Marine Resource Management Under Uncertainty: The Case of Eastern Spinner Dolphin Depletion

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Marine resource management regimes often require decisions that must be based on uncertain data and models. Despite theoretical and practical advances, one cannot count all the fishes in the sea. Models have difficulty capturing the complex interactions of species with other species and with their environment.

Data are frequently incomplete and uncertain, key scientists disagree, and fishery models are often flawed. For example, the Bristol Bay salmon run for 1975 was predicted to be 12 million sockeye with an 80 percent confidence interval between 6.2 and 17.8 million. The actual inshore run for this long and intensively studied stock complex was 24 million fish (University of Washington, 1976).

Many authors have commented on the frequent inadequacies of bioeconomic theory and data (Crutchfield, 1972; Larkin, 1972). It is clear that great uncertainties will characterize forthcoming management decisions. This paper examines the inherent role of uncertainty in such management situations and offers the case of eastern spinner dolphin, *Stenella longirostris*, depletion as an example where a special application of probability theory helped to clarify a difficult determination.

Where the descriptive and predictive powers of fishery scientists are strong, management can be the beneficiary (Cushing, 1974). Decisions, however, must frequently be made before scientific information is conclusive. Managers typically face the problem of making good decisions in the presence of scientific uncertainty and policy constraints.

Fortunately, there are aids to good management in such situations. It is often possible to describe uncertainty in probability terms. Once judgments are expressed in this form, the logic of mathematics is available to assist in making consistent choices. "Doing the best one can with what one has" should be the desideratum for management determinations where there is scientific dispute, uncertain data, or inadequate models.

Porpoise, Tuna, and the Marine Mammal Protection Act

A situation embodying such disagreement and uncertainty recently arose in an application of the Marine Mammal Protection Act (MMPA) of 1972 (U.S. Code, 1972). The legal and policy context is important to understand. This Act was passed, in part, because of concern over the porpoise kill incidental to commercial tuna fishing.

Tuna fishermen have observed that yellowfin tuna often associate with certain species of porpoise. When porpoise are sighted, speedboats are used to herd them to the area where a large purse seine will be deployed. The tuna follow the porpoise and are captured when the net is drawn closed. This procedure is called fishing "on porpoise" and began in the latter 1950's.

In 1975, for example, yellowfin tuna caught "on porpoise" represented 72 percent of the total U.S. yellowfin tuna catch, and 43 percent of the total U.S. tuna catch (National Marine Fisheries Service, 1975). Despite fisherman efforts to release the porpoise, many become entangled in the nets and drown. Over 300,000 porpoise were killed in 1971, the year before the MMPA was passed.

The MMPA was based on a concern that certain stocks of marine mammals were threatened by extinction or depletion. It declared that species should not be permitted to fall below their "optimum sustainable population (OSP)." According to the Act, "The term 'optimum sustainable population' means, with respect to any population stock, the number of animals which will result in the maximum productivity of the population of the species, keeping in mind the optimum carrying capacity of the habitat and the health of the ecosystem of which they form a constituent element" (U.S. Code, 1972).

The MMPA adopted an immediate goal that porpoise kill and serious injury incident to commercial fishing be reduced "to insignificant levels approaching zero." Nevertheless, the Secretary of Commerce could issue permits which allowed the taking of marine mammals so long as "such taking will not be to the disadvantage of those species and population stocks and will be consistent with the purposes and policies" of the Act. The Secretary had issued such permits

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to the tuna industry. In May 1976, however, these permits were invalidated by court action (Richey, 1976). The District of Columbia Court of Appeals upheld this decision the following August. The decision required the imposition of a quota and an analysis of its impact on optimum sustainable population. Unless new regulations were issued, no setting on porpoise could occur after 1 January 1977, with consequent economic impact on the industry.

The Eastern Spinner Dolphin and OSP

To issue new regulations before 1977 for incidental porpoise take, the National Marine Fisheries Service was required to make a number of findings. One requirement was a determination whether the eastern spinner dolphin was depleted. Legally, this would have been the case if the current eastern spinner dolphin stock size was below the range of its "optimum sustainable population." This determination would have been relatively easy if the data were good and scientists were agreed on the precise values of stock size and OSP. In that happy event, the two values could have been compared simply. This, however, was not the case.

A conference of 12 distinguished marine scientists was convened in La Jolla, Calif., in August 1976 to address issues of population size and OSP for numerous porpoise stocks. After studying the data, they decided that there is "a range of population sizes — between that giving the maximum net productivity [MNP] and the maximum population possible within the carrying capacity of the ecosystem — which is consistent with the MMPA" (SWFC, 1976). Thus, OSP should not be interpreted as a single number but rather as a range of population sizes. The eastern spinner dolphin depletion determination turned on whether the species' 1976 stock size was below the lower end of the range of OSP. The workshop participants made estimates of porpoise stock sizes before tuna purse seining began and estimates of present stock sizes as percentages of this unexploited population level.

On the basis of the best available data and models, the workshop participants were unable to determine precise values for the present (1976) stock size and the lower limit of OSP. Instead, they specified a range of values for each. They felt that the lower limit of the OSP range occurred at a level somewhere between 50 and 70 percent of the original porpoise stock size. Their estimate of the current eastern spinner dolphin population was within a range of 37-75 percent of the unexploited population size.

A Probabilistic Analysis

Because of the court decisions and the strict regulatory timetable, a prompt finding on the status of eastern spinner dolphin stocks had to be made by the National Marine Fisheries Service. The available scientific knowledge about stock sizes and the lower limit of OSP obviously did not justify picking single numbers in the ranges for comparison. Instead, the question was how to use this uncertain scientific information, consisting of ranges rather than precise figures, to arrive at a finding of whether or not the present eastern spinner dolphin stock was below the lower end of its optimum sustainable population range. One way to proceed was to describe the uncertainty formally and then to determine the probability that the current stock size was below the lower limit of the OSP range. This exercise, along with the advice of key scientists and the Marine Mammal Commission, could then guide the finding of depletion.

There were three steps involved in determination: 1) Translate the state of knowledge about the lower limit of OSP into probabilistic terms; 2) do the same for the current stock size of the eastern spinner dolphin; and 3) compare the two quantities stochastically.

To begin, consider what the final workshop report (SWFC, 1976) said about OSP: "The participants believe therefore that any porpoise stock whose abundance is less than 50% of the unexploited level is probably below the MNP level [equal to the lower limit of OSP], and that any stock much more than 70% of the unexploited stock is probably above the MNP level [lower limit of OSP] . . . Most of the participants believe that there is insufficient scientific evidence to select a particular value of the proportion of the unexploited porpoise population necessary for maximum net production [the lower limit of OSP] within the range of 50% to 70%."

One probabilistic interpretation of this statement was there was an equal chance of OSP occurring at any point within the 50-70 percent range. Analytically, this indicated a uniform probability distribution on the 50-70 percent interval (Fig. 1). Thus, it was equally likely in this interpretation that OSP was at 52, 57, or 65 percent of the unexploited level, for example.

It is worth noting that the translation of this state of knowledge into probability terms is not based on a relative-frequency concept of probability (von Mises, 1941). Instead, it considers probability to be a description of uncertainty. A brief elaboration of the basis of this interpretation may be helpful.

Numerous contributors to the theory of probability have conceived of probability as a rational measure of belief (i.e., see Jeffreys, 1961; or Savage, 1954); historical treatments are contained in de Finetti (1972) or Raiffa (1968). Under this approach, past information or analysis about the uncertain event under consideration should be taken into account in assigning probabilities to the different possible outcomes. If it were relevant, information about the relative frequency with which the event occurred would affect the probability assessment. It is important to note, however, that this "subjectivist" concept of probability — loosely typified by statements like "there is a 40 percent chance of rain" or "I'll give you five-to-one odds on the Yankees" — can be rigorously extended to events that cannot be repeated under identical conditions or that do not admit a long-run, relative-frequency interpretation. If certain principles are adhered to for making consistent probability assessments, it is possible to prove that the resulting measure satisfies the standard requirements for the definition of probability. The usual mathematics of probability can then be used to work with such formal descriptions of the uncertain quantity.

With this interpretation of probability statements in mind, the second step in the analysis of porpoise depletion re-

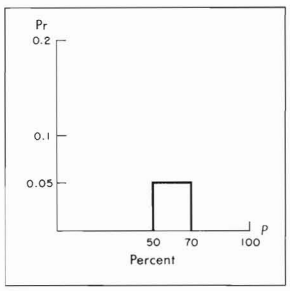

Figure 1.—Density function for lower end of OSP range (P).

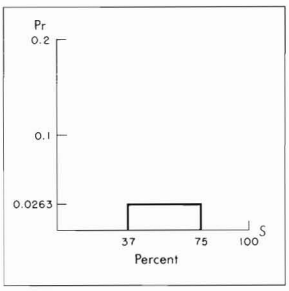

Figure 2.—Density function for stock size (S) as a percentage of unexploited population.

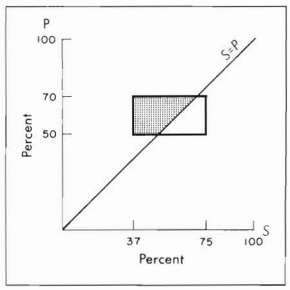

Figure 3.—Comparison of stock size (S) and OSP (P).

quired a description of the uncertainty in estimates of stock size (given as a percentage of the unexploited population). This number depended on estimates of the eastern spinner dolphin population before purse seining began, upon net recruitment rates, upon reproductive response lags, and upon alternative historical mortality vectors. Based on their information, the workshop participants concluded that the 1976 stock size was somewhere between 37 and 75 percent of the unexploited population level (SWFC, 1976). Rather than to combine the underlying factors probabilistically, an appropriate initial description of this uncertainty was to say that there was an equal chance of the true value occurring at any point from 37 to 75 percent of the unexploited population level. Thus, a density function as in Figure 2 is indicated.

The third step is to compare the lower limit of the OSP range and the stock size. It appears warranted to consider OSP and current stock size to be stochastically independent random variables, since knowledge of the distribution of one variable indicates nothing about that of the other.

Let S be the current population of the eastern spinner dolphin and let P be the lower limit of the OSP range. Their probability density functions can then be represented as

$$f(S) = \begin{cases} 0.0263 & , 37<S<75 \\ 0 & , \text{otherwise,} \end{cases}$$

and

$$g(P) = \begin{cases} 0.05 & , 50<P<70 \\ 0 & , \text{otherwise.} \end{cases}$$

The rectangle in the SP-plane is the region over which the joint density function of S and P is nonzero (Fig. 3). Note that above the line $S = P$, S is less than P, or the stock is depleted. The idea, then, is to calculate the probability of the event that S is less than P; that is, to determine the chances of being in the shaded area. Since the joint probability density function— the product of the independent marginal density functions of S and P—is constant above the region in this case, the depletion chance can be obtained by multiplying the area of the shaded region by the joint density function. Thus,

$$\begin{aligned} \Pr(S<P) &= (\text{shaded area in diagram}) \\ &\quad (\text{joint p.d.f.}) \\ &= [(13)(20) + (0.5)(20)(20)] \\ &\quad [(0.05)(0.0263)] \\ &= 0.6049. \end{aligned}$$

Hence, under these assumptions, there was a greater than 60 percent chance that stock size was below the lower limit of OSP.

This methodology could be extended to more complicated descriptions of the uncertainty. The only change in the analysis is that appeals to calculus or special properties of the random variables would be necessary.

For example, a more appropriate description of the uncertainty expressed in the workshop report might have been that the chances of OSP occurring at the 60 percent level are highest, with the probability falling off normally toward the 50 percent and 70 percent levels. A normal density function with a mean of 60 percent and standard deviation of 5 percent would imply a greater than 95 percent chance that the lower OSP limit was in the 50-70 percent interval with a 2.5 percent chance that the true value was greater than 70 percent, and a 2.5 percent chance that it was less than 50 percent. To see this, note that

$$\begin{aligned} &\Pr(50<P<70) \\ &\quad = \Pr\left(\frac{50-60}{5} < \frac{P-60}{5} < \frac{70-60}{5}\right) \\ &\quad = \Pr(-2<Z<2) \\ &\quad = 0.955, \end{aligned}$$

where Z is N(0,1). To construct a similar distribution for stock size, a normal density function with a 56 percent mean and a 9.5 percent standard deviation was indicated.

Stock size will be less than the lower limit of OSP where S is less than P. If the new variable D is defined as $P - S$, then the area where D is greater than zero is the region of interest. Now D is a random variable distributed as the difference of two independent normal random variables. Thus, D has a mean equal to the difference between the means of P and S, $(60-56=4)$, and a variance equal to the sum of the variances of P and S, $(5^2 + 9.5^2 = 10.74^2)$. The probability of depletion in this formulation is $\Pr(D>0)$, which can be easily calculated to be 64.34 percent.

These interpretations of the uncertainty expressed in the workshop report (SWFC, 1976) led to the conclusion that there were better than six chances in ten that the eastern spinner dolphin population was below the lower limit of the optimum sustainable population range. Of course, a probability distribution from each of the workshop participants could have been obtained and combined by various expert resolution techniques. As one input to the depletion determination, however, the above interpretation of the collective uncertainty seemed appropriate. It avoided the need to say precisely that the lower level of OSP, for example, was at 50 percent, 60 percent, or any other point in the range when actual knowledge simply did not justify the choice of a single, precise value.

The Policy Determination

Once this probability was established, the policy question had to be faced as to whether 60 percent was a sufficiently high chance of depletion to require such a declaration. The U.S. District Court had explicitly characterized the approach which must be employed in discharging marine mammal obligations: "The interests of the marine mammals come first under the statutory scheme, and the interests of the [tuna fishing] industry, important as they are, must be served only after protection of the animals is assured" (Richey, 1976). While the determination may have been less clear if the probability of depletion was, say, 20 percent, given the legal constraints, the 60 percent chance was high enough to be quite in line with the ultimate declaration of depletion.

Conclusion

This particular example, which contains the complicating factors of expert disagreement and poor data, illustrates the promising use of a method for specifying uncertain beliefs and drawing inferences from them. In this case, the Act had stipulated that the marine mammals must be kept in the range of their "optimum sustainable populations." For marine fisheries generally, Federal law now requires that "Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery" (U.S. Code, 1976). It is clear that, especially under these new regimes, similar determinations under uncertain conditions will be required. In the many difficult decisions which no doubt lie ahead in marine resource management, extension of these probabilistic techniques may help to clarify otherwise fuzzy situations.

Acknowledgments

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Literature Cited

Crutchfield, J. A. 1972. Economic and political objectives in fishery management. *In* B. J. Rothschild (editor), World fisheries policy, p. 74-89. Univ. Wash. Press, Seattle.

Cushing, D. H. 1974. A link between science and management in fisheries. Fish. Bull., U.S. 72:859-864.

de Finetti, B. 1972. Probability, induction and statistics. John Wiley and Sons, Lond.

Jeffreys, H. 1961. Theory of probability. Charendon, Oxford.

Larkin, P.A. 1972. A confidential memorandum on fisheries service. *In* B. J. Rothschild (editor), World fisheries policy, p. 189-197. Univ. Wash. Press, Seattle.

National Marine Fisheries Service. 1975. Fisheries of the United States, 1974. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Curr. Fish. Stat. 6700, 98 p.

Raiffa, H. 1968. Decision analysis: Introductory lectures on choices under uncertainty. Addison-Wesley, Reading, 309 p.

Richey, C. R. 1976. U.S. District Court of Appeals, C.A. 75-0227, at 22.

Savage, L. J. 1954. Foundations of statistics. John Wiley, N.Y., 294 p.

SWFC. 1976. Report of the workshop on stock assessment of porpoises involved in the eastern tropical Pacific tuna fishery. Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. LJ-76-29.

U.S. Code. 1972. Marine Mammal Protection Act of 1972. 16 U.S.C. 1361 et seq. University of Washington. 1976. 1975 Research in fisheries. Annu. Rep. Coll. Fish., p. 9. Univ. Wash., Seattle.

_____. 1976. Fishery Conservation and Management Act of 1976. 16 U.S.C. 1851.

von Mises, R. 1941. On the foundations of probability and statistics. Ann. Math. Stat., 12.