Overview Paper: Advice for Stock Rebuilding

Alec D. MacCall
NMFS Southwest Fisheries Science Center,
Tiburon Laboratory, Tiburon, Calif.

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.

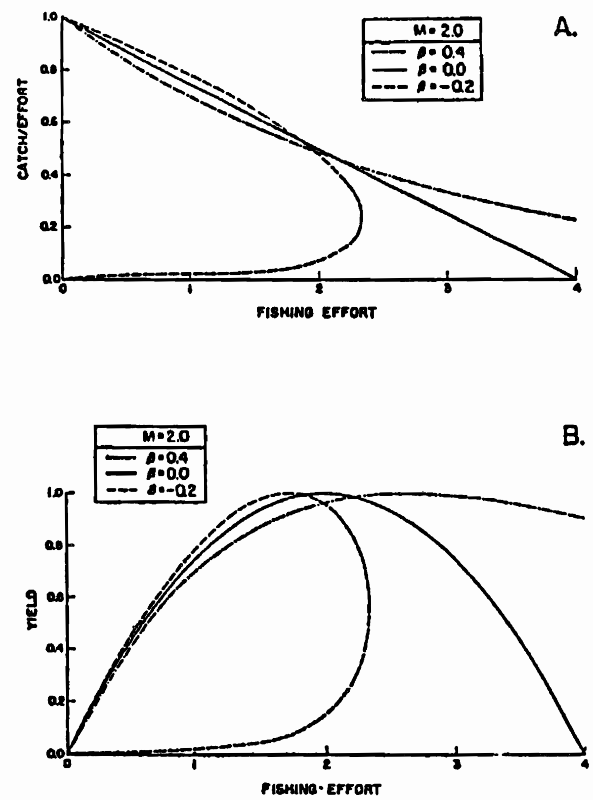

Figure 3.1.—Equilibrium relationships for a density-dependent catchability production model where the underlying biological production model is a symmetric Schaefer model. A is relationship of catch per unit effort to nominal fishing effort; B is relationship of equilibrium yield to nominal fishing effort. 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.

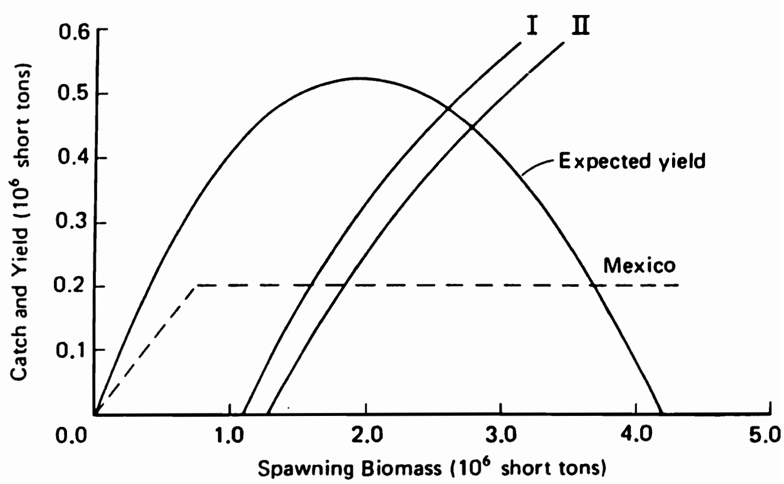

Figure 3.2.—Optimal anchovy harvest strategies for the U.S. reduction fishery, based on stochastic dynamic programming. Curve I is for fishery without Mexican competition. Curve II assumes Mexico takes an amount represented by the broken line. From Huppert (1981).

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.

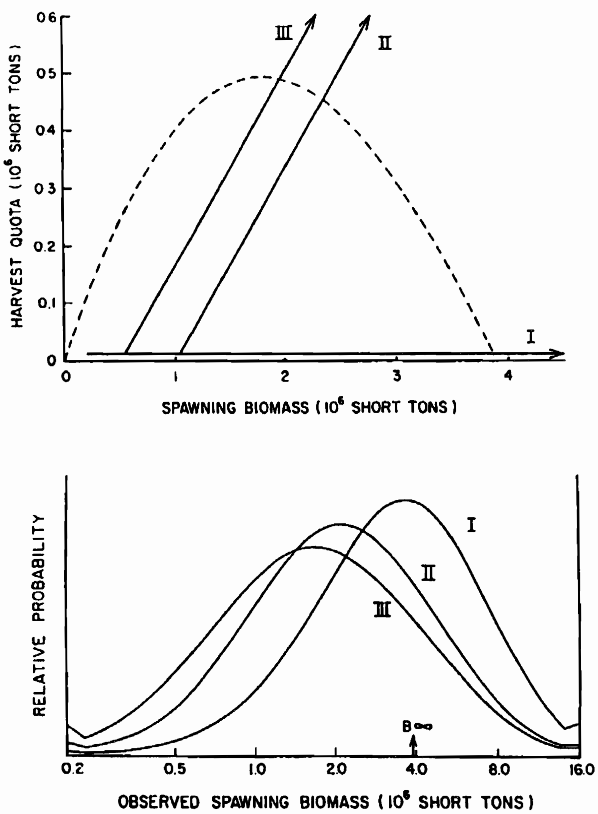

Figure 3.3.—Alternative anchovy harvest formulas and corresponding probability distributions of spawning biomass from a Markov model. Formula II was adopted by the Pacific Fishery Management Council. From MacCall (1980).

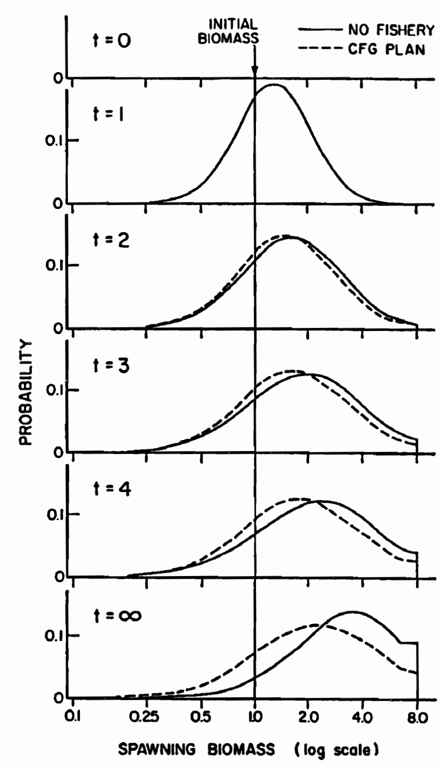

Figure 3.4.—Predicted northern anchovy population size distributions for years following an initial spawning biomass of one million tons, based on a Markov model. Solid line: no fishery. Broken line: fishing under quota formula of one-third of the excess spawning biomass over one million tons (II in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

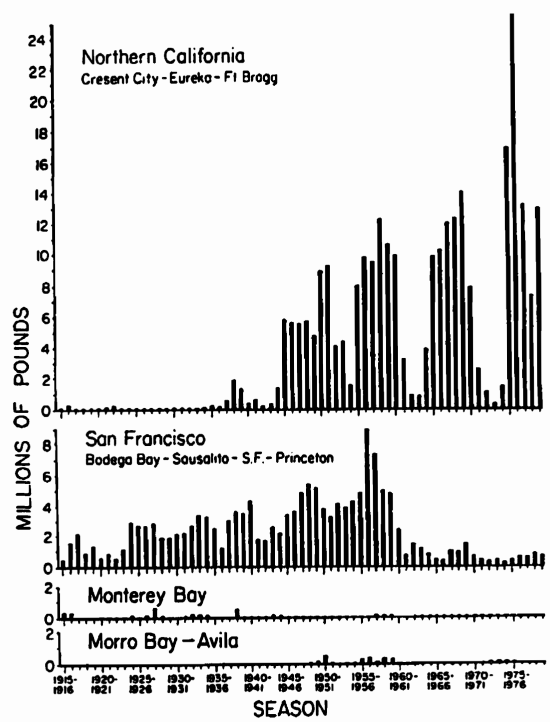

Figure 3.5.–Commercial landings of Dungeness crab in California by area for seasons 1915-16 through 1979-80. From Dahlstrom and Wild (1983).

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.

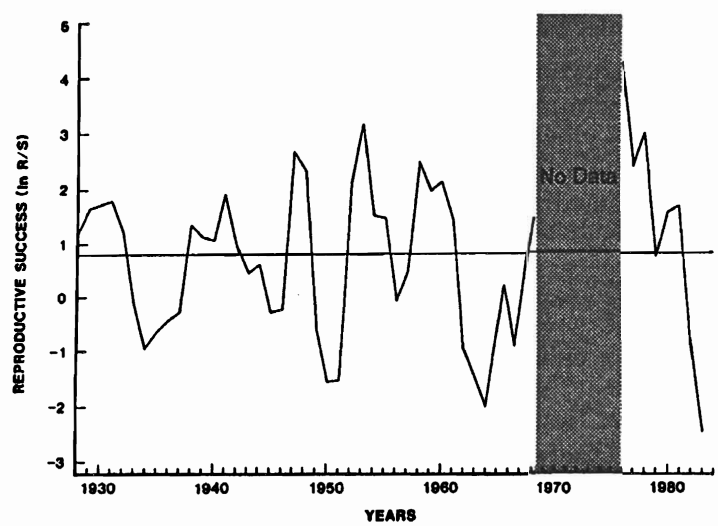

Figure 3.6.—History of Pacific mackerel reproductive success. From MacCall et al. (1985).

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.

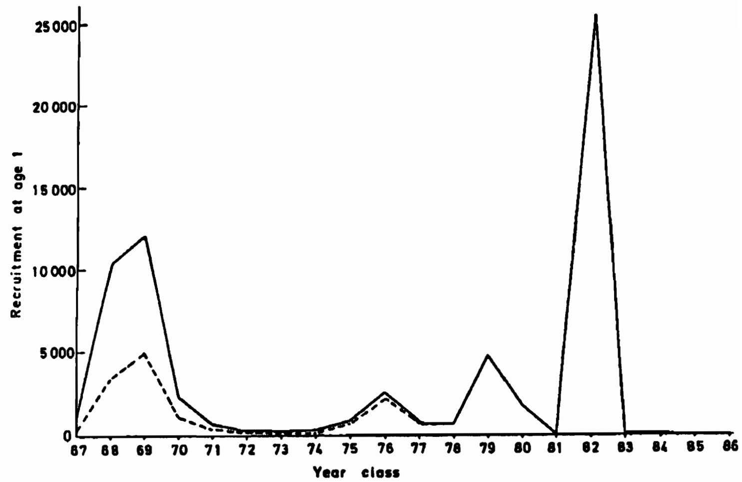

Figure 3.7.—The recruitment at age 1 of horse mackerel, *Trachurus trachurus*, in the eastern North Atlantic. Recruitment earlier than the 1981 year-class was estimated by back-calculation with the average total mortality rate (Z) of each age group (solid line). Dashed line is back-calculation with only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

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.

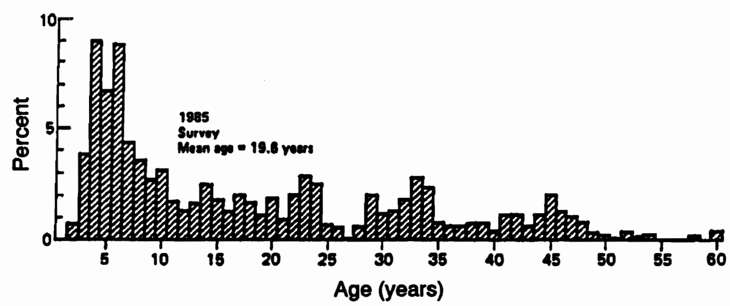

Figure 3.8.—Age composition from a survey of Pacific ocean perch in the INPFC U.S.-Vancouver area in 1985. From Ito (1990).

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.

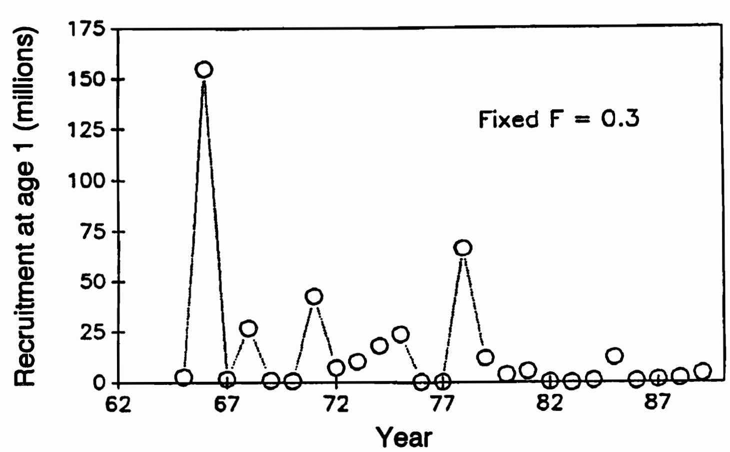

Figure 3.9.—Estimated bocaccio recruitments at age 1. Values prior to 1978 are projected backward from initial age composition estimates assuming no fishing mortality. From Hightower and Bence (1990).

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.

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.

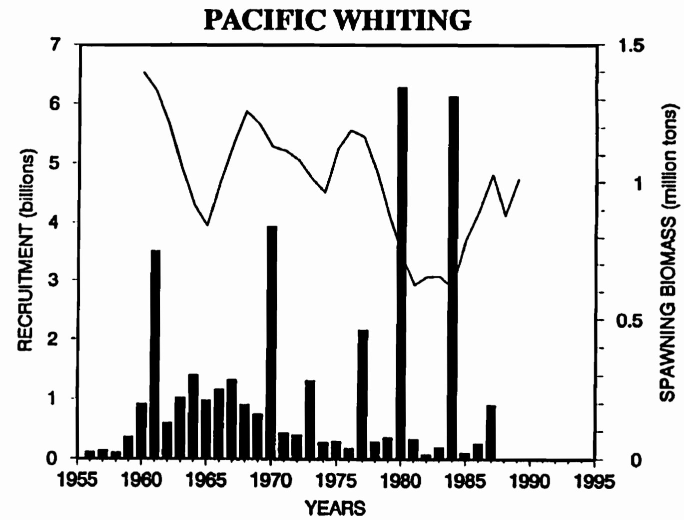

Figure 3.10.— Spawning biomass (line) and year-class strengths (bars, recruitment at age 2) for the Pacific whiting. From Dorn et al. (1990).

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).

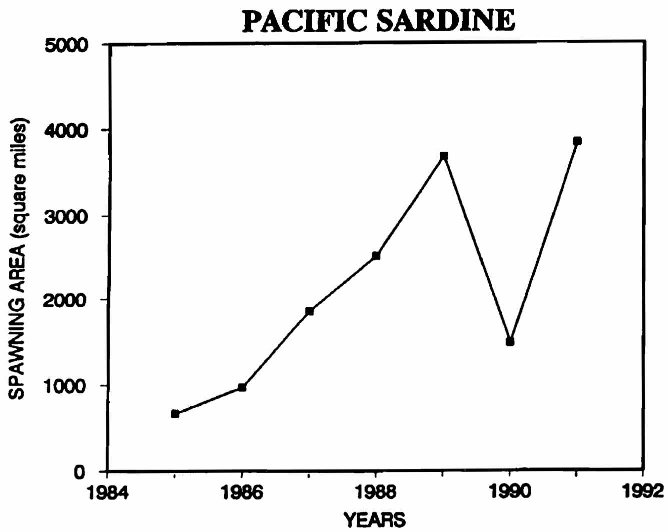

Figure 3.11.— Increase in Pacific sardine spawning area from egg surveys conducted by the California Department of Fish and Game. Data from Barnes et al. (1992).

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.

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