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REQUIEM FOR RICKER: UNPACKING MSY

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ABSTRACT

Much like the Cornucopia myth of the 19th and early 20th centuries that the oceans contained limitless and inexhaustible resources, MSY as a management tool simply won't go away, regardless of evidence that 'managing for MSY' has not been effective. The present paper therefore reports an investigation of Ricker's definition of MSY, focusing on words such as "average catch," "continuously taken," and "existing environmental conditions." The investigation involved development of a model for the squid fishery in California, probably the last great open-access fishery on the west coast of the United States. Constructing the model in a step-wise fashion permitted illustration of particular points. Insight from the model leads to a deeper understanding of the definition of MSY, particularly that different methods of averaging and explicitly including risk to the stock in MSY may allow MSY to be used in the context of precautionary fishery management. Finally, results from the Third Mote Symposium that also shed light on this issue are summarized.

In his classic book, Ricker (1975) defined MSY: "Maximum sustainable yield (MSY or YS): The largest average catch or yield that can continuously be taken from a stock under existing environmental conditions. (For species with fluctuating recruitment, the maximum might be obtained by taking fewer fish in some years than in others)."

(Our point in the present paper is to elucidate the full implications of the words *average*, *continuously*, and *existing environmental conditions*). Two years later, however, Larkin (1977) proposed that we bury MSY:

"An epitaph for the concept of Maximum Sustained Yield

M.S.Y.
1930s–1970s

Here lies the concept, MSY.
It advocated yields too high,
And didn't spell out how to slice the pie.
We bury it with best of wishes.
Especially on behalf of fishes.
We don't know yet what will take its place.
But hope it's as good for the human race."

MSY, much like the 19th and early 20th century Cornucopia myth of the limitless bountiful ocean, seems to have a life of its own. Indeed, Kurlansky's (1997, p. 186) comments about the Cornucopia myth could just as easily apply to MSY: "Furthermore, the Kirby report [a Canadian government report ca. 1990 that assessed the future of Atlantic fisheries] was still being influenced by Huxley's teaching about the resilience of indestructible nature. The idea itself seems to have more resilience than nature... As with

the sixteenth-century belief in a westward passage to Asia, the theory cannot be killed by mere experience."

The usefulness (or lack thereof) of the concept of MSY hinges on how we understand the words *average*, *continuously*, and *existing environmental conditions* in Ricker's definition, and that is what we explore here. To do so, we will examine the meaning of MSY in the context of the squid fishery in central California (Pomeroy and Fitzsimmons, 1998).

The Squid Fishery in Central California

The commercial fishery for California market squid (*Loligo opalescens*) dates from the 1860s in Monterey, when the Chinese used torches to attract squid and caught them in small purse seines (Dewees and Price, 1983; Lydon, 1985). In 1905 Monterey's Italian fishermen introduced lampara nets into the fishery. The fishery was centered in the Monterey Bay area until the 1960s, when the introduction of the power block, round-haul gear, and other innovations facilitated the development of the southern California fishery, primarily concentrating on spawning aggregations around the Channel Islands (Dewees and Price, 1983). Through the 1960s and 1970s, the southern California fishery continued to grow, while the Monterey Bay fishery remained relatively constant. Although interest in California market squid as a potential focus of fishery development prompted attention to its biological and ecological aspects, and to the development of processing and marketing strategies, annual squid landings remained below about 25,000 mt through those years, largely because of limited demand (Pomeroy and Fitzsimmons, 1998).

After extremely low catches associated with the 1982–83 El Niño, southern California landings increased steadily, outgrowing those of the Monterey fishery, where landings held at around 10,000 mt yr^{-1}. By 1995, squid ranked first in volume and second (to sea urchin) in value among California commercial fisheries; by 1996, it ranked first in both volume and value, with landings of more than 86,000 mt, worth over $32 million (Starr et al., 1997; Pomeroy and Fitzsimmons, 1998). In late 1997 through early 1999, however, both southern California and Monterey landings plummeted during El Niño conditions (Fig. 1). Statewide landings of squid dropped to just under 3000 mt, and 17 mt were landed at Monterey area ports in 1998. The southern California fishery rebounded in 1999, landing over 90,000 mt worth almost $32 million; squid have returned more slowly to Monterey (all catch data from the PacFIN data base, 2000). Since the early 1980s, catch per unit effort (CPUE), measured as metric tons per successful landing, appears to have increased, both in the Monterey Bay area and for the fishery as a whole (Fig. 2). Because unsuccessful landings are not included in CPUE, the data in Figure 2 are an overestimate of actual CPUE. Important technological, capacity, and regulatory changes have also contributed to CPUE. The increase in CPUE may reflect these more than the availability of squid; alternatively the increase may reflect a nonlinear relationship between squid abundance and catch, due to schooling behavior of squid and nonrandom distribution of fishing effort.

These trends in landings and CPUE are the product both of the changing availability of squid and of changing economic and regulatory conditions within and outside the squid fishery (Pomeroy and Fitzsimmons, 1998). Domestic markets have grown as consumers have come to value the nutritional benefits of seafood in general and have developed a taste for squid products marketed under the more appealing name of 'calamari'. Fluctuations in other squid fisheries (e.g., Falkland Islands) and the opening of new markets

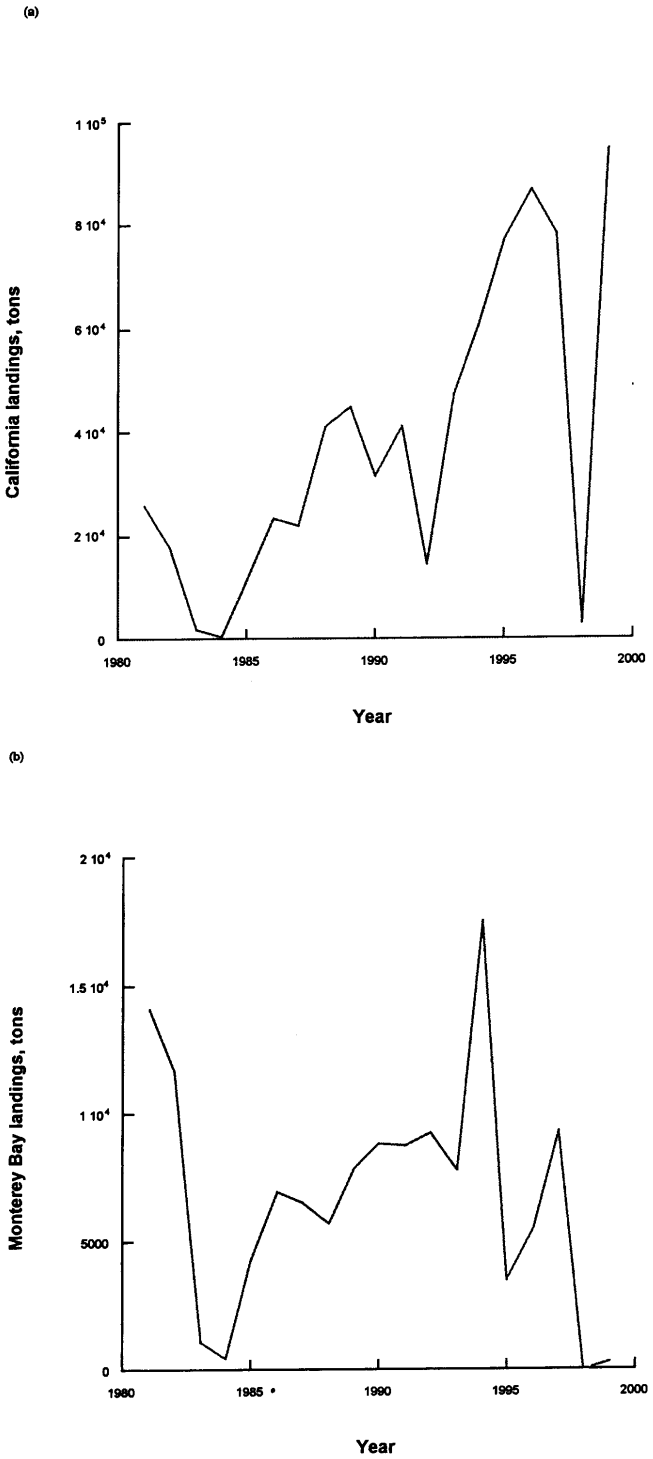

Figure 1. Statewide (panel A) and Monterey Bay (panel B) landings of squid, 1981–1999.

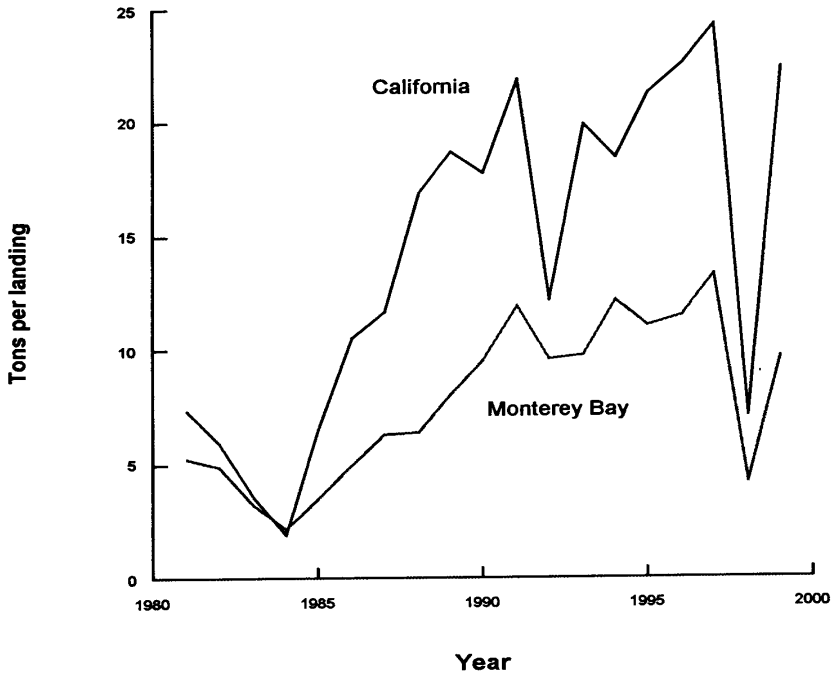

Figure 2. Mean tons of squid per landing (a measure of catch per unit effort) and, in the standard Schaefer model, a proxy for population size.

increased international demand from both traditional consumers (e.g., Greece, Italy) and new ones, most notably China in the mid 1990s. The scarcity of squid soon after the onset of El Niño conditions in late 1997, however, led to the loss of many of these markets, especially as ex-vessel prices increased from about $300 to well over $500 per metric ton. This high-priced squid did not move as quickly, and receivers accumulated inventories of frozen, packed squid. When the squid returned to California waters in abundance in mid 1999, landings jumped, but vessels were placed on limits of half their capacity or less, and ex-vessel prices declined to $250 per metric ton or less.

Regulatory changes also played a role in the development of the squid fishery and the observed trends in landings and CPUE. Historically, squid fishing has been regulated by the state with legislative measures that restrict the use of lights to attract squid, limits on days or times when fishing is allowed, and for several years, prohibition on the use of purse seines in Monterey Bay (Dewees and Price, 1983). The 1989 removal of the ban on purse-seine gear in the Monterey Bay fishery led to its nearly universal adoption and to the subsequent increase in vessel size to accommodate the new gear. This change enabled more of the Monterey fleet to venture south to participate in the winter fishery around the Channel Islands. In 1997, the California legislature passed SB 364, instituting a $2500 permit requirement for fishing vessels and light boats participating in the squid fishery, the funds to be used to support a 3-yr program of research on the resource and the fishery toward the development of a conservation and management plan (CFG Code Sec. 8420-8429). With the prospect of limited entry coming to one of the last open-access fisheries on the west coast of the United States, 241 vessel owners purchased squid fishery permits

for the temporary limited entry. Permittees include both historical and prospective participants, who now seek to establish landing records in the hope of qualifying for the anticipated permanent limited-entry system. One consequence is that the capacity of the fleet, based on vessel net tonnage, has increased. The California Department of Fish and Game estimated the fleet's maximum capacity in 1995 at 4520 net tons, compared to 3640 net tons in 1982. From net tonnage of vessels that had landings in 1997, overall fleet capacity seems to have risen to over 6000 net tons that year.

In addition to the change from lampara to purse-seine gear, other technological innovations have increased the efficiency and scope of squid fishing operations. These include the fish pump, depth sounders and sonar, and the use of light boats (small vessels that scout for fishable aggregations, then use halogen lamps to attract and hold the squid for a seiner to catch). These have facilitated the spread of the central California fishery from the inner waters of Monterey Bay to outer bay waters, while the southern California fishery has expanded its coverage of Channel Islands fishing sites.

As the size of the take of market squid increased, concerns about the sustainability of the fishery also increased. This is literally front page news: the center story in the *San Jose Mercury News* on 30 April 2001 was titled "State proposes new limits on growing squid harvest" and subtitled "In a rare move, California tries to rein in last Wild West fishery before the waters are emptied." In November 2000, the Statistical Committee of the Pacific Fishery Management Council planned a stock-assessment review committee in spring 2001. Simultaneously, the California Department of Fish and Game considered the use of two real-time management options instead of an MSY. These are (1) an escapement-based procedure, involving an index relating the weight of a mantle section and the degree to which a female has spawned, and (2) a DeLury model, similar to the ones used in the Falkland Islands (Beddington et al., 1990; Rosenberg et al., 1990), but estimates of effort, which are needed for removal methods, are still difficult to obtain.

The recommendations proposed in April 2001 included (1) a yearly quota of 125,000 short tons, (2) reduction in the number of permits by 45%, (3) expansion of the weekend fishing ban in Monterey Bay, and (4) study of the adoption of no-take spawning areas (see Coleman and Travis, 2000, for this topic).

Krill and Squid in the California Current System

Euphausiids, or krill, have the highest biomasses of all zooplankton grazers in the central California upwelling system (Barham, 1957; Benson et al., in press, Marinovic et al., in press). Krill form a key trophic link in coastal upwelling systems between primary production and higher-trophic-level consumers (Loeb et al., 1997), and squid feed almost exclusively on krill (Karpov and Cailliet, 1972). Thus, squid form the apex of a relatively simple, directly linked trophic system consisting of upwelling-induced nutrient enrichment, phytoplankton, krill, and squid. The productivity of this linked system is strongly affected by interannual events such as El Niño (Hayward et al., 1996; McGowan et al., 1998). Large-scale declines in zooplankton (and especially krill) abundance occurred in the central California upwelling system during the 1997–98 El Niño (Marinovic et al., in press), and similar observations were made off southern California during both the 1982–83 and 1997–98 El Niño events (McGowan et al., 1998). As described above, market squid landings in California declined dramatically after both these events. The abundance and spatial distribution of krill is also connected to environmental conditions within

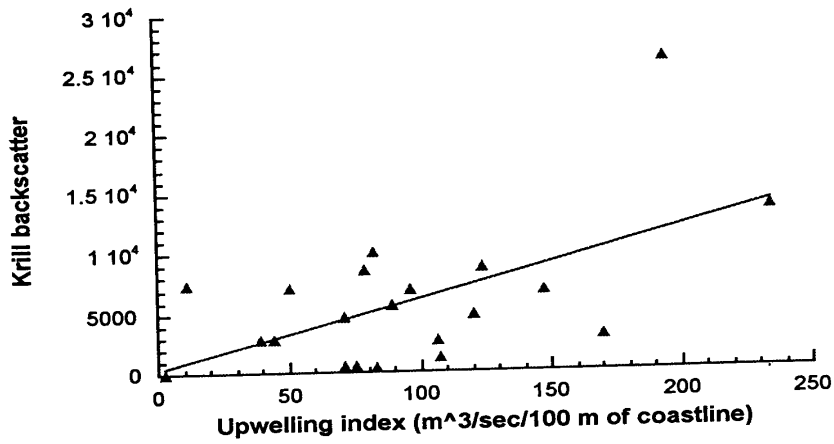

Figure 3. Relationship between acoustic backscatter from krill and an upwelling index in Monterey Bay, measured monthly May–November 1997, 1998, 1999, showing that krill abundance is correlated with the index of upwelling.

a year (Fig. 3). The upwelling index ($m^3\ s^{-1}\ 100\ m^{-1}$ of coastline) in this figure is calculated on the theoretical relationship between wind (resolved to a N–S vector) and Ekman transport resulting from Coriolis deflection. The wind data are obtained from the Navy in the form of 3° surface-pressure fields, and then the resulting upwelling is calculated. (A detailed description of how the upwelling index is calculated can be found at http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/how_computed.html)

The simplicity of the connection between physical and biological components and the relatively simple food web thus allow us to understand much about the system with simple models.

A Model Allowing Us to Unpack MSY

Here, we develop a conceptual model of the krill-squid fishery in California. We focus on yearly population dynamics, although squid are known to have flexible growth and reproductive strategies (Boyle et al., 1995; Brodziak and Macy, 1996; Maxwell and Hanlon, 2000) and to be semelparous (so mortality is not constant across age classes). Also, for simplicity, we use catch numbers rather than biomass (and thus ignore growth and environmental determinants of maturation; O'Dor, 1983) and yearly levels of effort rather than within-season management (e.g., Beddington et al., 1990; Rosenberg et al., 1990). The next step in the unpacking of MSY would be to add these features, because we know already that there fishing mortality and squid migration patterns show marked within-season differences (Brodziak and Rosenberg, 1993) and that, in some squid fisheries at least, multiple cohorts may recruit to the fishery (Agnew et al., 1998). For purposes of beginning to unpack MSY, however, the simpler model suffices.

Characterizing the Dynamic States.—The model includes terms that represent environmental forcing in the California Current system, krill abundance, and density-dependent availability of recruited squid biomass. The symbols characterizing these are $E(t)$, environmental state; $K(t|E(t))$, krill abundance, depending upon the environmental state;

and $S(t)$, squid abundance (measured in recruited biomass), depending upon krill abundance. For simplicity, we assume that the environment exists in one of two states, poor (also denoted by $E(t) = 1$) and good (also denoted by $E(t) = 2$) and that transitions between them are given by a Markov process (see MacCall, this issue, for an example and additional references).

$$\Pr\{E(t+1) = j \mid E(t) = i\} = p_{ij} \qquad \text{Eq. 1}$$

Thus $p_{i1} + p_{i2} = 1$ for $i = 1$ or 2 (see Table 1 for a list of parameters and their values). We refer to p_{ii} as the 'repeatability' of the environment, because it measures the likelihood that next year's environment (but not krill abundance, see below) will be the same as this year's environment. On average, the probability that the environment is in state 1 is

$$\bar{p} = \frac{p_{21}}{1 - p_{11} + p_{21}} \qquad \text{Eq. 2}$$

For simplification, we set $p_{11} = p_{22}$. Clearly, one could expand this description, for example by including extremely bad years (El Niño) and extremely good years (with relatively low sea-surface temperature). We will not do so here, because our goal is maintaining simplicity of the model to illustrate how to unpack MSY.

The environment itself is not observed; instead an upwelling index $U(t)$ is observed, related to the environmental state according to

$$U(t) = E(t) + \sigma_{env} Z(t) \qquad \text{Eq. 3}$$

In this equation σ_{env} is the standard deviation of the observation uncertainty (Hilborn and Mangel, 1997), and $Z(t)$ is a normally distributed random variable with mean 0 and standard deviation 1.

Given that the environmental state is i, we assume that krill abundance follows a gamma density with mean $\bar{k}(i) = (v/\alpha(i))$ and shape parameter v, which is assumed to be the same for both environmental states. Therefore, the frequency distribution for $K(t) = k$ is

$$f(k \mid E(t) = i) = c_n(i)\exp(-\alpha(i)k)k^{v-1} \qquad \text{Eq. 4}$$

Table 1. Parameters and their values.

Parameter	Interpretation	Value
p_{ij}	Probability of transition from environment state i to environment state j	Varies
$\bar{k}(i)$	Mean of the gamma density characterizing abundance of krill	1.5 or 4.0
v	Shape parameter of the gamma density characterizing abundance of krill	3
S_c	Squid abundance level at which density dependence begins to be important	1,000
b	Shape parameter in squid recruitment distribution	2
M	Squid natural mortality	0.2
σ_{env}	Observational uncertainty of the upwelling signal	0.2
U_{thr}	Threshold value of the upwelling index when fishing with cues	Varies

where $c_n(i)$ is a normalization constant (Fig. 4).

Squid dynamics are characterized for a semelparous annual species by

$$S(t+1) = \frac{K(t \mid E(t))S(t)}{1+\left(\frac{S(t)}{S_c}\right)^b}\exp(-M) \qquad \text{Eq. 5}$$

where S_c is critical value of squid abundance at which density-dependent effects become important, b is a shape parameter for squid recruitment, and M is natural mortality. In order to capture the variation of mortality with life-history stage, Eq. 5 could be expanded to include, for example, hatching (high M), juvenile/young adult (low M), and reproducing (high M) individuals.

THE CASE OF CONSTANT ENVIRONMENTS.—To begin, one can iterate Eq. 5 for the case in which krill abundance is fixed at the average value for the environment. That is, $K(t|E(t))$ is replaced by $\bar{k}(i)$, for $i = 1$ or 2. Doing so shows that, on the assumption of a constant environment and constant krill recruitment, a poor environment leads to squid steady-state population about 480; a good environment leads to squid steady-state about 1510.

Still maintaining the assumption of constant environment and constant abundance of krill, we can include fishing and consider MSY. The squid population dynamics are

$$S(t+1) = \frac{K(t \mid E(t))S(t)}{1+\left(\frac{S(t)}{S_c}\right)^b}\exp(-M-F) \qquad \text{Eq. 6}$$

where F is fishing mortality. Catch in year t, $C(t)$, is (Quinn and Deriso, 1999)

$$C(t) = S(t)\left(1-\exp(-M-F)\right)\frac{F}{F+M} \qquad \text{Eq. 7}$$

and the average cumulative catch between year $t = 1$ and $t = T$ is

$$C_T = \frac{1}{T}\sum_{t=1}^{T} C(t) \qquad \text{Eq. 8}$$

Note that this is an arithmetic average.

Varying fishing effort generates a value for maximum sustainable yield (MSY), an optimal level of fishing mortality (F_{MSY}), and a steady-state squid biomass (B_{MSY}). In the poor environment, these are about MSY = 31, $F_{MSY}(1) = 0.14$, and $B_{MSY} = 268$; in the good environment, they are MSY = 370, $F_{MSY}(2) = 0.62$, and $B_{MSY} = 869$; see Figure 5.

MISMATCHES BETWEEN THE ENVIRONMENT AND FISHING EFFORT.—Environments are not constant, and krill abundance fluctuates, so some mismatch between fishing mortality

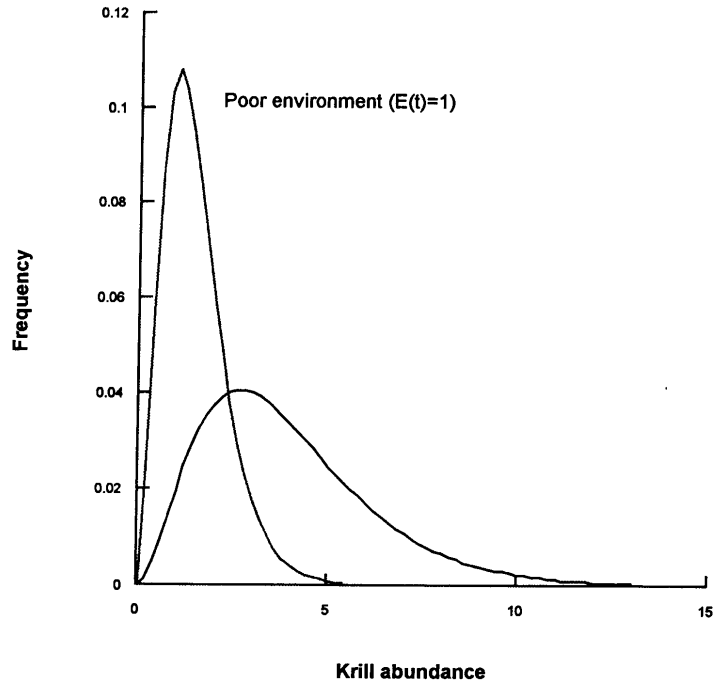

Figure 4. Frequency distribution of krill abundance generated by Eq. 4 under the two different assumptions about the environment.

and the environment is possible. Continuing to keep krill recruitment constant, one may ask what happens if the mismatch occurs and the environment is constant but the 'wrong' one for the fishing mortality. This is not a difficult question: if the fishing effort for a poor environment is applied in a constant good environment, the squid steady state is higher (1363 rather than 869) and the cumulative catch is lower; on the other hand if the fishing effort for a good environment is applied in a constant poor environment, the squid will be driven toward biological extinction (although economic extinction is likely to occur first), but the total catch taken from the environment is greater.

THE CASE OF FLUCTUATING ENVIRONMENTS.—To take account of fluctuating environments, according to the Markov process described previously and to allow for fluctuating krill recruitment, one must develop the stock dynamics with a Monte Carlo simulation, rather than numerically solving the stock equations. We begin by determining the state of the environment, according to the two-state Markov process described above, and from it the krill availability. Then by cycling over a fixed level of fishing mortality (see below for 'adaptive' approaches to fishing mortality) and applying Eqs. 6 and 7, we determine the squid stock dynamics and the catch in each year.

The cumulative average catch described by Eq. 8 is an arithmetic average, but average catches can also be calculated by either a geometric or a harmonic average; these are

$$C_T = \left[\prod_{t=1}^{T} C(t)\right]^{1/T} \qquad \text{Eq. 9}$$

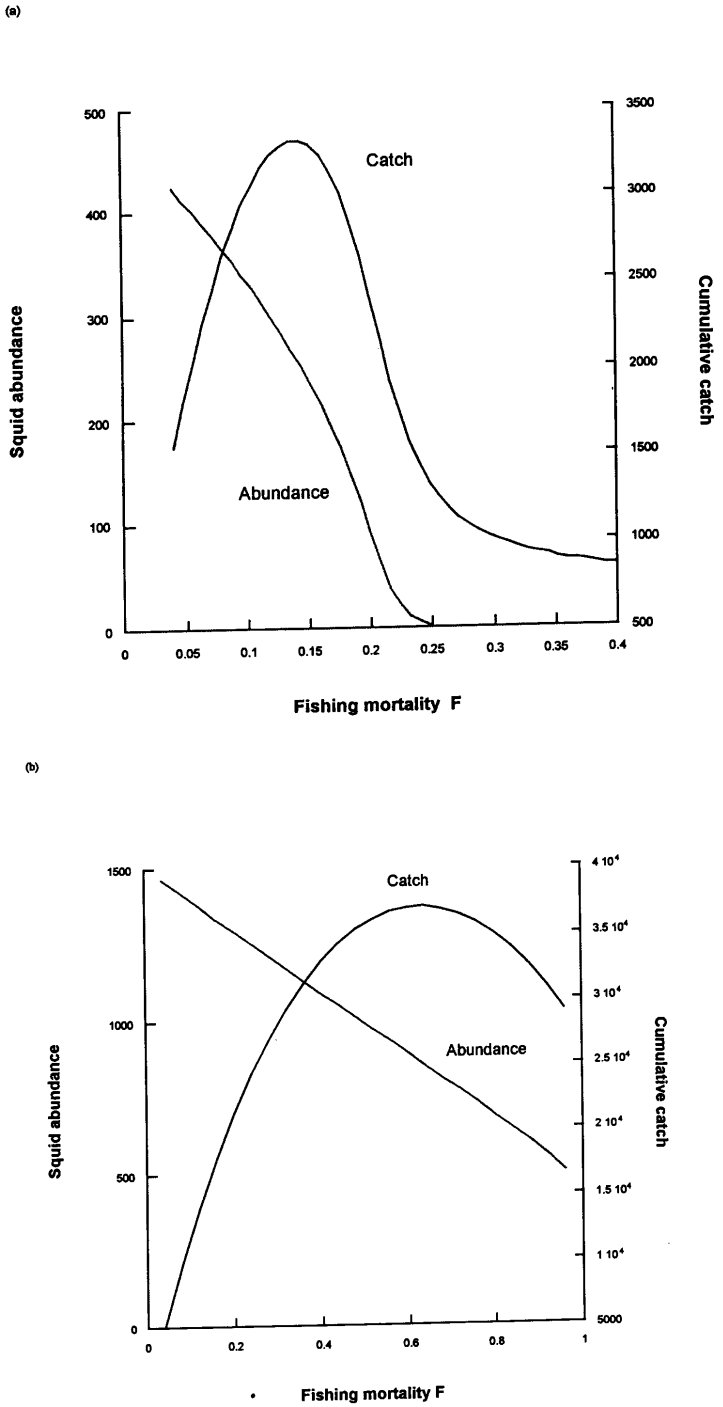

Figure 5. Squid abundance and cumulative catch on the assumption of constant environment and constant krill recruitment. (A) A poor environment, with lower krill recruitment. (B) A good environment, with higher krill recruitment.

for which

$$\log(C_T) = \frac{1}{T}\sum_{t=1}^{T}\log(C(t)) \qquad \text{Eq. 10}$$

and

$$C_T = T\left[\frac{1}{\sum_{t=1}^{T}\frac{1}{C(t)}}\right] \qquad \text{Eq. 11}$$

Which of these averages (arithmetic, geometric, or harmonic) Ricker meant in his definition is uncertain, but as will be seen below, the choice matters. Once the averaging method is chosen, the economically optimal level of fishing mortality can be determined, where optimal is understood to mean maximizing the catch over 100 yrs per simulation and 500 simulations. The optimal level of fishing mortality, for the parameters used here, was relatively insensitive to the value of p_{ii} over the range from 0.55 to 0.8, but it was sensitive to the averaging method used. For the arithmetic average, the optimal value of fishing mortality was about 0.3, whereas for the geometric average it was slightly higher than 0.2, and for the harmonic average it was slightly lower than 0.2. These should be compared with the constant-environment values of 0.14 and 0.62; note that even the arithmetic average is not simply an average of the two optimal values for constant environments. The lower levels of fishing mortality for geometric and harmonic averages translate into lower yearly and cumulative catch and higher stock abundance.

When the environment fluctuates, the stock may be depleted and put at risk (Musick, 1999). 'Depletion' is a relative term and must be carefully defined. For the results shown here, we defined depletion as a decrease in squid stock in a particular year to less than 30% of B_{MSY} in constant environment 1, equivalent to a level of about 80. In this model, squid can be depleted for two reasons. First, krill recruitment can be poor, leading to poor squid recruitment. Second, fishing effort can be too high for the given level of squid. Of course, the two are not mutually exclusive and can interact with each other. The risk to the squid stock increases as p_{ii} increases (Fig. 6), because one is more likely to be 'stuck' in the poor environment, and risk depends upon the averaging method used. By using a risk-averse averaging method (in this figure, a geometric average), however, one can reduce the risk to the stock.

Using Environmental Cues.—We have assumed that the environment and krill stocks are not directly observable, but in fact, an environmental cue, such as upwelling (Eq. 3) may be available. If this cue provides some information about the availability of krill, then using it may permit better management of both catch and risk.

For example, if the upwelling index is below some threshold, and the environment is therefore likely to be poor, a lower level of fishing effort might be applied; otherwise a

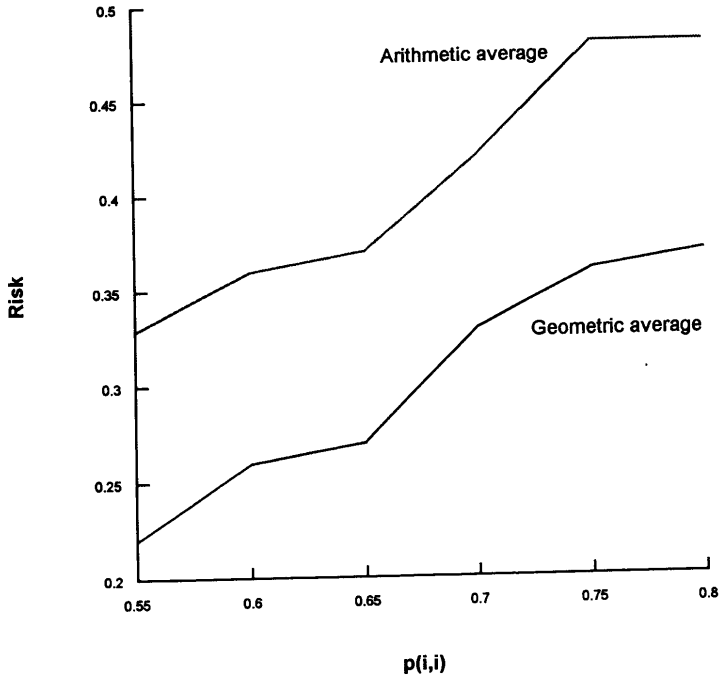

Figure 6. Risk to the squid stock (of falling below 30% of the steady-state value for constant krill in constant poor environment) as a function of environmental repeatability and the averaging method used to determine fishing mortality. The result for the harmonic average is similar to that for the geometric average and therefore not shown.

higher level might be applied. The fishermen might follow this rule themselves, by switching to different target species in years when squid are difficult to find.

Of course, the environmental variable and fishing effort might be related in an infinite number of ways, but a simple method is a bang-bang control

$$F(t)=\begin{matrix} F^*(E=1) \text{ if } U(t)\leq U_{thr} \\ F^*(E=2) \text{ if } U(t)>U_{thr} \end{matrix} \qquad \text{Eq. 12}$$

where U_{thr} is an adjustable parameter.

In Figure 7, we show the (arithmetic) average annual catch and risk as a function of the upwelling threshold for the case in which $p_{ii} = 0.65$. For comparison, when fishing effort is fixed, the average catch is only 3% higher (100.8 rather than 97.8), but the risk is nearly 20% higher (0.37 rather than 0.31). Thus, using this simple rule leads to equivalent catches but less risk to the stock. More complicated rules could be developed, of course, but the point of this illustration would not change. Thus, an environmentally based feedback rule may have much the same effect as a risk-averse averaging method of reducing the risk to the stock without having a severe negative impact on catch. It may seem counterintuitive that catch can increase and risk decline simultaneously. The explanation is that, conservatively, as the threshold value increases, the high level of fishing effort is applied in years

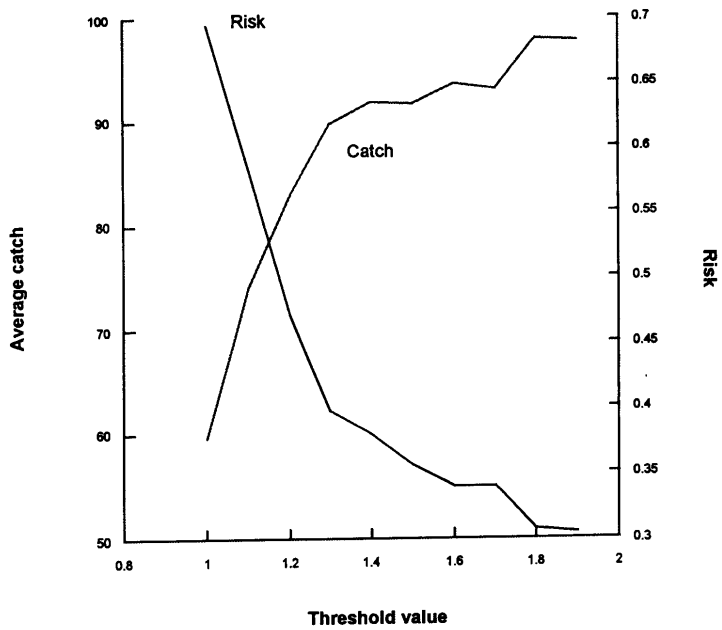

Figure 7. Average catch (over the 100-yr period of 500 simulations) and risk as a function of the upwelling threshold (Eq. 12).

that are more likely to be high-abundance years. The result is twofold: the risk of a stock collapse decreases, and the chance of higher abundance in subsequent years increases.

The difficulty with an effort rule like Eq. 12, however, is that, as the threshold value increases, the likelihood of displaced fishing effort increases. What happens to that effort is crucial for understanding the full fishery system, so the behavior of the fishing fleet, given a circumscribed set of opportunities, must be modeled. We are currently doing so.

Implications of the Mote Symposium for Unpacking MSY

The Third Mote Symposium was not dedicated to unpacking MSY, but many of the papers at the symposium touched on the issues raised here. All kinds of information are needed for the successful management of human intervention in ecosystems (Mangel et al., 1996; Pomeroy and Fitzimmons, 1998). Ricker's definition says nothing about the risk to the stock, which somehow must be included as one considers management action and biological reference points. Today's computing power, which did not exist when Ricker published in 1975, allows us to evaluate management action prospectively (Overholtz, 1999). Ricker's definition hinges on three notions: "average," "continuously," and "existing environmental conditions." The model here suggests that, given uncertainties and fluctuations in the world, one may want to choose an averaging method that is, of itself, risk averse. Both harmonic and geometric averages have that feature. Furthermore, catch can be taken continuously only if there are no interruptions, showing that maximum biological production must be modulated by the risk of stock collapse if one aims to determine MSY according to Ricker's definition. Finally, one must have a broad under-

standing of the temporal pattern of "existing environmental conditions"; local understanding is insufficient.

BIOLOGICAL CONSIDERATIONS.—We must recognize from the outset that setting fishing mortality on the basis of current abundance relative to unfished stock size B_0 is based on a theoretical construct (unfished stock size) that surely depends on existing environmental conditions (Hilborn, this issue; Walters and Martell, this issue).

Biological reference points such as MSY may be meaningless for species of limited mobility, species with complex life histories, mixed stock fisheries, or stocks with long-term changes in productivity (A. M. Parma, Centro Nacional Patagónico, Argentina, pers. comm.; MacCall, this issue). Indeed, managing a fishery with MSY in the face of decadal environmental events such as El Niño may be similar to farming while taking into account Dust Bowl events on a decadal scale.

Classic bioeconomic analysis (Clark, 1985; Clark and Munro, this issue) leads to the prediction that the bionomic population size (at which the fishery in aggregate makes no money) is $N_b = c/pq$ where c is the cost of unit effort, p the price of a unit of fish biomass, and q the catchability coefficient. Note that the bionomic population size has no 'bio' in it; this problem may indeed be the source of many of our management difficulties: the bioeconomic approach treats all biology as identical.

Regardless of what the economists say, one must know the organism one studies (Mangel, 1993) and do biology on the harvested species (Bolker et al., this issue; Hilborn, this issue). Furthermore, we should seek to integrate diverse information at the population, behavioral, and physiological level (Essington and Kitchell, pers. comm.) and exploit both fishery and fishery-independent data (Harris, pers. comm.) in our attempts at better management. MacCall (this issue) shows that rebuilding a slow-growing stock in a multispecies fishery may require exceptionally long periods because of the combination of environmental regime shifts and competitive and predator-prey interactions.

Fishing pressure is a form of artificial selection (Mangel et al., 1993), and we should expect that evolution (e.g., toward smaller size or younger reproduction) will occur (Heino and Godø, this issue).

TECHNICAL ISSUES.—We must be prepared to work with models that have parameter, process, observation, structural, and implementation uncertainty (Charles, this issue; McAllister and Kirchner, this issue; Sladek Nowlis and Bollerman, this issue; Siddeek, pers. comm.). Doing so will provide great benefits. For example Kinas (this issue) showed how Bayesian analysis of population dynamics and data on anthropogenous (incidental take) mortality allow one to separate the current size of a stock from its trajectory. The technical problems are considerable but not insurmountable. For example, de Valpine (this issue) shows how an approach based on paths in state space (Schulman, 1981; Freidlin and Wentzell, 1984) can allow one to fit models with both process and observational uncertainty.

No analysis of a fishery should proceed without multiple hypotheses (Hilborn and Mangel, 1997) that compete, and data must be the arbitrator. Imagine, for example, the case in which Canadian scientists charged with thinking about the cod fishery had observed an increase in the catch of age-3 cod and considered multiple hypotheses:

- The catch of age-3 cod increased because spawning biomass increased.
- The catch of age-3 cod increased because age at maturity evolved.

• The catch of age-3 cod increased because fishermen concentrated on them.

For what they actually did, see Hutchings and Myers (1994) or Hutchings (1996).

We must have models that incorporate fisherman behavior (Clark and Mangel, 2000; Cox et al., this issue; Wilen et al., this issue). These are more than optional: they are essential if we are to avoid unpleasant surprises (Wilen et al., this issue). In that context, we might actually ask whether fishermen ever try to optimize (rather than maximize) their catch and consider replacing the notion of Maximum Sustainable Yield by the concept of Pretty Good Yield.

To some extent, Congress already did that with the Sustainable Fisheries Act (1996) and its emphasis on sustainability rather than maximum or optimal yield.

IMPORTANCE OF PROSPECTIVE EVALUATION OF MANAGEMENT PROCEDURES.—Prospective evaluation of the management procedures, which includes fishing controls, monitoring, and decision rules for altering fishing controls or monitoring, to determine which ones satisfy the performance criteria (de la Mare, 1998; Cooke, 1999; Sainsbury et al., 2000) is essential. It involves

• Data
• Decision rules
• Advance agreement on how data are used in decision rules
• Testing (by simulation)

Indeed, it is often the lack of any management framework that causes problems, rather than a particular management framework (Polacheck, pers. comm.).

The evaluation of management procedures before their implementation provides the opportunity to eliminate management options that would fail to meet the objectives, thereby potentially preventing the trial-and-error approach that has led to stock collapses (e.g., of, whales, Holt, 1998; finfish, Ludwig et al., 1993). Methods for the development of new fisheries and for managing existing fisheries while introducing a precautionary approach that accounts for uncertainty have been developed by the Scientific Committee of the Commission for the Conservation of Antarctic Marine Living Resources (Constable et al., 2000) and the Food and Agriculture Organization of the United Nations (FAO, 1995). The elements to consider in a management procedure and its evaluation are well described (de la Mare, 1998; Smith et al., 1999; Sainsbury et al., 2000). Such evaluation allows the implementation of the management procedure that is most likely to achieve the objectives despite uncertainties in the various parts of the system, including the limitations of a monitoring program, such as incomplete data and low power in assessments. It can also be used to ensure that the costs of management are commensurate with the value of the fishery. Such forward projection is essential if we are to be able to evaluate short-term costs and long-term benefits (Peterman, this issue).

Furthermore, prospective management allows us to explore the consequences of possible management procedures—and to understand the range of dynamics of the stock—as well as allowing us to deal with discarding, incidental take, habitat damage, and food-web effects (Essington and Kitchell, pers. comm.).

CONNECTION BETWEEN SCIENCE AND POLICY.—Perhaps the most important conclusion that we can draw about the connection between science and policy is that the ultimate technical result is that the problem is not a technical one (Ludwig, this issue).

Management must be transparent and have clear and multiple metrics (Brodziak and Link, this issue). Data-based rules, rather than assessment-based rules, may be a step forward (Hilborn, this issue); Martell and Walters (this issue) provide an example show-

ing how monitoring effort and catchability coefficients through tagging may be more cost-effective and risk averse than standard methods.

The connection between science and policy also hinges on an understanding of the human behavioral response to property rights and incentives. Without it, well-intentioned plans may produce the opposite of the desired effect (see, e.g., Clark and Munro, this issue; Cox et al., this issue). Similarly, we must understand consumer behavior, for example in relation to ecocertification of product, which may provide an incentive for dealing effectively with uncertainty and risk (Peterman, this issue).

We should manage so that precise reference points are not needed, and if they are desired, we should use meta-analysis to construct them (R. Myers, pers. comm.). Management (Brodziak and Link, this issue) must be accountable (explicit about decision criteria), legitimate (explicit about policy strategies), and flexible (explicit about uncertainty) and must also deal carefully with issues concerning burden of proof (Charles, this issue).

Regardless of the technical or scientific considerations, management is an "incredibly tortuous negotiation process" (A. Rosenberg, pers. comm.), so we must be pragmatic:

"Being pragmatic does not mean the rejection of rules or principles in favor of ad hoc decision making or raw intuition. Rather, it means a rejection of the view that rules, in and of themselves, dictate outcomes... Hard policy decisions can't be programmed into a spreadsheet... But we also need an analytic framework to help structure the process of making environmental decisions... Rather than rigid rules or mechanical techniques, we need a framework that leaves us open to the unique attributes of each case, without losing track of our more general normative commitments" (Farber, 1994).

Conclusion: Wisdom from John Gulland

We began the paper quoting Bill Ricker and Peter Larkin, giants of fishery management in the 20th century. It seems only appropriate to end by quoting John Gulland: "MSY: a quantity that biologists say does not exist, that economists say would be irrelevant if it did exist. It is, in short, the most important concept in fisheries management" (R. Hilborn, pers. comm.).

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