be better examples of sustainability for our species than heterotherms with a body mass of 1 gram. We must account for any correlation between consumption rates and characteristics such as body size or metabolic rate to best find representative examples of sustainability applicable to humans. Further studies will be necessary to determine if there are subsets of data that better represent the normal ranges of natural

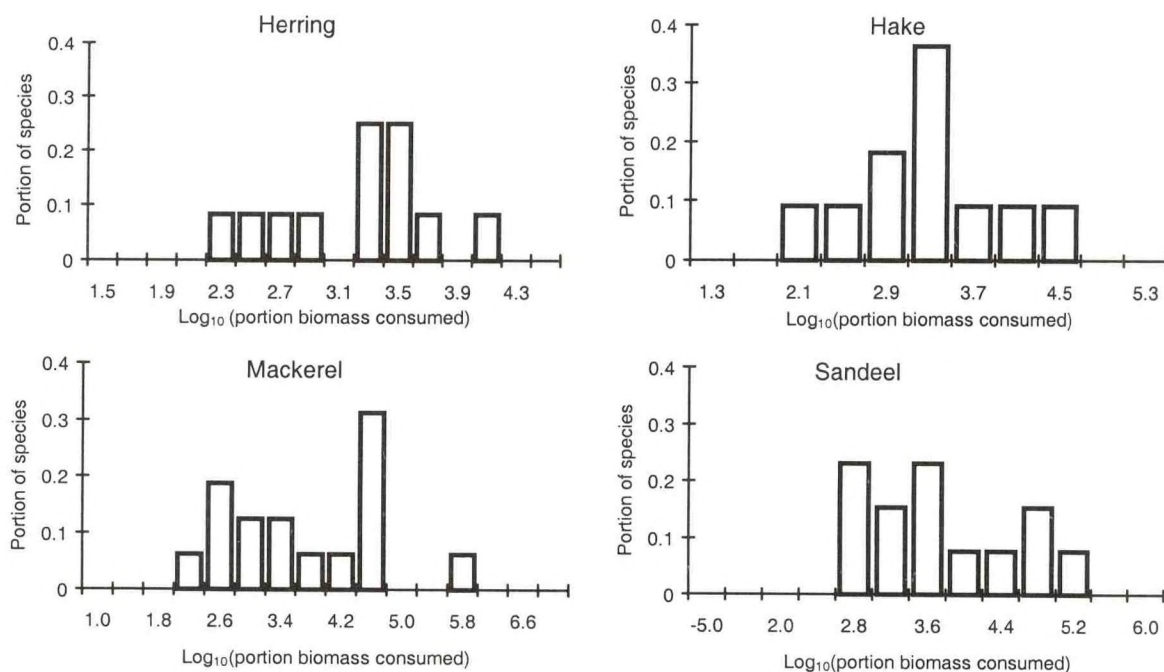


Figure 2. -The frequency distribution of non-human vertebrate species that consume hake (*Merluccius bilinearis*), herring (*Clupea harengus*), mackerel (*Scomber scombrus*), and sandeel (*Ammodytes americanus*) measured as the log of the total biomass consumed in an area (ecosystem) of the northwest Atlantic Ocean (Overholtz et al. 1991, Murawski and Overholtz pers. comm.). Each bar represents the fraction of the respective group of consuming species found in the category corresponding to the labeled rate of resource consumption.

variation for species with such human characteristics. On these grounds, fish, for example, might not serve as examples that are as good as small cetaceans with a body size and metabolic rate similar to that of humans.

Consistency

The examples above show that part of the first criterion of Table 1 can be met by using other species as empirical examples of sustainability to guide management. This approach to management applies at various levels of biological organization, but there is another part to this criterion. Management must apply to the variety of biological systems without conflict; there must be internal consistency. We can not give managers advice at the single species level followed by opposing advice at the ecosystem level.

One form of internal consistency is so obvious as to be nearly trivial. Empirical examples of sustainability are found in systems that are internally consistent. For example, two species cannot consume the same biomass in the examples used above.

But there is a form of consistency that scientists and managers must bring to the process. We must produce and use frequency distributions for both individual resource species and ecosystems. In the example chosen for this paper, the total of biomass harvested from a variety of fish species can not exceed the total established for the marine ecosystem in which they occur. It is important to use frequency distributions such as those in Figures 1 and 2 simultaneously. In other words, it is important to manage at both the single-species and ecosystem levels at the same time.

To fully account for complexity, however, other species frequency distributions must be taken into account (Fowler, in prep.). The number of species consumed was introduced in combining the examples above. There are frequency distributions for counts of the numbers of species consumed by consumers, although it is beyond the scope of this paper to consider this issue in detail. Nevertheless, such distributions would also be considered as information for use in management as being developed here. The number of species consumed would be restricted to within the normal range of natural variation for such counts.

The Management of Fishing Effort

The management of fisheries depends on having a basis for controlling either fishing effort or total takes (Criterion 7, Table 1). Maximum takes established in the use of data such as shown in Figure 1 is straightforward, even though it predictably will be unpopular.

One difficulty will emerge in attempts to avoid the central tendencies of distributions as shown in Figure 1. It might be argued, for example, that a fishing effort resulting in a harvest just below the upper 95% confidence limits of the relevant frequency distributions would be sufficient. This would help avoid the economic impact of changes necessary to achieve harvest reduced even further to correspond to the central tendencies of frequency distributions. However, it must be kept in mind that this is equivalent to arguing for a harvest level that we are 90% sure is larger than optimal, based on the empirical examples of sustainability.

This introduces the issue of burden of proof. In a strict reversal of the burden of proof (Mangel et al., 1996, Dayton, 1998), we would be required to prove that sustainability is maximized for harvest levels other than those corresponding to the central tendencies of frequency distributions such as those of Figure 1 (after being assured that they are applicable to species like humans and corrected for existing human influence, temporal dynamics, using species otherwise similar to humans, etc.).

Dealing with relative harvest rates leads to similar considerations in the application of information at the single-species level (Fig. 2). When we are dealing with relative or specific harvest rates, the conversion of information such as shown in Figure 2 can be converted to fishing effort if we have an established relationship between F (mortality rate caused by fishing) and measures of effort (e.g., boat-days fished). Effort allowed in management would then be based on fishing mortality (or biomass harvest) rates (F) derived from the ESYRs calculated as outlined above. The procedural (e.g., statistical) aspects of these conversions would be subject to the same kinds of scrutiny and scientific study as provided in today's management operations. The difference would be that the choice of F values would not be based on models that we recognize as falling short of representing the reality of the systems in which the empirical examples of sustainability occur.

Meeting other Criteria for Management

We can now see that management based on using other species as empirical examples of sustainability clearly meets a number of the criteria presented in Table 1. When addressing biomass consumption, it applies to individual species (including age groups within a species) and ecosystems (Criterion 1). At the core of this approach is maintaining elements of ecosystems within their normal range of natural variation (Criterion 3) by considering biomass consumption an option for humans (i.e., commercial fishing) within ecosystems (Criterion 8) and exercising constraint (control) where it is an option (Criterion 7). Maintaining ecosystems

within their normal range of natural variation is beyond direct human control. It may be promoted or facilitated, however, through human action to control human influence. Guidance for this control is found in the normal ranges of natural variation of distributions like Figures 1 and 2. Controlling human influence will allow the other species and ecosystems to exhibit homeostatic dynamics. Precaution can be exercised in avoiding the risks and constraints that prevent the accumulation of species in the tails of species frequency distributions while simultaneously achieving sustainability (Criterion 4). This approach uses the information (Criterion 5) derived from species frequency distributions.

We are left with several elements of Table 1, however, that have not been mentioned. These are considered in the remainder of this section, again restricting the treatment to the example of managing the rates of biomass harvests (consumption) by humans.

It is easy to see how the approach would be applied to "management at the biosphere level," a form of management that would be the next issue of importance after developing an approach that works at the ecosystem level. To do so, the total biomass consumption for other species (with similar body size, metabolic rate, trophic level and other characteristics similar to those of humans) would be estimated based on their total population size. The resulting species frequency distribution would be used in parallel with the process laid out above for ecosystems and single species. We would then have to deal with the total for consumption of biomass by humans from the various ecosystems from which harvests are extracted. This total would be constrained to the central tendency for the totals for other species. This clearly leads to serious implications for our species as laid out in Fowler (in prep.), and is well beyond the scope of this paper.

How does the approach account for reality and its complexity (Criterion 2, Table 1) to involve interdisciplinary considerations (Criterion 5)? The species found in the various frequency distributions are exposed to, and emerge from, the complexity of factors that result in the distributions. This reality includes the entire set of ecological mechanics involved in such things as predator/prey interactions, competition, and geographic distribution. The genetic information (Criterion 5) in its contribution to what species are, and where they fall in species frequency distributions, is taken into account as are all of the evolutionary dynamics that resulted in their evolution. Both the evolutionary dynamics experienced by species and the evolutionary field supplied by their environment (the set of selective forces to which they are exposed, including those from interspecific interactions) are accounted for as part of the elements contributing to the formation of frequency distributions among

species. Species frequency distributions are analogous to the probability distributions that emerge from Bayesian statistical analysis (Fowler et al., in prep.), except that the Monte Carlo-like models are real physical models (instead of computer models) and the code is genetic (rather than computer code).

Thus, the challenge of having an interdisciplinary contribution to decision-making is partially solved. The complexity of reality, each piece of which the respective science takes as a focus for study, is already accounted for. The impossibility of knowing the relative importance of the results of any particular field of science is no longer a problem. However, we can not over-emphasize the importance of the contributions of each field of science in producing the information for species frequency distributions and their correlative inter-relationships. Here, interdisciplinary contributions are invaluable (Criteria 5 and 6, Table 1). The same holds for the importance of monitoring the systems that we influence with our harvest strategies (species, ecosystems, etc. from which we consume biomass) to observe whether or not they achieve their own states within the respective normal ranges of natural variation (Criterion 6).

Nature's Monte Carlo Experiments in Sustainability

In part (and only in part) frequency distributions such as those shown here are the results of trial-and-error processes of natural selection. Part of natural selection is that of selective extinction and speciation (Lewontin 1970, Slatkin 1981, Arnold and Fristrup 1982, Fowler and MacMahon 1982, Levinton 1988, Eldredge 1989, Williams 1992, Fowler in prep). Species emerge as examples of sustainability through the trial-and-error process of natural selection in being exposed to the variety of factors that we wish to take into account (Criterion 2, Table 1). Species frequency distributions emerge because the species in them are exposed to reality including the ecological mechanics of interactions among species (e.g., predator-prey relationships, and competition) that we recognize as important elements of ecosystems. By using the guidance of empirical examples of sustainability, we would account for ecosystems themselves.

Thus, as mentioned above, species, which are made up of individuals, are like physical Monte Carlo trial-and-error models to result in a form of Bayesian integration in the frequency distributions. They are tested in the face of the suite of risks and complexities of their environment. The effects of these factors are integrated into the information content of species frequency distributions. Even extinction and related risks are taken into account. Existing species, serving as empirical examples of sustainability (rates of foraging that are sustainable

in the examples used in this paper), and represented in frequency distributions, have not succumbed to the risks leading to extinction as a process that has removed billions of species as failures in the grand Monte Carlo experiment. Collective risks prevent the accumulation of species in the tails of species frequency distributions and especially beyond the normal ranges of natural variation.

Conclusions

It has been argued above that non-human species serve as examples of sustainability, using rates of foraging from ecosystems and individual resource species as examples. We humans are not in a position to claim that we are our own example (e.g., by using cases where fishing has been carried out for decades at rates beyond the limits of species frequency distributions such as shown in Figs. 1 and 2). Even the species in the tails of these distributions cannot be viewed as particularly good examples. Decades of fishing cannot weigh against hundreds of thousands of years of evolutionary history. Part of the variance in the frequency distributions observed today stems from short-term ecological mechanical variation (and observational variance). Such information would be better if averaged (integrated) over longer periods of time. Emerging patterns among systems compared across varying environmental factors (latitude, mean temperature, etc.) will be of similar value. Science is faced with an immense challenge in providing such information.

A further challenge is that of research to elucidate the correlative information relating biomass consumption to trophic level, body size, metabolic rate and other species-level features. Such patterns will be very important in refining the nature of the frequency distributions and their information content as the source of guidance for management as developed in this paper.

The information in hand is preliminary. An interdisciplinary effort is required to proceed.

However, there is basis for proceeding. The form of management outlined above meets all of the 8 criteria laid out in Table 1. The management of biomass consumption (specifically the harvest of fish) is only one example of the application of the approach (Fowler in prep.).

Finally, the acceptance and implementation of this approach may be even more of a challenge than the scientific endeavor needed to produce more reliable information. Considerable institutional, social, economic, political, and behavioral changes are involved. The degree to which they are a challenge, however, is more a measure of the size of problems that we have to solve

than justification for avoiding the work required.

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The Role of Science in Applying the Precautionary Approach to the Magnuson-Stevens Fishery Conservation and Management Act

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Science underpins the precautionary approach which in essence is comprised of management protocols for making conservative decisions in the face of scientific uncertainty. The principal role for science is the accurate and complete display of uncertainty using pre-defined terms and protocols that couple scientific uncertainty and management actions to be undertaken by the agency. Science provides the information that triggers management actions. Management defines what those triggers are and makes the policy decisions on the levels of risk taken by the triggers. In reality, however, the development and selection of the triggers and the associated risk must be done collaboratively but with management bearing the burden of ultimate choice. To many, implementation of the precautionary approach is inherently at odds with training in the scientific method which prescribes the testing of a null (or no effect) hypothesis. In essence, one is trained to prove an effect. On the other hand, the precautionary approach presumes effects from controllable human actions and requires proof that those actions are safe. Furthermore, it requires proof of effects beyond human control. The standards of proof are set by the cost of a negative outcome. A collaborative effort between science and management is needed to assign the appropriate cost.

A Review of Biological Reference Points in the Context of the Precautionary Approach

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Abstract. Draft guidelines for National Standards under the Magnuson-Stevens Act state that Councils should adopt a precautionary approach to specification of Optimum Yield (OY), and list three features which characterize this approach: 1.) target reference points such as OY should be set safely below limit reference points (such as the Maximum Sustainable Yield, MSY); 2.) stocks at sizes below the level that produces MSY should be harvested at lower rates than stocks at sizes above the level that produces MSY; 3.) as uncertainty about stock status or productive capacity increases, target catch levels should be more cautious. The guidelines indicate limit reference points which include a maximum fishing mortality rate which produces MSY and minimum stock size thresholds from which a stock could be rebuilt to MSY within ten years. Reference points can be direct estimates or proxies for direct estimates, depending on adequacy of available data. In this paper, we review desirable properties of directly-estimated and potential proxy biological reference points, in the contexts of the National Standards, guidelines, approaches adopted by international management bodies, and other more generic contexts of the precautionary approach. We compare alternative candidate reference points in terms of their utility and potential performance as limit or target reference points in risk-averse management frameworks.

Introduction

The objective of this paper is to review model-based approaches to the estimation of biological reference points, review precautionary reference points as a component of the precautionary approach, and describe the relevant subset of biological reference points which are consistent with the MSY-related focus of the UN Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks (1995) and the revised Magnuson-Stevens Fisheries Conservation and Management Act (MSFCMA).

Biological Reference Points: A Brief Review

A biological reference point (BRP) in its most generic form is a metric of stock status from a biological perspective. The biological reference point often reflects the combination of several components of stock dynamics (growth, recruitment and mortality, usually including fishing mortality) into a single index. The index is usually expressed as an associated fishing mortality rate or a biomass level. The procedure for estimating the reference point and the underlying model is agreed within the scientific community.

The three most common models that underlie biological reference points have been summarized by Sissenwine and Shepherd (1987): (1) spawner-recruit, (2) dynamic pool and (3) production models. The choice of model is predicated on life history and availability of catch, relative abundance, stock-recruitment, and age-specific mortality, growth, and maturity data (Table 1).

Spawner-Recruit Reference Points (Semelparous Populations)

Ricker (1975) describes multiple features of the spawner-recruit relationship which may serve as biological reference points for semelparous populations such as Pacific salmon. In these models, spawners and recruits are both represented in terms of numbers. Age-structure is not incorporated, because spawners are assumed to spawn once and then die; and because recruits produced by spawners are all assumed to return to spawn at the same time. The underlying dynamic mechanism is density-dependent compensation in the stock-recruitment relationship, which results in an increased production of recruits per capita at lower spawner abundances and reduced per capita production at high stock sizes. This may arise when the survival of eggs and/or larvae is affected by density-dependent competition for food or space, compensatory predation, or cannibalism of young by adults (Ricker, 1975). Those reference points are derived from continuous spawner-recruit functions and include spawners needed for maximum recruitment (P_m in Ricker's notation), the replacement spawner abundance at which recruitment equals parent stock (P_r); spawners needed for maximum sustainable yield (MSY)(P_s) and rate of exploitation at MSY (u_s).

Dynamic Pool (Per-Recruit) Reference Points

Dynamic pool models were initially described by Thompson and Bell (1934) and Beverton and Holt (1957). These models serve as the basis for biological

Table 1. Summary of principal models that underlie biological reference points, and associated specification of age-structured and stock-recruitment data.

Age structure in population	S-R data required	S-R function required	Model type	Example citation	Reference points	Comments
Unknown	No	No	Surplus production	Schaefer, 1957 Prager, 1993	F_{MSY} , B_{MSY}	Very risk-prone without auxiliary data on recent relative recruitment
No (semelparous)	Yes	Yes	Spawner-recruit	Ricker, 1975	P_s , u_s	
Yes (iteroparous)	No	No	Dynamic pool, Y/R	Thompson and Bell, 1934	F_{max} , $F_{0.1}$	No information about reproductive dynamics
	By analogy	By analogy	Dynamic pool, SSB/R		$F_{20\%SPR}$, $F_{35\%SPR}$	No stock-recruitment relationship, except by analogy
	Yes	No	Dynamic pool, SSB/R	Shepherd, 1982	F_{med}	
	Yes	Yes	Dynamic pool, SSB/R	Mace, 1994	F_ϵ	
	Yes	Yes	Production	Sissenwine and Shepherd, 1987	F_{MSY} , B_{MSY}	

reference points on a cohort or year class basis, standardized to the number recruited to the cohort, and so are also referred to as yield-per-recruit, egg-per-recruit and spawning-stock-biomass-per-recruit models. Age structure is incorporated in terms of age-specific schedules of mortality, growth, and sexual maturity. Age-specific fishing mortality rates reflect the effects of a fishery selection (or exploitation) pattern, in which the vulnerability of a cohort changes as it ages. This could reflect changing patterns in availability to the fishery or vulnerability to the gear. “Knife-edge” exploitation patterns are approximations that assume that below the age at first capture, fishing mortality = 0, but at or above the age at first capture, the cohort is fully vulnerable to the same rate of fishing mortality. Age-specific schedules of weights in the spawning stock or weights in the catches (as landings or discards) are specified, as are age-specific maturity rates. The models enable an evaluation of the effects of alternative exploitation patterns and fully-recruited fishing mortality rates on the amount of yield or spawning stock biomass per recruit, over the lifetime of the cohort, independent of the initial size of the cohort at recruitment. The models do not usually incorporate density-dependent compensation: the same age-specific mortality, maturity, and growth schedules are assumed to apply regardless of year class size initially or at subsequent ages. The models do not incorporate density-independent effects: the age-specific rates are assumed to apply regardless of any changing environmental conditions, fishery behavior, predation levels, or prey availability over the life of the cohort. The schedules must be obtained over the entire lifespan of the cohort in order for the calculated yield per recruit or spawning stock biomass per recruit to be realized. In the case of spawning-stock-biomass-per-recruit analyses, all kilograms of spawning stock biomass are assumed to be equally productive in terms of recruitment, i.e., the production of viable eggs per kilogram of spawn-

ing stock biomass is assumed to be equal regardless of age composition, size composition, and number of previous spawning seasons of spawners contributing to the spawning stock biomass. For this reason, metrics other than spawning biomass are sometimes used (e.g., egg production). Length-based estimates of yield per recruit and spawning stock biomass per recruit are possible when growth, maturity at length and length-composition data are available (e.g., Gallucci *et al.*, 1996).

Reference points derived from yield-per-recruit analyses include F_{max} , the (fully-recruited) fishing mortality rate which produces the maximum yield per recruit; and $F_{0.1}$, the fishing mortality rate corresponding to 10% of the slope of the yield-per-recruit curve at the origin (Gulland and Boerema, 1973). The $F_{0.1}$ reference point was conceptualized as a biologically precautionary target relative to F_{max} : at $F_{0.1}$, catch per unit effort is not reduced substantially, but the fishing mortality rate is lower than F_{max} . Because the yield-per-recruit analyses only reflect schedules of mortality and weight at age in the catch, both F_{max} and $F_{0.1}$ are reference points in the context of growth overfishing, not recruitment overfishing.

A wide variety of reference points have been derived from spawning-stock-biomass-per-recruit models. In isolation, spawning-stock-biomass-per-recruit analyses reflect schedules of mortality, maturity, and spawning weight at age for a cohort. Under conditions of no fishing mortality, 100% of a stock’s spawning potential is obtained. As fishing mortality rates increase, spawning stock biomass per recruit decreases, as more spawning opportunities are lost over the lifetime of the cohort. The reduction in spawning stock biomass per recruit relative to the unfished level can be reflected as a percentage of the maximum spawning potential (*MSP*), e.g., a fishing mortality rate denoted $F_{35\%MSP}$ would allow a

stock to attain only 35% of the maximum spawning potential which would have been obtained under conditions of no fishing mortality. It is thus possible to calculate spawning stock biomass per recruit as a function of fishing mortality rate, in terms of either kilograms of spawning stock biomass per number of recruits or in terms of percentage of the maximum spawning potential (the ratio of kilograms of spawning stock biomass per recruit under a specific F compared to kilograms of spawning stock biomass per recruit under no F). These give rise to reference points of the form of e.g., $F_{20\%SPR}$ or $F_{35\%SPR}$, where SPR stands for spawning (products) per recruit, and “products” are biomass, egg production, or related metrics, and $x\%$ SPR has exactly the same meaning as $x\%$ MSP.

Results of spawning-stock-biomass-per-recruit analyses can be combined with stock-recruitment data to provide reference points in the context of recruitment overfishing. If a stock-recruitment model can be fitted, then the fishing mortality rate which corresponds to the slope of the function at the origin can be estimated, F_τ (Mace and Sissenwine, 1993). This is possible because the slope of the stock-recruitment function has units of R/SSB and if this value is inverted to units of SSB/R , a corresponding fishing mortality rate can be found from the relationship between SSB/R and F as described above.

It may not be possible to fit a stock-recruitment relationship because the range of observed stock sizes is narrow, data are dominated by environmental variability, or stock or recruitment estimates are imprecise or inaccurate, for example. In that case, it still may be possible to define fishing mortality reference points based on the distribution of observed R/SSB , from a ratio of observed SSB and subsequent recruitment. Such reference points include those introduced by Shepherd (1982) and ICES (Anon., 1984), F_{low} , F_{med} , and F_{high} , corresponding to the lower 10-percentile, 50-percentile, and upper 90-percentile of the observed R/SSB ratios, respectively. These reference points represent fishing mortality rates which can be supported by observed survival rates from spawning to recruitment in 90%, 50%, and 10% of the years, respectively. The same shortcomings in the data which would prevent fitting a stock-recruitment relationship make other reference points based on different forms of the same data less reliable, however. Depending on which part of the stock size range is observed, F_{med} may be close to F at the slope at the origin, F_{msy} , or close to zero. F_{med} may also be unsustainable depending on the age structure of the stock and degree of temporal correlation in survival ratios: although high recruitment rates may balance low recruitment rates over the long term, if age structure in a stock is severely truncated, (e.g., to four age classes) there is a higher probability the stock may collapse under exploi-

tation at F_{med} (e.g., if four consecutive years of poor R/SSB were obtained). G_{loss} (Cook, 1998) is a more elaborately formulated reference point which includes uncertainty in the estimation of the stock-recruitment data and the R/SSB calculations using simulation procedures, and a smoothed trend rather than a fitted stock-recruitment relationship: the distribution of R/SSB at the lowest observed stock size is simulated, and compared with the distribution of R/SSB at the current fishing mortality rates.

Surplus Production Reference Points I

The surplus production model is among the simplest of the models used for stock assessment: it does not reflect any age structure in a population, and the dynamics of natural mortality, growth, and recruitment are aggregated into a single intrinsic rate of population biomass increase, modified by fishing mortality. Model dynamics are also affected by the size of the population with respect to its carrying capacity. Data requirements are modest: the model can be fitted based on an abundance (catch per unit effort) index and catch. Models have been formulated which do not require an equilibrium assumption (e.g., Prager, 1994). However, both observation and process errors occur (random variation in the observed abundance index and catch of the stock; and in the population dynamics of the stock, respectively). Although observation error estimators have been fairly well developed, if process error is large, then parameter estimation may be poor (Prager, 1994; Chen and Andrew, 1998). Thus, if there is a trend or cycle to natural or fishing mortality, growth, or recruitment, for example, this type of model will perform poorly or separate fits would be required for each period in the stock's history. Although surplus production models produce relatively precise estimates of MSY and f_{MSY} , absolute values of F_{MSY} and B_{MSY} are usually not precise and require good estimates of q (the parameter that scales abundance indices into biomass estimates) (Prager, 1994).

Surplus Production Reference Points II

The production model described in Sissenwine and Shepherd (1987), in contrast, is one of the more data-intensive and complex models. It requires a functional stock-recruitment relationship, a spawning-stock-biomass-per-recruit analysis, and a yield-per-recruit analysis. For any specified rate of fishing mortality, an associated value of SSB/R is defined, incorporating the assumptions detailed in the previous section on dynamic pool models. When this value of SSB/R is inverted and superimposed on the stock-recruitment function as a slope (R/SSB), the intersection of this slope with the stock-recruitment function defines an equilibrium level of recruitment. When this value of recruitment is multiplied by the yield per recruit calculated for the same

fishing mortality rate, the equilibrium yield associated with the fishing mortality rate emerges. F_{MSY} , the fishing mortality rate which maximizes the yield from the system (conditional on selection pattern, schedules of growth and maturity, accuracy of stock-recruitment function, etc. as detailed in the preceding section on dynamic pool models) can be found; and B_{MSY} , the associated stock biomass which produces that yield can also be found.

Biological Reference Points and Fishery Management Reference Points

In a management context, a biological reference point can serve as a performance standard or a landmark for a fishery management regime. Other types of performance standards are also available in the domain of economics (e.g., the fishing mortality rate which produces maximum economic yield). Some performance standards are not quantitative but only directional (e.g., some social anthropological elements such as the social stability of local fishing villages). Others are not articulated (e.g., minimum sustainable whinge, *sensu* Pope)

The biological reference point itself is not equivalent to a management regime or the management objectives. If the management objective were to maximize economic efficiency, for example, the effect of any proposed measures would presumably be evaluated in terms of economic impact. Those proposed measures would also be evaluated with respect to the impact on stock status in terms of growth overfishing, recruitment overfishing, or the sustainability of yields from the stock, however. Appropriate biological reference points would provide standards by which to judge the performance of that management regime in a biological context, even though the ultimate aim of the management regime might be to achieve some specific economic end. As noted above, F_{max} or $F_{0.1}$ are biological reference points commonly used to index growth overfishing; $F_{35\%SPR}$, F_{med} or F_{τ} have been used to index recruitment overfishing; and F_{MSY} and B_{MSY} index stock conditions which produce surplus production as maximum sustainable yield (MSY). In the context of this paper, MSY or OY are considered emergent properties of other reference points or harvest control policies.

Precautionary Reference Points

Two types of precautionary reference points, limits and targets, and their management contexts are described in Annex II of the UN Straddling Stocks Agreement (1995): *Limit reference points set boundaries which are intended to constrain harvesting within safe biological limits within which the stocks can produce maximum sustainable yield.... Fishery management strategies shall ensure that the risk of exceeding limit reference points*

is very low. If a stock falls below a limit reference point or is at risk of falling below such a reference point, conservation and management action should be initiated to facilitate stock recovery... The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points. For stocks which are not overfished, fishery management strategies shall ensure that fishing mortality does not exceed that which corresponds to maximum sustainable yield, and that the biomass does not fall below a predefined threshold.

In Annex II, Target reference points are intended to meet management objectives...Fishery management strategies shall ensure that target reference points are not exceeded on average. For overfished stocks, the biomass which would produce maximum sustainable yield can serve as a rebuilding target.

Thus, the UN Straddling Stocks Agreement defines two fishery management reference points to achieve precautionary objectives: limit reference points and target reference points. These reference points are cast entirely in terms of biological reference points related to maximum sustainable yield, B_{MSY} and F_{MSY} .

The FAO guidelines on the precautionary approach (1995a) discuss operational targets and constraints, and treat biological reference points as measurable terms to express those targets and constraints. The guidelines recognize that what is measurable will vary, depending on species and fishery. Operational targets are associated with desirable outcomes to be attained, such as particular abundance levels or fishing mortality rates. Operational constraints are associated with undesirable outcomes to be avoided, such as risk of declining recruitment. The constraint is directly comparable to the limit: "it is highly desirable... to maintain acceptable low levels of probability that the constraints are violated." Under the precautionary approach, operational targets may require adjustment to be consistent with constraints, e.g., so that target fishing mortality rates are lower than F_{MSY} . Constraints have precedence over targets: if B_{MSY} (target) were lower than the biomass where there is a high probability of reduced recruitment (constraint), then the probability of violating the constraint while meeting the target would be too large. If targets can be approached rapidly, then there may be a possibility of overshooting the target and violating the constraints, which should be avoided.

The critical reference point within the precautionary context is the limit reference point. Within Annex II, paragraph 7 states that: *The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points.* Within the revised MSFCMA, Section 3(29)

Table 2. Summary of limit, threshold and target reference points as defined by U.S. advisory documents and legislation, and international management institutions. Initial definition of limit, threshold and target reference points are by Garcia (1995).

	Rosenberg <i>et al.</i> , 1996	National SAW SC/NSG, 1998	Revised MFCMA	ICES	NAFO	NASCO	ICCAT
Term: Limit	Absolute threshold	Threshold	Limit	Limit: B_{lim} , F_{lim}	Limit: B_{lim} , F_{lim}	Conservation limit	Overfishing BRPs
Term: Threshold	Precautionary threshold	Precautionary target		Precautionary value: B_{pa} , F_{pa}	Buffer: B_{buf} , F_{buf}		
Term: Target	Target	Target	Target	Target: B_{target} , F_{target}	Target: B_{tr} , F_{tr}	Management target	
BRP: F Limit	F where $E(R)=0.5$ $E(R_{max})$	$F =$ $\text{Min}(F_{MSY}, \text{ or } \text{proxies } F_{\%SPR}, F_{0.1}, F=M)=$ MFMT	F_{MSY}	$F_{lim}=F_{crash}, F_{loss}$ or F_{med} (left limb)	$F_{lim}=F_{MSY}, F_{max}, F_{med}$ or $F_{30\%SPR}$	Escapement producing B_{MSY}	$F = F_{MSY}, F_{0.1}$ or F_{max}
BRP: F Threshold		$F = 0.75$ MFMT		$F_{pa} = F_{lim} e^{-2s}$ or F_{lpg} or F_{med}	$F_{buf} = F_{lim} e^{-2s}$, M , or $F_{MSY}/2$		
BRP: F Target		$F_{OY} < F_{MSY}$	$F_{OY} < F_{MSY}$				
BRP: SSB Limit	SSB where $E(R)=0.5$ $E(R_{max})$	$B =$ $\text{Max}(B_{MSY}/2,$ $B \text{ to } B_{MSY} \text{ in } 10 \text{ years}) =$ MSST	B_{MSY} (for rebuilding)	$B_{lim} = B_{loss}$ or MBAL	$B_{lim} = B_{loss},$ MBAL, or $0.2 * B_{max}$ (survey)	Escapement producing B_{MSY}	$B = B_{MSY}$
BRP: SSB Threshold				$B_{pa} = B_{loss}$ or $B_{lim} e^{-2s}$	$B_{buf} = B_{lim} e^{-2s},$ $2/3 B_{MSY},$ or $0.5 * B_{max}$ (survey)		
BRP: SSB Target		B_{OY}	B_{OY}		B_{MSY}		

states that : *The terms ‘overfishing’ and ‘overfished’ mean a rate or level of fishing mortality that jeopardizes the capacity of a fishery to produce the maximum sustainable yield on a continuing basis.* There thus is indirect correspondence between limit reference points recommended under the UN Straddling Stocks Agreement and overfishing definitions under the revised MSFCMA: in both cases, F_{MSY} represents an upper bound to fishing mortality rates. Similarly, there is correspondence between target reference points intended to meet management objectives under the Straddling Stocks Agreement and OY under the revised MSFCMA.

Garcia (1995) distinguishes among limit, target, and threshold reference points in the precautionary context: limit points should never be reached, and if they were to be reached, severe and corrective management actions

should be implemented. He indicates that limits should be minimum rebuilding targets to be reached before any rebuilding measures are relaxed. The threshold reference point is defined as an “early warning” reference point, to reduce the probability that a target or limit point would be exceeded due to estimation or observation uncertainty or due to slow management reaction. Thresholds are advisable when there is an especially high probability of a negative outcome when the limit is crossed, e.g., in a highly variable environment, when species are at the edge of their geographic range or are relatively unresilient; or other circumstances when the cost of exceeding the limit is high (Garcia, 1995).

A relatively wide variety of precautionary reference points has been proposed by various different national and international working groups and fishery manage-

ment organizations. While biological reference points are based on scientifically agreed models, precautionary reference points reflect individual organizations' interpretations and implementations of precautionary management. Using Garcia's distinctions between limit, threshold, and target reference points as a basis for organization, we summarize a range of precautionary reference points currently or recently under consideration by various working and management groups (Table 2). Additional information on different organizations' applications of the precautionary approach is summarized in Mace and Gabriel, this volume. It is important to note that in the U. S. National Standard Guidelines, Technical Guidance on the Use of Precautionary Approaches to Implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act (Restrepo *et al.*, 1998), and Scientific Review of Definitions of Overfishing in U.S. Fishery Management Plans (Rosenberg *et al.*, 1994), the use of the term "threshold" corresponds to the "limit" reference point as defined in FAO guidelines rather than to the "early warning" reference point indicated by Garcia (1995).

Precautionary Management: Harvest Control Rules, Uncertainty and Precautionary Reference Points

The FAO Code of Conduct for Responsible Fisheries (FAO 1995b) summarizes the relationship between precautionary reference points and harvest control rules: *When precautionary or limit reference points are approached, measures should be taken to ensure that they will not be exceeded. These measures should where possible be pre-negotiated. If such reference points are exceeded, recovery plans should be implemented immediately to restore the stocks.* The biological reference points which serve as limits, thresholds, or targets are triggers for management actions or are parameters in harvest control rules. The harvest control rule is a pre-agreed course of management action as a function of stock status and other economic or environmental conditions. A recovery plan may be considered a specialized control rule which applies when the stock is outside safe biological limits. Harvest control rules (including their component biological reference points) should be developed in the management planning stage with the involvement of all stakeholders, and then evaluated for robustness to uncertainties in statistical estimates of stock status, environmental conditions, harvester behavior, and managers' ability to change harvest levels (FAO, 1995b). If harvest control rules are based on large amounts of uncertainty in terms of model, observation, process, or implementation errors (including estimation of reference points), then the formulation of the control rule should be more precautionary. If, on the other hand, inputs to harvest control rules are based on little uncertainty and/or if resulting controls more stringent, then a less precautionary formulation of the control rule should be successful.

In a different approach to the development of harvest control rules, the management community could specify performance criteria for harvest rules (including robustness) at the outset, and then alternative harvest control rules would be developed which meet those performance criteria. This different approach is implemented in the International Whaling Commission's revised management procedure, and focusses pre-agreement on the performance criteria rather than on any particular control rule or component reference points.

The need for simultaneous consideration of reference points and actions to be taken if they are exceeded is made in both the FAO Code of Conduct for Responsible Fisheries (1995b) and Article 6 of the United Nations agreement relating to the conservation and management of straddling fish stocks and highly migratory fish stocks (1995). In the FAO Code of Conduct,

7.5.2 *In implementing the precautionary approach, States should take into account, inter alia, uncertainties relating to the size and productivity of the stocks, reference points, stock condition in relation to such reference points, levels and distribution of fishing mortality and the impact of fishing activities, including discards, on non-target and associated or dependent species as well as environmental and socio-economic conditions.*

7.5.3 *States and subregional or regional fisheries management organizations and arrangements should, on the basis of the best scientific evidence available, inter alia, determine:*

- a. *stock specific target reference points, and, at the same time, the action to be taken if they are exceeded; and*
- b. *stock specific limit reference points, and, at the same time, the action to be taken if they are exceeded; when a limit reference point is approached, measures should be taken to ensure that it will not be exceeded.*

In Article 6 of the Straddling Stocks Agreement (1995):

3. *In implementing the precautionary approach, States shall:*
 - (a) *improve decision-making for fishery resource conservation and management by obtaining and sharing the best scientific information available and implementing techniques for dealing with risk and uncertainty;*
 - (b) *apply the guidelines set out in Annex II and determine, on the basis of the best scientific*

information available, stock-specific reference points and the action to be taken if they are exceeded;

- (c) take into account, inter alia, uncertainties relating to the size and productivity of the stocks, reference points, stock condition in relation to such reference points, levels and distribution of fishing mortality and the impact of fishing activities on non-target and associated and socio-economic conditions...

4. States shall take measures to ensure that, when reference points are approached, they will not be exceeded. In the event that they are exceeded, States shall, without delay, take the action determined under paragraph (3) to restore the stocks.

Implementation of the precautionary approach requires consideration of uncertainty in stock size and productivity. Unless stock sizes are known with perfect certainty, the estimation of uncertainty associated with a reference point is only part of the precautionary process, and the uncertainty associated with the current estimate of stock size or stock status is a critical part of the evaluation. The probability that the currently observed fishing mortality rate, for example, exceeds the limit reference point then would become conditional on the estimate of the limit reference point (e.g., Conser and Gabriel, 1992).

The harvest control rule has two components: the specification of the reference points (and other relevant parameters), and a functional form relating current stock status and reference points to management reaction (e.g., catch). The two components act together to determine the degree of precaution afforded by the rule. Rosenberg and Restrepo (1996) discuss the interaction among the acceptable probability of overfishing, the consequences of exceeding limit reference points, and the action to be taken when the stock is overfished. For example, an acceptable probability of overfishing could be higher if the action to be taken when the limit is exceeded is immediate and drastic. An acceptable probability of overfishing could be higher if stock conditions were exceptionally favorable, or if the result is simply that the probability of poor recruitment increases slightly in only one year, rather than resulting in a significant increase in the probability of repeated recruitment failure.

Parameterizing Limit Control Rules under National Standard Guidelines

As noted previously, within the precautionary context, the limit reference point is the critical reference point. Both the UN Straddling Stocks Agreement and the revised MSFCMA focus on *MSY*-related reference

points as limits. This constrains the range of relevant biological reference points to a subset of those described earlier.

A default limit control rule is outlined in the Technical Guidance on the Use of Precautionary Approaches to Implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act, which defines limits to fishing mortality rate as a function of stock biomass (Restrepo *et al.*, 1998). The rule is based on three parameters, F_{MSY} , B_{MSY} and c , a factor which reflects the expectation that a stock fished at F_{MSY} would naturally fluctuate around B_{MSY} :

$$F(B) = \frac{F_{MSY} B}{c B_{MSY}} \quad \text{for all } B \leq c B_{MSY}$$

$$F(B) = F_{MSY} \quad \text{for all } B > c B_{MSY}$$

The extent of that fluctuation is likely related to the natural mortality rate, and so c is defined as the maximum of $(1-M, 1/2)$. The fishing mortality rate cannot exceed F_{MSY} , regardless of stock size, and must be reduced below F_{MSY} to zero as biomass declines below cB_{MSY} to zero. A minimum stock size threshold (MSST) is also specified: in no case should MSST be less than half the level which produces *MSY* (i.e., $MSST > 1/2 B_{MSY}$), and MSST may be approximated as cB_{MSY} . The rule provides an approximate estimate of the maximum fishing mortality rate (MFMT).

The NMFS National Standard Guidelines for Standard 1 define *MSY* as "the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological and environmental conditions" with *MSY* stock size defined as "the long-term average size of the stock or stock complex, measured in terms of spawning biomass or other appropriate units, that would be achieved under an *MSY* control rule in which fishing mortality rate is constant." The *MSY* control rule is defined as "a harvest strategy which, if implemented, would be expected to result in a long-term average catch approximating *MSY*." In this context, the *MSY* stock size would be reflected by the biological reference point B_{MSY} , and the *MSY* fishing mortality rate would correspond to the biological reference point F_{MSY} .

Situations Requiring the Use of Proxies for F_{MSY} and B_{MSY}

The MSFCMA allows for the use of proxies in situations where there is insufficient knowledge to implement approaches outlined above. In general, proxies would be needed when *MSY*-related parameters cannot be estimated at all from available data, or when their estimated values are deemed to be unreliable for various reasons (e.g., extremely low precision, insufficient

contrast in the data, or inadequate models). We refer to these situations as “data-poor” and “data-moderate”, respectively. However, it should also be noted that there may also be circumstances under which proxies would also be useful in “data-rich” situations (e.g., when they are believed to be more robust or reliable than the estimates of MSY -related parameters). Thus, our use of the term “data-moderate” can be more generally interpreted as meaning “information-moderate”.

In this report, proxies are substitutes for key biological reference points, which are used in place of those key reference points because they are easier to calculate, or require fewer data, or are more robust. MSY -based reference points are often difficult to estimate, particularly when the calculations involve estimation of the parameters of a stock-recruitment relationship. However, MSY has been the central focus of management objectives for several decades in many national and international agreements, and many proxies have been developed and applied. In addition, empirical studies and computer models have suggested which proxies can generally be considered reasonable for use as “default” substitutes (point estimates or ranges corresponding to life history strategies) for MSY -related parameters.

The list of proxies presented in the following sections is not all-inclusive and fisheries scientists are encouraged to develop and examine alternatives.

Data-Moderate Situations

In general, reference points from yield-per-recruit (YPR) and spawning-stock-biomass-per-recruit (SPR) analyses are easy to calculate because relatively few data are required; in particular, it is not necessary to obtain stock-recruitment data. For this reason, YPR and SPR reference points are often used as proxies for other reference points that do require stock and recruitment data.

Proxies for F_{MSY}

F_{max} was one of the earliest measures used as a proxy for F_{MSY} . However, it was often believed to be an overestimate of F_{MSY} because it does not account for the fact that recruitment must decline at low spawning stock sizes. Computer models have also demonstrated that F_{max} invariably overestimates F_{MSY} if a Beverton-Holt (1957) stock-recruitment relationship applies, although F_{MSY} can sometimes exceed F_{max} with a Ricker (1958) curve. For this reason, and taking into account economic considerations, $F_{0.1}$ was developed and promoted as a more prudent alternative (Gulland and Boerema, 1973). Although $F_{0.1}$ is commonly interpreted as a conservative or cautious estimate of F_{MSY} , this is not always the case (Mace, 1994; Mace and Sissenwine, 1993). And even when $F_{0.1}$ does underestimate F_{MSY} , the equilibrium

yields associated with the two reference points may be relatively very close (based on the argument that the difference between the equilibrium yields associated with F_{max} and $F_{0.1}$ are usually small, and F_{MSY} is usually less than F_{max}).

Another class of reference points that has gained prominence as proxies or independent measures of targets and limits are those based on $F_{\%SPR}$. In particular, values in the range $F_{20\%}$ to $F_{30\%}$ have frequently been used to characterize recruitment overfishing thresholds (Rosenberg *et al.*, 1994), while values in the range $F_{30\%}$ to $F_{40\%}$ have been used as proxies for F_{MSY} . These defaults are supported by Mace and Sissenwine (1993) who advocated $F_{20\%}$ as a recruitment overfishing threshold for well-known stocks with at least average resilience and $F_{30\%}$ as a recruitment overfishing threshold for less well-known stocks or those believed to have low resilience, by Clark (1991, 1993) who advocated $F_{35\%}$ as a robust estimator of F_{MSY} applicable over a wide range of life histories, or $F_{40\%}$ if there is strong serial correlation in recruitment, and by Goodyear (1993) who advocated at least 20% SPR unless there were evidence of exceptionally strong density dependence.

Finally, in the uncommon situation where stocks have been maintained near B_{MSY} , F_{med} may be considered a reasonable proxy for F_{MSY} .

Proxies for B_{MSY}

The equilibrium biomass corresponding to the above-mentioned fishing mortality reference points can be used as proxies for B_{MSY} . In addition, B_{MSY} has been approximated by various percentages of the unfished biomass, usually in the range 30-60% B_0 (higher percentages being used for less resilient species, and lower percentages for more resilient species). B_{MSY} can also be approximated by the mean recruitment (R_{mean}) multiplied by either (a) the level of spawning per recruit at F_{MSY} , namely $SPR(F_{MSY})$, or some proxy thereof, or (b) 30-60% $SPR_{F=0}$. Note that if F_{MSY} is overestimated, then $SPR(F_{MSY})$ and B_{MSY} will both be underestimated, thus compounding the riskiness of control rules that use estimates of F_{MSY} and B_{MSY} in combination.

If catch and CPUE data are available, production models may provide useful proxies such as $CPUE_{MSY}$ which can be used as a relative index of B_{MSY} (in addition, the nominal effort (e.g., in boat-months) corresponding to F_{MSY} can be used as a relative index of F_{MSY}).

The risks of using CPUE as an index of or proxy for stock size with associated assumptions of constant catchability over all stock sizes and time may be sizeable and have been well-described (e.g., Hilborn and Walters, 1992).

Proxies for B_0

Where B_0 is unknown, it can be approximated by the product of average recruitment and $SPR_{F=0}$ (Myers *et al.*, 1994); however, this approximation assumes that there have been no density-dependent changes in growth, survival, or age at maturity during the “fishing down” period.

Proxies for MSY

The equilibrium yield corresponding to the above-mentioned F and/or B reference points can be used as a proxy for MSY , although of course such estimates of MSY must be considered long-term averages, and not treated as constant annual catches. For a fishery where annual quotas remain constant over a prolonged period (perhaps because there are insufficient data to update stock assessments), such quotas should be set at a level of 60-90% of the equilibrium or static estimate of MSY , with the high end of the scale applying to species with low natural variability or low M , and the low end applying to species with high natural variability or high M (Mace and Sissenwine, 1989).

Constraints on Acceptable Proxies

In addition, there are a number of estimators of, or approximations to, the limit reference F_L points based on the slope at the origin of stock-recruitment relationships (variously called $F_{extinction}$, F_{ext} , F_r (Mace, 1994), F_{crash} (ICES 1997a)). These estimators include F_{med} (if calculated from data collected during a period when the stock was at low biomass), F_{high} (the fishing mortality corresponding to the 90th percentile of survival ratios), $F_{20\%}$, F_{loss} (the fishing mortality corresponding to the lowest observed spawning stock and associated recruitment — Cook, 1998), and F_{COMFIE} (the minimum of F_{MSY} , F_{med} and F_{crash}). Suggested biomass limits that have been considered dangerously close to the origin include MBAL (the minimum biologically acceptable level of spawning biomass; Serchuk and Grainger, 1992), $B_{50\%R}$ (the spawning biomass corresponding to 50% of the maximum recruitment in a stock recruitment relationship; Mace, 1994; Myers *et al.*; 1994), $B_{90\%R, 90\%RS}$ (the biomass corresponding to the intersection of the 90th percentile of observed recruitment and the 90th percentile of survival; Serebryakov, 1991; Shepherd, 1991), and B_{loss} (the biomass corresponding to the lowest observed spawning stock; ICES, 1997a). Any proxies used for F_{MSY} or B_{MSY} should be more conservative than these extremes.

Recommended Data-Moderate Defaults

The recommended data-moderate default limit control rule is the limit control rule described above as in

Restrepo *et al.*, 1998, using proxies for F_{MSY} and B_{MSY} as described below.

We recommend that fishing mortality rates in the range $F_{30\%SPR}$ to $F_{40\%SPR}$ be used as general default proxies for F_{MSY} , in cases where the latter cannot be reliably estimated. In the absence of data and analyses that can be used to justify alternative approaches, it is recommended that $F_{30\%SPR}$ be used for stocks believed to have relatively high resilience, $F_{40\%SPR}$ for stocks believed to have low to moderate resilience, and $F_{35\%SPR}$ for stocks with “average” resilience. Less-preferred alternatives (in order of decreasing preference) are to use $F_{0.1}$, M , F_{max} , or F_{med} (when F_{med} is calculated from data collected when the stock was believed to be fluctuating around B_{MSY}) as the proxies for F_{MSY} . The equilibrium or average biomass levels corresponding to these fishing mortality rates should then be used as proxies for B_{MSY} in the same order of preference. The default limit control rule would then be defined with fishing mortality set to this default level when biomass exceeds $(1-M)*B_{MSY}$ or $1/2 B_{MSY}$, whichever is greater, and would decline linearly to zero for biomass levels below this threshold.. The recommended default MSST corresponds to $1/2 B_{MSY}$ (the absolute lowest limit triggering the need for a rebuilding plan) for species with $M \geq 0.5$; but occurs at a larger biomass for species with smaller M .

Data-Poor Situations

If data are insufficient data to conduct YPR and SPR analyses, or if estimates of F and B cannot be obtained for comparison with YPR and SPR reference points, there are far fewer options for defining meaningful targets and limits. Priority should be given to bringing the knowledge base at least up to “data-moderate” standards.

Proxies for F_{MSY}

The natural mortality rate M has often been considered to be a conservative estimate of F_{MSY} ; however, it is becoming more and more frequently advocated as a target or limit for fisheries with a modest amount of information. In fact, in several fisheries, $F=0.8*M$ and $F=0.75*M$ have been suggested as default targets for data-poor cases (Thompson, 1993; NMFS, 1996). In data-poor situations, M may not be reliably estimated either, however.

Proxies for B_{MSY}

The equilibrium biomass corresponding to $F=M$ or $F=0.8*M$ can be used as a proxy for B_{MSY} . However, in most data-poor situations, it will not be possible to calculate this quantity.

Proxies for B_0

If there are no data on recruitment, some function of CPUE might conceivably be used as a relative index of initial biomass. If information (perhaps anecdotal) exists on resource conditions prior to or shortly after the onset of fishing, some inferences of initial biomass (B_0) may be possible. Because the geographic area occupied by a stock may contract with declines in abundance, the contrast between present and early geographic distributions of the resource may be used to obtain a rough approximation of pre-fishery abundance. Early sport fishing records may provide useful information on resource conditions prior to intense exploitation (MacCall 1996). Estimates of early CPUE may relate to B_0 , but care must be taken to correct for the general tendency for CPUE to underestimate declines in resource abundance. For example, this may require geographic stratification, correction for temporal changes in fleet composition (e.g., loss of less efficient vessels as catch rate declines) and a variety of behavioral and biological interactions. Nonequilibrium production modeling (Hilborn and Walters, 1992; Prager, 1994) also may provide an inference of initial CPUE for the fishery.

Proxies for MSY

If there is absolutely no information available to estimate fishing mortality or biomass reference points, it may be reasonable to use the historical average catch as a proxy for MSY , taking care to select a period when there is no evidence that abundance was declining. In recognition of the danger of continually setting annual quotas at a constant level equal to the historical average catch (a common situation in data-poor fisheries), it might be best to scale down the historical average catch by multiplying by a factor in the range 0.6-0.9 where smaller multipliers would be used for highly variable stocks and larger numbers for less variable stocks (Mace and Sissenwine 1989).

Recommended Data-Poor Defaults

In the absence of data and analyses that can be used to justify alternative approaches, it is recommended that the default limit control rule be implemented by multiplying the average catch from a time period when there is no quantitative or qualitative evidence of declining abundance ("Recent Catch") by a factor depending on a qualitative estimate of relative stock size:

- Above B_{MSY} :
Limit catch = $1.0 * (\text{Recent catch})$
- Above $MSST$ but below B_{MSY} :
Limit catch = $0.67 * (\text{Recent catch})$
- Below $MSST$ (i.e., overfished):
Limit catch = $0.33 * (\text{Recent catch})$.

The multipliers 1.0, 0.67 and 0.33 were derived by dividing the default precautionary target multipliers in Section 3.3.2 of Restrepo *et al.* (1998) by 0.75, in order to maintain the 0.75 ratio recommended as the default distance between the limit and target reference points for stocks above $(1-M)*B_{MSY}$. Since it probably will not be possible to determine stock status relative to B_{MSY} analytically, an approach based on "informed judgement" (e.g., a Delphi approach) may be necessary.

Concluding Observations

The MSY -related reference points in the MSCFMA National Standard Guidelines and the FAO guidelines appear stringent in the context of current fishing mortality rates observed in open-access fisheries. Yet, historically, the risk associated with MSY -related reference points has been well detailed from a qualitative perspective: Larkin's (1977) famous summary cites the relative instability of stocks harvested at MSY which may arise from a relatively high proportion of young and first-time spawners (which may reduce the viability of eggs which are deposited) and the reduction in the number of spawning age classes; the risk to local subpopulations or substocks with lower productivities than the stock as a whole; the risk to less productive co-occurring species when highly productive species are fished at MSY levels; and the risk to productivity of competitors and predators when all stocks cannot be fished simultaneously at their respective MSY -related levels. Typical single-species reference points still treat all units of spawning stock biomass as equivalent, regardless of age structure or spawning history; and rarely include diversity of age structure as a component of the reference point. Maintenance of genetic diversity and problems of technological and biological interactions must be dealt with through compromises, and so there continue to be elements in the fishery system which are at risk under this approach.

For many of the model-based estimates of biological reference points, uncertainty has been evaluated using Monte Carlo or bootstrap procedures (e.g., surplus production models: Prager, 1994; Polacheck *et al.*, 1993; yield-per-recruit models: Restrepo and Fox, 1988; Pelletier and Gros, 1991; spawning-stock-biomass-per-recruit models: Cook, 1998). As more and more information about uncertainty becomes available or is included in the estimation process, the estimate of uncertainty related to the reference point increases. This may occur as more sources of observation error are included, or if process error is also included. The method used to fit a model may also affect the estimate of uncertainty, as a function of the types of errors included in the model (e.g., Chen and Andrews, 1997). Consequently, although procedures for estimating the reference point and the underlying model may be agreed

within the scientific community, the procedures for estimating uncertainty in those reference points are less standardized. In the most information-poor situations, quantification of uncertainty associated with the reference point may not even be possible. Thus, paradoxically, statistical uncertainty may appear to increase while the quality of information is increasing. The evaluation of alternative reference points as proxies for MSY -related reference points becomes problematic, because each reference point may be estimated with a different degree of certainty, some of which may be due to statistical artifact but which may affect its performance as a proxy in a precautionary context.

There is a fast-burgeoning body of literature which reviews various biological reference points as candidates for limit and target reference points in the precautionary contexts of various management institutions. Those papers almost universally endorse the evaluation of the performance of those reference points and associated harvest control rules using simulation modelling. We propose that for many management systems, the results of these simulations may show that the effect of the choice of a particular estimate of F_{MSY} or B_{MSY} (or its respective proxy) as a limit reference point may be tangential to the success of a precautionary management regime when compared to the effects of the form of the associated harvest control rules, and historically observed implementation errors (the difference between the intended effect of management action and the realized result; e.g., the difference between total allowable catch and actual catch in a year). There have been cases where biological reference points and stock status have been defined with reasonable quality data and with reasonable certainty, but associated management regimes have led to significant and undesirable stock declines. Although the specification of MSY -related limit reference points based on poor-quality data may be daunting, for many fishery systems it is likely to be the easiest component of the precautionary process to implement.

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Dealing With Bias in Estimating Uncertainty and Risk

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Abstract. To quantify the uncertainty of fisheries stock assessment results or the risk of alternative management actions, we need to characterize the cumulative frequency distribution of the quantities of interest. Fisheries management quantities, such as biomass or fishing mortality rate, can only take positive values. Furthermore, estimators for fisheries management quantities from many assessment models are biased as a result of non-linearity in the models. Standard methods which assume a Gaussian distribution, failed to adequately account for the skew. The bootstrap percentile method did not adjust for the statistical estimation bias. The bootstrap bias corrected percentile technique appears to be best suited for general application.

Introduction

There is increasing recognition for the merits of explicitly taking into account the uncertainty of stock assessment results and the risks associated with alternate actions, when considering fisheries management decisions (Restrepo et al 1992). Incorporation of knowledge about uncertainty and risk for the provision of fisheries management advice is an integral aspect of the Precautionary Approach (ICES 1997). Practically, this implies that it is not sufficient to estimate the statistics for quantities of interest. We must also investigate their probability distributions.

The format in which uncertainty and risk results are conveyed is influenced by the specific management regime. In the Northeast USA, fishery managers are receiving this type of information in the form of cumulative frequency distributions and confidence intervals for the terminal year population quantities, such as spawning stock biomass (Anon. 1997). These uncertainties are also carried forward into short- and medium-term projections in order to evaluate alternative harvest strategies. In eastern Canada, fishery managers are receiving this kind of information in the form of a risk profile for achieving identified goals, such as an increase in spawning stock biomass, over a range of quota options in the forecast year (DFO 1997). They are concerned with the risk of achieving established reference points in the short-term projection if they choose a specific quota.

The risk profile is directly related to and derived from the cumulative frequency distributions of the estimated fisheries management quantities of interest. This is readily appreciated if one considers a surface constructed of cumulative frequency distributions for fishing mortality rate over a range of quotas (Fig. 1). The risk profile is the cross section of that surface at the es-

tablished fishing mortality reference point. Therefore, the cumulative frequency distribution forms the basis of statements concerning uncertainty and risk.

It is recognised that estimators of fisheries management quantities from many typical fisheries assessment models are biased (Gavaris 1993, Prager 1994). This statistical bias arises from the non-linearity in the models. There may be other sources of bias, but here I only consider this statistical bias. The purpose of this study is to explore the impact of this statistical bias on the cumulative frequency distributions and the resulting risk profiles.

Methods

I describe three general methods for obtaining the cumulative frequency distribution of an arbitrary quantity, η , which is a function of estimated parameters, ξ , from some model. Let $\hat{\eta} = g(\hat{\xi})$ where g is the transformation function.

From an Assumed Distribution Type.

An obvious default method for constructing the cumulative frequency distribution is to invoke the Central Limit Theorem and assume that a Gaussian distribution adequately approximates the frequency distribution of the estimator $\hat{\eta}$. Applying the estimated statistics for $\hat{\eta}$, the desired cumulative frequency distribution is obtained by assuming $\eta \sim N(\hat{\eta} - \text{Bias}(\hat{\eta}), \text{Var}(\hat{\eta}))$. Note that this assumes the approximation $\text{Var}(\hat{\eta} - \text{Bias}(\hat{\eta})) \equiv \text{Var}(\hat{\eta})$. This approach will be referred to as the standard method.

The variance and bias of $\hat{\eta}$ can be obtained using the methods described in Ratkowsky (1983):

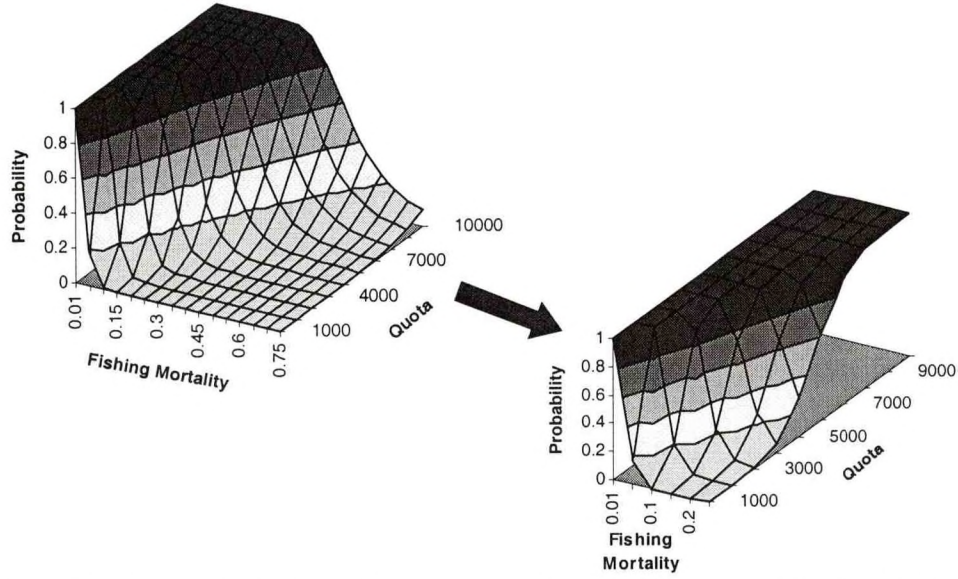


Figure 1. The risk that fishing mortality rate in the forecast year will exceed an established reference level, say 0.25, for some quota option, can be obtained as the cross section of the surface constructed from cumulative frequency distributions over that range of quotas.

$$\text{Var}(\hat{\eta}) = \text{tr} \left[G G^T \text{cov}(\hat{\xi}) \right]$$

$$\text{Bias}(\hat{\eta}) = G^T \text{Bias}(\hat{\xi}) + \text{tr} [W \text{cov}(\hat{\xi})] / 2,$$

where G is the vector of first derivatives of g with respect to parameters and W is the matrix of second derivatives of g with respect to parameters.

The covariance of the model parameters $\hat{\xi}$, can be estimated using the common linear approximation (Kennedy and Gentle 1980),

$$\text{Cov}(\hat{\xi}) = \hat{\sigma}^2 \left[J^T(\hat{\xi}) J(\hat{\xi}) \right]^{-1},$$

where $\hat{\sigma}^2$ is the mean square residual and $J(\hat{\xi})$ is the Jacobian matrix of the vector-valued objective function. The bias of the model parameters can be obtained using Box's (1971) approximation.

$$\text{Bias}(\hat{\xi}) = \frac{-\hat{\sigma}^2}{2} \left(\sum_i J_i(\hat{\xi}) J_i^T(\hat{\xi}) \right)^{-1} \left(\sum_i J_i(\hat{\xi}) \right) \text{tr} \left[\left(\sum_i J_i(\hat{\xi}) J_i^T(\hat{\xi}) \right)^{-1} H_i(\hat{\xi}) \right],$$

where $J_i(\hat{\xi})$ are vectors of the first derivatives with respect to ξ of the vector-valued objective function and $H_i(\hat{\xi})$ are the Hessian matrices with respect to ξ .

From Bootstrapping.

Non-parametric bootstrap techniques offer the advantage of not making any assumptions about the error distribution. The bootstrap samples are used to calcu-

late the bootstrap replicate estimates, $\hat{\eta}^b$, of the quantity of interest. I considered two bootstrap methods, the percentile and the bias corrected percentile, for using the bootstrap replicate estimates to construct the cumulative frequency distribution.

The percentile method (Efron 1982) is a simple and direct way of forming an empirical cumulative frequency distribution. The probability that $\hat{\eta}$ is less than or equal to some value is defined as the proportion of bootstrap replicates, $\hat{\eta}^b$, less than or equal to that value:

$$\hat{\Omega}(x) = \text{Prob}\{\hat{\eta} \leq x\} = \frac{\#\{\hat{\eta}^b \leq x\}}{B},$$

where B is the total number of bootstrap replicates. For conceptual and graphing purposes, it is convenient to consider the empirical cumulative frequency distribution as the set of paired values $(\alpha, \bar{\eta}^b)$, where $\bar{\eta}^b$ are the ordered bootstrap replicates and α are the respective probability levels equal to $1/B, 2/B, 3/B, \dots, B/B$.

Frequently, the median of the bootstrap percentile density function does not equal the estimate obtained with the original data sample. The bias-corrected percentile method (Efron 1982) makes an adjustment for this type of bias. The bias-corrected percentile method can be thought of as an algorithm to replace the $\bar{\eta}^b$ in the paired values $(\alpha, \bar{\eta}^b)$ with the bias adjusted quantity $\bar{\eta}_{BC}^b$. The notation $\hat{\Omega}^{-1}(\cdot)$ or $\Phi^{-1}(\cdot)$ is used to represent the inverse distribution function, i.e. the critical value corresponding to the specified probability level. For each α in the paired values $(\alpha, \bar{\eta}^b)$, calculate the bias

adjusted quantity $\tilde{\eta}_{BC}^b$:

$$\tilde{\eta}_{BC}^b = \hat{\Omega}^{-1}(\Phi(2z_0 + z_\alpha)).$$

Here, Φ is the cumulative distribution function of a standard normal variate, $z_\alpha = \Phi^{-1}(\alpha)$ and $z_0 = \Phi^{-1}(\hat{\Omega}(\hat{\eta}))$. The term z_0 achieves the bias adjustment. If the median of the bootstrap density function is equal to $\hat{\eta}$, then $\hat{\Omega}(\hat{\eta})$ will be 0.5, z_0 will be zero, and $\tilde{\eta}_{BC}^b$ will equal $\hat{\eta}^b$ (i.e. no bias adjustment). Note that computations are not carried out for $\alpha=B/B$ because $z_\alpha = \Phi^{-1}(\alpha=1)$ is not defined.

Results

To illustrate the potential differences in outcomes, the three general techniques were applied to the results from a specific age structured analytical fisheries assessment model (Annex 1) using data from eastern Georges Bank haddock. In this example, the quantity of interest for fisheries management was spawning stock biomass, SSB. The cumulative frequency distributions of terminal year SSB, were derived and compared. The cumulative frequency distributions of SSB in the forecast year were also derived and used to obtain the risk of not achieving growth relative to the terminal year as a function of quota. In this example, a model-conditioned non-parametric bootstrap approach was employed. Bootstrap samples were obtained by adding the set of residuals obtained by sampling with replacement, to the model predicted values.

Consider first the cumulative frequency distribution for SSB in the terminal year of the assessment, the type of advice portrayed in the NMFS SAW Advisory

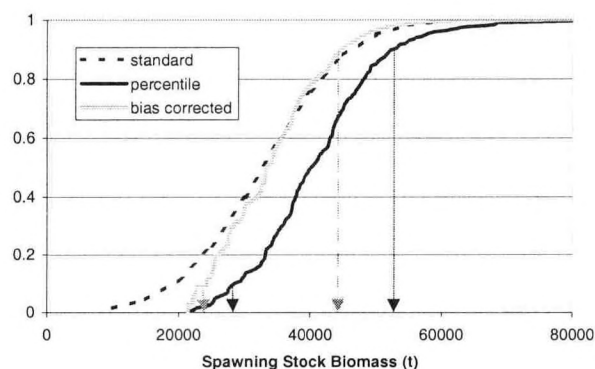


Figure 2. Comparison of the cumulative frequency distribution of spawning stock biomass in the terminal year indicates that the standard method does not reflect the skew displayed by the bootstrap methods. The percentile bootstrap method does not account for estimation bias and is shifted.

Reports. Figure 2 displays the results from the three approaches. The standard method gives the typically smooth and symmetric Gaussian distribution centred on the bias adjusted mean and characterised by the estimated variance. The empirical cumulative frequency distribution derived by the percentile method displays some skew and it is centred on the biased estimate. The corresponding 90% confidence interval associated with this approach gives values of [28,362t < SSB < 52,954t]. The bias-corrected percentile method appears to fully compensate for the bias and centres the empirical cumulative frequency distribution on the bias-adjusted estimate. It displays a greater degree of skew. For this example, the corresponding 90% confidence interval from the bias-corrected percentile method is more pessimistic with values of [24,249t < SSB < 44,968t].

Now consider how the statistical bias affects the risk profile for not achieving SSB growth in the forecast year, the kind of advice given in DFO Stock Status Reports. Recall that the risk profile is not a cumulative frequency distribution but a cross section of several cumulative frequency distributions. Figure 3 compares the results from the three approaches. Here again we see that the bias-corrected percentile method appears to compensate for the bias and results in a profile that is shifted towards that obtained with the standard method. The risk profile obtained from the percentile method gives a more optimistic outlook. For example, based on the percentile method, a 1997 quota of 5,000t implies an 18% risk of not achieving growth in SSB. This compares to a risk of 40% obtained from the bias-corrected risk profile.

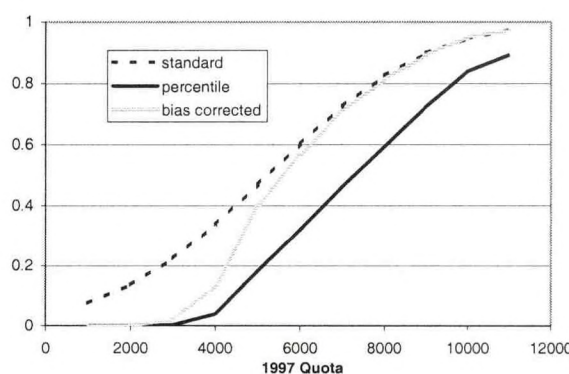


Figure 3. Comparison of the risk profiles for not achieving growth of the spawning stock biomass in the forecast year shows that results from the percentile method are shifted relative to the standard and bias corrected methods. For low risk levels, the distributional assumptions required by the standard method probably lead to erroneous results.

Discussion

Many fisheries management quantities of interest can only take positive values. In such instances, assuming a Gaussian approximation for these quantities does not capture the implied skew of their cumulative frequency distributions. This effect was apparent in the example using SSB. Consequently, the lower tail obtained with the standard method was considerably longer when compared to the bootstrap approaches. When the estimated variance is large, the lower confidence bound obtained from the standard method may be negative. It would appear that confidence statements based on results from the standard method might not be reliable for small cumulative probability levels. Assuming a log-normal distribution for some quantities may provide a better approximation, however theoretical justification may be lacking. For instance, in the example, it might be reasonable to assume, and there is some evidence to suggest, that the estimator of population abundance at age is lognormally distributed. The SSB then is the sum, multiplied by weight and maturity at age, of population abundance. The sum of lognormally distributed variables is not lognormal.

The bootstrap methods demonstrated that the empirical distribution for the SSB example was skewed. The results from the percentile method were shifted substantially, however. Confidence intervals or risk statements based on the percentile method can be markedly different from those based on the bias-corrected percentile method. Efron and Tibshirani (1993) argue that confidence statements based on the bias-corrected and accelerated method offer a substantial improvement over the percentile method, both in theory and in practice. The accelerated method was not used here. Loh and Wu (1987) indicated that the accelerated method might offer only marginal improvement over the bias-corrected method, but this aspect merits further investigation for the stock assessment problem. Nevertheless, we may conclude that the bias-corrected method should provide more accurate confidence statements than does the simple percentile method.

Recognising the potential to inadequately characterise the shape of the frequency distribution with the standard method, and the failure of the percentile method to account for estimation bias, the bootstrap bias-corrected percentile technique is recommended for general application.

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Annex 1: Fisheries Assessment Model

The available data were:

$C_{a,t}$ = catch at age, age $a = 0, 1 \dots 8$, time $t = 1986, 1987 \dots 1996$.

$I_{a,t}$ = DFO spring survey, age $a = 1, 2 \dots 8$, time $t = 1986, 1987 \dots 1997$.

The employed model formulation assumed that the error in the catch at age was negligible. The errors in the abundance indices were assumed independent and identically distributed after taking natural logarithms of the values. The annual natural mortality rate, M , was assumed constant and equal to 0.2. A model formulation using as parameters the natural logarithm of population abundance at the beginning of the year was considered because of close-to-linear behavior for such a parameterization (Gavaris 1993). Thus, a total of 16 parameters were estimated:

$\theta_{a,t'}$, ages $a = 1, 2, \dots 8$ at time $t' = 1997$,
 κ_a , ages $a = 1, 2, \dots 8$.

A solution for the parameters was obtained by minimizing the sum of squared differences between the natural logarithm observed abundance indices and the natural logarithm population abundance adjusted for catchability by the calibration constants:

$$\Psi(\hat{\theta}, \hat{\kappa}) = \sum_{a,t} \left(\psi_{a,t}(\hat{\theta}, \hat{\kappa}) \right)^2 = \sum_{a,t} \left(\ln I_{a,t} - (\hat{\kappa}_a + \ln N_{a,t}(\hat{\theta})) \right)^2$$

For convenience, the model's population abundance $N_{a,t}(\hat{\theta})$ is abbreviated by $N_{a,t}$. At time t' , the population abundance was obtained directly from the parameter estimates, $N_{a,t'} = e^{\hat{\theta}_{a,t'}}$. For all other times, the population abundance was computed using the virtual population analysis algorithm, which incorporates the common exponential decay model

$$N_{a+\Delta t, t+\Delta t} = N_{a,t} e^{-(F_{a,t} + M_a)\Delta t}.$$

Year was used as the unit of time. Therefore, ages were expressed as years and the fishing and natural mortality rates were annual instantaneous rates. The fishing mortality rate, $F_{a,t}$, exerted during the time interval t to $t + \Delta t$, was obtained by solving the catch equation,

$$C_{a,t} = \frac{F_{a,t} \Delta t N_{a,t} (1 - e^{-(F_{a,t} + M_a)\Delta t})}{(F_{a,t} + M_a)\Delta t},$$

using a Newton-Raphson algorithm. The fishing mortality rate for the oldest age in the last time interval of each year was assumed equal to the weighted average for ages fully recruited to the fishery during that time interval

$$F_{8,t} = \sum_{a=4}^7 N_{a,t} F_{a,t} / \sum_{a=4}^7 N_{a,t}.$$

Alternative Ways to Evaluate Uncertainty and Risk in Data-Poor and Hypothesis-Rich Situations

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Delay-difference models such as stock reduction analyses (Kimura et al. 1997) have played a major role in providing a biological basis for management in North Pacific groundfish fisheries, particularly when detailed age-structured data are lacking. These methods typically require relatively large numbers of assumptions that may result in underestimates of stock assessment uncertainty. We propose introducing some Bayesian methods as a means to better reflect assessment uncertainty. For example, we allow for uncertainty in the historical catch estimates and other key population parameters typically assumed as fixed or measured without error. Also, we show the effect of adding a stochastic component to the recruitment function. A general method for determining MSY quantities in a complex assessment model is presented. Marginal distributions are given using posterior integration methods and through simple approximations based on normal propagation of error (Delta) methods. We demonstrate the use of these methods on simulated data and in real applications to rockfish species in the Gulf of Alaska.

Proposed Changes to the Fishery Management Plan for Pacific Salmon

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A draft proposal for Amendment 14 to the Pacific Salmon Fishery Management Plan (FMP) is currently being developed by NMFS Northwest Region. The intent of the amendment is to make the FMP more consistent with the findings of coastwide status reviews conducted by NMFS under the Endangered Species Act (ESA), and to bring the FMP in compliance with the proposed National Standards Guidelines being developed by NMFS.

The Pacific Salmon FMP currently includes chinook, coho, and pink salmon, and sockeye salmon from Puget Sound. Amendment 14 proposes to drop sockeye salmon from the FMP and subdivide the management unit of the Pacific Salmon FMP into components corresponding roughly to evolutionarily significant units (ESUs) identified in the coastwide ESA status reviews for the remaining 3 species. Differences between the management unit components and ESUs include: coho and chinook salmon from streams entering the Strait of Juan de Fuca west of the Elwha River were placed in Washington coastal ESUs but are included with Puget Sound management components; fall chinook salmon from the lower Klamath River tributaries were placed in the coastal chinook salmon ESU but are included with the upper Klamath basin for management purposes; even-year and odd-year ESUs of pink salmon in Puget Sound were combined into a single management component.

The FMP for Pacific salmon currently defines overfishing as the failure to meet an FMP management objective for 3 consecutive years. Amendment 14 proposes to retain the current overfishing definition with the addition of annual abundance and fishing mortality thresholds which depend on the type of management objectives defined for individual stocks.

FMP management objectives currently fall into 3 categories: fixed spawner escapement or escapement range policies, constant exploitation rate policies with a minimum spawner escapement, and stepped exploitation rate policies where the target exploitation rate depends on forecast stock size and marine survival. These thresholds are proposed as proxies to the National Standards guidelines of $\frac{1}{2}$ MSY biomass and MSY fishing mortality rate. For fixed escapement policies, the pro-

posed abundance threshold is $\frac{1}{2}$ of the midpoint of the goal range, and the fishing rate threshold is the exploitation rate necessary to meet the lower bound of the escapement goal range (Figure 1a). For constant exploitation rate policies, the proposed abundance threshold is the minimum spawner escapement, and the mortality rate threshold is the exploitation rate goal (Figure 1b). For the stepped exploitation rate goal, the proposed abundance threshold is the breakpoint between low and critical spawning escapements (Figure 1c).

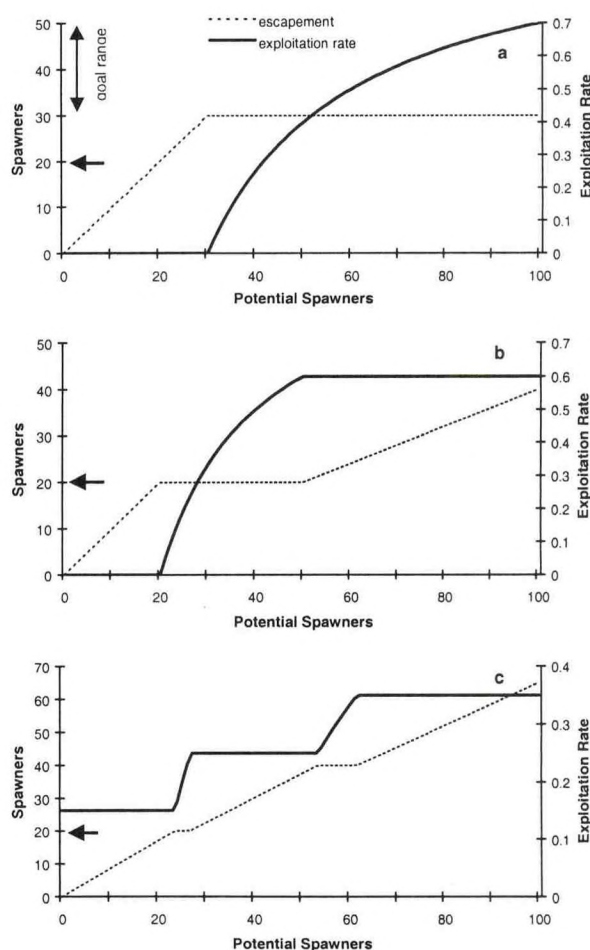


Figure 1. Thresholds for defining overfishing proposed in Amendment 14 to the Pacific Salmon Fishery Management Plan. Abundance thresholds are indicated by the arrow on the Spawner axis and fishing rate thresholds are indicated by the exploitation rate for (a) fixed escapement policy, (b) constant exploitation rate policy, and (c) stepped exploitation rate policy.

Use of Decision Tables to Develop a Precautionary Approach to Problems in Behavior, Life History and Recruitment Variability

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Abstract. – Decision tables provide a simple and systematic summary of the consequences of alternative management policies or decisions given various possible true, but generally unknown, states of nature. Decision tables are especially useful for evaluating the precautionary properties of those decisions, as they require explicit consideration of a variety of “what if” possibilities, some of which could be associated with otherwise inadvertent overfishing. Often this approach helps to identify robust solutions, that is, solutions that inherently tend toward desirable outcomes and away from undesirable outcomes. This paper uses the theme of decision tables to evaluate a variety of fishery problems that are significant in their own right.

Catch per unit effort (CPUE) remains a popular metric of stock abundance despite having a documented and dangerous tendency toward insensitivity to changes in true abundance. A simple decision table analysis of production model behavior demonstrates that a policy of first squaring raw CPUE has desirable precautionary properties and confers a robustness to production model assessments, whereas use of untransformed CPUE risks overfishing and stock depletion.

Use of spawning potential ratios (SPRs) is widespread in stock assessment and development of management policies. The practice of using spawning biomass as a metric of spawning potential can result in overfishing if reproductive value is differentially larger for older fish, e.g., due to multiple spawning or increasing relative fecundity with age. Similarly, some stocks may exhibit an increasing natural mortality rate with age, which appears in assessments as a dome-shaped selectivity curve when the natural mortality rate is assumed to be constant. Decision table analysis of resulting SPRs shows that in this case it is precautionary to assume that natural mortality rate is constant.

Some stocks exhibit low frequency patterns in recruitment variability, leading to boom-and-bust cycles over periods of decades. If there is evidence that recruitment strength is correlated with environmental factors, such as mean sea surface temperature, decision table analysis shows that it is precautionary to use the environmental correlate to adjust target fishing rates. Accurate prediction of recruitment strength is of little benefit if the management policy is static. The benefit arises from adjusting the management policy; failure to adjust fishing rates to long periods of low productivity leads to overfishing and stock depletion.

Rarely recruiting species pose especially difficult problems for management. One possible mechanism generating rare large recruitments arises from serial correlation in the sequence of survivorship events encountered during the early life history of a fish species. A power function probability density function (pdf) is consistent with the distribution of recruitment strengths of the bocaccio rockfish. A consequence of this pdf is that the underlying stock-recruitment relationship may not be knowable even from extensive data sets. A biomass reserve is a fixed quantity of biomass that is set aside before applying conventional management, such as a fixed harvest rate, on the remainder. Decision table analysis shows that use of a biomass reserve results in near-optimal fishery performance over a wide range of harvest rates.

Introduction

At the NMFS Stock Assessment Workshop, there was a serious debate as to whether precaution is appropriate in fishery research and stock assessment, as distinct from precaution in management. That debate was resolved to some extent by general agreement that stock assessments should always strive for accuracy, and that it would be wrong to introduce intentional biases into assessments in the name of a “precautionary approach.” In my own opinion, however, the process of stock assessment and subsequent generation of management advice invariably requires subjective choices among alternative approaches to biological or statistical problems, and there seldom is a truly neutral option against which bias can be evaluated. The most common criterion for

making such choices is simply convention, which is not necessarily neutral. While conventionality may promote consistency over time and perhaps reduce exposure to criticism, strict adherence to convention can bias an outcome strongly toward whatever is posed as the null case--a choice that is usually subjective.

Decision tables offer a flexible alternative to statistical hypothesis testing. The format is rather similar to the classical hypothesis test: The cells of the decision table summarize the anticipated outcomes of alternative management actions, given various possible conditions or true states of nature. We generally do not know the true state of nature, but in some cases may be able to

Table 1. Example decision table analysis of two alternative production models.

SIMULATED FISHERY MANAGEMENT DECISION	STATE OF NATURE	
	HIGH PRODUCTIVITY	LOW PRODUCTIVITY
EFFORT = 5 (HIGH)	CORRECT C = 5.0 (MSY) CPUE = 1.0	ERROR-overfishing C = 0.8 CPUE = 0.2
EFFORT = 3 (LOW)	ERROR-underfishing C = 4.2 CPUE = 1.4	CORRECT C = 1.5 (MSY) CPUE = 0.5

assign relative probabilities to the alternative true states shown in the decision table. Application of a decision table approach to real fishery problems requires that appropriate simulations be constructed for each case, reflecting the unique properties of those resources and fishery systems to the best practical extent.

Table 1 is an artificial example, summarizing the performance of two alternative management actions (high vs. low fishing effort) given two alternative states of nature (high vs. low stock productivity). Each cell represents a combination of state of nature and management decision for which we can evaluate various aspects of management performance, such as catch levels, abundances, economic yields, variances, etc. This information could be used in a formal quantitative risk analysis, but from the standpoint of a precautionary approach, that analysis reduces to a comparison of the severity of the potential errors under the alternative management actions. Note that if the two states of nature are equally probable, the expected yield is nearly the same for the high and low effort decisions (2.90 for high effort, and 2.85 for low effort), but the variance is higher for the high effort case, implying increased risk. Alternatively, the severity of the errors can be scaled relative to what is possible under a correct management decision for the state of nature. Although in Table 1 the absolute loss in catch due to an error in management is nearly the same for both states of nature (i.e., 0.8 under high productivity, and 0.7 under low productivity), the relative loss is quite different. Erroneous management in the low effort case achieves 84% of what is possible while preserving a high catch rate (low operating costs), but in the high effort case, erroneous management achieves only 55% of the possible sustainable yield, accompanied by a low catch rate (higher operating costs). In this simple example, the precautionary approach to management would be to use the low effort policy.

This is not intended to be a rigorous application of decision theory, although there are certainly many useful concepts and approaches to be gained from a formal decision-theoretic treatment. Here the decision table is

intended to provide a useful summary of possibilities and predicted outcomes as a guide for management decisions.

The remainder of this paper considers a variety of fishery problems and uses decision tables to assess the risk of incorrect management decisions as a guide for establishing a precautionary approach. The topics are loosely grouped into three categories: Nonlinearity in catch per unit effort is an example of a problem that arises from behavior of the fish and the fishermen. Multiple spawning, increasing fecundity with age, and increasing natural mortality rate with age are life history considerations that interact with model specifications used in stock assessment and management. Finally, I consider two problems in recruitment variability: environmentally-driven low frequency variability, and rarely recruiting species. In the latter case, I explore use of a biomass reserve as a robust precautionary approach to managing these problematic resources.

Considerations of Behavior

Nonlinear Catch per Unit Effort

Worldwide experience has shown that catch per unit effort (CPUE) is very often insensitive to changes in stock abundance. A notorious recent example contributed to the collapse of the northern cod fishery. According to Hutchings (1996), "As stock biomass declines, trawler catch rates will remain constant Failure to recognize the decline in northern cod biomass from the mid-1980s can be partly attributed to the use of catch rates by commercial trawlers as a metric of abundance." This insensitivity of CPUE arises from adaptive behaviors both of the fish and of the fishermen. Example adaptive fish behaviors include tendencies toward constant school size (Paloheimo and Dickie 1964), and abundance-dependent expansion and contraction of the range (MacCall 1990). Adaptive fishing behaviors are associated with maximizing profit by maximizing catch rate. Fishing operations consistently target the highest available concentrations of fish, and in many

cases those peak densities are not proportional to overall abundance. Fishermen use advanced technology to obtain information on the location of fishing targets, including radio communications among vessels, acoustic fish detection devices, aerial observers and even remote sensing of sea surface temperatures from satellites. Given the effectiveness of these technologies, it should be no surprise that catch rates may tend to remain high despite declines in resource abundance.

The classical treatment of CPUE has been to assume that the catchability coefficient (q , the fraction of the stock that is caught by a unit of nominal effort) is constant, so that

$$C = qfB \text{ or } C/f = qB$$

where C is catch, f is nominal effort, and B is mean stock biomass during the period that the catch is taken. In effect, this classical form is based on the questionable assumption that the catch rate remains strictly proportional to abundance over all stock sizes, and therefore, that fishermen do not utilize or gain information in attempts to improve their catch rates when the stock declines. A better functional representation of this relationship is

$$C = q(B)fB$$

where $q(B)$ represents the catchability “coefficient” now specified as a function of biomass. This allows us to consider how fish and fishing behaviors interact over a range of abundances. One useful parametrization of $q(B)$ is the power function, $q(B) = B^{\beta-1}$ so that

$$C/f = B^{\beta}$$

where $\beta=1$ if catchability is constant, and $\beta=0$ if CPUE is constant. Some example values of β from the literature are 0.44 for northern cod (Walters and Pearse, 1996), and 0.40 for Pacific sardine prior to World War II (MacCall, 1976). Fox (1974) incorporated this power function model of catchability in a Schaefer production model and found that it can severely distort the relationship between catch and nominal effort and easily lead to stock collapses (see below).

The modern fisheries literature contains numerous warnings against using CPUE (especially if it lacks spatial stratification) for stock assessment purposes. Walters and Ludwig (1994) put it strongly: “...we flatly recommend that [raw] catch/effort data never be used as a direct abundance index (assumed proportional to stock size).” On the other hand, there is growing pressure to use fishery-based sources of information in order to generate improved rapport with the industry.

If CPUE must be used, it should be estimated from a geographically and temporally stratified model (Walters and Ludwig, 1994) and then its use in the stock assessment model should be parametrized in the form of a power function or other flexible nonlinear transformation with estimated parameters. If that treatment does not allow estimation of β and rejection of the hypothesis of $\beta<1$, then **it is precautionary to first transform all of the CPUE values by squaring them (i.e., assume that $\beta=0.5$)**. A review of the literature could produce a distribution of the values of β for similar fisheries (species, gear, etc.), forming the basis for an assumed β , or alternatively for a prior distribution of β that could be used in a Bayesian approach such as that described by Walters and Ludwig (1994).

Table 2. Consideration of nonlinearity in CPUE vs. abundance. Nominal efforts levels are specified as multipliers of effort in year 10.

SIMULATED FISHERY	STATE OF NATURE	
MANAGEMENT DECISION	q IS CONSTANT	q VARIES AS $B^{-0.5}$
USE CPUE	CORRECT est. $f(0.1) = 1.38$ est. $C(0.1) = 198$ C year 15 at $f(0.1) = 204$ B/B_{msy} year 15 = 1.144 B/B_{msy} year 20 = 1.105	ERROR-overfishing est. $f(0.1) = 2.36$ est. $C(0.1) = 296$ C year 15 at $f(0.1) = 219$ B/B_{msy} year 15 = 0.58 B/B_{msy} year 20 = 0.0002
USE CPUE ²	ERROR-underfishing est. $f(0.1) = 0.78$ est. $C(0.1) = 122$ C year 15 at $f(0.1) = 150$ B/B_{msy} year 15 = 1.488 B/B_{msy} year 20 = 1.495	CORRECT est. $f(0.1) = 1.38$ est. $C(0.1) = 198$ C year 15 at $f(0.1) = 204$ B/B_{msy} year 15 = 1.144 B/B_{msy} year 20 = 1.105

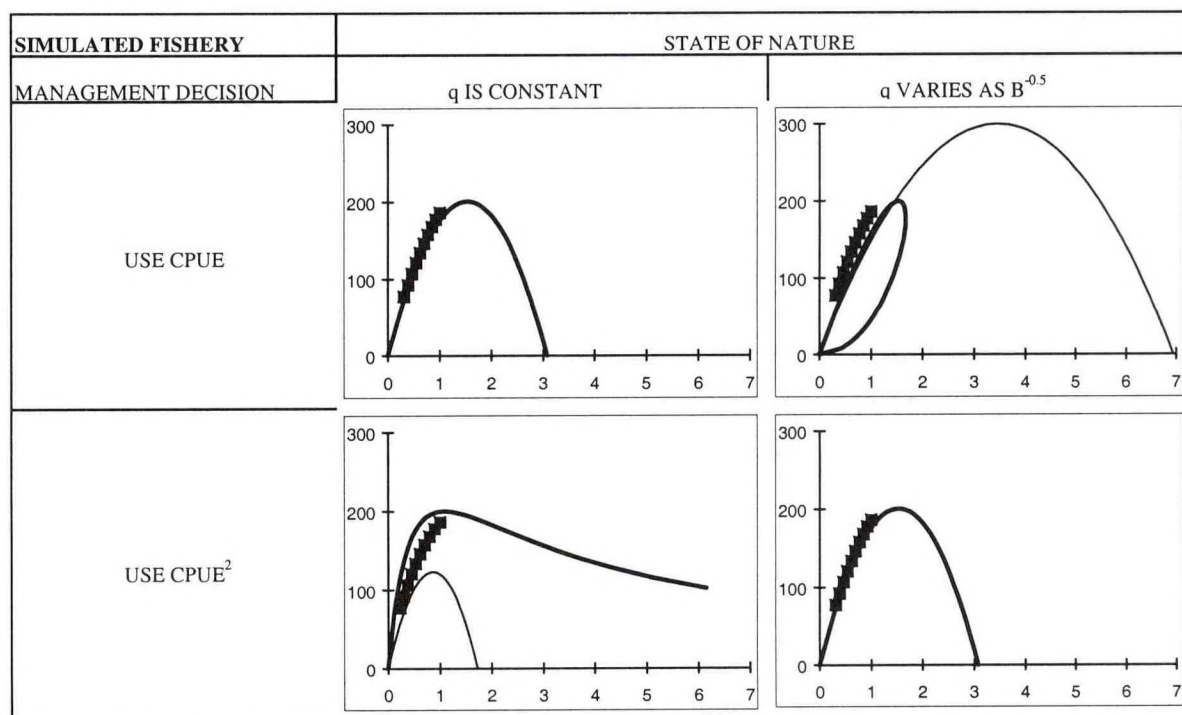


Figure 1. Graphical consideration of nonlinearity in CPUE vs. abundance, equivalent to Table 2. Nominal effort levels are specified as multipliers of effort in year 10. Light lines (parabolas) are expected behavior according to the fitted model; heavy lines are actual fishery equilibrium yield curves. Solid dots are data from an initial developmental fishery.

Some of the properties of this precautionary transform of CPUE (as well as the potential danger of not transforming it) can be evaluated by simulation of Schaefer production model performance under two alternative behaviors of the catchability coefficient. The two alternative states of nature are a constant catchability coefficient (CPUE is proportional to abundance) and a biomass-dependent catchability coefficient in the form of a power function so that the square of CPUE is proportional to abundance (i.e., $\beta=0.5$).

The biological model is a logistic Schaefer production model with moderate productivity ($r=0.8$, $K=1000$ and $MSY=200$). Initial data reflect an identical biological trajectory generated by a ten-year linear increase in fishing mortality rate, ending at 65 percent of F_{msy} , and drawing the stock down to about 70 percent of carrying capacity (Table 2). The nominal fishing efforts corresponding to this scenario differ slightly, according to the behavior of the catchability coefficient. At the end of this ten-year developmental period, a stock assessment is conducted using ASPIC (Prager 1994, 1995), a standard production modeling package. Based on that assessment, the nominal effort is set at $f(0.1)$ for the next ten years, in the expectation that the yield should be approximately 99 percent of MSY . A decision table (Table 2) summarizes the results of $f(0.1)$ management given the alternative behaviors of the catchability coefficient.

Graphical examination of the fitted models (Fig. 1) shows the reason for the peculiar results. It is clear that failure to square CPUE risks sudden fishery collapse followed by a difficult rebuilding program. This collapse can happen so quickly and unexpectedly that serious depletion may occur in the typical time lag between indications of a problem, data collection and reassessment. The level of nominal effort that causes collapse is dangerously close to the effort level that produces MSY , making it a risky target. The alternative mistake of unnecessarily squaring CPUE is benign and results in a viable fishery that does not preclude options for improving fishery management by periodic reanalysis of the accumulated data.

Considerations of Life History

Multiple Spawning and Increasing Fecundity with Age

Spawning biomass is a widespread and conventional metric for spawning potential, i.e., the egg output of a stock, especially in stock-recruitment studies and in calculation of spawning potential ratios. However, declines in spawning biomass may underestimate the actual decline in spawning potential if older fish are more fecund per unit of body weight. For example, widow rockfish, a west coast species of *Sebastes* that spawns once each year, shows an increasing fecundity per unit of body weight (Boehlert et al. 1982). The increase in fecundity per body weight is even more extreme in temperate pe-

Table 3. Consideration of alternative metrics of reproductive potential in calculation of SPR for widow rockfish (upper) and Pacific sardine (lower), assuming a target of SPR = 0.35.

WIDOW ROCKFISH		
MANAGEMENT DECISION	METRIC OF ABUNDANCE	
	SPAWNING BIOMASS	ANNUAL EGG PRODUCTION
USE F = 0.141	SPR = 0.35	SPR = 0.32
USE F = 0.129	SPR = 0.38	SPR = 0.35

PACIFIC SARDINE		
MANAGEMENT DECISION	METRIC OF ABUNDANCE	
	SPAWNING BIOMASS	ANNUAL EGG PRODUCTION
USE F = 0.54	SPR = 0.35	SPR = 0.26
USE F = 0.38	SPR = 0.45	SPR = 0.35

lagic fishes such as the Pacific sardine which may spawn a great many times each year, especially if the number of spawnings per year increases with age (Smith et al. 1992). The effect of using these alternative metrics of spawning potential can be seen in the following decision tables (Table 3). In this application, the columns represent the alternative metrics rather than alternative states of nature. The rows again represent management decisions, in this case use of $F_{35\%}$ based on the corresponding metric. In the case of widow rockfish, the error appears to be relatively small: The $F_{35\%}$ fishing mortality rate based on spawning biomass is about 10% higher than the $F_{35\%}$ based on egg production. However, this magnitude of error could constitute overfishing under the strict requirements of the new National Standard Guidelines. Ralston and Pearson's (1997) widow rockfish stock assessment used the metric of annual egg production. In the case of Pacific sardine, the error due to misuse of spawning biomass as a metric for spawning potential results in spawning biomass-based $F_{35\%}$ exceeding the egg production-based $F_{35\%}$ by over 40%. This magnitude of error could lead to depletion of the resource. Management of Pacific sardine is presently in development by the Pacific Fishery Management Council, and the nature of future stock assessments has not yet been determined. Both VPA and ichthyoplankton surveys have been used historically, both purporting to measure spawning biomass. In principle, the ichthyoplankton survey should provide an abundance index more closely related to actual egg production. Table 3 suggests that if there is evidence of increased weight-specific fecundity (egg production per body weight), use of spawning biomass may underestimate fishery impacts. **It is precautionary to use population egg production rather than spawning biomass as the metric of spawning potential.**

In his review of pelagic fish stock collapses, Beverton (1990) noted that in many collapses the reproductive rate, measured as recruits per unit of spawning biomass, declined as the stock declined. He concluded that fishing pressure speeded declines that would have happened anyway due to adverse environmental conditions. However, Table 4 suggests an alternative (supplementary, rather than exclusive) hypothesis: The apparent decrease in reproductive rate may have been an artifact of using spawning biomass as a metric for spawning potential. Poor recruitment may have been caused by a drastic reduction of egg production per unit of spawning biomass because of removal of older, more fecund age groups by intense fishing pressure.

Increasing Natural Mortality Rate with Age

Circumstantial evidence suggests the possibility that in many stocks the natural mortality rate, M , may increase with age (a condition I term "accelerated M "). For example, separable VPAs and equivalent maximum likelihood assessments that assume a constant M often produce dome-shaped selectivity curves, where availability of older fish declines to very low levels. These assessment models are fundamentally unable to distinguish between a combination of constant M and declining selectivity (implying that the old fish exist somewhere but are not caught) and a combination of an increasing M and relatively constant selectivity (implying that the old fish do not exist). For example, Tagart et al. (1997) looked extensively for evidence of "unavailable" older female yellowtail rockfish (*Sebastes flavidus*), and concluded that these older fish did not exist. Their yellowtail rockfish stock assessment model therefore specified an increasing M with age. It is worth noting that in this case there is no neutral model. The true model is unknown: assuming a constant M is sup-

Table 4. Consideration of constant vs. accelerated natural mortality rates (M) in a simulated rockfish population if the target spawning potential ratio (SPR) is 35%.

ROCKFISH (<i>Sebastes</i>)	STATE OF NATURE	
MANAGEMENT DECISION	CONSTANT M (domed selectivity)	ACCELERATED M (asymptotic selectivity)
USE $F(35) = 0.102$ (assumed constant M)	CORRECT SPR = 0.35	ERROR-underfishing SPR = 0.40
USE $F(35) = 0.117$ (assume accelerated M)	ERROR-overfishing SPR = 0.30	CORRECT SPR = 0.35

ported by convention, whereas assuming an increasing M is supported by an inability to detect the existence of older fish.

If a precautionary approach is to be taken by management, multiple stock assessments may be required, ranging from a constant M case to an asymptotic selectivity curve with an increasing M, and any number of possibilities in between. Once again, a decision table based on a simulated population helps evaluate the consequences of a wrong decision, and may provide useful guidance in conducting the stock assessment. In this example, an arbitrary catch curve (numbers at age) was constructed using a rockfish (*Sebastes* sp.) life history with a constant M of 0.15 and dome-shaped selectivity peaking at age seven. Using the same catch curve and an alternative assumption of asymptotic selectivity, the selectivity was held constant above age seven, and age-specific values of M were calculated to produce the identical catches at age. Because the catch curve is identical for the two states of nature, it contains no information on which to base a choice among alternative management policies.

I have heard arguments that failure to recognize an accelerated natural mortality rate is dangerous because it can lead to excessive TACs, i.e., attempting to catch fish that do not exist. This decision table shows that in the case of an SPR-based management target, this is not the case. For the same catch curve, the estimated $F(35)$ is actually higher for the case of accelerated M. The additional fishing mortality rate has relatively less effect on what is already a truncated age structure due to higher M for old fish. This result suggests that **it may be precautionary to assume a constant natural mortality rate unless the evidence is strong for an accelerated natural mortality rate.**

Considerations of Recruitment Variability

Environmentally-Driven Low Frequency Variability

Evidence is steadily growing that many fish stocks do not conform to the stationary properties (constant

parameters and variances, etc.) typical of most of our fishery population models. Rather, there are sudden increases or decreases in productivity that may then persist for one to several decades. These shifts appear to be driven by low frequency or interdecadal variability in ocean systems, and in some cases have been associated directly with measurable oceanographic properties such as sea surface temperature (Jacobson and MacCall 1995) and also with atmospheric patterns in the North Pacific (Francis and Hare 1994) and the North Atlantic (Alheit and Hagen 1997). Although this "regime problem" was first noted in the coherent patterns of worldwide fluctuations of sardine and anchovy stocks (Lluch-Belda et al. 1989), it is now clear that these changes affect entire ocean basins and fishery ecosystems (Francis and Hare 1994, MacCall 1996, Alheit and Hagen 1997).

Conventionally, the great fishery collapses such as those in California (sardines in the 1940's) and Peru (anchoveta in the 1970s) were attributed to overfishing, perhaps complicated by brief periods of unfavorable environment. The new view is that these collapses were associated with oceanic changes in which the fisheries would have declined severely in any case, but intense fishing greatly accelerated and deepened those declines. If sustainability is not possible, then what is an alternative basis for optimal management? Walters and Parma (1996) simulated effects of climate fluctuations on fish stocks and recommended that constant fishing rate policies allowed the harvest to track fluctuations in abundance and thereby provided a good solution to the problem of climate variability. Research being conducted by the author, Larry Jacobson (SWFSC, La Jolla) and Richard Parrish (SWFSC/PFEL, Pacific Grove) suggests that when fluctuations are as large as those in the Pacific sardine, a constant fishing rate may be suboptimal (Table 5); similar results were obtained by Spencer (1997). Unlike the simulations examined by Walters and Parma (1996), Pacific sardine spawning success has a high-amplitude low-frequency component in its fluctuations. Cold environmental periods of a decade or two may occur during which no level of fishing is sustainable, followed by warm periods of similar duration

Table 5. Consideration of constant vs. variable harvest rate policies for Pacific sardine, in view of possible low frequency variability in productivity as a function of long term temperature patterns. Performance is measured by mean catch and by the frequency of low biomasses (B falling below 50,000 tons).

PACIFIC SARDINE	STATE OF NATURE	
MANAGEMENT DECISION	NO T EFFECT	LOW FREQ T EFFECT
USE Fmsy = constant	CORRECT C = 62.7 P(B<50) = 0.27	ERROR-overfishing C = 47.5 P(B<50) = 0.42
USE variable Fmsy (T)	ERROR-underfishing C = 62.1 P(B<50) = 0.27	CORRECT C = 65.4 P(B<50) = 0.29

when recruitment rates are extremely high. Based on the temperature dependent stock-recruitment relationship developed by Jacobson and MacCall (1995), a temperature-specific Fmsy can be derived, and can be compared with performance of a fishing rate that is held constant at the long-term average MSY level. These two policies were applied to two simulated resources, one with, and one without an effect of low-frequency sea surface temperature variability on reproductive success. Two measures of performance are mean annual catch, and frequency of low abundance.

If there is actually no temperature effect, then using the temperature-dependent harvest policy will perform about the same as the correct constant Fmsy policy, but with added year-to-year variability in catches (not shown). However, if there is a temperature effect on productivity, then the constant Fmsy policy performs substantially worse than the temperature-dependent policy, both in terms of average catch and frequency of low stock levels. Thus, **a precautionary approach is to use the environmentally-dependent harvest policy even if there is only weak evidence of a low-frequency environmental effect.** This result presently applies to a stock such as the Pacific sardine. Further work will help determine whether this recommendation should extend to a wider range of environmentally-dependent low frequency variability and amplitude in reproductive success. Importantly, if low-frequency environmentally-dependent variability is a major source of population variability, then contrary to conventional thinking in fishery oceanography, improving predictions of recruitment strength may not result in significantly improved management performance. Rather, improved performance is gained by incorporating the environmental effect directly into the management policy itself by means of an environmentally-dependent variable harvest rate or control rule.

Rarely Recruiting Species

Rarely recruiting species pose an especially diffi-

cult problem for fishery management. Whatever the mean relationship between recruitment and parental stock may be, it is obscured by the variability of the data and the rarity of the large recruitments that contribute most of the productivity. This section will develop a statistical basis for one possible mechanism generating rare large recruitments, and the following section will consider an expanded decision table approach to evaluating alternative management policies. The stock-recruitment relationship estimated in a recent assessment (Ralston et al. 1996) of the west coast's bocaccio rockfish, *Sebastes paucispinis*, provides an example (Fig. 2).

An unusual probability distribution based on a power function appears to describe the bocaccio data. This "power probability distribution function" (power pdf), denoted $P(\alpha, \beta)$ is based on raising uniform $U(0,1)$ random numbers to a power, β , i.e.,

$$P(\alpha, \beta) = \alpha(U(0,1))^\beta$$

where constant α normalizes the integral of the probability distribution to unity. This highly skewed distribution has a mode at zero, its lowest value. A more conventional approach uses the lognormal distribution to account for rare large recruitments, but the lognormal pdf generates fewer near-zero values, and the mode and median coincide (the mode is at zero in the power pdf). It is well known that a product of several independent random variables, such as survivorships, tends toward a lognormal distribution (i.e., under log transformation, they are additive and approach normality according to the Central Limit Theorem). A distribution resembling the power pdf may arise if the multiplicative random variables are uniformly distributed and are not independent, but rather are highly correlated (near 1) with each other. A high positive serial correlation among survivorships at sequential life stages seems to be a plausible assumption in the early life history of some fishes. Such conditions may arise especially for depleted stocks, where most of the early life history is restricted

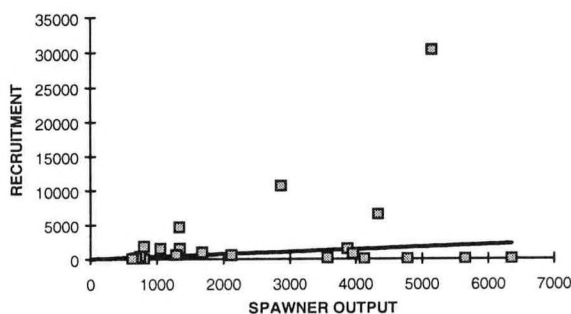


Figure 2. Stock and recruitment relationship of bocaccio rockfish. Solid line is replacement at $F=0$.

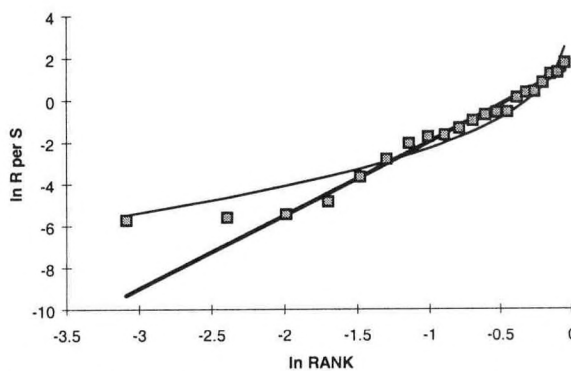


Figure 3. Log-log relationship of bocaccio spawning success (R/S) to rank ($n=21$). Linear fit (lowest two points omitted) indicates power pdf with $\beta=3.5$. Curved line is fit to a lognormal pdf (all points included).

to a small geographic area.

In the case of a power pdf, a plot of the logarithms of the observations against the logarithms of the ranks (r) produces a straight line with slope β . For the bocaccio data, a plot of log spawning success, $\ln(R/S)$, against log rank, $\ln(r/(n+1))$, is very nearly linear (Fig. 3) except for the smallest two values. The two smallest spawning successes appear to be too large to be strictly consistent with the power function distribution, but it can be argued that these extremely small values are near the limits of resolution, and strengths of the weakest recruitments are commonly overestimated due to errors in age determinations (erroneous age determinations result in a net transfer of observations from strong to weak year classes). The alternative of a lognormal pdf would produce the curved line in Figure 3 (the two lowest ranks are included in the fit), but it does not describe the data quite as well.

The power pdf can easily be combined with standard stock-recruitment models such as the Beverton-Holt stock-recruitment relationship. As usual, the regression line passes through the expected value of recruitment given stock size, but in this case there is no tendency for observations to cluster about the regression line, and the SRR is not visually apparent even for very large data sets (Figure 4 shows the stock and recruitment data from a 200-year simulation; details follow). This leads to the disturbing conclusion that even though there may be a well-defined underlying stock-recruitment relationship for a rarely recruiting species, it is possible that we may never be able to clearly discern that relationship as a basis for fishery management.

The remainder of the simulation model also represents a stock similar to the west coast's bocaccio rockfish. Both M and von Bertalanffy k are 0.15, and growth is isometric. Individual ages are tracked to age 50, with

an accumulator for ages over 50. Fecundity per unit body weight ramps linearly from zero at age 4 to unity at age 9.

The rarity of large recruitments generates low frequency variability in stock biomasses (Fig. 5). Very long declining trends, such as the first 50 years or the 80 years beginning ca. simulated year 60 (even in the absence of a fishery), are characteristic of the population behavior. The combination of difficulty in determining an optimal harvest policy from stock and recruitment data (Fig. 4) and the often false impression of chronic overfishing (Fig. 5) pose a difficult challenge for fishery management.

The Biomass Reserve as a Precautionary Management Tool

In the case of these rarely recruiting stocks, stock assessments are unlikely to resolve uncertainties in optimizing a management policy. When faced with this uncertainty, managers often resort to standard rules-of-

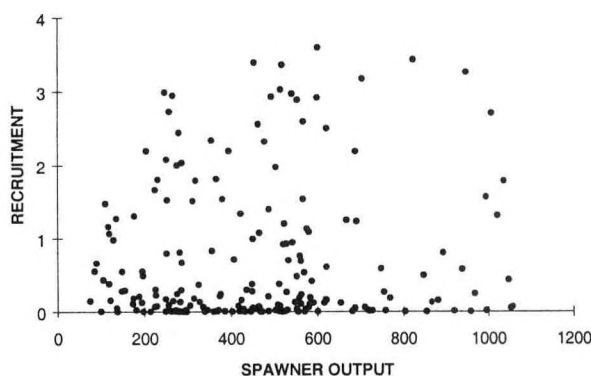


Figure 4. 200 years of simulated stock and recruitment data with a Beverton-Holt SRR and a power pdf, $\beta=4$.

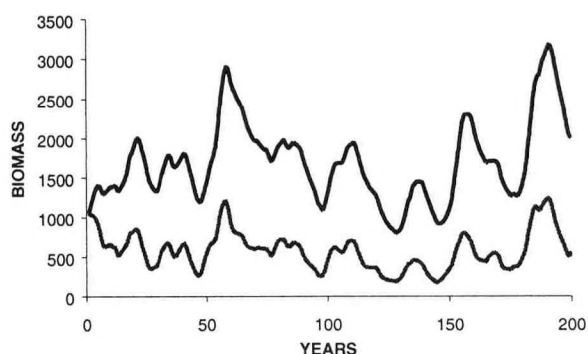


Figure 5. Simulated time series of biomasses for a rarely recruiting stock. The upper series is unexploited; the lower series is exploited at $F=0.15$.

thumb such as $F=M$, or $F_{35\%}$, but the risk in using those values tends to be unquantified and ignored. Here, I present the concept of a biomass reserve as an alternative approach to precautionary management and will show that it provides a desirable robustness to uncertainties such as are encountered in rarely recruiting species.

A biomass reserve is a quantity of stock that is set aside before implementing an otherwise conventional catch policy. In most applications the harvest has been set at a fixed proportion of the biomass in excess of a minimum threshold corresponding to the biomass reserve. More generally, any conventional harvesting policy can be implemented on the biomass in excess of the reserve amount. Biomass reserve policies have been used successfully in California to manage small pelagic fishes for over twenty years (for examples, see Parrish and MacCall 1978, and MacCall et al. 1985 for man-

agement of mackerel, *Scomber japonicus*, and Radovich and MacCall 1979, and MacCall 1980 for management of northern anchovy). At about the same time, a similar policy was developed independently for management of some Alaskan salmon harvests (Hilborn 1985) and was considered for management of west coast groundfish (Hightower and Lenarz 1989). Recently another development of this approach, called "proportional threshold harvesting," has been shown to perform well when biomass estimates are uncertain (Engen et al. 1997).

Conventional suggestions for a precautionary approach to harvesting have tended to involve explicit reductions in fishing mortality rate. Here I will use the model of a rarely recruiting species to examine how use of a biomass reserve compares with reductions in a conventional SPR-based constant harvest rate policy. Given the difficulty of estimating a stock-recruitment relationship from data such as are shown in Figure 4, the productivity of the stock will be considered to be any of three equally likely possibilities, corresponding to strong, medium and weak compensation in a Beverton-Holt SRR. Parametrized as the percentage of virgin recruitment expected at one-half the virgin stock size, these levels are 90%, 80% and 70% respectively.

The performances of alternative fishing policies, with and without a biomass reserve, are compared in a decision table (Table 6). Two measures of performance are considered: mean harvest (Y_{mean}) and relative risk (R), defined as $R = 100\%(Y_{\text{mean}} - Y_{\text{min}})/Y_{\text{mean}}$, where Y_{min} is the smallest of the three simulated harvests. Relative risk ranges from zero, indicating no difference in performance among the three possible states of nature, to 100%, indicating total loss as a worst case. As a

Table 6. Decision table analysis of harvest policy performance with and without a biomass reserve for a rarely recruiting stock where true productivity is unknown.

SIMULATED FISHERY		STATE OF NATURE (true productivity)				
MANAGEMENT DECISION		HIGH 90%R@50%B	MEDIUM 80%R@50%B	LOW 70%R@50%B	Y_{mean}	RELATIVE RISK
NO RESERVE	F(20%)	76.1	5.6	0	27.2	100%
	F(35%)	84.6	47.2	0.0	44.2	98%
	F(45%)	80.2	56.4	13.9	50.2	72%
	F(55%)	71.2	56.5	29.3	52.3	44%
RESERVE 10% of initB	F(20%)	86.8	54.6	26.7	56.0	52%
	F(35%)	82.1	58.9	31.6	57.5	45%
	F(45%)	75.0	58.1	34.6	55.9	38%
	F(55%)	65.3	53.9	36.1	51.8	30%

Table 7. Decision table analysis of standardized harvest policy performance with and without a reserve for a rarely recruiting stock where true productivity is unknown. Each yield is expressed relative to the maximum possible yield in the respective state of nature.

SIMULATED FISHERY		STATE OF NATURE (true productivity)				
MANAGEMENT DECISION		HIGH 90%R@50%B	MEDIUM 80%R@50%B	LOW 70%R@50%B	Y _{mean}	RELATIVE RISK
		max = 89.29	max = 61.71	max = 38.46		
NO RESERVE	F(20%)	0.852	0.091	0	31%	100%
	F(35%)	0.947	0.765	0.023	58%	96%
	F(45%)	0.898	0.914	0.361	72%	50%
	F(55%)	0.797	0.916	0.762	82%	8%
RESERVE 10% of initB	F(20%)	0.972	0.885	0.694	85%	18%
	F(35%)	0.919	0.954	0.822	90%	9%
	F(45%)	0.840	0.942	0.900	89%	6%
	F(55%)	0.731	0.873	0.939	85%	14%

basis for evaluating alternative policies, Table 6 contains a flaw: Low yields may be due either to excessive fishing pressure or to inherently low resource productivity, and the analysis in Table 6 does not distinguish between the two cases.

A better policy evaluation is obtained by first standardizing harvests relative to what can be expected in each state of nature. For each productivity level, an approximate maximum possible yield was calculated by searching over all possible biomass reserves and harvest intensities. These maxima typically featured reserves in the vicinity of 30% of initial biomass and high harvest rates, thus approaching a constant escapement policy. Table 7 expresses each yield as a fraction of this maximum. The mean harvest is now interpreted as the mean fraction of what is possible in each state of nature, and the relative risk no longer confounds productivity with effects of fishing intensity. While standardization results in minor changes in the rankings of mean yield, the estimates of relative risk tend to be much lower in Table 7, demonstrating the severity of the flaw in Table 6.

The robust properties of incorporating a biomass reserve are clearly apparent in Table 7. Without the reserve, the optimal fishing rates tend to fall in a relatively narrow range and run a high risk of stock depletion if productivity is actually low. For example, F(35%), which has seen widespread usage as a proxy for F_{msy} ,

works well if productivity is high, and works fairly well under medium productivity, but is disastrous under low productivity. In contrast, if $F_{35\%}$ is applied to the remaining biomass after setting aside a 10% reserve, all three potential states of nature produce reasonable performances relative to what is possible. Relative risk drops from 96% (i.e., risk of near-total loss) without the biomass reserve to only 9% with the reserve, indicating a consistent performance across the range of possible natural productivity levels. In the case of this simulated rarely recruiting species, among the non-reserve policies, $F_{55\%}$ performs the best; however this fishing rate is extraordinarily low by conventional standards. If a 10% biomass reserve is implemented, nearly any choice of F(SPR) on the remainder equals or outperforms $F_{55\%}$ without a reserve. The implication of these results is that if a biomass reserve is established, then any of a wide range of fishing rates will perform well. This robust property associated with use of a biomass reserve is especially suited to management of a rarely recruiting stock where information may never be sufficient to identify precisely an optimal harvest rate.

Acknowledgments

Many of the analyses in this paper were conducted in collaboration with other researchers, each of whom would merit coauthorship of that section. I hope and expect that many of those sections will eventually appear as proper publications with proper authorship. My

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Evolution, Scope, and Current Applications of the Precautionary Approach in Fisheries

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Abstract.— Overexploitation of natural fish stocks is a global and growing problem despite substantive advances in the disciplines of fisheries science and management. The problem has been well-understood by many professionals for several decades, but it is only in this decade that it has received widespread public recognition and reaction. In the 1990s, several international conferences and agreements embodying the essential need for precautionary approaches to fisheries have been initiated and concluded, primarily by the United Nations. The scope of the precautionary approach is extremely broad. It applies at all levels of fisheries systems: development planning, management, research, technology development and transfer, legal and institutional frameworks, fish capture and processing, fisheries enhancement, and aquaculture (FAO 1996). Current applications and discussions have for the most part focused on specifying, estimating, and applying target and limit biological reference points. Although this is an important and crucial component of the precautionary approach, it needs to be put in the context of a systems approach incorporating many other relevant features. Some fisheries organizations and management agencies have already made progress defining and implementing multifaceted precautionary approaches, but in most cases marked changes in institutions, management procedures, and expectations need to occur before precautionary approaches can be fully embraced.

Introduction

This paper gives a brief introduction to the history of development of the precautionary approach in fisheries, the overall scope of the precautionary approach with reference to the role of biological reference points and harvest control rules, and the approaches taken by fisheries organizations that are currently adapting or further developing precautionary approaches for their own use. We conclude with some thoughts on the prospect that truly precautionary approaches will ever be fully adopted as the norm in fisheries management.

Precautionary Approach vs. Precautionary Principle

The Precautionary Principle refers to a “hard line” rule originally conceptualized as a means of managing highly polluting activities. The aim was to control pollution at source even in the absence of scientific evidence proving a causal link between emissions and environmental effects. The Precautionary Principle guards against the possibility of making irreversible mistakes through ignorance. In several instances, the Precautionary Principle has been applied in an extreme form, resulting in a complete prohibition of a particular type of industry or technology (e.g. large-scale high seas driftnet fishing). This has resulted in a reluctance to embrace the Precautionary Principle in fisheries management where most mistakes have high probability of being reversible. Thus, the precautionary *approach* was created as a somewhat more flexible alternative that incorporates socio-economic considerations along with the essential requirement of promoting the long-term sustainability of natural resources.

Evolution

The United Nations Convention on the Law of the Sea (1982) provided an overall framework and mechanisms to promote responsible management of marine fisheries. However, it was not until the 1990s that work began in earnest to develop a precautionary approach to fisheries management. In 1991, the 19th Session of the Committee on Fisheries (COFI) of the Food and Agriculture Organization (FAO) of the United Nations requested that FAO develop an International Code of Conduct for Fisheries. Subsequently, FAO and the Mexican government sponsored an International Conference on Responsible Fishing, held in Cancun, Mexico in May 1992. Declarations formulated in Cancun were presented at the United Nations Conference on Environment and Development (UNCED) in Rio in June 1992. The Rio meeting highlighted the importance of the precautionary approach in the Rio Declaration and Agenda 21. For example, Principle 15 of the Rio Declaration states that:

“in order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation”

FAO International Code of Conduct for Responsible Fisheries

Several binding and non-binding agreements em-

bodying the precautionary approach were developed and concluded over the period 1991-1996. The most comprehensive of these is the FAO International Code of Conduct, adopted by FAO Conference in October 1995 (FAO 1995). The Code of Conduct addresses six key themes: fisheries management, fishing operations, aquaculture development, integration of fisheries into coastal area management, post-harvest practices and trade, and fisheries research. In total, there are 19 general principles and 210 standards in the Code. While a precautionary approach is integral to all themes, it is applied particularly to fisheries management, as detailed in Article 7.5. Paragraph 7.5.1 includes a broad statement to the effect that:

"States should apply the precautionary approach widely to conservation, management, and exploitation of living aquatic resources in order to protect them and preserve the aquatic environment".

The same paragraph also emphasizes that the absence of adequate scientific information is not a reason for failing to take appropriate conservation and management measures. The remaining paragraphs include similar provisions to those in Article 6 of the Straddling Stocks Agreement (see below); for example, determination of stock-specific target and limit reference points, together with action to be taken if they are exceeded, and the need to take account of uncertainties and impacts on non-target and associated or dependent species. In addition, guidelines are given for adopting a cautious approach in the case of new or exploratory fisheries, and for implementing emergency management measures when resources are seriously threatened due to environmental factors or fishing activity.

The Code of Conduct is a voluntary, non-binding agreement. However, it contains sections that are similar to those in two recently concluded binding agreements: the Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas (the Compliance Agreement) and the Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (officially abbreviated as the UN Implementing Agreement, or UNIA, but commonly referred to as the Straddling Stocks Agreement).

Compliance Agreement

An FAO Technical Consultation on High Seas Fishing was held in September 1992 and the Compliance Agreement was adopted by FAO Conference in November 1993. The Compliance Agreement specifies the ob-

ligations of Parties whose fishing vessels fish on the high seas, including the obligation to ensure that such vessels do not undermine international fishery conservation and management measures. The Compliance Agreement is considered to be an integral part of the Code of Conduct, as specified in a resolution to this effect adopted by the 1993 FAO Conference. The United States implemented the Compliance Agreement through the High Seas Fishing Vessel Compliance Act of 1995.

Straddling Stocks Agreement

The Straddling Stocks Agreement was negotiated over a similar period to the Code of Conduct and the content and wording on many issues, including those related to the precautionary approach and General Principles, is similar between the two Agreements. Although the Straddling Stocks Agreement is strictly only applicable to straddling fish stocks and highly migratory fish stocks, much of it is also relevant to fishing within national exclusive economic zones. The Straddling Stocks Agreement will almost certainly require international organizations to adopt strict overfishing criteria, if ratified.

The Straddling Stocks Agreement describes the "precautionary approach" in Article 6 and Annex II. Article 6 requires application of the guidelines set out in Annex II; determination of stock-specific reference points and action to be taken if they are exceeded; use of the best available scientific information; implementation of improved techniques for dealing with risk and uncertainty; account of uncertainties and impacts on non-target and associated or dependent species; and development of appropriate data collection, research, and monitoring programs.

Annex II of the Straddling Stocks Agreement provides guidelines for the application of precautionary reference points. Paragraph 2 states, "Two types of precautionary reference points should be used: conservation, or limit, reference points and management, or target, reference points." Paragraph 5 stipulates, "Fishery management strategies shall ensure that the risk of exceeding limit reference points is very low," and imposes the further constraint that target reference points should not be exceeded on average. Paragraph 7 states that "The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points." This combination of requirements implies that fishing mortality should always be well below the level associated with maximum sustainable yield (F_{MSY}). Such a requirement is a profound and significant departure from typical fisheries management practice, where F_{MSY} is usually treated as a target (and usually exceeded) rather than a limit.

FAO Technical Guidelines on the Precautionary Approach

As part of the process of developing the FAO International Code of Conduct for Responsible Fisheries, FAO was requested to elaborate technical guidelines in support of implementation of the Code. Accordingly, FAO and the Government of Sweden held a Technical Consultation and produced guidelines on the Precautionary Approach to Capture Fisheries and Species Introductions in June 1995. These guidelines were initially published by FAO in 1995, then reproduced with minor editing as part of a new series on "FAO Technical Guidelines for Responsible Fisheries" in 1996. They include sections on fisheries management, fisheries research, fishing technology and species introductions. The first three of these are considered in detail in the next section of this report.

More detailed treatments of the historical development of the precautionary approach are contained in ICES (1997), Serchuk et al. (1997), and Thompson and Mace (1997).

Scope of the Precautionary Approach

How important are biological reference points (BRPs) and harvest control rules in the overall context of the precautionary approach?

As mentioned above, the 1995 International Code of Conduct (FAO 1995) addresses several general principles and six key themes:

- Fisheries Management
- Fishing Operations
- Aquaculture Development
- Integration of Fisheries into Coastal Area Management
- Post-Harvest Practices and Trade
- Fisheries Research

According to FAO (1996), precaution is required at all levels; for example, in development planning, management, research, technology development and transfer, legal and institutional frameworks, fish capture and processing, fisheries enhancement, and aquaculture. Thus the precautionary approach is multi-faceted and broad in scope.

The FAO Technical Guidelines on the Precautionary Approach (FAO 1996) groups guidelines on the precautionary approach into three primary subject areas of relevance to capture fisheries: fisheries management, fisheries research, and fisheries technology. The next three subsections summarize the main issues covered under each area and, while they do not include every

aspect of the guidelines, they highlight the large number and diversity of issues involved.

Fisheries Management

The precautionary approach to fisheries management requires:

- prudent foresight;
- inclusion of precaution in all stages of the management process, from planning through implementation;
- taking account of unknown uncertainty by being more conservative;
- establishment of legal or social frameworks for all fisheries including rules to control access, data reporting requirements, and management planning processes;
- implementation of interim measures that safeguard resources until fisheries management plans are developed;
- avoidance of undesirable or unacceptable outcomes such as overexploitation of resources, overdevelopment of harvesting capacity, loss of biodiversity, major physical disturbances of sensitive biotopes, and social or economic dislocations;
- explicit specification of management objectives including operational targets and constraints;
- extensive consultation to ensure broad acceptance;
- prospective evaluation; and
- sound procedures for implementation, monitoring and enforcement.

Fisheries Research

In keeping with the precautionary approach, research should strive to:

- provide data and analyses of relevance to fisheries management;
- emphasize the roles that fisheries scientists and others must play in helping managers develop objectives;
- provide scientific evaluation of consequences of management actions;
- develop operational targets, constraints and criteria that are both scientifically usable and have management relevance;
- conduct both biological and socio-economic research;
- ensure that data are accurate and complete;
- monitor fisheries;
- conduct research on which management processes and decision structures work best;
- incorporate uncertainty into assessments and management;

- conduct research on reversibility in ecosystems;
- formulate implementation guidelines;
- promote multi-disciplinary research, including social, economic and environmental sciences, and research on management institutions and decision-making processes; and
- conduct research into environmentally-friendly fishing gears.

Fisheries Technology

A precautionary approach to fisheries technology would:

- not use technology to further increase capacity in already overcapitalized fisheries;
- use technology to improve sustainability, prevent damage to the environment, improve economic and social benefits, and improve safety;
- evaluate the effects of new technologies and gears;
- educate fishers and consumers towards responsible practices;
- consider impacts on non-target species and ecosystems;
- evaluate fishing gears with respect to selectivity by size and species, survival of escapees, ghost fishing, effects on habitat, contamination, pollution, generation of debris, safety and occupational hazards, user conflicts, employment, monitoring and enforcement costs, techno-economic factors (infrastructure and service requirements, product quality), and legal factors (existing legislation, international agreements, civil liberties);
- consider proper procedures for introducing new technology or changes to existing technology;
- promote research to encourage improvement of existing technologies and to encourage development of appropriate new technologies;
- ensure proponents and other stakeholders understand obligations and rights; and
- encourage research into responsible fisheries technology.

The Role of BRPs and Harvest Control Rules

From these three lists, it is obvious that biological reference points and harvest control rules are but one small part in the overall framework of the precautionary approach. In fact, BRPs are not mentioned at all in the summary section of the FAO Technical Guidelines on the Precautionary Approach (FAO 1996). Although they can be considered a central feature of any precautionary management strategy, biological reference points need to be put in proper perspective. Other needs may be just as important; for example, development of access control systems to ensure that fishing capacity is

commensurate with resource productivity, evaluation of alternative management systems and institutions, improvements in the quality and reliability of input data, improved monitoring and enforcement, design of "environmentally-friendly" fishing gear, and education of fishers and consumers.

As it happens, there is more work going into the development of new biological reference points and associated harvest control rules than into any of the other areas listed above. For many fisheries scientists, the term precautionary approach has almost become synonymous with setting a conservative upper bound on allowable fishing mortality. Yet there is a long history of devising biological reference points and incorporating them into management advice. Examples of biological reference points that have been proposed in the past include F_{MSY} , MSY , B_{MSY} , F_{max} , $F_{0.1}$, $2/3F_{MSY}$, F_{med} , F_{high} , F_{low} , F_c , $F_{20\%}$, $F_{35\%}$, $MBAL$, F_{loss} (see Gabriel and Mace, this volume, for descriptions of these reference points). Add to this the new reference points proposed by ICES and NAFO summarized later in this paper; viz. F_{lim} , F_{buf} , F_{PA} , B_{lim} , B_{buf} , and B_{PA} . One might ask whether adding progressively more biological reference points is likely to ensure that scientific advice will be taken more seriously. It should be noted that even though the concept of MSY has existed for several decades and many fisheries management plans explicitly identify MSY as the objective, in reality there are very few fisheries for which fishing mortality has been maintained near or below the level associated with MSY . It appears that as the list of biological reference points has lengthened, and as assessment scientists' advice has become progressively more risk-averse, average global fishing mortality has increased.

Putting Precaution in its Proper Place

In the authors' opinion, the FAO Technical Guidelines to the Precautionary Approach (FAO 1996) overuse the word "precautionary". The Guidelines refer to "precautionary research", "precautionary monitoring" of fishing, and a "precautionary system of enforcement", when what is really meant is relevant and informative research, and effective monitoring and enforcement. More misleading is the reference to "precautionary assessments" of stock status (paragraph 66, FAO 1996). The authors believe that terms like "precautionary assessments" and "precautionary science" should be avoided, and "precautionary" should generally be used only as an adjective describing "management".

Precautionary management supported by best available science

It is important that the term "precautionary" be applied in the proper context. In particular, care should be

taken when using the term in relation to the science used to support advice to managers. It is perfectly reasonable for a manager to select a “precautionary” management target (e.g. $F = 75\% F_{MSY}$ or $F =$ lower 80% CI of the probability distribution for F_{MSY}) based on advice from scientists, but it is not reasonable for scientists to add extra (non-transparent) conservatism or precaution into the estimation process by, for example, calculating a lower CI for a particular BRP and presenting it as the best estimate of that BRP (e.g. claiming that the lower 80% CI of the distribution of F_{MSY} is the best estimate of F_{MSY}). Thus, the “precautionary approach” should be restricted to the *selection* of biological reference points or fishing targets on which to base management advice, not to the *estimation* of those reference points and targets. Similarly, estimates of assessment-related quantities (e.g. M , growth rates, selectivity patterns and maturity ogives) should be “best estimates”, not “precautionary estimates”, and decisions made in stock assessments regarding model choice and estimation techniques should be based on scientific and statistical arguments, not on which model has the most precautionary interpretation (e.g. the choice between two different theoretical curves fit to stock-recruitment data).

There are already many instances where members of the fishing industry have argued that stock assessment results are deliberately biased low, and that there is therefore no harm in postponing restrictive management actions. It is appropriate (and necessary) for scientists to provide precautionary management advice, but such advice must be based on the “best” assessment, not a conservative assessment; otherwise the advice may not be taken seriously. In addition, precautionary elements of the management advice must be transparent and clearly understood.

Current Applications

There are at least three international organizations that can be said to have already adopted “precautionary” management procedures, even though that particular term may not have been in vogue at the time: the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), the International Pacific Halibut Commission (IPHC), and the International Whaling Commission (IWC). Two other international organizations have recently been actively developing new biological reference points and harvest control rules that embody the precautionary approach; namely, the International Council for the Exploration of the Sea (ICES) and the Northwest Atlantic Fisheries Organization (NAFO). The North Atlantic Salmon Conservation Organization (NASCO) and the International Commission for the Conservation of Atlantic Tunas (ICCAT) have both recently set up special committees to examine the implications of the precautionary approach. In

addition, at least two new organizations have pledged to adopt the precautionary approach and uphold other requirements of the Straddling Stocks Agreement (an organization covering highly migratory species in the western and central Pacific, based on the Majuro Declaration; and the Southeast Atlantic Fisheries Organization, SEAFO). Details follow.

Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR)

CCAMLR, which entered into force in 1982, has one of the longest histories of defining and implementing precautionary approaches, although they may not have been explicitly labeled as such. Most importantly, CCAMLR was the first international convention to explicitly attempt to specify and implement an ecosystem approach to fisheries management, acknowledging the needs of predators (e.g., whales, seals and birds) and the role of certain prey species (e.g., Antarctic krill) as a critical forage base. According to the Convention, harvesting and associated activities must be conducted so as to (1) prevent any harvested populations from falling below the level that ensures the greatest net annual increment, (2) maintain the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources and restore depleted populations, and (3) prevent or minimize the risk of changes in the marine ecosystem that are not potentially reversible over two to three decades. By any measure, these objectives have strong precautionary aspects, although the term “precautionary” does not appear specifically (Kirkwood and Smith 1995).

From the beginning, CCAMLR took a strong precautionary approach by prohibiting all directed fisheries on several severely depleted stocks of demersal finfish and setting restrictive catch limits for most other exploited stocks. There are currently detailed rules in place for new and exploratory fisheries. For example, at a recent meeting of the Commission, it was agreed that exploratory fishing on Antarctic toothfish must cease if catches reach levels sufficient to demonstrate commercial potential, at which time a detailed evaluation would need to be conducted before further fishing could be authorized. However, there are also obstacles to full implementation of a precautionary approach in the CCAMLR arena. For example, there are no guidelines to ensure that resumption of harvests in fisheries previously closed for the purpose of rebuilding depleted stocks does not again result in overfishing. There is also no mechanism to prevent fishing on stocks for which TACs have not been set. In addition, the Commission is a consensus body, with any one member having veto power, and this can sometimes make it difficult to get strong conservation actions accepted.

International Pacific Halibut Commission (IPHC)

Of all international fisheries commissions, the IPHC can be said to have had the longest run of successful management (at least from a conservation perspective, though until recently both the U.S. and Canadian fisheries have been characterized by too many vessels and too few fishing days). The stock has never collapsed and is still providing higher than average yields. Several elements of the precautionary approach are evident in the strategies adopted by the Commission. Maintaining a large spawning biomass has taken precedence over maximizing productivity (McCaughan 1996). Remarkably, the IPHC has set conservative quotas in the face of uncertainty, has not let short-term economic concerns influence decisions, and has not been subject to political interference (McCaughan 1996).

International Whaling Commission (IWC)

The revised management procedure of the IWC, developed during the late 1980s and early 1990s, did not explicitly consider a precautionary approach, yet the procedure ultimately adopted was one that was both precautionary by design and precautionary in performance (Kirkwood and Smith 1995). The first step was the identification and quantification of the IWC's management objectives. Next, simulation trials of management procedures were conducted and the performance of the procedures in meeting management objectives was evaluated statistically. The two key features of the process adopted by the IWC were that all elements of the management strategy were tested simultaneously and that robustness was examined to a much wider range of uncertainties than is normally considered (Kirkwood and Smith 1995).

International Council for the Exploration of the Sea (ICES)

ICES is in the process of developing and implementing the precautionary approach as part of its standard fisheries management advice. A comprehensive report has been developed by a study group (ICES 1997) and another is underway, based on a meeting in February 1998.

Whereas Annex II of the Straddling Stocks Agreement suggests use of F_{MSY} as the limit reference point, the ICES study group advised setting the limit reference point (F_{lim}) equal to a conservative estimate of F_{crash} , the fishing mortality corresponding to the tangent through the origin of a stock-recruitment relationship (referred to as $F_{extinction}$ or F_{τ} by Mace and Sissenwine (1993) and Mace (1994)), or a related quantity. While this may seem a rather risky reference point, the study group then suggested that the precautionary fishing mortality should

be expressed as $F_{PA} = F_{lim} e^{-2\sigma}$, where σ should take into account several sources of variation and error. If σ is as high as 0.35, F_{PA} will be about half of F_{lim} . For some stocks, this may result in F_{PA} levels quite close to the point estimate of F_{MSY} (e.g., Mace (1994) showed that point estimates of F_{MSY} could be up to 43% of point estimates of F_{τ} for certain life history parameter combinations in deterministic, age-structured fishery models). The ICES study group also defined B_{lim} as a biomass limit below which the stock is in imminent danger. As with precautionary fishing mortality rates, a precautionary biomass level should be defined based on B_{lim} as modified by some margin of safety.

The ICES study group met for the second time in February 1998 and further developed methods and guidelines for estimating these and related reference points, and provided preliminary estimates of precautionary reference points for most ICES stocks.

Northwest Atlantic Fisheries Organization (NAFO)

The approach currently under discussion by NAFO (see for example Serchuk *et al.* 1997) bears considerable resemblance to the ICES approach, with one key difference. NAFO appears to have accepted the literal interpretation of paragraph 7 of Annex II of the Straddling Stocks Agreement, and set $F_{lim} = F_{MSY}$ rather than a quantity related to $F_{extinction}$ (F_{τ}). Serchuk *et al.* (1997) further define a term, F_{buf} as "a fishing mortality rate below F_{lim} that acts as a buffer to ensure that there is a high probability that F_{lim} is not reached. As such, on average, F_{buf} should not be exceeded. The more uncertain the estimate of F_{lim} , the lower the value of F_{buf} and the greater the distance between F_{lim} and F_{buf} ". $F_{target, lim}$ a fishing mortality level based on management objectives, is defined to be a level below or equal to F_{buf} . Similarly, B_{lim} is defined as a "level the spawning stock biomass should not be allowed to fall below", and B_{buf} is "a level of spawning stock biomass, above B_{lim} , that acts as a buffer to ensure that there is a high probability that B_{lim} is not reached". In addition, for depleted stocks, B_{tr} is defined as the target total stock biomass recovery level that would produce maximum sustainable yield.

In March 1998, NAFO conducted a workshop to review the implications of this and other approaches (including the approaches reviewed or developed by ICES), and to begin attempting to apply them to NAFO stocks (NAFO 1998).

North Atlantic Salmon Conservation Organization (NASCO)

A meeting of the Working Group on the Precautionary Approach in North Atlantic Salmon Management was held in Brussels, Belgium in January 1998.

The Working Group recommended that “NASCO and its Contracting Parties should apply the Precautionary Approach widely and consistently to the conservation, management and exploitation of salmon in order to protect the resource and preserve the environments in which it lives...”, with subsidiary recommendations echoing the language of the FAO Technical Guidelines on the Precautionary Approach to Capture Fisheries and the Straddling Stocks Agreement. The Working Group agreed that the precautionary approach is not limited in its scope but is a philosophy which would apply generally in order to take into account scientific uncertainty and imperfect management. It was recommended that management measures should be aimed at maintaining all salmon stocks in the NASCO Convention Area above their conservation limit, currently defined by NASCO as the spawning stock level that produces maximum sustainable yield. It is currently unclear whether B_{MSY} is actually the limit or the target, and if not, exactly how the limit and the target differ.

International Commission for the Conservation of Atlantic Tunas (ICCAT)

ICCAT's management strategy is founded on MSY. In fact, the Convention itself (International Convention for the Conservation of Atlantic Tunas; Rio de Janeiro, 1966) never uses this acronym, does not imply that levels exceeding MSY constitute overfishing, does not use terms such as overfishing and overexploitation, and is not specific about the actual management objectives and how they will be applied. Nevertheless, ICCAT tends to evaluate the status of stocks relative to MSY-based reference points. Typically, ICCAT classifies stocks as “overexploited” when the exploitable biomass falls and stays below B_{MSY} , the average biomass level associated with MSY. ICCAT also raises concerns about overfishing for some species groups when estimated fishing mortality is well in excess of F_{MSY} .

In October 1997, ICCAT's Standing Committee on Research and Statistics (SCRS) agreed to form an ad hoc working group to develop recommendations on the application of the precautionary approach to Atlantic tunas and tuna-like species. The first meeting was held in May 1998.

Majuro Declaration

A Multilateral, High-Level Conference (MHLC) on the conservation and management of highly migratory fish stocks in the western and central Pacific was held in Majuro, Republic of the Marshall Islands in June 1997. The conference resulted in the “Majuro Declaration” which states that the entities represented at the conference declare their commitment to establish a mechanism for the conservation and management of highly migra-

tory fish stocks of the region in accordance with the Law of the Sea Convention and the Straddling Stocks Agreement, including wide application of the precautionary approach. The Declaration emphasizes the commitment to adoption of the precautionary approach several times in the text. A workshop on precautionary limit reference points for highly migratory fish stocks in the western and central Pacific Ocean is scheduled to be held in Honolulu in late May, 1998.

Southeast Atlantic Fishery Organization (SEAFO)

Another example of a current international initiative that incorporates the precautionary approach is the proposed establishment of the Southeast Atlantic Fishery Organization (SEAFO). SEAFO was proposed in 1997 by the three coastal states, Angola, Namibia, and South Africa, and the United Kingdom (on behalf of St. Helena and its other island dependencies in the area) as an organization which would have management responsibilities for the fish resources (except highly migratory species and cetaceans) in the southeast Atlantic. The draft SEAFO Convention that was distributed and discussed in December 1997 in Windhoek, Namibia, is replete with references to the precautionary approach and precautionary reference points. Equally significant is the fact that the coastal states are urging the creation of SEAFO primarily to manage and conserve a recently discovered and poorly understood handful of high seas or straddling stocks, many of which are believed to have low productivity (e.g. orange roughy, toothfish, alphonsons and armourheads).

Other Applications of the Precautionary Approach

The term “precautionary approach” has quickly become an integral part of the vocabulary of fisheries professionals. However, its precise interpretation and operational procedures for its implementation have not yet been formally developed by most governmental and international organizations. The precautionary approach has so many facets that it is possible for fisheries management agencies to claim that they have already adopted the approach, particularly in the case of stocks that have not yet collapsed or are in the process of rebuilding. And almost every reform currently under development can be construed as adhering to one or more components of the precautionary approach. Thus, a comprehensive global overview of attempts at implementing a precautionary approach is not really practical, and perhaps not even useful (see Thompson and Mace 1997 for an early attempt to summarize applications of the precautionary approach on a global basis). Suffice to say that many countries are in the process of integrating the precautionary approach into their national fisheries policies. Those at the forefront include the United States, Canada, New Zealand, Australia, and South Africa.

Prospects and Prognosis

For most national and international fisheries organizations, implementation of the precautionary approach will radically change both the form of scientific advice and the level of conservatism embodied in that advice. The primary reason is the requirement that F_{MSY} be used as an upper bound on permissible fishing targets (as implied by the definition of Optimum Yield in the Magnuson-Stevens Act), or a limit to be avoided (as stated in Annex II of the Straddling Stocks Agreement), rather than a frequently-exceeded target. Since fishing mortality rates in many of the world's commercial marine fisheries are already well beyond F_{MSY} , substantial overall reductions in fishing mortality will be required.

Even if management agencies have sufficient authority and resolution to implement such reduced fishing limits, they will encounter numerous impediments to the full adoption of the precautionary approach in fisheries. The first and most obvious of these is human population growth, particularly in coastal developing nations where food security is becoming an increasingly alarming problem. Pressures of population growth have resulted in increased demand for fish in subsistence fisheries, as well as increased demand for fish imports in some nations, with the latter resulting in an overall increase in exports of fish from developing to developed nations. The net effect is gross overcapacity (both in terms of capital and labor inputs) on a global scale, relative to what natural marine resources are capable of producing on a sustainable basis. The current situation of overcapacity and overdependence on natural marine resources represents a tremendous obstacle to effective fisheries management, particularly when coupled with the lack of political will to confront the problem in most countries. Mace (1996) discussed these issues in detail, along with the related problems of the common mentality that still perceives fishing as the "last frontier", belief in the status quo (the status quo should be retained at all costs; change is bad), oversimplified objective functions, conflicting objectives of user groups, and the propensity for short-term economic gain to win out over long-term sustainability.

Unfortunately, solutions to the overcapacity and overdependence problem generally remain elusive. Development of aquaculture may assist in reducing dependence on natural marine resources, and reduced dependence may alleviate the overcapacity problem. However, to date, most attempts to reduce fleet capacity have been expensive and largely ineffective (the exception being some instances where individual transferable quotas or other forms of property rights systems have been implemented).

A necessary precursor to the adoption of a precau-

tionary approach to fisheries management is an overall change in the mindset of users and consumers alike; expectations of the ability of natural marine resources to provide food and income for current and future generations need to be aligned with reality. On the positive side, there is evidence of growing public awareness of the extent of overfishing, the resultant depletion of the world's fisheries resources, and the need for risk-averse approaches to the exploitation of natural resources. This awareness is being fueled by the growing involvement of the conservation community and growth of the recreational and "ecotourism" sectors. Public awareness may be further elevated by "eco-labelling" projects currently underway, provided these maintain credibility based on sound scientific analysis. There is also a world-wide movement to discourage or abolish government subsidies in a number of different areas, including fisheries. Already, the breakup of formerly heavily-subsidized economies has helped alleviate overfishing in some parts of the world. Ultimately, sustained public involvement and outcry should mobilize the political will needed to fully adopt the precautionary approach.

The scientific community also needs to become more involved. To date, scientists have generally been reluctant to make recommendations on matters that can be construed as "allocation issues". However, in the future, it may be beneficial for scientists to become much more involved in so-called allocation issues; for example, making recommendations on environmentally-friendly vs. destructive fishing gears; highlighting the ills of overcapacity and excess competition and their implications for assessment, management, monitoring and enforcement; and calculating MSY and other reference points on the basis of an "optimum" catch-at-age distribution (and subsequently making recommendations about where, when and how to fish) instead of just going along with the existing partial recruitment pattern.

In many respects, the precautionary approach is simply the newest in a long list of "buzz words" that don't have concise operational definitions, but do have similar management implications. This list includes recent calls for risk-averse management, ecosystem approaches, maintaining biodiversity, maintaining genetic diversity, reducing bycatch, and so forth. The management implications of each of these are simple and straightforward: all imply that fishing mortality must be reduced across the board -- on all species at all trophic levels in all oceans. Ultimately, this is what the precautionary approach will entail.

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The Need for Guidance on The Precautionary Approach and The Proposed National Standard Guidelines

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Abstract.- The most recent assessment of stocks subject to the jurisdiction of the Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act) indicated that 96 of 279 species for which information was available are “overfished” or are approaching an overfished condition. The status of an additional 448 species relative to overfishing is unknown. The benchmark against which overfishing was measured in this compilation was generally recruitment overfishing, suggesting that recruitment failures are potentially imminent, unless dramatic action is taken to reverse this condition. This comes at the culmination of 20 years of active management of the fisheries supported by these species pursuant to the Magnuson-Stevens Act. Further, this 20-year period of management has brought with it the first ever listings of fishes in the U.S. beyond the freshwater environment (several salmonid stocks in the Pacific Northwest) as threatened and endangered under the Endangered Species Act. In short, the record of marine fisheries management by the Federal Government does not have many success stories. NMFS has been presented with a tremendous opportunity to reverse the current situation. The Sustainable Fisheries Act of 1996 fundamentally changed the Magnuson-Stevens Act by integrating the internationally adopted precautionary approach throughout its provisions. Among those provisions are the National Standards for fishery conservation and management and the guidelines that must be developed by NMFS to assist the Regional Fishery Management Councils in developing Fishery Management Plans and amendments thereto. The revision of the existing guidelines is currently underway. Once completed, they will form the basis upon which determinations will be made that can lead to ending overfishing and rebuilding overfished stocks within statutorily specified time frames and in a way that minimizes the impact on fishermen and dependent communities and economies during the transition to sustainable fisheries. Technical guidance is needed to assist fishery managers in the development of conservation and management measures that will accomplish this transition.

Introduction

Marine, estuarine, and anadromous fishes support economically and socially important capture fisheries throughout the world, including the United States. While complete employment statistics for the global fisheries sector are not available, it is estimated that about 120 million people are partly or wholly economically dependent upon it (FAO 1995). These fish have a variety of uses in our society, including supplying commercial markets for human and animal food, satisfying subsistence and cultural needs, and providing recreational opportunities. The impact of the fishing mortality that results, both directly and indirectly, is now recognized globally as having a major effect on stocks. Fishing kills in excess of 100 million metric tons annually (FAO 1995); the exact amount may even exceed 200 million metric tons when recreational, subsistence, and release mortality are considered.

Marine capture fisheries are popularly considered to be at the brink of disaster (Mace 1996). FAO (1995) has concluded that almost 70% of those stocks of marine fisheries for which assessments are available are being harvested at or beyond the maximum sustainable yield (MSY). Further, it was concluded at the Kyoto International Conference on Sustainable Contribution

of Fisheries to Food Security held in 1995 by Japan and FAO that there is a considerable danger that overfishing will continue and worsen. The continuing increase in the number and capacity of fishing vessels resulting, in part, from technological advances, stands as the single most directly controllable factor affecting overfishing (Mace 1996). Indeed, the FAO Kyoto conference concluded that the pervasive cause of non-sustainable resource use is the free and open access to resources (FAO 1995). Further, the impacts of overcapacity that result become exacerbated when coupled with natural and man-induced environmental perturbations.

In the U.S., the situation is no less dire. The most recent assessment of stocks subject to the jurisdiction of the Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act) indicated that 96 of 279 species for which information was available are “overfished” or are approaching an overfished condition. The status of an additional 448 species relative to overfishing is unknown. The benchmark against which overfishing was measured in this compilation was generally recruitment overfishing, suggesting that recruitment failures are potentially imminent unless dramatic action is taken to reverse this condition.

A Need for Stronger Management

A sense of urgency has developed. FAO's 1995 conference in Kyoto, Japan concluded that *"If it is assumed, under the most pessimistic assumption regarding future supply, that governments and resource users take no action to reverse the disastrous level of overfishing and degradation of coastal environments, the supply of fish for direct human consumption from marine capture fisheries could fall to 40 million metric tons in 2010; certain stocks would be likely to collapse."* If the world's fisheries are to be rescued from the "brink of disaster", action must be swift and decisive.

The U.S. Congress has concluded this situation applies similarly to U.S. fisheries. In the Findings section of the Sustainable Fisheries Act of 1996, Congress stated,

"(2) Certain stocks of fish have declined to the point where their survival is threatened, and other stocks of fish have been so substantially reduced in number that they could become similarly threatened as a consequence of (A) increased fishing pressure, (B) the inadequacy of fishery resource conservation and management practices and controls, or (C) direct and indirect habitat losses which have resulted in a diminished capacity to support existing fishing levels."

This comes at the culmination of 20 years of active management of the fisheries supported by these species pursuant to the Magnuson-Stevens Act. Further, this 20-year period of management has brought with it the first ever listing of fishes in the U.S. that extend beyond the freshwater environment (several salmonid stocks on the West Coast) as threatened and endangered under the Endangered Species Act. In short, the record of marine fisheries management by the Federal government does not have many success stories.

The causes for the current status of these fisheries are many. But, they begin with the optimistic view generally held for centuries that fishing mortality, especially on marine stocks, was unlikely to be a significant factor in reducing stock size. This conclusion failed to anticipate the phenomenal technological advances that have occurred during the latter half of this century and the demand for seafood and recreation that an exponentially expanding population has imposed on fish. As a result, U.S. fisheries management has focused on developing and Americanizing fisheries with few, if any, constraints to protect against (i.e., prevent) overfishing. As fisheries have developed, the response has generally been reactionary at best (i.e., wait until overfishing is documented to have occurred before initiating effective fishing restrictions). Even the criteria against which the need

for management (i.e., restrictive regulations) is determined has reflected the confidence that serious fishing reductions are probably seldom needed. The minimum biological level necessary for stocks to replace themselves is the current threshold used to define overfishing in most fishery management plans (Rosenberg et al. 1996). The appropriateness of this threshold requires that rapid management action be taken when it is crossed, a result seldom achieved in the Act's 20 year history.

I should inject that the generalized picture presented to this point is just that, a generalization. There are exceptions. In fact, the status of Alaska's fish stocks is typically used as the example of the results that "proper", conservative management can produce. Perhaps there is reason to think that we can do better.

An Opportunity for Change

NMFS has been presented with a tremendous opportunity to reverse the current situation. The Magnuson-Stevens Act was fundamentally changed in 1996 by the integration of the internationally adopted precautionary approach throughout its provisions. Examples of this are the National Standards for fishery conservation and management and the guidelines that must be developed by NMFS to assist the Regional Fishery Management Councils in developing FMP's and amendments thereto. However, the Magnuson-Stevens Act does not explicitly state that the precautionary approach is to be taken in future fisheries management.

The Magnuson-Stevens Act requires that U.S. fisheries be managed pursuant to fishery management plans (FMP's) developed by eight regional fishery management councils or the Secretary of Commerce. These FMP's are to be consistent with 10 conservation and management national standards (section 16 USC, 1851, section 301(a)). These standards are rather generic and leave much to interpretation. Therefore, the Magnuson-Stevens Act also requires the Secretary to establish advisory guidelines (guidelines) that do not have the force and effect of law to assist in the development of FMP's (16 USC, 1851 section 301(b)). The requirement for these guidelines is not new; previous guidelines for 7 of the 10 national standards have existed since 1977.

The existing guidelines have been in place since 1989, and their revision is currently occurring. After a very extensive intra-NOAA process, proposed guidelines were published in the Federal Register on August 4, 1997, for a 45-day comment period. The public comment period on national standard 1 guideline was reopened for 30 days on December 29, 1997. The proposed guidelines attempt to define and expand considerably on the Magnuson-Stevens Act's requirements. Once completed, they will form the basis upon which

determinations will be made that can lead to ending overfishing and rebuilding overfished stocks within statutorily specified time frames and in a way that minimizes the impact on fishermen and dependent communities and economies during the transition to sustainable fisheries.

The Work Ahead

However, there remains the need to translate the conceptual aspects of the guidelines to the operational level. This need was recognized in the proposed guidelines, specifically as it relates to optimum yield (OY) because (1) OY must now be no higher than MSY for all stocks; and (2) for overfished fisheries (stocks), OY must be based upon a rebuilding schedule that increases stock levels to those that would produce MSY. These changes in the Magnuson-Stevens Act are considered by NMFS to be expressions of a precautionary approach, the specification of which can be a complicated exercise. As such, the technical guidance that will result from this workshop is intended to supplement the national standard guidelines. It is important to note that this guidance should not necessarily be limited to only OY and National Standard 1. There are 10 national standards, and our lack of scientifically sound information is greater for the non-biological aspects of fisheries than for the biological ones.

The likelihood of achieving success during the next 3 days would have been much more certain had the new national standard guidelines been finalized. Unfortunately, they have not been; so we find ourselves in exactly the same situation as is all too often the case in fisheries management: decisions in the face of incomplete, imprecise, and uncertain information. It is exactly this uncertainty that dictates the need for guidance to implement the precautionary approach beyond the conceptual level of the Magnuson-Stevens Act and the national standard guidelines.

As I indicated earlier, the Magnuson-Stevens Act does not explicitly state that the precautionary approach is to be the foundation for U.S. fisheries management. This conclusion is drawn from the changes made to specific sections of the Act like those relating to OY, the new rebuilding requirements for overfished fisheries, and the new requirements concerning fishing gear. The conclusion is further supported by debates in both the U.S. House of Representatives, and the Senate, and by the U.S. adoption of the United Nations Code of Conduct for Responsible Fisheries. It is the lack of an explicit statement in the Magnuson-Stevens Act, and its requirements for national standard guidelines that create the need for technical guidance for applying the precautionary approach with respect to the national standards.

There are several areas for which specific technical guidance appears most needed. These include: MSY estimates, MSY control rule, OY estimates, inclusion of estimates of fishing mortality from all sources (directed, incidental, research, and other exempted fishing activities), lack of stock assessments, mixed stock fisheries, rebuilding plans, bioeconomic modeling, and aquaculture. I am optimistic that the results of your efforts over the next 2 days will produce invaluable technical advice with which fisheries managers can achieve the societal desire to reverse the current status of U.S. marine fisheries.

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Impacts of Demographic Variation in Spawning Success on Reference Points for Fishery Management

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Abstract. Parametric relationships between recruitment and an index of parental stock size assume the latter is proportionally related to spawning potential (usually indexed by spawning biomass), irrespective of the demographic composition of adults. Recent empirical information, however, suggests that spawning by older, more experienced females is more successful than that by the young, small or inexperienced within a population. New models are proposed incorporating the proportion of the i th age class spawning for the j th time (PSP_{ij}), from information contained in the maturity ogive, and experimental results relating the survival of eggs and larvae to the age, size or reproductive experience of adults. A series of spawning metrics (spawning stock biomass or SSB , egg production, hatched egg production, viable larval production) and associated recruitment-based fishing mortality reference points (F_{med} , $F_{crash} = F_{extinction} = F_{\tau}$) and the F that allows at least one lifetime spawning per recruit) are contrasted for the Georges Bank cod stock. We conclude: (1) the time series of cod spawning intensity is significantly altered when hatched eggs or viable larvae are used as the metric, reflecting the importance of first- and second-time spawners in some years, and the increasing trend in F over time, (2) percent maximum spawning potential (%MSP) curves in relation to fishing mortality are steeper (e.g. result in lower %MSP for a given F), when the metric is hatched eggs and viable larvae rather than SSB or egg production per recruit, (3) lifetime expected numbers of spawnings per recruit are significantly reduced when the effects of spawning experience on egg hatching success are included, and (4) the median F estimated from 5,000 bootstrap realizations of the Beverton-Holt S - R curve for viable larvae ($F=0.88$) is much lower than that from SSB ($F=1.40$), with narrower confidence bounds. Our results suggest that traditional approaches to F -based reference points using SSB systematically overestimate the resiliency of stocks to fishing. This adds impetus to the need for adopting precautionary approaches to fisheries management. Additional laboratory studies of the life history of spawners in relation to the fate of eggs and larvae are clearly warranted.

Introduction

A critical assumption of all models of stock and recruitment is that the effective spawning potential of the population is proportional to its index. Typically, spawning stock biomass (SSB) is used as the metric of spawning potential, but concerns have been raised recently that the proportionality assumption may not hold in cases where contributions to SSB are increasingly reliant on first- or second-time spawners or where the age composition of the SSB has undergone significant change (Chambers and Trippel 1997; Trippel et al. 1997a). In the case of western Atlantic groundfishes, severe depletions in fish abundance have occurred (Murawski et al. 1997), along with substantial reductions in the age and size at first sexual maturity (O'Brien et al. 1993; Trippel 1995; Hunt 1996; Trippel et al. 1997b), and a disproportionate loss of old, repeat-spawning fish (Myers and Cadigan 1995; Trippel 1995). Laboratory experiments on Atlantic cod, *Gadus morhua*, suggest that first-time spawners perform poorly compared to more experienced animals, breeding for a shorter period, producing fewer egg batches, exhibiting lower fecundity, and producing smaller eggs with lower fertilization and hatching rates (Solemdal et al. 1995; Trippel 1998). If these mechanisms are important in nature, then traditional approaches to evaluating harvest strategies based on recruitment vs. SSB data may overestimate the resiliency of stocks to

exploitation particularly since depleted or recovering fisheries may be dependent on inexperienced spawners to support population reproduction. In this study we incorporate some recent experimental findings on reproductive success in relation to spawner size/age and maternal experience, into alternative metrics of spawning potential. These alternative spawning metrics are used to re-calculate biological reference points related to recruitment failure and stock collapse (Smith et al. 1993; ICES 1997). The results of new models are contrasted with traditional approaches for the Georges Bank cod stock (Anonymous 1997).

Overview of Some Experimental Studies of Spawning Demographics

Two important factors in relating adult population structure to effective spawning potential of a stock are: (1) numbers of years that an iteroparous fish has previously participated in spawning (i.e., spawning experience), and (2) the relationship between spawner size/age and the quality of reproductive products (Trippel et al. 1997a). Trippel (1998) found that $13 \pm 6.7\%$ of cod eggs hatched from first time spawners, compared to $62 \pm 4.4\%$ from second-time spawners.

Models described below account for the differential effects of spawning experience by tracking each spawning platoon comprising each age group, identified by the age they begin breeding. In the case of Georges Bank cod, individuals may begin spawning anywhere from the first to the fifth year; there are thus up to five potential spawning platoons in each age group (Anonymous 1997).

A direct relationship between maternal age/size and egg diameter has been observed for cod (Kjesbu 1989; Solemdal et al. 1993; Solemdal et al. 1995; Chambers and Waiwood 1996; Kjesbu et al. 1996; Trippel et al. 1997a). Egg diameter has been positively correlated with several indices of cod egg and larval viability, including larval dry weight, yolk weight, percent of larvae comprised of yolk, hatching percentage (Trippel 1998), resulting larval length, percent of larvae feeding on day five, percent of larvae with a swim bladder on day 10, and specific growth rate (SGR as a percent) of 15-day-old larvae (Marteinsdottir and Steinarsson 1998). We chose to model the effects of maternal age/size on larval viability via a function relating spawner age to the percent of larvae with swim bladders at age 10 days (Marteinsdottir and Steinarsson 1998).

Our model strategy relates variation in hatching success to maternal experience, and variation in larval viability to age/size effects. Our analyses are primarily intended to illustrate the potential impacts of these assumptions on results of stock-recruitment analyses, and to motivate further experimental work.

Metrics of Spawning Potential and Biological Reference Points

Metrics of Spawning

Spawning stock biomass (*SSB*) is typically computed for iteroparous annual spawning species as:

$$SSB = \sum_{i=1}^n N_i \cdot \overline{WS_i} \cdot PM_i \quad (1)$$

where N_i = numbers alive at spawning age i , determined by $N_i = N_{i-1} \cdot [\exp(-\{F+M\})]$; $F_i = PR_i \cdot F$, where PR_i is partial recruitment to the fishery. The numbers of animals from the beginning of the calendar year to the spawning time is decremented by the fraction of $F+M$ that occurs before spawning. The oldest age is considered a plus group, for which the total lifetime contribution to the spawning population in numbers is given by: $1/[1-\exp(-\{F+M\})]$;

$\overline{WS_i}$ = mean weight (kg) at age for the stock;
 PM_i = proportion of females, age i , that are sexually mature.

Population egg production (*EGGS*) is given by:

$$EGGS = \sum_{i=1}^n N_i \cdot E_i \cdot PM_i \quad (2)$$

where E_i = mean fecundity (numbers of spawned eggs) at age i .

If hatching success is related to spawning experience, the calculation of the number of hatched eggs requires that numbers at age be subdivided into groups that vary from one another in their spawning experience, based on the age at which each first becomes mature. We refer to those groups that show a common age at first maturation and a common number of previous spawning experiences as 'platoons'. For cod we assume that hatching success is 100% for the third and greater numbers of times spawning. Numbers of hatched eggs (*HATCHED*) is evaluated by the double summation:

$$HATCHED = \sum_{i=1}^n \sum_{j=1}^3 N_i \cdot \overline{E_i} \cdot PM_i \cdot PSP_{i,j} \cdot HP_j \quad (3)$$

$PSP_{i,j}$ = the proportion females age i , spawning for the j th time, determined by:

$$PSP_{i,j} = \begin{cases} \frac{PM_i - PM_{i-1}}{PM_i} & \text{for } j = 1 \\ \frac{PM_{i-1}}{PM_i} & \text{for } j = 2 \\ \frac{PM_{i-2} + PM_{i-1}}{PM_i} & \text{for } j \geq 3 \end{cases} \quad (4)$$

HP_j = the proportion of eggs hatching from first, second and third+ time spawners, irrespective of age, as described above for cod:

$$HP_j = \begin{cases} 0.13 & \text{for } j = 1 \\ 0.62 & \text{for } j = 2 \\ 1.00 & \text{for } j \geq 3 \end{cases} \quad (5).$$

Numbers of viable larvae (*V-LARVAE*, defined as those having a swim bladder at day 10 after hatching) are computed from:

$$V-LARVAE = \sum_{i=1}^n \sum_{j=1}^3 N_i \cdot \overline{E_i} \cdot PM_i \cdot PSP_{i,j} \cdot HP_j \cdot LS_i \quad (6)$$

LS_i = the proportion of larvae surviving at day 10 which have formed a swim bladder, resulting from spawners of age i . This function is determined by combining the survival at length relationships and the length/weight/age curves given in Table 1.

Table 1. Parameter estimates and data used in simulations of the effects of fishing on demographic variation in spawning success of Georges Bank cod.

Parameter	Equation or Value	Reference (Comments)
Length at Age (cm)	$L_t = 148.1 \cdot (1 - \exp[-0.12(t+0.616)])$	Penttila and Gifford (1976)
Length (cm) / Weight (kg)	$W = 8.10443e-6 \cdot L^{3.0521}$	NMFS, Woods Hole Lab., File Data
Weight (kg) / Length (cm)	$L = \exp((\ln(WS)+11.7231)/3.0521)$	Inverse of L/W
Stock Weight at age (WS, kg), (observed, recent)	A1=0.749, 2=1.217, 3=1.866, 4=2.882, 5=4.240, 6=5.791, 7=7.976, 8=8.881, 9=10.510, 10+=15.170	Anonymous (1997) Stable over time
Natural Mortality Rate	0.2	Pope (by acclimation)
Partial Recruitment at Age, PR, (Recent)	A1=0.0003, 2=0.1318, 3=0.5316, 4+=1.00	Anonymous (1997) Increasing over time
Fecundity (E) vs. Length (cm)	$E = 1.10 L^{3.28}$	Buzeta and Waiwood (1982) Gulf of St. Lawrence
% Hatching Success of Eggs (by Number of Spawns)	First Time = 13, Second Time = 62, 3+ Times = 100	Trippel (1998) Young fish in the lab
Proportion of Larvae w/swim bladder @ day 10 vs. Egg Diameter (ED, mm)	$SB_{10} = 1/(1+(ED/1.4237)^{-16.9596})$	Marteinsdottir and Steinarsson (1998) Icelandic Fish, our fit
Egg Diameter (mm) vs. Fish Length (L, cm)	$ED = 1.6(1 - \exp(-0.0282 \cdot [L+7.3889]))$	Trippel et al. (1997b) Norwegian Fish, our fit
Proportion Mature at Age, PM (three historic stanzas)	1986-1996: A1=0.23, 2=0.64, 3=0.91, 4=0.98, 5+=1.00 1982-1985: A1=0.13, 2=0.47, 3=0.94, 4=0.97, 5+=1.00 1978-1981: A1=0.07, 2=0.34, 3=0.78, 4=0.96, 5+=1.00	Anonymous (1997)

Biological Reference Points for Fishery Management

One “rule of thumb” approach to biological reference points is that, on average, members of an exploited stock should spawn for an arbitrary number of times - usually at least once over their life span- taking into account overall rates of fishing and natural mortality and the partial recruitment pattern of the fishery (ICES 1997). The lifetime expected number of spawnings per recruit (*LTSR*) is given by:

$$LTSR = \frac{\sum_{i=1}^n N_i \cdot PM_i}{R} \quad (7)$$

where R = number of recruits = N_1 .

If the effects of maternal experience on egg hatchling success are taken into account, lifetime expected number of *effective* spawnings per recruit (*LTESR*) is given by:

$$LTESR = \frac{\sum_{i=1}^n \sum_{j=1}^n N_i \cdot PM_i \cdot PSP_{i,j} \cdot HP_j}{R} \quad (8)$$

The value of fishing mortality corresponding to median (=replacement) R/SSB (F_{med}) is computed by solving the spawning index per recruit function for the F giving the replacement $(R/SSB)^{-1}$ (Sissenwine and Shepherd 1987; ICES 1997).

A number of parametric stock-recruitment relationships have been used to calculate the maximum fishing mortality rates at which the stock can persist, associated with the curvature of the S - R function near the origin (Smith et al. 1993; Mace 1994; Myers et al. 1995; Myers and Barrowman 1996; ICES 1997; Myers and Mertz 1998). We illustrate the use of S - R functions with the Beverton and Holt model (Hilborn and Walters 1992), which can be expressed as:

$$R = \frac{\alpha \cdot SI}{\beta + SI} \quad (9)$$

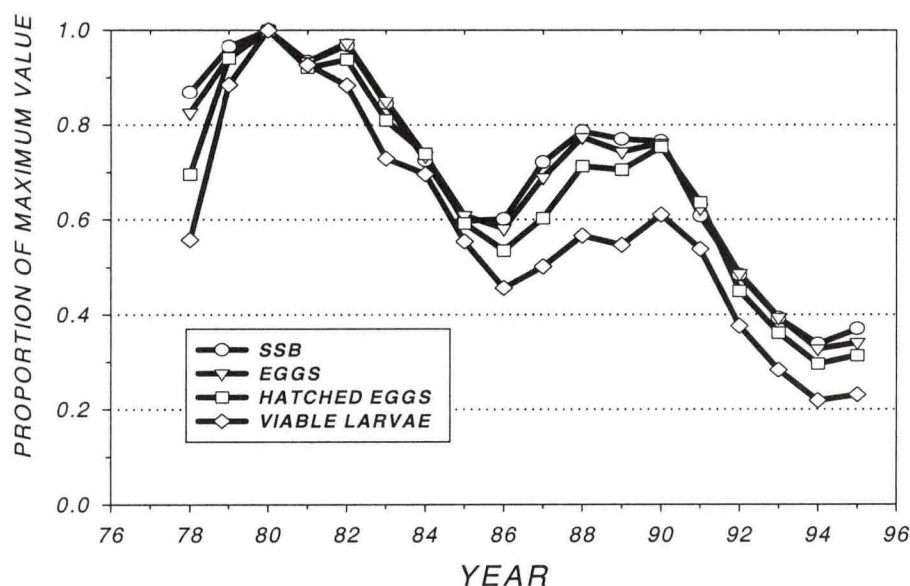


Figure 1. Calculated indices of spawning intensity for Georges Bank cod, 1978-1995. Indices are: spawning stock biomass (equation 1), total egg production (equation 2), hatched egg production (equation 3), and numbers of viable larvae (equation 6). Values are expressed as proportions of the maximum for each index (i.e. 1980 in all cases).

where R = recruits; SI = spawning index (e.g., spawning stock biomass, eggs, hatched eggs or viable larvae).

The slope of the tangent line to the predicted stock-recruitment curve at the origin is given as the quotient α/β . This tangent predicts the maximum recruits per unit spawning index (highest compensatory survival) possible for the stock. The inverse of the slope of the tangent line at the origin (β/α) is the spawning index per recruit, which can be calculated for any given fishing mortality rate as in equations 1, 2, 7 and 10 (Sissenwine and Shepherd 1987). The fishing mortality rate associated with the tangent line at the origin is the maximum at which the stock can persist, and is termed F_{crash} (ICES 1997) = $F_{extinction} = F_{\tau}$ (Mace 1994).

Fitting this relationship assuming lognormal error is accomplished by:

$$\log(R) = \log\left(\frac{\alpha \cdot SI}{\beta + SI}\right) \quad (10)$$

Bias in the estimate of α is corrected by: $\hat{\alpha} = \alpha \exp(0.5 \text{ RMSE})$; the slope at the origin is then $\hat{\alpha}/\beta$. We fit the lognormal form to stock-recruitment data using both SSB and viable larvae as the metrics of spawning. Results of the normal and lognormal approaches were compared.

Application to Georges Bank Cod

We re-constructed the time series of spawning metrics and calculated biological reference points for the Georges Bank cod stock (Anonymous 1997). Population dynamics parameters for the stock are given in Table 1. The time series of spawning stock biomass (equation 1) as calculated in Anonymous (1997) was contrasted with estimates of annual egg production (equation 2), hatched egg production (equation 3) and numbers of viable larvae (equation 6; Figure 2).

Trends in *HATCHED* and *V-LARVAE* differ from *SSB* and *EGGS* (in the early part of the time series and from 1986 onward) primarily due to the effects of large year classes (e.g. 1980 and 1985) which produced high proportions of first and second-time *SSB* in some years, and the increasing trend in F , which resulted in a progressive diminution of the proportion of older fish comprising the spawning stock. The index of viable larvae recovered to only about 60% of the maximum in the mid-late 1980s, whereas the other indices recovered to about 80% of the 1980 value (Figure 1).

Under conditions of no fishing and $M=0.2$, the life-time expected number of spawnings per age 1 recruit ($LTSR$, equation 7) is 4.24, declining to slightly less than

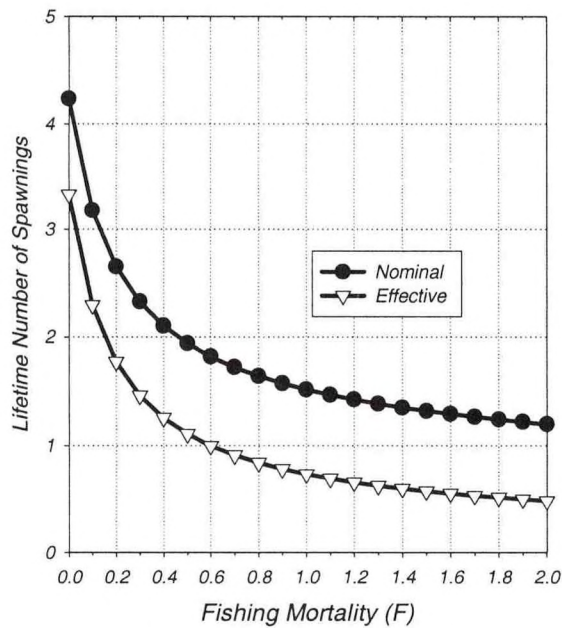


Figure 2. Expected lifetime number of spawnings per recruit for Georges Bank cod as a function of instantaneous fishing mortality rate. Nominal spawnings per recruit (equation 7) assume no differences in mortality of eggs and larvae by female size or spawning experience, while effective numbers of spawnings per recruit (equation 8) decrement the importance of first and second time spawnings.

two spawnings per recruit at $F=0.5$ (Figure 2). Because of the partial recruitment pattern, even at very high fishing mortality rates, the numbers of expected spawnings per recruit exceeds one. If the first and second spawnings are adjusted for maternal experience (equation 8), the expected number of effective spawnings (*LTER*) vs. F is shifted substantially downward, declining from 3.33 at $F=0$, to 1.11 at $F=0.5$, and to 0.49 at $F=2.0$ (Figure 2).

The expected number of spawnings for each maturity platoon comprising the populations changes differentially with fishing mortality rate (Figure 3). This analysis is based on the partial maturity patterns observed in the most recent period (Table 1), and the total number of recruits for all maturity cohorts summing to 1. If the stock is unexploited, the maturity cohort spawning first at age 2 has the greatest expected number of lifetime spawnings (1.75), followed by those at ages 1 and 3. The maturity cohorts spawning first at ages 4 and 5 have low lifetime expected spawnings, due to their proportionally low numbers (Table 2). Increasing fishing mortality changes the expected numbers of spawnings of various maturity cohorts, resulting in about equal expectations by age 1 and age 2, and relatively low contributions by the other maturity cohorts with $F = 0.7$ or greater (Figure 2).

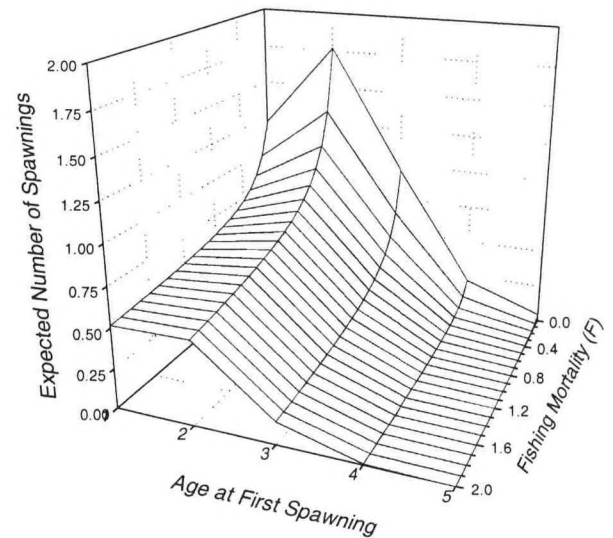


Figure 3. Expected number of spawnings per recruit for each maturity platoon for Georges Bank cod, as a function of instantaneous fishing mortality (F). Platoons are defined based upon the age at which they spawn for the first time (i.e., ages 1 to 5).

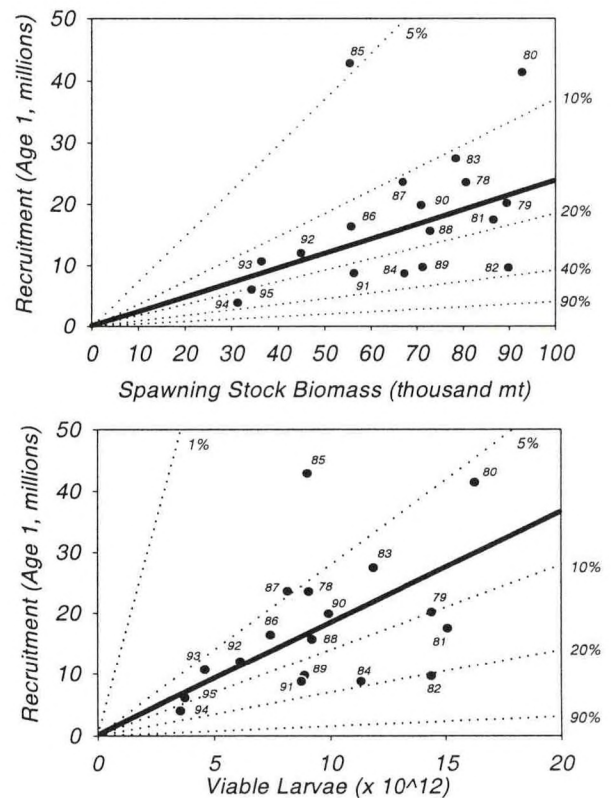


Figure 4. Stock-recruitment relationships for Georges Bank cod, 1978-1995, based on two metrics of spawning intensity. The relationship between spawning stock biomass and recruitment is plotted above. The relationship between numbers of viable larvae produced and recruitment is plotted below. In both cases, the dark line represents the median line plotted through all data. Dotted lines are associated with percentages of maximum *SSB/R* and *Viable Larvae/R*.

Table 2. Estimates of fishing mortality rate reference points for Georges Bank cod, based on calculations of F_{med} and F_{τ} . The number of successful bootstrap replicates is indicated by $n=$, from a maximum of 5,000.

Metric of Spawning Potential	Statistic	F _{med} Reference Point			F _τ Reference Point Lognormal Error Model					F _τ Reference Point Normal Error Model				
		F _{med}	%MSP	Slope	$\hat{\alpha}$	β	$\beta/\hat{\alpha}$	F _τ	%MSP	$\hat{\alpha}$	β	$\beta/\hat{\alpha}$	F _τ	%MSP
Spawning Stock Biomass	$n=$	5000	5000	5000	4095	4095	4095	4095	4095	2715	2715	2715	2715	2715
	Median	0.61	15.0	0.246	42288	92411	2.21	1.43	8.2	47.06	107.60	2.24	1.40	8.3
	Lower 80th CI	0.48	18.3	0.201	22211	20487	0.89	0.71	13.3	26.04	28.69	1.06	0.76	12.7
	Upper 80th CI	0.76	12.7	0.280	475643	1698488	3.62	7.71	3.3	171.69	571.24	3.42	5.40	3.9
	Point Est.	0.61	15.0	0.246	43723	95827	2.19	1.45	8.1	126.87	399.39	3.15	0.85	11.7
Viable Larvae (day 10)	$n=$	5000	5000	5000	4662	4662	4662	4662	4662	3969	3969	3969	3969	3969
	Median	0.57	7.7	1.831	52883	18576	0.35	0.78	4.9	42.97	12.56	0.29	0.88	4.1
	Lower 80th CI	0.47	10.1	1.397	25748	4645	0.18	0.59	7.3	24.90	4.29	0.16	0.64	6.6
	Upper 80th CI	0.65	6.4	2.208	726969	371242	0.52	1.26	2.4	159.36	71.04	0.47	1.32	2.3
	Point Est.	0.57	7.7	1.831	56458	20230	0.36	0.77	5.0	53.18	18.06	0.34	0.79	4.7

Stock-recruitment plots and estimates of F_{med} (Table 2; Figure 4) for spawning indices expressed as *SSB* and numbers of viable larvae differ from each other. Some year classes (e.g. 1978, 1989) change relative position when viable larvae is used as the spawning metric. Both *S-R* plots include isolines of percentages of the maximum spawning index per recruit (Figure 4). For *SSB* as the spawning index, the majority of data points lie between 10 and 40% of the maximum spawning potential. The point estimate of F_{med} (0.61, calculated as above) is equivalent to 15% MSP. Confidence intervals for F_{med} were determined by bootstrapping the 18 data points 5,000 times, with replacement. The bootstrap 80% confidence interval for F_{med} using *SSB* is 0.48 to 0.76 (12.7 to 18.3% MSP). Most data points for viable larvae lie between 5 to 20% MSP, with the point estimate of F_{med} (0.57 = 7.7% replacement MSP) slightly, but not significantly lower (80% confidence interval = 0.47 to 0.65), than that derived using *SSB*.

The Beverton-Holt *S-R* relationship was fit to age 1 recruitment (millions of fish) and the two indices of spawning in a non-linear least squares analysis (Table 2) using the normal and lognormal error models. The

S-R fits were slightly better for the *R* vs. *V-LARVAE* than they were for *R* vs. *SSB*, as measured by residual sums of squares. The point estimate of F_{τ} was higher for *R* vs. *SSB* (0.85 equivalent to 11.7% MSP) than for *R* vs. *V-LARVAE* (0.79, 4.7% MSP).

Quantiles and confidence intervals for the parameter estimates of the *S-R* curves and F_{τ} were determined by bootstrapping the 18 data points and fitting the curve to each of 5,000 potential realizations of the original data selected randomly with replacement (Hilborn and Walters 1992, p. 274). Bootstrap realizations from the lognormal model were derived by resampling the residuals from the nominal model fit, adding this error to the predicted recruitment for each observed annual spawning index value, and re-fitting the model parameters. Bootstrapping of *R* vs. *SSB* data for the normal error model produced 2,715 of 5,000 realizations (54%) wherein the model either solved or produced realistic parameter estimates (Table 2; Figure 5). The distribution of F_{τ} values is highly skewed for *SSB* (Figure 5); the median (1.4) is substantially greater than the point estimate and the 80% confidence interval is very wide (0.76 to 5.4). Bootstrapping of *R* vs. *V-LARVAE* with

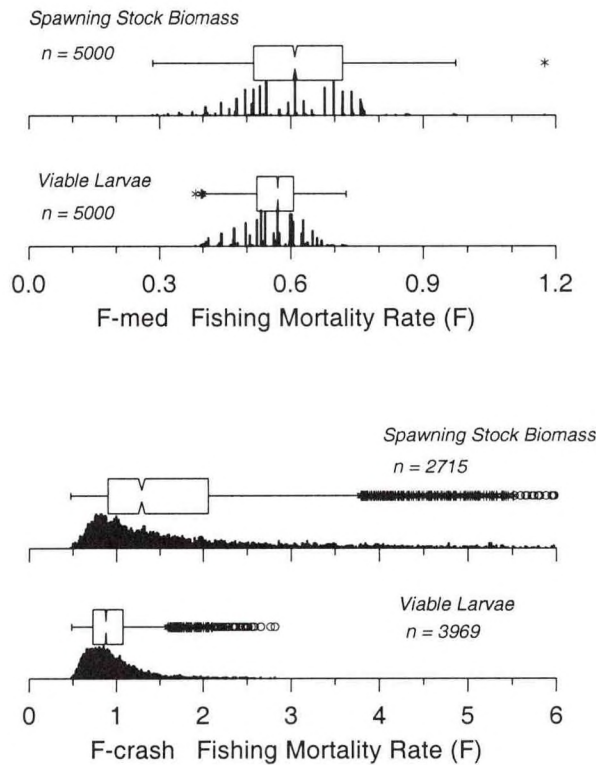


Figure 5. Frequency distribution and box plot of estimated instantaneous fishing mortality rate (F) associated with F_{med} and the slope of the stock-recruitment curve at the origin ($F_{\tau} = F_{crash}$), for Georges Bank cod. Results are for 5,000 bootstrap realizations of SSB and viable larvae vs. recruit data from 1978–1995, used to fit the Beverton-Holt stock recruitment relationship. Notch and ends of the box represent the median, and quartiles of the distribution, respectively.

the normal error model resulted in a higher proportion of realizations producing usable parameter estimates (3,969 cases or 79%). The distribution of values of F_{τ} for V-LARVAE was much less skewed (Figure 5). The median of F_{τ} for V-LARVAE (0.88) was close to the point estimate and the 80% confidence interval was relatively narrow (0.64 to 1.32).

The lognormal model results were similar in most regards to those derived from the normal model approach. The lognormal model could be fit to a higher proportion of SSB (0.82) and viable larvae (0.93) bootstrap realizations. Median F_{τ} estimates were similar to results obtained from the normal error model, and the confidence intervals were approximately equal. The only substantive difference in results between the approaches is in the point estimates using spawning stock biomass. The lognormal error model produced a substantially higher estimate (1.45) than the normal error model (0.85). These results are indicative of the highly skewed distribution of the bootstrap results and suggest

that the median of stochastic estimates is more robust than the point estimates. Results also suggest that the value of F_{τ} is poorly determined and likely overestimated from R vs. SSB data as compared to R vs. viable larvae.

Discussion

Our results suggest that traditional approaches for estimating biological reference points for fishery management, based on SSB as a measure of reproductive output, may systematically overestimate the potential resiliency of stocks to exploitation. If the viability of eggs or larvae is related to maternal experience, age, or size, the effective spawning potential of the stock will not be invariant for a given SSB, particularly if the age structure of the spawners has changed significantly over time. The time series of spawning metrics (SSB, total egg production, hatched eggs and viable larvae) applied for Georges Bank cod differ in those years when large year classes were spawning for their first or second time, and when F was increasing, resulting in proportionally fewer old animals in the breeding population.

The estimate of F_{med} was relatively insensitive to the choice of spawning metric (Table 2). This is not surprising since this non-parametric technique does not account for the distances that individual data points are shifted from the median line (Figure 4) due to changes in the spawning index. The time series of R/SSB and $R/V-LARVAE$ were stationary; both spawning metrics produced adequate estimates of F_{med} , although the calculated reference point based on viable larvae was slightly lower, and was estimated more precisely (Table 2).

The estimation of maximum fishing mortality rates that the stock can withstand varies greatly with the choice of spawning metric. F_{τ} is, by definition, the point at which the calculated stock-recruitment relationship intersects the maximum feasible replacement survival rate (equivalent to the lowest possible %MSP and the extinction reference point). Using SSB as the spawning metric produced a median $F_{\tau} = 1.4$ (80% CI of 0.76 to 5.4), a value substantially greater than any fishing mortality rate the stock has experienced, notwithstanding the substantial reduction in stock size to about one third of its recent maximum (Figure 2). Using viable larvae as the spawning metric produced a median estimate of $F_{\tau} = 0.88$ (80% CI of 0.64 to 1.32). The latter estimate is not only preferable considering its statistical properties (Figures 9 and 10, Table 2), but is more plausible given the recent exploitation history of the stock (Figure 2). A precautionary approach to managing this stock would clearly indicate that long term replacement would not occur at $F > 0.88$, and lower if the precision of the estimate is considered.

The “rule of thumb” reference point of at least one

spawning per recruit (e.g. Myers and Mertz 1998) is seriously compromised if the first and second spawnings are discounted by the anticipated lowering of egg quality and larval viability. For the Georges Bank cod stock, the partial recruitment pattern assures at least one nominal spawning irrespective of fishing mortality rate. However, if *effective* spawnings are calculated, fishing mortality rates in excess of 0.6 result in less than one lifetime spawning per age one recruit. Our calculations also suggest that arbitrary %MSP targets (e.g. 20 to 35%; Clark 1991; Mace and Sissenwine 1993) may be inappropriate, and overly restrictive (i.e. relative to using hatched eggs or viable larvae as the spawning metric; Table 2).

The simple models proposed herein can lend new insights into the effects of exploitation on complex breeding systems that have evolved in marine fishes. Why are there up to five different maturity platoons present in the Georges Bank cod stock (and potentially more for stocks that mature later in life)? The adaptive significance of initiating breeding at different ages has not been studied intensively for cod, but is probably related to reproductive optimization, trade-offs of somatic growth at age for reproductive quality or other such considerations (Trippel et al. 1995). Clearly, variable age at first spawning is a source of diversity in a stock that has been progressively reduced by increasing exploitation (Figure 1), and intensive exploitation on juveniles and first- and second time spawners is counter to any such reproductive strategy. Indeed, the reproductive consequences of this exploitation strategy are implicated in the decline of this and similar stocks. An even more compelling question is whether or not the decline in relative reproduction by the older platoons is reversible if exploitation rates are reduced. Depending on the degree of heritability of age at first reproduction, restoring a broader representation of the various maturity platoons in the population may take generations, even if fishing mortality is reduced to very low levels.

These results suggest the directionality of biases associated with using spawning stock biomass as an estimate of reproductive output. Modeling the effects of exploitation on various metrics of spawning potential for the Georges Bank cod stock required information from studies conducted on at least four other stocks across the North Atlantic. In fact, necessary data are not available for any single Atlantic cod stock or any other fish stock to conduct these types of calculations. We expect that reproductive dynamics are at least partially local (e.g., fecundity, egg size, biochemical composition of larvae and timing of spawning). Thus, using information from one stock to apply to another is a significant source of uncertainty in our analyses. Clearly there is an urgent need to conduct additional integrated and well-designed field, laboratory and modeling stud-

ies, to evaluate the interacting effects of maternal size, age and experience on the fate of eggs and larvae. Given the universality of *SSB* as the default metric of estimates of spawning potential, such studies should not be confined to groundfish species.

Acknowledgments

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Use of Stock-Recruit Data in Estimating Biological Reference Points

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A bootstrap procedure was used to estimate the precision of biological reference points calculated from stock-recruitment data. A Beverton-Holt model was used for the Georges Bank yellowtail flounder stock while a Ricker model was used for the Northwest Atlantic stock of Atlantic mackerel. Results indicate this method should be useful in developing management strategies and control laws to allow for sustainable harvests of marine fish stocks on a long-term basis. Statistics and estimates of precision from bootstrap results can be used to develop risk averse management strategies, and thresholds for recruitment overfishing, examine fishery management policies and the utility of limit and target reference points, and to investigate sustainable levels of yield for fish stocks. A current goal of many organizations is the development of robust target and limit biological reference points for fisheries management; findings from this study seem appropriate for providing advice on this topic. The current study shows that even with highly variable stock-recruitment data, there are major benefits in managing fish stocks in a conservative fashion. Results from this study also emphasize the potential benefits of using S_{MSY} as a limit reference point and not a target reference point for fish stocks.

CCAMLR's Application of the Precautionary Approach¹

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Abstract. Article II of the CCAMLR Convention sets out the principles of conservation under which all harvesting and associated activity in the Convention Area shall be conducted. The three principles are 1) prevention of population decline to levels which threaten stable recruitment of harvested species, 2) maintenance of ecological relationships between the harvested, dependent and related species, and 3) minimization of the risk of ecosystem changes that are not potentially reversible in 20-30 yrs. These principles form the basis for the application of the Precautionary Approach in the management of Antarctic fisheries.

To support the management decisions taken by the Commission in its attempts to meet the aims of Article II, the scientific bodies of CCAMLR - the Scientific Committee and its Working Groups - undertake annual assessments of population status and trends of both harvested and dependent species. The methods used to assess the effects of harvesting activities have become increasingly sophisticated in recent years. A framework has been developed under which long term annual yields are assessed against the objectives of protection of the spawning stock and provision for the requirements of dependent predators. These objectives are expressed in terms of probabilistic decision rules, including limit reference points adopted by the Commission, based on the advice of the Scientific Committee. This represents a more comprehensive treatment of uncertainty than previously achieved, as envisaged in the Precautionary Approach.

CCAMLR has also developed mechanisms for the precautionary management of new and developing fisheries. Since 1991, CCAMLR has included a specific provision in its regulatory instruments (conservation measures) for the rational and responsible control of the development of new fisheries in the Convention Area. In 1993 this was supplemented with a measure which defines exploratory fisheries and provides guidelines for their management. At its most recent meeting, the Commission acknowledged the need to consolidate these initiatives into a unified regulatory framework which would provide guidelines for the management of fisheries throughout their existence, whatever their stage of development.

Introduction

The signing of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) can be considered, in itself, as an application of the Precautionary Approach³ by the international community. In the mid 1970's serious concerns were raised about the future management of Antarctic marine living resources. Of particular concern was the expansion in harvesting of krill *Euphausia superba*, the conservation of which is considered to be fundamental to the maintenance of the Antarctic marine ecosystem and vital to the recovery of depleted whale populations. In addition, large scale exploitation of fish stocks had started at the end of the 1960's and there was already evidence of major stock decline. For example the catch of the marbled rock cod, *Notothenia rossii* declined from 400,000 tonnes in the

1969/70 season to 100,000 tonnes the following year, and zero from 1972/73 to 1974/75. The drop in catch was the result of declines in both fishing effort and catch per unit effort. Despite no directed fishing on this species for more than a decade, there has been no appreciable recovery of the stock abundance to former levels.

These concerns were addressed by the Antarctic Treaty nations in a series of international meetings which lead to the drafting and ultimately the signing of the Convention in May 1980. The Convention came into force in 1982. Since that time the Commission for the Conservation of Antarctic Marine Living Resources has met annually at its headquarters in Hobart, Tasmania. The Commission operates as a body which attempts to

¹ Amongst other texts, this paper draws on material in the CCAMLR document 'Understanding CCAMLR's Approach to Management' SC-CAMLR-XVI/BG/15, CCAMLR 1997.

² Graeme Parkes has been a member of the UK Scientific Delegation to CCAMLR since 1991, however, the opinions expressed in this paper are entirely those of the author and do not necessarily represent the views of the UK Government nor of CCAMLR.

³ As elaborated by the FAO/Government of Sweden Technical Consultation on the Precautionary Approach to Capture Fisheries (Including Species Introductions), Lysekil, Sweden 6-13 June 1995.

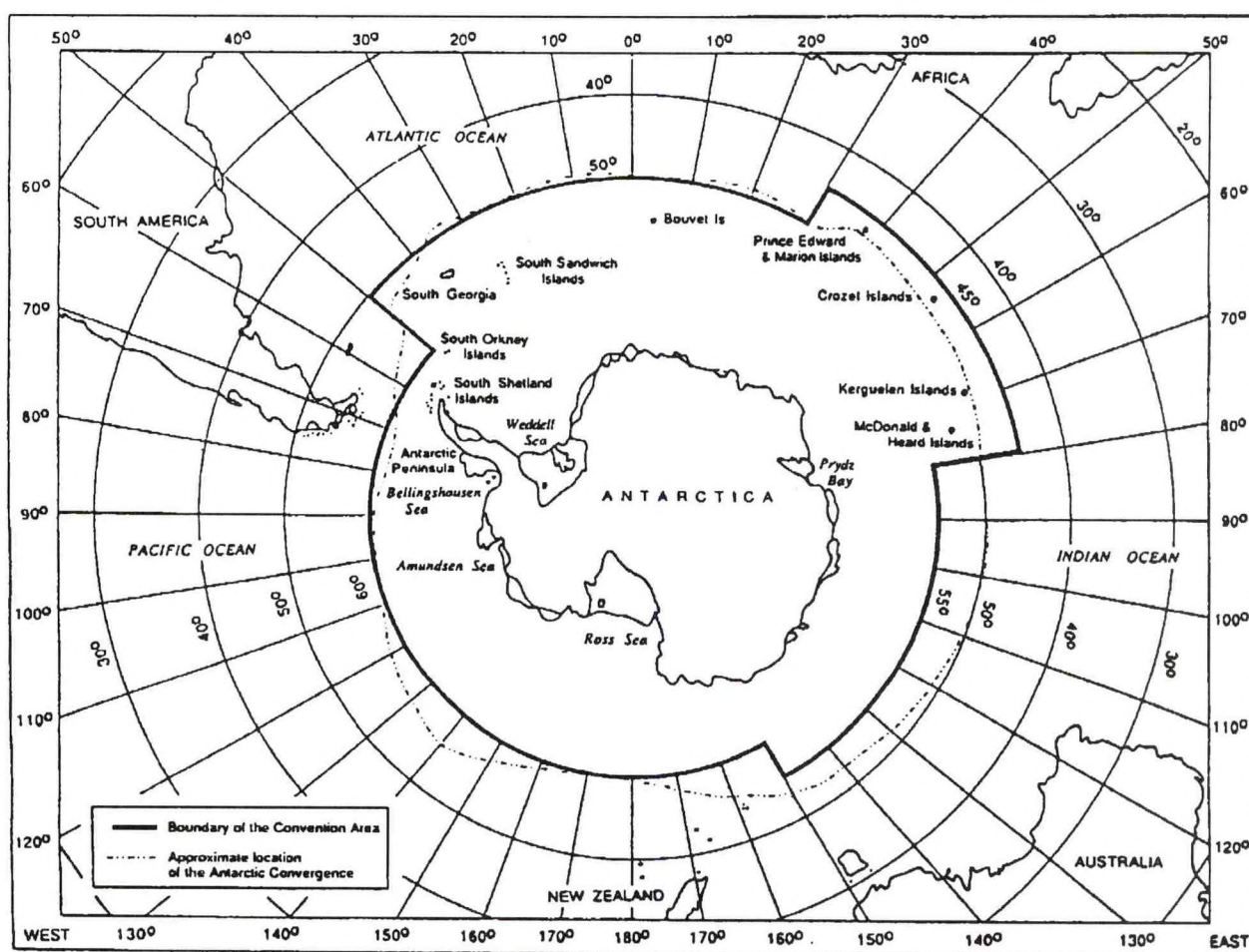


Figure 1. The Southern Ocean showing the boundary of the area covered by the Convention for the Conservation of Marine Living Resources.

come to agreement on issues which Members are then under obligation to implement. Decisions of the Commission on matters of substance, such as the setting of conservation measures, are taken by consensus. The major innovation of CCAMLR is that it is not only concerned with the regulation of harvesting activity, but has a mandate to conserve the ecosystem as a whole.

The Convention Area which CCAMLR seeks to regulate is essentially the Southern Ocean, which is bounded to the south by continental Antarctica and to the north by the Antarctic Convergence. The latter is located between 47 and 63 degrees south, depending on longitude and season. The administrative boundary of the Convention Area roughly follows the position of the Antarctic Convergence varying from 45° S in the Indian Ocean sector to 60° S in the Pacific Ocean Sector (Figure 1). The Convention Area contains a number of sovereign sub-Antarctic islands.

A substantial proportion of the work undertaken by CCAMLR, including the drafting of the Convention, predates the formal application of the term Precautionary Approach to fishery management. There is consequently

no mention of the term in the CCAMLR documentation. Nevertheless, most, if not all of CCAMLR's resource management activities have been in accordance with the intent of the formalisation of the Precautionary Approach. In fact, it is probably fair to say that the CCAMLR experience has helped to shape much of the current thinking behind the Precautionary Approach.

After explaining briefly the basis for CCAMLR's approach to management, this paper focuses mainly on two aspects of CCAMLR's work which are of direct relevance to the Precautionary Approach. These are firstly the assessment of appropriate catch limits in accordance with the criteria laid out in the Convention, including the taking into account of uncertainty, and secondly the management of the development of new and exploratory fisheries in the Convention Area.

Principles of Conservation

The principles of conservation governing all harvesting and associated activity in the Convention Area are set out in Article II of the Convention. Paraphrasing, the three principles are

- (i) prevention of population decline to levels which threaten stable recruitment of harvested species,
- (ii) maintenance of ecological relationships between the harvested, dependent and related species, and
- (iii) minimization of the risk of ecosystem changes that are not potentially reversible in 20-30 yrs.

These guiding principles underpin the essential elements of CCAMLR's approach to management. They encompass both the Precautionary Approach, in that prudent foresight should be exercised in avoidance of the taking of decisions which have a high risk of long term adverse effects, and an ecosystem approach, in the adoption of precautionary catch limits aimed at ensuring that the effects of fishing on prey abundance are limited to a level which will be unlikely to have a major impact on predators. Article II also makes it clear that the Convention includes the idea of 'rational use' of resources. In accordance with the Precautionary Approach, whilst uncertainty should not result in a delay in establishing management measures, this does not imply that no fishing can take place until all potential impacts have been assessed and found to be negligible.

The CCAMLR Management Mechanism

In setting conservation measures, including catch limits, the 23 Members of the Commission are advised by the Scientific Committee. The work of this Committee is supported by two subsidiary Working Groups; one on ecosystem monitoring and management (WG-EMM) and the other on fish stock assessment (WG-FSA). CCAMLR places substantial emphasis on scientific advice when debating conservation measures and other resource management requirements.

CCAMLR agreed the first conservation measure at its third meeting in 1984; a mesh size regulation for fin-fish trawlers. The following year saw the first closure of a fishery; the trawl fishery for *Notothenia rossii* around South Georgia, which is still closed today. The measure governing this closure has no time limit, meaning that it remains in force until there is consensus to revoke it. In 1986 a conservation measure was agreed which provided a framework within which, in subsequent years, conservation measures could be adopted specifying limitations of catch, or 'equivalent' measures, for species upon which fisheries were permitted around South Georgia, the main focus of fishing activity in the 1970's and 1980's (Statistical Subarea 48.3, Atlantic sector of the Southern Ocean). This was a significant step forward, because it set the precedent for CCAMLR to agree on measures, including total allowable catches (TACs), to limit the scope of exploited fisheries within the Convention Area.

Since that time, the basic format of conservation measures has been to specify:

- the fishery to which the measure applies, specified by species, Subarea (FAO convention) and sometimes gear type;
- the season to which the measure would apply (usually either the period between the end of one Commission meeting and the end of the meeting the following year, or some shorter period within that time frame);
- the TAC for the season; and
- the requirements for reporting data to the CCAMLR Secretariat during the fishing season, to enable it to monitor the progress of the fishery and issue a notice informing all Members of the closure of the fishery when a TAC is reached.

The last of these provisions was added when it became clear that in some cases the actual catch was exceeding the TAC before CCAMLR was able to take action to close the fishery. In addition to the flag state responsibility to report catch and effort data from commercial fisheries, CCAMLR also receives information from the Scheme of International Scientific Observation (the observer program), and fishery independent surveys and other scientific work carried out by Member States.

CCAMLR's application of the Precautionary Approach extends not only to managing fisheries in the single species sense, but also to making explicit allowance for the requirements of dependent species, and the uncertainty in ecological relationships within the Antarctic ecosystem. Monitoring of key dependent species is carried out under the CCAMLR Ecosystem Monitoring Program (CEMP). CEMP has two central aims:

1. to detect and record significant changes in critical components of the ecosystem to serve as a basis for conservation, and
2. to distinguish between changes due to harvesting of commercial species and changes due to environmental variability.

To meet Aim 1, selected life history parameters such as abundance, distribution, feeding, reproduction, growth and condition are monitored for designated predator species, which are likely to reflect changes in the availability of harvested prey species, such as krill. Currently monitored species include crabeater and Antarctic fur seals, four species of penguins, the black browed albatross and two species of petrels. Monitoring is carried out by Member states at specially designated sites. To contribute towards Aim 2, prey species,

environmental factors and the links between these and predators are monitored. To mitigate against the difficulties imposed by the high level of complexity of the ecosystem, CCAMLR has adopted a strategic modeling approach. This uses computer simulation as a key tool in setting scientific priorities and developing management options. The aim is not to develop a comprehensive ecosystem model, but rather to develop simpler models for strategic purposes which capture important features of the ecosystem, whilst recognizing the multiple linkages which exist between components.

Taking uncertainty into account in resource assessment

In recent years the CCAMLR Working Groups have begun to utilize more sophisticated assessment methodologies, which include a more comprehensive treatment of uncertainty than previously achieved, as envisaged in the Precautionary Approach.

The method currently applied to krill (the krill yield model - Butterworth *et al* 1992) has its origins in an approach developed by Beddington and Cooke (1983). This approach derives a numerical factor (termed γ) which can be used to multiply a single estimate of biomass obtained from a survey before the onset of exploitation, to give an estimate of the potential annual sustainable yield. Given that a single biomass estimate is all that is available for krill in the Atlantic sector of the Southern Ocean, albeit from a survey undertaken after the onset of exploitation, this approach is appropriate. One essential feature of this approach is that the evaluation of potential yield is made on the basis of satisfying a risk criterion; in this case that, even under harvesting, the probability that spawning biomass falls below a level at which recruitment 'on average' might be impaired is kept small. The model is particularly sensitive to two key parameters; the natural mortality M and the variability in annual recruitment. Considerable effort has been directed at improving estimates of these parameters, mainly through the analysis of krill length data from research surveys.

CCAMLR has developed a three-part decision rule for determining the value of γ :

- (i) Choose γ_1 so that the probability of the spawning biomass dropping below 20% of its pre-exploitation median level over a 20 year harvesting period is 10%;
- (ii) Choose γ_2 so that the median escapement in the spawning biomass over a 20 year period is 75% of the pre-exploitation median level;
- (iii) Select the lower of γ_1 and γ_2 as the level of γ for the calculation of yield.

The first part of the decision rule considers krill only in the standard single species context. It aims to meet the requirement for stable recruitment in Article II by keeping the probability low of the spawning biomass dropping below a level at which the chance for successful recruitment might be impaired. The second part of the decision rule is a first attempt to give some explicit effect to the requirements under Article II to limit the effects on predators of harvesting their prey. Detailed modeling of how a fishery on a prey species might impact predators dependent on that species has yet to provide reliable quantitative results. This *ad hoc* approach is therefore being applied in the interim. Conventional fisheries management models suggest that if only single species considerations are pertinent then an appropriate target level for the ratio in part (ii) of the decision rule would be 50%. The best position for the predators might be no fishing at all on prey species (i.e. a ratio of 100%). 75% is therefore a compromise between these two levels. The third part of the decision rule involves the selection of whichever of γ_1 and γ_2 is limiting on the size of the yield.

Future development of this model is in two main areas. Firstly more data are becoming available to reduce the uncertainty in the input parameters and better understand the correlation between them. Secondly, and more importantly from the point of view of the ecosystem approach, is the refinement of krill/krill-predator models in order to provide a more scientifically defensible target krill escapement value.

The krill yield model has been generalized in order to explore its applicability to finfish fisheries in the Convention Area (the Generalized Yield (GY) model - Constable and de la Mare 1996). The same decision rule is applied, although the period of the simulation (20 years in the case of krill) may be varied depending on the generation time of the species being studied. Also for some species, such as the Patagonian toothfish *Dissostichus eleginoides*, a large predatory fish, the escapement criterion in part (ii) of the decision rule is not applicable because they are not an important prey species. Under these circumstances this criterion has been modified to maintain populations at the level likely to give the 'greatest net annual increment', conventionally assumed to be around 50% of the unexploited level. The computer program which implements the GY model allows the user to include a wide range of expressions of uncertainty in input parameters. One innovation in the model, compared to its predecessor, is that recruitment can be specified explicitly (with uncertainty), enabling the effects of given catch levels to be evaluated even though there have been no direct estimates of absolute abundance for the whole stock.

Prior notification and management of new and exploratory fisheries

Another important component of the CCAMLR management mechanism, which is directly relevant to the Precautionary Approach, is the controls placed on the development of new and exploratory fisheries in the Convention Area. In 1991 a conservation measure with indefinite duration was adopted, which defines what the Commission understands by New Fisheries, and specifies the criteria under which such fisheries will be allowed to develop (Appendix 1). In essence, no fishing activity on a species in a management area, using a particular gear type, which has not been fished before, can proceed without prior notification to the Commission. The Commission must be notified by the Member(s) intending to undertake New Fisheries in the Convention Area at least three months in advance of its next regular meeting to allow the proposal to be considered.

There is no specific mechanism within the New Fisheries measure by which the Commission can reject a proposal for new fishing activity. This could be done by adopting a separate conservation measure explicitly closing the fishery in question, before it has even opened, but in practice this is unlikely to happen, because such a measure would have to be agreed by consensus. The notification procedure does, however, provide an element of early warning of expansion of fishing within the Convention Area and affords the Commission the opportunity to comment on the planned activity. Among other things, the Commission would normally comment on the proposed harvesting method, the intended level of catch, the limit on and distribution of fishing effort, measures to avoid impacts on non-target species and the intended mechanism for the collection of data and information needed for the assessment of the future potential of the fishery. Once a plan for initiating a New Fishery has been approved by the Commission, it is embodied in the provisions of a separate conservation measure for the following season, which restricts fishing activity to the terms specified in the plan.

Two years after the adoption of the New Fisheries conservation measure, recognizing the need to control the *development* as well as the *initiation* of new fishing activity, the Commission adopted a measure covering Exploratory Fisheries (Appendix 2). This measure is of a similar form in that it first defines what the Commission understands by the term Exploratory Fisheries, and then goes on to explain what is required in terms of notification of the intent to enter such a fishery, and the preparation of data collection and fishery operations plans.

The Exploratory Fisheries measure is considerably more prescriptive than the New Fisheries measure. This

partly reflects the development of thinking within the Commission in the period between the meetings at which they were each adopted. However, both of these measures were designed with the intent that they would enable CCAMLR to control and monitor the initiation and development of new fishing activity in the Convention Area in the spirit of the Precautionary Approach. The control mechanism aims to prevent fisheries from expanding faster than the acquisition of information necessary for the development of management advice.

A large number of notifications for New and Exploratory fisheries, principally for toothfish (*D. eleginoides* and *D. mawsoni*) longline fisheries, were considered by the Commission at its meetings in 1996 and 1997. Advice was received from the Scientific Committee regarding appropriate precautionary catch levels and the limitation and distribution of fishing effort. There was clearly very little information on which to base this advice and much had to be gleaned from experience in other parts of the Southern Ocean. Precautionary catch limits were calculated on the basis of adjustments for seabed area, use of the GY model with input parameters selected as most appropriate for the area under consideration, and allowances for any information about recent catch history, including estimates of illegal and unreported catches. As a further precautionary measure, yields calculated in this way were reduced by multiplying them by an arbitrary discount factor. In 1997, the values applied were 0.45 for *D. eleginoides* and 0.3 for *D. mawsoni*, the latter reflecting the greater degree of uncertainty in the life history parameters of that species. The scientific view was that this calculation method was the best available given existing information, but the Scientific Committee emphasized that the precautionary limits estimated did not imply that such quantities of fish would necessarily be available for capture. In 1997, conservation measures specifying, *inter alia*, precautionary catch limits, season length, effort limitations and the requirement to carry CCAMLR designated scientific observers and satellite vessel monitoring transponders were adopted to apply to each new or exploratory fishery in the 1997/98 season. In addition a general measure specifying provisions for the distribution of fishing effort over as large a geographical and bathymetric range as possible, and a data collection plan, applicable to all new and exploratory fisheries was adopted. The results of the new and exploratory fisheries undertaken in the 1997/98 season will be analysed at the 1998 meeting of WG-FSA and advice for TACs and other management measures revised accordingly.

The New and Exploratory Fisheries conservation measures (Appendices 1 and 2) are currently under review, because although the intentions of the Commission in agreeing these two measures are reasonably clear,

their practical application is not without its problems. For example, there are no guidelines in the New Fisheries measure on how a fishery should be conducted during its first year of operation and how information should be collected and made available to CCAMLR. This has led to a wide range of interpretations amongst the Members of CCAMLR and a varying degree on detail in notifications submitted to the Commission. Considerably more guidance on notification requirements is included in the Exploratory Fisheries measure, but there is no formal relationship between this and the New Fisheries measure, nor clear understanding of how a fishery should progress from one stage to the next. A further deficiency of the present system is that there is no formal mechanism for the re-opening of fisheries which have been closed, nor for the resumption of those which have lapsed for reasons other than closure.

In recognition of these deficiencies, and the need to address the inter-relationship of all stages of fishery development, the Commission at its meeting in November 1997 requested Members to examine this matter before the next meeting. What is needed is essentially a unified regulatory framework which sets out guidelines for the assessment and regulation of fisheries at all stages of development. These guidelines should include agreed biological reference points for overfishing, as envisaged in the Precautionary Approach. The framework should be designed to meet two criteria: on the one hand to be sufficiently comprehensive to provide guidelines for the management of all existing and potential fisheries, and on the other to be adequately flexible to allow the Commission to adopt measures tailored to the specific needs of individual fisheries, on a case by case basis.

Other Examples of CCAMLR's Application of the Precautionary Approach

There are a number of other areas where CCAMLR has been pro-active in promoting the Precautionary Approach. Most notable amongst these are various measures aimed at the protection of non-target species, including bycatch limits, technical measures and season limitations to reduce incidental mortality of seabirds in longline and trawl fisheries, and a ban on the use of plastic packaging bands, in which marine mammals can become entangled, for bait boxes and other uses. CCAMLR has also taken steps in recent years to improve the transparency of its scientific work through the validation of models and computer programs used by the working groups and the establishment of a peer reviewed journal, *CCAMLR Science* for the publication of articles concerned with the conservation and rational utilization of Antarctic marine living resources.

Illegal and Unregulated Fishing

In practice, despite the good intentions of the New and Exploratory conservation measures, new fishing activity has been able to develop in an unregulated and uncontrolled manner in the Convention Area. For example, CCAMLR has been unable to control the 'gold rush' style expansion of the demersal longline fishery for toothfish in the Indian Ocean sector of the Southern Ocean. Despite the existence of measures restricting the level and distribution of fishing effort, there has been an unprecedented increase in unregulated fishing in this area over the last few years. CCAMLR has a System of Inspection under which Members can designate Inspectors. However, enforcement of CCAMLR conservation measures is largely a matter of flag state control - i.e. the Members must monitor the activities of vessels flying their flags, and impose sanctions on those found to be transgressing regulations that have been agreed by CCAMLR. There is a wide range of issues to be considered here, including the re-flagging of vessels to non-CCAMLR states, which are outside the scope of this paper. However, it is clear that if CCAMLR's intentions in adopting measures in accordance with the Precautionary and Ecosystem Approaches are to achieve their aims, some means of ensuring a much higher level of compliance will have to be found. A very useful first step was taken at the 1997 Commission meeting, which adopted a conservation measure that requires all Contracting Parties to the Convention to licence their vessels when they are operating in the Convention Area.

Conclusion

CCAMLR has clearly been a front runner in the development and adoption of management measures which conform to the philosophy of the Precautionary Approach. This is a particularly laudable achievement in the context of an international organisation with 23 Members and a system which requires decisions to be taken by consensus. However it is equally clear that CCAMLR faces major problems in the implementation and enforcement of its conservation measures, particularly with regard to the regulation and control of the expansion of new fishing activity in the Convention Area. The Commission has been quick to recognise this and applied itself to solving the problem at its meeting in November 1997. New initiatives adopted at that meeting include the requirement for Contracting Parties to licence their flag vessels when operating in the Convention Area, a resolution to establish, by the end of the Commission meeting in November 1998, an automated vessel monitoring system on such licenced vessels, with the exception of the krill fishery, and a scheme

to promote compliance by non-contracting party vessels with CCAMLR conservation measures. It will be necessary to build on these initiatives in subsequent years if CCAMLR is to achieve its aims.

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Appendix 1

CONSERVATION MEASURE 31/X^{1,2} Notification that Members are Considering Initiating a New Fishery

The Commission,

Recognising that in the past, Antarctic fisheries have been initiated in the Convention Area before sufficient information was available upon which to base management advice,

Noting that in recent years new fisheries have started without adequate information being available to evaluate either the fishery potential or the possible impacts on the target stocks or species dependent on them,

Believing that without prior notification of a new fishery, the Commission is unable to fulfil its function under Article IX, hereby adopts the following Conservation Measure in accordance with Article IX of the Convention:

1. A new fishery, for the purposes of this Conservation Measure, is a fishery on a species using a particular fishing method in a statistical subarea for which:
 - (i) information on distribution, abundance, demography, potential yield and stock identity from comprehensive research/surveys or exploratory fishing have not been submitted to CCAMLR;
 - or
 - (ii) catch and effort data have never been submitted to CCAMLR;
 - or
 - (iii) catch and effort data from the two most recent seasons in which fishing occurred have not been submitted to CCAMLR.
2. A Member intending to develop a new fishery shall notify the Commission not less than three months in advance of the next regular meeting of the Commission, where the matter shall be considered. The Member shall not initiate a new fishery pending the process specified in paragraphs 4 and 5 below.
3. The notification shall be accompanied by as much of the following information as the Member is able to provide:
 - (i) the nature of the proposed fishery including target species, methods of fishing, proposed region and any minimum level of catches that would be required to develop a viable fishery;
 - (ii) biological information from comprehensive research/survey cruises, such as distribution, abundance, demographic data and information on stock identity;
 - (iii) details of dependent and associated species and the likelihood of them being affected by the proposed fishery; and
 - (iv) information from other fisheries in the region or similar fisheries elsewhere that may assist in the valuation of potential yield.
4. The information provided in accordance with paragraph 3, together with any other relevant information, shall be considered by the Scientific Committee, which shall then advise the Commission.
5. After its review of the information on the proposed new fishery, taking full account of the recommendations and the advice of the Scientific Committee, the Commission may then take such action as it deems necessary.

¹ Except for waters adjacent to the Kerguelen and Crozet Islands.

² Except for waters adjacent to the Prince Edward Islands.

Appendix 2

CONSERVATION MEASURE 65/XII^{1,2} Exploratory Fisheries

The Commission,

Recognising that in the past, some Antarctic fisheries had been initiated and subsequently expanded in the Convention Area before sufficient information was available upon which to base management advice, and

Agreeing that exploratory fishing should not be allowed to expand faster than the acquisition of information necessary to ensure that the fishery can and will be conducted in accordance with the principles set forth in Article II,

hereby adopts the following Conservation Measure in accordance with Article IX of the Convention:

1. For the purposes of this Conservation Measure, exploratory fisheries are defined as follows:
 - (i) an exploratory fishery shall be defined as a fishery that was previously classified as a 'new fishery', as defined by Conservation Measure 31/X;
 - (ii) an exploratory fishery shall continue to be classified as such until sufficient information is available:
 - (a) to evaluate the distribution, abundance, and demography of the target species, leading to an estimate of the fishery's potential yield,
 - (b) to review the fishery's potential impacts on dependent and related species, and
 - (c) to allow the Scientific Committee to formulate and provide advice to the Commission on appropriate harvest catch levels, as well as effort levels and fishing gear, where appropriate.
2. To ensure that adequate information is made available to the Scientific Committee for evaluation, during the period when a fishery is classified as exploratory:
 - (i) the Scientific Committee shall develop (and update annually as appropriate) a Data Collection Plan, which will identify the data needed and describe the actions necessary to obtain the relevant data from the exploratory fishery;
 - (ii) each Member active in the fishery shall annually (by the specified date) submit to CCAMLR the data specified by the Data Collection Plan developed by the Scientific Committee;
 - (iii) each Member active in the fishery or intending to authorise a vessel to enter the fishery shall annually prepare and submit to CCAMLR by a specified date a Research and Fishery Operations Plan for review by the Scientific Committee and the Commission;
 - (iv) prior to any Member authorising its vessels to enter an exploratory fishery that is already in progress, that Member shall notify the Commission not less than three months in advance of the next regular meeting of the Commission, and the Member shall not enter the exploratory fishery until the conclusion of that meeting;
 - (v) if the data specified in the Data Collection Plan have not been submitted to CCAMLR for the most recent season in which fishing occurred, continued exploratory fishing by the Member which failed to report its data shall be prohibited until the relevant data have been submitted to CCAMLR and the Scientific Committee has been allowed an opportunity to review the data;
 - (vi) fishing capacity and effort shall be limited by a precautionary catch limit at a level not substantially above that necessary to obtain the information specified in the Data Collection Plan and required to make the evaluations outlined in paragraph 1(ii);
 - (vii) the name, type, size, registration number, and radio call sign of each vessel participating in the exploratory fishery shall be registered with the CCAMLR Secretariat at least three months in advance of starting fishing each season; and
 - (viii) each vessel participating in the exploratory fishery shall carry a scientific observer to ensure that data are collected in accordance with the agreed Data Collection Plan, and to assist in collecting biological and other relevant data.
3. The Data Collection Plan to be formulated and updated by the Scientific Committee shall include, where appropriate:
 - (i) a description of the catch, effort, and related biological, ecological, and environmental data required to undertake the evaluations described in paragraph 1(ii), and the date by which such data are to be reported annually to CCAMLR;
 - (ii) a plan for directing fishing effort during the exploratory phase to permit the acquisition of relevant data to evaluate the fishery potential and the ecological relationships among harvested, dependent, and related populations and the likelihood of adverse impacts; and
 - (iii) an evaluation of the time-scales involved in determining the responses of harvested, dependent and related populations to fishing activities.
4. Research and Fisheries Operations Plans to be prepared by Members participating or intending to participate in the exploratory fishery shall include as much of the following information as the Member is able to provide:

- (i) a description of how the Member's activities will comply with the Data Collection Plan developed by the Scientific Committee;
- (ii) the nature of the exploratory fishery, including target species, methods of fishing, proposed region and maximum catch levels proposed for the forthcoming season;
- (iii) biological information from comprehensive research/survey cruises, such as distribution, abundance, demographic data, and information on stock identity;
- (iv) details of dependent and related species and the likelihood of them being affected by the proposed fishery; and
- (v) information from other fisheries in the region or similar fisheries elsewhere that may assist in the evaluation of potential yield.

¹ Except for waters adjacent to the Kerguelen and Crozet Islands.

² Except for waters adjacent to the Prince Edward Islands.

Requirements for Recovering Fish Stocks

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Abstract. Recently, requirements for recovering fish stocks were examined in the context of the Fisheries Conservation and Management Act of the United States. It was suggested that simple constant fishing mortality rate policies imposed difficulties because of uncertainties and variability in both management and biological processes; and that recovery plans for fishery resources that are depleted should include four necessary components: 1) a threshold measure (or measures) of the overfished state and periodic monitoring of the fishery resource relative to that measure; 2) a recovery period; 3) a recovery trajectory for the interim stock status relative to the overfished state; and 4) transition from a recovery strategy to an "optimal yield" strategy. A constant fishing mortality rate without an accepted recovery trajectory does not provide for "mid-course corrections" needed to adjust to differences between projected and realized resource status and in the risk choices of the managers relative to over-runs and under-runs of annual quotas. Recent changes in US fisheries policy suggest that additional constraints on recovery periods are being requested which addresses some of those difficulties. The implications of these policy changes relative to technical aspects of recovery plans are discussed.

Introduction

The Fisheries Conservation and Management Act (FCMA) of the United States and its amendments established domestic marine fisheries policy in relation to recovery processes for overfished stocks in the late 1980's. Through that legislation, requirements were developed for definitions of overfishing, i.e. definitions of the fishing rate, productivity and/or the stock level that presents a substantial risk of recruitment decline (Rosenberg, et al. 1994). The initial focus of these definitions was on the appropriateness of the criteria and the efficacy of measures relative to the criteria. However, the regulatory guidelines that establish the need for overfishing criteria also required that recovery plans be implemented for those stocks that are in an overfished state. Requirements for recovery plans under FCMA and problems that arose in implementation were presented (Powers 1996). Recent changes in United States marine fisheries legislation through the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) has provided further guidance to address recovery plans. The objective of this paper is to revisit recovery plan requirements (Powers 1996) in the context of the MSFCMA and to relate these to "control law" approaches (Restrepo and Rosenberg 1994) being considered for technical implementation.

Characteristics of a Recovery Plan

A recovery plan is a strategy of selecting fishing mortality rates or equivalent catches that will increase the status measure (e.g. biomass) above some minimum standard threshold within a specified period of time.

Biological reference points relating to overfishing have been studied for many years (Gulland and Boerema 1973, Sissenwine and Shepherd 1987, Goodyear 1993) and have led to several fishery benchmarks used to guard against recruitment overfishing. The word *overfishing* implies an act of depletion; thus, is related to the fishing mortality rate. Additionally, there is the state of being *overfished* where the stock's status (e.g. biomass) is reduced below minimum standards. A recovery plan addresses both situations. However, the actions which might be imposed when the fishing mortality rate is exceeded will often differ depending upon the status of stock biomass. For example, a stock which is high in biomass and has little previous fishing history is not at as high a risk of recruitment collapse from a high fishing mortality rate as one with a low biomass that is below a biomass threshold. Hence, the actions to be taken for recovery depend heavily on the overfished status.

Four components were suggested as being necessary for a recovery plan (Powers 1996): 1) a threshold measure (or measures) of the overfished state and periodic monitoring of the fishery resource relative to that measure; 2) a recovery period; 3) a recovery trajectory for the interim stock status relative to the overfished state; and 4) transition from a recovery strategy to an "optimal yield" or target strategy.

The first of these (a threshold measure and monitoring of status) has its own uncertainties and scientific debate (Rosenberg et al 1993, Rosenberg et al 1994, Goodyear 1993, Mace and Sissenwine 1993) both in

terms of the criteria to be used and the uncertainties commonly encountered in the estimation. With the new legislation (MSFCMA) it appears that the management debate about the criteria has been clarified [see Restrepo et al. 1998: maximum sustainable yield (MSY) is to be utilized as a limit threshold where fishing mortality rate at MSY (F_{MSY}) is not to be exceeded and spawning biomass is not to drop much below spawning biomass at MSY (B_{MSY})]. However, the other components of a recovery plan (recovery period, trajectory for recovery and transition to optimum) are often not addressed (Rosenberg et al. 1994). Therefore, the discussion in Powers (1996) is re-presented as a basis for examining effects of MSFCMA on their definition.

Recovery Period

The duration of recovery is the time until the status measure (e.g. spawning biomass) increases above the limit threshold. In several recovery plans of the south-east United States under FCMA, the duration of recovery has been based on a multiple (λ) of the lifespan (t) of the fish (king and Spanish mackerel, red snapper and other reef fishes). In those cases the recovery measure being utilized is the spawning potential ratio which is, in essence, a per-recruit measure. Therefore, once a constant reduced fishing mortality rate is applied for λt years, then (by definition) recovery is achieved. In practice the actual time to recovery depends upon year-class effects and regulatory implementation errors; nevertheless, the recovery periods in these cases were still defined in terms of the lifespan. The biological scientific input into this process was through the biological definition of the term "lifespan"; whereas, the fisheries management decision was in selecting the multiplier of the lifespan which was most appropriate for their management goals.

With MSFCMA, the threshold measure of an overfished status will be in units such as biomass or spawning stock levels. Thus, there is no direct argument for linking the duration of recovery period with lifespan, as suggested above for per-recruit measures. However, such a linkage is still useful because lifespan indicates the time in the future at which recruitment totally depends upon spawning from fish that have yet to be spawned as opposed to depending partially on those fish that already exist.

The recovery period should be long enough to allow an acceptable probability that the status measure(s) exceed the rebuilding target given the productivity of the stock. If the period is too short, recovery may not be feasible even with no fishing. If the period is too long, then biological advice becomes very uncertain due to uncertainties about future recruitment. Biological information on stock productivity should define whether a recovery period is infeasible (too short). Whether a re-

covery period is too long or not is more ambiguous to define biologically. Further research is needed to characterize the risk and uncertainty in recruitment projections. However, the proposed course of management action also will affect the recovery period. Delayed implementation might allow further stock deterioration and it would take longer for the stock to recover. If the recovery period is too long, then the achievement of other management goals may be delayed.

There should be stability and continuity to the recovery duration and, indeed, to the entire recovery plan. As new socioeconomic and biological/ecological information becomes available, there may be a need for flexibility to modify the duration of the recovery period to satisfy overall management goals. However, the process of modification should not be so flexible as to make the annual stock assessment advice offered to management ineffectual. Modifications should be subject to sufficient layers of review so that the changes are both significant and justified before they are implemented. Modifications should be responsive to realized recruitment and fishery changes during rebuilding and to credible scientific advice, rather than changes in short term non-biological objectives.

The MSFCMA has indeed provided guidance on the specification of a recovery period (Restrepo et al. 1998). The legislation has addressed the management role by providing overall constraints on the duration of the recovery period: limiting it to a minimum number of years (ten years) unless such a recovery is not biologically feasible. If it is not biologically feasible (the stock cannot recover within the minimum number of years with no fishing), then it is suggested that the recovery period revert to the minimum year constraint plus one generation time (see Restrepo et al. 1998).

Recovery Trajectory

An accepted recovery trajectory for each status measure should be a central theme for a recovery plan. Initiation of a recovery plan starts with a determination that the stock is overfished at a particular point in time. Then an end point is established which specifies the time at which we wish the status measure(s) to rise above the rebuilding target. However, there are infinite number of pathways by which the stock can get from the starting point to the end point. Without further guidance, there is no basis for scientific advice on management measures and monitoring of recovery. Any annual quota or fishing mortality rate would be biologically acceptable as long as there was a feasible route to recovery within the required time period (and with sufficient probability). However, effects such as dynamic recruitment patterns, quota overages and shifts in fishing strategies that arise subsequent to the implementation of the plan could

lead to implementation errors (Rosenberg and Brault 1993) that could accumulate to the point that it is no longer feasible to reach the recovery target within the required timeframe. Mid-course corrections may be needed to bring recovery back on track or to allow fisheries utilization of "windfalls" brought about by events such as good recruitment or shifts in selectivity. Another strategy would be to utilize the "windfalls" to shorten the time needed for recovery and then only use mid-course corrections when the resource falls below the planned trajectory. While biological constraints will limit the options, it is ultimately the manager's responsibility for selecting among the feasible trajectories. Biological constraints will limit how quickly a stock will grow and the characteristics under which it will grow, even when there is no fishing. However, the benefits of conservation must be balanced against the social and economic costs in both the short and long terms.

As with the recovery period, new socioeconomic, biological or ecological information will require modifications to the recovery trajectory by management. However, modifications should be subject to sufficient layers of input and review so that the changes are both significant and justified, before they are implemented. The evaluation should be based on the expectation that the trajectory will or will not meet the recovery plan given the selected harvest rate strategy in the context of established socioeconomic objectives for the fishery.

Transition from Recovery to Target Objectives

Under MFCMA, recovery plans were to move from recovery towards optimal yield, i.e. toward the targeted management objectives. During the recovery period the goal was to bring the status measure(s) above the rebuilding target. Once recovery was complete then the management target should promote optimum yield. What was undesirable is for the overfished and overfishing thresholds and the optimum target to be identical after recovery has been achieved. If that were to be the case, then even in the best of circumstances the status measure would decline to the threshold and then randomly deviate about the threshold. Stock assessments would classify the stock as overfished every time the deviation was below. This, of course, would cause enormous difficulties for management to implement or dismantle recovery plans whenever there was a small deviation between the status measure and the management target. A primary objective of fisheries management should be to avoid the overfished status.

An example of a transition to an optimum might be one in which there is a transition from recovery fishing mortality rate which is half of the rate to be used to obtain optimum. When the status measure(s) recover to levels above the threshold, then fishing mortality rate

can be increased to that which would produce the optimum, as defined by the managers. The important thing is that the "optimum" not be defined to maintain a stock at the overfished threshold (Rosenberg et al. 1994). This cannot be deemed optimum in a biological sense.

The role of the scientists in this process is to determine whether the optimum fishing mortality rate defined by management will put the stock at risk of being overfished, i.e. to determine the likelihood that a particular harvest rate or stock size could put the stock at risk of being overfished. In that case an optimum based on that particular rate or stock size would not be acceptable. Given that a stock has recovered and that an acceptable fishing mortality rate is selected, scientific advice should offer acceptable catch levels to realize that rate and an interim probability of the state of the resource relative to the overfished state. The transition to optimum should be selected from feasible options by the fisheries managers. For severely depleted stocks, transition plans to optimum are not high priority as compared to determining the threshold measure, the recovery period and the recovery trajectory. If the recovery period is lengthy, then the inevitable debates associated with defining optimum are not as important as the initiation of recovery. As recovery approaches the threshold, then debates over what form optimum yield should take and how quickly it should be achieved rise in priority.

Relationship of Recovery Plans with Control Rules

The above argument has stressed the importance of the four components of a recovery plan: threshold criteria, recovery period, recovery trajectory and transition to a target. However, the dominant school of scientific thought has argued in terms of control rules, i.e. specific advice relating fishing mortality rates with current biomass (Rosenberg et al. 1994, Restrepo and Rosenberg 1994, Restrepo et al. 1998). In fact, the two approaches are equivalent. Defining a control rule is essentially the process of determining an appropriate trajectory, recovery period, target and threshold. This is demonstrated by the following simple example using a population described by logistic dynamics ($r=0.3$, $K=1$) and an initial biomass of 20% of carrying capacity.

First examine the linear control rule in the solid line of the lower panel in Figure 1. This control rule generates specific biomass and yield trajectories (solid lines in upper panel of Figure 1). An alternative control rule (dashed lines in Figure 1) generates different trajectories. A manager would look at the trajectories and quickly note that the dashed alternative has less impact on yield initially with a slower recovery rate than the solid line trajectories.

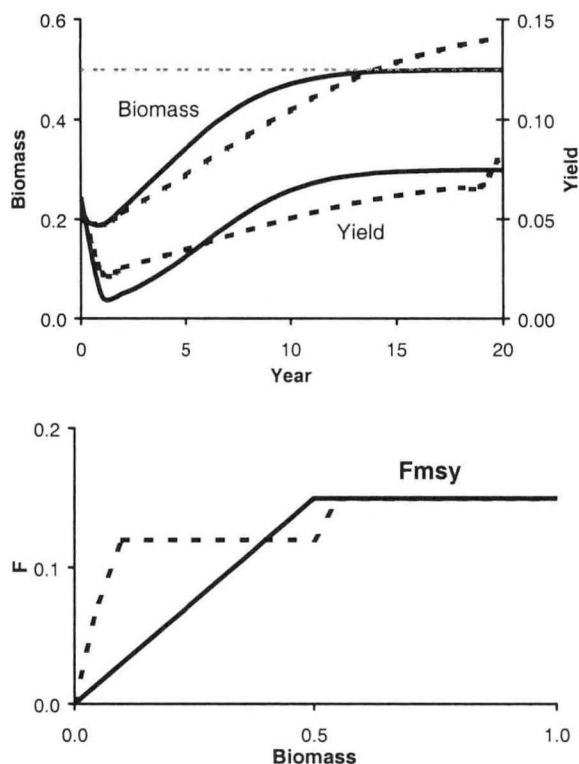


Figure 1. Biomass and yield trajectories (upper panel) given control rules (lower panel); the solid line control rule in the lower panel corresponds to the solid line trajectories in the upper panel; the dashed lines also correspond.

The crux of defining a control rule (especially in the ascending limb) is to determine the short term and long term management constraints in recovery: can large reductions in yield be implemented quickly? Is this technologically and politically feasible? These are the questions that must be addressed in developing the recovery plan. Therefore, it is my opinion that these issues are best discussed and communicated with managers in the context of recovery trajectories and recovery periods, rather than as control rules. At the scientific level one can easily transform control rules to recovery trajectories and *vice versa*.

Also, a control rule (for example as in Figure 2) implies that an adjustment is to be made in fishing mortality rate when implementation has not been perfect. If fishing mortality rate is too high or too low than the recommended F in the next year is adjusted, based upon perceived biomass. An example of this is shown (using the same logistic dynamics) assuming that fishing mortality was mis-implemented twice during a recovery period, once where it was too high and once where it

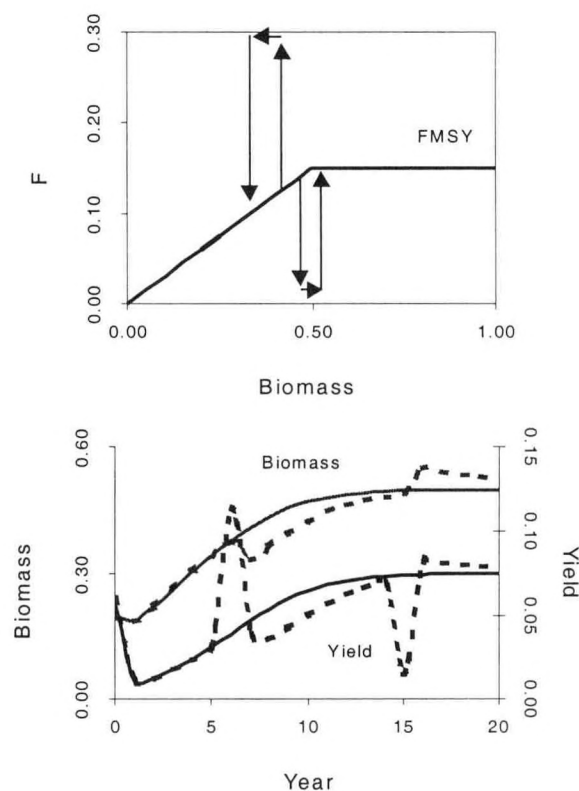


Figure 2. Control rule (upper panel). The arrows in the upper panel indicate the adjustment when actual F is too high and again when it is too low. The bottom panel gives the corresponding biomass and yield trajectories (dashed lines) compared to the perfectly implemented control rule (solid lines).

was too low. The adjustments that are made (using the control rule) are depicted by the arrows in the upper panel of Figure 2. The resulting dynamics in the biomass and yield trajectories are shown in the dashed lines in the lower panel. These are compared to the trajectories with a perfectly-implemented control rule (solid lines). When fishing mortality rate is too high, yield increases and biomass decreases.

Under the control rule in the example, compensation in the fishing mortality rate is done linearly based upon stock dynamics in the intervening period. Another adjustment procedure might be to return the biomass trajectory back to the original (perfectly implemented) alternative (Powers 1996). In this case this implies a particular F control rule, as well. But again, I argue that this is best discussed in a management context using biomass and yield trajectories, rather than as control rules, *per se*. The control rule approach is certainly appropriate in defining feedback mechanisms, but these rules should be couched in terms of biological and management quantities, as well.

Summary Comments

A constant fishing mortality rate policy based on standard fisheries benchmarks such as $F_{30\% SPR}$, F_{MSY} or $F_{0.1}$ theoretically should be adequate for a recovery plan even when there are stochastic fluctuations. However, experience shows that implementation of a constant F policy may be imperfect and the variations in F can be non-random around the target. There may be a series of risk-prone decisions which lead to cumulative deleterious effects on the fish stock or there may be year class effects that accumulate over several years. These are especially troublesome with recovering stocks in that there may be political and economic pressures to harvest the surplus which has accumulated from previous regulations which would allow the stock to grow toward recovery. Thus, the recovery rate may slow or stop completely. Rosenberg et al. (1994) and Restrepo and Rosenberg (1994) addressed this issue in the context of "control laws", i.e. rules that specify F levels depending upon where the stock is relative to its overfishing and overfished thresholds. This paper repeats the Powers (1996) argument that the control law should be translated into an acceptable trajectory of the metric used to define the overfished level and that the target F level should be the F that will keep the trajectory on track. If the fishing mortality rate is the one that keeps the stock on its recovery trajectory, then progress toward recovery can be evaluated directly, as well as short term gains or losses of risk-averse or risk-prone decisions. This allows the development of a long term strategy. This approach also makes the management objectives clear so that scientific advice can be more direct.

The MSFCMA has provided some guidance in terms of defining threshold and target criteria, recovery periods and transition to targets. It also spawned discussion which has stressed the importance of interim milestones for evaluating recovery which is, in effect, the beginning of discussions on appropriate trajectories. However, there is still a need to develop further criteria for recovering trajectories. In particular, what sort of actions ought be taken when stock sizes are very low. When a recovery plan is implemented, there should be a low probability of further deterioration and a high probability of short term improvement. But, there is no consensus on what appropriate definitions of "low" and "high" ought to be. There is a need for scientific work (presumably by simulation studies) to guide this choice.

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Depletion Estimators of Survey Catchability: Theory and Field Experiments

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Quantitative assessment of sessile invertebrate populations has become increasingly important in view of their high economic value and vulnerability to localized overexploitation. Survey-based indices of abundance can be scaled to absolute abundance if capture efficiency can be quantified. In recent years numerous attempts to apply the Leslie-Davis depletion estimator have been reported in the literature. Fortunately this trend has coincided with rapid advances in underlying theory. Maximum likelihood estimation (MLE) methods are sufficiently flexible to allow development of complex models. We apply MLE methods to six separate depletion experiments of surfclams (*Spisula solidissima*) conducted in the May 1997 off the coast of New Jersey. One depletion study was conducted by the R/V Delaware II; the other five were performed by commercial fishing vessels. Capture probability of a hydraulic dredge on the Delaware II was estimated at 0.59; comparable values for commercial vessels ranged from 0.38 to 1.0.

A key ingredient in the application of the depletion estimators to sessile organisms is knowledge of the position of sampling gear. Sessile organisms do not randomly mix after each tow so it is important to estimate the number of times that each patch of substrate has been covered. If this component is ignored and the sampling gear has a greater tendency to sample some areas more than others (e.g., near the center line of the depletion area) then the capture probability will be overestimated and population size will be underestimated. The magnitude of these biases depends on the pattern of sampling within the experimental area. We compare and contrast the estimates of population size and gear efficiency using traditional models and a new model in which the spatial position of the dredge is incorporated into the estimator.

How Can Managers Use Precautionary Management Advice?

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There has been an extraordinary amount of activity over the last five years concerning the development of a precautionary approach to fishery management. The language and sentiment of the precautionary approach is contained in the new U.N. Straddling Stocks agreement, the FAO Code of Conduct for Responsible Fisheries, and the U.S. Sustainable Fisheries Act. On the scientific side, there are a number of technical consultations, conferences and papers developing the structure for giving precautionary management advice. This is a natural extension of the body of work concerning incorporating uncertainty and risk assessment into fishery management advice that has developed over the past decade or so.

The challenge is, as always, turning the advice into management measures which provide real benefits from healthier resources, environments and industries. In order to implement a precautionary approach it will be necessary to focus attention on at least four areas: pre-agreed management measures, default actions that will take place if agreement can't be reached, a mechanism for incorporating new information, and the ability to make rapid adjustments both up and down, in a precautionary manner. In this talk I will use examples from the New England groundfish fishery, scallop fishery, lobster fishery and summer flounder fishery to illustrate my points. None of these fisheries currently use precautionary management, but each contains some elements which may be important to moving in that direction.

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A Conceptual Framework for the Implementation of the Precautionary Approach to Fisheries Management within the Northwest Atlantic Fisheries Organization (NAFO)*

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Abstract. In June 1997, the Scientific Council of the Northwest Atlantic Fisheries Organization (NAFO) established an *Ad hoc* Working Group to develop a conceptual framework for the implementation of the precautionary approach to fisheries management by NAFO. After undertaking a review of (1) various binding and non-binding national and international agreements embodying the Precautionary Approach and (2) various documents and reports pertaining to the consideration and implementation of the Precautionary Approach within ICES and by the USA and Canada, the *ad hoc* Working Group developed a framework and action plan for implementing the precautionary approach within NAFO. The framework prescribes actions (control laws/decision rules) for controlling F with respect to pre-defined, stock-specific, precautionary reference points for both biomass and fishing mortality (B_{lim} , B_{buf} , B_{ur} , F_{lim} , F_{buf} , F_{target}). The objectives are to ensure that $SSB >> B_{buf} > B_{lim}$ and to maintain $F_{target} \leq F_{buf} < F_{lim}$. Guidance is also provided on the determination of these reference points under three levels of data richness: data-rich, data-moderate, and data-poor. A 15-month action plan was proposed for implementing and applying the precautionary approach for managing stocks within the NAFO Regulatory Area. As part of this action plan, a Scientific Council Workshop will be held during 17-27 March 1998 at NAFO HQs in Dartmouth, Nova Scotia to: (1) determine precautionary reference points for all stocks managed by NAFO; (2) specify decision rules to achieve target reference points and to avoid exceeding limit reference points; (3) develop criteria to be used in consideration of possible fisheries re-openings; (4) identify data collection and monitoring activities required to reliably evaluate resource status with respect to reference points; and (5) define research requirements to improve the quantification and evaluation of uncertainty (i.e. risk analysis), as well as methodological developments required to reduce uncertainty. At its June 1998 meeting, it is envisaged that the NAFO Scientific Council will formally implement the precautionary approach in formulating its scientific and management advice for 1999.

Introduction

During the June 1997 meeting of the NAFO Scientific Council, the Council's deliberations led to the creation of an *Ad hoc* Working Group to develop a conceptual framework for the implementation of the precautionary approach in the NAFO context. Cognizant that a number of national and international meetings and initiatives had taken place in recent years focusing on the incorporation and application of the precautionary approach in fisheries management, the Working Group conducted a review of how the precautionary approach was being addressed within ICES and by the USA and Canada. The Working Group considered the relevant sections of various binding and non-binding agreements embodying the precautionary approach:

- the UN Agreement on the Management of Straddling Fish Stocks and Highly Migratory Fish Stocks [see Appendix 1 and 2];
- the FAO Code of Conduct for Responsible Fisheries [see Appendix 3];

- and the FAO Guidelines on the Precautionary Approach to Capture Fisheries and Species Introductions [see Appendix 4].

As well, several other documents relating to over-fishing definitions (Rosenberg et al., 1994) and sustainable harvesting (FRCC, 1996) were also consulted.

What follows is the report of the Working Group to the Scientific Council. Documentation taken into consideration during the discussions of the Working Group is annexed to this report.

Request of the NAFO Fisheries Commission to the NAFO Scientific Council

The Scientific Council was requested by the NAFO Fisheries Commission to:

"... comment on Article 6 [Application of the Precautionary Approach] and Annex II

*This report initially appeared as NAFO SCS Doc. 97/12 (Serial No. N2911), "Report of the *Ad hoc* Working Group of the NAFO Scientific Council on the Precautionary Approach", 61 p. Minor editorial changes have been made to clarify a number of statements in the original report and correct several typographical errors.

[Guidelines for Application of Precautionary Reference Points in Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks] of the Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks; and provide the following information for the 1997 Annual Meeting of the Fisheries Commission, a report that includes for all stocks under the responsibility of the Fisheries Commission (i.e. cod in 3M and 3NO, American plaice in 3M and 3LNO, yellowtail flounder in 3LNO, witch flounder in 3NO, redfish in 3M and 3LN, Greenland halibut in SA 2+3, capelin in 3NO, shrimp in 3M and squid in SA 3+4):

a) recommendation[s] for the limit and target precautionary reference points described in Annex II indicating areas of uncertainty;

b) information including medium term consideration and associated risk or probabilities which will assist the Commission to develop the management strategies described in paragraphs 4 and 5 of Annex II in the Agreement;

c) information on the research and monitoring required to evaluate and refine the reference points described in paragraphs 1 and 3 in the Agreement Annex II; these research requirements should be set out in order of priority considered appropriate by the Scientific Council; and,

d) any other aspect of Article 6 and Annex II of the Agreement which the Scientific Council considers useful for the implementation of the Agreement's provisions regarding the precautionary approach to capture fisheries."

The Scientific Council was also requested by the Fisheries Commission to: "...develop criteria to be evaluated during any consideration of possible fisheries reopenings."

Presentations Made to the Council on the Precautionary Approach

Five reports were reviewed and discussed by the Scientific Council relative to the Fisheries Commission's requests (ICES, 1997; Thompson and Mace, 1997; Sinclair, 1997; Mace and Sissenwine, 1989; FRCC 1996). In addition, a demonstration was provided

to the Council on "FISHLAB: Software for fisheries evaluation and simulation" as this software might be of potential use in calculating precautionary reference points. FISHLAB, developed by M. Smith and L. Kell of the CEFAS Lowestoft Laboratory (UK) consists of a library of Excel and Visual Basic functions, as well as a wide variety of statistical functions, fisheries assessment functions, fisheries prediction functions, and fisheries simulation and evaluation functions. The software is presently available free of charge from the developers.

Highlights of each of the reports are summarized below:

1. Report of the Study Group on the Precautionary Approach to Fisheries Management (ICES, 1997)

i) "The precautionary approach, sustainable development, rational exploitation and responsible fishing have been given a central place in international conferences and agreements devoted to the environment and fisheries... There can be no disagreement that sustainable, productive fisheries require management approaches which ensure a high probability of stocks being able to replenish themselves. Because of the inherent uncertainty in all aspects of fisheries management (assessment, regulation and enforcement), this can only be achieved by taking a precautionary approach. Such an approach needs to be adopted for all aspects of management, 'from planning through implementation, enforcement and monitoring to re-evaluation' (FAO, 1995, page 7), not just in the scientific bases for advice."

ii) Article 7.5 of the FAO Code of Conduct for Responsible Fisheries (FAO, 1995b), and Article 6 and Annex II of the UN Agreement on the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (UN, 1995) are of particular relevance in the interpretation of the precautionary approach. These international instruments "call for the following technical developments: (1) the determination of reference points, with a priority for limit reference points that define the constraints on long-term sustainability, both in theory and as applicable to each stock; (2) improvements in the methods for dealing with uncertainties, notably in relation to evaluating the risk of either approaching or exceeding the limit reference points; [and] (3) the evaluation of how well alternative harvest control rules either maintain stocks in, or restore them to, healthy states. These developments come in addition to assessments of the size, productivity and state of the stocks, and to improved understanding of their biology, which constitute essential pre-conditions of progress in these new directions."

iii) The scientific advisory implications of the precautionary approach suggest that fisheries scientists

should: “(1) explicitly consider and incorporate uncertainty about the state of stocks into management scenarios; explain clearly and usefully the implications of uncertainty to fishery management agencies; (2) propose thresholds which ensure that limit reference points are not exceeded, taking into account existing knowledge and uncertainties; (3) encourage and assist fishery management agencies in formulating fisheries management and recovery plans. To do this effectively may require ... assist[ing] fishery management agencies in the development of coherent, measurable objectives; (4) quantify and advise on the effects of fisheries on target and non target species, and on biodiversity and habitats; (5) provide advice on fishing fleets and multispecies fisheries systems as well as on single stocks; [and] (6) evaluate fisheries management systems incorporating biological, social and economic factors as appropriate.”

iv) Implementation of the precautionary approach has a number of significant implications for fishery management agencies and the fishing industry. Among these are: (1) most of the current fishery management regimes were established before the formulation of the precautionary approach and are not fully in accordance with the precautionary approach. Management agencies will therefore need to implement the precautionary approach to numerous aspects of current practice; (2) the precautionary approach requires that uncertainty be allowed for in both the understanding of the state of the stocks and the effects of future management actions. “This implies that when less is known, fishery management agencies should adopt a more cautious choice. This may require a change in culture towards a management approach less focused on and influenced by short-term considerations, and more concerned with long-term sustainability”; (3) all desirable management objectives cannot usually be met simultaneously and in the precautionary approach fishery management agencies would derive trade-offs between competing objectives in consultation with interested parties, and translate these into measurable factors such as levels of fishing mortality; (4) the way that fishery management agencies attempt to restrict and manage fisheries exploitation (e.g. TACs, effort controls, technical measures, etc) has implications on the way scientific advice is provided and also for the quality of data acquired and the subsequent use of these data in assessments; “it should be obvious that the precision of the advice decreases when the quality of data deteriorates”; and (5) the precautionary approach requires that fishery management agencies find effective means to restrict fishing mortality within safe biological limits. If there are no means to effectively implement precautionary management advice, the advice itself cannot ensure resource sustainability.

v) Based on the distinctions between target and limit reference points given in Annex II of the UN Agreement

on Straddling Fish Stocks and Highly Migratory Fish Stocks (see Appendix 2), “reference points stated in terms of fishing mortality rates or biomass, or in other units, should be regarded as signposts giving information on the status of the stock in relation to predefined limits that should be avoided or targets that should be aimed at in order to achieve the management objective... The introduction of the concept of limit reference points to be avoided with a high probability may in some cases complicate the utilization of target reference points, especially when the precision of the data is low and the uncertainties are high. In such cases, it may be necessary to aim for a fishing mortality rate lower than the target in order to ensure that the limit is not exceeded.”

vi) A provisional list of reference points was developed (see Appendix 5) which contains a number of reference points which could be considered as limit reference points. Limit reference points are to be avoided, thus the probability of exceeding these values must, by definition, be very low. Within ICES, “the precautionary basis for advice given by ACFM will be that, for a given stock, the probability of exceeding the limit reference point will be no greater than 5% in any given year.” This implies that ACFM must recommend that fishing mortality stays below a value considerably lower than the fishing mortality limit reference point. This type of upper bound on fishing mortality (which is significantly below the limit reference point) will be known as the precautionary fishing mortality (F_{pa}). When a fishery is managed such that the annual fishing mortality is at or below F_{pa} , there should be only a low probability that the realized fishing mortality is not sustainable. Similar considerations pertain to biomass limit reference points. Thus, a precautionary biomass level B_{pa} will be determined that is sufficiently higher than the limit biomass reference point to assure with high probability that stock biomass is far above the limit biomass level. Target reference points (either in terms of fishing mortality or biomass) should be more conservative than the precautionary reference points.

vii) Limit, precautionary, and target reference points should be stock specific. The distance between the precautionary reference point and the limit reference point will depend on the data available and their precision, as well as the uncertainties of other parameters such as the environment. The greater the uncertainties, the greater the need to be precautionary. Although some guidance on calculating reference points is provided in the Report, it will be the task of the ICES Methods Working Group to provide ICES Assessment Working Groups with complete guidelines for determining these limit and precautionary reference points.

viii) As part of the precautionary approach, control rules should be implemented which relate target and

precautionary reference points to stock conditions. These rules may be formulated in terms of fishing mortality, fishing effort, or catch - and should be implemented as changes in catch or fishing mortality contingent upon (or in anticipation of) changes in stock biomass. Such decision rules should be established at the outset so that any needed actions are specified in advance of the actual situation. More stringent conservation measures should be applied as stock status worsens. Recovery plans for rebuilding depleted stocks should have control rules to regulate fishing mortality and catches in a pre-agreed way as stock biomass increases. Rebuilding programs are most effective when large reductions in fishing mortality are implemented immediately, rather than when small reductions are phased in over long periods of time. Rebuilding generally proceeds more rapidly when exploitation patterns are improved at the same time. It may also be desirable to restore a stock to (1) a heterogeneous age structure to rebuild population fecundity and buffer against recruitment failure; and (2) a wide spatial distribution to spread risk at spawning over a broad range of environmental conditions.

2. The Evolution of Precautionary Approaches to Fisheries Management, with Focus on the United States (Thompson and Mace, 1997)

i) The precautionary approach gained prominence as a result of the Rio Declaration and Agenda 21. Principle 15 of the Rio Declaration, formulated at the 1992 United Nations Conference on Environment and Development (UNCED), states that "in order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." Subsequently, the precautionary approach has been embodied in: (a) the 1995 FAO Code of Conduct for Responsible Fisheries; (b) the Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas; and (c) the Agreement for the Implementation of the Provisions of the United Nations Convention of the Law of the Sea of 10 December 1982 Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks. Annex II of the latter requires that target and limit reference points be used and stipulates that "Fishery management strategies shall ensure that the risk of exceeding limit reference points is very low" and target reference should not be exceeded on average. Paragraph 7 prescribes that the fishing mortality rate which generates MSY should be regarded as a minimum standard for limit reference points. This combination of requirements implies that fishing mortality should always be

well below F_{MSY} . This is a significant departure from typical fisheries management practice where F_{MSY} is usually treated as a target (and often exceeded), rather than as a limit.

ii) A small number of organizations and nations have already adopted one or more aspects of the precautionary approach and/or have recently conducted studies aimed at interpreting/evaluating the approach as it applies to their fisheries. These include: CCAMLR (Convention for the Conservation of the Antarctic Marine Living Resources); IPHC (International Pacific Halibut Commission); Canada [see FRCC, 1996]; New Zealand, and Australia.

iii) In the United States, recent amendments (September 1996) to the Magnuson Act (the act which governs U.S. marine fishery management activities) have injected many elements of the precautionary approach into the management of marine fishery resources. The amended Act, renamed the Magnuson-Stevens Act, includes new definitions of overfishing, overfished, and optimum yield; requires the establishment of objective and measurable criteria for determining the status of a stock or stock complex; and mandates specific remedial action in the event that overfishing is occurring or if a stock or stock complex is overfished. Sustainability is a key theme in the Magnuson-Stevens Act. Optimum yield [defined as the amount of fish that will provide the greatest benefit to the Nation, particularly with respect to food production and recreational opportunities and taking into account the protection of marine ecosystems] is now prescribed on the basis of MSY (it can never be greater than MSY). In the case of an overfished fishery, the new Act requires rebuilding to the MSY level. As used implicitly in the new Act, "to 'overfish' means to fish at a rate or level that jeopardizes the capacity of a stock or stock complex to produce MSY on a continuing basis. "Overfished" is used in the new Act in two senses: "first, to describe any stock or stock complex that is subjected to overfishing, and second, to describe any stock or stock complex whose size is sufficiently small that a change in management practices is required to achieve an appropriate level and rate of rebuilding. In either sense, "overfished" stocks must be rebuilt.

iv) The Magnuson-Stevens Act further requires that each Fishery Management Plan (FMP) specify objective and measurable status determination criteria for identifying when the stocks or stock complexes covered by the FMP are overfished. A possible interpretation of this requirement is that the stock determination criteria contain two components: a maximum fishing mortality rate and a minimum stock size level. Since the Act mandates that overfished stocks be rebuilt to the MSY level, an MSY control rule will be required to prescribe limits on fishing mortality as a function of stock

biomass [so that sustained application of the rules actually results in rebuilding to MSY]. Obviously, any such rule will also define the rate of rebuilding for all other stocks below the MSY level. Choosing an MSY control rule is the key because it establishes the maximum fishing mortality threshold and plays a role in defining the minimum stock size threshold. Given that OY can never be greater than MSY, the MSY control rule would also define an upper bound on any OY control rule that might be specified.

v) Management of the U.S. EEZ portion of the North Pacific (eastern Bering Sea, Aleutian Island Region and the Gulf of Alaska) is an example where the application of the precautionary approach has been very successful. In 1990, an objective and measurable definition of the overfishing level (OFL) was adopted which provided an upper limit on the amount of fish that could be harvested in any given year. Harvest control laws were implemented in 1996 which were organized in six tiers according to the types of data and information available for a given stock. However, irrespective of tier level, catch targets (ABC) are set well below the overfishing level (OFL) thereby maintaining a buffer between the overfishing level and the catch target. When a stock is above the biomass level associated with MSY (i.e. B_{MSY}), neither the ABC nor the OFL harvest rates varies with stock size. However, if the stock size falls below B_{MSY} , both the ABC and OFL harvest rates decrease linearly as a function of stock size, down to a value of zero at a very low stock size level (typically 5% of B_{MSY}). Although the absolute magnitudes of the ABC and OFL rates vary, the ratio between them remains constant. The minimum buffer between the two rates is established by setting the OFL harvest rate at the arithmetic mean (AM) of the probability density function of F_{MSY} , while capping the ABC harvest rate at the harmonic mean (HM). Since the HM is always less than the AM (and the ratio of the HM to the AM decreases as uncertainty increases), greater uncertainty always corresponds to greater caution - a highly desirable feature.

3. Biological Reference Points Relevant to a Precautionary Approach to Fisheries Management: an Example for Southern Gulf Cod (Sinclair, 1997)

i) The precautionary approach guidelines contained in Annex II of the UN Straddling Stocks Agreement calls for the estimation of stock-specific fishing mortality and biomass reference points related to maximum sustainable yield (i.e. F_{MSY} and B_{MSY}). For many stocks, the necessary information to calculate these reference points is not available. Management strategies for these stocks have typically been based on yield-per-recruit (YPR) and spawning stock biomass per recruit (SSB/R) analyses, not stock/recruitment relationships or stock production models.

ii) Using data from the southern Gulf of St. Lawrence cod stock (NAFO 4TVn(N-A)), age-structured production modeling was conducted to estimate F_{MSY} and B_{MSY} , and to evaluate the effects of changes in size at age, partial recruitment at age, and uncertainty in the stock/recruitment relationship on reference points calculated from production models vs those calculated from YPR models.

iii) "Point estimates and median bootstrap estimates of F_{MSY} and B_{MSY} were virtually identical (0.23 and 207,000 t, respectively) indicating that bootstrapping was reliable." Ninety-five percent of the F_{MSY} estimates were between 0.153 and 0.359, while 95% of the B_{MSY} estimates were between 160,000 t and 325,000 t. Cumulative frequency distribution curves were calculated and displayed in the form of risk curves. Using these curves and adopting a risk averse approach to select a limit B_{MSY} with a low probability (20%) of exceeding the true B_{MSY} resulted in a limit B_{MSY} value of about 240,000 t. Similarly using the same 20% rule to select a fishing mortality limit reference point that would have a low probability of exceeding the true value, resulted in a limit F_{MSY} value of about 0.20.

iv) Management actions implied by changes in size at age or by partial recruitment at age would be quite different depending on whether production models or YPR models were being used. Decreases in size at age had little impact on $F_{0.1}$ [which remained relatively stable] but produced significant declines in F_{MSY} values suggesting that target fishing mortality rates should have been reduced based on the stock production modeling results. Similarly, YPR analyses were relatively insensitive to changes in the age of full recruitment, but F_{MSY} markedly declined in the age-structured production analyses as age at full recruitment declined. However, these results need to be tempered by several of the assumptions used in the production analyses (i.e. a rather simple approach was used to estimate equilibrium stock biomass; a constant knife-edge maturity ogive was applied; and fecundity was assumed to be a simple function of weight).

4. Biological Reference Points for New Zealand Fisheries Assessments (Mace and Sissenwine, 1989)

This document was considered to be a possible aid in developing approaches to determining limit and target reference points in both data-rich and data-poor circumstances.

5. A Discussion of Practical Considerations in Developing Re-Opening Criteria (FRCC, 1996)

The experience of the Fisheries Resource Conservation Council (FRCC) in developing criteria for re-

opening fisheries was reviewed. In recent years, the FRCC has been pursuing a process of deliberation and consultation on when and how to re-open fisheries which presently are closed. A detailed account of this process is given in the October 1996 FRCC report *Building the Bridge – 1997 Conservation Requirements for Atlantic Groundfish* (FRCC, 1996). As background for the FRCC consultations, a list of stock status indicators was developed to characterize the status, growth potential, and exploitability of a stock (e.g. total biomass; spawning biomass; recruitment; growth; stock age composition; geographical distribution; fish condition factor; physical environment; etc).

There was agreement that any indicators used for decision-making should be (a) simple; (b) reliable; and (c) widely understood. Indicators that relate directly to stock abundance (biomass, recruitment, age structure) were considered to be more closely linked to stock status than indicators such as habitat or condition factor. Indicators that are easy to calculate and understand - and which can also be rapidly evaluated - are highly desirable in order to minimize the time lag between information acquisition and decision-making and to allow decisions to be made soon enough to have the most impact. All fishery participants should be able to understand how indicator values are derived and agree upon the utility and reliability of these values.

Once stock status indicators have been identified which satisfy the requirements of clarity, simplicity, and reliability, the question remains how to use them in considering a decision to re-open a fishery. The FRCC acknowledged that the Precautionary Approach must be used to ensure that fisheries are only re-opened when there is sufficient certainty that “(1) fish stocks are in good enough shape; and (2) the re-opened fishery can operate in a conservationist manner, keeping fishing mortality to a low enough level.” The FRCC noted that it was “crucial that BOTH of these conditions be satisfied”.

A review of the stock conditions that prompted fishery closures indicated that the following conditions generally prevailed at the time of closure:

- (1) Low stock size (e.g. declining trends followed by the lowest survey estimates on record);
- (2) Low recruitment;
- (3) Low growth (as evidenced by declines in mean weight at age in catch and/or survey samples);
- (4) Low fish condition factor (a measure of the physiological state of fish which may affect reproductive capacity);
- (5) Loss of spawning components (in some stocks);

- (6) Contraction of geographical distribution; and
- (7) Changes in migration patterns.

Clearly, re-opening of a fishery should not occur until stock conditions have significantly improved from those that existed at the time of closure. To determine whether such improvements have actually transpired, however, an evaluation of stock status indicators (“the report card”) must be performed to decide, guided by the precautionary principle, whether the most crucial indicators have reached acceptable levels (i.e. levels sufficient to support fishing activity). For the FRCC discussions, the “half-way point” (midway between the low level that existed when the fishery was closed and the average level over a recent period), was selected as the benchmark level denotative of sufficient improvement for each indicator.

The “report card” compares past and current values for each stock status indicator and depicts these in relation to the “half-way point”. This framework provides a simple approach to defining conditions (criteria) that should be satisfied prior to re-opening fisheries.

While “reference points or conditions at closure” are NOT substitutes for long-term reference points based on stock dynamics, they serve to capture the conditions that prompted the closures. In essence, they constitute valuable guideposts that - in the context of the Precautionary Approach - delimit danger zones to be avoided in the future.

Endorsement of the Precautionary Approach by the Scientific Council

After reviewing the development, evolution and application of the precautionary approach in fisheries management, the Scientific Council endorsed the precautionary approach as described in Article 6 and Annex II of the UN Agreement of the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (i.e. see Appendix 1 and 2). In addition, the Council intends to use the practical guidance given in FAO 1995 (Guidelines on the Precautionary Approach to Capture Fisheries and Species Introductions; see Appendix 4 for the precautionary guidelines elaborated for fishery research) on how to exercise such precaution.

The Council recognizes that implementation of the precautionary approach will be a challenging and ongoing process. To address this challenge in a rigorous and objective fashion, the Council has initiated development of a framework and action plan, and arranged for a *Scientific Council Workshop on the Precautionary Ap-*

proach to Fisheries Management². This Workshop, to be chaired by the Chairman of the Scientific Council, will meet for 10 days at NAFO Headquarters during March 1998 to address the following terms of reference.

- (1) Describe procedures for determining limit and target reference points under various levels of stock-specific information;
- (2) Determine the limit and target precautionary reference points for all stocks under the responsibility of the NAFO Fisheries Commission (i.e. cod in 3M and 3NO, American plaice in 3M and 3LNO, yellowtail flounder in 3LNO, witch flounder in 3NO, redfish in 3M and 3LN, Greenland halibut in SA 2+3, capelin in 3NO, shrimp in 3M and squid in SA 3+4).
- (3) Specify decision rules (e.g. courses of action) to achieve target reference points and to avoid exceeding limit reference points;
- (4) Develop criteria to be used in consideration of possible fisheries re-openings.
- (5) Identify data collection and monitoring activities required to reliably evaluate resource status with respect to reference points;
- (6) Define research requirements to improve the quantification and evaluation of uncertainty (i.e., risk analysis) as well as methodological developments required to reduce uncertainty; and
- (7) Indicate time frames and funding required to successfully implement the precautionary approach.

General Principle of the Precautionary Framework

The Scientific Council, recognizing the need to apply the precautionary approach in providing scientific advice, proposes the following provisional framework. This framework prescribes the requisite actions to be taken for controlling fishing mortality in relation to various levels of spawning stock biomass and pre-determined, stock-specific reference points.

Paragraph 7 of Annex II of the UN Agreement on the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (see Appendix 2) states that:

“The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points. For fish stocks which are not overfished, fishery management strategies shall ensure that fishing mortality does not exceed that which corresponds to

maximum sustainable yield, and that the biomass does not fall below a predefined threshold. For overfished stocks, the biomass which would produce maximum sustainable yield can serve as a rebuilding target.”

Given these guidelines, the Scientific Council framework defines three reference points for biomass and three reference points for fishing mortality, viz:

Biomass Reference Points

- B_{lim}** The level of spawning stock biomass that the stock should not be allowed to fall below.
- B_{buf}** A level of spawning stock biomass, above **B_{lim}**, that acts as a buffer to ensure that there is a high probability that **B_{lim}** is not reached. The more uncertain the estimate of **B_{lim}** is, the **higher** the value of **B_{buf}**, and the greater the distance between **B_{lim}** and **B_{buf}**. When **B_{buf}** is reached, immediate action is required to ensure stock rebuilding.
- B_{tr}** The target recovery level. In accord with Annex II of the UN Agreement of the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, for overfished stocks this could be the total stock biomass level which would produce maximum sustainable yield (MSY).

Fishing Mortality Reference Points

- F_{lim}** The rate of fishing mortality that should not be exceeded. In accord with Annex II of the UN Agreement of the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, this level should be no higher than the fishing mortality rate which generates MSY.
- F_{buf}** A fishing mortality rate below **F_{lim}** that acts as a buffer to ensure that there is a high probability that **F_{lim}** is not reached. As such, on average, **F_{buf}** should not be exceeded. The more uncertain the estimate of **F_{lim}** is, the **lower** the value of **F_{buf}**, and the greater the distance between **F_{lim}** and **F_{buf}**.
- F_{target}** The target fishing mortality depending on management objectives. This is a level below or equal to **F_{buf}**.

The general, overall objectives of the precautionary approach to management may then be summarized as follows:

² The draft report of this Workshop (held 17-27 March 1998) was issued as NAFO SCS Doc. 98/1 (Serial No. N2987), 60 p.

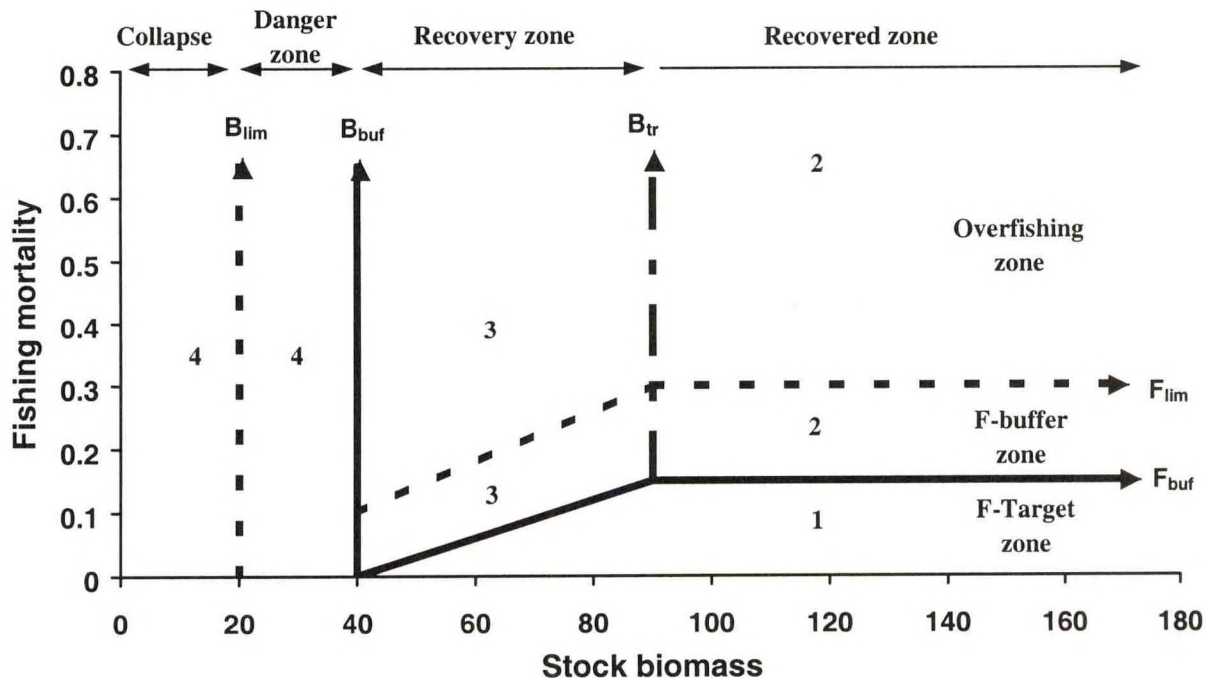


Figure 1. Schematic of the framework for implementation of the precautionary approach.

1. Ensure that spawning stock biomass (SSB) is well above the buffer level (B_{buf}) [which by definition is above the biomass limit reference point (B_{lim})];

2. Maintain fishing mortality such that, on average, it does not exceed F_{buf} , and which will allow the stock to increase towards B_{tr} and ultimately be maintained at the B_{tr} level.

These objectives may be defined in shorthand as follows:

1. Ensure $SSB \gg B_{buf} > B_{lim}$
2. Maintain $F_{target} \leq F_{buf} < F_{lim}$

Schematically, this framework is portrayed in Figure 1 which depicts the courses of action to be taken for given combinations of fishing mortality (F) and spawning stock biomass (B). Spawning stock biomass is represented on the horizontal axis; the three vertical arrows represent the biomass reference points described above. These reference points divide the figure into 4 biomass regions - labeled from left to right as **Collapse**, **Danger Zone**, **Recovery Zone**, and **Recovered Zone**. The level of fishing mortality is shown on the vertical axis; three zones are delimited by the F_{lim} and F_{buf} fishing mortality reference points; these are labeled **Overfishing Zone**, **F-buffer Zone** and **F-Target Zone**.

Within each of the joint biomass/fishing mortality zones depicted in Figure 1, a specific course of action is specified by reference to a numerical label from 1 to 4. The courses of action corresponding to these numeric labels are given below:

Course of Action 1

Current Stock Status: At or above B_{buf}
 Current F: Below F_{buf}
 Action: Continue to fish below F_{buf} .

Course of Action 2

Current Stock Status: At or above B_{tr}
 Current F: Above F_{buf}
 Action: Reduce F to F_{buf} or below over a predetermined time horizon.

Course of Action 3

Current Stock Status: Below B_{tr} ; above B_{buf}
 Current F: Above F_{buf}
 Action: Reduce F towards F_{buf} or below so as to ensure B increases towards B_{tr} over a predetermined time horizon. Note that F_{buf} is lower in the recovery zone than in the recovered zone.

Course of Action 4

Current Stock Status: Below B_{buf}
Current F: Level not relevant
Action: Close fishery; initiate precautionary monitoring of stock, with a view to reopening the fishery only when predetermined reopening criteria are satisfied.

Determination of Precautionary Reference Points with Respect to Data Availability and Data Quality

The reference points for biomass and fishing mortality should be selected in accordance with the precautionary approach framework (as described above). The specific reference metric, however (as given in Appendix 5), may vary according to the quantity and quality of the data available for a given stock. As well, the quantification of uncertainty associated with the reference points will vary with data quality and quantity.

Therefore, the association of the three precautionary reference points (F_{lim} , B_{buf} , and B_{tr}) with the appropriate candidate metrics must take account of the available data. The following discussion illustrates the derivation of each precautionary reference point with respect to three levels of data richness - from very rich (e.g. age-structured population model) to very poor (only catch and/or survey data).

The three levels of information considered, each with a varying amount of richness, are given below.

Level 1: Data-Rich Environment. Age-structured population model, incorporating catch at age with auxiliary information, that provides reliable estimates of current F, recruitment, and biomass. The uncertainty of the limit and threshold reference points, and the risk of exceeding thresholds, are determined. Limit reference points may be derived from production models, stock-recruitment analyses, and yield and spawning stock biomass per recruit analyses. The uncertainty associated with estimates of current F and biomass may be derived from the precision of annual population parameter estimates. The reference points, F_{buf} and B_{buf} are defined in relation to F_{lim} and B_{lim} , respectively; the difference between the limit and the buffer reference point is a function of the uncertainty associated with annual estimates of F and biomass.

As examples, the following candidate measures may be used to determine limit reference points:

$$\begin{aligned} F_{lim} &= (F_{MSY}, F_{max}, F_{med}) \\ F_{buf} &= F_{lim} e^{-2s} \end{aligned}$$

$$\begin{aligned} B_{lim} &= (MBAL, B_{loss}) \\ B_{buf} &= B_{lim} e^{+2s} \\ B_{tr} &= B_{MSY} \end{aligned}$$

Level 2: Data-Moderate Environment. Non-age-structured (production) population model with auxiliary information that provides reliable estimates of current biomass. Information on exploitation pattern, growth and natural mortality is available. Limit reference points may be derived from production models, relative stock-recruitment analyses (based on survey data) and yield and spawning stock biomass per recruit analyses. The uncertainty associated with estimates of current F and biomass may not be available. Biomass trends and recruitment patterns may be derived from research vessel surveys.

As examples, the following candidate measures may be used to determine limit reference points:

$$\begin{aligned} F_{lim} &= (F_{MSY}, F_{max}, F_{30\%}) \\ F_{buf} &= (M, 0.5 * F_{MSY}) \end{aligned}$$

$$\begin{aligned} B_{lim} &= B_{loss} \\ B_{buf} &= 2/3 B_{MSY} \\ B_{tr} &= B_{MSY} \end{aligned}$$

Level 3: Data-Poor Environment. Information on catch trends is available with some auxiliary information. Information on exploitation pattern and growth may not be available. Limit reference points may be derived from relative stock-recruitment analyses (based on survey data). Estimates of current F and biomass, as well as the uncertainty associated with these estimates, are not likely to be available. Biomass trends and recruitment patterns may be derived from research vessel surveys.

As examples, the following candidate measures may be used to determine limit reference points:

$$\begin{aligned} F_{lim} &= F_{30\%} SPR \\ F_{buf} &= M \end{aligned}$$

$$\begin{aligned} B_{lim} &= 0.2 * B_{max} \text{ (survey index)} \\ B_{buf} &= 0.5 * B_{max} \text{ (survey index)} \end{aligned}$$

The Scientific Council evaluated various reference points applicable to each stock for which advice was requested. Results were collated and are summarized in Table 1. Data for each stock were collected using the data forms depicted in Tables 2 and 3.

Reference points vary among stocks, depending on information richness. For those stocks under moratorium (e.g. 3NO cod and 3LNO plaice), biomass indices were given in terms of survey biomass estimates. A similar approach was used in considering possible pre-

Table 1. Possible candidates for reference points under the Precautionary Framework for stocks under the responsibility of the NAFO Fisheries Commission. P = Provisional Reference Point; L = Limit Reference Point; T = Target Reference Point; Q = Qualitative Consideration.

Source	Reference Point	Cod 3M	Cod 3NO	Plaice 3M	Plaice 3LNO	Yellowtail 3LNO	Witch 3NO	Redfish 3M	Redfish 3LN	G. halibut 2+3LMNO	Capelin 3NO	Squid 3-4	Shrimp 3M
Catches	% LTA						P	P	P		P	P	P
Indices	B _{loss}	L	L	L	L	L	L		L	L			
	% Max (e.g. 20%)	L	L	L	L	L	L		L	L			
	% Max (e.g. 50%)	T	T	T	T	T	T		T	T			
	B _{at closure} R _{at closure}	L	L	L	L	L	L						
Y/R	F _{0.1}	T	T		T	T		T	T	T			
	F _{max}	L	L		L	L		L	L	L			
	Age at F _{max}	L	L		L	L		L	L	L			
SSB/R	F _{4,SPR} (e.g. 20%)	L	L		L	L				L			
	B _{4,SPR} (e.g. 20%)	L	L		L	L				L			
S/R Plot	F _{low}	T	T		T	T							
	F _{med}	L	L		L	L							
	F _{high}	L	L		L	L							
	F _{loss}	L	L		L	L							
	MBAL	L	L		L	L							
S/R Model	B _{4,R} (e.g. 50%)	?	?		?								
Production	B _{MSY}	T	T		T	T				T			
	F _{MSY}	L	L		L	L				L			
	2/3 F _{MSY}	T	T		T	T				T			
	F _{crash}	L	L		L	L				L			
Other	Geographic range	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	
	Migration pattern	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	
	Spawning season	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	
	Loss of component	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	
	Age/size structure	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	
	Maturity	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	
	Fish condition	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	
	Environment	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	

Footnote: These candidates for precautionary reference points are provided here as examples only of the types of reference points that could be provided; this list is not meant to be all encompassing. For shrimp in 3M, candidates for reference points are to be identified at the fall [1997] assessment meeting.

Table 2. Sample form to summarize available data on various stock status indicators that may be useful in determining reference points.

Indicator		Long-Term Average (19 - 19)	Max/Min Values & Years		Status at Closure (19)	Present Status (19)	Comments on Stock Status
			Max (19)	Min (19)			
Calculated Indicators from last analytical assessment (19)	Total Biomass (mt)						
	Spawning Biomass (mt) (Age +)						
	Recruitment Levels Age ; Millions of Fish						
Data from Scientific Surveys (Mean #/wt Per Tow)	Total Abundance Index (#/tow)						
	Total Biomass Index (wt/tow)						
	Recruitment Index (#/tow) Age ;						
Changes in Spatial/Temporal Distributions of the Stock and/or Fishery							
Changes in Recruitment Levels or Indices							
Changes in Catch Age/Size Composition							
Changes in Fishery Exploitation Pattern							
Changes in Survey Age/Size Composition							
Changes in Natural Mortality Rate							
Changes in Diet and Feeding Patterns							
Changes in Prey and/or Predator Abundance							
Changes in Average Size Length/Weight at Age							
Changes in Average Length/Age at Maturity							
Changes in Spawning Patterns (Time/Duration/Area)							

Table 3. Sample form to list data availability for calculation of reference points.

Commercial fishery data	Data available now	Data available some time ago	Year data/assessment
Landings			
Catch			
Effort			
CPUE			
Catch-at-length			
Catch-at-age			
Weight-at-age			
Maturity-at-age			
Survey data			
Abundance indices			
Biomass indices			
Density index (e.g. mean CPUE)			
Length composition			
Age composition			
Weight-at-age			
Maturity data			
Length-weight conversion factor			

cautionary reference points for stocks where fisheries are open but where data are minimal (e.g. 3M cod, 3M redfish, and 3LN redfish).

Action Plan for the Development of a Framework on the Precautionary Approach³

The Scientific Council (SC) proposes the following action plan for implementing the Precautionary Approach to Fisheries Management for stocks in the NAFO Regulatory Area.

June 1997:

At its June meeting, the Scientific Council: (a) reviewed the evolution and application of the precautionary approach in fisheries management throughout the world; (b) developed a draft framework for consideration by the NAFO Fisheries Commission; and (c) identified possible candidates for limit and target reference points.

Summer 1997:

ICES Comprehensive Fisheries Evaluation (COMFIE) Working Group Meeting. Members of the Scientific Council will work by correspondence to review the results of the ICES COMFIE WG meeting and

evaluate the applicability of various precautionary reference points for stocks in the NAFO Regulatory Area.

September 1997:

At the September 1997 meeting of the Fisheries Commission, the Chairman of the Scientific Council will propose that the Fisheries Commission: (a) adopt the draft framework for implementation of the Precautionary Approach; (b) endorse the Action Plan developed during the June meeting of the SC meeting; and (c) endorse the convening of the *Scientific Council Workshop on the Precautionary Approach to Fisheries Management* in March 1998.

September 1997 (and November 1997):

Scientific Council to discuss the draft framework for implementing the Precautionary Approach with respect to shrimp stocks in the NAFO area.

September 1997:

ICES Annual Science Conference (Baltimore USA). The 1997 ICES Annual Science Conference will include a Theme Session (Session V) on the "Application of the Precautionary Approach in Fisheries and Environmental Management". Members of the SC will take note of the information discussed at this Session, and review

³ Activities in the Action Plan that occurred between June 1997 and March 1998 were reviewed at the March 1998 Scientific Council Workshop on the Precautionary Approach to Fisheries Management. See Sections I and II in the "Report of the Scientific Council Workshop on the Precautionary Approach to Fisheries Management", NAFO SCS Doc. 98/1, 64 p.

these findings at the March 1998 *Scientific Council Workshop on the Precautionary Approach to Fisheries Management*.

March 1998:

Scientific Council Workshop on the Precautionary Approach to Fisheries Management.

June 1998:

Meeting of the Scientific Council. The Council will implement the Precautionary Approach in formulating advice for 1999 for stocks in the NAFO Regulatory Area and specify precautionary reference points wherever possible.

September 1998:

Meeting of the Fisheries Commission. The Chairman of the Scientific Council will table a report at the September 1998 meeting of the Fisheries Commission entitled "Framework for Implementing the Precautionary Approach to Fisheries Management within NAFO".

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APPENDIX 1

UN Agreement on the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks

Article 6. Application of the Precautionary Approach

1. States shall apply the precautionary approach widely to conservation management and exploitation of straddling fish stocks and highly migratory fish stocks in order to protect the living marine resources and preserve the marine environment.
2. States shall be more cautious when information is uncertain, unreliable or inadequate. The absence of adequate scientific information shall not be used as a reason for postponing or failing to take conservation and management measures.
3. In implementing the precautionary approach, States shall:
 - (a) improve decision-making for fishery resource conservation and management by obtaining and sharing the best scientific information available and implementing improved techniques for dealing with risk and uncertainty;
 - (b) apply the guidelines set out in Annex II and determine, on the basis of the best scientific information available, stock-specific reference points and the action to be taken if they are exceeded;

(c) take into account, *inter alia*, uncertainties relating to the size and productivity of the stocks, reference points, stock condition in relation to such reference points, levels and distribution of fishing mortality and the impact of fishing activities on non-target and associated or dependent species, as well as existing and predicted oceanic, environmental and socio-economic conditions; and

(d) develop data collection and research programmes to assess the impact of fishing on non-target and associated or dependent species and their environment, and adopt plans which are necessary to ensure the conservation of such species and to protect habitats of special concern.

4. States shall take measures to ensure that, when reference points are approached, they will not be exceeded. In the event that they are exceeded, States shall, without delay, take the action determined under paragraph 3 (b) to restore the stocks.
5. Where the status of target stocks or non-target or associated or dependent species is of concern, States shall subject such stocks and species to enhanced monitoring in order to review their status and the efficacy of conservation and management measures. They shall revise those measures regularly in the light of new information.
6. For new or exploratory fisheries, States should adopt as soon as possible cautious conservation and management measures, including *inter alia*, catch limits and effort limits. Such measures should remain in force until there are sufficient data to allow assessment of the impact of the fisheries on the long-term sustainability of the stocks, whereupon conservation and management measures based on that assessment shall be implemented. The latter shall, if appropriate, allow for the gradual development of the fisheries.
7. If a natural phenomenon has a significant adverse impact of the status of straddling fish stocks or highly migratory fish stocks, States shall adopt conservation and management measures on an emergency basis to ensure that fishing activity does not exacerbate such adverse impact. States shall also adopt such measures on an emergency basis where fishing activity presents a serious threat to the sustainability of such stocks. Measures taken on an emergency basis shall be temporary and shall be based on the best scientific evidence available.

APPENDIX 2

ANNEX II. UN Agreement on the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks

Guidelines for the Application of Precautionary Reference Points in Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks

1. A precautionary reference point is an estimated value derived through an agreed scientific procedure, which corresponds to the state of the resource and of the fishery, and which can be used as a guide for fisheries management.
2. Two types of precautionary reference points should be used: conservation, or limit, reference points and management, or target, reference points. Limit reference points set boundaries which are intended to constrain harvesting within safe biological limits within which the stocks can produce maximum sustainable yield. Target reference points are intended to meet management objectives.
3. Precautionary reference points should be stock-specific to account, *inter alia*, for the reproductive capacity, the resilience of each stock and the characteristics of fisheries exploiting the stock, as well as other sources of mortality and major sources of uncertainty.
4. Management strategies shall seek to maintain or restore populations of harvested stocks, and where necessary associated or dependent species, at levels consistent with previously agreed precautionary reference points. Such reference points shall be used to trigger pre-agreed conservation and management action. Management strategies shall include measures which can be implemented when precautionary reference points are approached.
5. Fishery management strategies shall ensure that the risk of exceeding limit reference points is very low. If a stock falls below a limit reference point or is at risk of falling below such a reference point, conservation and management action should be initiated to facilitate stock recovery. Fishery management strategies shall ensure that target reference points are not exceeded on average.
6. When information for determining reference points for a fishery is poor or absent, provisional reference points shall be set. Provisional reference points may be established by analogy to similar and better-known stocks. In such situations, the fishery shall be subject to enhanced monitoring so as to enable revision of provisional reference points as improved information becomes available.

7. The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points. For stocks which are not overfished, fishery management strategies shall ensure that fishing mortality does not exceed that which corresponds to maximum sustainable yield, and that the biomass does not fall below a predefined threshold. For overfished stocks, the biomass which would produce maximum sustainable yield can serve as a rebuilding target.

APPENDIX 3

FAO CODE OF CONDUCT FOR RESPONSIBLE FISHERIES

Article 7.5 Precautionary Approach

Paragraph 7.5.1: States should apply the precautionary approach widely to conservation, management and exploitation of living aquatic resources in order to protect them and preserve the aquatic environment. The absence of adequate scientific information should not be used as a reason for postponing or failing to take conservation and management measures.

Paragraph 7.5.2: In implementing the precautionary approach, States should take into account, inter alia, uncertainties relating to the size and productivity of the stocks, reference points, stock condition in relation to such reference points, levels and distribution of fishing mortality and the impact of fishing activities, including discards, on non-target and associated and dependent species as well as environmental and socio-economic conditions.

Paragraph 7.5.3: States and subregional or regional fisheries management organizations and arrangements should, on the basis of the best scientific evidence available, inter alia, determine:

- a) stock specific target reference points, and, at the same time, the action to be taken if they are exceeded; and
- b) stock specific limit reference points and, at the same time, the action to be taken if they are exceeded; when a limit reference point is approached, measures should be taken to ensure that it will not be exceeded.

Paragraph 7.5.4: In the case of new or exploratory fisheries, States should adopt as soon as possible cautious conservation and management measures, including, inter alia, catch limits and effort limits. Such measures should remain in force until there are sufficient data to allow assessment of the impact of the fisheries on the long-term sustainability of the stocks, whereupon conservation and management measures based on that assessment should be implemented. The latter should, if appropriate, allow for the gradual development of the fisheries.

Paragraph 7.5.5: If a natural phenomenon has a significant adverse impact of the status of living aquatic resources, States should adopt conservation and management measures on an emergency basis to ensure that fishing activity does not exacerbate such adverse impact. States should also adopt such measures on an emergency basis where fishing activity presents a serious threat to the sustainability of such resources. Measures taken on an emergency basis should be temporary and should be based on the best scientific evidence available.

Article 12 Fisheries Research

Paragraph 12.13: States should promote the use of research results as a basis for the setting of management objectives, reference points and performance criteria, as well as for ensuring adequate linkage between applied research and fisheries management.

APPENDIX 4

PRECAUTIONARY APPROACH TO FISHERIES

Part 1: Guidelines on the precautionary approach to capture fisheries and species introductions (FAO Fisheries Technical Paper No. 350, Part 1. Rome, FAO. 1995 52 p.)

Section 4. Precautionary Approach to Fishery Research

51. Application of the precautionary approach to fishery management depends on the amount, type and reliability of information about the fishery and how this information is used to achieve management objectives. The precautionary approach to fishery management is applicable even with very limited information. Research to increase information about a fishery usually increases potential benefits while reducing the risk to the resource. The scientific and research input that is required for the precautionary approach to fisheries is considered under the following headings; management objectives, observations and information base, stock assessment and analysis and decision processes.

Section 4.1 The Role of Research in Establishing Management Objectives

52. There is a valid scientific role in helping managers develop objectives, so that scientific input to the overall management process is as effective as possible in achieving management intent. The precautionary approach requires continuing and anticipatory evaluation of the consequences of management actions with respect to management objectives. Scientific evaluation of consequences with respect to management objectives requires explicit definition of quantifiable criteria for judgement. An important scientific contribution is in the development of operational targets, constraints and criteria that are both scientifically usable and have management relevance.
53. Research is required to help formulate biological objectives, targets and constraints regarding the protection of habitat, the avoidance of fishing that significantly reduces population reproductive capacity, and reduces the effects of fishing on other (e.g., non-target) species. Combined with biological research, research on socio-economics and the structure of fishing communities is needed to formulate management objectives.
54. Until stock specific research leads to the establishment of alternative operational target based on research and practical experiences, a precautionary approach would seek to: (a) maintain the spawning biomass at a prudent level (i.e., above 50% of its unexploited level), (b) keep the fishing mortality rate relatively low (i.e., below the natural mortality rate), (c) avoid intensive fishing on immature fish, (d) protect the habitat.

Section 4.2 Observation Processes and Information Base

55. A precautionary approach to fisheries requires explicit specification of the information needed to achieve the management objectives, taking account of the management structure, as well as of the processes required to ensure that these needs are met. Periodic evaluation and revision of the data collection system is necessary.
56. A precautionary approach would include mechanisms that ensure that, at a minimum, discarded catch, retained catch and fishing effort are accurate and complete. These mechanisms could include use of observers and identification of incentives for industry co-operation.
57. Recognizing that resource users have substantial knowledge of fisheries, a precautionary approach makes use of their experience in developing an understanding of the fishery and its impacts.
58. The precautionary approach is made more effective by development of an understanding of the sources of uncertainty in the data sampling processes, and collection of sufficient information to quantify this uncertainty. If such information is available it can be explicitly used in the management procedure to estimate the uncertainty affecting decisions and the resulting risk. If such information is not available, a precautionary approach to fishery management would implicitly account for the unknown uncertainty by being more conservative.
59. Precautionary fishery monitoring is part of the precautionary approach. It includes collection of information to address issues and questions that are not only of immediate concern but which may reasonably be expected to be important for future generations in case objectives are changed. Information should be collected on target species, bycatch, harvesting capacity, behaviour of the fishery sector, social and economic aspects of the fishery, and ecosystem structure and function. Measures of resource status independent of fishery data are also highly desirable.
60. The precautionary approach relies on the use of a history of experience with the effects of fishing, in the fishery under consideration and/or similar fisheries, from which possible consequences of fishing can be identified and used to guide future precautionary management. This requires that both data and data collection methods are well documented and available.
61. There are many management processes and decision structures used throughout the world, such as regional management bodies, co-management, community-based management, and traditional management practices. Research is needed to determine the extent to which different management processes and decision structures promote precaution.

Section 4.3 Assessment Methods and Analysis

62. Biological reference points for overfishing should be included as part of the precautionary approach.
63. A precautionary approach specifically requires a more comprehensive treatment of uncertainty than is the current norm in fishery assessment. This requires recognition of gaps in knowledge, and the explicit identification of the range of interpretations that is reasonable given the present information.
64. The use of complementary sources of fishery information should be facilitated by active compilation and scientific analysis of the relevant traditional information. This should be accompanied by the development of methods by which this information can be used to develop management advice.

65. Specifically the assessment process should include:
 - a. scientific standards of evidence (objective, verifiable and potentially replicable), should be applied in the evaluation of information used in analysis;
 - b. a process for assessment and analysis that is transparent, and
 - c. periodic, independent, objective and in-depth peer review as a quality assurance.
66. A precautionary approach to assessment and analysis requires a realistic appraisal of the range of outcomes possible under fishing and the probabilities of these outcomes under different management actions. The precautionary approach to assessment would follow a process of identifying alternative possible hypotheses or states of nature, based on the information available, and examining the consequences of proposed management actions under each of these alternative hypotheses. This process would be the same in data-rich and data-poor analyses. A precautionary assessment would, at the very least, aim to consider: (a) uncertainties in data; (b) specific alternative hypotheses about underlying biological, economic and social processes, and (c) calculation of the theoretical response of the system to the range of alternative management actions. A checklist for consideration under these headings is found in the following paragraphs.
67. Sources of uncertainty in data include: (a) estimates of abundance; (b) model structure; (c) parameter values used in models; (d) future environmental conditions; (e) effectiveness of implementation of management measures; (f) future economic and social conditions; (g) future management objectives, and (h) fleet capacity and behaviour.
68. Specific alternative hypotheses about underlying biological, economic and social processes to be considered include: (a) compensatory recruitment or other dynamics giving rapid collapse; (b) changes in behaviour of the fishing industry under regulation, including changes in coastal community structure; (c) medium-term changes in environmental conditions; (d) systematic underreporting of catch data; (e) fishery-dependent estimates of abundance not being proportional to abundance; (f) changes in price or cost to the fishing industry; and (g) changes in ecosystems caused by fishing.
69. In calculating (simulating) the response of the system to a range of alternative management actions, the following should be taken into account:
 - a. short-term (1-2y) projections alone are not sufficient for precautionary assessment; time frames and discount rates appropriate to inter-generational issues should be used, and
 - b. scientific evaluation of management options requires specification of operational targets, constraints and decision rules. If these are not adequately specified by managers, then precautionary analysis requires that assumptions be made about these specifications, and that the additional uncertainty resulting from these assumptions be calculated. Managers should be advised that additional specification of targets, constraints and decision rules are needed to reduce this uncertainty.
70. Methods of analysis and presentation will differ with circumstances, but effective treatment of uncertainty and communication of the results are necessary in a precautionary assessment. Some approaches that could prove useful are:
 - a. when there are no sufficient observations to assign probabilities to different states of nature that have occurred, decision tables could be used to represent different degrees of management caution through Maximin and Minimax criteria;
 - b. where the number of different states of nature and the number of potential management actions considered are small, but probabilities can be assigned, decision tables can be used to show the consequences and probabilities of all combinations of these, and
 - c. where the range of states of nature is large, the evaluation of management procedures is more complex, requiring integration across the various sources of uncertainty.
71. A precautionary approach to analysis would examine the ability of the data collection system to detect undesirable trends. Where the ability to detect trends is low, management should be cautious.
72. Since concern regarding the reversibility of the adverse impacts of fishing is a major reason for the precautionary approach, research on reversibility in ecosystems should be an important part of developing precautionary approaches.

APPENDIX 5

SOME COMMONLY USED REFERENCE POINTS

(From: Updated Draft Report of the ICES Study Group on the Precautionary Approach to Fisheries Management, ICES CM 1997/Assess:7)

RP	Definition	Data Needs	Possible PA-Use
$F_{0.1}$	F at which the slope of the Y/R curve is 10% of its value near the origin	Weight at age, natural mortality, exploitation pattern	
F_{max}	F giving the maximum yield on a Y/R curve	Weight at age, natural mortality, exploitation pattern	LIMIT ¹
F_{bw}	F corresponding to a SSB/R equal to the inverse of the 10% percentile of the observed R/SSB	Data series of spawning stock size and recruitment, weight and maturity at age, natural mortality, exploitation pattern.	
F_{med}	F corresponding to a SSB/R equal to the inverse of the 50% percentile of the observed R/SSB	Data series of spawning stock size and recruitment, weight and maturity at age, natural mortality, exploitation pattern.	LIMIT ¹
F_{high}	F corresponding to a SSB/R equal to the inverse of the 90% percentile of the observed R/SSB	Data series of spawning stock size and recruitment, weight and maturity at age, natural mortality, exploitation pattern.	
F_{MSY}	F corresponding to Maximum Sustainable Yield from a production model or from an age-based analysis using a stock recruitment model	Weight at age, natural mortality, exploitation pattern and a stock recruitment relationship or general production models	LIMIT ¹
$2/3 F_{MSY}$	$2/3$ of F_{MSY}	as above	
$F_{20\% SPR}$	F corresponding to a level of SSB/R which is 20% of the SSB/R obtained when $F=0$	Weight and maturity at age, natural mortality, exploitation pattern.	LIMIT ¹
F_{crash}	F corresponding to the higher intersection of the equilibrium yield with the F axis as estimated by a production model; could also be expressed as the tangent through the origin of a Stock-Recruitment relationship.	Weight at age, natural mortality, exploitation pattern and a stock recruitment relationship	LIMIT ¹
F_{loss}	F corresponding to a SSB/R equal to the inverse of R/SSB at the Lowest Observed Spawning Stock - LOSS	Weight at age, natural mortality, exploitation pattern and a stock recruitment relationship	LIMIT ¹
F_{comf}	F corresponding to the minimum of F_{med} , F_{MSY} and F_{crash}		LIMIT ¹
$F \geq M$	Empirical (for top predators)	M and sustainable F's for similar resources	
$F < M$	As above (for small pelagic species)	M and sustainable F's for similar resources	
Z_{mbp}	Level of total mortality at which the maximum biological production is obtained from the stock	Annual data series of standard catch rate and total mortality	
B_{MSY}	Biomass corresponding to Maximum Sustainable Yield from a production model or from an age-based analysis using a stock recruitment model	Weight at age, natural mortality, exploitation pattern and a stock recruitment relationship or general production models	LIMIT ¹
MBAL	A value of SSB below which the probability of reduced recruitment increases	Data series of spawning stock size and recruitment (not necessarily from an VPA)	LIMIT ¹
$B_{50\% R}$	The level of spawning stock at which average recruitment is one half of the maximum of the underlying stock-recruitment relationship.	Stock recruitment relationship (not necessarily from an VPA)	LIMIT ¹
$B_{90\% R, 90\% Surv}$	Level of spawning stock corresponding to the intersection of the 90th percentile of observed survival rate (R/S) and the 90th percentile of the recruitment observations	Data series of spawning stock size and recruitment	LIMIT ¹
$B_{20\% B-vrg}$	Level of spawning stock corresponding to a fraction (here 20%) of the unexploited biomass. Virgin biomass is estimated as the point where the replacement line for $F=0$ intersects the stock- recruitment relationship or as the biomass from a spawning stock per recruit curve when $F=0$ and average recruitment is assumed	Weight at age, natural mortality, exploitation pattern and a stock recruitment relationship	LIMIT ¹
B_{loss}	Lowest observed stock size	Data series of spawning stock size	LIMIT ¹

¹ Not all limit reference points are intrinsically equal, and their interpretation depends on the specifics of each particular case they are applied to. For example, F_{max} can in some cases be considered as a target, when it is well defined and corresponds to a sustainable fishing mortality, while it would be a limit when it is ill defined and/or corresponds to unsustainable fishing mortality. Similarly F_{MSY} that is suggested as a minimal international standard for a limit reference point in the UN Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks, could in some particular cases be considered a target. F_{crash} on the other hand is an extremely dangerous level of fishing mortality at which the probability of stock collapse is high. The probability of exceeding F_{crash} should therefore be very low.

Patterns of Population Variability in Marine Fish Stocks, with Application to Precautionary Rebuilding Projections of the Georges Bank Haddock

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Exploited marine fish and invertebrate stocks fluctuate in myriad complex patterns, with variability on interannual, decadal, and longer time-scales. To characterize various patterns of variation, time series of catch, catch per unit effort, or biomass, 30 stocks were examined with a variety of statistical methods including autocorrelation analysis and Lowess smoothing (Spencer and Collie, 1997a). A hierarchical cluster analysis classified the stocks into six identifiable groups: steady-state; low-variation, low-frequency; cyclic; irregular; high-variation, high-frequency; and spasmodic. These patterns are consistent with life-history traits; for example, stocks with high variability are generally small pelagic species, whereas low-variability stocks are generally slow-growing demersal fish. The specific mechanisms producing population fluctuations generally remain unknown, but likely involve some interrelation of 1) the effect of harvesting on future recruitment, 2) inter- and intraspecific biotic interactions (predation, competition), and 3) environmental variability. Each of the six general patterns of variability can be produced from a simple multiple-equilibrium population model (Steele and Henderson, 1984) by varying the intrinsic rate of population growth, and the time-scale and amplitude of environmental variability.

Suitable management policies depend on the type of variation observed, and the vast majority of examined stocks did not correspond to the steady-state assumptions of classical fisheries models. Characteristic patterns of variation may suggest general management strategies; for example, management of spasmodic stocks may alternate between periods of active exploitation and rebuilding, a process enhanced by the existence of other exploitable stocks. However, a specific precautionary management strategy will likely require a focused examination that considers uncertainty in future stock production and a variety of harvest strategies and management goals.

The collapse of several northwest Atlantic ground-fish stocks, including the Georges Bank haddock (*Melanogrammus aeglefinus*), has generated interest in precautionary fishery management. The sharp break between prolonged periods of high (pre-1965) and low (post-1965) haddock abundance suggests the existence of two levels of stock productivity, which would be consistent with the Steele and Henderson model. The Steele and Henderson model and the simpler Schaefer production model (Schaefer, 1957) were fit to the haddock data and used to evaluate various rebuilding strategies with two performance measures—the sum of discounted yield and sum of discounted revenue (Spencer and Collie, 1997b). The Steele and Henderson model provided plausible parameter estimates for the entire data set (1931–1993), whereas the Schaefer model provided plausible parameter estimates only for the recent years of low productivity (1976–1993). For either model, the levels of the instantaneous fishing mortality rate F that maximize either yield or revenue were lower than the recently adopted target level of $F_{0.1} = 0.24$. For both models, the time required to rebuild to 80 kt was approximately 10 years when $F \sim 0.10$; recovery times increased more rapidly with increasing F under the Steele and Henderson model. The low production in recent years provides impetus for managers to consider a variety of plausible stock-production models, and the uncertainty of production dynamics, in choosing rebuilding strategies.

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Incorporating Uncertainty into Management Models for Marine Mammals

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Good management models and good models for understanding biology differ in basic philosophy. Management models must facilitate management decisions despite large amounts of uncertainty about the managed populations. Such models must be based on parameters that can be readily estimated, must explicitly account for uncertainty and should be simple to understand and implement. In contrast, biological models are designed to elucidate the workings of biology and should not be constrained by management concerns. Past marine mammal management was based on a simple biological model that, although it may have adequately represented population dynamics, failed as a management tool because the parameter that triggered management action, maximum net productivity level, was extremely difficult to estimate for the majority of populations (Taylor et al. in press). Uncertainty in parameter estimation resulted in few conservation actions. The recently adopted management scheme translates management objectives into quantitative objectives called performance criteria. This allows the management scheme to be adjusted to meet objectives using simulation models (Wade 1997) and puts management decisions on a quantitative footing such that those disagreeing with the management outcome must openly state that they disagree with the performance criteria.

The marine mammal example shows how a rarely implemented law can be turned into a functioning and pro-active law through appropriate consideration of uncertainty. The new management regime grew out of proposals from NMFS, the Marine Mammal Commission, fishing groups and environmental organizations. It sought to do three things: (1) explicitly consider uncertainty in management, (2) base management on parameters that could be estimated, and (3) provide incentives to gather better data. The management goals of the Act are to maintain populations 1) above optimum sustainable yield, and 2) as functioning elements of their ecosystem. These were interpreted as performance criteria: 1) populations starting at 50% of K (MNPL) should remain at that level or above over the next 20 years with a 95% probability, 2) populations at 30% of K should reach MNPL in 100 years with a 95% probability, and 3) stocks should be defined so as to maintain the species' range. A mortality limit, called the Potential Biological Removal (PBR), is calculated as:

$$PBR = N_{\min} \frac{1}{2} R_{\max} F_R \quad (1)$$

where, N_{\min} = minimum population estimate, R_{\max} = maximum population growth rate, and F_R = recovery factor.

The idea of the model is basic: humans should not remove more than the population needs to maintain at least half of its current carrying capacity (K) (or if K has been constant, historical numbers). The model explicitly incorporates two types of data uncertainty: imprecision and bias. To get an intuitive grasp of the PBR management scheme, consider an analogy of shooting at a target. Instead of a bullseye, the target is a square with a horizontal line bisecting the midpoint. For any given shot at the target, the goal is to always (i.e., with high probability) place your round above the line. This symbolizes maintaining populations above MNPL. Imagine that you want to make certain when you shoot that you hit above this line 95% of the time. Now consider two guns: a pilgrim's musket and a sniper's rifle. The rifle shoots with great precision and is equivalent to an abundance estimate with a very low coefficient of variation (CV). Even an expert marksman, however, would be considerably less precise with the musket; repeated attempts with the musket results in a more diffuse pattern than with the rifle. In order to insure a high chance of hitting the target above the line, the marksman would deliberately aim the musket higher than the rifle. Using N_{\min} in the PBR equation effectively raises the aiming point to adjust for poorer precision in the abundance estimates. How high above the line the marksman needed to aim was decided by simulating the response of the hypothetical population to PBR-type management. The simulations both estimated abundance and removed the estimated PBR from model populations. Finding the proper level needed to adjust for poor precision is termed tuning. Repeated simulations using different lower percentiles of the abundance distribution for N_{\min} were used to find the level of precision that met management objectives. This level would allow the marksman to place his/her round above the line 95% of the time. Wade (1997) found the appropriate level for N_{\min} to be the lower 20th percentile of the distribution of an abundance estimate.

The simulations illustrated that using the “best” estimate manages less well known populations (with lower precision abundance estimates) less conservatively. Using a lower percentile of the abundance, in contrast, manages less well known populations more conservatively. Thus, simply incorporating the uncertainty due to the precision of the abundance estimate met two management goals: increasing the margin of safety commensurate with the level of our ignorance of the population, providing an incentive to gather more precise data.

The second type of uncertainty is bias, which was incorporated through the recovery factor parameter (F_R). Returning to the marksman analogy, bias would be indicated if shots aimed at a target consistently missed in one direction. The correction is to tune the sights. If the sights are improperly adjusted, the marksman may aim above the line but consistently hit below it. There are many ways that bias could lead to unfavorably overestimating PBR; therefore, a second set of simulations considered bias in the estimated parameters. One scenario considered was overestimating the abundance by a factor of two. Such an overestimate could come from the relatively unlikely event of animals being attracted to the survey vessel or, more likely, from animals being included in the abundance estimate that were really part of another population. The possibility of such errors led to the setting of default values for the recovery factor (F_R) such that 95% of the simulated populations equilibrated within OSP despite such errors. If the possible factors that cause bias are eliminated, this parameter can be raised to a value of one. However, doing so dramatically reduces the safety margin for managing the species (Taylor 1997).

The final parameter in eq. 1 is R_{MAX} . Here again we chose to use conservative default values when data are lacking. Using data from recovering populations, conservative default values were chosen as 0.04 for whales and dolphins and 0.12 for seals and sea lions. Of course, data from the species or population of concern are used whenever available. Details of the simulations and rationale for default values are given in Wade (1997).

Uncertainty about how the law will be implemented by government agencies was also considered. PBR's are calculated for each stock by federal government scientists and are presented in stock assessment reports. These reports are reviewed by three regional Scientific Review Groups, a body of non-federal scientists (representing perspectives of state agencies, academia, fisheries and environmental groups) who make recommendations on research priorities and the adequacy of the data used. Stocks for which estimated fishery-caused mortality exceeds PBR are termed “strategic”. Regulations are not automatically imposed on fisheries when kills exceed the PBR. Instead, data are scrutinized for the potential

that biases can be reduced by improving abundance estimates or stock definitions. If the data are sound and fisheries contribute significantly to mortalities in strategic stocks, a Take Reduction Team is formed. The team of fishers, environmentalists, state and federal government representatives and scientists is charged with the task of recommending means to reduce the kills (take) to levels at or below PBR within 14 months subsequent to the finalization of the stock assessment reports.

Results of current management model

After the first year of implementation (1994), stock assessment reports were written for 153 stocks in U.S. waters, and PBRs were published for 89 stocks (Barlow et al. 1995; Blaylock et al. 1995; Small and DeMaster 1995). Kills exceeded PBR for 24 stocks of marine mammals. Although some of these, such as harbor porpoise in the Gulf of Maine, were known to be at risk before the management scheme was instituted, many were species that had received no attention in the past. Chief among these are species of whales that spend long times beneath the surface, including sperm whales (*Physeter macrocephalus*) and numerous species of beaked whales (Family *Ziphiidae*). Some of the greatest advances in knowledge since the new management regime came into place are for the relatively rare and unstudied species, like the beaked whales. New assessment techniques that are more suitable for these rare species have been created (Barlow and Sexton 1996).

The stock assessment reports reveal both stocks that are at risk and gaps in our knowledge required for proper management. Comprehensive surveys of the Pacific coast were completed in 1996 and are scheduled for the Atlantic coast in 1998. Because the law mandates monitoring, surveys are planned to continue on a rotational schedule. Testing of the scheme has also made clear the importance of understanding population structure and genetic sampling (which are becoming an integral part of survey design). Knowing the spatial distribution of kills allows formulation of stock boundary hypotheses needed to interpret genetic data (Taylor and Dizon 1996, Taylor 1997, Taylor et al. in press). Take Reduction Teams have been formed and research is underway to develop techniques to reduce the number of marine mammals killed in fisheries to as near zero as practicable.

Despite the initial appearance that for many species and areas this management scheme seems to be working well, there are some concerns. The most neglected parameter is the estimate of kills. Estimates are especially poor for fisheries with large numbers of very small boats, often operated by one person. Assuring adequate coverage would require a much higher level of funding than is currently allocated to this problem.

Another area of concern is the definition of stocks. Although a single definition was used in the PBR guidelines published to standardize management (Barlow et al., 1995, Wade and Angliss 1997), different regions did not agree with this definition and created their own definitions. The success of this management scheme depends in large part on proper definition of stocks or use of F_R to account for potential biases. If stocks are defined in large units, such as the entire Pacific coast, it is likely that localized fisheries will never exceed PBR and therefore any management actions needed to preserve the integrity of the range would not occur. Nevertheless, many scientists feel it is beyond the prerogative of science to draw lines on a map when data are few to nonexistent. Refusing to draw stock boundaries does not, however, leave the stock as "undefined" with no kills allowed. Rather, refusal defines the management unit as the range of the species and puts the burden of proving that population structure exists on scientists before any management actions will be taken. Obtaining measures of population structure for marine animals is difficult because their aquatic nature limits access for research. Requiring proof of structure means at the least lengthy delays until management units are adequately defined. Indeed, requiring such proof may make the new management scheme as ineffective as the old scheme for some species because a required parameter is essentially impossible to estimate.

Indirect and direct human-caused mortality pose the greatest risks for marine species and we have directed our management efforts accordingly. General lessons from our marine experience are: 1) models must be based on parameters that are easily estimated, 2) model performance is guided by performance criteria, which are a quantitative form of management objectives, 3) uncertainty should be directly incorporated so that not only can management proceed despite uncertainty but that management is more conservative the greater the uncertainty, and 4) management models should be rigorously tested using simulations.

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Optimizing Harvest Control Rules In the Presence of Natural Variability and Parameter Uncertainty

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Abstract.— Classical one-parameter harvest policies (such as those based on maintaining a constant optimal catch, constant optimal fishing mortality rate, or constant optimal escapement) and full optimal control solutions (such as those generated through stochastic dynamic programming) represent two ends of a spectrum of possible *harvest control rules*. The classical one-parameter policies have little flexibility and may be substantially sub-optimal, but are easy to describe. True optimal control policies, on the other hand, are completely flexible and fully optimal, but they can be inaccessible. As a compromise between the classical one-parameter policies and a full optimal control solution, several authors have suggested that fisheries be managed by specifying the functional form of a control rule *a priori* and then choosing values for one or more of the parameters so as to maximize a management objective function. The purpose of this paper is to gain an increased understanding of how such harvest control rules can be used to address the problem of optimal fishery management. This is undertaken in three stages, proceeding in order of increasing complexity. In Stage 1, the analysis assumes that population dynamics are completely deterministic and that the values of all biological parameters are known with certainty. Here, the focus of optimization is on maximum sustainable yield (MSY). In Stage 2, the analysis is generalized to the case in which natural (stochastic) variability is present but the values of all biological parameters are still known with certainty. Here, the focus of optimization is on a stochastic analogue of MSY, with attention paid also to tradeoffs between long-term average yield and the level of variability around that average. In Stage 3, the analysis is further generalized to the case in which natural variability is present and the values of biological parameters are uncertain. Here, the focus of optimization is on decision-theoretic analogues of MSY, with attention paid to the various features desired under a precautionary approach. At each stage of development, a general treatment of the problem is attempted, followed by a specific example. Some implications of alternative control rules with respect to the special problem of rebuilding a depleted stock are also given for the first two stages.

Introduction

Background

Development of the Theory

Design of optimal harvest strategies has been a major emphasis of fisheries science throughout most of this century. Early on (e.g., Russell 1931, Hjort et al. 1933), efforts focused on identification of a “constant catch” policy; that is, a single, time-invariant *catch* which could be taken year after year. Soon, though, investigators (e.g., Thompson and Bell 1934, Graham 1935) began focusing on identification of a “constant fishing mortality” policy; that is, a single, time-invariant *fishing mortality rate* which could be applied year after year. Some twenty years later, Ricker (1958) focused on use of a “constant escapement” policy; that is, a single, time-invariant *escapement* which would remain in the stock following each year’s harvest. Each of these strategies was developed in the hope of obtaining the maximum sustainable yield (MSY) from the fishery, although the definitions of this term have sometimes been unclear or inconsistent. Since these early investigations, many studies have compared the policies of constant catch, constant fishing mortality, and constant escapement. One of the earliest and most thorough comparative evaluations of these three policies was conducted by Reed

(1978). Other comparisons of two or more of these policies have been made by Tautz et al. (1969), Gatto and Rinaldi (1976), Beddington and May (1977), May et al. (1978), Hilborn (1979), Deriso (1985), Hilborn and Walters (1992), Frederick and Peterman (1995), and Steinshamn (1998).

Although the focus of each of the above policies is distinct from the others, they share the characteristic that each distills the optimal harvest problem into a single (albeit different) parameter. More complicated policies have also been explored. At about the same time that Ricker was considering the merits of a constant escapement policy, Scott (1955) noted that a truly optimal management strategy would not necessarily be describable in terms of a single parameter. Rather, Scott argued that the optimal harvest should be conceptualized as an entire time series of future catches, *each* of which is chosen in the context of all the others so that the overall benefits from the fishery are maximized. It was not until the 1970s, however, that formal analyses of such a policy were successfully undertaken. These analyses typically involved application of the Pontryagin maximum principle (Pontryagin et al. 1962). Such treatments include those given by Quirk and Smith (1970), Plourde (1970, 1971), and Cliff and Vincent (1973), but Clark’s

(1973, 1976) solution of the simple, deterministic model attributed to Gordon (1954) and Schaefer (1954) is probably the best remembered of this group of studies. Somewhat ironically, it turned out that the strategy which resulted in full optimization of the Gordon-Schaefer model was simply a particular type of constant escapement policy.

While Clark's (1973, 1976) use of the Pontryagin maximum principle in solving simple fishery models was instrumental in bringing an "optimal control" perspective to the design of harvest strategies, application of the maximum principle to more complicated models involving natural variability or parameter uncertainty has not been particularly successful (for an exception, see Gleit 1978). Instead, other techniques such as stochastic dynamic programming have been employed to identify optimal control strategies. Examples are given by Reed (1974, 1979), Walters (1975), Hilborn (1976), Getz (1979), Dudley and Waugh (1980), Mendelsohn (1980, 1982), Charles (1983), Mangel (1985), Hightower and Grossman (1987), Horwood et al. (1990), and Horwood (1991, 1993).

Unfortunately, full optimal control solutions are at best computationally intensive, and at worst completely opaque. Describing such solutions, Horwood (1993, p. 341) states,

"For deterministic problems they are costly in time, but more importantly do not allow the construction of a general management control. The stochastic laws cannot be derived."

The classical one-parameter policies and the full optimal control solutions thus represent two ends of a spectrum of possible *harvest control rules* ("feedback control laws" in the terminology of Clark 1976): The classical one-parameter policies have little flexibility and may be substantially sub-optimal, but they are easy to describe. True optimal control policies, on the other hand, are completely flexible and fully optimal, but they can be inaccessible. As a compromise between the classical one-parameter policies and a full optimal control solution, several authors have suggested that fisheries be managed by specifying the functional form of a control rule *a priori* and then choosing values for one or more of the parameters so as to maximize a management objective function. Walters and Hilborn (1978) called this approach "fixed form optimization," and described it as follows (p. 167):

"There are two basic steps in the development of a fixed-form optimization. The first is to find an algebraic form of the control function. Intuition, common sense, etc. can often be used to guess at a reasonable form.... The second

step in fixed-form optimization is to find the optimal values of the control parameters."

Larkin and Ricker (1964) were among the first to suggest such an approach. Specifically, their suggestion was to prohibit fishing whenever escapement failed to reach a specified level but to allow fishing at a constant rate whenever escapement exceeded the specified level. This 2-parameter policy has also been explored by Aron (1979), Quinn et al. (1990), and Zheng et al. (1993). Other multi-parameter forms for possible control rules were subsequently suggested or evaluated by Allen (1973), Walters and Hilborn (1978), Shepherd (1981), Ruppert et al. (1984, 1985), Hilborn (1985), Getz et al. (1987), Hightower and Lenarz (1989), Hightower (1990), and Engen et al. (1997).

Implementation of the Theory

As is often the case when moving from "theory" to "application" in fisheries management, it has proven easier to evaluate harvest control rules in the literature than to implement them in practice. However, significant progress has been made in the past decade. In the United States, a 2-parameter control rule (based on the functional form suggested by Shepherd 1981) was adopted for management of groundfish off Alaska in 1990. In an official review of overfishing definitions used in the United States, Rosenberg et al. (1994) recommended that a control rule approach be used "when-ever it is practical," and suggested a possible functional form. Based in part on this suggestion, the Alaska groundfish control rule was later modified to a 3-parameter form (U.S. National Marine Fisheries Service 1996). More recently, the Northwest Atlantic Fishery Organization (Serchuk et al. 1997) and the International Council for the Exploration of the Sea (1997) have explored the use of harvest control rules. Finally, the U.S. Government issued a set of "National Standard Guidelines" in 1998 which assigned a fundamental role to harvest control rules (U.S. Department of Commerce, 1998).

Harvest Control Rules and the Precautionary Approach

Much of the current interest in harvest control rules stems from a perception that they can play an important role in implementing a "precautionary approach" to fisheries management. At the international level, calls for adoption of such an approach have been featured in several agreements developed under the auspices of the United Nations, including the Code of Conduct for Responsible Fisheries prepared by the United Nations Food and Agriculture Organization (FAO), the FAO Technical Consultation on the Precautionary Approach to Capture Fisheries, the Rio Declaration of the United Na-

tions Conference on Environment and Development, and the United Nations Convention on the Law of the Sea Relating to the Conservation and Management of Straddling Stocks and Highly Migratory Fish Stocks (the "Straddling Stocks Agreement"). For example, Annex II of the Straddling Stocks Agreement (United Nations 1995) includes the following provisions:

"Two types of precautionary reference points should be used: conservation, or limit, reference points and management, or target, reference points";

"fishery management strategies shall ensure that the risk of exceeding limit reference points is very low"; and

"the fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points."

In the U.S., the National Standard Guidelines (U.S. Department of Commerce 1998) also encourage the use of a precautionary approach with the following features:

"Target reference points ... should be set safely below limit reference points...";

"a stock ... that is below the size that would produce MSY should be harvested at a lower rate or level of fishing mortality than if the stock ... were above the size that would produce MSY"; and

"criteria used to set target catch levels should be explicitly risk averse, so that greater uncertainty regarding the status or productive capacity of a stock or stock complex corresponds to greater caution in setting target catch levels."

A more detailed description of the historical development of the precautionary approach has been given by Thompson and Mace (1997).

Purpose and Outline

The purpose of this paper is to gain an increased understanding of how harvest control rules can be used to address the problem of optimal fishery management. This will be undertaken in three stages, proceeding in order of increasing complexity. In Stage 1, the analysis will assume that population dynamics are completely deterministic and that the values of all biological parameters are known with certainty. Here, the focus of optimization will be on MSY. In Stage 2, the analysis will be generalized to the case in which natural (sto-

chastic) variability is present but the values of all biological parameters are still known with certainty. Here, the focus of optimization will be on a stochastic analogue of MSY, with attention paid also to tradeoffs between long-term average yield and the level of variability around that average. In Stage 3, the analysis will be further generalized to the case in which natural variability is present and the values of biological parameters are uncertain. Here, the focus of optimization will be on decision-theoretic analogues of MSY, with attention paid to the various features desired under a precautionary approach (U.S. Department of Commerce 1998). At each stage of development, a general treatment of the problem will be attempted, followed by a specific example. Some implications of alternative control rules with respect to the special problem of rebuilding a depleted stock will also be given for the first two stages.

The outline of the remainder of the paper is thus as follows:

Stage 1: Determinism Under Known Parameter Values

Dynamics
Solution
Rebuilding
Optimization

Stage 2: Incorporating Natural Variability

Dynamics
Solution
Rebuilding
Optimization

Stage 3: Incorporating Parameter Uncertainty

Discussion

Table 1 lists the symbols used in the remainder of the paper. A definitional change regarding one parameter will prove helpful in moving from Stage 2 to Stage 3. This is addressed in the text.

Stage 1: Determinism Under Known Parameter Values

Dynamics

In General

In the absence of both natural variability ("process error") and fishing, let the dynamics of stock size x be modeled in continuous time t as the ordinary differential equation

$$\frac{dx}{dt} = f(x|\chi), \quad (1)$$

where f is a function and χ is a parameter vector of length m .

Table 1.- Symbols used in this paper.

Variables	Means of a Random Variable
t time	A arithmetic mean
x stock size	G geometric mean
y yield	H harmonic mean
Elementary Parameters	Parameters of Statistical Distributions
a Gompertz growth parameter	α first beta shape parameter
b Gompertz scale parameter	β second beta shape parameter
c control rule intercept parameter	η inverse Gaussian scale parameter
d control rule slope parameter	θ inverse Gaussian shape parameter
s process error scale parameter	μ ln(lognormal scale parameter)
z objective function weight parameter	σ lognormal shape parameter
Functions of Stock Size Only	Parameter Vectors
f function describing deterministic dynamics	χ vector of parameters used in f
g function describing process error scale	ψ vector of parameters used in g
h function describing harvest control rule	ω vector of parameters used in h
Functions of Stock Size or Other Variables	Constants
p probability density function	e Napier's constant (2.7183...)
q objective function	m dimension of χ
r normalized process error function	n dimension of ψ
Composite Parameters	Functions of Means
u ratio of a to $a+d$	k_a function of H_a/A_a and w
v ratio of s^2 to $2a$	k_b function of H_b/A_b and A_u
w ratio of d to a (Stage 2) or d to A_a (Stage 3)	k_v function of H_v/A_v , A_u , and A_v

Next, consider a function which uses a parameter vector ω to map stock size x into an instantaneous harvest (fishing) mortality rate h . Such a function constitutes a "harvest control rule." The purpose of a harvest control rule is to associate a reference fishing mortality rate (either a target or a limit) with each possible stock size. For any harvest control rule, yield y at time t will be the product of x at time t and h , where h itself is a function of x . The time derivative of stock size then becomes

$$\frac{dx}{dt} = f(x|\chi) - h(x|\omega)x, \quad (2)$$

For Example

When fishing is absent, the Gompertz (1825) biomass dynamic model can be viewed as an example of Equation (1), with $\chi=(a,b)^T$:

$$\frac{dx}{dt} = ax \left(1 - \ln \left(\frac{x}{b} \right) \right), \quad (3)$$

where a is a growth rate and b is a scale parameter.

The simplest case of a harvest control rule occurs when ω is a scalar c and h is a constant (i.e., $h(x) = c$). When this control rule is assumed, the Gompertz model becomes the Gompertz-Fox model (Fox 1970):

$$\frac{dx}{dt} = ax \left(1 - \ln \left(\frac{x}{b} \right) \right) - cx.$$

More complicated rules can be imagined as the dimension of ω increases. For example, if ω consists of a pair of control parameters c and d , some possible harvest control rules include the hyperbolic form $h(x) = c - d/x$, the square-root form $h(x) = c + d\sqrt{x}$, the linear form $h(x) = c + dx$, and the logarithmic form $h(x) = c + d \ln(x)$. In any of these examples, setting $d=0$ gives the one-parameter control rule $h(x) = c$. The hyperbolic form was considered (after translating to (x,y) -space; that is, $y(x) = cx - d$) by Hilborn (1985), Hightower and Lenarz (1989), and Engen et al. (1997). In addition, it conforms to a special case of the three-parameter control rule considered by Ruppert et al. (1984, 1985) and Hightower and Lenarz (1989). (The square-root and linear forms, both with $c=0$, also correspond to special cases of this three-parameter control rule.) The linear form was considered by Hightower (1990). If the underlying stock dynamics are governed by a model of the form suggested by Graham (1935) and Schaefer (1954), a linear control rule would be a natural choice in that such a control rule would not change the stock dynamics in any qualitative way. Given stock dynamics of the form suggested by Gompertz (1825), however, the logarithmic form is the natural choice, as shown below. Assuming Gompertz dynam-

ics and a logarithmic control rule, the time derivative of stock size becomes

$$\begin{aligned}\frac{dx}{dt} &= a x \left(1 - \ln \left(\frac{x}{b} \right) \right) - h(x) x \\ &= a x \left(1 - \ln \left(\frac{x}{b} \right) \right) - (c + d \ln(x)) x \quad (4) \\ &= (a + d) x \left(\frac{a(1 + \ln(b)) - c}{a + d} - \ln(x) \right)\end{aligned}$$

Comparing the above with Equation (3) shows that use of a logarithmic control rule does not alter the underlying stock dynamics in any qualitative way. The Gompertz-Fox model corresponds to the special case of the above in which $d=0$. Examples of logarithmic control rules are shown in Figure 1.

Solution

In General

The time trajectory of stock size will generally be

of the form $x(\chi, \omega, x_0, t)$, where x_0 represents an initial condition and t is measured with respect to an initial time $t_0=0$. In the limit as t approaches infinity, the trajectory will converge to the equilibrium value $x^*(\chi, \omega)$, assuming such an equilibrium exists.

For Example

The equilibrium stock size implied by Equation (4) is given by

$$x^*(a, b, c, d) = e^{\frac{a(1 + \ln(b)) - c}{a + d}}$$

and the time trajectory is given by

$$x(a, b, c, d, x_0, t) = x^*(a, b, c, d) \left(\frac{x_0}{x^*(a, b, c, d)} \right)^{e^{-(a + d)t}} \quad (5)$$

For the special case $c=d=0$ (i.e., no fishing), the equilibrium stock size is simply be .

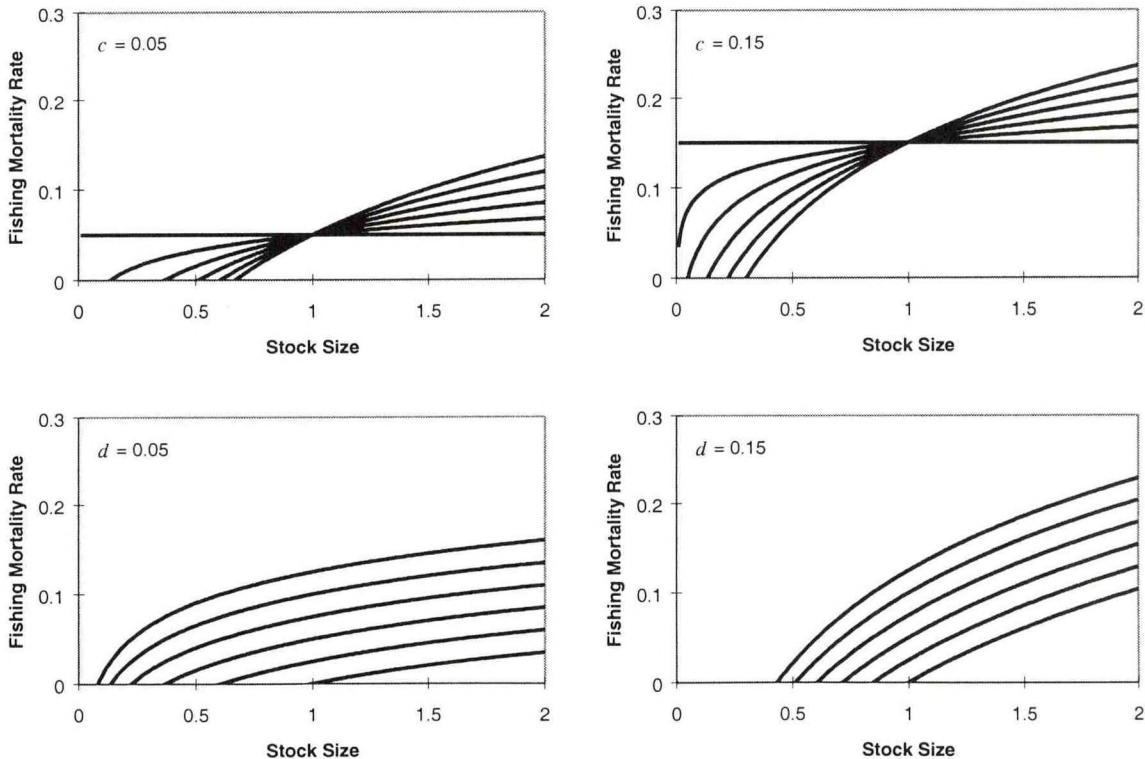


Figure 1. Example control rules. In each of the upper panels, the slope of the control rule increases directly with d . In each of the bottom panels, the height of the control rule increases directly with c .

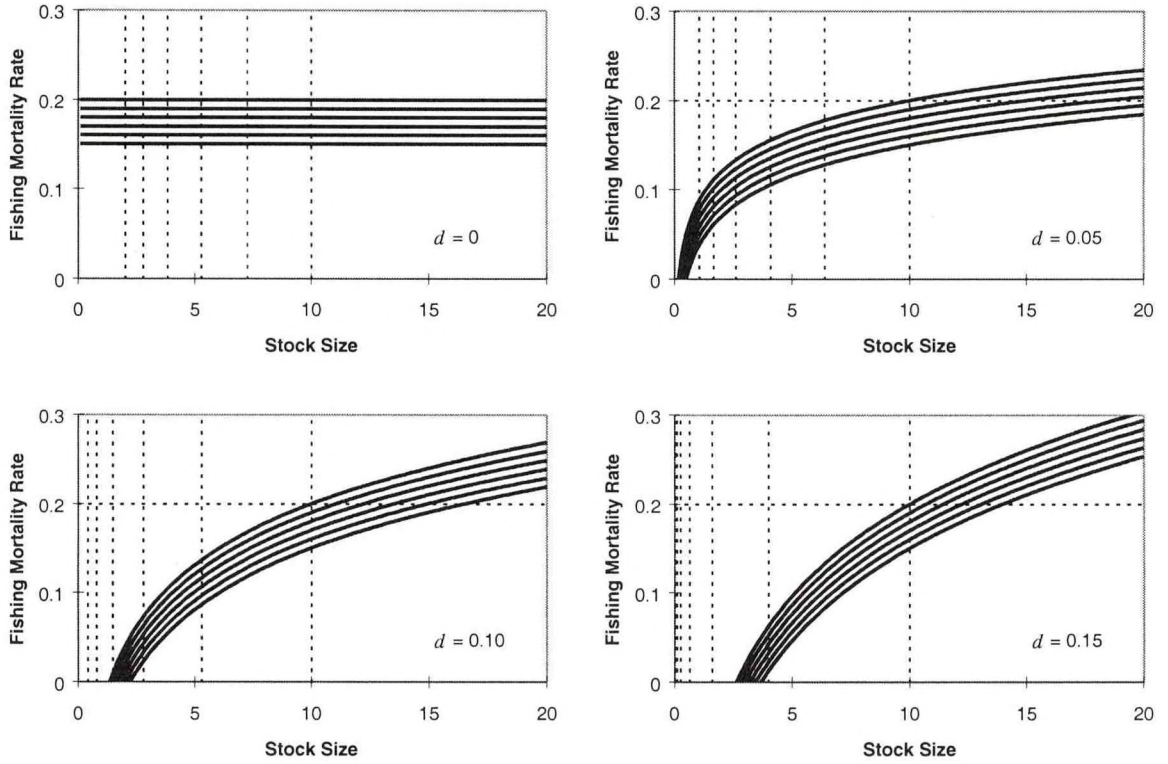


Figure 2. Example control rules (solid curves) and associated thresholds (vertical dotted lines). In each panel, as c decreases, the control rule moves down and the threshold moves left.

Rebuilding

In General

In practice, fish stocks are often observed to be at levels of abundance well below those considered to be optimal, or even safe. In such situations, fisheries scientists are frequently asked to estimate how much time will elapse before the stock rebuilds to some reference level, contingent upon implementation of a specified harvest policy in the interim. More proactively, the “rebuilding” question may be phrased this way: How low can a stock’s level of abundance fall and still rebuild to a size x_{reb} within a time period t_{reb} under a specified harvest policy? This is not the only issue which a rebuilding plan might logically address (e.g., Powers 1996), but it is a central one (e.g., as implied by U.S. Department of Commerce 1998). The answer is obtained by solving the equation $x(\chi, \omega, x_{thr}, t_{reb}) = x_{reb}$ for the “threshold” stock size x_{thr} .

For Example

Setting Equation (5) equal to x_{reb} , setting $t=t_{reb}$, and solving for x_0 (relabeled x_{thr}) gives

$$x_{thr} = x^*(a, b, c, d) \left(\frac{x_{reb}}{x^*(a, b, c, d)} \right)^{e^{(a+d)t_{reb}}}$$

In the special case where $x_{reb}=b$, the above simplifies to

$$x_{thr} = b \exp \left[- \left(\frac{a - c - d \ln(b)}{a + d} \right) \left(e^{(a+d)t_{reb}} - 1 \right) \right] \quad (6)$$

Examples of logarithmic harvest control rules and their corresponding stock size thresholds for parameter values $a=0.2$, $b=10$, $x_{reb}=10$, and $t_{reb}=10$ are shown in Figure 2. In each of Figure 2’s four panels, the uppermost control rule passes through the point (b, a) , indicated by the intersection of the horizontal dotted line and the rightmost vertical dotted line. Whenever $x_{reb}=b$, any harvest control rule passing through the point (b, a) , meaning any control rule in which $h(b)=a$, will always have a threshold stock size equal to b . Furthermore, control rules in which $h(b)<a$ will always have a threshold stock size less than b in such cases (i.e., whenever $x_{reb}=b$).

Optimization

In General

Sustainable (equilibrium) yield can be viewed as a function of the parameter vectors χ and ω . To keep things relatively simple throughout the remainder of the paper, let the control parameter c correspond to the i th element of ω and let $\omega_{(i)}$ denote the vector ω with the i th element (i.e., c) removed, and let sustainable yield be written $y^*(c|\chi, \omega_{(i)})$ to emphasize the dependence of sustainable yield on c . Then, MSY is achieved conditionally on χ and $\omega_{(i)}$ by finding the value $c_{\text{MSY}}(\chi, \omega_{(i)})$ such that the following equation is satisfied:

$$\frac{d y^*(c|\chi, \omega_{(i)})}{d c} \Big|_{c=c_{\text{MSY}}(\chi, \omega_{(i)})} = 0.$$

For Example

The sustainable yield corresponding to Equation (4) is given by substituting $x^*(a, b, c, d)$ into the logarithmic control rule, giving

$$y^*(c|a, b, d) = (c + d \ln(x^*(a, b, c, d))) x^*(a, b, c, d)$$

$$= \left[c + d \left(\frac{a(1 + \ln(b)) - c}{a + d} \right) \right] \exp \left(\frac{a(1 + \ln(b)) - c}{a + d} \right).$$

Given a value of either of the control parameters c and d , it is possible to solve for the value of the other so that sustainable yield is maximized. For example, if the solution is conditioned on control parameter d , MSY is obtained by setting

$$c_{\text{MSY}}(a, b, d) = a - d \ln(b).$$

Thus, an "MSY control rule" for this model is any rule of the form

$$h(x|a, b, d) = c_{\text{MSY}}(a, b, d) + d \ln(x)$$

(cf. U.S. Department of Commerce 1998). In Figure 2, for example, the uppermost curve in each panel is an MSY control rule. The Gompertz-Fox model corresponds to the special case where $d=0$, giving $c_{\text{MSY}}(a, b, 0) = a$. Changing the value of d allows the MSY control rule to be viewed as a continuum extending from a constant fishing mortality policy at one end ($d=0$) to a constant escapement policy at the other end (in the limit as d approaches infinity).

For any MSY control rule of the above form, equilibrium stock size is equal to b . MSY itself is equal to the product ab , and is thus independent of d .

Stage 2: Incorporating Natural Variability

Dynamics

In General

Equation (2) can be generalized to a stochastic differential equation incorporating random natural variability as follows:

$$\frac{d x}{d t} = f(x|\chi) + g(x|\psi) r(t) - h(x|\omega) x, \quad (7)$$

where $r(t)$ is a standard white noise process and g is a function of x , with parameter vector ψ of length n , that scales the intensity of the noise. It should be noted that the interpretation of stochastic differential equations given by Stratonovich (1963) is used here (e.g., Ricciardi 1977).

For Example

Natural variability can be added to the deterministic Gompertz model with a logarithmic harvest control rule by setting $\psi=s$, $g(x|\psi) = sx$ and recasting the time derivative as a stochastic differential equation of the form

$$\frac{d x}{d t} = a x \left(1 - \ln \left(\frac{x}{b} \right) \right) + s x r(t) - (c + d \ln(x)) x. \quad (8)$$

Solution

In General

Broadly speaking, stock size at time t could potentially range anywhere from zero to arbitrarily large, though some stock sizes are more probable than others. Given an initial condition x_0 , this fact can be modeled as a pdf with parameter vector $(\chi^T, \psi^T, \omega^T, x_0, t)^T$. More precisely, the probability that stock size falls between x_1 and x_2 at time t may be written in terms of the "transition distribution" $p_x(x|\chi, \psi, \omega, x_0, t)$ as follows:

$$Pr(x_1 \leq x(t) \leq x_2) = \int_{x_1}^{x_2} p_x(x|\chi, \psi, \omega, x_0, t) dx.$$

In the limit as t approaches infinity, p_x (if it still exists) describes the "stationary distribution" of x . The stationary distribution can be written $p_x^*(x|\chi, \psi, \omega)$.

For Example

Using a different parametrization, the solution to Equation (8) was considered for the special case $c=d=0$ (i.e., no harvesting) by Capocelli and Ricciardi (1974). The less restricted case $d=0$ (with c arbitrary) was considered by Thompson (1998). When no restrictions are placed on either c or d , the stationary distribution of

stock size is lognormal, specifically,

$$p_x^*(x|a, b, s, c, d) = \frac{1}{\sqrt{2\pi}} \left(\frac{1}{\sigma_x^*(a, s, d) x} \right) \times \exp \left(- \left(\frac{1}{2} \right) \left(\frac{\ln(x) - \mu_x^*(a, b, c, d)}{\sigma_x^*(a, s, d)} \right)^2 \right),$$

where

$$\mu_x^*(a, b, c, d) = \frac{a(1 + \ln(b)) - c}{a + d} = \ln(x^*(a, b, c, d))$$

and

$$\sigma_x^*(a, s, d) = \frac{s}{\sqrt{2(a + d)}}.$$

Similarly, the transition distribution of stock size at time t is also lognormal, specifically,

$$p_x(x|a, b, s, c, d, x_0, t) = \frac{1}{\sqrt{2\pi}} \left(\frac{1}{\sigma_x(a, s, d, t) x} \right) \times \exp \left(- \left(\frac{1}{2} \right) \left(\frac{\ln(x) - \mu_x(a, b, c, d, x_0, t)}{\sigma_x(a, s, d, t)} \right)^2 \right) \quad (9)$$

where

$$\mu_x(a, b, c, d, x_0, t) = e^{-(a+d)t} \ln(x_0) + (1 - e^{-(a+d)t}) \mu_x^*(a, b, c, d)$$

and

$$\sigma_x(a, s, d, t) = \sqrt{1 - e^{-2(a+d)t}} \sigma_x^*(a, s, d).$$

Rebuilding

In General

In the presence of natural variability, discussion of rebuilding trajectories can become much more complicated than in the deterministic case. Because an infinite number of rebuilding trajectories is possible in the stochastic case, rebuilding is typically described using some sort of summary statistic. For example, the following equation could be solved for x_{thr} after substituting some desired probability of successful rebuilding (e.g., 50%) for the left-hand side:

$$\Pr(x_{reb} \leq x(t_{reb}) \leq \infty) = \int_{x_{reb}}^{\infty} p_x(x|\chi, \psi, \omega, x_{thr}, t_{reb}) dx.$$

Alternatively, the solution could be expressed in terms of expected values of x (or some transformation thereof) at time $t=t_{reb}$, for example, by equating x_{reb} with

the arithmetic mean or geometric mean of x at time $t=t_{reb}$.

For Example

Unlike the general case, a fortunate property of the model used here is that consideration of rebuilding schedules in the presence of natural variability need not be any more complicated than in the deterministic situation described in Stage 1, depending on the choice of summary statistic. Because the geometric mean of the transition distribution [Equation (9)] is identical to the deterministic solution of the time trajectory [Equation (5)], and because the lognormal form of the transition distribution implies that the geometric mean is equal to the median, using either the geometric mean or a 50% probability of exceeding x_{reb} to compute the threshold stock size x_{thr} gives the same result as in the deterministic case [Equation (6)].

Optimization

In General

The conditional arithmetic mean of the stationary distribution of yield is defined as

$$A_y(\chi, \psi, \omega) = \int_0^{\infty} y(x|\omega) p_x^*(x|\chi, \psi, \omega) dx.$$

The dependence of the conditional arithmetic mean on a particular control parameter can be emphasized by rewriting $A_y(\chi, \psi, \omega)$ as $A_y(c|\chi, \psi, \omega_{(i)})$, following the Stage 1 convention in which control parameter c corresponds to the i th element of ω . Then, this quantity can be maximized with respect to control parameter c by differentiating, setting the resulting expression equal to zero, and solving with respect to c . Maximizing $A_y(c|\chi, \psi, \omega_{(i)})$ with respect to c gives the control parameter value associated with maximum expected stationary yield (MESY):

$$\left. \frac{d A_y(c|\chi, \psi, \omega_{(i)})}{d c} \right|_{c = \tilde{c}_{MESY}(\chi, \psi, \omega_{(i)})} = 0,$$

where use of the “~” symbol is intended to denote that the maximization is conducted with respect to the conditional mean (alternative maximizations will be described later).

Much of the literature concerning optimal harvest strategies in the presence of natural variability deals with tradeoffs between the magnitude of yield on average and the variability about that average. In the context of comparisons between the classical one-parameter harvest policies, such tradeoffs have been considered by Ricker (1958), Larkin and Ricker (1964), Gatto and Rinaldi (1976), Beddington and May (1977), May et al. (1978), Reed (1978), Hilborn (1979), Hilborn and

Walters (1992), Frederick and Peterman (1997), and Steinshamn (1998). In the context of optimal control policies, they have been considered by Walters (1975), Mendelsohn (1980), and Horwood et al. (1990). In the context of fixed-form control rules, they have been considered by Allen (1973), Aron (1979), Hilborn (1985), Ruppert et al. (1985), Getz et al. (1987), Hightower and Lenarz (1989), Hightower (1990), Quinn et al. (1990), Zheng et al. (1993), and Engen et al. (1997).

One way to characterize the variability of yield on a scale equivalent to that of the arithmetic mean is by the standard deviation. If c is set equal to $\tilde{c}_{\text{MESY}}(\chi, \psi, \omega_{(i)})$, both the arithmetic mean and standard deviation of the stationary distribution of y will be functions of χ , ψ , and $\omega_{(i)}$, meaning that tradeoffs between the arithmetic mean and standard deviation can be viewed as a function of the control parameter sub-vector $\omega_{(i)}$ for given values of χ and ψ .

For Example

By defining a natural variability level

$$v \equiv \sigma_x^*(a, s, 0)^2 = \frac{s^2}{2a}$$

(i.e., by defining v as the variance of the stationary distribution of log stock size when $d=0$), the equations for many quantities of interest in the example model can be simplified considerably. Thus, wherever s appears as a parameter in a particular equation, it can be replaced with the quantity $\sqrt{2av}$, and whenever s appears as a function argument in a particular equation, it can be replaced with the parameter v . Similarly, by defining a scaled control parameter

$$w \equiv \frac{d}{a}$$

(i.e., by viewing the control parameter d relative to a rather than in absolute terms) and reparametrizing accordingly, it turns out that a appears only as a constant of proportionality in many (but not all) quantities of interest in this model. Thus, wherever d appears as a parameter in a particular equation, it can be replaced with the quantity wa , and wherever d appears as a function argument in a particular equation, it can be replaced with the parameter w .

With these composite parameters, the conditional arithmetic mean of the stationary distribution of stock size x can be written as

$$A_x(a, b, v, c, w) = \int_0^\infty x p_x^*(x|a, b, v, c, w) dx$$

$$= \exp \left[\left(\frac{1}{1+w} \right) \left(\frac{c}{wa} + 1 + \ln(b) + \frac{v}{2} \right) - \frac{c}{wa} \right],$$

and the conditional arithmetic mean of the stationary distribution of yield y can be written as

$$\begin{aligned} A_y(a, b, v, c, w) &= \int_0^\infty (c + d \ln(x)) x p_x^*(x|a, b, v, c, w) dx \\ &= wa \left(\frac{1}{1+w} \right) \left(\frac{c}{wa} + 1 + \ln(b) + v \right) A_x(a, b, v, c, w) \\ &= wa \left(\frac{1}{1+w} \right) \left(\frac{c}{wa} + 1 + \ln(b) + v \right) \times \\ &\quad \exp \left[\left(\frac{1}{1+w} \right) \left(\frac{c}{wa} + 1 + \ln(b) + \frac{v}{2} \right) - \frac{c}{wa} \right] \end{aligned} \quad (10)$$

Given w , the value of c that maximizes expected stationary yield is

$$\tilde{c}_{\text{MESY}}(a, b, v, w) = (1 - (\ln(b) + v))a. \quad (11)$$

Note that $\tilde{c}_{\text{MESY}}(a, b, v, w)$ approaches $c_{\text{MSY}}(a, b, w)$ as v approaches zero. Also, in the special case where $w=0$, the solution simplifies to $\tilde{c}_{\text{MESY}}(a, b, v, 0) = c_{\text{MSY}}(a, b, 0) = a$ regardless of the value of v . Generally, then, the stochastic equivalent of an MSY control rule (without considering parameter uncertainty) is given by the MESY control rule

$$\tilde{h}_{\text{MESY}}(x|a, b, v, w) = \tilde{c}_{\text{MESY}}(a, b, v, w) + wa \ln(x).$$

Examples of MESY control rules are shown in Figure 3. As shown previously in Figure 2, if the rebuilding level is set equal to b , an MSY control rule (i.e., a MESY control rule with $v=0$) always has a threshold stock size equal to b . As shown in Figure 3, however, a MESY control rule with $v>0$ will always have a threshold stock size less than b except in the special case where $w=0$. The distance between the threshold stock size and b increases monotonically with both w (seen by comparing curves *within* a particular panel of Figure 3) and v (seen by comparing curves *between* panels of Figure 3). The direct relationship between the difference $b - x_{\text{thr}}$ and w is consistent with the fact that higher values of w imply greater cutbacks in the harvest rate as stock size falls, meaning that acceptable rates of recovery can be achieved from lower stock sizes. The direct relationship between the difference $b - x_{\text{thr}}$ and v is consistent with the fact that natural variability is the factor that enables b to diverge from x_{thr} in the first place (i.e., in the Stage 1 case, a stock harvested under an MSY control rule will never recover to $x=b$ in finite time).

When the right-hand side of Equation (11) is substituted for c in Equation (10), the expected value of stationary yield becomes

$$\text{MESY}(a, b, v, w) = ab e^{\left(1 - \frac{1}{2(1+w)} \right) v}.$$

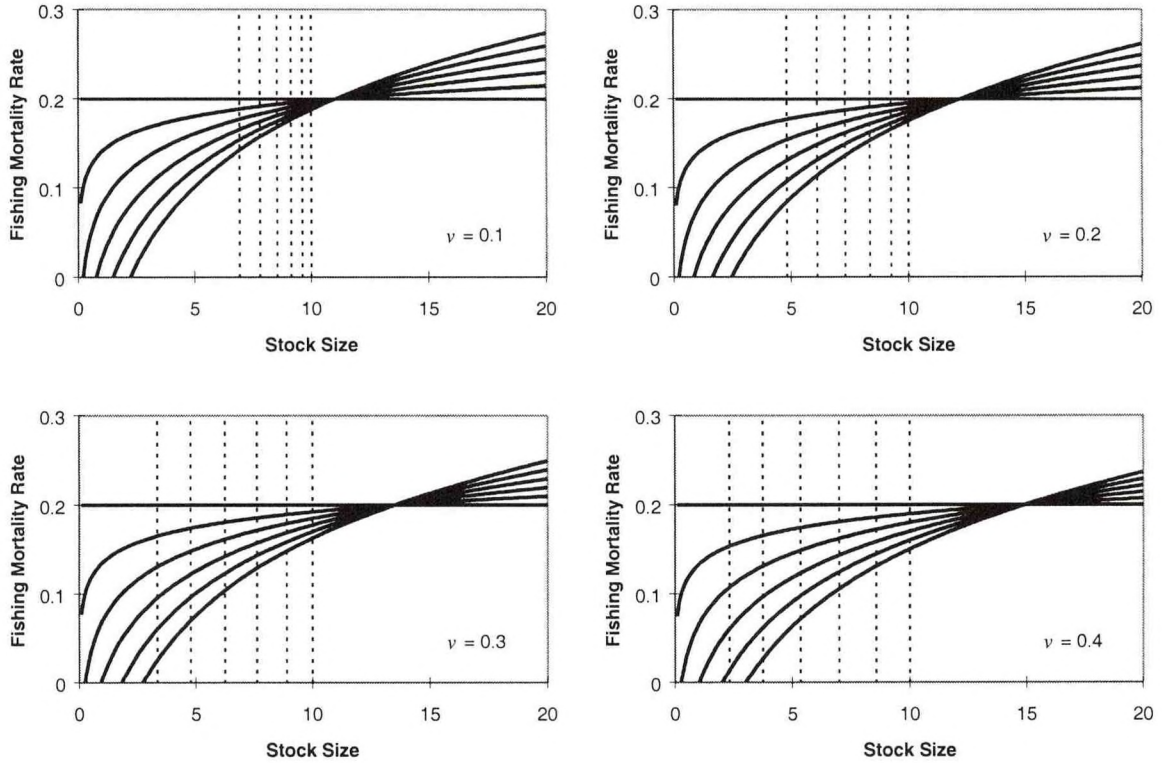


Figure 3. Example MESY control rules (solid curves) and associated thresholds (vertical dotted lines). In each panel, as w increases (with c implicit), the slope of the control rule increases and the threshold moves left.

Unlike the deterministic case where MSY was independent of the control parameter d , MESY does depend on the value of d , through the latter's dependence on w . The exponent in the above equation reaches a minimum of $v/2$ when $w=0$ and a maximum of v as w approaches infinity.

When $c = \tilde{c}_{\text{MESY}}(a, b, v, w)$, the standard deviation of stationary yield can be written

$$\text{SDSY}(a, b, v, w) = abe^v \sqrt{1 + \left(\frac{2+w}{1+w}\right) w v + \left(\frac{w}{1+w}\right)^2 v^2 - e^{-\frac{v}{1+w}}}.$$

The term under the square root symbol reaches a minimum of $1 - e^{-v}$ when $w=0$ and increases without limit as w approaches infinity. MESY (expressed as a proportionate increase over MSY) and SDSY are plotted for $a=b=1$ and several values of v and w in Figure 4.

In managing a fishery, suppose that any increase in MESY were viewed as a desirable result (all other things being equal), and that likewise any decrease in SDSY were viewed as a desirable result (all other things being equal). Because both MESY and SDSY increase monotonically but nonlinearly with w , it may be possible to find an optimal value for w depending on the prefer-

ence associated with a unit increase in MESY relative to the preference associated with a unit decrease in SDSY. For example, suppose that the goal was to choose the value of the control parameter w so as to maximize the following objective function, which uses the parameter z to form a linear combination of MESY and (negative) SDSY:

$$q(v, w) = \frac{z \text{MESY}(a, b, v, w) - \text{SDSY}(a, b, v, w)}{z \text{MESY}(a, b, v, 0) - \text{SDSY}(a, b, v, 0)} - 1$$

$$= \frac{z \sqrt{e^{-\frac{v}{1+w}}} - \sqrt{1 + \left(\frac{2+w}{1+w}\right) w v + \left(\frac{w}{1+w}\right)^2 v^2 - e^{-\frac{v}{1+w}}}}{z \sqrt{e^{-v}} - \sqrt{1 - e^{-v}}} - 1$$

The above equation is scaled so that $q(v, 0) = 0$. The parameter z represents the amount by which a unit increase in MESY is preferred relative to a unit decrease in SDSY. This objective function is plotted for several values of v and z in Figure 5.

While it is not possible to obtain a closed-form solution for the value of w that maximizes q , it is possible to derive the value of z for which a particular value of w would be optimal, given v :

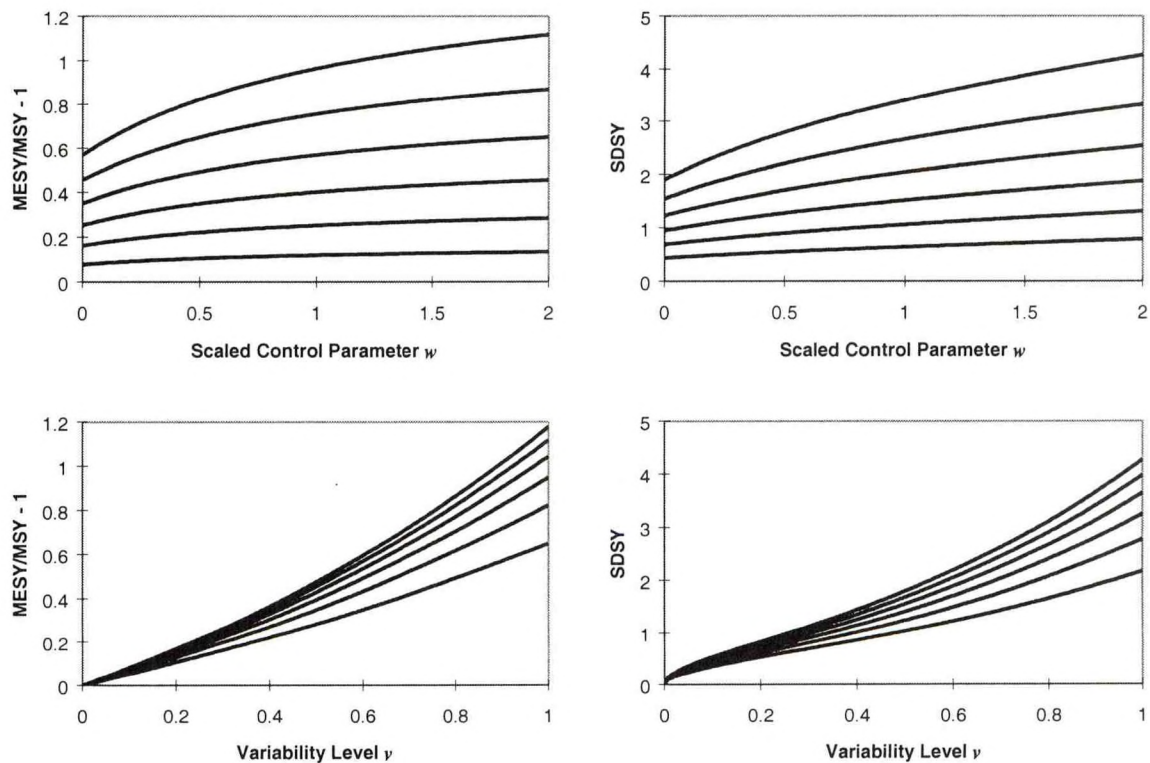


Figure 4. Profiles of MESY and SDSY. In the upper panels, higher curves correspond to higher values of variability level v . In the lower panels, higher curves correspond to higher values of control parameter w .

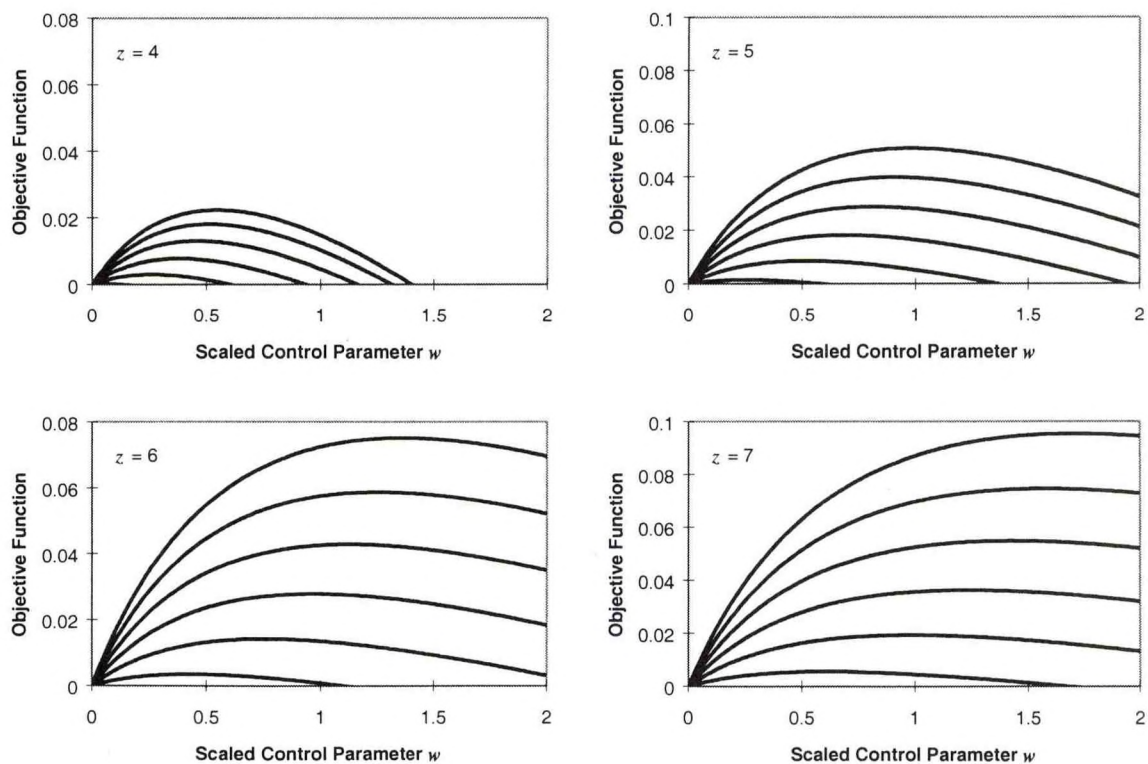


Figure 5. Examples of objective functions used to evaluate tradeoffs between mean and standard deviation of yield. In each panel, higher curves correspond to higher values of v . As z or v increases, maxima shift right.

$$z(w_{\text{opt}} | v) =$$

$$\frac{(w_{\text{opt}}^3 + 3w_{\text{opt}}^2 + (4 + 2v)w_{\text{opt}} + 2)e^{\frac{v}{1+w_{\text{opt}}}} - (1 + w_{\text{opt}})}{\sqrt{(w_{\text{opt}}^2 + (3 + v)w_{\text{opt}} + 2)vw_{\text{opt}}e^{\frac{v}{1+w_{\text{opt}}}} + (1 + w_{\text{opt}})^2 \left(e^{\frac{v}{1+w_{\text{opt}}}} - 1 \right)}}$$

The above relationship is plotted for several values of w_{opt} in Figure 6. Note that a positive value of w is never optimal when $z < 2\sqrt{2} \approx 2.8$. Also, the value of w that maximizes q can vary considerably with v or z . For example, $w=0.260$ is optimal when $v=0.2$ and $z=4$, but increasing v to a value of 0.6 (with z held constant at 4) more than doubles the optimal value of w (0.546). Alternatively, increasing z to a value of 6 (with v held constant at 0.2) nearly triples the optimal value of w (0.756).

Stage 3: Incorporating Parameter Uncertainty

In General

All of the above assumes that the true values of χ and ψ are known. When uncertainty exists regarding the true values of these parameters, additional complications arise. Many of these relate to the objective of management under a precautionary approach: Exactly what is being maximized, and how does the answer to this question differ between limit control rules and target control rules? One way to address this question is to

view the distinction between limit and target control rules as a distinction between levels of relative risk aversion in a decision-theoretic framework. For example, a limit control rule might be defined by the decision-theoretic optimum derived under a risk-neutral stance, while a target control rule might be defined by the decision-theoretic optimum derived under a risk-averse stance. A simple way to characterize this difference is as follows: the risk-neutral solution maximizes the expectation of stationary yield (MESY, pronounced “mezzy”), while the risk-averse solution maximizes the expectation of log stationary yield (MELSY, pronounced “melzy”). Such use of a logarithmic loss (or utility) function in developing harvest strategies has been advocated or analyzed by Gleit (1978), Lewis (1981, 1982), Mendelsohn (1982), Opaluch and Bockstael (1984), Ruppert et al. (1984, 1985), Deriso (1985), Walters (1987), Walters and Ludwig (1987), Getz and Haight (1989), Hightower and Lenarz (1989), Hightower (1990), Parma (1990), Parma and Deriso (1990), and Thompson (1992).

Maximizing the expectation of log stationary yield is formally equivalent to maximizing the geometric mean of stationary yield. Just as the conditional arithmetic mean was defined above as a function of the parameters χ , ψ , and ω , the conditional geometric mean of the stationary distribution of yield is defined (if it exists) as

$$G_y(\chi, \psi, \omega) = \exp \left(\int_0^\infty \ln(y(x|\omega)) p_x^*(x|\chi, \psi, \omega) dx \right).$$

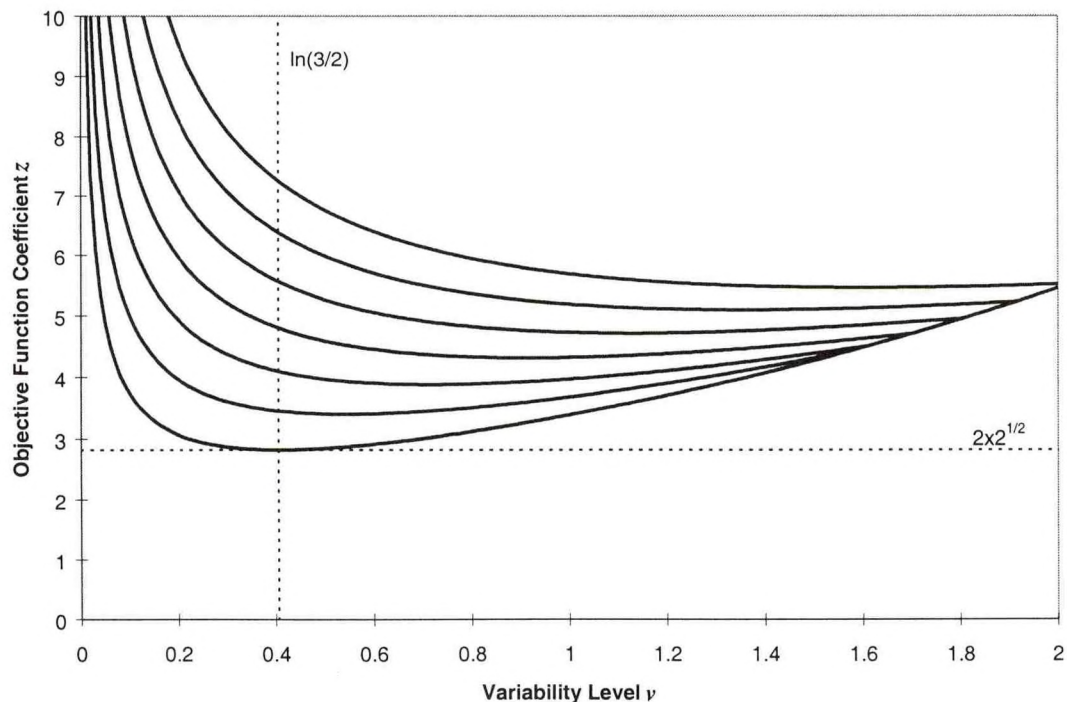


Figure 6. Value of z at which a specified value of w is optimal, given v . Beginning with the lowest curve and moving upward, curves correspond to optimal w values of 0, 0.25, 0.50, 0.75, 1.00, 1.25, and 1.50.

Likewise, in a manner analogous to that used to develop the conditional MESY solution, $G_y(\chi, \psi, \omega)$ can be rewritten as $G_y(c|\chi, \psi, \omega_{(i)})$ and then maximized with respect to c , giving the control parameter value associated with the maximum expected log stationary yield, conditional on χ, ψ , and $\omega_{(i)}$:

$$\frac{d G_y(c|\chi, \psi, \omega_{(i)})}{d c} \Big|_{c=\tilde{c}_{\text{MESY}}(\chi, \psi, \omega_{(i)})} = 0.$$

However, when the values of χ and ω are uncertain, maximization of the mean (either arithmetic or geometric) of the conditional pdf is not particularly helpful by itself, as the solution is a function of parameters whose values are unknown. Rather, it is the moments of the *marginal* pdf that are of interest. For example, the arithmetic mean of the marginal pdf is defined as

$$\begin{aligned} \bar{A}_y(\omega) &= \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \\ &A_y(\chi, \psi, \omega) p_{\chi, \psi}(\chi, \psi) \\ &d\chi_1 \dots d\chi_m d\psi_1 \dots d\psi_n. \end{aligned}$$

Rewriting the above as $\bar{A}_y(c|\omega_{(i)})$ and maximizing with respect to c gives $c_{\text{MESY}}(\omega_{(i)})$; that is,

$$\frac{d \bar{A}_y(c|\omega_{(i)})}{d c} \Big|_{c=c_{\text{MESY}}(\omega_{(i)})} = 0.$$

The above derivation involves two operations: integration and differentiation. The order in which these two are performed can make a difference (though perhaps not always). In the above, integration precedes differentiation. In other words, the arithmetic mean of the marginal distribution of stationary yield is computed conditionally on c , then c is chosen so as to maximize this expectation. An alternative approach would be to choose the value of c that maximizes expected stationary yield conditional on χ, ψ , and $\omega_{(i)}$, and then compute the expectation of this value. This is accomplished by multiplying $\tilde{c}_{\text{MESY}}(\chi, \psi, \omega_{(i)})$ by $p_{\chi, \psi}(\chi, \psi)$ and integrating over the elements of χ and ψ , giving

$$\begin{aligned} \bar{c}_{\text{MESY}}(\omega_{(i)}) &= \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \\ &\tilde{c}_{\text{MESY}}(\chi, \psi, \omega_{(i)}) p_{\chi, \psi}(\chi, \psi) \\ &d\chi_1 \dots d\chi_m d\psi_1 \dots d\psi_n. \end{aligned}$$

The same procedure can be followed for the geometric mean. The geometric mean of the marginal pdf is defined as

$$\bar{G}_y(\omega) = \exp \left(\frac{\int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \ln(G_y(\chi, \psi, \omega)) p_{\chi, \psi}(\chi, \psi) d\chi_1 \dots d\chi_m d\psi_1 \dots d\psi_n}{\int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} p_{\chi, \psi}(\chi, \psi) d\chi_1 \dots d\chi_m d\psi_1 \dots d\psi_n} \right).$$

Rewriting the above as $\bar{G}_y(c|\omega_{(i)})$ and maximizing

with respect to c gives $c_{\text{MESY}}(\omega_{(i)})$; that is,

$$\frac{d \bar{G}_y(c|\omega_{(i)})}{d c} \Big|_{c=c_{\text{MESY}}(\omega_{(i)})} = 0,$$

while multiplying $\tilde{c}_{\text{MESY}}(\chi, \psi, \omega_{(i)})$ by $p_{\chi, \psi}(\chi, \psi)$ and integrating over the elements of χ and ψ gives

$$\begin{aligned} \bar{c}_{\text{MESY}}(\omega_{(i)}) &= \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \\ &\tilde{c}_{\text{MESY}}(\chi, \psi, \omega_{(i)}) p_{\chi, \psi}(\chi, \psi) \\ &d\chi_1 \dots d\chi_m d\psi_1 \dots d\psi_n. \end{aligned}$$

Thus, there are a number of alternative ways to proceed. In either the MESY case or the MELSY case, at least three solutions can be envisioned: 1) considering uncertainty due to natural variability only, solve for the optimum value of c as a function of the parameters $\chi, \psi, \omega_{(i)}$, then evaluate that solution at the “best” estimate of those parameters (the “solve-then-evaluate” method); 2) considering uncertainty due to natural variability only, solve for the optimum value of c as a function of the parameters $\chi, \psi, \omega_{(i)}$, then take the expectation of that solution over the parameters χ and ψ (the “solve-then-integrate” method); and 3) considering both natural variability and parameter uncertainty, solve for the optimum value of c (the “integrate-then-solve” method). These three solutions are summarized in the table below:

Attitude toward risk	Solution technique	Solution notation
risk neutral	solve-then-evaluate	$\tilde{c}_{\text{MESY}}(\chi, \psi, \omega_{(i)})$
risk neutral	solve-then-integrate	$\bar{c}_{\text{MESY}}(\omega_{(i)})$
risk neutral	integrate-then-solve	$c_{\text{MESY}}(\omega_{(i)})$
risk averse	solve-then-evaluate	$\tilde{c}_{\text{MELSY}}(\chi, \psi, \omega_{(i)})$
risk averse	solve-then-integrate	$\bar{c}_{\text{MELSY}}(\omega_{(i)})$
risk averse	integrate-then-solve	$c_{\text{MELSY}}(\omega_{(i)})$

For Example

In Stage 2, the quantity w (defined as $w \equiv d/a$) was a constant. To retain the interpretation of w as a constant in Stage 3, it will prove convenient at this point to redefine $w \equiv d/A_a$ and to reparametrize the model accordingly. Thus, wherever w appears as a parameter in a previous equation, it can be replaced with the quantity $A_a w/a$. Use of the redefined parameter w renders many quantities of interest in this model proportional to A_a .

A general solution for $c_{\text{MESY}}(w)$ cannot be obtained, because any particular solution will depend on the form of the joint pdf of a, b , and v . However, because $\tilde{c}_{\text{MESY}}(a, b, v, w)$ is linear in a , $\ln(b)$, and v [Equation (11)], the following solution for $\bar{c}_{\text{MESY}}(w)$ will be independent of the form of the joint pdf of a, b , and v :

$$\bar{c}_{\text{MESY}}(w) = (1 - (\ln(G_b) + A_v) w) A_a \quad (12)$$

Obtaining general solutions for MELSY is even more difficult than in the MESY case. For one thing, the fact that the logarithmic control rule forces yield to equal zero at $x = \exp(-c/d)$ means that $\bar{G}_y(a, b, v, c, w)$ does not exist except when $w=0$. For purposes of illustration, however, an exact solution for a quantity closely related to $c_{\text{MELSY}}(w)$ can be obtained if a , b , and v are assumed to be independent and if particular functional forms are chosen for their respective pdfs. Specifically, let $p_a(a)$ follow a 3-parameter F distribution with scale parameter d , let $p_b(b)$ follow a lognormal distribution, and let $p_v(v)$ follow an inverse Gaussian distribution (Appendix).

For any positive random variable, the ratio of the harmonic mean to the arithmetic mean may be viewed as a measure of the degree of certainty surrounding the value of that variable. This ratio ranges from a lower bound no less than zero, representing complete uncertainty, to an upper bound no greater than unity, representing complete certainty (e.g., Mitrinović et al. 1993). For the particular distributional forms assumed here, the ratios of harmonic to arithmetic means may be expressed in terms of the coefficient of variation (CV) as follows (the harmonic and arithmetic means are also given as functions of their respective distributional parameters in the Appendix):

$$\begin{aligned}\frac{H_a}{A_a} &= \frac{1 + w + (1 - w) \text{CV}_a^2}{1 + w + 2 \text{CV}_a^2}, \\ \frac{H_b}{A_b} &= \frac{1}{1 + \text{CV}_b^2}, \\ \frac{H_v}{A_v} &= \frac{1}{1 + \text{CV}_v^2}.\end{aligned}$$

Given the assumption that a follows an F distribution with scale parameter d , the quantity $u \equiv a/(a+d)$ is beta-distributed with arithmetic mean

$$A_u = \frac{\frac{H_a}{A_a} + w}{\frac{H_a}{A_a} + 2w + w^2}.$$

Then, a quantity closely related to $c_{\text{MELSY}}(w)$ can be written (Appendix) as

$$\hat{c}_{\text{MELSY}}(w) = (k_a - (\ln(G_b k_b) + A_v k_v) w) A_a, \quad (13)$$

where

$$\begin{aligned}k_a &= \left(\frac{H_a}{A_a} + w \right) \left(\frac{1}{1 + w} \right), \\ k_b &= \left(\frac{H_b}{A_b} \right)^{-A_u},\end{aligned}$$

$$k_v = \left(1 - A_v \left[\left(\frac{H_v}{A_v} \right)^{-1} - 1 \right] A_u \right)^{\frac{1}{2}}.$$

For all practical purposes, the adjustment factors k_a , k_b , and k_v vary directly with the ratios H_a/A_a , H_b/A_b , and H_v/A_v , respectively, so that an increase in uncertainty regarding any of the parameters results in a downward shift in the control rule. Examples of limit control rules (using Equation (12)) and target control rules (using Equation (13)) are shown in Figure 7 for four values of w , in Figure 8 for four values of $H_a/A_a = H_b/A_b = H_v/A_v$, and in Figure 9 for four values of A_v (because the axes in Figures 7-9 are scaled relative to A_a and G_b , the curves are independent of these two parameters). The upper left panels of Figures 7-9 are all identical, giving a common point of reference against which to contrast results associated with different parameter values. In each of these figures, the control rules developed under this model are contrasted with the existing control rules for "Tier 1" of the harvest policy established in 1996 for Alaska groundfish (U.S. National Marine Fisheries Service 1996).

Discussion

Harvest control rules provide a tractable and heuristic means of comparing alternative fishery management strategies. They can be analyzed in the context of a wide variety of models, ranging from simple deterministic models with known parameter values to complex stochastic models with uncertain parameter values. Moving from the classical one-parameter control rules (e.g., constant fishing mortality, constant escapement) to a two-parameter control rule such as the logarithmic form considered in the example model here can sometimes render comparisons between the former more meaningful by framing them as special cases along a continuum of possible strategies rather than as conceptually unrelated policies. More elaborate functional forms, in which various two-parameter control rules might emerge as special cases, can also be imagined. Generally, the ideal level of complexity to build into a harvest control rule, as well as the appropriate number of parameters to be left free therein, remain open questions. Relative to a full optimal control solution, some degree of optimality may be sacrificed whenever the functional form of the control rule is constrained *a priori*. However, the sacrifice may be slight. For example, in the deterministic Gordon-Schaefer model considered by Clark (1976), the optimal control solution consisted of a one-parameter constant escapement policy. Even when more complicated stochastic models are used, the difference between a full optimal control solution and a fixed-form optimization can be negligible (e.g., Mendelsohn 1980, Horwood 1993).

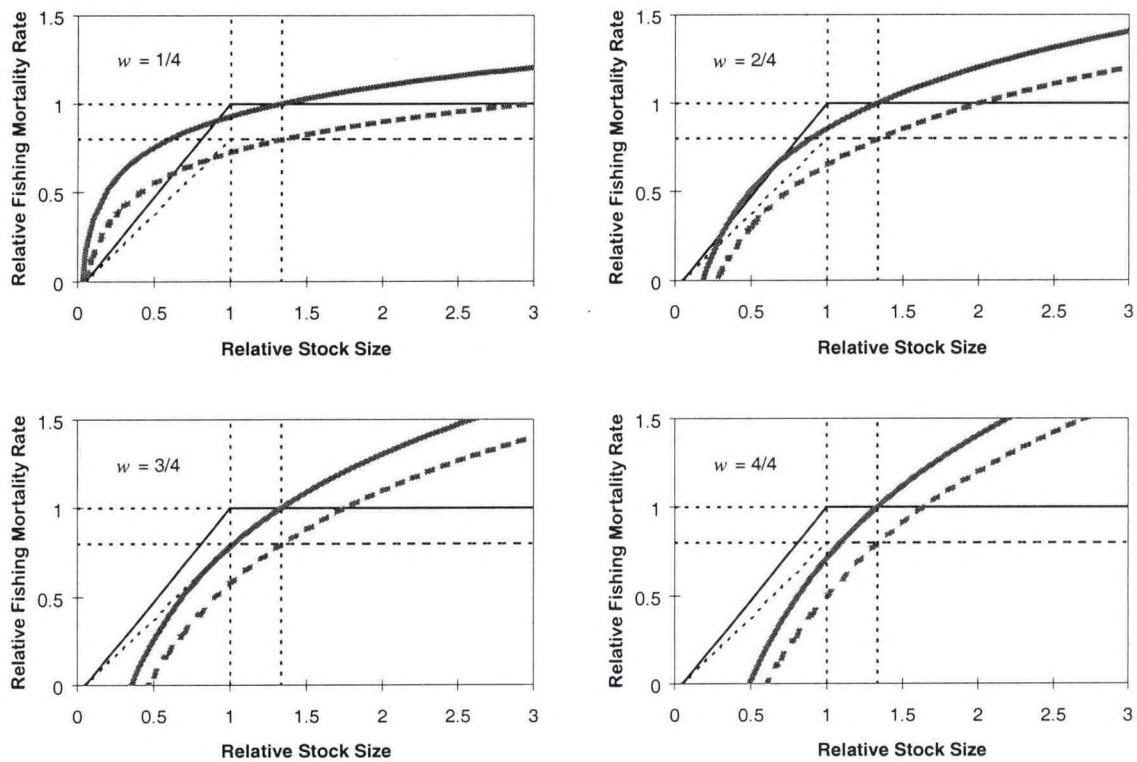


Figure 7. Limit (solid) and target (dashed) control rules in the example model (thick) and Alaska groundfish policy (thin). Horizontal and vertical dotted lines depict additional reference points.

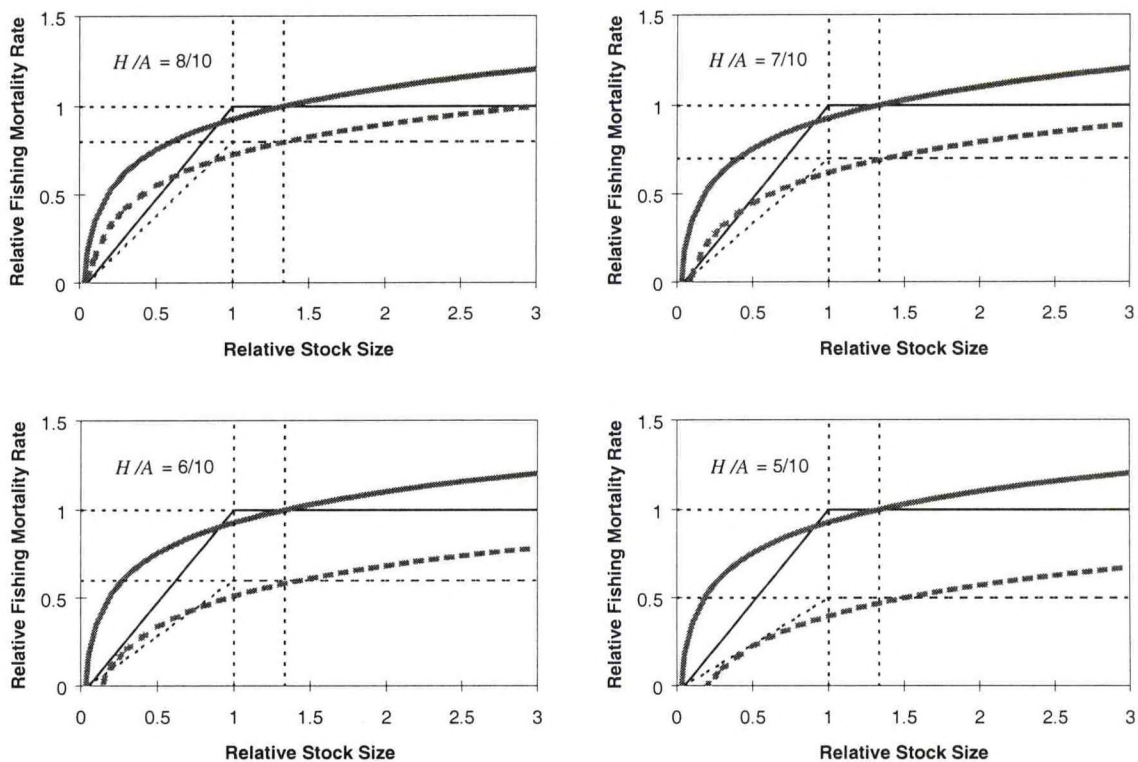


Figure 8. Limit (solid) and target (dashed) control rules in the example model (thick) and Alaska groundfish policy (thin). Horizontal and vertical dotted lines depict additional reference points.

For the most part, it has been assumed here that optimization of the control rule is confined to a single control parameter (c , in the case of the example model). This is a convenient restriction, but not a necessary one. For instance, in the Stage 2 example model considered here, it is possible to maximize expected stationary yield with respect to both c and d . This results in a strategy of the constant escapement type, confirming the conclusion of Reed (1978) and others that a constant escapement policy dominates the other classical one-parameter control rules when the objective is maximization of long-term average yield. However, leaving at least one control parameter (say, d) to be fixed independently of the optimization has previously been advocated (e.g., Ruppert et al. 1984) on the basis that it facilitates consideration of management objectives other than yield maximization. For instance, in the Stage 2 example model considered here, allowing d to be fixed independently means that the full range of tradeoffs between long-term average yield and the level of variability around that average can be presented (Figure 5). As in previous studies (e.g., Beddington and May 1977), the example model shows that the arithmetic mean and standard deviation of stationary yield vary together. However, the example model here goes further than previous studies in showing that this result holds true across a continuum of MSY control rules (i.e., as a function of control parameter d with c set at its conditional MESY value).

Figures 7-9 contrast the example model with the existing control rules for "Tier 1" of the harvest policy established in 1996 for Alaska groundfish (U.S. National Marine Fisheries Service 1996). The three-parameter control rules used in the Alaska groundfish policy are, in fact, based partly on a special case of the example model. Specifically, the horizontal portions of those control rules correspond to the special cases of Equations (12) and (13) in which $w=0$. When $w=0$, \bar{c}_{MESY} and c_{MESY} (or \hat{c}_{MESY}) are simply the arithmetic and harmonic means, respectively, of the marginal distribution of a . Interestingly, this result holds regardless of the functional form of the joint distribution of a , b , and s . In contrast, the general ($w>0$) form of Equation (13) depends on several assumptions regarding the joint distribution of a , b , and s .

As Figures 7-9 show, the logarithmic control rule used in the example model can be implemented in a manner that satisfies the requirements of a precautionary approach specified by the U.S. Department of Commerce (1998): 1) target harvest rates are less than limit harvest rates, 2) harvest rates at low stock sizes are less than harvest rates at high stock sizes, and 3) the buffer between limit and target harvest rates widens as uncertainty regarding a stock's size or productive capacity increases. The use of a logarithmic control rule (with $w>0$) automatically satisfies the second requirement, whereas satisfaction of the first and third requirements

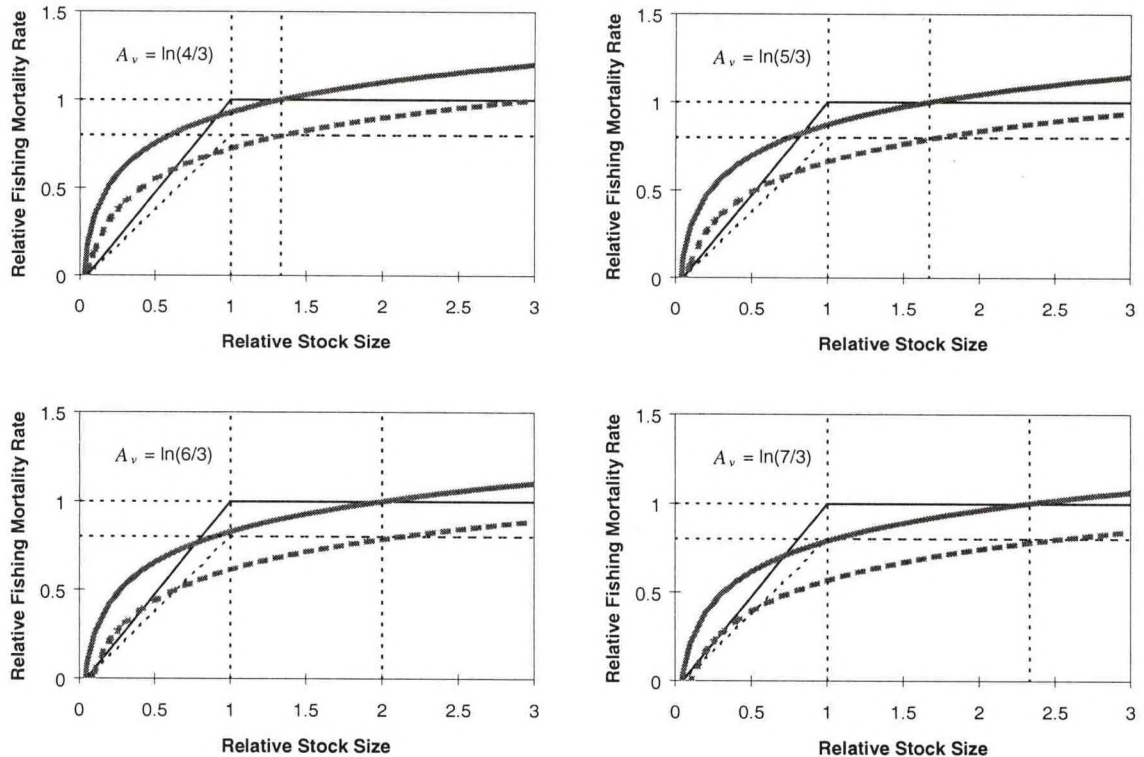


Figure 9. Limit (solid) and target (dashed) control rules in the example model (thick) and Alaska groundfish policy (thin). Horizontal and vertical dotted lines depict additional reference points.

is achieved by basing the limit control rule on a *risk-neutral* optimization and the target control rule on a *risk-averse* optimization. The Alaska groundfish policy also satisfies these three requirements, with the exception that the size of the buffer increases directly with uncertainty regarding productive capacity only (not stock size).

It may also be noted that the limit control rule shown for the example model in Figures 7-9 qualifies as an MSY control rule, whereas the limit control rule used in the Alaska groundfish policy does not. The failure of the limit control rule used in the Alaska groundfish policy to qualify as an MSY control rule is due to the fact that the presence of the descending limb was not considered in the process of setting the height of the horizontal limb. That is, in setting the height of the horizontal limb, the optimization was conditional on the assumption that a constant fishing mortality policy would apply, whereas in fact such a policy applies only when the stock is above its MSY level.

In Stages 1 and 2, it was assumed that estimates of the biological parameters a , b , and s (or v) are obtainable. In Stage 3, it was assumed that pdfs of these parameters are obtainable. In practice, obtaining these estimates or distributions will typically be a non-trivial exercise. However, the functional form of the example model described here is particularly amenable to this task. Thompson (1998) showed how a log transformation of this model satisfies the assumptions of the Kalman filter (e.g., Harvey 1990) exactly, meaning that either maximum likelihood or Bayesian methods can be used in a straightforward manner to obtain parameter estimates or posterior distributions of parameters (if maximum likelihood is used, distributions could be obtained by appealing to the asymptotic normality of the parameter estimates). The model is sufficiently simple, in fact, that the maximum likelihood estimate of the deterministic carrying capacity ($=be$) can be written in closed form.

The subject of rebuilding depleted stocks was considered for the Stage 1 and Stage 2 cases, but not for the Stage 3 case. A Stage 3 treatment should not prove too problematic, however, insofar as computing the geometric or arithmetic mean of Equation (6) for the case where the values of a and b are uncertain does not appear to pose any special difficulty (note that the natural variability parameter s does not enter into Equation (6)). Despite the omission of a Stage 3 treatment of rebuilding, the results obtained under Stages 1 and 2 in the example model offer some interesting insights on their own. For example, suppose that the goal of a rebuilding program is to return a depleted stock to its deterministic MSY stock size b . In this case, the Stage 1 example model indicates that the threshold stock size prescribed by any MSY control rule will also be equal to b regard-

less of the allowable time frame for rebuilding. Thus, under Stage 1 conditions, anytime a stock falls below its deterministic MSY stock size, it will be impossible to rebuild to the deterministic MSY level in finite time while fishing according to any MSY control rule. In the Stage 2 example model, however, the conclusions are different. Specifically, if the geometric mean of the transition distribution is used to define the threshold stock size, the threshold stock size prescribed by any MESY control rule with $d>0$ and $s>0$ will always be less than b regardless of the allowable time frame for rebuilding. Thus, under Stage 2 conditions, it is possible for a stock to fall below its deterministic MSY stock size to some extent and still rebuild to the deterministic MSY level within an allowable time frame while fishing according to a given MESY control rule. The difference in conclusions reached under Stages 1 and 2 in this regard is due to the fact that a Stage 1 MSY control rule evaluated at the point $x=b$ always gives a harvest rate equal to a , whereas a Stage 2 MESY control rule evaluated at the same point always gives a harvest rate less than a so long as $d>0$ and $s>0$. However, under a MESY control rule with $d=0$ (i.e., a constant fishing mortality policy), even the Stage 2 example model prescribes a threshold stock size equal to b .

Another aspect of rebuilding that was not addressed here is the question of whether rebuilding should be viewed primarily in terms of stock size x or in terms of rebuilding time t . In other words, is it more important to consider the probability that the stock size will exceed x_{reb} at time t_{reb} , or the probability that the time needed for the stock size to exceed x_{reb} will be greater than t_{reb} ? The two approaches are not equivalent (e.g., Dennis et al. 1991).

In conclusion, some caveats are probably appropriate. First, the logarithmic control rule used in the example model exhibits some features that may require getting used to. For example, one must either interpret the control rule as exhibiting a discontinuity at the point where it crosses the x axis (making the mathematics more complicated), or be prepared to accept (as an approximation, at least) the idea of a small negative "yield" at sufficiently low stock sizes. Also, the fact that the control rule has no finite upper bound may not be appealing to some. Second, the results pertaining to the example model may not extend to other models. For instance, a discrete rather than a continuous representation of stock dynamics, other functional forms for Equation (1), or other interpretations of the stochastic differential (Equation (7); for example, Ricciardi 1977) could alter the conclusions either quantitatively or qualitatively. Finally, the derivation of the MELSY solution presented in Equation (13) requires some strong assumptions. For instance, the assumption that the parameters a and v are independent is problematic unless a and s happen to vary

together in a particular manner. Also, the form assumed for the pdf of a implies that, for given values of H_a and A_a , the coefficient of variation changes with the choice of w , which is probably an undesirable property.

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Appendix: Derivation of a MELSY Solution

As discussed in the main text, one type of MELSY solution is achieved by maximizing the geometric mean of the marginal distribution of stationary yield, which can be written as

$$\bar{G}_y(c, d) = \exp \left[\frac{\int_0^\infty \int_0^\infty \int_0^\infty \left(\int_0^\infty \ln(y(x|c, d)) p_x^*(x|a, b, v, c, d) dx \right) p_{a,b,v}(a, b, v) da db dv}{p_{a,b,v}(a, b, v) da db dv} \right]$$

Unfortunately, several difficulties arise. For example, if the joint distribution of the parameters $p_{a,b,v}(a, b, v)$ is left completely general, it is not possible to obtain an analytic solution except for the special case in which $d=0$. The following simplifying assumptions will therefore be made:

1) The model can be reparametrized by substituting $\sqrt{2av}$ for s wherever the latter occurs.

2) The parameters a , b , and v are independent, so that $p_{a,b,v}(a, b, v) = p_a(a)p_b(b)p_v(v)$.

The above assumptions imply that the solution can be written as

$$\bar{G}_y(c, d) = \exp \left[\frac{\int_0^\infty \int_0^\infty \int_0^\infty \left(\int_0^\infty \ln(y(x|c, d)) p_x^*(x|a, b, v, c, d) dx \right) p_a(a) da p_b(b) db p_v(v) dv}{p_a(a) da p_b(b) db p_v(v) dv} \right]$$

Next, there is a problem in that the control rule $h(x) = c + d \ln(x)$ implies that yield falls to zero at $x = \exp(-c/d)$, at which point the logarithm no longer exists. Therefore, a compromise will be made by defining, tentatively, a "quasi-geometric mean" that involves taking the logarithm *after* integrating with respect to x (rather than before):

$$\begin{aligned} \hat{G}_y(c, d) &\equiv \exp \left[\frac{\int_0^\infty \int_0^\infty \int_0^\infty \ln \left(\int_0^\infty y(x|c, d) p_x^*(x|a, b, v, c, d) dx \right) p_a(a) da p_b(b) db p_v(v) dv}{p_a(a) da p_b(b) db p_v(v) dv} \right] \\ &= \exp \left[\frac{\int_0^\infty \int_0^\infty \int_0^\infty \ln(A_y(a, b, v, c, d)) p_a(a) da p_b(b) db p_v(v) dv}{p_a(a) da p_b(b) db p_v(v) dv} \right] \end{aligned}$$

Next, there is a problem in that the form of the conditional arithmetic mean implies that yield falls to zero at $b = \exp(-c/d - 1 - v)$, at which point the logarithm no longer exists. Therefore, another compromise will be made by redefining the "quasi-geometric mean" so that the exponentiation occurs immediately after integrating

with respect to a (rather than waiting until *all* integrations have been completed):

$$\begin{aligned} \hat{G}_y(c, d) &\equiv \int_0^\infty \int_0^\infty \exp \left[\int_0^\infty \ln(A_y(a, b, v, c, d)) p_a(a) da \right] \\ &\quad p_b(b) db p_v(v) dv \end{aligned}$$

Finally, it will be assumed that $p_a(a)$, $p_b(b)$, $p_v(v)$ have particular functional forms. Specifically, the following will be assumed:

1) The uncertainty surrounding a can be described by an F distribution with scale parameter d , meaning that the uncertainty surrounding the variable $u = a/(a+d)$ can be described by a beta distribution, that is,

$$p_a(a) = \frac{\left(\frac{a}{d}\right)^{\alpha_a-1} \left(1 + \frac{a}{d}\right)^{-\alpha_a-\beta_a}}{d \left(\frac{\Gamma(\alpha_a)\Gamma(\beta_a)}{\Gamma(\alpha_a+\beta_a)} \right)}$$

or

$$p_u(u) = \frac{u^{\alpha_a-1} (1-u)^{\beta_a-1}}{\frac{\Gamma(\alpha_a)\Gamma(\beta_a)}{\Gamma(\alpha_a+\beta_a)}},$$

where α_a and β_a are parameters. The harmonic and arithmetic means of a are given by

$$H_a = d \left(\frac{\alpha_a - 1}{\beta_a} \right)$$

and

$$A_a = d \left(\frac{\alpha_a}{\beta_a - 1} \right),$$

respectively. The ratio of H_a to A_a (i.e., the degree of certainty regarding the true value of a) is thus independent of d . The arithmetic mean of u is dependent on both the scaled control parameter w and the degree of uncertainty regarding the true value of a , as shown below:

$$A_u = \frac{\alpha_a}{\alpha_a + \beta_a} = \frac{\frac{H_a}{A_a} + w}{\frac{H_a}{A_a} + 2w + w^2}.$$

2) The uncertainty surrounding b can be described by a lognormal distribution, that is,

$$p_b(b) = \sqrt{\frac{1}{2\pi}} \left(\frac{1}{\sigma_b b} \right) \exp \left[-\left(\frac{1}{2} \right) \left(\frac{\ln(b) - \mu_b}{\sigma_b} \right)^2 \right],$$

where μ_b and σ_b are parameters. The harmonic, geometric, and arithmetic means of b are given by

$$H_b = \exp\left(\mu_b - \frac{\sigma_b^2}{2}\right),$$

$$G_b = \exp(\mu_b),$$

and

$$A_b = \exp\left(\mu_b + \frac{\sigma_b^2}{2}\right),$$

respectively.

3) The uncertainty surrounding v can be described by an inverse Gaussian distribution, that is,

$$p_v(v) = \frac{\left(\frac{v}{\eta_v}\right)^{\frac{3}{2}} \exp\left(-\left(\frac{\theta_v}{2}\right)\left[\left(\frac{v}{\eta_v}\right) + \left(\frac{v}{\eta_v}\right)^{-1}\right]\right)}{\eta_v e^{-\theta_v} \sqrt{\frac{2\pi}{\theta_v}}},$$

where η_v and θ_v are parameters. The harmonic and arithmetic means of v are given by

$$H_v = \eta_v \left(\frac{\theta_v}{\theta_v + 1}\right)$$

and

$$A_v = \eta_v,$$

respectively.

Given the above, $\hat{G}_y(c, d)$ can be written, up to a constant of proportionality, as follows:

$$\hat{G}_y(c, d) \propto \left[c + \left(1 + \mu_b + \sigma_b^2 A_u + \eta_v \sqrt{\frac{\theta_v}{\theta_v - \eta_v A_u}} \right) d \right] \times \exp\left[c \left(\frac{A_u - 1}{d} \right) \right]$$

Differentiating the above with respect to c , setting the resulting expression equal to zero, solving for c , and substituting wA_a for d gives

$$\hat{c}_{\text{MELSY}}(w) = (k_a - (\ln(G_b k_b) + A_v k_v)w) A_a,$$

where

$$k_a = \left(\frac{H_a}{A_a} + w \right) \left(\frac{1}{1 + w} \right),$$

$$k_b = \left(\frac{H_b}{A_b} \right)^{-A_u},$$

$$k_v = \left(1 - A_v \left[\left(\frac{H_v}{A_v} \right)^{-1} - 1 \right] A_u \right)^{\frac{1}{2}}.$$

The Implications of Incorporating Uncertainty into Fisheries Management for Policy Makers

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Abstract.- The inclusion of uncertainty in determining fleet size is particularly important in determining excess capacity in a fishing fleet. Multinomial logit, a technique developed to account for uncertainty in the fishery management process, is used to determine the probability of an event occurring under the biological and market conditions existing at a point in time. In the case of the Gulf of Mexico shrimp fishery, the probability of entry and exit of fishing vessels can be used to estimate fleet size as well as the optimum scale of production for an individual fishing craft in a common property fishery under various proposed management regulations. It is also important in determining the response of the fleet to proposed regulations designed to reduce excess capacity through the reduction of vessels and their scale of operation. However, predictions of fisher behavior based on constant stock abundance indices differ from predictions incorporating the unknown variable stock abundance indices; another form of uncertainty. The implication is that the fish stock and the effort effects need to be determined simultaneously to accurately predict the response of a fishery to a proposed management regulation.

Introduction

Bioeconomic modeling sometimes requires a number of separate systems to be in equilibrium. Fish stocks which act as constraints on the production of fish are subject to uncertain stock-recruitment relationships. Individual recreational and commercial fisher behavior is determined by goals and objectives that are not well understood. Market allocation mechanisms are distorted in unknown ways by management regulations that distribute fish between different user groups based on historic catch rates determined in markets characterized by negative externalities. Uncertainty is prevalent in harvesting sector prices, costs, catch rates, equipment performance, weather, quality of inputs, and fishery management institutions. Processors face supply and demand uncertainty from changes in fishery regulations, imports, exports, and levels of aquaculture production, which are further exacerbated by the nonexistence of futures markets for nearly all fishery products. Consumer demand uncertainty exists because the quality of fishery products is determined post consumption, sea-food safety and health risks are unknown prior to consumption, and per capita income levels are known only as a national index.

However, since Bishop (1978) developed the safe minimum standard (SMS) approach to public decisions, techniques have been developed to account for uncertainty in the fishery management process. For example, multinomial logit is used to determine the probability of an event occurring under the biological and market conditions existing at a point in time. In the case of the Gulf of Mexico shrimp fishery, the probability of entry and exit by fishing vessels can be used to estimate fleet

size as well as the optimum scale of production for an individual fishing craft in a common property fishery under various proposed management regulations (Ward and Sutinen 1994). The inclusion of uncertainty in determining fleet size is particularly important in determining excess capacity in a fishing fleet. It is also important in determining the response of the fleet to proposed regulations designed to reduce excess capacity through the reduction of vessels and their scale of operation.

However, predictions of fisher behavior based on constant stock abundance indices differ from predictions incorporating variable stock abundance indices, which is another form of uncertainty. The implication is that the fish stock and the effort effects need to be determined simultaneously to accurately predict the response of a fishery to a proposed management regulation.

Sources of Uncertainty

Fishing effort is a function of ex-vessel prices, harvest or operating costs, and the abundance of fish. While the emphasis of the National Stock Assessment Workshop is on the uncertainty in stock abundance and biological reference points, other forms of uncertainty in the fishery management problem also exist. Ex-vessel prices, for example, vary due to changes in import levels caused by new sources of supply such as increased production from aquaculture or the discovery of new shrimp fishing grounds. The development of new substitute or complementary products or changes in existing products can affect ex-vessel prices. In addition,

changes in the levels of consumer income can cause demand for a fishery product to change and affect its price. Other factors that can affect the demand for a fishery product include changes in the perceptions of food quality and health aspects of food. Processor market structure can impact ex-vessel prices. Vertically integrated firms for example can reallocate profits from the harvest sector to the retail sector by reducing the ex-vessel price it pays internally. In fisheries, the lack of futures markets that allow for price hedging which smooth price fluctuations can result in increased variability in ex-vessel prices.

Operating costs are also subject to variation over time. Changes in the supply of factor inputs and their prices are due to demand by competing industries for the same input. Inputs that are traded in world markets such as fuel can have price changes influenced by events in foreign countries. Fuel costs can change as a result of embargoes, wars, economic growth and recession in the world economy, and by changes in the availability of substitute sources of energy. Changes in the quality of the inputs can cause relative costs to increase. As quality declines with a constant price, other costs such as maintenance and repair will increase or the input might have to be used in greater quantities to offset the decline in quality causing total operating costs to increase. Finally, declines in the stock abundance can cause the relative cost per pound of fish harvested to increase even though cost per unit of effort is constant. Other sources of uncertainty that can affect both prices and harvesting costs include changes in equipment performance, weather, and predator-prey and competitor species relationships.

A major source of uncertainty is the fishery management regulations designed to control harvest levels in common property, domestic fisheries. Command and control fishery management regulations such as total allowable catch (TAC) regulations, size limits, trip limits, and closed seasons or areas, can exacerbate the race-for-fish. Open access management of common property fishery resources can result in excess capacity and over capitalization in the domestic fishing fleet that increases harvesting costs. Even when limited entry is strictly enforced, capital stuffing can occur within the existing fleet. As capital investment increases, fishing costs rise and the fishing season if managed under a TAC becomes shorter. The same volume of fish is landed in shorter periods of time and can depress fresh fish market prices, and create a frozen fish market that sells a lower quality product at a lower market price while the fishery is closed. If the restrictive TAC is successful in conserving the fish stock, the race for fish and its effect on market prices and harvesting costs are exacerbated as the stock abundance increases.

Gulf of Mexico Shrimp Fishery

The Gulf of Mexico shrimp fishery is one of the most valuable fisheries in the United States and as a result also one of the most closely studied and monitored. However, even in fisheries such as shrimp with extensive data collection and quality control programs, uncertainty can still remain a problem. Three separate estimates of fleet size can be derived depending upon which data set collected and maintained by the National Marine Fisheries Service is used (Ward and Nance 1994). The vessel operating units file (VOUF) provides a higher annual estimate of fleet size based on gear type reported on board the fishing craft than the shrimp landings file (SLF) which is based on reported landings. A third and lower estimate of fleet size is developed from a comparison of the SLF and VOUF data files. Consolidated records and incomplete reporting as well as coding errors can account for these different estimates of fleet size in the shrimp fishery.

Another estimate of fleet size can be generated by comparing vessel activity over time. Full-time vessels are identified as operating in the fishery for three consecutive years. Entering vessels operate in the fishery in the base year and in the subsequent year, but not in the preceding year. Exiting vessels operate in the base year and in the preceding year, but not in the subsequent year. According to this definition, an annual average of 20 percent of the fleet consists of vessels that are entering or exiting the fishery (Ward and Nance 1994). More importantly, entry and exit behavior is occurring simultaneously in any given year. Some of this behavior can be explained by the heterogeneous nature of the fishing fleet. However, this behavior is also caused by socio-cultural attributes that affect fishers' decisions. When facing the same biological and market conditions in a similar fishing craft, two fishers may make different decisions about participating in the fishery. There will always be unobservable characteristics that vary among fishers that cause uncertainty in determining their behavior. This behavior can be modeled using multinomial logit techniques to estimate the probability that an individual vessel will enter, remain in, or exit the fishing fleet.

Constant Stock Abundance

The probability of entry-exit behavior in the Gulf of Mexico shrimp fishing fleet has been estimated using this multinomial logit estimation technique. These probabilities can be used to determine how fishers will behave under different proposed management regulations, the resulting size of the fishing fleet that results from this behavior, and the resulting scale of operation within the fleet. For example, Table 1 indicates how the probabilities of entry, remain in the fishery, and exit,

Table 1. Estimated probability of entry and exit for an individual vessel in the Gulf of Mexico shrimp fishery.

Entry Vessel Length	Entry new entrant	Remain switch gear	Exit in fishery	Exit switch gear	left fishery
25	0.0255	0.0012	0.9511	0.0026	0.0195
26	0.0245	0.0011	0.9513	0.0027	0.0203
27	0.0236	0.0011	0.9513	0.0029	0.0211
28	0.0227	0.0010	0.9513	0.0030	0.0219
29	0.0219	0.0010	0.9513	0.0031	0.0228
50	0.0125	0.0006	0.9420	0.0052	0.0397
51	0.0122	0.0006	0.9414	0.0053	0.0405
52	0.0120	0.0005	0.9408	0.0054	0.0413
53	0.0117	0.0005	0.9401	0.0055	0.0421
54	0.0115	0.0005	0.9394	0.0056	0.0429
55	0.0113	0.0005	0.9388	0.0057	0.0437
100	0.0061	0.0003	0.9048	0.0100	0.0790
110	0.0055	0.0003	0.8969	0.0108	0.0866
120	0.0050	0.0002	0.8890	0.0116	0.0941
130	0.0046	0.0002	0.8812	0.0124	0.1015
150	0.0040	0.0002	0.8658	0.0140	0.1161

are affected as vessel size changes for a given set of biological and market conditions. The probability of an entry by a fishing vessel either as a new entrant to the fishery or by an existing vessel switching gear declines as vessel size increases. The probability of exiting the shrimp fishery increases either by leaving the fishery or by switching to another gear as vessel size increases. Although the highest of the five categories indicate a tendency for the fleet to remain unchanged, the probability of remaining in the fishery also declines as vessel size increases. That is, for this set of economic conditions existing in the fishery, the trend is for smaller vessels to replace larger vessels in the Gulf of Mexico shrimp fishery.

These probabilities can also be used to determine how fleet size will change under different economic conditions or for various proposed fishery management regulations when combined with other economic analyses under an assumption of constant stock abundance. In Figure 1, the impact of access rights on fleet size is determined. First, the fishing fleet is allowed to come to a long-run equilibrium between years zero and sixty-eight. Once the fleet has stabilized at approximately 3,100 vessels, the regulatory change is introduced (Figure 1a). This results in a decline in fleet size to about 2,600 vessels over the next twenty-two years. This decline in fleet size accounts for the variability in prices due to changes in imports and domestic landings (Keithly *et al.* 1993). In Figure 1b, the effect of the proposed access rights program on the shrimp fleet causes a decline in fleet size while ex-vessel prices increase from

approximately \$1.60 per pound to \$1.81 per pound. This price increase results in an increase in the landings of individual shrimp vessels in Figure 1c which results from incorporating operating costs and production into the shrimp model (Ward *et al.* 1995). This increase in ex-vessel price and landings is also accompanied by a decline in discarded finfish bycatch in Figure 1d. Although bycatch increases on a per-vessel basis because landings increase, this decline in total discarded bycatch is primarily the result of a reduction in the size of the fishing fleet (i.e., fewer vessels discarding finfish.)

This result occurs because the annual rent generated by the shrimp resource is internalized into the decision-making processes of the individual firm. The capturing of these rents changes the behavior of the individual fisher. While both entry into and exit from the fishery occurs, the number of fishers leaving the fishery out weights the number entering. While these rents benefit the nation, the benefits that accrue to individual fishers depend on how the access right is allocated initially. If it is in the form of an annual auction, then fishers pay for the access right and receive no direct benefit from the program. If, however, fishers are allocated transferable, annual coupons to land shrimp, then all the benefits of the program accrue to them. In this second case, the fishers who elect to leave the shrimp fishery are compensated by those who decide to remain in the fishery. In either case, the nation is better off under the access rights program than the open access fishery system assuming constant stock abundance.

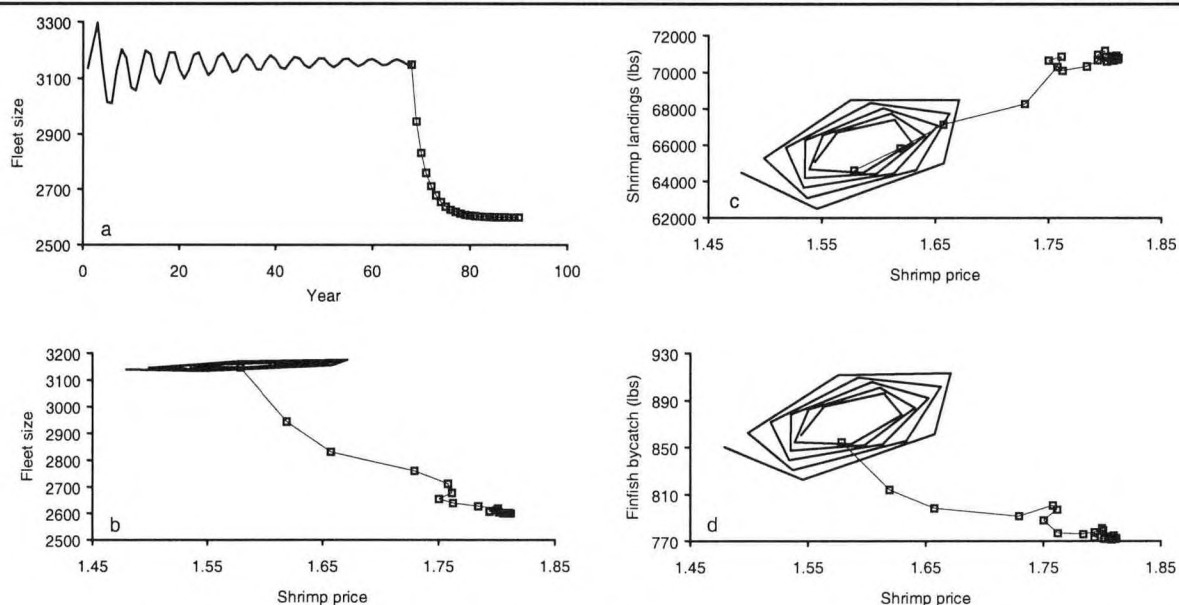


Figure 1. Impact of access rights on fleet size, shrimp landings and bycatch, in the Gulf of Mexico shrimp fishery. The lines with symbols depict the deterministic trajectories expected under the proposed regulatory program.

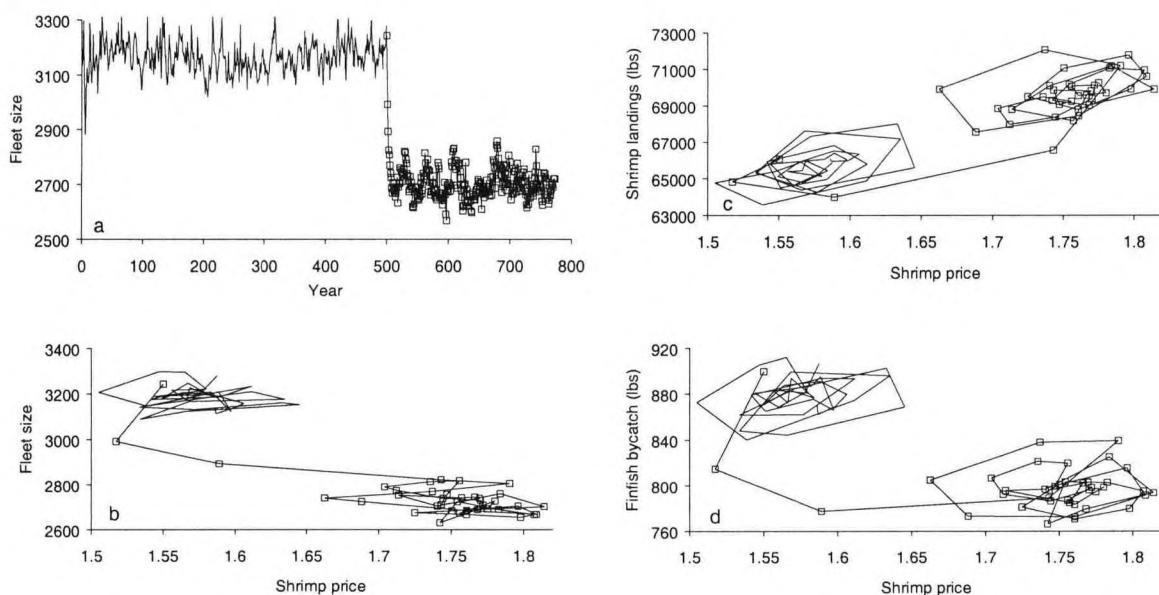


Figure 2. Impact of access rights on fleet size, shrimp landings and bycatch, in the Gulf of Mexico shrimp fishery, estimated with a variable abundance model. The lines with symbols depict the stochastic trajectories expected under the proposed regulatory program.

Variable Stock Abundance

Incorporating uncertainty about the vessel entry-exit decision with variation in ex-vessel price, cost, and individual vessel production levels allows the estimation of both short-run variation in fleet size over time as well as the long-run equilibrium fleet size. However, short-run variation in shrimp stock abundance needs to

be addressed in determining how fleet size, costs, and benefits generated by the Gulf of Mexico shrimp fishery are affected by proposed fishery management regulations. The assumption of constant stock abundance is relaxed by incorporating a random number generator with mean 53.3 and a variance of 50. The mean reflects the average value from the Gulf of Mexico brown shrimp stock abundance index developed by the NMFS,

Galveston Laboratory. The variance estimate is set to allow abundance to range between 29 and 71 over the course of the simulation. Although the intraseasonal changes in shrimp stocks are well documented and complex models explaining changes in stock size and migration patterns exist, the random number generator is used since an interseasonal stock recruitment relationship for shrimp is not presently available to incorporate into the model of the fishery.¹

Figure 2 demonstrates how fleet size varies over time when variable stock abundance is incorporated into the model. Instead of coming to a long-run equilibrium over time, the fleet remains in disequilibrium until an arbitrarily determined point when the access right regulatory change is introduced (Figure 2a). Although the fleet declines in size after this change, it remains in disequilibrium responding to the random shocks caused by the variation in annual stock abundance.

This long run disequilibrium is not the only effect of variable stock abundance. In Figure 2a, the fleet size declines less than it did under the constant stock assumption. In Figure 2b, the decline in fleet size is accompanied by an increase in price to approximately \$1.75 per pound; less than under the constant stock assumption. In Figure 2c, the variable stock abundance assumption causes individual vessel shrimp landings to increase, but by a slightly lesser amount than occurred under the constant stock assumption. This results in a larger decline in discarded finfish bycatch in Figure 2d than was found in the constant stock abundance scenario.

Stock abundance variability introduces changes in the behavior of fishers relative to their expected behavior when stock is assumed to be constant. While the direction of change is not affected, the magnitude of the change is affected. That is, the generation of rents in the fishery is reduced. In Table 2, cost and benefits are reported for the constant stock and variable stock scenarios. Increased stock variability does reduce net benefits from the adoption of the access rights program, depresses ex-vessel prices, and increases the level of bycatch reduction in the fishery.

Table 2. Impact of access rights on fleet size in the Gulf of Mexico shrimp fishery. PV = present value (in millions of dollars).

Stock	Tot. PV After	Tot. PV Before	PV Change	Cost: Benefit	%Bycatch reduction
Constant	4404.86	1940.49	2464.38	2.27	9.68
Variable	4289.35	1966.49	2322.86	2.18	11.42

Conclusions

Capturing uncertainty in fleet size using statistical techniques such as multinomial logit and variability in ex-vessel prices, and operating costs by incorporating them as endogenous variables in simulation models, enables better predictions of changes in fleet size under different proposed management regulations. However, while the direction of change remains the same, the magnitude of predictions of fisher behavior based on constant stock abundance indices differs from predictions incorporating variable stock abundance indices. As variability in stock abundance increases, so does variability in the estimated equilibrium values of the dependent variables, and causes the ability of the models to accurately predict changes due to proposed management measures or changes in economic conditions to decline. The implication is that the fish stock and the effort effects need to be determined simultaneously to accurately predict the response of a fishery to a proposed management regulation.

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¹ The analysis of a brown shrimp stock recruitment model reported in Gulland and Rothschild (1984) was reviewed in Garcia (1983) and may have been a statistical artifact. Another stock recruitment analysis of brown shrimp by Parrack (no date) is reported to have found a statistically valid relationship, but was not available to be included in this analysis.

3

WORKING GROUP REPORTS

During the afternoon of the second day of the Workshop, participants joined one of four working groups to discuss technical aspects of the precautionary approach. This section contains their reports. The four working groups were more or less defined by level of information complexity, as explained below. The first three groups are relevant to single-species approaches to setting target and limit harvest levels when that can be accomplished effectively. The last group is relevant to multi-species approaches to setting harvest levels, even though the stock assessments may be carried out on a single-species basis for each stock in the complex.

1. Information-rich cases: Reliable estimates of MSY-related quantities and current stock size are available. Harvest control rules typically involve parameters such as F_{MSY} , B_{MSY} , etc. Stock assessments may be sophisticated, and provide a reasonably complete accounting of uncertainty.

2. Intermediate cases: Reliable estimates of MSY-related quantities are either unavailable or of limited use due to peculiar life history or high recruitment variability, but reliable estimates of current stock size and all critical life history (e.g., growth) and fishery (e.g., selectivity) parameters are available. Harvest control rules typically involve parameters such as $F_{35\%}$, $B_{35\%}$, etc., or other proxies for MSY-related benchmarks. Stock assessments may range from simple to sophisticated and uncertainty can be reasonably characterized and quantified.

3. Information-poor cases: Reliable estimates of MSY-related quantities are unavailable, as are reliable estimates of either current stock size or certain critical life history or fishery parameters. Harvest control rules typically involve parameters such as M , historical average catch, etc. Stock assessments are minimal, and measurements of uncertainty may be qualitative rather than quantitative.

4. Mixed-information cases in multi-species settings: Target and limit harvest levels for each species in a fishery may need to be established jointly with those for the other species in the fishery, as the stocks are harvested together and cannot be targeted or effectively managed independently. Within constraints specified by the proposed national standard guidelines, it may be necessary to overfish one or more species in order to achieve OY for the complex. Reliability of MSY-related quantities, current stock size, and other parameters, may range from high to low for the various stocks in the complex. Stock assessments vary from minimal to sophisticated, and uncertainty characterization ranges from qualitative to reasonably complete.

Central questions

According to the guidelines for National Standard 1, a precautionary approach should contain three main features: “First, target reference points, such as OY, should be set safely below limit reference points, such as the catch level associated with the maximum fishing mortality threshold. Second, a stock that is below its MSY level should be harvested at a lower rate or level of fishing mortality than if it were above its MSY level. Third, the criteria used to set target catch levels should be explicitly risk averse, so that greater uncertainty regarding a stock’s status or productive capacity corresponds to greater caution in setting target catch levels” (Federal Register, Aug. 1997, Volume 62, Number 149).

A central question is the development of frameworks for control laws, e.g. a relationship between management recommendations and stock assessment results. These control laws can be used to define a limit that cannot be exceeded, and/or a management target that is safely below the limit. The working groups should aim to provide practical advice on these features for their level of information complexity. A preliminary set of questions for each group to consider is:

1. How to define control laws that can be implemented and monitored with available information and that are consistent with the proposed National Standard Guidelines?
2. How to quantify or categorize uncertainty (in biological relationships and assessment results) so that it can be incorporated into control laws?
3. How to describe tiers of uncertainty so that lack of information truly leads to greater caution?
4. How to calculate and communicate assessment results so that they facilitate and encourage risk averse management actions, but leave opportunity for the management process to incorporate other considerations?
5. How to include other approaches, such as the use of marine protected areas or other gear/size/time/area restrictions?

Report of the “Data-Rich” Working Group

Chair: G. G. Thompson

General Procedure

In general, the following procedure is suggested for specifying limit and target control rules:

1) Consider a candidate limit control rule.

a) How does it qualify as an MSY control rule (i.e., in what sense would long-term average yield be maximized by the control rule’s sustained application)?

2) Consider a candidate target control rule.

a) How does it satisfy the following three requirements of a precautionary approach?

- i) target \leq limit
- ii) $F(\text{low stock size}) < F(\text{high stock size})$
- iii) $F(\text{high uncertainty}) < F(\text{low uncertainty})$

More Specific Procedure

For an n -parameter control rule, it may be easiest to fix $n-1$ parameters *a priori* through a simple rule or formula, and treat only the remaining control parameter as free.

1) For the limit, the Group suggests setting the free control parameter at the value that maximizes expected stationary yield, or something analogous.

2) For the target, one of the following options is suggested:

- a) set the free control parameter at the value that maximizes expected log stationary yield, or something analogous.
- b) set the free control parameter at the value where the probability of the true fishing mortality rate exceeding the limit control rule is α .

Examples of Control Rules

The following are some control rules that the Group felt at least somewhat positive about:

One-Parameter Control Rules

1) $f(x)=F$

Comments: This control rule does not satisfy the

second requirement of a precautionary approach. Probably results in a minimum stock size threshold close to x_{MSY} . A good proxy for the target control rule might be the harmonic mean of the pdf of deterministic F_{MSY} .

Two-Parameter Control Rules

2) $f(x)=F+bx$

3) $f(x)=F+b\ln(x)$

Three-Parameter Control Rules

4) $f(x)=a+bx$ for all $x < (F-a)/b$

$f(x)=F$ for all $x > (F-a)/b$

A special case:

4a) $(F-a)/b = x_{MSY}$, i.e.,

4ai) $f(x)=a+bx$ for all $x < x_{MSY}$

$f(x)=a+bx_{MSY}$ for all $x > x_{MSY}$, or

4a ii) $f(x)=a+(F-a)(x/x_{MSY})$ for all $x < x_{MSY}$

$f(x)=F$ for all $x > x_{MSY}$, or

4a iii) $f(x)=F+b(x-x_{MSY})$ for all $x < x_{MSY}$

$f(x)=F$ for all $x > x_{MSY}$

Comments: To minimize the potential for mischief, the Group recommends that F be treated as the free parameter. In order to qualify as an MSY control rule, F will probably have to be greater than the F_{MSY} level calculated under control rule 1. The minimum stock size threshold may still be close to x_{MSY} .

5) $f(x)=a+bx$ for all $x < (F-a)/b$

$f(x)=F/x$ for all $x > (F-a)/b$

A special case:

5a) $\frac{-a + \sqrt{a^2 + 4bF}}{2b} = x_{MSY}$,

with three ways of eliminating a parameter as in 4a.

Comments: The same comments as in 4a apply. This control rule satisfies the second requirement of a precautionary approach only for stock sizes below x_{MSY} .

Suggestions for Setting α

The “alpha” approach defines the target control rule by specifying a probability that the true fishing mortality rate, though intended to equal the *target*, may actually exceed the *limit*. Values for α suggested by members of the Group included 0.05, 0.10, and 0.20. It was also suggested that α be set on a case-by-case basis, because methods of expressing variance and uncertainty are not consistent across stock assessments and because fixed values of α may be too conditional on model speci-

fication and error distribution assumptions. Most Group members were generally pessimistic regarding the "alpha" approach, though it should not be ruled out as an option.

Suggestions for Rebuilding Rates

The Group had little advice to provide in terms of choosing an appropriate rate of rebuilding. It was suggested that phrasing the discussion in terms of the stock size below which the fishery would close might help Councils to view the question in practical terms. Some members of the Group believe that it would be valuable to have at least default measures for rebuilding defined *a priori*. Doing this might help to prevent excessive delay in implementing rebuilding plans when the stock is at a critically low level.

Report of the "Data-Moderate" Working Group

Chair: Richard Methot

Introduction

This Group was charged with developing recommendations for applying the precautionary approach to situations in which a quantitative stock assessment can be conducted, but there is insufficient information to develop a reliable estimate of MSY. The general features of harvest control rules developed for data-rich situations should apply to data-moderate situations and are not considered further here. However, by definition, the data-moderate harvest control rule will need to use a proxy for F_{MSY} . In addition, the data moderate situation is likely to have higher variance in estimates of stock abundance and harvest rates.

A primary outcome of the working group's deliberations was dissemination of the general principles of the harvest control rules, precautionary approach, and rebuilding plans. This aspect of the small-group discussion is not reported here, but was a major benefit from this opportunity.

Proxies for F_{MSY}

A primary consideration for data-moderate situations is identification of a suitable proxy for F_{MSY} . It is now common to express these proxy harvest rates in terms of their expected impact on spawning biomass (itself a proxy for reproductive output) per recruit. Harvest rates in the range of $F_{35\%}$ to $F_{45\%}$ have been proffered as reasonable proxies for MSY, and $F_{20\%}$ was used as an overfishing threshold for many stocks during

the mid-1990s (Rosenberg et al). The actual level of the proxy harvest rate will be based upon information gleaned from comparable, data-rich stocks; life history characteristics of the stock in question; and selectivity characteristics of its fisheries. The working group recommends continued efforts to conduct a meta-analysis of stock productivity estimates in order to guide selection of suitable proxies for individual stocks.

The working group recommends calculating harvest rates under current selectivity patterns, including the current mixture of fisheries with different selectivity patterns. This avoids confusing allocation issues with optimum yield issues. However, these allocation and selectivity issues may need to be re-considered when a rebuilding plan is developed.

One impediment to estimating MSY is lack of contrast in spawning biomass levels, even though data quality may be sufficient to obtain good estimates of current abundance and harvest rates. Successful future management under a MSY proxy may further delay observing the stock at contrasting biomass levels. If the proxy is too aggressive (i.e. greater than the true F_{MSY}), then the stock will decline and information about the true F_{MSY} will be obtained. However, if the proxy is too conservative, then we will have little opportunity to learn whether or not the stock is capable of producing a greater yield. In this circumstance, only extreme natural fluctuations in recruitment will allow collection of information about stock productivity at different stock levels. If it is suspected that the proxy is much too conservative, then a carefully controlled adaptive management regime could be used to probe contrasting biomass levels in order to improve the estimate of long-term MSY.

This MSY-based distinction between data-moderate and data-rich assessments can turn into a smooth transition when assessments are conducted with Bayesian methods to introduce a prior distribution on the curvature of the stock-recruitment function. In this case, the same sort of information that currently is used to establish a proxy will be used to specify a prior distribution on the potential stock productivity. When there is little actual data from the subject stock, this prior will dominate the result. As stock-specific data accumulate, the posterior estimate of the stock's productivity will be drawn towards the information from that stock.

Variance Components

In the evaluation of the potential performance of a F_{MSY} proxy, it is important that the major components of variance are identified so that appropriate precautionary adjustments can be recommended. The evaluation should be based upon simulation studies that include relevant types and levels of assessment uncertainty, vari-

ability in recruitment on a range of relevant time scales, and potential variance in the management application of the recommended harvest control rule.

The assessment uncertainty includes three components of variance. First is the suitability of the proxy for F_{MSY} . Clearly we cannot do this perfectly, otherwise we would know MSY for each stock already. Any future meta-analysis of stock productivity should attempt to estimate this component of variance. Second is the estimate of the harvest rate that would correspond to the selected proxy. This depends on technical estimates of growth, mortality, maturation, and fishery selectivity. While this component of variance may be relatively low for many stocks, it should not be ignored in the evaluation of the proxy's performance. Finally, accurate implementation of the proxy depends upon accurate estimates of current stock abundance and harvest rates.

The level of precaution should decrease monotonically as the level of true variance decreases. Unfortunately, our "best" estimates in data-poor situations rarely have a relevant variance estimate and rarely result in a large precautionary adjustment. As we emerge from data-poor situations and begin to conduct quantitative assessments with variance estimates, we often find that these first estimates of variance are very large. It is important that the way in which these large estimates of variance enter into precautionary harvest control rules not be an impediment to acceptance of these first variance estimates. Thus, when data quality or model methods are insufficient to develop good estimates of assessment variance, it may be necessary to develop a proxy for assessment variance itself.

Report of the "Data-Poor" Working Group

Chair: Alec MacCall

Rapporteurs: Loh-Lee Low and Pamela Mace

Introduction

This Group was charged with developing recommendations for applying the precautionary approach to data-poor fishery cases. "Data-poor" refers to cases where standard stock assessment tools (ADAPT, Stock Synthesis, CAGEAN, etc.) cannot be applied because of insufficient data. For the purpose of this group's discussions, it is assumed that formal MSY estimates or proxy policies such as those based on spawning potential per recruit (SPR) cannot readily be developed. Data series may be incomplete, censored (in the statistical sense, possibly due to a prior history of restrictive management), or simply lack sufficient contrast to define critical relationships, such as between effort and catch per unit effort.

We are obligated to use available information, however poor or incomplete, to implement a management policy consistent with the revised MSFCMA and National Guidelines. The challenge is to gain some indication of current abundance (B) and fishing intensity (F), and to relate these estimates to corresponding reference points, B_{MSY} and F_{MSY} . This can be very difficult to do in a data-poor case, and the resulting imprecision necessarily merits a precautionary approach.

Simple, practical methods for assessing data-poor stocks or fisheries were developed extensively by FAO and others during the 1960s and 1970s. Use of these methods has declined in recent years, perhaps associated with the rise of computationally intensive methods often requiring richer data sets. However, the simple methods were designed especially for data-poor cases of the sort being considered here, and a review of those methods would be a worthwhile first step toward stock assessment. Some of those approaches may require modification to meet the present requirement for precaution.

The category of "data-poor" or "information-poor" situations encompasses a wide variety of possibilities, and defies generalization. Some examples are:

- Nearly total lack of data
- Catch history consist of poorly monitored bycatch
- Historical catches or rates may have been constrained (e.g., squid)
- Catch history is known, but little biology (e.g., scallops)
- No fishery, but history of surveys or indexes
- Fishery occurs only in a small portion of range (e.g. blue shark in Hawaii)
- Under-developed fishery, only knowledge is from an experimental fishery
- Peculiar life history traits (e.g., hermaphroditic groupers)

The Group preferred to consider individual examples spanning a representative variety of actual fishery cases. These cases are taken progressively in approximate order of information richness. The final example treats the special case of a newly-developing fishery. All of these cases tend to address the problem of stock assessment. Stock assessment serves two purposes in the present context: It reduces (or at least quantifies) uncertainty, and it defines the options available for precautionary management.

Example 1 -- Very poor information

There are some fishery resources for which we have almost no information whatsoever. The early development of Australia and New Zealand's orange roughy

fisheries are example cases. Best available information may consist of little more than expert opinion. Formalization of that information or advice is beneficial, and techniques such as the Delphi Method provide a means of comparing and cross-checking different individuals' expert opinions. Qualitative stock assessment may be appropriate, e.g., abundant vs. depleted, or lightly exploited vs. heavily exploited.

With only slightly more information it may be possible to use analogies drawn from similar species or resources that have better-known properties. A large number of the west coast's rockfish (*Sebastes* spp.) could fall in this category. As information becomes more quantitative, analogies may be formalized into meta-analysis or Bayesian treatments, and precaution can be quantified by appropriate loss functions.

Example 2 -- Some catch history

Quite often there is a history of estimated catches, but little else. The catches may be from a directed fishery or perhaps from estimated by-catch in other fisheries. All of the approaches suggested in the previous example apply equally in this case. Because exploitation is already underway, development of more information is urgent. Catch alone is not an adequate basis for managing a fishery and should be supplemented by other information as soon as possible. Unless an arbitrary level of catch has been maintained for an exceptionally long period of time (several times the maximum fish lifespan), there is little basis for assuming that an existing catch level is actually sustainable. The "reversal of proof" aspect of the precautionary approach requires that the catch level be proven to be sustainable rather than assuming it is sustainable and requiring proof to the contrary. An interim precautionary approach might be to restrict allowable catches to 75% of their historical average, or some other percentage value based on qualitative perceptions of resource condition, e.g., based on fishermen's perceptions of trends in catch rates.. Mace (personal communication) has conducted simulations suggesting that percentages in the range 60%-90% are often appropriate.

In many respects, this is the most challenging scenario for implementing a precautionary approach. Because there is an existing fishing tradition, there are likely to be strong advocates for continuing or even expanding harvest despite a general lack of information. Although the National Guidelines indicate that this condition of high uncertainty should result in strong precaution, it is not clear what is gained by a precautionary reduction in what may already be an arbitrary level of harvest. The key to solving this problem is development of a stock assessment (perhaps qualitative) based on expert judgement if necessary, and using that assess-

ment as the basis for advice on precautionary measures.

Example 3 -- Some catch history with minimum biological knowledge

This is perhaps the most common "data-poor" case. In the 1960's and 1970's the FAO and others developed a variety of stock assessment tools for treating this information level, and some of those approaches merit reconsideration. A tentative natural mortality rate can be inferred from simple growth or age information, using analogies to better-known species. Changes in age or size compositions over time may reveal trends in recruitment or exploitation effects. Virtual Population Analysis (VPA) of synthetic cohorts, or length-based VPA may provide rough estimates of fishing mortality rate and population size. Age determinations should be validated if possible.

A popular management rule-of-thumb has been to set the fishing mortality rate (F) approximately equal to the assumed natural mortality rate (M), i.e., $F=M$. Gulland's potential yield estimate of $MSY = \frac{1}{2}MB_0$, where B_0 is the estimated unfished abundance, is roughly equivalent to this policy if B_{MSY} is assumed to be $\frac{1}{2} B_0$ as in a Schaefer or logistic model. A precautionary approach would be to reduce the fishing intensity from this level to perhaps $F = 75\%M$. If there are other indications of potential vulnerability to overfishing (e.g., fish become available to fishing before they mature, or if recruitment events are rare and widely separated in time), the precautionary reduction in fishing intensity should be greater.

Example 4 -- Catch history and some survey information

This case borders on "data-intermediate," depending on the extent and information content of the survey. Assuming that the species under consideration was not a target of the survey(s), conversion of the survey results to an absolute abundance estimate may be difficult. If the surveys provide a series of tentative abundance indexes, production modeling may be possible. A precautionary approach could be based on the precision (coefficient of variation) of the survey estimate or index, including the calibration procedure. Simulation modeling may provide useful guidance.

Example 5 -- Data are available for only a portion of stock range

Information on oceanic and/or transboundary stocks may be limited to a small portion of the presumed range (e.g., many highly migratory species such as tunas and sharks). It may be possible to draw limited inferences of stock characteristics by analogy or by comparison

with known oceanographic properties. While it is nearly always desirable to engage agencies responsible for other parts of the range, in many cases actual management must be unilateral. Identification and clarification of objectives will provide useful guidance to management. With respect to these objectives, simulation of alternative stock structures and dynamics may help assess risks associated with unilateral management of a portion of the range, and help identify appropriate precautionary adjustments. If the managed portion of the range is small, risk may be low and there may be relatively little need for explicit precaution.

Example 6 -- Short CPUE series lacking contrast

Although it may not be possible to assess the stock quantitatively (e.g., by production modeling), a precautionary approach would be to establish a threshold CPUE below the current level so that a future drop in CPUE would automatically trigger a precautionary management response.

Example 7 -- Peculiar life history

Unusual or peculiar life histories may require added precaution. Often the nature of the risk can be inferred logically, but is difficult to quantify. The demographic structure of protogynous hermaphrodites such as groupers can easily be disrupted by exploitation, especially if the large males are preferred fishing targets. In California, a fishery for sheep crab (family Majidae, the spider crabs) claws poses another unusual life history problem: These crabs undergo a terminal molt, and adults cannot regenerate a lost claw, posing a risk of decreased survival and/or reproduction of clawless crabs returned to the water.

Example 8 -- New fishery

Planned fishery development should incorporate an objective of generating the information necessary for managing the resource. This includes not only fundamental data collection, but also a controlled pace of development that is sufficiently slow that optimal fishing rates and abundance levels can be estimated before those levels have already been exceeded, i.e., to avoid overshooting MSY. "Fishing down" of the standing stock provides a large windfall yield that is not sustainable, and can create false expectations of continuing high harvest levels, especially for long-lived species. A simple rule-of-thumb, based on the potential yield estimate described above in Example 3, is that the ratio of windfall to maximum sustainable yield is equal to $1/M$, i.e., $MSY = \frac{1}{2}MB_0$, and $Windfall = \frac{1}{2}B_0$, so $Windfall/MSY = 1/M$. For a species with $M=0.1$, fishing down of the virgin stock will yield a one-time harvest tenfold greater than the annual sustainable yield. Even if this

windfall harvest were spread over ten years, those ten years would see average harvest levels substantially greater than the sustainable levels that must eventually support the fishery.

Traditional fishery management provisions such as size limits and closed areas and/or seasons may be useful auxiliary tools to assure that sufficient precaution is taken in development of a new fishery.

Recommendation

Stock assessment is the first element of precaution, and an attempt at assessment must be made whatever the level of available information. This includes qualitative stock assessments based on little more than expert opinion, if that is all that can be done. A large fraction of the nation's fish resources have never been assessed. A nationwide effort should be made to assess all stocks under federal management.

Report of the "Multi-species" Working Group

Chair: Wendy L. Gabriel

Multispecies Aspects addressed in the Magnuson-Stevens Fishery Conservation and Management Act

The Act's requirements to prevent overfishing are not restricted to commercial species. Recreational and subsistence fisheries are also affected and must be managed to achieve optimal yield. The requirement to minimize bycatch (fish harvested in a fishery but not sold or kept for personal use) extends to all fisheries.

The MSFCMA includes the importance of a variety of multispecies effects within an ecosystem context. Within the Act, the definition of "optimum", with respect to yield from a fishery, is the amount of fish which provides the greatest overall benefit to the Nation, taking into account the protection of marine ecosystems.

Precautionary advice must thus consider the impacts of fisheries on non-target species including discard species and forage species; as well as short-term and long-term ecosystem effects. Characteristics such as species composition and diversity (and its variance) consequently become important in the ecosystem context.

Prevention of Overfishing in the Multispecies Context

National Standard Guidelines

The draft National Standard Guidelines allow ex-

ceptions to the requirement to prevent overfishing in the case of a mixed-stock complex. If one species in the complex is harvested at OY, overfishing of other components in the complex may occur if 1.) long-term net benefits to the Nation are obtained and 2.) similar long-term net benefits cannot be obtained by modification of fleet behavior or gear characteristics or other operational characteristics to prevent overfishing and 3.) the resulting fishing mortality rate will not cause any species or ecologically significant unit to require protection under the ESA, or any stock or stock complex to fall below its minimum stock size threshold¹. Thus, the fishing mortality rate for a stock in a mixed-stock fishery may exceed the limit rate if this will not cause the stock to fall below a.) $\frac{1}{2} B_{MSY}$, or b.) the minimum size at which rebuilding to the MSY level would be expected to occur within 10 years (if the stock were exploited at the limit fishing mortality rate), whichever biomass level is larger.

Precautionary Implications

When co-occurring species are harvested simultaneously by the same gear type, a single level of fishing effort may give rise to a wide variety of different fishing mortality rates on individual stocks. This is because catchability (vulnerability) of each co-occurring species by the gear type is likely to be different.

When more than one stock in the complex becomes fished at rates above their limits, especially when rates are substantially above limits, the risk of falling below biomass limits may increase for several species; and in a precautionary context, control rules which reduce the risk to the complex should be implemented, to prevent the need for rebuilding multiple overfished stocks.

The discussion group noted that aggregate TACs were not precautionary. The National Standard Guidelines provide for specification of a fishery-wide OY for a mixed-stock fishery, where management measures for separate harvest levels for individual stocks may be specified, but are not required. Although the guidelines recommend that the sum of individual target levels be less than fishery-wide OY, if individual OY levels are not specified and the entire OY could be removed from one or few unproductive stock components, overfishing of those components could occur: under those circumstances, a precautionary approach should be used minimize the risk of successive removals of the least productive components in the mixed-stock fishery. Management to prevent overfishing of the least productive components will afford significant protection to marine ecosystems in terms of maintaining species di-

versity, and associated species interactions including trophic structure.

Recommended Precautionary Control Rule for Multispecies Fisheries

Precautionary management of a multispecies complex must be based on the harvest control rules which applies to the least productive, weakest or least resilient stocks in the complex.

If a single species in the complex is being maintained at its optimum yield, then individual species biomasses of other species in the complex must each be greater than the established minimum stock size threshold (MSST) for each individual species. It must be possible to rebuild each individual stock to B_{MSY} in 10 years or less (at $F = F$ to rebuild). B_{MSY} in this context refers to B_{MSY} for the individual stock, not an aggregate for the complex.

Data-Poor Situations

In some multispecies fisheries, there may be a large amount of information about population dynamics and status of principal (e.g., target commercial or recreational) species, but relatively little may be known about some or most of the species within the complex. Most fisheries are in fact multispecies fisheries when the impacts on non-target organisms are taken into account. The most precautionary harvest control rules would be expected for species with the least information. Consequently, harvest control rules for data-poor species can drive the management of the entire complex, when management is precautionary.

Because precautionary management applies to non-target as well as target species, catches and harvest control rules for species which are always discarded could result in management of the complex based on the status of bycatch species or non-target species. However, National Standard 9 requires that "*Conservation and management measures shall, to the extent practicable, (A) minimize bycatch, and (B) to the extent bycatch cannot be avoided, minimize the mortality of such bycatch.*" National Standard 9 always applies, and may mitigate the impacts on non-target organisms.

The discussion group recommended that observer programs be established to measure discards. In addition, research is needed to determine the impacts of cryptic mortality on fish stocks. Indirect impacts may be significant, and there may be non-fishery effects which are not accounted for, including predator-prey interac-

¹In the final rule National Standard Guidelines, the third criterion is modified so that the only condition is that the resulting fishing mortality rate will not cause any species or ecologically significant unit to require protection under the ESA, with no other restrictions on exceeding limit rates.

tions, competition, evolutionary interactions, and effects of changing habitats.

Conclusions

The first line of defense in precautionary management of multispecies complexes is to change selectivity for species near their individual minimum stock size thresholds. The overall management basis for the complex is thus less affected by species near those thresholds. If it is not possible to change the selectivity for the weakest species in the complex, then change affecting all species must be implemented.

The status of the “weakest” species determines the imposition of management actions. The law does not discriminate among commercially important species and other species. If biomass or fishing mortality rates for any species fall outside the individual harvest control rule for that species, then management action is implemented which could affect fishing activity for other species in the complex.

Biological reference points (or proxies) and harvest control rules for each stock in the mixed-stock complex should be developed, even though information may be limited. In order to prevent irreversible changes in species composition or diversity, the fishing mortality rate should not exceed the limit for any individual stock in a mixed-stock complex; the precautionary target control rule for that individual stock should apply. Similarly, if values of indices fell below precautionary target biomass levels (or their proxies or other buffer-type values above the limit, where estimates of fishing mortality rates were unavailable), then the precautionary target control rule would apply. The relevant control rule should be implemented regardless of the level of information from which the rule was developed. This should lessen the possibility of reducing less-productive stocks to levels at which they would require protection under the ESA, especially if relatively little were known about those stocks.

Annex A

List of Participants

Frank Almeida (NEFSC)	Steven Murawski (NEFSC)
David Au (SWFSC)	James Nance (SEFSC)
James Balsiger (AKFSC)	Kim Newlin (SEFSC)
Norman Bartoo (SWFSC)	Loretta O'Brien (NEFSC)
James Bohnsack (SEFSC)	Mauricio Ortiz (SEFSC)
Craig Brown (SEFSC)	William Overholtz (NEFSC)
Steven Cadrin (NEFSC)	Graeme Parkes (MRAG)
Mark Chandler (OST)	Michael Parrack (SEFSC)
Alex Chester (SEFSC)	Donald Pearson (SWFSC)
Ramon Conser (NWFSC)	Clay Porch (SEFSC)
Jean Cramer (SEFSC)	Jennifer Potts (SEFSC)
Paul Crone (NWFSC)	Joseph Powers (SEFSC)
George Darcy (OSF)	Michael Prager (SWFSC)
Gerard DiNardo (SWFSC)	Eric Prince (SEFSC)
Peter Eldridge (SERO)	Paul Rago (NEFSC)
Mark Farber (SEFSC)	Alvin Rainosek (OSF)
Michael Ford (NWFSC)	Victor Restrepo (OST, UM)
Charles Fowler (NMML)	Jean Rogers (NWFSC)
William Fox (OST)	Patricia Rosel (NOS)
Wendy Gabriel (NEFSC)	Andrew Rosenberg (NERO)
E. Spencer Garrett (OSF)	Gary Sakagawa (SWFSC)
Stratis Gavaris (DFO)	Michael Schirripa (SEFSC)
Hannah Goodale (NERO)	Gerald Scott (SEFSC)
Wayne Haight (SWFSC)	Fred Serchuk (NEFSC)
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Alec MacCall (SWFSC)	Usha Varanasi (NWFSC)
Pamela Mace (SEFSC)	Douglas Vaughan (SEFSC)
Gary Matlock (OSF)	John Ward (OST)
Richard Merrick (NEFSC)	Gordon Waring (NEFSC)
Richard Methot (NWFSC)	Susan Wigley (NEFSC)
Michael Mohr (SWFSC)	Thomas Wilderbuer (AKFSC)
Chris Moore (MAFMC)	John Witzig (OST)

AKFSC: NMFS Alaska Fisheries Science Center
DFO: Canada Department of Fisheries and Oceans
MAFMC: Mid-Atlantic Fishery Management Council
MRAG: Marine Resource Assessment Group - Americas, Inc.
NEFSC: NMFS Northeast Fisheries Science Center
NERO: NMFS Northeast Regional Office
NMML: NMFS National Marine Mammal Lab
NOS: NOAA National Ocean Service Lab

NWFSC: NMFS Northwest Fisheries Science Center
OSF: NMFS Office of Sustainable Fisheries
OST: NMFS Office of Science and Technology
SEFSC: NMFS Southeast Fisheries Science Center
SERO: NMFS Southeast Regional Office
SWFSC: NMFS Southwest Fisheries Science Center
UM: University of Miami
UW: University of Washington

ANNEX B

WORKSHOP AGENDA

Tuesday, February 24

- 8:30 Welcome. *J. Powers*
- 8:35 Introduction. *V. Restrepo*
- 8:45 The Need for Guidance on the Precautionary Approach and the Proposed National Standard Guidelines. *G. Matlock*
- 9:10 The Role of Science in Applying The Precautionary Approach to the MSFMCA. *W. Fox*
- 9:35 Evolution, Scope, and Current Applications of the Precautionary Approach in Fisheries. *P. Mace and W. Gabriel*
- 10:00 Break
- 10:30 How can Managers use Precautionary Management Advice? *A. Rosenberg*
- 10:55 Socioeconomics and the Precautionary Approach. *J. Ward*
- 11:20 Nature's Monte Carlo Experiments in Sustainability. *C. Fowler*
- 11:45 Incorporating Uncertainty in the Management of Marine Mammals. *B. Taylor*
- 12:10 A Conceptual Framework for the Implementation of the Precautionary Approach to Fisheries Management within the Northwest Atlantic Fisheries Organization. *F. Serchuk, D. Rivard, J. Casey, and R. Mayo*
- 12:35 Lunch Break
- 13:45 CCAMLR's Application of the Precautionary Approach. *G. Parkes*
- 14:10 A Review of Biological Reference Points in the Context of the Precautionary Approach. *W. Gabriel and P. Mace*
- 14:35 Optimizing Harvest Control Rules in the Presence of Natural Variability and Parameter Uncertainty. *G. Thompson*
- 15:00 A Precautionary Approach to Fishery Control Rules Based on Surplus Production Modeling. *S. Cadrin*
- 15:25 Break
- 15:55 Requirements for Recovering Fish Stocks. *J. Powers*
- 16:20 Alternative Ways to Evaluate Risk in Data-poor and Hypothesis-rich Situations. *J. Ianelli*
- 16:45 Dealing with Bias in Estimating Uncertainty and Risk. *S. Gavaris*
- 17:10 Use of Stock-Recruit Data in Estimating Biological Reference Points. *W. Overholtz*
- 17:35 Adjourn

Wednesday, February 25

- 8:30 Proposed Changes in the Overfishing Definition for Pacific Salmon. *R. Kope*
- 8:55 Some Considerations of Behavior, Life History and Recruitment Variability. *A. MacCall*
- 9:20 Patterns of Population Variability in Marine Fish Stocks, with Application to Precautionary Rebuilding Projections of the Georges Bank Haddock. *P. Spencer and J. Collie*
- 9:45 The Application of Precautionary Principles to the Northwestern Hawaiian Island Lobster Fishery: Life in the Trenches. *G. DiNardo*
- 10:10 Using the Precautionary Approach to Control Deleterious Effects of Artificial Propagation on Natural Populations. *M. Ford and S. Waples*
- 10:35 Break
- 11:05 Impacts of Demographic Variation in Spawning Success on Biological Reference Points. *S. Murawski, P. Rago, and E. Trippel*
- 11:30 Discussion of Tasks for Breakout Groups. *R. Methot*
- 12:00 Lunch Break
- 13:15 Breakout Group Meetings
- 17:30 Adjourn

Thursday, February 26

- 9:00 Depletion Estimators of Survey Catchability: Theory and Field Experiments. *P. Rago, C. Weidman, and J. Weinberg*
- 9:25 Incorporating No-Take Marine Reserves into Stock Assessment. *J. Bohnsack*
- 9:50 Ideas for a Stock Assessment Toolbox. *J. Witzig, S. Murawski, and G. Swartzman*
- 10:45 Break
- 11:15 Group 1 Report. *G. Thompson*
- 11:45 Group 2 Report. *R. Methot*
- 12:15 Lunch Break
- 13:30 Group 3 Report. *A. MacCall*
- 14:00 Group 4 Report. *W. Gabriel*
- 14:30 Plenary Discussion on Precautionary Advice
- 15:30 Open Discussion
- 15:45 Adjourn