Defining Overfishing—Defining Stock Rebuilding

Report of the Second Annual National Stock Assessment Workshop

La Jolla Laboratory
Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
La Jolla, California
March 31 - April 2, 1992

Andrew A. Rosenberg (Editor)

U.S. Department of Commerce
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July 1993
NOAA Tech. Memo. NMFS-F/SPO-8

U.S. Department of Commerce
Ronald H. Brown, Secretary
National Oceanic and Atmospheric Administration
D. James Baker, Under Secretary for Oceans and Atmosphere
National Marine Fisheries Service

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[1] N.i. = paper presented at the meeting, but summary not included here.

Session III: Developing Advice for Stock Rebuilding Programs

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Introduction

The National Marine Fisheries Service (NMFS), NOAA, convened its second annual National Stock Assessment Workshop at the La Jolla Laboratory, Southwest Fisheries Science Center, La Jolla, Calif., at the end of March 1992. This workshop was intended to bring together NMFS scientists from around the country to discuss major issues in the assessment of living marine resources and the provision of scientific advice for their management. Sixty-five scientists from all regions of the country attended the meeting to discuss the theme, "Defining Overfishing—Defining Stock Rebuilding." This Technical Memorandum summarizes the discussions and includes three overview papers prepared by invitation of the conveners to open discussion in each of the main sessions. In addition, summaries of many of the contributed papers are included to highlight the range of research being conducted in this area.

Defining threshold and target levels for exploitation of living resources is an important component of the scientific advice NMFS scientists are called upon to provide to resource managers. A wide range of approaches have been taken around the country, and both the background information used for developing definitions of overfishing and the form of the definitions varies by region. Our discussions at this workshop were fruitful. While a number of papers focused on what had been done and what justification was used for recommending a definition of overfishing or a rebuilding program, our discussions considered where we should go in the future. There was clearly a strong consensus that we could improve our advice on management strategies by recommending more comprehensive overfishing definitions and rebuilding schemes, rather than employing the simple targets and thresholds currently in place in most areas. There is room within the present guidelines to expand and develop advice on harvesting strategies, and, in fact, this has already been done in a number of regions.

I believe that the workshop was a success, both for the substantive group discussions that we held and for the opportunity for scientists throughout NMFS to get together and talk more informally about the work in which we are all engaged. This workshop was organized by a Steering Committee representing all NMFS Fisheries Science Centers (FSC's): V. Anthony (NEFSC), D. DeMaster (SWFSC), J. Powers (SEFSC), D. Somerton (AFSC), and M. Schiewe (NWFSC), with R. Kope (SWFSC) and A. Rosenberg (NMFS HQ) as co-conveners. I would particularly like to thank Keith Sainsbury from Australia's CSIRO for attending the meeting, preparing an overview paper, and taking a leading role in the discussions unhindered by the mangling of his slides after a long trip, tourist class. I also thank Alec MacCall, Steve Swartz, and George Darcy for their hard work on the other two overview papers. Finally, I would like to thank, for all the workshop participants, the SWFSC staff for their hospitality and assistance in La Jolla and particularly Alice West for her hard work in organizing 65 unruly scientists.

A. A. Rosenberg
Co-convener

Session I: Criteria for Defining Recruitment Overfishing for Fish and Marine Mammals

Session I Summary

Moderator: David Somerton, AFSC
Rapporteur: Robert Kope, SWFSC

A. Rosenberg presented a survey of overfishing definitions presently incorporated into fishery management plans (FMP). He classified each according to type of definition, assessment method for the stock, quality of life-history data, basis for the definition, and degree of conservatism of the definition. Of the 95 overfishing definitions surveyed, the majority (68) define overfishing in terms of fishing mortality rate and 64 of these are expressed as spawning biomass or egg production per recruit. A substantial number (46) of the stocks are assessed by age-structured methods with indices and surveys constituting the basis of assessments for another 35 stocks. In general we have good life-history data for most stocks (54) and poor data for only 4 of the stocks. In spite of this, overfishing definitions for a majority of stocks (67) are based on analogy to other stocks with similar life histories. Even for the stocks assessed by age-structured methods, 26 out of 46 definitions are based on analogy. For stocks where the conservatism of the overfishing definition could be evaluated (76 stocks), 40 definitions appear cautious or conservative, 33 appear risk neutral, and only 3 appear to be inherently risky.

S. Swartz then presented a review of the definition of depletion and methods of assessing stock status for marine mammals. He noted the differences between marine mammals and fishes in terms of data availability and management objectives. Operationally, marine mammal populations are considered depleted when they are below the maximum net productivity level (MNPL) for the population. For most marine mammal populations MNPL appears to be very close to the pristine population level, or K. This contrasts with most fish populations where maximum productivity typically occurs at something less than half of the pristine population level. Assessment and monitoring methods also differ from fisheries owing to the protected status of marine mammals. Assessments rely on survey data and comprise back-calculation of population histories from life-history data and removals, dynamic response methods for populations with adequate data, or the default assumption that populations are near carrying capacity if human impacts are insignificant and assessment data are lacking.

Contributed Papers

R. Methot described the development of overfishing definitions for Pacific groundfish as defining overfishing in the same terms as the management target for groundfish with a buffer between the target and the threshold for overfishing. Overfishing was defined for key species only, with the assumptions that these species experienced higher fishing mortality than other groundfish in the complex, F_{opt} does not differ significantly for most species, and protecting target species will protect the entire complex. The fishing mortality rate, $F_{35\%}$, that reduces spawning biomass per recruit (SPR) to 35% of pristine level was chosen as a harvest guideline, based on the work of Clark (1991). Overfishing was defined as fishing that reduces relative SPR to 20% or less of the unfished level. Methot also reviewed the status of major west coast groundfish fisheries relative to harvest guidelines and overfishing definitions.
F. Serchuk reviewed the history and development of the advice provided by the Advisory Committee on Fishery Management (ACFM) to the Northeast Atlantic Fisheries Commission

on stock status. In the 1980's, the ACFM defined a series of stock categories based on the status of the stocks. Advice currently provided by the ACFM differs in that now, for each stock, a threshold referred to as the minimum biologically acceptable level (MBAL) is defined below which the probability of poor recruitment increases. Stocks are now classified as either below MBAL or expected to be so in the near future, not in imminent danger of falling below MBAL, or the status of the stock cannot be precisely assessed. In addition to stock status, a number of biological reference points are calculated and reported including F_{max}, $F_{0.1}$, F_{high}, F_{med}, and F_{low}.

G. Thompson presented his results obtained from an analytical model. Thompson argued that overfishing as defined in 50 CFR Section 602 cannot occur unless there is depensation in the production function. He claimed that without depensation a stock can always rebound, and the long-term productive capacity cannot be impaired. He developed a model based on a generalized Beverton-Holt stock recruitment relationship with depensation. His analysis of the model indicated that thresholds of approximately 20% of pristine stock biomass or 30% relative SPR served to safeguard against overfishing over a broad range of values of the depensation parameter in the model.

P. Goodyear presented an evaluation of F_{med} based on simulation results. He observed that the plot of stock and recruitment data used to compute F_{med} contains no explicit information about fishing mortality. Goodyear developed a simulation model using a Ricker stock recruitment relationship to generate simulated stock-recruit data for the computation of F_{med}. He simulated fishing mortality with both random variability and systematic change. Results indicated that F_{med} provides an accurate estimate of the average fishing mortality rate over the period of record when fishing mortality is stationary and the stock is in quasi-equilibrium. When fishing is nonstationary, F_{med} is influenced by the history of fishing mortality.

M. Prager advocated the use of production models because they include population response, are easy to use and explain, use simple MSY for a management goal, and have minimal data requirements. Using a logistic type Schaefer model, Prager stressed the versatility of production modeling by pointing out that the approach can include internal age structure, be applied to multiple fisheries, be tuned to a biomass index, accumulate residuals in effort, and provide bootstrap estimates of variance. He demonstrated how production modeling can provide a cohesive picture of the history of a fishery with an application to yellowfin tuna data.

Discussion

Much of the discussion focused on the distinction between "overfishing" and "overfished." For most stocks managed under fishery management plans (FMP), overfishing has been defined in terms of fishing mortality rate without reference to stock abundance. National Standard 1 of the Magnuson Fishery Conservation and Management Act (MFCMA) requires that "Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimal yield from each fishery for the United States fishing industry." To implement Standard 1, the 602 guidelines (50 CFR Section 602) specify in §602.11 (c) (1) that "Overfishing is a level or rate of fishing mortality that jeopardizes the long-term capacity of a stock or stock complex to produce MSY on a continuing basis. Each FMP must specify, to the maximum extent possible, an objective and measurable definition of overfishing for each stock or stock complex covered by that FMP, and provide an analysis of how the definition was determined and how it relates to reproductive potential." These statements were interpreted by some workshop participants as requiring overfishing to be defined as a fishing mortality rate.

However, §602.11 (c) (2) states: "The definition of overfishing may be developed or expressed in terms of a minimum level of spawning biomass ("threshold"); maximum level or rate of fishing mortality; or formula, model, or other measurable standard designed to ensure the maintenance of the stocks' reproductive capacity." This clearly allows much latitude in the formulation of overfishing definitions. In addition, §602.11 (c) (6) identifies actions that must be taken by the Council when the stock is in an "overfished condition." This subsection, and subsequent requirements for rebuilding programs and reducing fishing mortality when stocks are at low levels, imply that there is a need to identify some threshold level of stock abundance in an FMP below which a stock is considered to be overfished or depleted.

Rate vs. Biomass

A number of workshop participants expressed concern that defining overfishing in terms of mortality rate does not take account of the status of the stock. The intent of the 602 guidelines was to prevent stocks from becoming depleted and to clarify the need to rebuild stocks that are depleted. V. Anthony argued that defining overfishing in terms of fishing mortality skirts the issue and does not force action to rebuild stocks when they become depleted. P. Mace pointed out that defining overfishing in terms of a rate allows other stocks with similar life histories to be used as analogies whereas biomass levels need to be assessed for each individual stock. R. Parrish pointed out that, for monitoring purposes, it makes little difference whether overfishing is defined in terms of mortality or biomass because fishing mortality is effectively the ratio of catch to biomass. Thus the precision of estimates of F and biomass are comparable.

A. Rosenberg noted the preponderance of rate-based overfishing definitions based on analogy even though good life-history data and age-structured assessments are often available. W. Overholtz recommended that all available data should be used in formulating overfishing definitions. Mace reported that she and M. Sissenwine have an extensive review of biological reference points for assessed stocks in preparation.

Target vs. Threshold

Some concern was expressed that a number of overfishing definitions are specified or interpreted as management targets rather than as limits beyond which fisheries should not pass. In some cases it may be appropriate for management targets to coincide with thresholds, but in most cases targets should be set well away from threshold levels. A number of suggestions about management thresholds were proposed. L. Jacobson and Rosenberg suggested that management targets could be expressed as fishing mortality rates with thresholds in terms of biomass. S. Murawski suggested that rather than a single threshold, multiple thresholds triggering suites of management measures could be employed. B. Brown argued that multiple options allow room for indecision and inaction on the part of councils in implementing measures to rebuild stocks. Threshold definitions should also take into account monitoring imprecision and the risk due to environmental variability. R. Methot and Overholtz both pointed out difficulties in applying thresholds to stock complexes.

Defining Overfishing vs. Guiding Recovery

Defining overfishing is simply providing a dichotomous classification: either a stock is overfished or it isn't. If a stock is considered overfished, the 602 guidelines require that action be taken to rebuild the stock, but there is some ambiguity about what those actions should be. §602.11 (c) (6) requires that an FMP must contain measures to prevent overfishing and to rebuild stocks that are in an overfished condition. Some workshop participants felt that these measures should be incorporated into the definition of overfishing. An overfishing definition could, in effect, explicitly specify how harvest must be reduced as a stock approaches an overfished condition, and what constraints on harvest are needed when the stock is in an overfished condition.

Control Laws

K. Sainsbury observed that avoiding overfishing, or rebuilding an overfished stock, is a policy objective. To achieve an objective we need to describe a management route in terms of observable measures as a means of getting there. What we may be talking about is a control law relating fishing mortality rate to stock biomass (Fig. 1.1a). The control law may or may not contain a biomass threshold below which no fishing is allowed, and it may increase or level off at some target fishing mortality rate as stock biomass increases (Fig. 1.1b).

In the ensuing discussion, approaching overfishing definitions as control laws was generally viewed favorably. It was recognized that a control law should probably be a continuous function of stock biomass. If abrupt changes in management policy occur at critical points or threshold levels of stock biomass, then when a point estimate of biomass is near a threshold, too much attention will be focused on which side of the threshold the stock is on and how much confidence can be placed in the biomass estimate. If the control law is a smooth function, then small changes in stock biomass can only produce relatively small changes in management policy, rather than large quantum changes. These changes in degree are more likely to be accepted and less likely to result in unproductive contention over point estimates of stock size relative to the threshold. Figure 1.1b incorporates these ideas. The target fishing mortality rate is indicated as a function of the abundance of the stock. At healthy stock levels, this harvest rate is constant and the catches vary appropriately. At abundance levels below the healthy range, the target fishing mortality rate decreases proportionately to stock size. Note that this applies whether the stock is in a rebuilding phase or is in the early stages of being overfished. There is a clear threshold stock abundance where fishing is halted. Along with the target rate, there is also a threshold fishing mortality rate, beyond which, at any given stock level, overfishing is clearly defined. Crossing this threshold implies fishing should be immediately reduced.

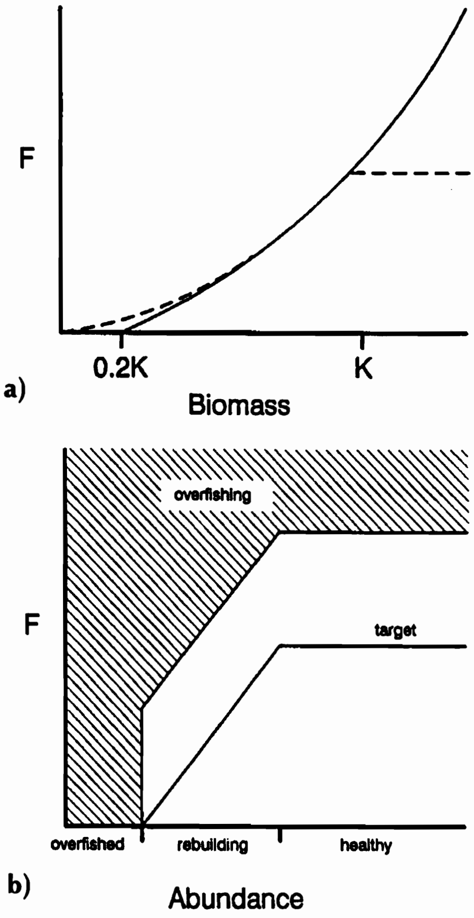

Figure 1.1.— a) Example control laws which specify fishing mortality rate (*F*) as a function of stock biomass. b) Example control law indicating the difference between fishing mortality rates and threshold rates for different stock conditions.

T. Smith suggested that we should be focusing on evaluating the performance of different control laws, and Methot pointed out that performance of control laws will depend entirely on the assumed dynamics of the stock at low levels. In effect, this is what the NMFS Risk Assessment Working Group will be investigating and reporting on in the future.

Overview Paper: The Scientific Basis for Definitions of Overfishing in the United States

Andrew A. Rosenberg, Steven Swartz, and George C. Darcy
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Introduction

Formulation of quantitative definitions of overexploitation is an important step in the development of living marine resource management plans. Conceptually, the goal is to determine a stock level and/or rate of harvesting which, if surpassed, will jeopardize the long term capacity of the resource to renew itself. To develop a quantitative definition requires constructing an underlying population model and collecting as long a time series as possible on the dynamics of the population under harvesting.

In the United States, the development of overfishing definitions for commercially and recreationally valuable fish and invertebrates has been prompted by the enactment of the Magnuson Fishery Conservation and Management Act of 1976 (MFCMA) and its amendments. The subsequent development of the 602 guidelines (Code of Federal Regulations, 50 CFR, Part 602, July, 1989), for the preparation of fishery management plans, requires that such a definition be incorporated into each fishery management plan (FMP) before approval by the regulatory authority, the U.S. Department of Commerce.

For marine mammal stocks, the Marine Mammal Protection Act of 1972 (MMPA), as amended, requires that populations be maintained at or above the optimum sustainable population (OSP), defined as the abundance of animals which will result in the maximum productivity of the population with respect to the carrying capacity of the habitat and the state of a given ecosystem. The National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (FWS) are responsible for monitoring marine mammal resources and developing regulations for their protection. They have interpreted this definition to mean a population size that falls within a range from the population level that is the largest supportable within the ecosystem, to the level that results in the maximum net productivity or greatest net annual increment in population numbers or biomass.

In this paper we review the definitions of overfishing that have been approved for various stocks of marine fish, invertebrates, and mammals in the United States. We describe the underlying scientific basis for the definitions and attempt to qualitatively evaluate whether each definition is likely to be conservative in protecting the resource.

Overfishing Definitions for Exploited Fish and Invertebrates

To date, 95 stocks of fish and invertebrates managed under federal fishery management plans (FMP's) administered by the NMFS have approved definitions of overfishing (Table 1.1). These stocks are from all regions of the country and are managed under a wide variety of regulations. Here, we are only concerned with the definition of overfishing within each FMP. Many FMP's contain several stocks (Table 1.1). The information tabulated for each stock includes the approved definition, the type of definition, the type of stock assessment providing basic population data, a qualitative judgment of the availability of life-history data for the animals, the basis for the definition, and a judgment of how conservative the definition is likely to be for that stock. Each of these columns will be described in detail below.

Table 1.1.—Definitions of overfishing in Federal FMP's for U.S. fish and shellfish resources. Entries are described in the text.

FMP	Case	Stock	Definition	Type	Assessment	Life history	Basis	Conservative
American Lobster	1	Gulf of Maine &	10% EPR Georges Bank— Southern NE lobster	F	Index	good	Analogy	Neutral, current level of EPR probably 5-7%
Northeast Multispecies	2	Gulf of Maine haddock	20% SPR	F	Index	good	Analogy	Risky, given Georges Bank definition and current stock level
	3	Gulf of Maine cod	20% SPR	F	Age structured	good	Analogy	Conservative, other cod stocks 6.8%, assessed 8.4%
	4	Gulf of Maine winter flounder	20% SPR	F	Index	fair	Analogy	Neutral, Other flatfish 14.5%
	5	Gulf of Maine witch flounder	20% SPR	F	Index	fair	Analogy	Neutral, Other flatfish 14.5%
	6	Gulf of Maine American plaice	20% SPR	F	Index	fair	Analogy	Neutral, Other flatfish 14.5%
	7	Gulf of Maine redfish	20% SPR	F	Index	good	Analogy	Unknown
	8	Georges Bank haddock	30% SPR	F	Age structured	good	Estimated	Neutral, other gadoids 25.7%, assessed 20.6%, but recent data indicate much higher SPR needed
	9	Georges Bank cod	20% SPR	F	Age structured	good	Analogy	Conservative, Other cod 6.8%, assessed 11.9%
	10	Georges Bank yellowtail flounder	20% SPR	F	Age structured	good	Analogy	Neutral, Other flatfish 14.5%, assessed 14.2%, stock size low
	11	Georges Bank winter flounder	20% SPR	F	Index	fair	Analogy	Neutral, Other flatfish 14.5%
	12	Georges Bank witch flounder	20% SPR	F	Index	fair	Analogy	Neutral, Other flatfish 14.5%
	13	Georges Bank American plaice	20% SPR	F	Index	fair	Analogy	Neutral, Other flatfish 14.5%
	14	Southern New England yellowtail flounder	20% SPR	F	Age structured	good	Analogy	Neutral, Other flatfish 14.5%, assessed 10.3%, stock size low
	15	Southern New England winter flounder	20% SPR	F	Age structured	fair	Analogy	Neutral, Other flatfish 14.5%
	16	northern silver hake	4 yr average <31% MSP	F	Age structured	good	Estimated	Neutral, other gadoids 25.7%, assessed 30.8%
	17	southern silver hake	4 yr average <42% SPR	F	Age structured	good	Estimated	Neutral, other gadoids 25.7%, assessed 42.4%
	18	red hake	5 yr ave survey <50% of long-term ave	S	Index	fair	History	Unknown
	19	ocean pout	5 yr ave survey <50% of long-term ave	S	Index	fair	History	Unknown
Mackerel, Squid, and Butterfish	20	Atlantic mackerel	Lowest stock	S	Age structured	good	Estimated	Cautious, long time series w/good recruitment
	21	illex	3 yr ave lowest quartile	S	Index	fair	History	Risky, annual species highly vulnerable
	22	loligo	3 yr ave lowest quartile	S	Index	fair	History	Risky, annual species highly vulnerable
	23	butterfish	3 yr ave lowest quartile	S	Index	fair	History	Unknown
Bluefish	24	bluefish	F msy	F	Index and Production Model	fair	Estimated	Unknown
Summer Flounder	25	summer flounder	F	max F	Age structured	good	Estimated	Cautious, F rep much higher
Spiny Lobster	26	spiny lobster	5% EPR and 3 yr declining recruitment	F&S	Index	fair	Analogy	Unknown
Corals	27	corals	OY = 0 for most	F		poor	Protection	Hopefully!
Gulf of Mexico Reef Fish	28	red snapper	20% SPR	F	Age structured	good	Analogy	Neutral, around average for all stocks
	29	vermilion snapper	20% SPR	F	Index	fair	Analogy	Neutral, around average for all stocks
	30	Nassau grouper	20% SPR	F	Index	fair	Analogy	Neutral, around average for all stocks
Gulf of Mexico Red Drum	31	red drum	20% SPR	F	Age structured	good	Analogy	Neutral, around average for all stocks

Continued on page 8.

Table 1.1.—Continued.

FMP	Case	Stock	Definition	Type	Assessment	Life history	Basis	Conservative
Gulf of Mexico Shrimp	32	brown shrimp	stock <125 M shrimp Nov-Feb	S	Age structured	good	Estimated	Unknown
	33	pink shrimp	stock <100 M shrimp	S	Age structured	good	Estimated	Unknown
	34	royal red shrimp	OY	F	None	poor	Analogy	Unknown
Gulf of Mexico Stone Crabs	35	stone crab	70% EPR	F	Index	good	Estimated	Conservative, keyed to claw production
Coastal Migratory Pelagics	36	king mackerel	>20% SPR as determined by S&S Committee	F	Age structured	good	Analogy	Cautious, flexible based on trend
	37	Spanish mackerel	>20% SPR as determined by S&S Committee	F	Age structured	good	Analogy	Cautious, flexible based on trend
	38	other coastal pelagics	>20% SPR as determined by S&S Committee	F	Index	fair	Analogy	Cautious, flexible based on trend
South Atlantic Snapper–Grouper and Reeffish	39	jewfish	40% SPR	F	Index	fair	Analogy	Cautious, high compared to other stocks, but sex change complication
	40	gag grouper	30% SPR	F	Age structured	good	Analogy	Cautious, sex change complication
	41	scamp grouper	30% SPR	F	Age structured	good	Analogy	Cautious, sex change complication
	42	yellowtail snapper	30% SPR	F	Age structured	good	Analogy	Cautious, sex change complication
	43	gray snapper	30% SPR	F	Age structured	good	Analogy	Cautious, sex change complication
	44	wreckfish	30% SPR	F	Index	fair	Analogy	Cautious, sex change complication
	45	red porgy	30% SPR	F	Age structured	good	Analogy	Cautious, relatively high compared to other stocks
	46	black sea bass	30% SPR	F	Age structured	good	Analogy	Cautious, relatively high compared to other stocks
Caribbean Lobster	47	spiny lobster	20% SPR	F	Index	fair	Analogy	Unknown
Caribbean Shallow Water Reeffish	48	snapper- groupers	20% SPR	F	Index	fair	Analogy	Unknown
Atlantic Red Drum	49	red drum	30% SPR	F	Age structured	good	Analogy	Cautious, relatively high compared to other stocks
Northern Anchovy	50	anchovy	SSB in current and preceding season <50KMT	S	age structured	good	Estimated	Cautious, long history of low exploitation
Western Pacific Crustaceans	51	spiny and slipper lobsters	20% SPR	F	Index and Production Model	fair	Analogy	Unknown
Western Pacific Precious Corals	52	deepwater corals	20% SSB	S	Age structured	good	None	Unknown
Bottomfish and Seamount Groundfish, W. Pacific	53	onaga	20% SSB	S	Survey, production model	fair	Analogy	Unknown
	54	opakapaka	20% SSB	S	Survey, production model	fair	Analogy	Unknown
	55	uku	20% SSB	S	Survey, production model	fair	Analogy	Unknown
	56	butaguchi	20% SSB	S	Survey, production model	fair	Analogy	Unknown
Western Pacific Pelagics	57	swordfish, sailfish, marlins, mahimahi, wahoo	20% SPR or SSB	F or S	Production models	fair	Analogy	Unknown
	58	sharks	35% SPR or SSB	F or S	Production models	poor	Analogy	Unknown
Pacific Coast Groundfish	59	sablefish	20% SPR	F	Age structured	good	Analogy	Neutral, similar to other demersal stocks
	60	Pacific whiting	20% SPR	F	Age structured	good	Analogy	Neutral, similar to other demersal stocks
	61	widow rockfish	20% SPR	F	Age structured	good	Analogy	Neutral, similar to other demersal stocks
	62	yellowtail rockfish	20% SPR	F	Age structured	good	Analogy	Neutral, similar to other demersal stocks
	63	Pacific ocean perch	20% SPR	F	Stock Reduction Analysis	good	Analogy	Neutral, similar to other demersal stocks
	64	shortbelly rockfish	20% SPR	F	Index	fair	Analogy	Neutral, similar to other demersal stocks
	65	bocaccio	20% SPR	F	Age structured	good	Analogy	Neutral, similar to other demersal stocks
	66	canary rockfish	20% SPR	F	Age structured	good	Analogy	Neutral, similar to other demersal stocks
	67	chilipepper rockfish	20% SPR	F	Index	good	Analogy	Neutral, similar to other demersal stocks
	68	jack mackerel	20% SPR	F	Index	good	Analogy	Neutral, similar to other demersal stocks

Continued on page 9.

Table 1.1.—Continued.

FMP	Case	Stock	Definition	Type	Assessment	Life history	Basis	Conservative
	69	ling cod	20% SPR	F	Index	fair	Analogy	Neutral, similar to other demersal stocks
	70	Pacific cod	20% SPR	F	Index	good	Analogy	Neutral, similar to other demersal stocks
	71	dover sole	20% SPR	F	Size structured	good	Analogy	Neutral, similar to other demersal stocks
	72	English sole	20% SPR	F	Age structured	good	Analogy	Neutral, similar to other demersal stocks
	73	petrale sole	20% SPR	F	Index	fair	Analogy	Neutral, similar to other demersal stocks
	74	other groundfish	20% SPR	F	Survey or Index	poor	Analogy	Neutral, similar to other demersal stocks
Ocean Salmon	75	pink	Stock <escapement target for 3 yrs.	S	Age/Size (counts)	good	Estimated	Cautious, long time series but changing habitat
	76	sockeye	Stock <escapement target for 3 yrs.	S	Age/Size (counts)	good	Estimated	Cautious, long time series but changing habitat
	77	chum	Stock <escapement target for 3 yrs.	S	Age/Size (counts)	good	Estimated	Cautious, long time series but changing habitat
	78	coho	Stock <escapement target for 3 yrs.	S	Age/Size (counts)	good	Estimated	Cautious, long time series but changing habitat
	79	chinook	Stock <escapement target for 3 yrs.	S	Age/Size (counts)	good	Estimated	Cautious, long time series but changing habitat
High Seas Salmon	80	pink	Stock <escapement target for 3 yrs.	S	Age/Size (counts)	good	Estimated	Cautious, long time series but changing habitat
	81	sockeye	Stock <escapement target for 3 yrs.	S	Age/Size (counts)	good	Estimated	Cautious, long time series but changing habitat
	82	chum	Stock <escapement target for 3 yrs.	S	Age/Size (counts)	good	Estimated	Cautious, long time series but changing habitat
	83	coho	Stock <escapement target for 3 yrs.	S	Age/Size (counts)	good	Estimated	Cautious, long time series but changing habitat
	84	chinook	Stock <escapement target for 3 yrs.	S	Age/Size (counts)	good	Estimated	Cautious, long time series but changing habitat
Gulf of Alaska/ Bering Sea Groundfish	85	walleye pollock	30% SPR	F	Age structured	good	Analogy	Cautious, estimate similar to F 0.1
	86	Pacific cod	30% SPR	F	Age structured	good	Analogy	Cautious, estimate similar to F 0.1
	87	yellowfin sole	30% SPR	F	Age structured	good	Analogy	Cautious, estimate similar to F 0.1
	88	flathead sole	F msy	F	Index	fair	Analogy	Cautious, estimate similar to F 0.1
	89	Alaska plaice	F msy	F	Index	fair	Analogy	Cautious, estimate similar to F 0.1
	90	rock sole	30% SPR or F msy	F	Index	fair	Analogy	Cautious, estimate similar to F 0.1
	91	arrowtooth flounder	30% SPR	F	Index	fair	Analogy	Cautious, estimate similar to F 0.1
	92	sablefish	30% SPR	F	Stock Reduction Analysis	fair	Analogy	Cautious, estimate similar to F 0.1
	93	Greenland turbot	30%SPR	F	Stock Reduction Analysis	fair	Analogy	Cautious, estimate similar to F 0.1
	94	other groundfish	30%SPR	F	Survey and Production Model, some age structured	fair	Analogy	Cautious, higher than overall average
King and Tanner Crab	95	king and tanner	F msy	F	Index	good	Estimated (as F 0.1)	Cautious, estimated by F 0.1

Definitions

Definition (Col. 4) and Type (Col. 5) in Table 1.1 relate to the type of definition approved for each stock. In Type, the definitions are categorized as either a fishing mortality rate (F), a stock abundance level (S), or both. Most of the definitions (68 stocks) specify a fishing mortality rate that should not be exceeded in order to prevent overfishing (Fig. 1.2), although the rate is chosen based on a variety of criteria. Only a small number of definitions use both a rate and a stock level (3 cases), while for the remaining 24 stocks a minimum stock level is specified.

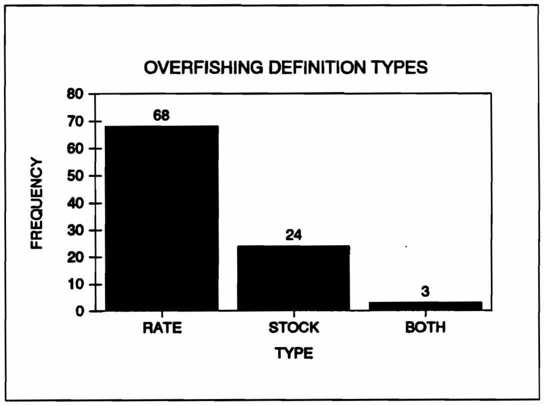

Figure 1.2.—Number of overfishing definitions which specify fishing mortality rates (rate) or minimum spawning stock abundance (stock) or both.

Definitions (Col. 4) are expressed in six different ways throughout the country. The most commonly used type of definition (64 stocks) specifies the minimum spawning biomass per recruit (SPR) or egg production per recruit (EPR) as a percentage of the unexploited level. This type of analysis has been described in detail by Beverton and Holt (1957), Goodyear (1977, 1980, 1989), Sissenwine and Shepherd (1987), and Gabriel et al. (1989) and will not be repeated here. The underlying idea is that an overfishing definition can be expressed as a replacement line (Ricker, 1954) on a diagram of recruitment vs. parent spawning stock (biomass or eggs). The inverse of the slope of this line specifies a level of SPR (or EPR) and, for a given exploitation pattern at age, has a one-to-one correspondence with a fully recruited fishing mortality rate. Therefore, this type of definition relates to the reproductive capacity of the stock, through the stock and recruitment relationship, and to the act of fishing, through the harvest rate. Definitions of this type are used in all regions of the country.

Five stocks (in the U.S. northeast and Alaska) specify a fishing mortality rate corresponding to the maximum sustainable yield level (F_{msy}), and one stock in the northeast uses the rate giving the maximum yield per recruit (F_{max}). The F_{msy} reference point is calculated using surplus production models. F_{max} is used as a proxy for F_{msy}.

A minimum spawning stock biomass (SSB) is used in the definitions for 21 stocks in all regions, sometimes expressed as a percentage of the unexploited virgin biomass. In cases where an absolute level is used, a long time-series of data is required and the definition usually is the minimum observed stock size which resulted in good recruitment.

Like the SPR definitions, an assumption that dynamics are stationary is implicit in specifying a minimum stock biomass, i.e., environmental or biological conditions do not have a trend, improving or degrading, over time and variance does not increase over time. Note that this does not imply the stock is in equilibrium or that recruitment is constant. Considerable annual variability in production is allowed in either type of definition as long as there is no trend. However, SPR definitions may be more tolerant of variations in annual productivity. A definition based on 20% of the unexploited biomass may be violated frequently if recruitment variability is high, whereas recruitment variability has less impact when the definition is based on 20% SPR.

For five stocks in the northeast, an index of relative abundance is used to define overfishing, rather than an absolute abundance measure. In these cases, a running average of survey catch rate is compared to the time series of observations as described above for SSB-based definitions.

Finally, for two stocks where very little biological information is available (Gulf royal red shrimp and corals), the definitions of overfishing are optimum yield, that is maximum sustainable yield as modified by socioeconomic and other factors.

Assessment types

For almost all of the resources managed under FMP's, an assessment of the current and past conditions of stock abundance and harvest rates have been attempted. Estimates of the past production performance of the resource at different stock levels allow a much stronger foundation for developing an appropriate definition of overfishing. Index-based assessments contain a time series of relative abundance information but usually no estimation of harvest rate, biological reference points, or absolute abundance. Production models and stock reduction analyses produce estimates of surplus production in relation to fishing effort, harvest rate, or stock size. Age- or size-structured assessments give detailed estimates of numbers and biomass at age or size along with fishing mortality rate at age or size and, usually, some estimates of biological reference points. Stock and recruitment information can then be used as a measure of productivity. Finally, for Pacific salmon stocks, the stock assessment is based on detailed survey counts of returning spawners. Because of salmon homing behavior and their semelparous life history, these counts can provide quite accurate time series of stock productivity to be used as a basis for overfishing definitions.

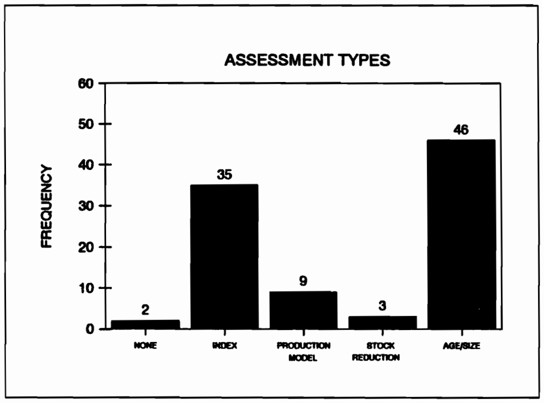

Figure 1.3.—Number of fish and shellfish stocks assessed by different methods. See text for details.

Most of the resources covered by Federal FMP's are assessed using age/size-structured analyses or production modeling approaches (Fig. 1.3). However, a substantial fraction of the stocks have only indices of relative abundance available, and little is known about their productivity. For these resources it is difficult to judge how a particular definition of overfishing might perform in protecting the stock and obtaining the largest feasible yield.

Life history information

The rate of harvest that a population can sustain is closely related to the life history of the animals. Life-history data are used for calculating biological reference points and are intrinsic to developing definitions of overfishing and harvesting policies. They are also some of the first information that is obtained for many species, although this does not necessarily imply that life-history parameters are constant and do not need to be continuously updated.

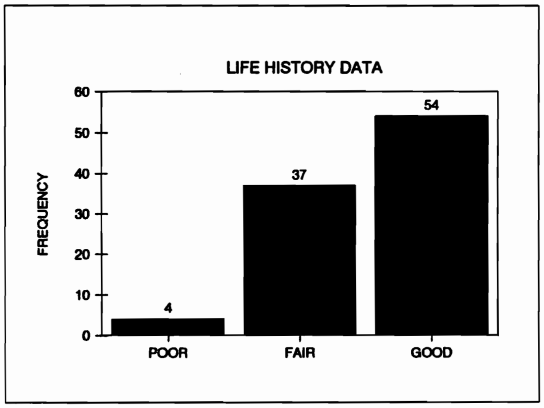

Figure 1.4.—Subjective ratings of the available life-history information for each stock.

For most of the stocks under consideration in this survey, good life-history data, such as size at age, or stock size or age composition, age or size at maturity and recruitment to the fishery, longevity or rough estimates of the rate of natural mortality, were available (Fig. 1.4). There is clearly room for improvement and for updating these data to improve the estimation of biological reference points and definitions of overfishing.

Basis for the definition

Overfishing definitions in this survey were put into four categories according to the types of information upon which they were based (Fig. 1.5). If a direct estimate of the reference point was made for the given stock using, for example, stock recruitment and life-history data, it was classified as "estimated." This category includes stocks where the "estimate" is made in an ad hoc manner by choosing, for example, the lowest stock size that produced good recruitment. Also, stocks where the reference level is not based on stock and recruitment, but on yield per recruit, fall in this category if the reference is estimated from yield-per-recruit-data. If the reference level value was selected by analogy with other similar stocks and from theoretical studies, such as produced by Clark (1991), it was termed "analogy." If a long time series of data on relative abundance, but not explicitly on stock and recruitment, was available for determining a reference level, it was classified as "history," and finally, if there was no obvious basis for the definition, it was categorized as "none."

For most of the stocks, analogy to other species was used as the basis for the definition. This is generally the case for the large number of SPR definitions. In 21 cases, stock and recruitment data have been used directly for estimating the appropriate sustainable harvest rate. In many cases, the analogies should be considered weak at best, since there may be little reason for believing a gadoid has similar productivity to a scombroid. In many instances, even though an age-structured assessment has been performed, there is an insufficient time series of information to estimate the sustainable harvest rate from the stock recruitment data. It should be noted, however, that theoretical work by Goodyear (1989, In press) and Clark (1991) and empirical, comparative work by Mace and Sissenwine (In press) lend substantial support to the definitions most often used. The majority of the SPR definitions are between 20% and 40% of the unexploited level (Fig. 1.5) which accords well with the studies cited above.

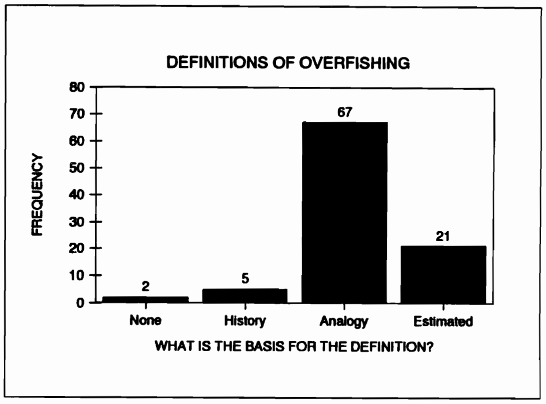

Figure 1.5.—Classification of the underlying basis for each definition. See text for details.

How conservative is the definition?

It is not possible to determine definitively how conservative a given definition will be in the future for protecting the resource from overharvesting. However, there are some indications that can qualitatively suggest that the definition is likely to be safe for the stock. Here, we have compared the overfishing definitions to other similar stocks where more detailed studies of productivity are available. To a large extent, this relies on the sort of comparative study recently compiled by Mace and Sissenwine (In press) where estimates of sustainable harvest rates were made for a large number of fish stocks using stock and recruitment data. In Table 1.1, a definition is considered conservative if it gives a harvest rate well above the threshold replacement level for that stock or other stocks of the same species. Harvesting in accordance with a conservative definition is unlikely to result in recruitment failure or continued stock decline. A definition is classified as cautious if the overfishing level is above the average for similar species. A cautious definition should not lead to a stock decline if it is used as a threshold for setting management measures. A neutral definition is at the estimated threshold replacement level for the stock and is not clearly risky or cautious. A risky definition is not expected to protect the stock in the long term. For some definitions, there is no basis for judging whether they will protect stocks in the long term, and they are classified as unknown.

Figure 1.6 summarizes the classification for the stocks in the table. In most cases, the definitions were judged as neutral or cautious according to the available information on other stocks. However, it should be emphasized that the classifications in Table 1.1 are the subjective evaluations of the authors and are unlikely to represent a consensus of the scientific community. Also when interpreting “conservative,” “cautious,” etc., it is necessary to remember that the yardstick used to make the evaluations — the threshold replacement level — corresponds to a fishing mortality rate that is believed to stress the stock to its limit; i.e., fishing targets should be set well away from these thresholds.

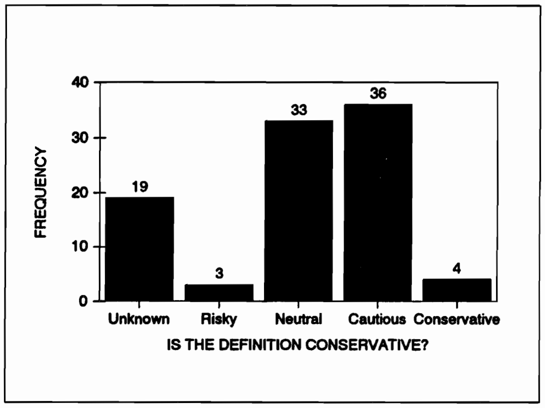

Figure 1.6.—Subjective classification of the conservative nature of the definitions. See text for details.

Depletion of Marine Mammal Populations or Stocks

The Marine Mammal Protection Act (MMPA) established a moratorium on the taking of marine mammals by persons and vessels subject to U.S. jurisdiction and on the importation of marine mammals and marine mammal products into the United States except in certain cases (United States Government, 1972). The Secretary of Commerce may authorize, for example, taking from nondepleted marine mammal species and populations incidental to commercial fishing, although this provision was suspended in 1988 for a period of 5 years. The NMFS is responsible for assessing the status of whale, dolphin, seal, and sea lion populations subject to such takes.

Although marine mammals are not harvested commercially in the United States, 38 species are known to interact with and/or be taken incidentally in commercial fisheries found within the U.S. EEZ. The magnitude of marine mammal/fishery interactions relative to marine mammal populations is difficult to ascertain because most marine mammal populations have not been extensively studied, so data regarding stock size and distribution are not available. Marine mammal status assessments are usually based on data that are incomplete and often provide only minimum estimates of stock sizes. Assumptions regarding the magnitude of the effects of fishery interactions or other perturbations on mammal populations are usually conservative. Estimates of minimum population size are available for about 40% of marine mammal populations that interact with fisheries, while population trend estimates are generally known for only 20% (Fowler and DeMaster, 1991). Table 1.2 gives the current status of 95 stocks or populations of marine mammals in U.S. waters. Of these, the population trend is known for only 29 stocks (Assessment, Table 1.2).

Definitions

The MMPA requires that marine mammal populations be managed at "optimum levels." As amended, it defines the term optimum sustainable population (OSP) to mean, "with respect to any population stock, the number of animals which will result in the maximum productivity of the population or the species, keeping in mind the carrying capacity of the habitat and the health of the ecosystem of which they form a constituent element."

For operational purposes, the NMFS has interpreted this definition to mean "a population size which falls within a range from the population level of a given species or stock which is the largest supportable within the ecosystem to the population level that results in maximum net productivity (MNPL)." Maximum net productivity is defined under the MMPA as "the greatest net annual increment in population numbers or biomass resulting from additions to the population due to reproduction and/or growth less losses due to natural mortality" (50 C.F.R. 216.3). Populations below MNPL are classed as "depleted" under the MMPA, and populations of species that are listed as endangered or threatened under the Endangered Species Act (ESA) are automatically "depleted" as well.

Of the 95 stocks listed in Table 1.2, 65 are of unknown status with respect to the MMPA or the ESA. Only 6 stocks are at or above the optimum sustainable population level. Many of the stocks are endangered or threatened under the ESA (Fig. 1.7), and thus 22 stocks can be considered depleted under the MMPA.

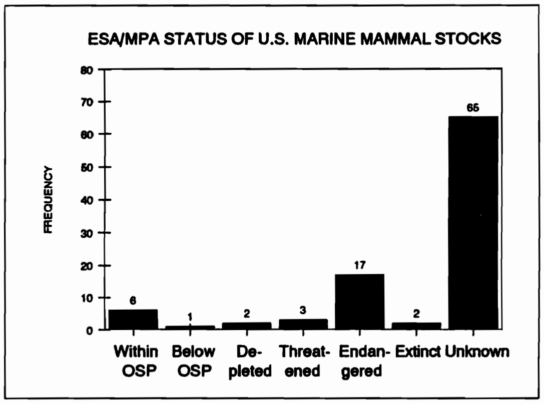

Figure 1.7.—Status of marine mammal stocks in U.S. waters classified under the ESA and MMPA criteria.

Table 1.2.—Marine mammal stocks in U.S. waters: Available information and current status.

Species/ population	Abundance[1] estimate	Assessment[2] basis	Stock[3] definition	Life[4] history	MMPA/ESA[5] status	Population trend
Pacific, Hawaii and Alaska						
Steller sea lion						
Alaska	34,835	Count	Yes	Good	Threatened	Declining
Continental U.S.	5,410	Survey	Yes	Good	Threatened	Declining
California sea lion	110,000	EPC	Yes	Fair	Unknown	Increasing
N. Pacific fur seal						
E. Bering Sea	1,012,000	Survey	Yes	Good	Depleted	Stable
San Miguel	4,000	Count	Yes	Good	Unknown	Increasing
Harbor seal						
Alaska	63,000	Count	Unknown	Poor	Below OSPL	Declining
Puget Sound	10,000	Survey	Unknown	Poor	Unknown	Increasing
Wash./Ore.	28,275	Survey	Unknown	Poor	Unknown	Increasing
California	20,000	Survey	Unknown	Poor	Unknown	Increasing
Guadalupe fur seal	3,000	None	Yes	Poor	Endangered	Unknown
N. elephant seal	60,000	EPC	Yes	Good	Within OSPL	Increasing
Hawaiian monk seal	1,500	Count	Yes	Good	Endangered	Decreasing
Spotted seal	4,000	Survey	Unknown	None	Unknown	Unknown
Bearded seal	Unknown	Unknown	None	Unknown	Unknown	
Ringed seal	Unknown		Unknown	None	Unknown	Unknown
Ribbon seal	Unknown		Unknown	None	Unknown	Unknown
Beaked whales	Unknown	None	Unknown	None	Unknown	Unknown
Beluga whale						
Gulf of Alaska	500	Survey	Yes	Fair	Unknown	Unknown
West Arctic	13,500	Survey	Unknown	Fair	Unknown	Unknown
Rough-toothed dolphin	Unknown	None	Unknown	None	Unknown	Unknown
Common dolphin	269,940	Survey	Unknown	Fair	Unknown	Unknown
Bottlenose dolphin						
Coastal Calif.	240	Survey	Unknown	Fair	Unknown	Unknown
Offshore Calif.	3,875	Survey	Unknown	None	Within OSPL	Unknown
N. right-whale dolphin	Unknown	None	Unknown	None	Unkown	Unknown
P. white-side dolphin						
NE Pacific	207,000	Survey	Unknown	None	Unknown	Unknown
Alaska	14,232	Survey	Unknown	None	Unknown	Unknown
Eastern tropical Pacific dolphins						
N. spotted	1,515,500	Survey	Known	Poor	Unknown	Stable
S. spotted	268,000	Survey	Known	Poor	Unknown	Increasing
E. spinner	589,000	Survey	Known	Poor	Unknown	Stable
White-belly spinner	994,000	Survey	Known	Poor	Unknown	Stable
N. common	468,000	Survey	Known	Poor	Unknown	Stable
Cent. common	594,000	Survey	Known	Poor	Unknown	Stable
S. common	2,118,000	Survey	Known	Poor	Unknown	Stable
N. striped	172,000	Survey	Known	Poor	Unknown	Stable
S. striped	1,314,000	Survey	Known	Poor	Unknown	Stable
Killer whale						
Gulf/S.E. Alaska	286	Count	Yes	Good	Unknown	Unknown
Aleutians/Bering	Unknown	None	Unknown	None	Unknown	Unknown
Continental U.S.	260	Survey	Unknown	None	Unknown	Unknown
Grampus	5,560	Survey	Unknown	None	Unknown	Unknown
False killer whale	Unknown	None	Unknown	None	Unknown	Unknown
Shortfin pilot whale	Unknown	None	Unknown	None	Unknown	Unknown
Harbor porpoise						
California	4,924	Survey	Unknown	Fair	Unknown	Unknown
Wash./Ore.	3,998	Survey	Unknown	None	Unknown	Unknown
Inland Wash.	975	None	Unknown	None	Unknown	Unknown
Alaska	Unknown	None	Unknown	None	Unknown	Unknown
Gulf of California	<300	Survey	Yes	Fair	Endangered	Unknown
Dall's porpoise						
Bering Sea	216,118	Survey	Unknown	Good	Within OSPL	Unknown
NW Pacific	692,854	Survey	Unknown	Good	Within OSPL	Unknown
NE Pacific/GOA	608,000	Survey	Unknown	Good	Unknown	Unknown
Gray whale	21,113	Count	Yes	Good	Within OSPL	Increasing
Humpback whale	2,000	Count	Unknown	Good	Endangered	Unknown
Minke whale	Unknown	None	Unknown	None	Within OSPL	Unknown
Blue whale	1,600	Survey	Unknown	None	Endangered	Unknown
Fin whale	16,625	Survey	Unknown	None	Endangered	Unknown
Sei whale	9,110	Survey	Unknown	None	Endangered	Unknown
Bryde's whale	Unknown	None	Unknown	None	Unknown	Unknown

Continued on page 15.

Table 1.2.—Continued.

Species/ population	Abundance[1] estimate	Assessment[2] basis	Stock[3] definition	Life[4] history	MMPA/ESA[5] status	Population trend
N. right whale	<10	Count	Yes	None	Endangered	Unknown
Bowhead whale	7,500	Count	Yes	Fair	Endangered	Increasing
Sperm whale	930,000	Survey	Unknown	Good	Endangered	Unkown
Atlantic and Gulf of Mexico						
Harbor seal	15,000	Survey	Yes	Fair	Unknown	Increasing
Gray seal	100,000	Survey	Unknown	Fair	Unknown	Increasing
Caribbean monk seal	Extinct	None	Extinct	None	Extinct	Extinct
Beaked whales	Unknown	None	Unknown	None	Unknown	Unknown
Spotted dolphin	200	Survey	Unknown	None	Unknown	Unknown
Spinner dolphin	Unknown	None	Unknown	None	Unknown	Unknown
Striped dolphin	4,300	Survey	Unknown	None	Unknown	Unknown
Common dolphin	31,100	Survey	Unknown	None	Unknown	Unknown
Bottlenose dolphin						
NE U.S. offshore	7,500	Survey	Unknown	Fair	Unknown	Unknown
Coastal Mid.-Atl.	560	Survey	Unknown	Good	Depleted[6]	Unknown
E. Gulf Mexico	7,265	Survey	Unknown	Good	Unknown	Stable
W. Gulf Mexico	6,677	Survey	Unknown	Good	Unknown	Stable
White-sided dolphin	27,600	Survey	Unknown	None	Unknown	Unknown
Rough-toothed dolphin	Unknown	None	Unknown	None	Unknown	Unknown
Melon-headed whale	Unknown	None	Unknown	None	Unknown	Unknown
Grampus	11,700	Survey	Unknown	None	Unknown	Unknown
Killer whale	Unknown	None	Unknown	None	Unknown	Unknown
False killer whale	Unknown	None	Unknown	None	Unknown	Unknown
Pygmy killer whale	Unknown	None	Unknown	None	Unknown	Unknown
Pilot whale	11,200	Survey	Unknown	None	Unknown	Unknown
Harbor porpoise	45,000	Survey	Unknown	Fair	Unknown	Unknown
Sperm whale	190,000	Survey	Unknown	Fair	Unknown	Unknown
Pygmy sperm whale	Unknown	None	Unknown	None	Unknown	Unknown
Dwarf sperm whale	Unknown	None	Unknown	None	Unknown	Unknown
Humpback whale	5,500	Count	Yes	Good	Endangered	Unknown
Minke whale	300	Survey	Unknown	None	Unknown	Unknown
N. right whale	350	Survey	Yes	Good	Endangered	Unknown
Blue whale	500	Survey	Unknown	None	Endangered	Unknown
Fin whale	5,200	Survey	Unknown	None	Endangered	Unknown
Sei	4,000	Survey	Unknown	None	Endangered	Unknown
Bryde's whale	Unknown	None	Unknown	None	Endangered	Unknown
U.S. Fish and Wildlife Service Authority						
West Indian manatee	1,856	Count	Yes	Good	Endangered	Unknown
Walrus	234,020	Survey	Yes	Good	Unknown	Unknown
N. sea otter	100,000	Survey	Unknown	Good	Unknown	Increasing
S. sea otter	1,941	Count	Yes	Good	Threatened	Increasing
Polar bear	Unknown	None	Unknown	Fair	Unknown	Unknown

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[1] Abundance estimate = lower 95% confidence interval or "best" estimate.
[2] Assessment basis: Count = estimates based on or extrapolated from raw counts; Survey = estimates extrapolated from survey counts; EPC = estimates extrapolated from pup counts.
[3] Stock definition: Yes = discrete stock known or assumed; Unknown = number of stocks in population unknown.
[4] Life history: Good = available life history information good; Fair = some information available; Poor = little information available; None = no information available.
[5] MMPA/ESA status: Endangered or Threatened under the ESA = Depleted under the MMPA = below Optimum Sustainable Population Level (OSPL); Below OSPL = population below Maximum Net Production Level (MNPL) but not listed as depleted under the MMPA; Within OSPL = population above MNPL.
[6] Proposed status pending final rule.

Theoretical basis

The MNPL is defined, in the absence of a harvest, as a function of the way birth and death rates change with density. Some wildlife managers and scientists believe that the range of MNPL's for large, long-lived animals, like marine mammals, could be as high as or higher than 70% of the initial population level or K (Fowler, 1984). For practical purposes and in the absence of data indicating otherwise, 60% of initial population level has been used by managers as the lower bound of MNPL for marine mammals.

To substantiate the population levels used for MNPL for many marine mammals requires basic information on the range and definition of the population or stock and its life-history characteristics. Table 1.2 indicates that there is no clear definition of the stock in the majority (79%) of cases. Life-history data are poor or lacking for 62% of the stocks. Better data will be essential to improve the estimates of biological reference points such as MNPL for marine mammals.

Empirical evidence for MNPL exists for a few stocks. Northern elephant seals along the U.S. Pacific coast have recovered from very heavy exploitation at the beginning of this century. Despite a complete reoccupation of their historical range, the population's rate of increase continues, suggesting that its MNPL is greater than 60% of K (Gerrodette and DeMaster, 1990). Reilly's (1991) analysis of Soviet gray whale catch data suggests a recent decline in per-capita pregnancy rate for this species, which could be interpreted as evidence for a density-dependent response to the population size approaching K. The population has recovered to approximately 21,000 animals compared to its estimated pre-exploitation size of 24,000, suggesting that MNPL may be close to 80% of K for this population.

Assessment methods

Gerrodette and DeMaster (1990) reviewed methods for determining the status of marine mammal populations relative to OSP, the management goal specified by the MMPA. OSP determination methods fall into three types: Those that require an estimate of a population's maximum net productivity level (e.g., back-calculation methods), those that utilize trends in indices of population size (e.g., pup counts, number of breeding females) over time (e.g., dynamic response analysis), and default "unexploited" types. Because these methods have different data requirements and limitations, they suggested that no single assessment method could be used in all instances. Fig. 1.8 summarizes the types of assessment methods used for the stocks in Table 1.2. Population estimates based on survey counts exist for most stocks, but a substantial fraction of the stocks (27%) are currently not assessed.

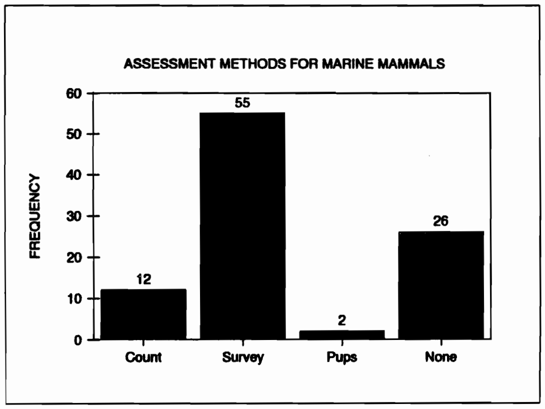

Figure 1.8.—Number of marine mammal stocks assessed by different methods.

Gerrodette and DeMaster (1990) noted that a change in population size does not necessarily mean a change in OSP status, because carrying capacity might also have changed owing to natural causes. They concluded that marine mammal monitoring programs designed to detect trends in both the abundance of a population and its condition relative to carrying capacity should also assess changes in carrying capacity because both quantities are involved in the definition of OSP.

Estimates of MNPL are made using the ratio of current population size to historical pre-exploited size. These methods assume that the upper limit of the OSP level (carrying capacity or K) is the historical population size. Carrying capacity normally refers to an equilibrium population level under conditions of no harvest or effects of human activities, and is usually back-calculated from catch history information, estimates of life-history parameters, and current population size estimated from surveys. Because human activities may contribute to reduction in carrying capacity of a habitat, K for a population has been difficult to measure because few marine mammal populations today have not been affected by human activities in some way, either directly or indirectly, and marine mammal habitats have likely also been affected by human development.

Dynamic response analysis avoids the need to estimate carrying capacity and MNPL by focusing on recent trends in population size indices over time. Dynamic response analysis assumes that the rate of increase in abundance first accelerates as the population moves toward the lower bound of its OSP range (i.e., MNPL), and decreases as the stock approaches the upper bound of the OSP range (i.e., K). It requires a temporal sequence of an abundance index, augmented by data on mortality due to harvest or incidental kill. Whether such data are of sufficient number and precision for dynamic response analysis to be useful is case specific.

Dynamic response analyses are most responsive to the number and precision of the population estimates, and least sensitive to environmental variability and the population's intrinsic growth rate. In this regard, Gerrodette (1988) demonstrated that the power of dynamic response analysis is unacceptably low for populations with a maximum per-capita growth rate of less than 10% per year and CV's of the census estimates of greater than 10%. Unfortunately, these levels of precision prevail in most marine mammal population data.

Default or "unexploited" methods assume that there have been no significant direct or indirect human-caused effects on the stock and that there have been no other changes in the ecosystem, generally because the populations in question occupy habitats that are not used or are rarely visited by humans (e.g., Arctic ice fields). Marine mammal populations living under these circumstances are assumed to be within OSP range and possibly near K.

Finally, condition indices have also been suggested as alternative indicators of OSP status. Eberhardt and Siniff (1977) proposed 12 criteria for establishing a relative population level. These criteria include individual and population measures, and they have been used to assess many species of marine mammals when data on historical take and population size were not available. These criteria are:

Behavioral attributes

1. Antagonistic and/or displacement behavior
2. Time spent in searching for food or in tending and feeding young
3. Shifts in dietary components

Individual responses

4. Physical condition, including growth rates
5. Incidence of disease and parasitism

Reproductive characteristics

6. Age at first reproduction
7. Annual reproductive rates of mature females

Population aspects

8. Age structure
9. Survival rates, especially of young
10. Occupancy of marginal range
11. Rate of change of population size
12. Effects on habitat or food base

Discussion

For the majority of fish and invertebrate stocks surveyed, the approved definitions of overfishing appear to be cautious with respect to not exceeding the harvest rate which is likely to cause the stock to decline in the long term. The majority of the definitions are related to the act of fishing, that is, they are in terms of harvest rate, not stock abundance. It should be noted in those cases where the stock is currently at a low level, harvesting at the overfishing definition level will not necessarily allow stock rebuilding unless the definition is very conservative.

Although the definitions appear to be cautious by the somewhat subjective criteria used here, it should be noted that the replacement levels of fishing mortality have only been estimated directly for 22% of the stocks. Most definitions have been derived by analogy to other stocks or from theoretical considerations in spite of the fact that the majority of the fish and invertebrate stocks are assessed in great detail. The lack of clear linkage between the assessment of each stock and its definition of overfishing may in part be due to the relatively short time series of assessment estimates available for most stocks. In general, determining threshold replacement levels of fishing mortality or the appropriate minimum spawning stock size directly from, say, stock and recruitment data, will likely be very imprecise, unless a long time series of estimates is available for a stock whose dynamics were stationary. In addition, consistency among the definitions of overfishing levels can be helpful in making them understandable and acceptable to managers and the public.

Another important aspect of the definitions of overfishing is their adaptability as new information becomes available. For the purpose of summarizing the definitions it was not possible to include additional provisions which are included in many FMP's for updating and revising the overfishing definition level.

The shortcomings of marine mammal population assessments have been blamed largely on either imperfect information or a paucity of comprehensive information. However, Barlow (1990) and others have demonstrated by simulation that, even if reliable information were available, assessment of marine mammal population status will be limited because of practical limitations of surveys, owing largely to the nature of marine mammal natural history.

Back-calculation approaches, while demonstrating some degree of success, have often yielded biologically reasonable results from combinations of unrealistic values for input parameters. Also, as noted above, dynamic response analysis has very real limitations concerning the precision required for input parameter values and its ability to detect changes of <10% per year.

In recent years the International Whaling Commission has developed a Revised Management Procedure that, in theory, is free from stringent data requirements. The approach deals largely with the management of uncertainty and management of the risk of inadvertently overharvesting a stock to the point where it falls below a certain threshold level. Its primary input parameters are recent population estimates and a catch history. The more precise the input information and the more frequent the assessment surveys, the greater the allowable harvest for a given population level.

There is clear room for improvement in the development of definitions of overfishing for fish, invertebrates, and marine mammals. Some of this improvement will come with methodological developments, but in all cases, additional data will be required for developing and validating various biological reference points for resource management.

Summaries of Contributed Papers

Revised Procedures for Providing Fishery Management Advice by the International Council for the Exploration of the Sea: The New Form of ACFM Advice

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and

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Summary

The International Council for the Exploration of the Sea (ICES), founded in 1902, is the oldest intergovernmental organization in the world concerned with marine and fisheries science. ICES is an exclusively scientific body whose principal functions are the promotion and coordination of biological and environmental research on the sea and its living resources, and the provision of scientific information and advice on environmental and fisheries management requested by various international regulatory commissions and national administrations.

Since its creation in 1978, the ICES Advisory Committee on Fishery Management (ACFM) has been responsible, on behalf of ICES, for providing fisheries management advice. Currently, ACFM annually provides advice on over 100 fish stocks to three management commissions (North-East Atlantic Fisheries Commission; International Baltic Sea Fishery Commission; North Atlantic Salmon Conservation Organization), ICES member countries (17), and the Commission of the European Communities (EC). In formulating its advice, ACFM reviews and utilizes the results of stock assessment analyses conducted by about 20 ICES assessment working groups, established to provide information on the status of stocks.

In 1981, in light of discussions during the first two ICES Dialogue Meetings (ICES Dialogue Meetings were established in 1980 to provide a forum for regular communication between scientists, managers, and the fishing industry on issues related to management objectives, policies, and advice), ACFM established principles for the presentation of its advice. In its 1981 report (ICES Coop. Res. Rep. No. 114), ACFM explained that,

> "Ideally managerial authorities would define their objectives for the different stocks or fisheries and ACFM would thereafter evaluate the consequences of these management strategies and define the biological constraints for the attainment of these objectives. Without clear objectives at hand from managerial bodies, ICES has had to develop certain management objectives which are mainly based on purely biological considerations. These are $F_{0.1}$ and $F_{\max}$, which define a certain level of fishing mortality associated with the optimal use of the growth potential for the existing pattern of exploitation."

The 1981 ACFM report also defined five categories of stocks for the purposes of providing management advice:

1. Stocks which are depleted and suffering from recruitment failure. In these cases, ACFM shall not calculate options but shall recommend a single fishing mortality rate.

2. Stocks which are fished at levels largely in excess of the levels indicated by biological reference points. In these cases, ACFM shall give options inside safe biological limits and shall recommend one of these options, according to the general principles of aiming at more stable levels.

3. Stocks which are fished at levels not very different from the biological reference points. In these cases, ACFM shall give options inside safe biological limits, but shall not recommend any particular one of these. It shall indicate only a preference, which is in line with the general principles mentioned above.

4. Stocks where at present it is not possible to carry out any analytical assessment with an acceptable reliability. In these cases, ACFM shall indicate precautionary TAC's to reduce the danger of excessive effort being exerted on these stocks.

5. In cases where fisheries on a stock are not subject to TAC regulation, there may be a danger of catches taken from stocks of the same species in adjacent areas being misreported as having been taken in areas of unregulated fisheries. To reduce the risk of this happening, ACFM, on occasion at the request of management bodies, has advised the implementation of TAC's, and their levels on this basis. As in the majority of cases, the data on these stocks are inadequate for analytical assessment, and they too will generally be recommended as precautionary TAC's based on historical catch levels.

In 1982, ACFM revised the type of recommendation it would provide for stocks in Category 2 and indicated that its biological advice should not be considered entirely apart from economic aspects (ICES Coop. Res. Rep. No. 119). Later, in 1987, ACFM introduced the additional biological reference points F_{med} and F_{high} into its advice and noted that these were intended to provide guidelines for levels of fishing mortality at which it is probable (in the case of F_{med}) and doubtful (in the case of F_{high}) that recruitment will, in the long term, be sufficient to sustain a stable stock (ICES Coop. Res. Rep. No. 153).

The issue of "safe biological limits" was addressed by ACFM in both 1986 and 1987. ACFM requested that all ICES assessment working groups "try to define safe biological limits for the stocks which they assess and to indicate whether sufficient data exist on which to base a definition." Although working group responses varied, "target" or "minimum acceptable" spawning stock levels were identified for many stocks. ACFM informally adopted the approach taken by the Irish Sea and Bristol Channel Working Group in addressing "safe biological limits" (1987 Report of the Irish Sea and Bristol Channel WG):

> "Biologically safe limits should be based on the historical experience of recruitment, stock size, and fishing mortality for each stock. Precise "safe limits" cannot be defined but indications of the current stock situation in relation to safe limits can be obtained by addressing the following questions:
>
> > "1) Is there any evidence from the stock/recruit data that recruitment is reduced at the lowest levels of spawning stock which have been observed in the historic series?

"2) Is the spawning stock currents at a level which is lower than any previously observed?

"3) Does spawning biomass show a declining trend which, taken with available evidence on recruitment, might indicate that a historically low level will be reached in 1987 [the current year] or 1988 [next year]?

"4) What level of F in 1988 [next year] would be needed to reduce the spawning stock biomass to a historically low level in 1989 [the following year] and what would the corresponding catch be in 1988?"

In general, the basis and form of advice used by ACFM during 1981-90 was accepted without major reservations by the various fisheries commissions requesting information and scientific guidance from ICES. On more than one occasion, however, ACFM was criticized for assuming responsibilities for the selection of management objectives and for the time-scales (rates) at which objectives should be reached. Such responsibilities were deemed more appropriate (or solely appropriate) to management bodies. As well, dissatisfaction was expressed that the ACFM advice had occasionally made reference to socioeconomic considerations, which were felt to be outside of ACFM's purview. At various times, ACFM was also criticized for not providing sufficient detail or justification for its recommendations.

The New Form of ACFM Advice

In 1990, ACFM began to reexamine and reevaluate the basis, form, and criteria used in developing and presenting its advice since 1981. In November 1991, after a year-long process, ACFM adopted a new approach to formulating its advice. ACFM believes that this new protocol is a significant improvement over its previous approach and will result in more objective, consistent, and credible management advice.

Under the new system, ACFM defined its own objective to be: "To provide the advice necessary to maintain viable fisheries within sustainable ecosystems." The specification of objectives for fisheries management is recognized as a responsibility of management bodies. ACFM's role will be to present options as to how management objectives can be reached, and to clearly describe the implications and consequences of various options and their associated risks. ACFM may comment, for example, that an increase in fishing mortality is not expected to produce an increase in long-term yield. However, recommendations will only be made in cases where stocks are exploited outside safe biological limits, i.e., where stocks are below a "minimum biologically acceptable level" (MBAL) or expected to fall below the MBAL in the near future at present rates of exploitation. When stocks are exploited within safe biological limits, ACFM will provide options without indicating a preference — but ACFM will indicate the biological consequences and risks associated with each option. In this latter situation, the choice of a particular option is left to the managers. For those stocks where an analytical assessment is not yet possible, precautionary TAC's will be provided by ACFM only if specifically requested.

As technical and biological interactions become incorporated into assessments and predictions, it will be necessary for ACFM to receive suggestions from management bodies concerning scenarios for evaluation, as well as management objectives. This is particularly true in relation to mixed-species fisheries and ecosystem effects.

ACFM has invited management bodies to comment upon the new form of advice. The new protocol has already been presented to the North-East Atlantic Fisheries Commission at its annual meeting in November 1991, and presentations will also be given at the 1992 annual meetings of the North Atlantic Salmon Conservation Organization and the International Baltic Sea Fishery Commission.

ACFM has also proposed that its new approach for developing and providing advice be presented at the ACFM Theme Session at the 1992 ICES Statutory Meeting for scientific review and critique. It is envisaged that by formally vetting the new protocol through the ICES scientific community, ACFM will receive a wide range of constructive criticism. As such, ACFM does not consider the present version of the new form of advice to be final but rather as a text which can be modified in light of relevant feedback from scientists and managers.

Stock Biomass, Fishing Mortality, and Long-term Productive Capacity: Rationale Used in the North Pacific Overfishing Definition

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Summary

The 602 guidelines (50 CFR 602) define overfishing as "a rate of fishing that jeopardizes a stock's long-term productive capacity." For example, exceeding the fishing mortality rate associated with maximum sustainable yield (MSY) does not necessarily constitute overfishing; it constitutes overfishing only when the MSY rate is exceeded to such an extent that the stock's capacity to return (eventually) to the MSY biomass level is jeopardized. In other words, the 602 guidelines envision overfishing not simply as another point on the sustainable yield curve, but as the point at which the curve collapses. Unfortunately, comparatively little effort has gone into the study of long-term productive capacity, let alone the fishing mortality rates that might cause this capacity to collapse.

As a preliminary step toward a capacity-based view, the overfishing definitions used in the North Pacific groundfish fisheries were derived from a depensatory stock-recruitment relationship in which the phenomenon of stock collapse is well defined. This stock-recruitment relationship (a straightforward generalization of the classic Beverton-Holt curve) leads naturally to a pair of constraints that should safeguard against stock collapse under a wide range of life history characteristics: A threshold biomass level set at 20% of the pristine level and a maximum fishing mortality rate corresponding to a 30% relative biomass-per-recruit ratio.

Given certain assumptions, the ability of these constraints to prevent stock collapse is independent of the parameter values used in the stock-recruitment relationship. Both a general theoretical evaluation and a comparison with actual fishing mortality rates applied to 22 groundfish stocks in the eastern Bering Sea and Gulf of Alaska indicated that the constraints would be unlikely to impose new restrictions on fisheries that are already managed for maximum sustainable yield. However, the constraints should insure against pursuit of overly aggressive harvest strategies when detailed biological information is lacking.

An Evaluation of F_{med} as a Tool for Specifying Spawning Potential Thresholds for Management

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Summary

Analyses of the robustness of using median (or other) values of scattergrams of stock-recruitment data pairs to estimate critical minimum levels for spawning stock biomass per recruit (SSBIR) were conducted. The median bisector (F_{med}) technique (Gabriel et al. 1989) was applied to data from population simulations with known stock-recruit relations, sources of variability, etc. The simulations used life-history characteristics of haddock. The experiments were designed to evaluate the method under quasi-optimum conditions. Results indicate that $\mathrm{F_{med}}$ appears to be biased low with respect to the average level of fishing mortality applied to the simulated population. Even so, it provides a remarkably good estimate of current F given sufficient years of observation and accurate knowledge of natural mortality and the partial recruitment vector. Evidently, the median bisector of the points on a scattergram of stock and recruitment is a fairly good estimator of recent levels of SSB/R.

The principal assumption when using F_{med} is that the population be in (quasi) equilibrium in the fished state. Fishing mortality may be at a level well below MSY or near the extinction level. The estimates of SSB/R and fractions of the unfished levels will provide valid estimates of critical levels only if there is contrast in the data reflecting persistent shifts from sustainable to unsustainable levels of fishing mortality that are evaluated separately. Estimates from more or less "stable" conditions provide estimates of SSB/R and F for the prevailing historical conditions and by themselves provide no information whatever on whether or not those levels are optimum, suboptimum, or critical. Levels of fishing mortality less than F_{med} and SSB/R levels greater than the median values in stock-recruitment scattergrams from such stocks should be protective of the stock. However, higher values of F or lower values of SSB/R associated with reciprocals of slopes derived from other percentiles of the distribution of R/SSB will have unpredictable consequences.

Robust Estimation of MSY: Production Models Revisited

Michael H. Prager
NMFS Southeast Fisheries Science Center, Miami, Fla.

Summary

Surplus-production models are enjoying a resurgence of use and acceptance. The models are relatively simple and robust, and their major drawback, reliance on effort data, seems equally difficult to avoid with other methods (in particular, VPA). Today's faster computers make it practical to discard the equilibrium assumption often used in the past.

The simplest production model is the logistic (Schaeffer) model. It has a catch equation that can be solved analytically, which simplifies fitting the model to data. I have incorporated several extensions into a logistic model that I call ASPIC (A Surplus Production model Incorporating Covariates). The three main extensions are the ability to analyze data from more than one fishery (i.e., to estimate more than one catchability coefficient); the related ability to tune the model to indices or estimates of population abundance; and the use of a bootstrap to examine the precision of estimated benchmarks (MSY, effort at MSY) and other quantities of interest.

A recent application is illustrative. At the 1991 ICCAT meeting, two questions arose on the status of yellowfin tuna in the eastern Atlantic: 1) Did the low catch in 1984 result from overexploitation or from an anomalous warming of the surface waters? 2) Did catchability increase with the recent introduction of bird radar? A baseline ASPIC analysis indicated that the low catch in 1984 was due to lower effort and to a depressed stock level caused by heavy exploitation. In a second ASPIC analysis, a separate catchability coefficient was estimated for 1984. It was slightly lower than for other years, but the difference was not significant (F-ratio test: $P = 0.45$), suggesting that any environmental effect was small. A third ASPIC analysis suggested that catchability increased by around 60% after introduction of bird radar ($P = 0.11$, marginally significant given the expected low power of the test).

Production models contribute a fundamental perspective to assessments and also complement other methods well. They are invaluable in assessing species that cannot be aged reliably. Their chief disadvantage is that they do not estimate absolute levels of stock biomass or fishing mortality very well. However, they appear to estimate levels relative to the appropriate benchmark (MSY or F_{opt}) quite robustly. The models can be extended to use age-specific indices for tuning. Confidence envelopes around relative biomass levels are smallest in the most recent years, a valuable property not shared by VPA. Being simple, the models are easy to explain, especially when the equilibrium assumption is discarded. In summary, production models form a set of useful tools that still have much to offer the assessment scientist and the fishery manager.

Session II: Evaluating the Performance of Overfishing Definitions

Session II Summary

Moderator: Andrew A. Rosenberg, NMFS HQ
Rapporteur: Vidar Wespestad, AFSC

An excellent presentation on approaches to evaluating management targets for Australian fisheries by K. Sainsbury, CSIRO, Hobart, Tasmania, Australia, focused on the interrelationships between policy, resource dynamics, and strategy implementation in the management strategy evaluation cycle. He discussed the management cycle from the standpoint of adaptive management showing the feedback and interrelationship among policy, resources, and implementation.

Central to the session topic was the development of policy implementation strategies and measurable performance criteria to evaluate policy objectives. Examples of policy objectives are MSY, OY, and population or catch stability. Performance criteria may be operating costs, CPUE, harvest levels, etc. Implementation of policy feedback is through observed changes in the population structure or productivity. These observations provide updated parameter estimates which can be used to modify policies or management decisions (tactics).

Implementation of harvest policies may be based on "control laws" which determine a harvest objective, such as the harvest rate or the catch level, based on the level of a performance criterion (e.g., spawning stock size) relative to the spectrum of that population parameter. These control laws may encompass rules such as constant quota, proportional escapement, constant escapement, proportional harvest rate, and may include features such as a harvest threshold (Fig. 2.1).

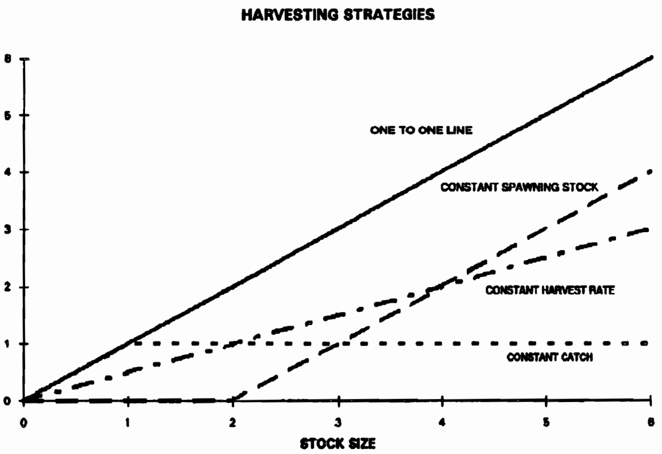

Figure 2.1.—General illustration of control laws for fishery management with catch quota as a function of stock biomass.

A discussion of the use of adaptive management to test control laws and criteria focused on the ability to evaluate uncertainties in data, the robustness of control laws, and the cost-benefit of various kinds of observations or data for different control laws. Examples of passive adaptive management (International Whaling Commission) and active adaptive management (Australian groundfish) were presented to show the range of policies that could be evaluated relative to data structure, monitoring capabilities, and the application of management.

Contributed Papers

R. Conser and W. Gabriel reported that the current status of fish stocks is evaluated by comparison to biological reference points. One difficulty in the evaluation is that both the current estimate and the reference point are estimated with error. They described a method for obtaining bootstrap estimates of the variance and shape of the probability distributions of current values and the reference points. They showed how the method was applied to Georges Bank cod, haddock, and yellowtail flounder to test if current F was =, >, or $<F_{med}$.

D. Vaughn presented an event tree analysis to evaluate the cumulative probability of exceeding reference points in the Atlantic menhaden fishery. A series of reference points which consist of age composition, recruitment, spawning stock biomass, recent catch, and current spawning biomass relative to maximum potential is used to estimate ABC. In the process, recruitment is estimated from the current spawning biomass at high, medium, and low levels. The results are used to estimate the likelihood of the estimated ABC exceeding the reference points. Also the procedure is used to examine the effectiveness of the reference points as performance criteria.

T. Smith outlined the revised management procedures developed by the Scientific Committee of the International Whaling Commission which conducted a very extensive series of simulation experiments using different control laws and information bases to achieve management goals of enabling a sustained harvest of whales with little risk to the populations. A primary objective in the revised procedures is to evaluate the value of various data sets and their robustness in monitoring population levels. Testing was via 100-year simulations using production models with random variability. Several cases were examined, and robustness trials developed performance statistics which corresponded to management goals. Five control laws were compared with feedback through "tuning" of management goals. Testing of the procedures will be through application to small areas with multistocks.

L. Jacobson, M. Dorn, and A. Hollowed described how overfishing was evaluated in three fisheries: Northern anchovy, Pacific hake, and walleye pollock. In the anchovy fishery there are thresholds to allow a fishery to occur and a higher level to allow a larger industrial fishery. A series of reference points, similar to the menhaden resource, are examined and the level of fishing is determined based on the relationship of current biomass to the reference points. Jacobson described the development of the reference points and their evaluation through simulation.

Dorn discussed some of the problems which could occur if two common biological reference points, F_{med} and $F_{35\%}$, are used as target fishing mortality rates when recruitment is extremely variable. He noted that populations can persist when only a few year classes replace the spawning biomass that gave rise to them. F_{med}, which is based on the premise that at least 50% of the year classes need to replace themselves (median bisector of the stock and recruitment data), will be overly conservative if the stock persists with only an occasional good year class. For Pacific hake, the average survival ratio, rather than the median survival ratio, was suggested as a better procedure for calculating a replacement fishing mortality rate.

Hollowed described the fishery for walleye pollock in the Gulf of Alaska. Only a short time series is available, so biological reference points are not well defined. Fishing levels are set relative to survey estimates; however, data obtained from hydroacoustic and bottom trawl surveys produce contradictory results. Additional research is needed to reconcile contradictory data and to evaluate the error in quota estimation.

Discussion

Part of the discussion centered on a perceived problem of distinguishing between when a stock had been overfished and when overfishing occurs. Anthony pointed out that while northeast groundfish stocks are overfished, the current overfishing definition approved by the New England Council addresses only the problem of the current rate of fishing and does not reference the current state of the stock. There are several other examples of this, but it was noted that the guidelines allow definitions which include both stock size and harvest rate. A. MacCall noted that the issue of determining the appropriate action needed on a depleted stock (which had been overfished in the past) could be dealt with as a specification of a rebuilding program.

The participants agreed that a reliance on fishing mortality as a measure of over- fishing could cause problems since *F* does not provide information on population level or the direction of change in the population. The consensus was that management actions would better be planned in the control law framework described by Sainsbury and others. A control law would map the action taken, usually regulated harvest rate or catch quota, to a measure of stock condition such as spawning biomass. It was noted by Thompson that the North Pacific Fishery Management Council had explored and discussed a number of such control laws in developing their groundfish management plan (Fig. 2.2). MacCall pointed out that the Pacific Council had also explored a variety of control laws for the management of pelagic resources (Fig. 2.3).

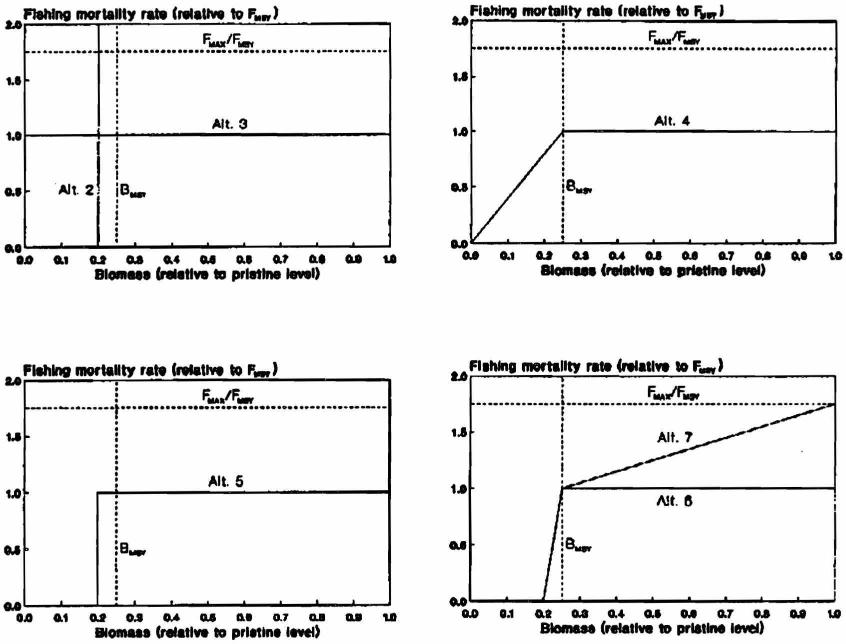

Figure 2.2.–Control policy options considered by the North Pacific Fishery Management Council for Gulf of Alaska, Bering Sea, and Aleutian Islands groundfish (Fishery Management Plans for Gulf of Alaska, Bering Sea, and Aleutian Islands groundfish, NPFMC, 1990).

There are clear advantages in specifying a management strategy as a control law, since the course of action is agreed in advance, outside, to some extent, of the pressures for or against action in any one year. It was suggested by Anthony that a step-wise control policy was appropriate, using a series of reference points. For example, if the stock was to be fished at F_{msy} when the biomass was at the MSY level, the biomass dropping to two thirds of the MSY level would trigger a fishing mortality rate (or catch quota) reduction and so on. While such a policy could be an effective management strategy, Rosenberg noted it may be preferable to specify a continuous function for control to avoid abrupt changes and arguments over when a particular trigger point is reached.

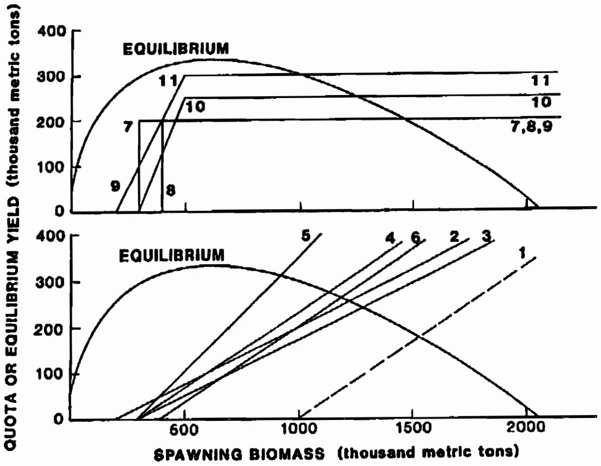

Figure 2.3.–Control law options considered by the Pacific Fishery Management Council for northern anchovy (Northern Anchovy Fishery Management Plan Amend. 5, PFMC, 1983).

Conser suggested the following general form of a control law for consideration by the Workshop:

$$F_{t+1} = \Pr[F_t < F_{ref}] * \Pr[\text{Ab.} > \text{Thr.}] * F_{ref},$$

where F_t is the fishing mortality rate in year t, F_{ref} is the reference rate of fishing mortality such as $F_{20\%}$ from the definition of overfishing. Ab. is some measure of stock abundance such as spawning biomass, and Thr. is some abundance threshold defining an overfished stock condition. It was suggested that this type of control law be explored by a working group, and this task was referred to the NMFS Risk Assessment Working Group for further consideration.

An important point in the session was the need to test the behavior of specified definitions or control laws using simulation experiments as well as analysis of existing data. These analyses enable management to be adaptive. It was pointed out that with only one observation per year it may difficult to evaluate resource dynamics, but economic effects could also be examined within and between years.

Overview Paper: The Use of Simulation to Evaluate the Performance of Stock Rebuilding Strategies, Including the Use of Reference Points

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Introduction

In this paper I will outline a general framework for the use of simulation in the evaluation performance of fishery management strategies and then briefly describe two example applications. The first application, the development of a stock rebuilding strategy for whales by the International Whaling Commission (IWC), is one that I have not been involved with directly, and so I must emphasize from the outset that the interpretation I present here is my own and in no way necessarily represents the views of the Whaling Commission (IWC), scientists involved. However, I gratefully acknowledge G.P. Kirkwood and J.G. Cooke for discussions I have had with them on this subject and the opportunity to discuss the approach further that was provided by a Project Prospero meeting (Anonymous, 1991). The second application relates to the development of a stock rebuilding strategy for a tropical groundfish resource in northern Australia. I must take the full responsibility for that one.

A General Framework for Evaluation of Stock Rebuilding Strategies

Stock rebuilding is just one example, with the specific objective of increasing stock abundance, of a fishery management strategy. A fishery management strategy is taken here to mean the combination of observation, interpretation, decision making, and implementation processes that are used to try to achieve management policy objectives. A management strategy may include the use of reference points and a specified way in which the reference points are used in the decisions on fishery management controls (e.g., catch levels). However the essential point is that the management strategy to be evaluated is one aspect of a process that includes stock dynamics, economic dynamics, observations, estimation procedures, management decision, and management implementation, all operating under a management policy with specific goals or objectives. Evaluation of a stock rebuilding strategy requires comparison of the performance of alternative rebuilding strategies according to performance criteria that are derived from the policy objectives. The performance of a rebuilding strategy involves all of the elements of the resource-observation-management process, and consequently the whole process should be considered when evaluating a particular strategy. The complexities of the whole process dictate that simulation approaches be used in this evaluation.

There are several ways of viewing the resource dynamics- observation-management process, and several different nomenclatures to chose from, but Figure 2.4 provides a view that I have found useful. It includes three of the major aspects of the overall process: Policy, resource dynamics, and the management decision process (taken here to include observation, interpretation, decision making, and implementation). Each of these major aspects of the process is likely to be operating on different time scales; for example, the resource dynamics may be changing significantly on a seasonal time scale while the management process may be operating on annual time steps. There is a fourth major aspect which for simplicity is not explicitly included in Figure 2.4, and that is economics. Economics functions in the framework of Figure 2.4 in a similar way to the representation of resource dynamics. Economic and resource dynamics interact with one another, generate observations that influence the management decisions, and form the basis of performance criteria for assessment of the achievement of management objectives. While the overall framework as described here emphasizes resource dynamics for the sake of simplicity of presentation, the parallel treatment of economic dynamics is assumed.

Examination of the Three Major Aspects

The policy component of Figure 2.4 begins with the statement of "policy objectives." Common objectives for fisheries include that catches should be high (and not vary greatly), that there should be a low risk to biological continuity of the resource, and that economic returns should be optimized. "Performance criteria" are derived from these objectives and can be used to judge how well the policy objectives are being met. Examples relating to the common objectives mentioned earlier could be whether the average catch is greater than 70% of the maximum sustained yield with a coefficient of variation of less than 30%, whether biomass is maintained at greater than 20% of the unfished level, and whether the average net economic return is close to the calculated economic optimum. Statistical "performance measures" can be used to indicate how well the identified performance criteria are being met. "Performance variables" are the realizations from the fishery from which the performance measures are calculated, and include such things as the resource biomass, fishery effort, fishery catch, revenue flow, and capture costs. In a simulation model and in real life, the performance variables are determined by what is happening to the actual resource and economic system being considered, and not by what is observed; if the resource is rapidly recovering, then the performance variables reflect this even if the observations being made on the resource do not for some reason (e.g., inadequacy of the observations to detect such change).

The resource dynamics loop of Figure 2.4 represents how the state of the resource changes in response to previous management and fishing actions. In a simulation context this provides the "truth" for the calculation of performance — the catch, cost, biomass, and economic return — and the "truth" which is observed through the observation process that links the state of the resource with the management decision process.

The management decision process of Figure 2.4 begins with "observations," which includes the choice of what data to collect, the cost of data collection, and statistical properties of the data collected. These new observations are then used along with historical data to update knowledge of the fishery. This usually involves the statistical reestimation or "updating of model parameters" using techniques such as least squares or maximum likelihood estimation,

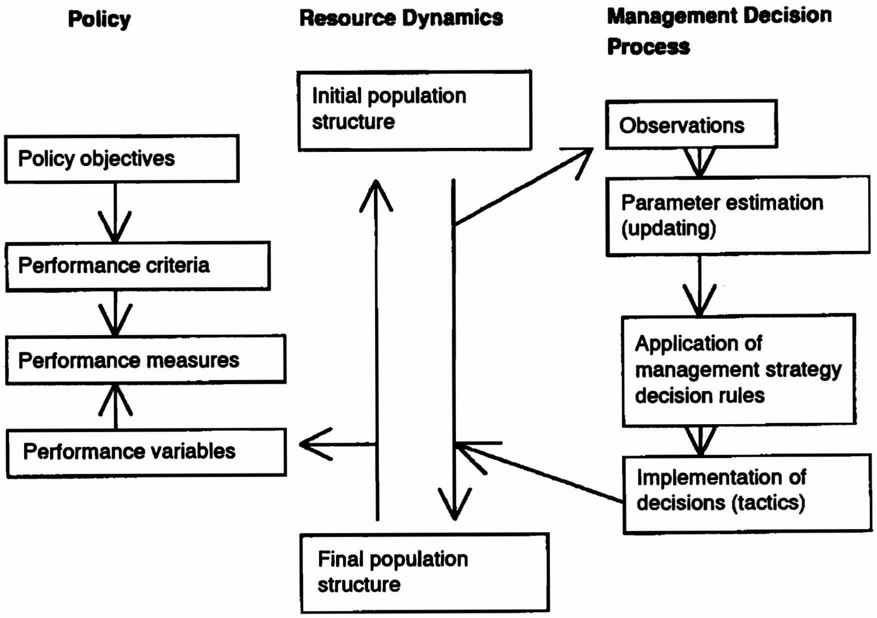


Figure 2.4.—A general framework describing the linked processes in the evaluation of a fishery management strategy. See text for description of the terms and flows. This framework can be used to simulate and examine the performance of different management strategies.

Bayesian updating or filtering (e.g., Meinhold and Singpurwalla, 1983). The application of the management strategy decision, the next step in the process, involves the question of how the controls of the management strategy are changed as new information becomes available. Two general categories of control are input controls (e.g., control of fishing effort, gear, area of operation, etc.) and output controls (e.g., control of total catch, minimum allowable size, etc.). The rules by which the control is varied according to the perceived state of the stock are referred to as "control rules." Figure 2.5 shows the form of these control or feedback rules relating catch level to stock abundance (for an output control) and relating fishing mortality to stock abundance (for an input control) for some common management strategies, and

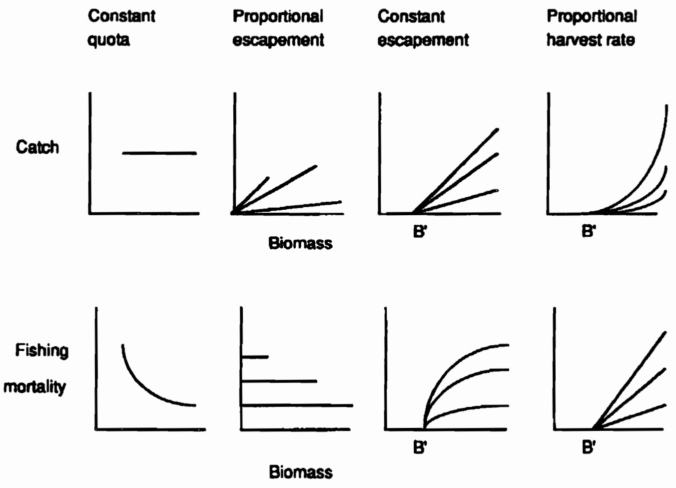


Figure 2.5.—The general form of the control rules relating the control variable (here catch as an example of output controls and fishing mortality as an example of input controls) to the estimated biomass of the exploited stock for some commonly used management strategies. The management strategies examined are a constant quota, proportional escapement (i.e., a fixed effort or harvesting rate, of which the $F_{0.1}$ strategy is an example), constant escapement (or threshold proportional escapement), and proportional harvest rate. The relationships between catch and biomass, and fishing mortality and biomass are given in Table 2.1.

Table 2.1.—The general form of the control law for the common fishery management strategies shown in Figure 2.5. Here C = the catch determined by a control rule, F = the fishing mortality determined by a control rule, Q = a catch quota, q = catchability, E = fishing effort, B = estimated present stock biomass, B′ = a constant threshold biomass, and a = a constant.

	Management strategy			
Control variable	Constant quota with threshold B	Proportional escapement	Constant escapement	Proportional harvest rate with threshold B
Catch	$C=Q$ if $B>Q$ $C=O$ if $B>Q$	$C=qEB$	$C=(B-B')$ if $B>B'$ $C=O$ if $B<B'$	$C=aB^{2}\cdot aB'B$ if $B>B'$ $C=O$ if $B<B'$
Fishing mortality	$F=Q/B$	$F=qE$	$F=(1-B'/B)$	$F=a(B-B')$

Table 2.1 gives the general relationships. The common management strategies examined in Fig. 2.5 and Table 2.1 are:

- Constant quota, in which a fixed quota is taken so long as there is sufficient stock.
- Proportional escapement (i.e., constant *F*), in which a fixed proportion of the available stock is taken by the fishery leaving a fixed proportion to escape. This includes, for example, the $F_{0.1}$. and F_{rep} strategies in which the estimated value of $F_{0.1}$ and F_{rep} are used respectively to determine the proportion taken by the fishery.
- Constant escapement, in which a constant quantity of stock is allowed to escape the fishery (see Table 2.1 with a = <1). A variation on this includes the use of a proportional escapement beyond some minimum threshold stock abundance (see Table 2.1 with a).
- Proportional harvesting rate, in which a linearly increasing fraction of the stock is taken as stock size increases.

Much more complex control rules are possible, and in particular the control rules may use the available data, parameter estimates, and models to examine the statistical distribution of the estimated control variable (e.g., catch or fishing mortality) at the time of decision making. Then selection of the value of the control variable for management implementation (e.g., the catch level for the next year) can be based on a combination of the perceived probability of various outcomes and the utility to managers of each outcome. For example, the control rule may provide for selection of a management action in the situation where one alternative management action results in a high sustainable catch under one set of possible model parameters and a very low sustainable catch under a second equally likely set of parameters, while the other alternative management action results in a moderate sustainable yield under both sets of model parameters. The control rules in this situation must consider the utility to the manager of the various outcomes, the probability of each outcome, and the attitude of the manager to risk (i.e., risk averse, risk neutral, or risk prone). The utility is usually related to the policy objectives, in that the same categories of issues are often considered (e.g., the size and sustainability of yields and economic returns). However, it must be born in mind that the use of such considerations in the control rules is quite different from their use in the performance criteria; the control rules deal with perceptions or estimates of the outcomes that are based on observations that are made, whereas the performance criteria reflect what is actually occurring with the real or simulated fishery.

It can be seen from Figure 2.5 that many of the strategies use a threshold biomass, with catch or fishing mortality being controlled to decline as the threshold is approached. Commonly, the question being addressed in the evaluation of a management strategy is what this threshold should be and how should the catch or fishing mortality be changed as the threshold is approached. The threshold is often thought of as the level below which overfishing occurs. However the avoidance of overfishing is a policy objective, and the avoidance of specific biomass levels is a management performance criterion, rather than a specific element of the management strategy. In the context of a management strategy evaluation, the threshold in the control rule (or any other element in the control rule) is not a policy objective or performance criterion. Rather, the parameters of the control rule are best chosen to meet the performance criteria derived from the policy objectives for a certain process of observing the fishery, decision making, and implementing management decisions. For example, if the accuracy of the observation process was suddenly increased, it would be expected that the most appropriate parameters of the control rule would also change to reflect this decreased uncertainty, whereas the policy objectives and performance criteria would remain the same. Similarly, the extent to which control measures can be implemented in the fishery will effect the best parameters of the control rules. In a perfectly observable and controllable situation, some of the control rule parameters may indeed directly correspond to policy objectives, but usually they are expected to be different. Uncertainty in the parameters of the resource dynamics model, uncertainty in the estimate of present stock abundance (derived from the observation process), the probability placed on different outcomes of a decision, and the utility placed by managers on these different outcomes can all affect the best control rule and the comparative performance of different strategies.

"Implementation of decisions" (tactics) of the chosen control is mentioned as a specific item in Figure 2.4 because it is a crucial but often overlooked feature in the evaluation of the performance of management strategies. However, it is obvious that any management strategy will be ineffective if it cannot be implemented, and that some strategies could perform better than others under different limitations in the implementation process.

In the application of the general framework shown in Figure 2.4, the performance of alternative strategies are compared with respect to the performance criteria. Because different performance criteria will be derived from different and conflicting management policy objectives, the comparison of strategy performance may include consideration of the "weight" of different objectives, and these weights may change under different circumstances (e.g., a biological continuity objective are very important at very low stock sizes but become less important at high stock sizes). The development and evaluation of management strategies often revolve around issues such as finding the best way of relating observations to management decisions (i.e., the best control rules) and the most cost effective observation or monitoring package to employ.

The control rules may employ a reference level or threshold. The crucial issue, however, is how the reference point is best used in relation to observations on stock condition so as to reach management decisions that result in the meeting of management objectives (as specified by the performance criteria). The intellectual appeal and interpretation of the reference point itself is not of great relevance in this, although of course these are important considerations when specifying the biologically related performance criteria.

An evaluation of management strategies is often seeking to identify a cost-effective strategy that is robust in meeting the performance criteria across a range of uncertainties that are known or suspected to exist in the whole resource dynamics-observation-management process. Key uncertainties in particular applications are often the structure of the resource dynamics model, the initial and current population sizes, the relationship between abundance and indices of abundance, and the reliability of the catch history. The approach outlined by the framework in Figure 2.4 allows examination of such robustness. Key elements in the development of a cost effective strategy are:

- Identification of uncertainties (particularly in the models of resource and economic dynamics) that make no substantial difference to management action and achieving management policy objectives.
- Identification of observations that cost more than they return in improved achievement of the management objectives.
- Identification of observations that are of value in guiding management decisions so that they achieve the management objectives.

In the context of observations and the value of observations, it is worth emphasizing that there is a feedback between management actions, parameter estimation (learning), and the meeting of performance criteria, and that this feedback can be used to advantage. Management actions are often perceived as an end in themselves and separate from the more "scientific" issues, such as how to structure models, what to measure, and how to measure it. However the management actions do more than affect just the management performance variables, such as catches, population sizes and revenues; they can also have a great influence on the statistical properties and ultimately the usefulness of the data that can be obtained by observing the fishery. In particular, the management actions affect the statistical contrast of key variables in the data set, which in turn affects the ability to estimate model parameters, the power to discriminate different hypotheses about resource and economic dynamics, and the power to test different management strategies. In a statistical sense, the management actions and measures effectively provide the "experimental design" from which the observation process obtains data. Obviously the statistical inferences that can be validly drawn from the data set will be affected by the particular experimental design used, and the ability to scientifically answer particular questions could be increased or decreased by changing the experimental design. The question of whether or not such changes are worthwhile in terms of improving the achievement of management policy objectives can be examined using the framework outlined in Figure 2.4.

Most fishery management systems do not act to exploit the potential feedback between management action (the "experimental design") and improved learning. Such approaches are called passively adaptive, in that the experimental design is set by consideration of objectives other than learning. It is left to variations of nature or mistakes in assessment/management to provide the data to show when model structures or parameter estimates are wrong. This can result in data sets that are statistically confounded with respect to variables of interest (e.g., population size and exploitation rate) and difficulty in testing hypotheses about resource and economic dynamics. This, in turn, can result in the adoption of suboptimal strategies that cannot be recognized for what they are. The alternative approach, that explicitly considers and uses this feedback between management action and improved learning, is called actively adaptive. This approach specifically considers the gain, with respect to management performance criteria, from taking management actions and observations that improve parameter estimation and the power to discriminate between alternative hypotheses about resource dynamics. For use of an adaptive strategy to be warranted, it must be shown that any costs associated with altering the management actions and monitoring are justified by improved attainment of the management policy objectives. In the two examples that follow, the IWC development of a rebuilding strategy for whales used a passively adaptive approach, whereas the rebuilding strategy for the Australian Northwest Shelf used an actively adaptive approach.

Development of a Stock Rebuilding Strategy for Whales by the IWC

I must reiterate here that I have not been involved with this research myself, but rather I am providing a second-hand report of the work of the Scientific Committee of the IWC. Details are provided in the reports to the IWC of the Subcommittee on Management Procedures (Anonymous 1990, 1991b), and references therein.

The research task can be summarized as identification of rules for setting the catch levels that would meet the management objectives of (1) providing the highest continuing yields, (2) providing stable yields, and (3) not seriously increasing the probability of extinction by exploitation. The data available and the problems associated with them were:

- Catch histories, but there were many unresolvable questions about accuracy and precision of the data.
- Catch rate from the commercial fleets, but when examined in depth it was concluded that there was no reliable way to derive an index of abundance from these data even for data subsets for which accuracy and precision was thought to be reasonable.
- Basic biological parameters such as growth, mortality, and birth rates, but these estimates were found to be very weak and many important biological parameters were unknown.
- Absolute abundance estimates from sightings, which were found to have many problems, but were thought to be the most objective and quantitatively accessible data available (the statistical properties are mostly at least estimable).

Consequently, there was a strong emphasis in the development of a management strategy that used fishery independent survey data as the main scientific data input to decision making. The main uncertainties that were of concern in development of the strategy were stock structure, the appropriate structure of the population dynamics model, the initial population size, bias and trends in the survey abundance estimates, and the accuracy and precision of catch histories.

The approach taken was to develop an agreed set of performance criteria based on the management objectives, to identify a range of models and conditions that encompassed the main uncertainties and concerns (i.e., resource model structures, stock structures, initial population sizes and bias, and imprecision in catch histories and abundance estimates), to use these models and conditions in random combination to generate many example data sets of catch and survey observations, and to pass these data sets to independent working groups of scientists for analysis. These groups of scientists had developed different methods of analysis (e.g., see Anonymous, 1990), and the aim was to try to find a combination of resource model, estimation methodology, and decision rule that would best meet the performance criteria across the range of uncertainties considered.

The method that was found to perform best (as of July 1991) had the following features.

The resource model

Biologically mechanistic, complex models did not perform well owing to difficulties in parameter estimation and model specification. This finding is consistent with the suggestion that the optimal model complexity for prediction, given the data available from most fisheries, is low (e.g., Sugihara et al. 1984). The resource dynamics model chosen as performing best under the trial conditions was a difference-equation-based production model,

$$B_{T+1} = B_T + rB_{T-1}(1-B_{T-1}/K) - C_{(T,T-1)},$$

where B_T is the biomass at time T, $C_{(T,T-1)}$ is the catch in the interval $(T,T-1)$ and r and K are estimated constants. B_O, the unfished equilibrium biomass, is also an estimated parameter.

Parameter estimation

In each time step a Baysian updating method was used to update the estimates of r, K and B_O from observations of catch and the estimated stock biomass from surveys. The particular updating procedure gives very low weight to the most recent data, and so the updated estimates change very slowly as new information becomes available. This strong damping means that the parameter values will remain close to the values determined by historical data for a long period, and will remain unresponsive to new data indicating that the historical data are unreliable or reflect genuinely different productivity levels. On the other hand the strong damping will prevent management from being misled by a few outlying data points from the surveys.

The decision or control rule

It was found that the use of a proportional harvest-rate control rule (see Figure 2.2) performed very well in providing an appropriate annual catch level in the situations examined. This rule results in a more rapid reduction in catch as population size decreases, which is the case for most of the commonly used control rules in fisheries management. To calculate the appropriate catch level, first the statistical distribution of the predicted annual catch level was calculated from the estimated joint distribution of the parameters of the production model (r, K, B_O) and the underlying control rule. This approach does not explicitly estimate the biomass in the current year and derive the appropriate current years catch level from that estimate. Rather, it treats the distribution of annual catch level as a function of the random variables (r, K, B_O) and the catch history so as to calculate the corresponding distribution of the annual catch level. The catch limit to be actually imposed was then chosen to be the median of the resulting distribution of the predicted annual catch level. The procedure could be made more or less conservative by decreasing or increasing the chosen point on the cumulative frequency distribution from 50%. More complex treatments of utility across the distribution of the annual catch level were examined, but it was found that the simple use of the median performed acceptably.

The use of the approach outlined above resulted in the development of scientific and agreed upon management advice despite considerable uncertainty in knowledge of the resource and strongly held views about the fisheries concerned.

Development of a Stock Rebuilding Strategy for a Tropical Demersal Trawl Fishery

The details of this example are given in Sainsbury (1991). The background to the problem was that the Northwest Shelf of Australia had been extensively trawled by a foreign fleet, over which time the species composition had changed considerably. In particular, the more highly valued species groups had declined in abundance, while the less valued species groups had increased. There was a desire to develop a domestic fishery on the Northwest Shelf, and a small domestic trap fishery existed in inshore areas that were not trawled, but only the more highly valued species were economically marketable in Australia. A stock rebuilding strategy for the higher valued species was required, but there were major uncertainties about the dynamics of the resource and the economic responses of the Australian fishing industry. The dynamics of diverse tropical fish communities are not understood, and it was possible that the changes were not reversible; it was also unclear whether an Australian industry would invest and develop in this remote region even if the resource did recover.

The approach taken was to use a framework similar to Figure 2.4 to examine the performance of some active and passively adaptive management strategies across some major sources of uncertainty. The uncertainties explicitly considered included:

- The structure and biological basis of the resource dynamics models.
- The parameter values for the resource dynamics models.
- The success of implementation of management controls.
- The response of industry catching capacity to changed resource availability.

The performance criterion used for comparison of different strategies was the expected net present economic value from the resource to Australia, which follows from the policy objective of maximizing the benefit to Australia from the resource. The evaluation considered two periods of time, beginning from the present: A learning period, during which an actively adaptive management regime might be attempted and during which annual resource surveys would be conducted (the cost of which is included in the economic calculations); and a subsequent period of a fixed long-term management regime. At the end of the learning period the available data were used to select the long-term regime from a set of possible regimes, which included the optimal regime for each resource dynamics model considered. The expected net present value was calculated from the revenue/cost flow through time for each of a large number of simulations of the learning period, the decision process, and the subsequent long-term regime. The objective was to determine what actions (management actions and monitoring) through the learning period, and what duration of learning period, results in the greatest expected net present value from the resource. A good learning period management regime and observation regime would allow correct and cheap identification of each alternative resource model if it was true, so that the appropriate long-term regime is selected at the end of the learning period. A poor learning-period regime would either result in frequent incorrect identifications of the resource model, so that an inappropriate long-term regime was often selected, or would have cost more to implement than was returned through improved management. The cost effectiveness of the observation process is an integral part of the calculation, and the evaluation is made across all of the uncertainties mentioned above.

The approach had the following general features.

The resource dynamics models

Four types of models were examined, each emphasizing a different ecological interpretation. All models were consistent with the available historical data and the parameter values were estimated from those data. The models were a multiple single-species model, two different versions of competition/predation interactions, and a habitat-limited carrying capacity model. The habitat limitation model was based on the observations that the more valuable species tended to occupy demersal habitat containing large epibenthic organisms (e.g., sponges and corals), the less valuable species tended to occupy open demersal habitat, and that trawling could convert habitat with large benthic organisms to open habitat. All models were simple difference equation production models.

Parameter estimation

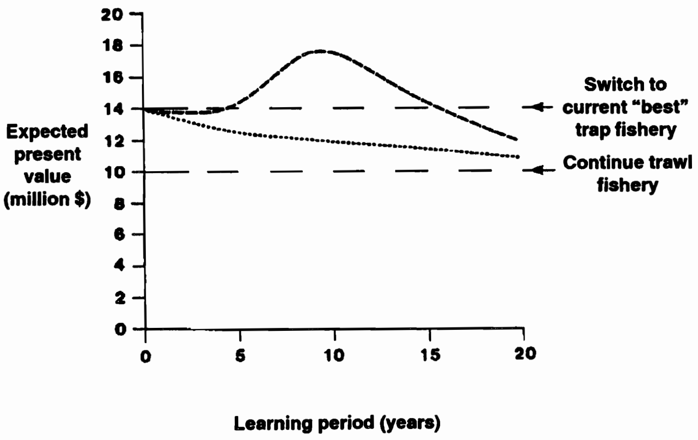
Model parameter values were estimated from historical data at the beginning of the simulations, and uncertainties in this estimation were used to define a number of model-parameter set combinations that were treated as fixed alternative models in the evaluation (i.e., combining parameter uncertainty and model structure uncertainty in the resource dynamics model). The initial probability placed on each of these alternative fixed models was calculated from the likelihood of the historical data fitted to these models. At the end of the learning period the probability placed on each alternative model was updated using Bayes Theorem. In this context, the updated probability is conditional on the correct model, so that the procedure calculates the probability placed on model *i* when model *j* is true. It is these conditional probabilities that reflect the success or failure of the learning period in providing discrimination between the alternative resource dynamics models.

The decision or control rule

The focus of this evaluation was not the nature of the appropriate control rule. Rather, it was to compare the performance of active and passively adaptive management strategies during the learning period in resolving the uncertainties in resource and economic dynamics. In this application, a constant catch quota was used as the long-term management regime, with the decision about the size of the quota and whether to use a foreign trawl or domestic trap fishery being made at the end of the learning period on the information available. For each alternate management action (quota level and fishery type) applied to each resource model, there is a perceived economic return (based on the estimated parameter values for that model and the estimated state of the stock at the end of the learning period), and there is also a probability placed on each model being true. In the evaluation, a risk neutral decision is assumed, so that the management action with the greatest expected return is chosen.

The results of the evaluation are shown in Figure 2.6. An immediate switch from foreign trawling to domestic trapping was calculated to give a higher expected economic return than

Figure 2.6.—The relationship between expected net present value from the resource (for a discount rate of 0.05) and duration of the actively adaptive learning period for a number of possible fishing regimes. The two horizontal lines relate to the degenerate cases of immediately adopting the apparently best trap fishery and continuing the foreign trawl fishery, and so neither are actively adaptive strategies. The expected economic return from adopting a trap fishing regime is higher than that of the foreign trawl fishery. The finely dashed line gives the expected return from the passively adaptive strategy of monitoring the foreign trawl fishery for the duration of the learning period. This is not an informative strategy and the expected economic returns continue to decline the longer that strategy is followed. The course dashed line is for an actively adaptive strategy that closes half of the Northwest Shelf to all fishing for the first half of the learning period and then allows a trap fishery to expand in the second half of the learning period; the trawl fishery is continued on the other half of the shelf for the duration of the learning period. The expected economic return for this strategy is greater than the next best strategy for learning period durations of about 5 to 15 years.



the passively adaptive approach of continuing to monitor the foreign trawl fishery. In the situation examined, a passively adaptive strategy cannot resolve the key uncertainties about resource and economic dynamics because it does not provide the opportunity for the collection of data with the necessary statistical contrasts for model discrimination. Some actively adaptive strategies gave a higher expected economic return than the immediate switch to a trap fishery. Particular strategies that intentionally closed some areas to trawling and later allowed expansion of a trap fishery gave higher economic returns than an immediate switch to trapping if the trials were conducted for an appropriate duration. The trials gave a higher expected economic return if they were conducted for longer than about 5 years and less than about 15 years. Trials that operated for less than about 5 years were suboptimal because there were too few observations made over such short periods to allow reasonable model discrimination, and so they would frequently provide ambiguous or incorrect indications of resource productivity. Trials that operated for more than about 15 years provided good model discrimination and identification of the most appropriate long-term regime, but the cost (research surveys and forgone catch) in obtaining this information exceeded the returns in improved long-term management of the resource. Trial trawl closures were implemented on the Northwest Shelf, and have now been in place for 7 years.

Discussion

The use of simulation to examine the performance of management strategies is a very valuable tool in fisheries science, and in my view it has not been used enough. Simulation studies can not only help identify key weaknesses in strategies that are being applied, but can also be used to derive strategies that are robust to particular uncertainties and concerns. They make explicit the links between objectives, observations, reference points, and decision rules, and they make it clear that at least as much thought should be given to the way reference points are to be used as is given to how they are defined. Most importantly, in my view, the approach encourages evaluation of the whole interacting management process, encourages the development and use of management policy performance criteria, and raises the question of what is actually needed to achieve the performance criteria. The evaluation of management strategies, and answers obtained, are multidisciplinary. Effective interaction between the research, management, and fishing industry groups is necessary to get the most benefit out of what can be done.

And finally, the overall framework outlined here provides for the evaluation of actively adaptive management strategies, which I believe are vastly underutilized in fisheries management. The application of actively adaptive strategies is not limited to large and extreme actions, such as the trawl closures on the Northwest Shelf. Rather there are many small but potentially informative possibilities for actively adaptive strategies associated with most fishery management actions. Every time a management measure is changed, for whatever reason, the introduction of the change could be used as an actively adaptive manipulation from which we could learn about the dynamics of the resource, the fleet, or the dynamics of the economic system. Each time a change is made the questions that should be asked are:

- How can this change be introduced in such a way as to allow learning about some aspect of the fishery that is of value to future management, and
- Are the costs associated with attempting to use the introduction in this way warranted by the expected benefits to future management?

The answers to one or both of these questions in many, perhaps even most, cases may well be "no." On the other hand, just a few cases where the answer is "yes" should help maintain and improve the scientific basis of fisheries management.

Summaries of Contributed Papers

A Comparison of Event Tree Risk Analysis to Spawner-Recruit Simulations for Evaluating Management Targets

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Summary

Fishery stock assessments often attempt to provide future projections of population abundance and landings on which management decisions can be based. However, uncertainties in estimating important variables that drive such projections are often considerable. One approach for characterizing these uncertainties is to project future population abundance with an age-structure model incorporating uncertainty in a spawner-recruit relationship. An alternative approach involves reducing spawners and recruits to discrete categories, and applying conditional probabilities to determine subsequent recruitment from spawning biomass (Event Tree analysis).

The purpose of this study is to compare two approaches using parallel simulations with Atlantic menhaden data. The Atlantic States Marine Fisheries Commission's Atlantic Menhaden Advisory Committee selected six biological "trigger" variables for invoking a potential management response. These variables include landings in weight, proportion of age 0 menhaden by numbers in the landings, proportion of age-3 and older menhaden by numbers in the landings, recruits to age 1 by numbers, spawning stock biomass, and maximum spawning potential. The final variable, maximum spawning potential (MSP), serves to define different constant levels of fishing mortality for the simulations, while the first five variables serve as biological reference points for comparing the simulation results.

For four of the five biological "triggers" (Fig. 2.7–2.9), the risk associated with the Ricker simulation approach was greater than that associated with the Event Tree approach at the 1980's level of fishing mortality (MSP of 4.5%). However, the risk associated with the Ricker approach did not decrease significantly when fishing mortality was decreased to correspond to an MSP level greater than 10%, while the risk associated with the Event Tree approach continued to decline when fishing mortality was decreased to correspond to MSP levels of 20% and 30%.

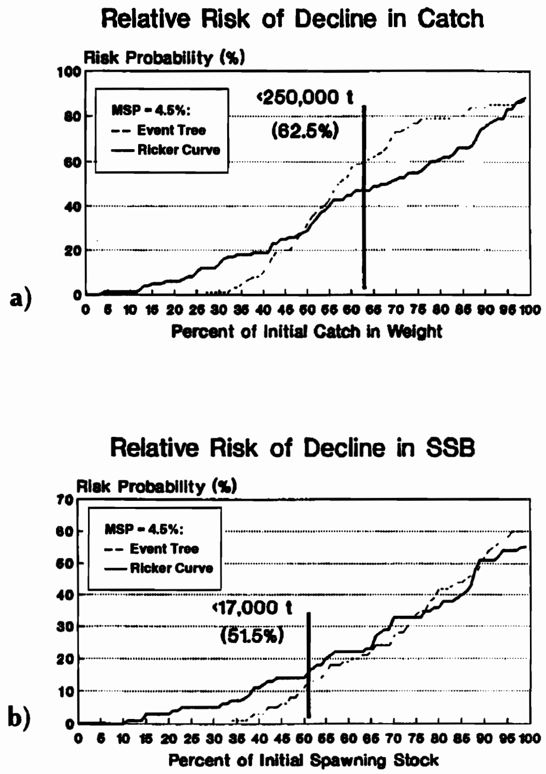
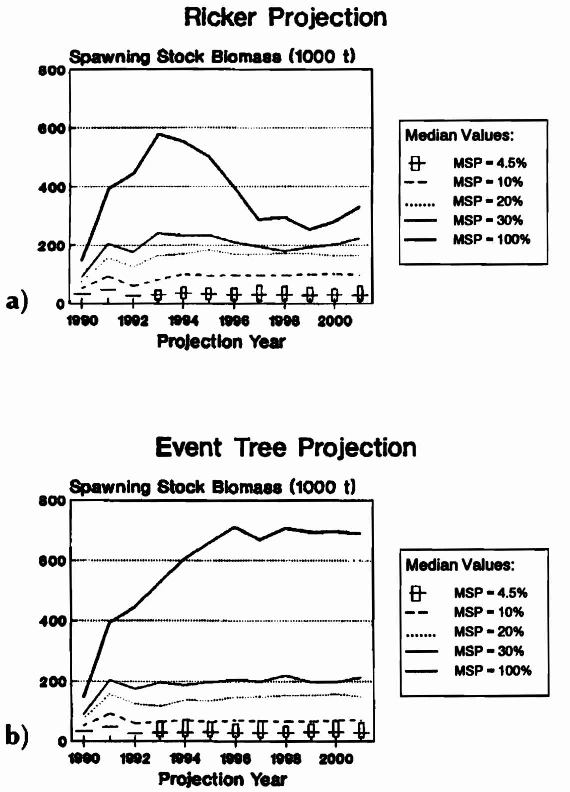
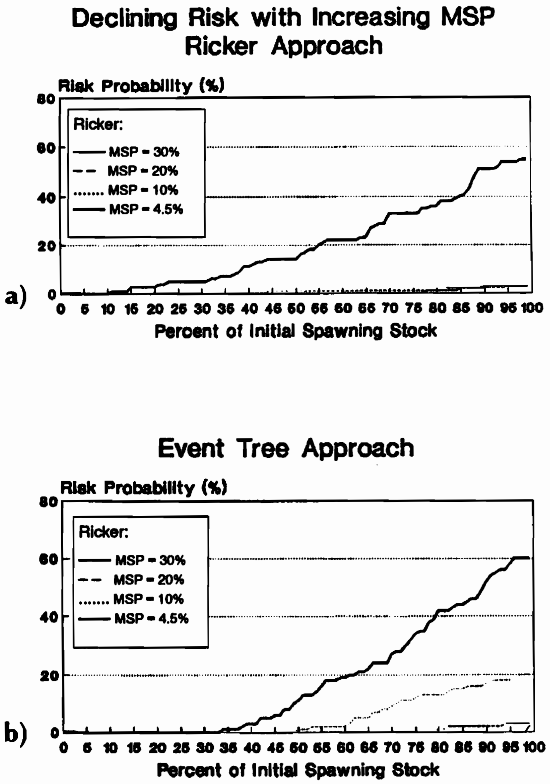


Figure 2.7.—Probability that a) catch, and b) spawning stock size decline to percent of the initial year given on the abscissa.


Ricker Projection

Event Tree Projection

Figure 2.8.—Projections using the a) Ricker stock recruitment relationship, and b) Event Tree stock recruitment relationship for different levels of fishing mortality rate expressed as percent maximum spawning potential.


Declining Risk with Increasing MSP Ricker Approach

Event Tree Approach

Figure 2.9.—Probability of spawning stock declines for different levels of fishing mortality expressed as percent maximum spawning potential for the a) Ricker stock recruitment relationship, and b) Event Tree stock recruitment relationship.

Probabilities Associated with Biological Reference Points in Relation to Current Stock Status

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Summary

Increasingly, overfishing is being defined in management plans by fishing mortality-based, biological reference points (e.g., $F_{0.1}$, F_{med}, $F_{\max}$, etc.). In implementing these plans, it is common to compare the fully recruited fishing mortality rate in the most recent year (F_t) with the applicable reference point (F_{ref}) and to draw conclusions with regard to overfishing based on this comparison. It must be realized, however, that both F_t and F_{ref} are estimated with error (Fig. 2.10). The variance of these estimators and the shape of their parent distributions are germane in any such comparison.

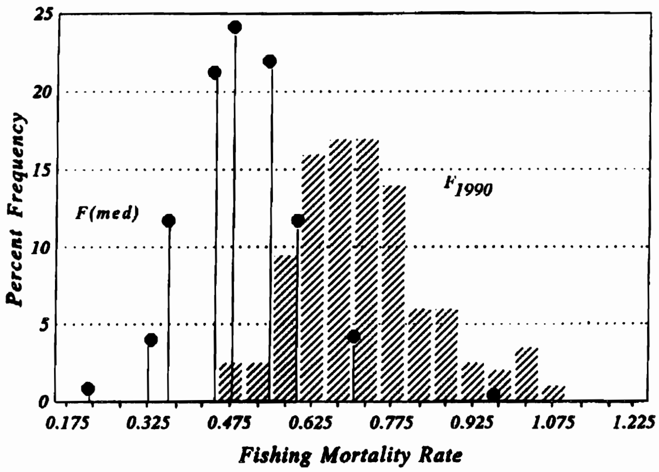

Figure 2.10.—Probability density function for the estimate of fully-recruited fishing mortality rate in 1990 - F_{1990} - (pattern-filled bars); and probability density function for the estimate of F_{med} (vertical lines topped with dots) for Georges Bank cod. Both density functions were estimated using the bootstrap procedure.

Bootstrap procedures are used to categorize the variances and distributions of F in 1990 (F_t) and a commonly used reference point (F_{med}) for Georges Bank cod, haddock, and yellowtail flounder. Probabilities are calculated for three hypotheses:

(1) That $F_{1990} = F_{\text{med}}$ (within some tolerance level).
(2) That $F_{1990} > F_{\text{med}}$ (for various tolerance levels).
(3) That $F_{1990} < F_{\text{med}}$ (for various tolerance levels).

The resulting probability profiles for Georges Bank cod under hypothesis (2) are shown in Figure 2.11. The method described should prove to be a useful tool for providing stochastic, risk-averse management advice based on standard stock assessment results, e.g., results typically available from age-structured models.

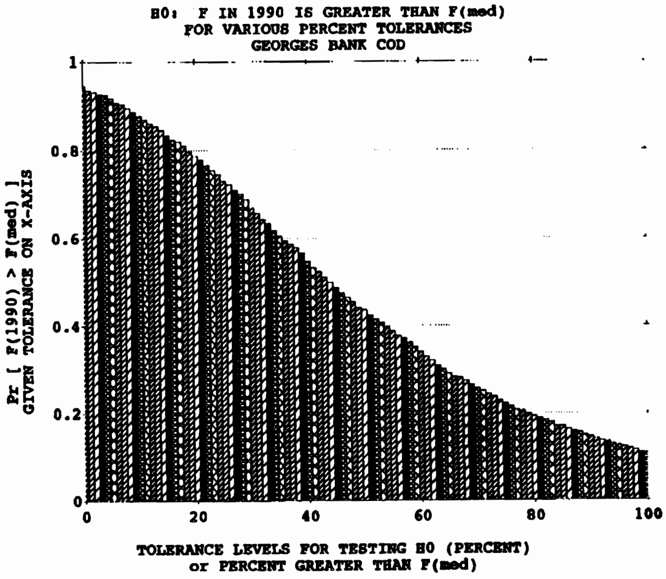

Figure 2.11.—Probability that the fully-recruited fishing mortality rate in 1990 (F_{1990}) is greater than F_{med} by the various percentage levels given along the X-axis for Georges Bank cod. For example, the probability that F_{1990} is at least 20% greater than F_{med} is 0.78.

Overfishing Definition for Anchovy—A Simulation Model Approach

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Summary

Management of northern anchovy, *Engraulis mordax*, including the definition of overfishing and annual quotas, is based on estimates of spawning biomass rather than fishing rates. The current definition of overfishing in the FMP for northern anchovy stops all fishing when the estimated spawning biomass falls below 50,000 tons two years in a row. Annual quotas for the U.S. reduction fishery are set to the difference (not to exceed 200,000 tons) between estimated spawning biomass and a 300,000 tons threshold level. The reduction quota is zero when estimated spawning biomass is less than the 300,000-ton threshold. Thus, the issue of an overfished stock is addressed by eliminating harvests at low biomass levels, while the issue of overfishing is addressed by reducing harvest as biomass declines. This approach illustrates how the definition of overfishing and procedures for specifying harvest levels can be used together to prevent overfishing or to rehabilitate an overfished stock.

Options for the definition of overfishing in the FMP for northern anchovy were evaluated using a simulation model that included population dynamics of the anchovy stock, reproductive success of brown pelicans (an endangered species that utilizes anchovy as forage), and economics of the fishery. Economic data were used in the model to determine when fishery segments would cease fishing as biomass declined and profits decreased. One version of the model was used to evaluate options in terms of anchovy biomass levels, harvest levels, fishery profits, and brown pelican reproductive success. Another version of the model was used to estimate recovery times (duration of intervals required to increase from low to high biomass levels).

Evaluation of overfishing definitions as carried out for anchovy requires a great deal of biological and economic data that may not be available in many cases. There were no biological data available for northern anchovy from periods of very low biomass, although such data would have been useful for evaluating a definition of overfishing. Simple surplus production models, such as the one used in the simulation for anchovy, may be too optimistic for evaluating the performance of management options at low biomass levels, particularly if autocorrelation in process errors affecting stock dynamics is not included. Explicit consideration of fishery economics was useful in the model for anchovy and may be for other fisheries as well. Potentially important issues not addressed in the model for northern anchovy include errors in spawning biomass estimates used to set quotas and to trigger the definition of overfishing, and the effects of fishing effort at low biomass levels (is it possible to catch the last fish?).

Session III: Developing Advice for Stock Rebuilding Programs

Session III Summary

Moderator: Vaughn Anthony, NEFSC
Rapporteur: Gerald Scott, SEFSC

A. MacCall of the NMFS Southwest Fisheries Science Center's Tiburon Laboratory led off this Session by providing a thoughtful overview paper to stimulate and guide our subsequent discussion. His theme was the practical considerations of defining and determining stock rebuilding programs with emphasis on the biological and ecological concepts that we must consider in developing rebuilding criteria and the management policies that such criteria imply.

In characterizing rebuilding, we must note the difference between overfishing (an excessive rate of fishing) and depletion (a state of low stock abundance). Rebuilding refers to the improvement of a stock from an initial state of depletion. The dimensions of this might include a threshold of abundance or relative abundance, age (size) distribution attributes and geographical distributions.

Stock rebuilding is always difficult because it calls for a change in the status quo. This requires the exploration of many management scenarios in order for management to determine the least disruptive action. Numerical modeling and stochastic programming have become important tools in this process.

However, patterns of recruitment variability are often an important obstacle in projecting the consequences of management actions: Recruitment that is cyclic, long-lived fish with rare exceptional recruitment events, high variances of recruitment and environmental regimes. Additionally, activities such as bycatch, hatcheries, and artificial habitats may contribute both positively and negatively to rebuilding.

Contributed Papers

D. DeMaster discussed the history of U.S. Pacific coast pinnipeds and efforts to rebuild those resources. Complete protection of pinnipeds has resulted in increases through the 1980's and increased direct (and presumably indirect) conflicts with finfish and invertebrate fisheries. Sea lion abundance increased an average of approximately 11% per year with a high of 14%. Elephant seals have increased 14-15% per year. Resulting fishery conflicts have led to research approaches to address the problems including evaluation of prey populations, consumption, and experimental culling activities.

Recovery actions for U.S. Gulf of Mexico king mackerel and the implications of increased research effort to reductions in risk were reported by J. Powers and V. Restrepo. Short time series, limited information, and risk-prone management actions resulted in overfishing of this resource in the early 1980's. A "control law" of $F_{0.1}$ was established to allow the stock to recover. While management implementation has not been perfect, progress has been made toward recovery. The authors conducted Monte Carlo simulations of VPA's and projections of allowable biological catch using several scenarios of enhanced research investment. Risk averse management resulted in expected yield increases and opportunity loss of foregone yield and lost surplus decreases.

D. Ito examined the scientific assessment activities related to the development of Pacific Ocean perch (POP) recovery plans. POP are extremely long-lived with low natural mortality (M=0.05) and low fecundity. The resource is monitored by several survey indices which relate to abundance in varying degrees. Impacts of survey variability upon status assessments and recovery *F*'s were evaluated by 200 iterations of bootstrap survey estimates. Results indicated that $F_{0.1}$ performed well in recovery.

Overholtz, R. Mayo, Gabriel, and Murawski discussed the assessment efforts and criteria that have been developed to address the recovery of New England groundfish. Litigation and legislation actions have occurred to establish a goal of recovery of the suite of groundfish resources within 5 years. This implies *F* and effort reductions of the fleet will be needed. Implications for SSB/R were analyzed using a multispecies model with stochastic recruitment. Recruitment uncertainty remains the largest component of overall uncertainty.

The implications of indeterminate spawning and migratory behavior of small pelagic stocks on rebuilding processes were discussed by Parrish. Traditional MSY, virgin biomass, and K concepts are less appropriate for these dynamic populations. Reproductive success is driven by rather specific environmental and ecological phenomena, leading to highly skewed recruitment distributions. This may argue for lower thresholds, but with probabilistic evaluation approaches.

Discussion

A rebuilding program implies that 1) a level at which the stock is determined to be depleted is defined; 2) a level at which it is deemed not depleted is also defined (it does not have to be the same level); 3) population/ecosystem characteristics of the preferred state are determined; 4) rates of fishing are specified over the entire time of program; and 5) acceptable probabilities of membership in the set of depleted or nondepleted states are specified.

The question of the level to which we are to rebuild includes socioeconomic and policy aspects of what is considered to be optimum. While there may be some minimum level of abundance at which the stock is removed from appreciable risk, there may still be economic criteria for continuing the recovery program. However, a minimum recovery level should not be viewed as a target about which realized abundance fluctuates. The level should be sufficiently high so that the probability of falling below it in a particular year is small.

The *F* strategy should be tailored to desires of management and to account for environmental and ecological contingencies. For example, reductions in *F* do not have to be proportionally adjusted for all ages. Equivalent consequences in terms of SSB/R may often be achieved using a variety of *F*-at-age vectors. Some of these may be more socially acceptable than others.

It was noted that mandates exist to include ecological and multispecies criteria in the process of developing a plan for recovery. The MMPA calls for consideration of the health and stability of the ecosystem and for functioning parts of the ecosystem. ICES approaches have looked at technical as well as biological multispecies interactions. Policy objectives of multispecies plans must be clearly spelled out.

Perhaps, the most difficult aspect of defining the time stream of *F*-targets in a recovery plan is the uncertainty imposed by recruitment variability. We need to consider the stochastic consequences of the recovery program including this source of variability.

Essentially we are in the process of developing criteria within the F-SSB space to define the region of depletion-overfishing, the region of surplus-underexploitation, and the region of transition from the former to the latter. Many alternatives may exist in the transitional region, but we need to explore both empirically and theoretically, the efficacy of the various pathways.

Overview Paper: Advice for Stock Rebuilding

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Introduction

Stock rebuilding is a treacherous area of fishery research and an even worse area for fishery management. Rebuilding usually requires imposition of crippling constraints on fishing activity at a time of already severe economic hardship. Fishery scientists may have to advocate very unpopular actions, knowing that the results of the rebuilding program may not be apparent for years. And there is always the possibility that the proposed program may be ineffective, or alternatively, that the stock will miraculously recover without a rebuilding program. If rebuilding is successful, there will be a clamor to loosen the restrictions prematurely. Rather than being hailed as heroes for saving the resource, the scientists and managers are once again cursed, this time for their reluctance to free the industry to harvest the weak but recovering resource.

Fishery managers are like referees in a brutal game of industry vs. resource, except that at the beginning of the game no one has ever located the book of rules. The fishery scientists are supposed to infer the rules of the game, and to explain those suspected rules so that the manager-referees will make good "calls." Stock rebuilding is even more difficult. With a depleted stock, both teams are playing with severe injuries, and the players risk being cut from next year's teams if they slack off. Uncertainty is magnified, and many undiscovered rules are waiting to trip up the participants.

In cases of rebuilding or otherwise, fishery scientists are often faced with having to provide an "educated guess" of what resource conditions are, and to recommend appropriate management actions. Caddy and Gulland (1983) warned managers that "Account should also be taken of the fact that the greater the general uncertainty, the greater the likelihood that the advice will contain some element of the subjective views and prejudices of the scientific experts." In the case of stock rebuilding, there are few if any experts, but there are many subjective views and prejudices. The following is a sampling of some of my own, drawn mostly from my experience with west coast stocks.

Overfishing vs. depletion

The term "rebuilding" implies an initial state of depletion, i.e., a starting point where abundance or other important stock attributes need to be enhanced. The term "overfishing" has taken on a multitude of formal definitions under the Regional Fishery Management Councils (FMC's), but very few of those definitions are close to being synonymous with "depletion." Most of the overfishing definitions have focused on overfishing as a process, and typically define overfishing in terms of harvest rates (*F*). These process-oriented definitions potentially allow a stock to classify as being "overfished" even when abundance is high, and to escape that classification even when abundance is unacceptably low. A minority of FMC overfishing definitions have focused on the state of the stock, such as relative abundance; these definitions relate more directly to depletion and stock rebuilding.

For the purpose of this discussion, I will assume that rebuilding is needed to improve the state of the stock from an initial condition of depletion. Importantly, the depleted state may or may not have been caused by excessive harvesting. Adverse environmental conditions may also contribute to depletion. Stock rebuilding programs must recognize these forces, some of which we can control (harvesting rate, perhaps habitat quantity or quality), and some of which we cannot control (natural environmental influences, economic climate).

Dimensions of depletion and recovery

The most general measure of depletion is relative abundance, although other attributes of the stock may warrant consideration. While it is easy to set nominal depletion thresholds for stocks in the abstract (e.g., an arbitrary 20% of B_{MSY}), the problem can be much more difficult in real cases. Some practical considerations might be whether biological reference points such as B_{MSY} can be measured or estimated, whether those points are meaningful and/or whether they vary naturally, and how frequently an unfished stock might decline to the proposed threshold level of abundance. These technical problems will be addressed in a later section.

The prior history of the stock or fishery can have a strong influence on management perceptions and hence on setting a nominal depletion threshold. While stock is abundant early in the development of a new fishery, managers and industry might find it easy to agree on a high or conservative nominal depletion threshold level of perhaps 50% of B_{MSY}. In contrast, managers of an already depressed stock might be inclined to set their threshold much lower. This tendency is encapsulated in the universal management epitaph of collapsed fisheries, “Too little, too late.”

Once we have defined a threshold level for “depletion,” we are faced with a similar dilemma in defining a complementary threshold level for “recovery.” In principle, the recovery threshold might be thought of as the level at which rebuilding is no longer necessary or distinguishable from management-as-usual. Again, due to the contextual viewpoint of managers, the recovery threshold may tend to be set higher from the viewpoint of a healthy stock and much lower from the viewpoint of a recovering fishery which is suffering economic hardship.

There may be other stock attributes in need of rebuilding, and recovery thresholds may be multidimensional or hierarchical. Recreational fishermen often value large “trophy” fish, in which case the recovery criteria may specify a minimum percentage of individuals larger than W_{trophy}. Demographically, rebuilding the spawning potential of a depleted stock may require similar considerations. For example, in some multiple-spawning clupeoid populations, older fish make a disproportionately large contribution to population fecundity (Parrish et al., 1986). The number of age groups in the population may also be important in buffering against prolonged spawning failures (Murphy, 1967, 1968). Corresponding recovery criteria could be cast in terms of a minimum proportion of fish older than age at recruitment, a minimum variance of ages, or a minimum mean age in the population.

Another attribute which may require rebuilding is geographic distribution. Depleted populations often exhibit a contraction in range (MacCall, 1990). Range contractions may be accompanied by a loss of spatial risk-spreading by the spawning population and increased coefficient of variation in reproductive success (Parrish and MacCall, 1978). Reproductive locations may be abandoned (e.g., herring, fur seals), leading to decreased current carrying capacity, decreased productivity, and slower recovery. Contraction in range can have severe economic consequences, leading to collapse of regional economies, as happened with the loss of the Pacific sardine, *Sardinops sagax*, at Monterey (Ueber and MacCall, 1992). If geographic distribution is a concern, the recovery criteria could include a minimum geographic range.

A variety of economic considerations may bear on setting depletion and recovery thresholds. Economically optimal abundances are usually above B_{MSY} and would argue for a higher recovery threshold. Conversely, discounting (i.e., the argument that $1.00 earned this year may be equivalent to $1.05 earned next year) would argue for a somewhat earlier declaration of recovery in the time course of rebuilding.

This author offers the following recommendation: Fishery management plans should include (to the extent possible) specifications of depletion thresholds which trigger a rebuilding program and recovery thresholds at which the rebuilding is complete. These specifications should emphasize relevant measurable states or properties of the stock (abundance, age or size structure, distribution). These thresholds should be specified as early as possible in the course of fishery development, and well in advance of their being reached. Their function is to provide managers with objective reference points so that rebuilding is neither initiated too late nor abandoned too soon.

Note that this recommendation resembles the MFCMA guidelines for overfishing definitions recently implemented for the Nation's FMP's. My recommendation differs in that it is oriented directly to the problem of rebuilding, whether the depleted state is due to excessive harvesting or to natural variability.

Developing Reasonable Expectations

Management of healthy fisheries may suffice with little more than an attempt to maintain the status quo; there is no pressing need to define what the status quo is. Stock rebuilding poses much more difficult problems. Not only do we have to define the status quo as a point of departure, but we have to evaluate alternative choices of how to rebuild with regard to a variety of goals and performance criteria, from recovery rate to socioeconomic impact. Fishery managers may be under severe pressure to minimize restrictions due to economic hardships being suffered by the fishing industry. One task of fishery analysts is to provide decisionmakers with a clear set of "reasonable expectations" of possible future resource and fishery developments, problems, and interactions. This calls for a formal, objective approach to forecasting future environmental, biological, economic, and social aspects of the fishery.

Exploration of scenarios

A useful first step in the process of developing reasonable expectations is to explore "scenarios" of possible or likely future events. The scenario approach to forecasting was popularized by Herman Kahn of the Rand Corporation. Development of possible future histories of the resource and fishery allows much more intuitive freedom than does a numerical model, but may suffer from lack of objectivity. Useful and insightful scenarios can be developed without detailed knowledge of demographic parameters, many of which may not be known in any case. This approach also allows participation by knowledgeable participants who may lack the mathematical training to conduct numerical modeling.

A further strength of exploring scenarios is the ability to address societal issues. Societal issues are difficult to quantify, and are seldom addressable by conventional numerical models. Previous societal responses to resource collapses and rebuilding attempts have been documented for a wide variety of fisheries (Glantz, 1992). Glantz offers these cases as a basis for "forecasting by analogy," a method closely related to scenario building.

These scenarios can be reviewed for features and critical elements that should be incorporated or explored in subsequent attempts at numerical modeling, as well as being addressed in the rebuilding plan itself. Moreover, participation by managers and decisionmakers in a scenario-building exercise may improve their understanding of the more long-range consequences of their decisions and may strengthen their commitment to a rebuilding program.

Numerical modeling

Thorough evaluation of alternative stock rebuilding policies is very difficult without quantitative models of their performance. A variety of numerical modeling techniques can be used, and desktop computers are sufficient for most applications.

Deterministic Models

Deterministic equilibrium models such as surplus production models or stock-recruitment models can be useful for purposes of approximation. For example, a surplus production model can provide estimates of expected time-to-recovery given alternative harvesting rates. Unfortunately, the standard formulations of these models provide very limited information on the precision of the approximation. In principle, a range of times-to-recovery could be estimated from the confidence limits on the fitted production curve. A useful study would be to compare these estimates with actual times-to-recovery from corresponding stochastic simulation models.

Production models can be useful tools for examining some systematic behaviors of fisheries and their economics. For example, Fox (1974) showed that a systematic increase in catchability coefficient at lower abundances produces a curiously recurved production model (Fig. 3.1). The equilibrium yield curve retains its conventional shape at high abundances, but becomes unstable at low abundances and predicts collapse at fishing intensities only slightly greater than those producing MSY. The pattern of this instability would not be as easily interpreted in a stochastic model, but understanding this mechanism can be of crucial importance to rebuilding fisheries. If management decides to reduce nominal effort (such as fleet size), it may be necessary to reduce that effort drastically. A similar instability can result from depensation in the stock-recruitment relationship at low abundances (Clark, 1974), again requiring drastic reduction of fishing pressure.

The general utility of deterministic models is still a matter of debate; their strong assumptions are seldom defensible, but their simplicity may possess a robustness which makes them nonetheless useful. While deterministic models may provide useful guidance for healthy fisheries, I suspect that these models may lose reliability increasingly as stock size becomes small.

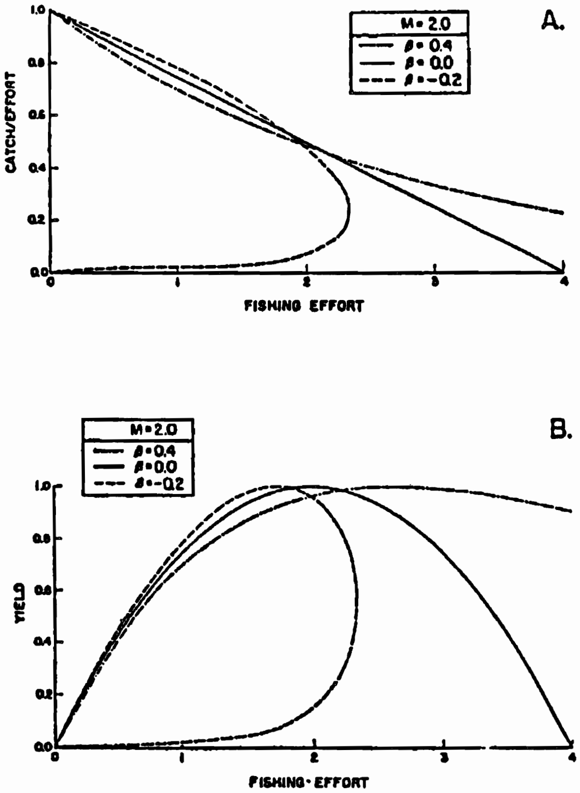

Figure 3.1.—Equilibrium relationships for a density-dependent catchability production model where the underlying biological production model is a symmetric Schaefer model. A is relationship of catch per unit effort to nominal fishing effort; B is relationship of equilibrium yield to nominal fishing effort. The recurved relationship occurs when catchability increases with decreasing abundance; the lower limb is an unstable equilibrium. From Fox (1974).

Stochastic Models

Stochastic models (i.e., models explicitly incorporating random variability) are more generally useful for examining stock rebuilding, especially where recruitments are subject to large year-to-year variability. Stochastic models do not predict specific future events but rather provide an overview of possible futures, and allow inference as to which futures are more likely than others. These models tend to be demanding both in information and in computation. Fortunately, depleted resources are often relatively rich in fishery data and information gained during the process of depletion. For example, it has been said that "VPA works best for post-mortems," the reason being that the high fishing mortality rates associated with resource declines also provide the high ratio of catch to natural mortality needed for precise population estimates.

Some stochastic models provide a concise analytic result. I discuss dynamic programming and Markov models as examples. A more common form of stochastic modeling is computer simulation which is much more flexible, but can be difficult to summarize or interpret.

Dynamic programming

Techniques of dynamic programming were first applied to problems of fishery management in the late 1970's (e.g., Walters and Hilborn, 1978), and more recently have been applied to a variety of problems in ecology by Clark and Mangel (1988). Dynamic programming is a technique for developing optimal sequential decision rules for a process where each decision affects likely future states of the system. In fishery applications, system states may be represented by various discrete levels of resource abundance and several states can be reached in the following year with various probabilities. This variant is called stochastic dynamic programming. The method requires a probabilistic model of the resource dynamics to generate the transition probabilities and an "objective function" specifying the quantity to be optimized or maximized by the decision rule. The key to solving for optimality is that the calculations become relatively easy if the process is considered backwards in time.

Although it was not applied to a depleted stock, Huppert's (1981) use of stochastic dynamic programming for the northern anchovy is an excellent example of this technique. The northern anchovy is relatively short-lived, and the resource dynamics can be approximated by a production model with large random variability about the average annual production. The desired decision rule took the form of a quota formula where allowable catch is a function of initial stock abundance (Fig. 3.2). The objective function consisted of estimated net economic value of the harvest after considering such details as price elasticity and variable operating costs of catching the quota at various stock abundances.

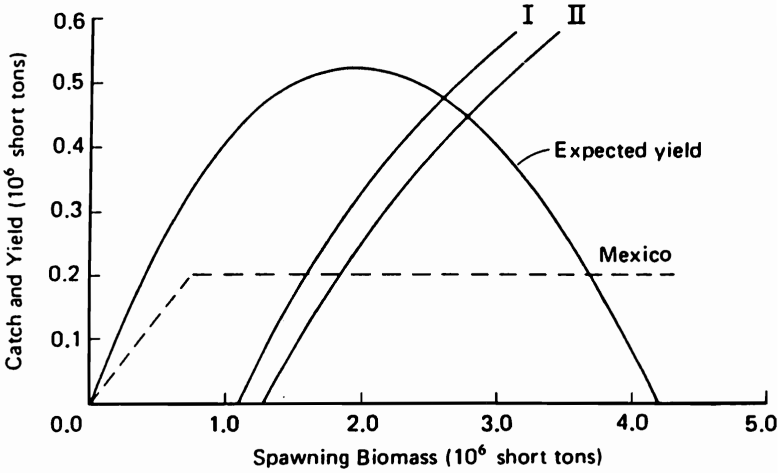

Figure 3.2.—Optimal anchovy harvest strategies for the U.S. reduction fishery, based on stochastic dynamic programming. Curve I is for fishery without Mexican competition. Curve II assumes Mexico takes an amount represented by the broken line. From Huppert (1981).

The significance of Huppert's dynamic programming solution is that the optimal decision rule, cast as an adaptive control policy or quota formula, clearly specifies a depletion threshold below which the allowable catch should be zero. In this case, the depletion threshold is a level of abundance below which it can be shown quantitatively to be economically unwise to fish the stock. In the case of the northern anchovy, the threshold was near 50% of B_{MSY}, somewhat higher if fleet size is large or if an independent Mexican fishery is assumed. Conversely, the threshold is lower if the fleet size is very small (Huppert, 1981). Moreover, the concept of stock rebuilding was integrated directly into the routine management of this highly variable resource. Above the depletion threshold, the allowable catch increases gradually and crosses the average equilibrium yield curve at a spawning biomass somewhat above that estimated to produce MSY, as is consistent with optimality in the standard bioeconomic version of the production model.

Markov models

The stochastic dynamic programming approach required calculation of transition probabilities between pairs of discrete stock sizes. For a particular adaptive control policy or quota formula, the model produces a matrix of transition probabilities which can form the basis of a Markov model. An important limitation of the Markov model is its requirement of ergodicity: Probability transitions must depend only on the initial state, independently of how that state was reached. MacCall (1980) developed a Markov model for the northern anchovy stock. The short-lived nature of anchovies allowed the ergodicity requirement to be met, at least approximately.

The Markov model allows development of several pieces of information useful to stock rebuilding. Under a decision rule of "no fishing," the probability distribution of unfished stock abundance can be estimated. This can be compared with the probability distribution for a fished stock, and provides a basis for distinguishing the effects of fishing from that of purely natural variability (Fig. 3.3). Also, the time course of future stock size probabilities can be projected from any arbitrary initial low abundance (Fig. 3.4), providing detailed statistical information on performance of alternative rebuilding policies.

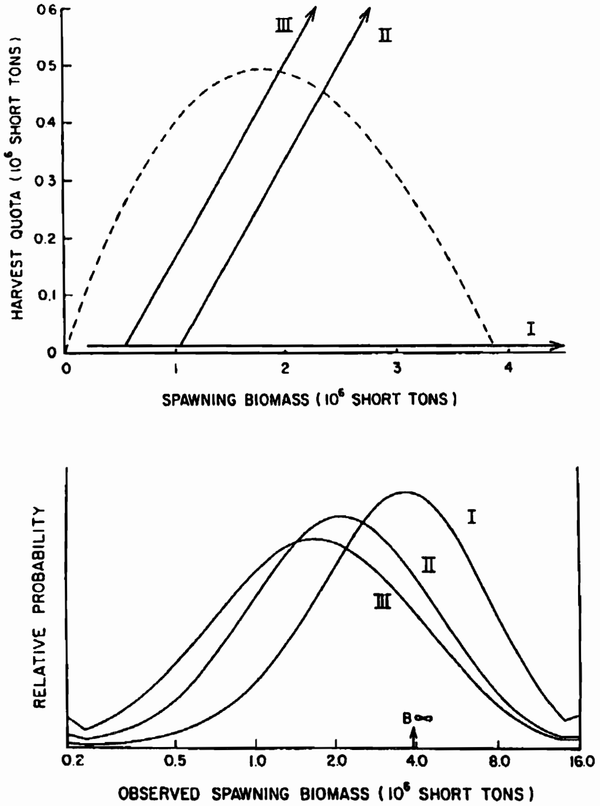

Figure 3.3.—Alternative anchovy harvest formulas and corresponding probability distributions of spawning biomass from a Markov model. Formula II was adopted by the Pacific Fishery Management Council. From MacCall (1980).

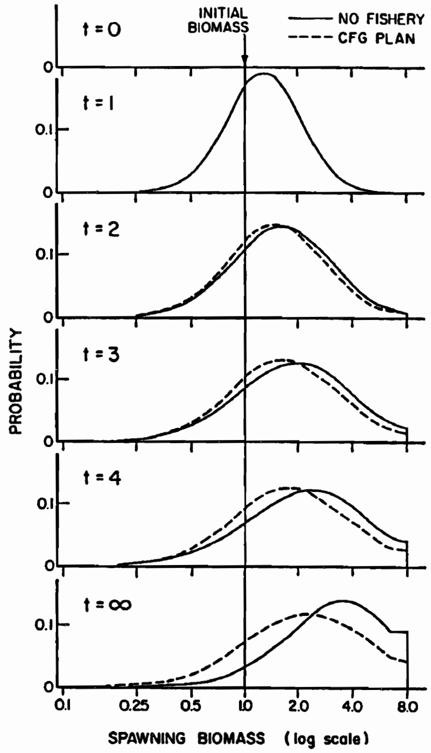

Figure 3.4.—Predicted northern anchovy population size distributions for years following an initial spawning biomass of one million tons, based on a Markov model. Solid line: no fishery. Broken line: fishing under quota formula of one-third of the excess spawning biomass over one million tons (II in Fig. 3.3). From PFMC (1978).

Both dynamic programming and Markov models have difficulties with common statistical phenomena encountered in fisheries such as observation error and serial correlation in recruitment strength. Walters and Hilborn (1978) point out that dynamic programming is unable to handle more than a "few (4 or 5)" state variables; Robert Kope (NMFS SWFSC Tiburon Laboratory) tells me even that may be overly optimistic, based on his own experience. No doubt, modern computational power should allow some of these problems to be overcome by consideration of larger and more complicated state-spaces. However, if intensive computation is required, one may as well explore simulation models.

Simulation models

Simulation-based forecasting models allow extraordinary flexibility in representing system structures and processes. For each model (i.e., set of parameters or other unique model specifications), random numbers allow simulation of the future history of the fishery out to the planning horizon. Each alternative simulated history is based on a different set of random numbers, and constitutes a "run." Hundreds of runs may be necessary to understand the properties of the simulated system or rebuilding program for each model. As in any statistical sampling problem, a large number of replicates is necessary in order to understand the extent of variability and to compare results with other cases.

Simulation allows examination of many biological attributes such as size composition and even geographic distribution. Also, important economic or social aspects of the fishery can be incorporated, including effects of such details as individual differences among fishermen or vessels, their behavioral characteristics and patterns of entry, participation, and exit from fisheries.

Problematic patterns of recruitment variability

One of the largest sources of uncertainty in forecasting possible stock rebuilding is that of variability in recruitment. Many of the standard equilibrium fishery models give an erroneous view of rebuilding as a smooth, gradual process. This view can be seriously wrong, and correct portrayal of recruitment patterns is an especially important element in developing reasonable expectations for a rebuilding program.

There have been several attempts to define categories of fishery variability, e.g., Kawasaki (1983), Caddy and Gulland (1983), and Caddy (1984). Of Caddy's four categories, three of them pose potentially difficult simulation problems, "cyclical," "irregular," and "spasmodic" fisheries. Only "steady state or predictable" fisheries present relatively few problems and perhaps can be represented by random variability about a stock-recruitment curve. Truly cyclical fisheries may not require elaborate rebuilding programs, under the assumption that the resource will recover in the next upswing of the cycle. However, unless the cause of the cycling is understood, logical induction of a recovery may be seriously in error, as in the case of the post-1960 Dungeness crab, *Cancer magister*, fishery off San Francisco (Fig. 3.5).

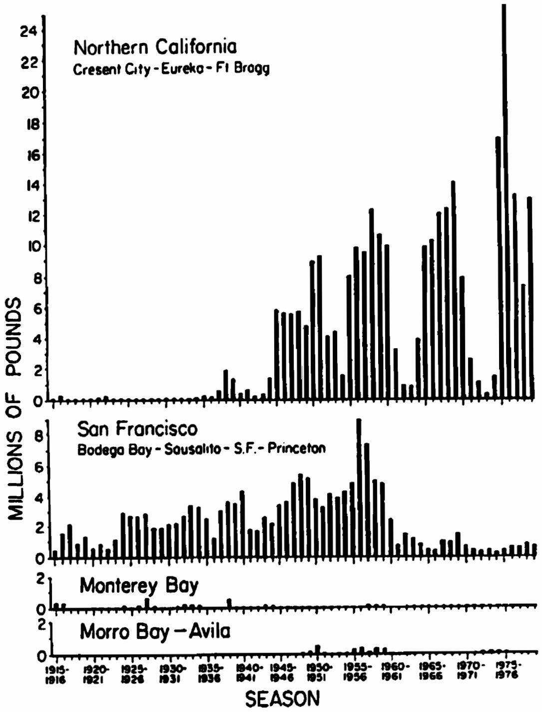

Figure 3.5.—Commercial landings of Dungeness crab in California by area for seasons 1915-16 through 1979-80. From Dahlstrom and Wild (1983).

The "recruitment problem" in a fishery simulation is quite different from the problem in standard fishery research. Rather than attempting to predict individual recruitment strengths based on knowledge of environmental factors and processes, recruitment simulation is a problem of portraying patterns. Knowledge of environmental factors or correlates is of little help except in the rare case where future environmental states can themselves be predicted. Knowledge of biological mechanisms such as cannibalism can be much more valuable, as they potentially create predictable or characteristic patterns of variability.

From a rebuilding viewpoint, the initial stock abundance is sufficiently low that the mean stock-recruitment relationship for temperate stocks may well simplify to a straight line through the origin. Unfortunately, this simplification is of little help unless the residuals are well behaved, e.g., distributed as normal or log-normal random numbers with minimal autocorrelation. In the following sections, I review three categories of problematic residuals or patterns in stock-recruitment relationships. This list is certainly not complete; other problems may arise, and combinations of patterns also may occur.

Cyclic recruitment

The Pacific (a.k.a. chub) mackerel, *Scomber japonicus*, population off southern California collapsed in the 1960's owing to excessive fishing pressure and a sequence of poor recruitments. A novel rebuilding program eventually was implemented by the State of California; Klingbeil (1983) gives an account of the history and difficulties. The rebuilding program was based on adaptive control policies developed by Richard Parrish (Parrish and MacCall, 1978), with a moratorium on fishing until the spawning biomass recovered to 10,000 t, followed by a quota which increased as a function of spawning biomass.

Historical patterns of Pacific mackerel reproductive success are intensely autocorrelated, with a rough periodicity of 5-6 years (Fig. 3.6). Although somewhat predictable, the seemingly cyclic pattern provided no clue of exactly when a recovery would occur or how strong it would be. The actual recovery was very strong and coincided with a late-1970's shift in long-term ocean climate off southern California (see "environmental regimes" below) which was neither predictable nor was it clearly recognizable until some years after it had occurred.

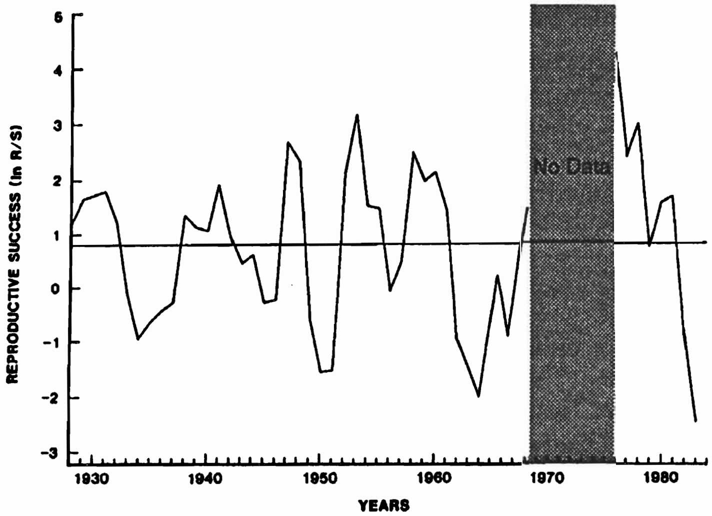

Figure 3.6.—History of Pacific mackerel reproductive success. From MacCall et al. (1985).

Long-lived fish with rare recruitment

Some long-lived species may experience very infrequent large recruitments. A large recruitment event may be a single year or a small cluster of years. Note that imprecision in age determination of old fish from a single strong year-class can tend to give the false appearance of a cluster of several adjacent good years of recruitment. Traditional stock-recruitment models are inappropriate for these fishes, as there is no central tendency about a regression line.

An example from a fishery that is not presently depleted is the horse mackerel, *Trachurus trachurus*, stock in the eastern North Atlantic. The oceanic fishery has been sustained by two recruitment events in the last 25 years: One in 1982, and the other in 1968 or 1969 (or perhaps both). The interval between the two good recruitments was 13 or 14 years (Fig. 3.7), but information on this one known interval is clearly not sufficient to determine how frequently these events occur.

A west coast example is the Pacific ocean perch, *Sebastes alutus*, which was depleted by foreign fishing prior to enactment of the MFCMA. This stock has been very slow to recover, despite limitations on catches. Ito (1990) reports an age composition from a 1985 survey in the vicinity of the U.S.-Canadian border (Fig. 3.8). The age composition suggests that strong recruitments occurred about 23, 33, and 45 years earlier, or ca. 1940, 1952, and 1962. Ito concluded that the abundance of 4- to 6-year-old fish in his samples represents improved recruitment but does not necessarily indicate a historically strong recruitment event. Although the first two intervals are 10 and 12 years, the interval since 1962 is not yet complete and is already approaching 30 years.

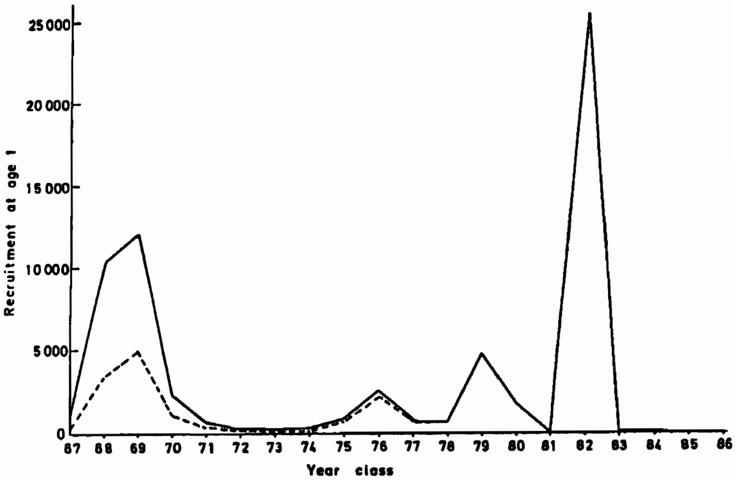

Figure 3.7.—The recruitment at age 1 of horse mackerel, *Trachurus trachurus*, in the eastern North Atlantic. Recruitment earlier than the 1981 year-class was estimated by back-calculation with the average total mortality rate (Z) of each age group (solid line). Dashed line is back-calculation with only natural mortality rate (M). From ICES (1988).

Figure 3.8.—Age composition from a survey of Pacific ocean perch in the INPFC U.S.-Vancouver area in 1985. From Ito (1990).

Another west coast example is that of the bocaccio, *Sebastes paucispinis*, which has not seen significant recruitment since the 1977 year-class (Fig. 3.9) and is now approaching a depleted state (Bence and Hightower, 1990). A very large recruitment was spawned in 1965, but most of the intervening year-classes have been inconsequential. It appears that the probability distribution of recruitment strengths is highly skewed, and that the fishery has been sustained mostly by rare events corresponding to the tail probabilities.

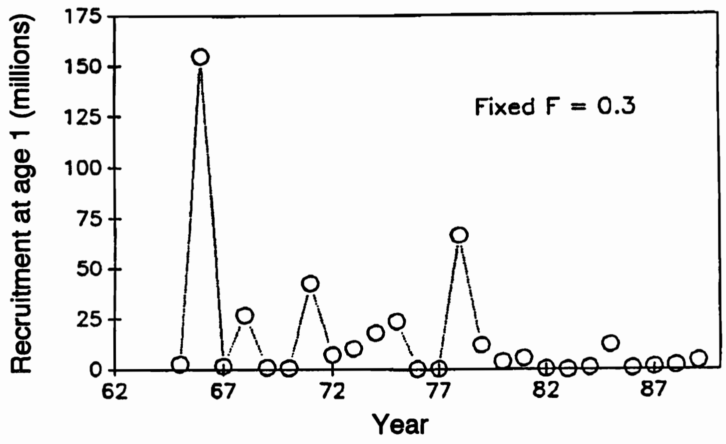

Figure 3.9.—Estimated bocaccio recruitments at age 1. Values prior to 1978 are projected backward from initial age composition estimates assuming no fishing mortality. From Hightower and Bence (1990).

Simulation of long-lived stocks with rare recruitments does not provide much guidance in rebuilding, which in these cases is a management exercise in patience, restraint, and limiting by-catch in related fisheries. As described in the Introduction, industry will be eager to exploit any strong year-classes that appear. With the exception of some dynamic pool ("-per recruit") models, few standard management models and methods are suited to fisheries based on rare recruitment. For example, F_{med} will be oriented to the typical median year wherein recruitment is weak, and will miss the functional importance of the rare year of strong recruitment and the demographic effects of the elapsed time between those recruitments. For these rarely-recruiting stocks, it is vital that a rebuilding program be an integral part of an overall management policy. Simulation may be valuable in developing and exploring such an integrated management policy.

Environmental regimes

Several genera of coastal pelagic fishes off California, Peru/Chile, Japan, Northwest Africa, and South Africa/Namibia have experienced prolonged periods of high and low productivity (Lluch-Belda et al., 1989). This concern was raised by the late John Isaacs at a CalCOFI Symposium where he described the problem as follows:

> "There are internal, interactive episodes locked into persistence, and one is entirely fooled if one takes one of these short intervals of a decade or so and decides there is some sort of simple probability associated with it....fluctuations of populations must be related to these very large alternations of conditions" (Isaacs, 1976).

Isaacs, and later Lluch-Belda et al., referred to these prolonged periods as environmental "regimes." For the purpose of this discussion, I will define a regime as a prolonged period during which recruitment statistics are approximately stationary, and which contrasts with other prolonged stationary periods with different statistical properties. The statistics defining the regime could be the mean recruits generated per spawner (i.e., the curve of expected recruitment given stock size), the shape or dispersion of the probability distribution, the time series spectrum of residuals, or some combination of these. We know very little about the mechanisms causing these prolonged changes in levels or patterns of productivity. In some cases there may be a large associated signal in ocean climate, such as the warming of waters off California since the late 1970's which has been associated with recovery of depleted Pacific sardine and Pacific mackerel stocks (MacCall and Prager, 1988). Adding to the mystery of this problem is the apparent synchrony of regime shifts for widely separated regions such as Japan and Chile (Lluch-Belda et al., 1989).

The problem of regimes is relevant to detection of overfishing and to rebuilding depleted stocks. Environmental regimes are generally associated with systematic changes in biological productivity, and hence in reference levels such as theoretical unfished abundance or carrying capacity, B_{MSY}, and F_{med}. A fishing mortality rate which is optimal during a regime of high productivity may result in overfishing during a regime of low productivity. Similarly, reference points such as B_{MSY} (or equivalently, maximum net productivity level, MNPL, as used in marine mammal management), and carrying capacity can vary among regimes, leading to management errors. Fishery science does not yet have the ability to recognize regime shifts in "real time," nor does it have the understanding to specify proper adjustments in management reference values such as overfishing and recovery thresholds or optimum sustainable populations. Fishery scientists and managers of coastal pelagic stocks, especially in eastern boundary systems, should remain cognizant of the transience of highly productive periods, the speed with which a stock can be depleted following a shift to a regime of low productivity, and the need to conserve a "seed" population to initiate rebuilding after a period of low productivity.

Combinations of problematic recruitment patterns

The history of bocaccio recruitments (Fig. 3.10) suggests that this rarely recruiting stock may also have experienced a regime shift since the late 1970's. Many more intermediate year-classes appear to have been spawned prior to 1977. The cause of this seeming change in recruitment probabilities is unknown, and could be due to exploitation as well as to environmental change.

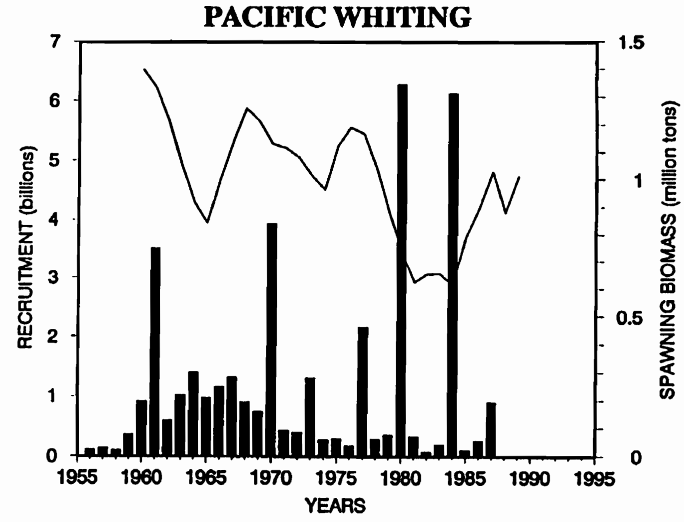

Figure 3.10.— Spawning biomass (line) and year-class strengths (bars, recruitment at age 2) for the Pacific whiting. From Dorn et al. (1990).

The recruitment pattern of the Pacific whiting (a.k.a. hake), *Merluccius productus*, is an interesting example of what may be a mix of all three of the preceding recruitment patterns. Dorn et al. (1990) provide estimates of historical recruitment from a stock synthesis model (Fig. 3.10). Nearly all of the productivity comes out of infrequent large recruitments. Since 1970, these large recruitments are generally separated by two or three very weak year-classes, giving the time series a periodic appearance. A regime shift may have occurred in the early 1970's, after which contrast increased between strong and weak year-classes. The sequence of intermediate year-classes during the 1960's has very different statistical properties. Dorn et al. considered the possibility that errors in age determination may have contributed to the apparent lack of variability in the earlier years, but drew no conclusions. Fortunately, the Pacific whiting stock is still abundant.

By-catch

By-catch can pose severe difficulties for rebuilding programs. In the rebuilding program for the Pacific mackerel fishery off southern California, an 18% "tolerance" was adopted for by-catch of Pacific mackerel taken in other fisheries such as that for jack mackerel, *Trachurus symmetricus*. Unfortunately, the threshold for reinitiating a fishery was stated in terms of spawning biomass, rather than total biomass as favored by the fishery biologists. Predictably, by-catch frequently exceeded the tolerance level during the early years of the recovery when age-1 and 2 fish were abundant and catchable but did not yet contribute to the spawning biomass. Under pressure from the industry, the California state legislature subsequently did a lot of tinkering to loosen up the rebuilding program, including raising the by-catch tolerance to 40% (Klingbeil, 1983). Fortunately, the recovery was strong enough to withstand this weakening of the rebuilding program.

Hatcheries and Other Technological Tools

Enhancement of marine fisheries by means of fish hatcheries is becoming technologically feasible, and experience has shown that they can generate strong popular support. The cost-effectiveness of marine fish hatcheries has yet to be evaluated for fish other than salmonids. A more serious problem may be that hatchery operations (even when done in a "research" rather than a "production" mode) offer decision makers an alternative to implementing needed but politically unpopular restrictions on fishing (MacCall, 1989). This happened recently in southern California in the case of white seabass, *Atractoscion nobilis*. In the mid-1980's the state legislature was on the verge of implementing strict limitations on fishing for this depleted species, but dropped the action in favor of an unproved experimental marine hatchery program. If hatchery enhancement is to be considered, it must be combined with regulations which bring harvesting rates into balance with natural productivity.

It is unlikely that creation of artificial habitat will be useful to rebuilding depleted marine fish stocks. Even if habitat creation were successful, the magnitude of the effort needed to rehabilitate a fish stock is likely to be overwhelming. Artificial habitat could prove useful in recovery efforts associated with some designated threatened or endangered species with localized habitat needs, such as salmonids and pinnipeds. In the case of the threatened Sacramento winter-run chinook salmon, *Oncorhynchus tshawytscha*, artificial maintenance of stream flows and temperatures by controlled releases of water from reservoirs and placement of fish screens on water diversion facilities are feasible technological components of a recovery or rebuilding program.

Monitoring Depleted and Recovering Resources

Data from fishery monitoring are the mainstay of fish stock assessment. Rebuilding plans necessarily force a reduction or cessation of fishing, with a consequent loss of fishery information. Even if a low-level fishery is allowed, VPA methodologies may be unreliable due to a combination of imprecise catch compositions and low exploitation rates. Although by-catch in other fisheries is the bane of rebuilding programs, it also may be the best source of fishery-based information, providing information on relative year-class strengths and geographic distribution. Indeed, if a recovery begins, fishermen will first notice it in their by-catch. Fishery scientists and managers also should monitor by-catch in order to anticipate and address recovery issues raised by the industry.

Changes in predator diets can provide qualitative and in some cases quantitative information on stocks and may be especially useful during rebuilding when fishing is curtailed. Adams and Silberberg (1991) have monitored diets of chinook salmon, *Oncorhynchus tshawytscha*, caught by recreational fishermen near San Francisco and have found that incidence of juvenile rockfish, *Sebastes* spp., provides an index of recruitment strength. In southern California, the brown pelican, *Pelecanus occidentalis californicus*, eats small surface schooling pelagic fishes, and until recently has been a near-obligate predator on northern anchovies. Based on this, Sunada et al. (1981) showed that the anchovies consumed by the pelicans were nearly identical in composition to those caught by the commercial fishery, and suggested the novel idea that these seabirds could provide a means of sampling the anchovy population in the absence of a fishery. In 1991 the diets of brown pelicans in southern California suddenly shifted to sardines (Ainley and Hunt, 1991). It is notable that 1991 was the first year in which the recovering sardine population attained a biomass which was comparable with the anchovy biomass off southern California.

Fishery-independent surveys can be expensive, but are the most reliable source of information on depleted populations. In some cases, information on the depleted stock may be provided by ongoing general-purpose surveys such as the west coast groundfish trawl surveys used in part by Ito (1990) for Pacific ocean perch, or the CalCOFI ichthyoplankton surveys used by Barnes et al. (1992) for Pacific sardine. The low abundance of depleted stocks contributes to low catch rates and low sampling precision in surveys, and strategies should be developed to maximize the effectiveness of dedicated surveys. For example, alternative statistics on spawning area of Pacific sardines based on presence/absence of eggs and larvae have been examined by Mangel and Smith (1990) and Smith (1990). While the increase in sardine egg or larva abundances is very imprecise because of their geographically patchy and statistically skewed distributions, the increase in sardine spawning area provides a clear indication of the rate and extent of recovery (Fig. 3.11).

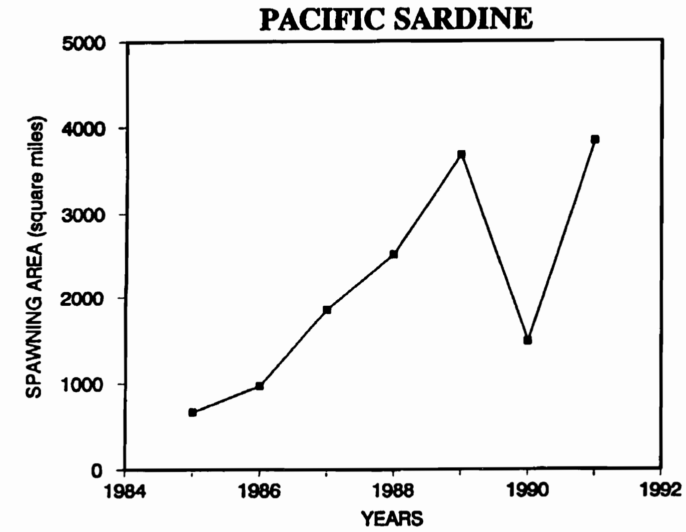

Figure 3.11.— Increase in Pacific sardine spawning area from egg surveys conducted by the California Department of Fish and Game. Data from Barnes et al. (1992).

Depletion as Management Opportunity

In several cases I have suggested that a rebuilding program should be incorporated explicitly in an overall management policy. While this is best done early in development of a fishery, management doesn't always have the will and foresight to address problems that haven't yet occurred. Rebuilding depleted stocks presents a belated opportunity: Management is looking forward to a recovery and may be more willing to consider a programmed shift from the rebuilding policy to a less restrictive long-term fishing policy for the future rehabilitated stock. Also, when depletion is severe enough (as was the case of sardines and Pacific mackerel in California), the industry may drop its opposition to the strict measures needed to rehabilitate the resource, freeing the decision makers to take needed actions.

Summaries of Contributed Papers

Opportunity Losses and Risk Strategies for a Rebuilding Stock

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Summary

The results from fishery stock assessments used by decision makers are subject to uncertainty owing to the characteristics of the data and models used. Any decisions made regarding future fishing regulations will have different consequences on the short- and long-term status of the stock and on the performance of the fishery, depending on the nature of the decision. For this reason, it is important that the uncertainty inherent in the assessment results be quantified as realistically as possible and be integrated into the scientific advice. Only when this uncertainty is presented in a probabilistic framework is it possible to associate a given management decision with the likelihood of its consequences, e.g., the risk that overfishing will take place, the risk that fishable biomass will decline, etc. Monte Carlo simulation is a useful tool for incorporating measured, perceived, and model uncertainties into the entire assessment procedure, including stock projections under various management regimes. In this presentation we describe how Monte Carlo methods are being used for this purpose in age-sequenced analyses and discuss the merits of the procedure.

The effect of research programs designed to reduce variation in estimates of stock assessment parameters were evaluated for Gulf of Mexico king mackerel using Monte Carlo simulations of the entire assessment analysis consisting of separable VPA, calibrated VPA, estimation of target fishing mortality rate, and projection of catch at that rate. The distribution of estimates of allowable biological catch (ABC) from the simulations indicated that realistic improvements in research could substantially decrease the uncertainty in ABC estimates from a coefficient of variation of 40% to 20%. Expected yield for risk-averse strategies increased with enhanced research programs. Opportunity loss of foregone yield and lost surplus were diminished as well. Research combined with risk averse management strategies appears to provide benefits to the fishery and to the economy that substantially exceed the costs of the research.

Small Pelagic Fishes and Fishery Management in the California Current: Or, What to Do After the Collapse

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Summary

A review of the population dynamics of small pelagic fishes that dominate the California Current fisheries characterizes these stocks as extremely variable. The observed population collapses of sardine, mackerel, and anchovy were extremely precipitous, and the population recovery of mackerel, which occurred under a moratorium on landings and after a decade of extremely low biomass levels, also was very rapid once it began. Annual recruitment rates in these species are highly variable and autocorrelated. In addition, recent studies suggest that natural mortality and fecundity rates are highly variable; however, annual measurement of these rates has, to date, received little attention.

In response to the historical failures of California's traditional pelagic fisheries, a management regime based on catch quotas, in which the fishing mortality rate is a function of stock biomass, is currently in place. Under existing regulations, fishing mortality rates are intended to increase (decrease) gradually as the stock biomass increases (decreases); at low biomass levels (in some cases at very low levels) moratoria on directed fishing are automatically triggered. Management thus depends on assessments (predictions) of current biomass. These assessments (i.e., look ahead VPA analyses and stock synthesis models) have resulted in stable fisheries when biomass levels were relatively stable. However, to date they have greatly overestimated biomass levels during periods of population collapse and greatly underestimated biomass levels during recoveries. The failure (bias) of these types of predictive models is not restricted to fisheries in the California Current, and it has recently been recognized as a worldwide fisheries management problem.

It has been the general consensus that the relatively robust California management regime should prevent recruitment overfishing by reducing the exploitation rate at lower biomass levels. Four factors suggest that what is thought to be a robust management regime may in fact not prevent severe economic and biological disruptions. First, the California Current sardine, anchovy, and mackerel fisheries have each experienced changes in catches of close to an order of magnitude within two seasons. Second, to date, fisheries scientists have not been successful in developing the ability to predict, or even measure on a real time basis, shifts in population size. Third, annual recruitment rates appear to be highly autocorrelated. Fourth, although transitions occur quite quickly, stocks remain at high or low levels for periods of 1-3 decades.

Two lines of research appear to be the most likely to produce significant results. The first is to decrease the level of uncertainty by ascertaining the environmental processes that alter the population dynamics of these stocks. The second is to utilize new modeling techniques to develop a better understanding of the economic and biological risks associated with harvesting these fishes under different exploitation regimes.

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