

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

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

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

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

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

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

Introduction

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

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

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

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

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

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

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

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

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

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

Considerations of Behavior

Nonlinear Catch per Unit Effort

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

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

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

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

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

$$C = q(B)fB$$

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

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

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

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

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

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

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

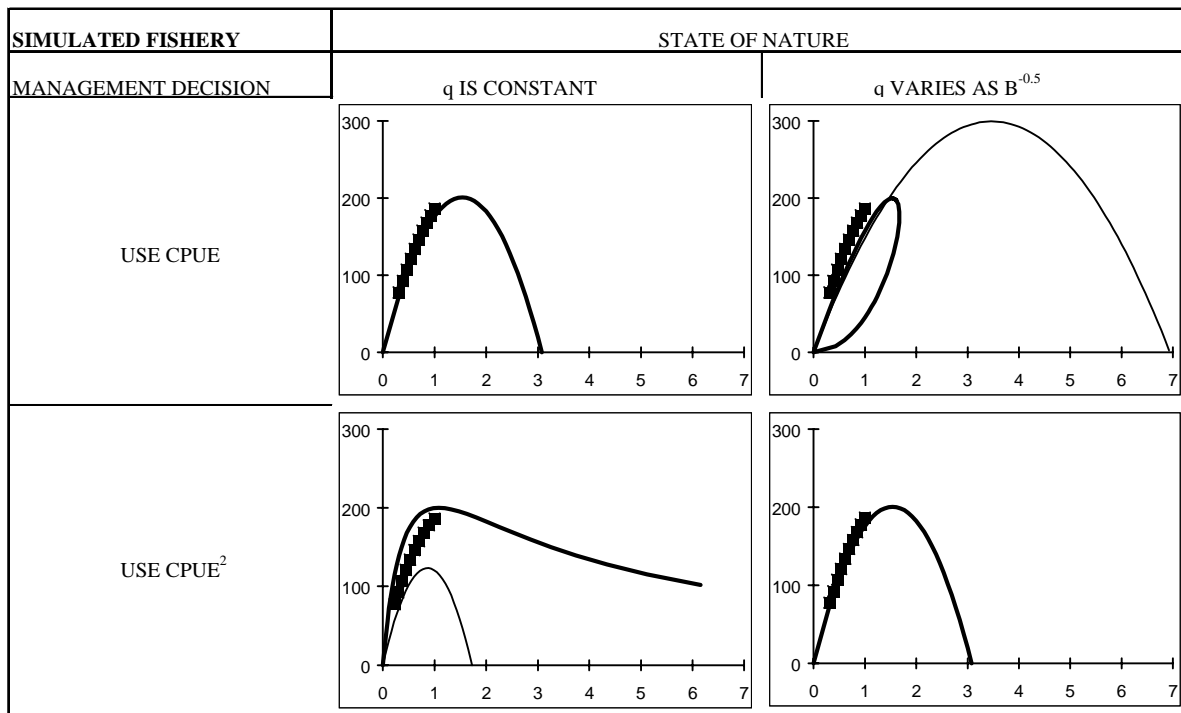


Figure 1. Graphical consideration of nonlinearity in CPUE vs. abundance, equivalent to Table 2. Nominal effort levels are specified as multipliers of effort in year 10. Light lines (parabolas) are expected behavior according to the fitted model; heavy lines are actual fishery equilibrium yield curves.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

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

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

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

Considerations of Life History

Multiple Spawning and Increasing Fecundity with Age

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

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

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

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

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

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

Increasing Natural Mortality Rate with Age

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

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

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

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

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

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

Considerations of Recruitment Variability

Environmentally-Driven Low Frequency Variability

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

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

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

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

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

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

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

Rarely Recruiting Species

Rarely recruiting species pose an especially diffi-

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

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

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

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

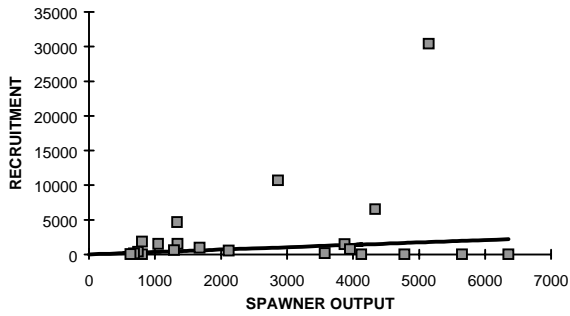


Figure 2. Stock and recruitment relationship of bocaccio rockfish. Solid line is replacement at $F=0$.

to a small geographic area.

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

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

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

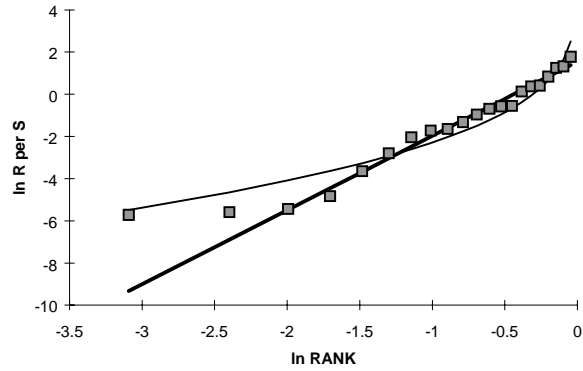


Figure 3. Log-log relationship of bocaccio spawning success (R/S) to rank ($n=21$). Linear fit (lowest two points omitted) indicates power pdf with $\beta=3.5$. Curved line is fit to a lognormal pdf (all points included).

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

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

The Biomass Reserve as a Precautionary Management Tool

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

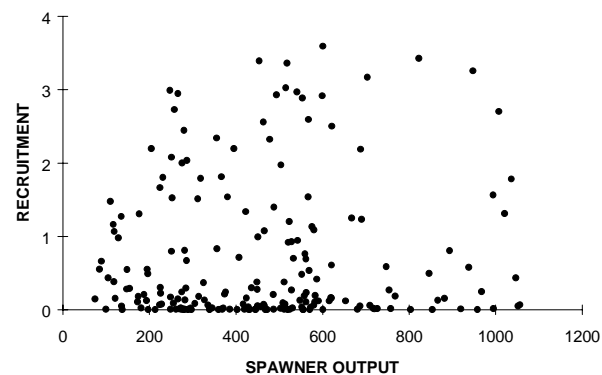


Figure 4. 200 years of simulated stock and recruitment data with a Beverton-Holt SRR and a power pdf, $\beta=4$.

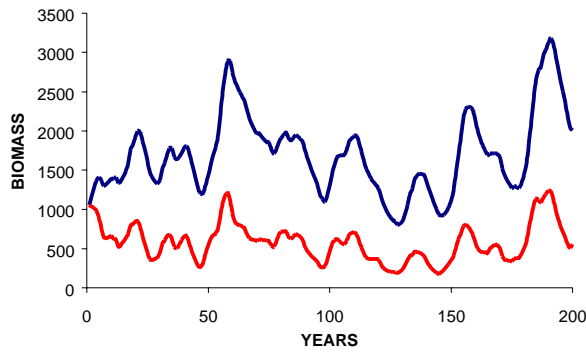


Figure 5. Simulated time series of biomasses for a rarely recruiting stock. The upper series is unexploited; the lower series is exploited at $F=0.15$.

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

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

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

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

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

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

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

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

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

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

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

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

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

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treatment of these subjects in this paper has been restricted to a minimum and is not intended to preempt those publications. Taken in order of the sections as they appear in this paper, Mike Prager provided valuable help in simulating alternative behaviors of the catchability coefficient and in analyzing the results with his production modeling program, ASPIC. Stephen Ralston made many valuable suggestions that improved the manuscript, and will be senior author of an eventual publication on precautionary treatment of increasing natural mortality rates with age. Larry Jacobson and Richard Parrish are actively working on the subject of low-frequency fluctuations in recruitment and use of environmental indicators in management.

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