CHAPTER 3

ECONOMIC ANALYSIS FOR NORTHERN ANCHOVY MANAGEMENT

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Published in July of 1978, the Pacific Fishery Management Council's management plan for the northern anchovy fishery off of California was the second plan (after salmon) to be implemented on the West Coast. The high priority given to the development of the anchovy plan was due largely to the apparent ecological importance of the fish stock and to the great political sensitivity of anchovy management issues in California. For the most part, traditional economic issues were drowned out by the noneconomic concerns of recreationists and public agencies. Nevertheless, a moderate amount of economic information was assembled and analyzed for inclusion in the plan that was eventually adopted. After the introduction of the planned regulations in September 1978, the economists and biologists responsible for most of the analysis at the National Marine Fisheries Service Southwest Fisheries Center continued to examine management strategies and issues pertinent to the northern anchovy. Most of the ideas, data, and analytical results presented in this paper resulted from the joint efforts of the management planning team at the Southwest Fisheries Center.[1]

This chapter is organized into four major sections. In the first section, five important economic issues are listed and described. Following that, a section is devoted to the presentation of biological, institutional and economic information providing a necessary real-world context for the management problems. In the third section economic theories are tailored to the specific needs of anchovy management, and analytical results are presented. In applying economics to the fishery, areas of theoretical weakness and data deficiency are revealed. In the concluding section the strengths and weaknesses of the existing economic analyses are reviewed, and recommendations for further research are advanced.

ECONOMIC ISSUES FOR ANCHOVY FISHERY MANAGEMENT

While no short list of topics can fully represent the complex management issues at stake in the formulation of public regulations for northern anchovies, the following five points cover the most substantial areas for economic analysis:

1. evaluation of the aggregate harvest rate by the U.S. fishery;
2. allocation of the fish harvest among various end uses;
3. analysis of the optimum investment in harvesting and processing capacity;
4. formulation of regulatory mechanisms to achieve the desired objectives for catch, investment and so forth; and
5. design of management information and monitoring programs.

To analyze any of these issues one must adopt some criterion or objective for management. A single economic objective that will provide the framework for the following discussions is the traditional one of maximizing the economic value of goods produced, net of production costs. Within this objective is contained the requirement that the fishery achieve productive efficiency, the minimization of costs incurred in producing the desired level of output. Within this context the careful identification of costs and values is clearly a principal task. Since neither the fish stock nor the recreationally caught fish are traded in markets, the economic analysis must account for nonmarketed and unpriced goods as well as commercial product values. As any student of welfare economics knows, the adoption of this "net economic yield" criterion for management cannot be rigorously defended since the distribution of income will be influenced by the fishery policy and we have not determined what changes in income distribution are desirable. Bromley and Bishop [1977] examine this aspect in great detail, concluding that the traditional approach to fisheries economics by focusing on economic efficiency issues ignores income distributional impacts and much of economic welfare theory. Assuming that any income distributional consequences of anchovy management decisions are on a small scale and that these can be remedied by other means, however, the traditional efficiency objective will serve as a useful guide in the following discussion.

Much of the economic theory of fisheries is devoted to the first topic listed above—evaluation of aggregate harvest rates. Since many extensive reviews of this theory are available [Anderson 1977; Clark 1976; and Peterson and Fisher 1977], no lengthy theoretical treatise is called for here. In application, however, the theory leaves much to be desired. As noted by Peterson and

Fisher, the "functional forms are too simple and their empirical content too low." Institutional, geographical and organizational content is often sacrificed to preserve mathematical tractability or to allow two-dimensional, pedagogical diagrams. Since we are addressing an actual management problem, simplicity-destroying complications must be introduced in some fashion. Three apparently important complications arising in the anchovy fishery are (1) the multipurpose nature of the fishing fleet; (2) the stochastic variability of the stock; and (3) the importance of anchovies as forage. Economic implications of these are discussed below.

Allocation among end uses, the second topic, is an important consideration for anchovy management because the widespread use of anchovies for live bait by both recreational and commercial fishermen is politically and economically more significant than their use as meal and oil. Market values per unit weight for live bait are estimated to be 8-10 times the value of fish used by reduction plants. One might be tempted to assume, therefore, that the free market forces could be counted on to assure the proper allocation to live bait, reduction fish and other end uses. This is not the case, however, because the two products are produced by two separate groups of fishermen having different equipment, locations and alternative opportunities. Most importantly, there is no institutional framework within which the live-bait interests can bargain with the reduction fishery interests to assure that the reduction fishery does not take all the available fish. In part this is a problem caused by the existing management procedures. An annual quota is set in the fall, while the major live-bait market occurs in the summer months. If the quota is taken before the summer begins, live bait would not be available at the appropriate time. Thus a set of separate quotas, or some other allocative device, is needed.

The third issue has occupied fishery economists concerned with the problem of "overcapitalization." Under some regulatory schemes, the fishery may be induced to harvest the proper quantity of fish (by some definition) but private, profit-oriented fishermen will have strong incentives to construct and operate far more fishing vessels than necessary to take the allowable catch. Arbitrary limits on some inputs to the production function encourages greater (and uneconomic) use of other inputs. This breach of the productive efficiency criterion is especially likely when regulations rely on "standards" (like quotas, size limits and gear restrictions) rather than incentive-compatible mechanisms (like taxes and property rights) to achieve narrowly defined harvest goals. A public policy toward fishery inputs, however, must rely on a normative theory of optimum input use, especially the optimum level of capital investment. An important secondary issue is whether the expected extra cost associated with unregulated input use exceeds the benefits of regulation.

The fourth issue listed above is concerned primarily with the economic efficiency of the management operations once the specific objectives of management have been defined. Experience with regulatory programs elsewhere, especially in pollution control and environment regulation, has led most economists to recommend pricing mechanisms rather than absolute standards as regulatory tools. Others prefer property right arrangements. But as Scott [1979] points out, either system can achieve a given set of goals regarding efficiency, equity and conservation. One of the principal considerations in choice of regulatory tools must be the prospective cost (economic and political) of gathering and monitoring the data needed to assure that the regulations are being obeyed with sufficient regularity to support the management program. This issue has not received the extensive formal analysis that it deserves in the fisheries literature. The cost of running a successful management program with a given set of regulations probably depends crucially on the extent to which the rules incite individual fishermen to evade enforcement and monitoring efforts. And these incentives will depend on the physical ease with which rules can be broken without detection, as well as upon the financial consequences of rule-breaking behavior.

The final issue I have suggested for economic examination requires that the tools of economics be turned inward on the analysts themselves. One frequently hears that more economic data, better stock assessments and more extensive enforcement of regulations are "needed." These claims are sometimes motivated by requirements laid down in the Fishery Conservation and Management Act (FCMA), such as National Standard (2) (Sec. 301) calling for the use of the "best scientific information available," or the "optimum yield" definition [Sec. 3(18)] which requires the consideration of economic and social factors. But information is costly to obtain. Thus optimum yield cannot logically call for vast reservoirs of data which contribute little to the decision-making process. Similarly, "best" scientific information is not necessarily the most comprehensive or conclusive information, but rather the most appropriate level of knowledge, given cost and time constraints. The economic theory of information suggests that new data be valued by the expected increase in discounted future returns associated with the decisions dependent on that information. (See, for example, Hirshleifer and Riley [1979].) This opens up a relatively unexplored area for analysis in fisheries management, but one which could potentially contribute significantly to the efficiency of management operations.

There are undoubtedly fruitful areas for economic analysis in addition to the five discussed here. But these five seem sufficiently important to the management of northern anchovies to demand immediate attention. As implied in much of the earlier discussion, the author considers it to be crucial that economic analysis be guided by the biological, economic and institutional context in which the managed industry exists. To adequately understand the relative importance of various policy issues and to intelligently judge the adequacy of economic analyses, therefore, the reader must have a firm grasp of the situation faced by fishery managers in California. Consequently, the next section of the paper is devoted to a presentation of pertinent background information.

THE BIOLOGICAL, INSTITUTIONAL AND ECONOMIC CONTEXT

Biological Basis

Important characteristics of the fish stock include location, size, potential yield and function in the ecosystem. The following summary information on these characteristics for the anchovy stock is drawn from Huppert et al. [1980a] which is a slightly modified version of the Anchovy Fishery Management Plan [1978], and Huppert et al. [1980b], an updated investigation of the population dynamics model and other technical issues. These two reports rely upon the many scientific studies carried out by the California State Department of Fish and Game (CF&G), the National Marine Fisheries Service, Scripps Institution of Oceanography and California Academy of Sciences. The brief review contained below serves to place the discussion of fishery management in context, but is not a substitute for the more extended treatments available elsewhere.

The northern anchovy, *Engraulis mordax*, is a small, pelagic schooling fish occurring along the west coast of North America from Queen Charlotte Sound in the north to the southern tip of Baja California. Significant physical differences in the fish found within this range suggest the existence of three separate subpopulations [Vrooman and Paloma 1975]. As shown in Figure 1, the northern subpopulation occurs essentially north of San Francisco; the central subpopulation extends from San Francisco to Punta Baja; and the southern subpopulation stretches south from Punta Baja to the tip of the Baja California peninsula. The central subpopulation is the most abundant of the three, and it is the stock unit adopted for management by the Pacific Fishery Management Council (PFMC). The bulk of the population biomass is consistently located in the Southern California Bight, an area of approximately 20,000 square nautical miles bounded by Point Conception, California in the north and by Ensenada, Mexico in the south.

Estimates of the central subpopulation's spawning biomass (Table I) are based on anchovy larva abundance estimates derived from the ichthyoplankton collections of the California Cooperative Oceanic Fisheries Investigations (CalCOFI), a consortium of scientific research agencies involved in oceanographic research. The biomass estimates for the 1951-1966 period suggest a logistic-shaped growth path. After reaching a peak biomass of 4.7 million

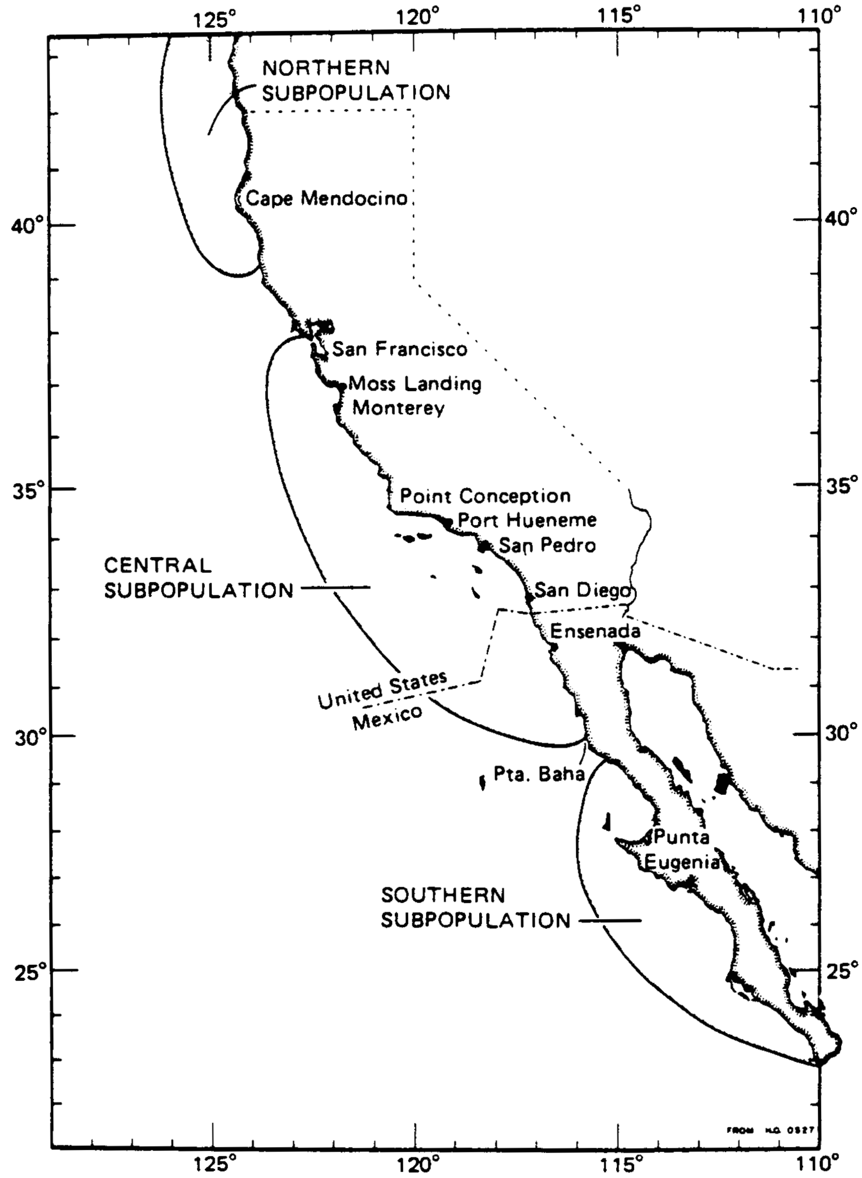

Figure 1. Approximate location of three subpopulations of northern anchovy.

Table I. Population Size and Harvests from the Central Subpopulation of Northern Anchovies (in thousands of short tons)[a]

Year	Estimated[b] Biomass	California Landings		Ensenada Landings[c]
		Commercial	Live-bait	
1951	180	3	5	-
1952	156	28	7	-
1953	510	43	6	-
1954	768	21	5	-
1955	845	22	6	-
1956	485	28	6	-
1957	1167	20	4	-
1958	1479	6	4	-
1959	1514	4	5	-
1960	1540	3	5	-
1961	1159	4	6	-
1962	2989	1	6	-
1963	4254	2	4	-
1964	2901	3	5	-
1965	4659	3	6	10
1966	3572	31	7	15
1967	-	35	5	25
1968	-	16	7	17
1969	2999	68	5	4
1970	-	96	6	6
1971	-	45	6	4
1972	2784	69	6	7
1973	-	133	6	2
1974	-	83	6	48
1975	3603	159	5	61
1976	-	122	5	79
1977	-	110	5	157
1978	1304	11	5	143
1979	1723	52[d]	5[d]	208[d]
1980	1775	-	-	-

[a] Sources: California Department of Fish and Game and Instituto Nacional de Pesca.

[b] After 1966 the ichthyoplankton cruises upon which the biomass estimates depend were reduced from annual to tri-annual; in 1979 annual survey were resumed.

[c] Data not available for Ensenada before 1965.

[d] Preliminary estimates.

short tons in 1965, however, the stock has fluctuated and declined sharply. The 1978 biomass of 1.3 million tons was the smallest anchovy stock encountered since 1961. In addition to the spawning biomass measured by the larva census estimate, there is a substantial biomass of juvenile fish. In view of the rapid growth in juvenile anchovies, the cohort of immature fish probably reaches a maximum biomass slightly before the end of its first year of life. The fish mature between their first and second years, and the recruiting yearclass of fish begins to appear in the commercial catch a few months before it reaches one year of age. Thus the fishery could exploit a stock larger than the estimated spawning stock in the absence of any minimum size regulations to protect juveniles.

Although there was a small anchovy fishery for canning in the early 1950s, the fluctuations in biomass prior to the inception of the California reduction fishery in 1966 were due primarily to natural causes.[2] Additional evidence of natural fluctuations in stock size is provided by the anaerobic sediment data from Soutar and Isaacs [1974]. Smith [1978] converted the scale depositions in the sediment samples into biomass estimates for 38 five-year intervals from 1775 to 1970. The average anchovy biomass over this period is estimated to be 4.5 million metric tons with a coefficient of variation equal to 0.47.[3] This degree of variability is consistent with that observed in clupeoid fish stocks around the world [Murphy 1977].

The central subpopulation also undergoes north-south shifts. Stauffer [1978], again using CalCOFI larva census data, found that the percent of the standing stock of anchovy larvae north of the United States/Mexico boundary varied between 45 and 86% during the 1951-1975 period. Over the whole period combined 70% of the larvae were found in U.S. waters. Assuming that larva distribution is a good indicator of fish distribution, the data suggest that 70% of the fishable stock is within the United States jurisdiction.[4]

Published studies of the potential yield from the central subpopulation are based on a variety of population models and result in a disturbingly wide range of biological yield estimates. The most optimistic estimate was that of MacCall et al. [1976]. Using a crude, rule-of-thumb method suggested by Gulland [1970], MacCall et al. concluded that the potential yield of northern anchovy is over 2 million tons.[5] A cautionary note following the estimate suggested that this level of yield would not be sustainable due to the year-to-year fluctuations in the stock.

Radovich and MacCall [1979][6] presented a model based on the assumption that the stock observed during 1951-1975 followed a logistic growth equation. The estimated model is:

$$B(t) = B_{max}/\{1 + e^{-r(t - t_o)}\} \qquad (1)$$

where B_{max} = 4.0 million tons

r = 0.36

t_o = the time at which the inflection in the growth curve occurs

The stock growth rate is given by the time derivative of the logistic equation. A maximum to the growth rate occurs at $B_{max}/2$ where dB/dt = 360,000 tons/yr. To calculate the potential yield from a fishery Radovich and MacCall assumed that the biomass measurement represents the spring spawning stock just after the new cohort of fish recruits to the spawning stock, and that the fishery takes fish from the stock at a steady rate during the year. Since the maximum annual growth represents the change in stock size at year-end, and the fishing mortality competes with natural mortality during the year, a fishery should be able to take more than the annual growth in equilibrium. Estimating that the excess of potential yield over potential growth at about 25%, Radovich and MacCall estimate MSY to be 450,000 short ton/yr.

In developing the yield estimates for the Anchovy FMP, MacCall modified his population model somewhat. The main innovation was the explicit treatment given to the size of and yield from the recruiting yearclass. Also, the logistic equation was reestimated after adjusting for the levels of harvest taken in California. The most recent estimates for the parameter of the logistic equation are $B_{max} = 4.207 \times 10^6$ short tons and $r = 0.3638$ (see Huppert et al. [1980b]). A reparameterization allows the population transition equation to be written as:

$$B_{t+1} = B_t K/(H + B_t) \qquad (2)$$

where $K = B_{max}/(1 - e^{-r}) = 13.8 \times 10^6$ tons

$H = Ke^{-r} = 9.6 \times 10^6$ tons

The population transition equation applies to an unfished population.

Noting that the rate of natural mortality is due primarily to predation, starvation and other factors not related to the fishery, we assume that the percentage rate of mortality to the spawning biomass is constant. Since both somatic growth and mortality in numbers of fish occur simultaneously, we use a net mortality rate, (M-G), equal to 0.8 (see MacCall [1980]). If the measured spawning biomass disappears at this rate during a calendar year between biomass measurements, then any excess of biomass over adult fish survival appearing in accordance with Equation 2 must be recruitment. Thus recruitment can be expressed as a function of the previous year's biomass as follows:

$$R_{t+1} = B_tK/(H + B_t) - B_te^{-(M - G)} \tag{3}$$

In the presence of a fishery which causes a constant percentage rate of mortality, denoted F, the population transition equation becomes:

$$B_{t+1} = B_tK/(H + B_t) - B_te^{-(M - G)}(1 - e^{-F}) \tag{4}$$

where it is assumed that the juveniles are unaffected by the fishing. The catch taken during a year can be expressed as the following function of B_t and F:

$$Y_t = (F/F + M - G)(1 - e^{-(F + M - G)})B_t \tag{5}$$

Figure 2 depicts the equilibrium annual stock growth and the equilibrium yield curve given the parameter estimates noted above.

To examine the effects of harvesting juveniles Equations 3 to 5 must be modified to account for fishing mortality on juveniles. This involves specifying the relative availability of juveniles to the fishing effort. In MacCall [1978] and Huppert et al. [1980a,b] the juveniles are estimated to be available for 20% of the year with about 76% of the catchability of adults. Since the insertion of the juvenile harvest complicates the algebra while introducing no useful insight into the model, the interested reader is referred to the above-mentioned reports. The only important aspect of the harvest of juveniles is its impact on the equilibrium yield curve. As juveniles become more vulnerable the equilibrium yield from the fish stock falls as shown in Figure 2.

Another way of viewing the population dynamics shows the mortality of adults and recruitment to the stock as two separate components. In Figure 3, for example, the biomass at time T generates the recruitment at time T + 1 through the function labeled A. This recruitment function is just the graph of Equation 3, and the straight line out of the origin labeled "replacement" represents the total loss of adult biomass due to natural causes in a year. If the size of recruitment equals the total mortality, the population just maintains itself; hence the term "replacement." For spawning biomasses below the equilibrium level of 4.2 million tons, the recruitment exceeds the replacement level and net growth occurs. Two important issues regarding the validity of the estimated population model can be discussed with the aid of this figure. First, the estimated stock-recruitment relationship is not a very close "fit" to the 15 observations shown on the diagram, but the null hypothesis that recruitment is unrelated to spawning stock size can be rejected with better than 95% confidence.[7] Thus the statistically fitted equation can be used to make conditional predictions, but with a high degree of uncertainty. The standard deviation of the error about the recruitment function for the 15 observations

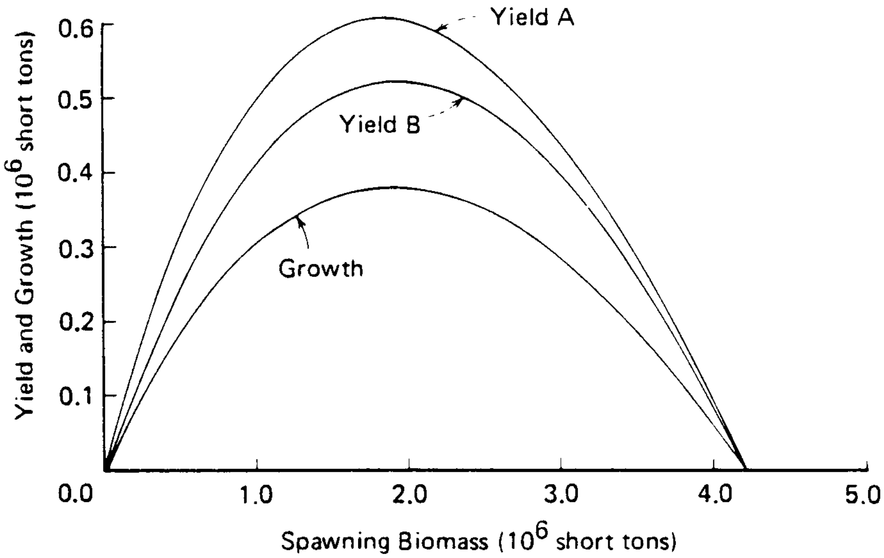

Figure 2. Population growth and yield curves for the northern anchovy, central subpopulation, with (Yield A) and without (Yield B) harvest of immature fish.

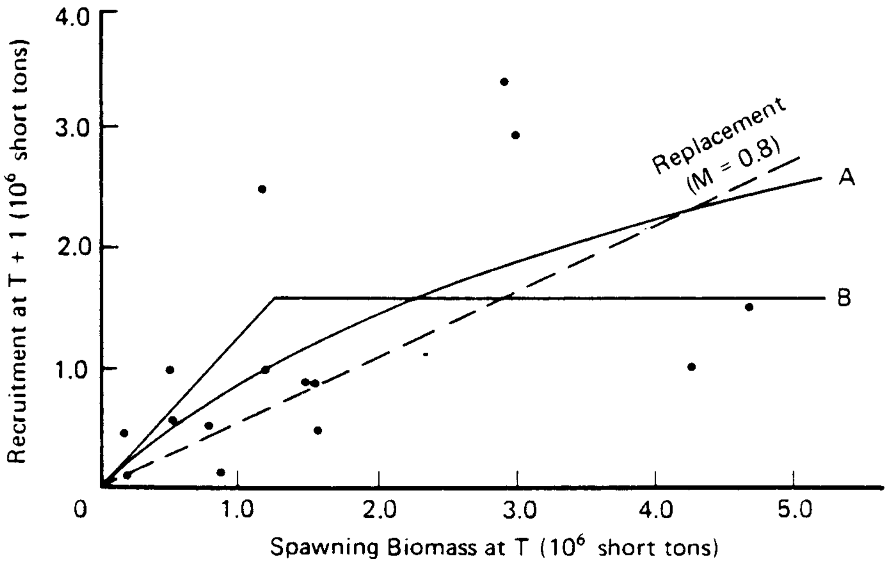

Figure 3. Alternative stock-recruitment models. Model A is the logistic model, and Model B is the modified constant Recruitment Model.

is about 860,000 tons. Second, an alternative model of recruitment, which is labeled B in Figure 3 assumes that recruitment equals 1.247 times spawning biomass up to a biomass of 1.225 million tons and equals 1.527 million tons for larger stock sizes. This alternative model cannot be distinguished statistically from the original logistic-based model with a reasonable degree of confidence.[8] Given these two facts, the approach to management of the anchovy fishery must somehow recognize the level of uncertainty in the population model. One method described below is to adopt a stochastic decision-making framework.

One immediate consequence of the stochastic recruitment and yield curves is that the concept of sustainable yield is inapplicable. Although the peak of the yield curve may occur at 520,000 tons, this level of yield is in no sense sustainable. An attempt to take this "MSY" year after year can be expected to severely deplete the population within a short period of time. Although the theory of managing stochastic, fluctuating fish populations is not very well developed, the few published papers seem to support some general conclusions. Beddington and May [1977], for example, conclude that populations fluctuating due to environmental conditions will become unstable under either constant fishing effort or constant catch policies. They conclude that a feedback control policy should be adopted.

All the above comments address anchovy management solely in terms of the fish catch and the dynamics of the stock. But anchovies, like most clupeoid fishes, are a forage stock for many predators. In the California Current some of the known predators are commercially and recreationally important fish. These include tunas, barracuda, sea basses, jack mackerel, Pacific mackerel, Pacific bonito, yellowtail, striped bass, salmon, swordfish, striped marlin and others. Other known or suspected predators of northern anchovy include marine mammals (common dolphins, northern fur seals, California sea lions and others), and many varieties of marine birds including the brown pelican, a designated endangered species.

Anchovies are, of course, just one of a group of small schooling fish species that are preyed on by larger fish, birds and mammals. Other species are sardine, saury, mackerel, herring and lanternfish. In her "biomass budget" for the California Current Region, Green [1978] estimated that the total predation on small schooling fish amounts to at least 24 million ton/yr. Of this total estimated consumption of small fish only a small portion could be contributed by the anchovy stock.[9]

Management policies for anchovies should take into consideration the effect of reduced anchovy stocks on the food supply for, and resultant average stock size of predator species. But the available information is rather sparse and inconclusive regarding these interspecies impacts. Some predators may be much more dependent on the availability of anchovies than would be suggested by an examination of average food intake. For instance, there may be a short, but critical mating or spawning season during which the need for anchovy schools is essential. Comprehensive research may someday provide reliable, predictive models to reveal these ecosystem linkages. But current knowledge simply lacks the detail necessary to contribute quantitative models to the fishery management process.

Political/Institutional Setting

Management of the anchovy reduction fishery in California must, as Kaneen [1977] remarked, "walk in the shadow of the sardine fishery." Two legacies of the now-defunct sardine fishery play a significant role. First, the obvious failure of state authorities to prevent catastrophe in the sardine fishery, despite intense and lengthy scientific study, bolstered the mistrust of fisheries managers by recreational fishing and environmental groups. California sardines supported the United States' largest (by tonnage) fishery during the mid-1930s and early 1940s. The peak catch of 791,000 tons occurred in 1936-1937, and the average annual catch during 1934-1946 was 600,000 tons. A severe drop in stock size occurred in the late 1940s, followed by a moderate rebound in 1950-1951, and another collapse in 1952. After many years of small landings, sardine harvests were prohibited entirely in 1970. Years of scientific research resulted in some detailed post mortems [Murphy 1966; Ahlstrom and Radovich 1970], but the causes for the stock collapse are still not fully understood. Perhaps the most common view, as expressed by Murphy [1966; 1967; 1977], is that the fishery was extracting sardines faster than could be sustained during the 1940s until the recruitment of two successive poor year classes (1949 and 1950) reduced the stock to a size too small to generate large year classes. There is still controversy over the annual yield that the sardine population could have sustained (see Murphy, [1966] and MacCall, [1979]).

A second legacy from the sardine days is the institutionalized bias against the reduction of fish into meal and oil. Early in the sardine fishery the state legislature was persuaded to regulate the reduction fishery (without, of course, putting effective restraints on the fishing for canneries). Interested readers are directed to Schaefer et al. [1951] for a detailed account of these regulatory actions. The important fact is that producers, who had begun to pass a larger fraction of the fish through reduction plants, were prevented from utilizing the fish in the way they found most profitable. Mandel [1975] notes that this constituted a specific rejection of economic profit as a criterion for determining the best use of California resources. Clearly, this was not the only or most prominent rejection of simple economic criteria for resource allocation.

When the state legislature transferred control of the anchovy reduction fishery to the California Fish and Game Commission in 1965, it was largely motivated by the sharp and politically unrewarding controversy between commercial interests and recreational groups. Strengthening the commercial fishermen's argument for a reduction fishery was the scientific recommendation that a 200,000-ton experimental quota be established for anchovies. The CalCOFI committee had reasoned that the vastly expanded anchovy stock might be retarding the reestablishment of the more valuable sardine (see CalCOFI [1966]). A 200,000-ton catch was reckoned to be about 10% of the standing stock, a minimum withdrawal necessary to produce a measurable change in the anchovy/sardine system. The commission established an annual quota of 75,000 tons for the 1965-1966 season and maintained the quota until 1970 when the fishery expanded enough to justify larger quotas. The U.S. fishery has yet to reach a catch total of 200,000 tons.

Because of its ancestry, therefore, California's anchovy management program has had an undeniably conservative slant. Whether this is justifiable or not depends largely on subjective judgment. A sympathetic evaluation would emphasize the risk inherent in an aggressive fishery. Undetected failures of recruitment, combined with heavy fishing could easily lead to the demise of another fish stock. One suspects that rugged commercial fishermen, and perhaps society-at-large, would be willing to accept these risks in a simple commercial venture. The remaining unquantified factor, however, is the potential impact on other fish stocks and the subsequent deleterious effect on marine recreational and commercial fishing activities. As noted in the previous section of the paper, multispecies and ecosystem models are as yet unable to provide practical advice on these issues, and the possibility exists that some delicate balances in the system might be tipped inadvertently by a more extensive anchovy fishery.

Mexico's attitude toward the development of a reduction fishery for anchovies is spawned in a different environment. Establishment of income-generating fisheries is a key component in Mexico's national plan for marine resources. The Food and Agriculture Organization of the United Nations (FAO) assisted Mexico in developing plans for fishery development specific to the northern anchovy off of Baja California. Wadsworth [1974] outlined a plan for an eventual 500,000 ton/yr. fishery with 200,000 tons being produced at Ensenada and 100,000 tons at each of three more southerly ports. A later report [FAO-Mexico 1978] repeats the earlier plan and specifically mentions the fact that California does not intend to exploit its portion of the anchovy stock.

Mexico's plan for fishery development is reaching fruition through the efforts of Pesquera Zapata S.A. de C.V., a company jointly held by Mexican investors and Zapata Corporation of the United States. This new venture established a reduction plant in Ensenada and brought in six new U.S.-built purse seine vessels. Initial operations in 1976 were followed by rapid growth of the fishery to about 150,000 ton/yr. in 1977 and 1978 (see Table I). The Mexican fishery evidently takes some unknown fraction of its fish from the southern subpopulation, but most undoubtedly comes from the central subpopulation. Because of the rapid diffusion of fish throughout their range, it can be expected that withdrawals to the south of the international border will affect the average abundance of anchovies to the north. Thus the need for some reconciliation of goal and procedures is clear. To date the United States government has been unable to induce Mexican officials to seriously consider a joint fishery management regime.

Economic Characteristics

The three main segments of the anchovy fishing fleet are (1) the so-called "wetfish" fleet in southern California[10]; (2) a smaller group of vessels in Monterey Bay; and (3) the live-bait fishing vessels scattered along the southern California coast in ports with substantial amounts of marine recreational fishing. All of these vessels use roundhaul nets, with the purse seine type predominating in the commercial reduction fishery and the lampara type being commonly used for live-bait fishing. Many of the wetfish vessels are survivors of the sardine fishery, but some are small tuna purse seiners and one is newly constructed specifically for the anchovy/mackerel fishery. As indicated in Table I, nearly all the anchovy catch is for the reduction processors. The U.S. reduction harvests are distributed geographically with 80% of the catch landed in Los Angeles, 16% in Port Hueneme and 4% in Monterey.

The number of vessels landing anchovies varies considerably from year to year. In 1975, the peak year for U.S. reduction fishery landings, 80 vessels participated, while only 29 reported landing anchovies for reduction during the 1979-1980 fishing season. Many of the vessels capable of fishing extensively for anchovies shift to the mackerel fishery (jack and Pacific mackerel) for substantial portions of the year and fish opportunistically for Pacific bonito, bluefin tuna and squid. Table II shows that anchovy landings generally account for the bulk of the wetfish landings by weight. But due to the lower prices received for anchovy (about $42 vs $160/ton for mackerel in 1980), the revenue derived from anchovy fishing is less than half of the total revenue for the fleet.

Live-bait operations generally consist of at least one roundhaul vessel and some bait receivers for holding the fish in good condition. Currently, there are 11 or 12 such live-bait operations. A major portion of the typical live-bait dealer's business is covered by contract obligations to local partyboat and charter boat businesses. Gruen, Gruen and Associates [1979] estimated the 1977 live-bait sales to be worth $2.6 million. Aggregate estimated live-bait landings have remained consistently between 500,000 and 700,000 tons over the past 10 years.

Although a wide range of vessel sizes and catch rates is exhibited in the anchovy reduction fishery, existing data are sufficient only to support a

Table II. Landings and Values of Wetfish Fleet in San Pedro and Port Hueneme, 1960-1979[a]

Landings (short tons)

Year	Anchovy[b] (Reduction)	Jack Mackerel[c]	Pacific Mackerel[c]	Pacific Bonito[d]	Bluefin Tuna[e]	Pacific Sardine[f]	Squid[g]	Total	Deflated Value[i]
1960	–	36.338	18.279	603	1,488	27.185	163	84,056	–
1961	–	46.968	22.011	4.199	2,553	21.006	3.299	100.036	–
1962	–	43.963	24.265	975	4,702	6.386	1,855	82,146	–
1963	–	46.895	20.109	1,964	4,441	2.895	2,337	78,641	–
1964	–	43.554	13,411	1.236	2,602	10.043	3,530	74,376	–
1965	171	31,957	3.517	2.729	1,881	792	4.695	45,742	–
1966	19.009	19,806	2.290	8,748	3.140	425	3.736	57,154	–
1967	23.952	18,623	571	7,714	1.528	70	3.799	56,257	–
1968	9.518	27,354	1,564	7,423	1,921	51	4,781	52.612	–
1969	62.390	25.736	1.173	6.340	2,008	41	4.256	101,944	–
1970	91.892	23.615	309	4,292	691	134	7,305	128,238	–
1971	42,288	29,854	77	4.684	1.211	82	2,598	80.794	–
1972	65,843	25.495	53	7.708	2,525	163	2.288	104.075	–
1973	126,082	10,016	27	9.203	1,911	66	1,278	148.583	–
1974	75.420	12.709	66	6.801	2,157	7	2.910	100,070	–
1975	148,516	18,370	142	1.680	3.796	3	4.350	176.857	–
1976	118.463	22,380	173	1,922	2.013	8	3.015	147.974	–
1977	101,402	52.288	3.650	1,334	868	2	4.709	164,253	–
1978	10,898	34.000	12,282	800	1.424	1	3.307	62,712	–
1979	48.545	17,575	29,503	250	1,597	17	2.260	99,747	–

Ex Vessel Value ($1000)

Year	Anchovy[b] (Reduction)	Jack Mackerel[c]	Pacific Mackerel[c]	Pacific Bonito[d]	Bluefin Tuna[e]	Pacific Sardine[f]	Squid[g]	Total	Deflated Value[i]
1960	–	1.534.1	751.1	34.9	362.7	1,117.7	7.6	3,808.1	9,177.5
1961	–	1,952.7	1,182.6	214.2	661.7	1.108.7	102.2	5,222.1	12,475.6
1962	–	1,826.3	1,024.9	55.6	1,320.7	408.7	46.5	4,682.7	10,985.6
1963	–	1,954.5	860.0	108.6	1,000.7	235.1	61.6	4,220.5	9.757.8
1964	–	2,048.2	666.2	60.3	633.1	456.2	86.0	3,950.0	8,990.2
1965	5.9	1,753.5	222.7	141.3	491.5	89.7	101.0	2.805.6	6.248.1
1966	388.2	1.377.9	185.8	694.5	920.9	147.0	104.1	3,818.4	8.232.4
1967	484.4	1,411.5	71.3	646.4	373.7	28.4	124.9	3.140.6	6,576.4
1968	167.0	2,085.4	167.3	616.2	584.3	14.5	142.8	3.777.5	7,570.1
1969	1.224.2	1,949.9	121.2	588.4	641.1	9.2	153.4	4,687.4	8,943.7
1970	2,030.1	1.860.6	49.1	609.3	258.4	57.7	291.6	5.156.8	9,344.0
1971	999.8	2,408.9	7.2	845.9	504.0	35.2	85.5	4,886.5	8,424.1
1972	1,566.0	2,147.6	6.0	1,403.5	1,086.7	48.9	81.9	6.340.6	10,493.7
1973	6.250.3	959.3	3.6	1,887.2	902.7	21.8	88.8	10.113.7	15,818.1
1974	3,076.6	1,493.6	10.6	1,811.6	1,238.5	0.9	215.8	7,847.6	11,198.1
1975	4,455.5	1,691.2	14.3	414.7	1,874.6	0.3	255.4	8.706.0	11,334.8
1976	4.326.3	2,237.3	18.1	524.3	1.215.1	0.7	149.4	8,471.2	10,487.2
1977	4,563.1	5.228.8	365.0	428.6	880.3	0.2	353.2	11,819.2	13,804.7
1978[h]	490.4	3.740.0	1,351.0	312.0	1.167.3	0.1	330.7	7,391.4	8,041.8
1979[h]	2,184.5	2,525.0	4,208.0	97.5	1.309.5	1.5	226.0	10.552.0	10.552.0

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[a] Sources: California Department of Fish and Game, Fish Bulletins, California Marine Fish Landings, 1960-1976; Statistical Report of Fishery Products, 1977; unpublished preliminary estimates, 1978-1979; U.S. Dept. of Commerce, Fishery Statistics of the U.S., 1960-1975; Fisheries of the U.S., 1975-1979.

[b] Anchovy reduction landings, southern permit area.

[c] Total landings, all vessels.

[d] Total landings, all vessels, in California waters, 1960-1977; estimates for 1978-79.

[e] Landings by a group of vessels described by CF&G as wetfish, So. Calif. pelagic, or small (class 1 or 2) purse seiners, 1960-1976, estimates for 1977-1979.

[f] Total landings, all vessels.

[g] Landings by purse seine and lampara vessels, 1960-1975; estimates for 1977-1979 (excludes landings by dip and brail gear).

[h] Preliminary estimates, CF&G.

[i] Values adjusted for inflation by GNP implicit price deflator, 1979 = 100.

simple model of fishing costs representing a typical 58-ft purse seiner. Combs [1977] provides an estimate of minimum operating cost per ton landed of $24.58. Given that the better vessels averaged 78.1 ton/day fished in 1975, the daily operating cost is estimated to be about $1920. A vessel with this daily cost had a new price of about $425,000 in 1978.

The relationship between daily catch rate (i.e., catch per effort) and anchovy stock size has not been established, but MacCall [1976] has examined the relationship for sardines.[11] Since the sardine fleet operated in a fashion similar to that of the anchovy fleet, we may borrow the shape of the catch curve from the sardine fishery and then rescale it to the 1975 anchovy catch per effort. MacCall's equation introduces a nonlinear catch curve by specifying that the "catchability coefficient" be a function of fish stock biomass, B, so the catch equation becomes:

$$y = qfB \tag{6}$$

with $q = aB^b$

Inserting the estimated value of b (= −0.6) into Equation 6 gives us

$$y = afB^{0.4} \tag{7}$$

Catch per effort, y/f, of 78.1 tons in 1975 corresponds to a biomass of 3.6 million tons. Placing these values in Equation 6 allows us to solve for a = 0.186. Furthermore, noting that operating cost per day for a standard vessel is fixed at $1920, we can specify the operating cost per ton as the following function of stock biomass

$$C_1 = 10315\ B^{-0.4} \tag{8}$$

This operating cost function and the capital cost of $425,000 per vessel represents the known cost structure of the reduction fishing fleet.

Fish reduction plants in Los Angeles, Port Hueneme and Monterey produce fish meal, fish solubles and fish oil from anchovies. The product yields per ton of fresh fish processed varies among fish species, and, for a given species, among seasons of the year. The average product yields per ton of anchovy landed are:

Meal:	0.182 ton (348 lb)
Solubles:	0.112 ton (224 lb)
Oil:	0.0384 ton (76.8 lb)

Oil yield is especially variable, ranging from 140 lb/ton in September to 38 lb/ton of anchovy in the spawning season, February-April.

The meal and liquid solubles are sold as protein supplements for use in feeds for chickens, turkeys and freshwater fish. Local southern California poultry farmers buy most of the local fish meal and solubles. Imported anchovy, tuna/mackerel mix and menhaden meal from the Gulf and South Atlantic coasts are nearly perfect substitutes. Also, meat and bone meal from beef is a close substitute, and various vegetable protein meals (especially soybean and cottonseed meal) are readily available alternative sources of high-protein meal for poultry rations. Due to the cost-minimizing behavior of poultry growers and the ease of substitution, anchovy meal demand is naturally highly elastic. The only sources of market advantage for southern California anchovy meal seem to be (1) its higher protein content as compared with local tuna/mackerel and soybean meals, and (2) the cost of transporting fish meal to California from more distant production sites. A single-equation, linear least squares estimate of the inverse demand curve contained in Department of Commerce [1978] and Huppert et al. [1980a] is

$$p_m = 359.13 - 1.147\,q_m \tag{9}$$

where p_m is price per ton of meal and q_m is annual quantity of meal produced (in thousands of tons).

Neither the fish solubles nor oil markets for anchovy have been investigated sufficiently to yield similar, quantitative estimates of demand curves. Instead, we adopt a fixed-price for oil and solubles based on the average prices observed during 1970-1977. The average price of 12.87 ¢/lb for anchovy meal, implies a contribution of $9.88/ton of anchovies processed. Similarly, the average price for solubles was $105/ton, which converts to $11.76/ton of anchovies. Assuming these fixed prices, and converting the anchovy meal price equation to a function of fish landings (landings equal 5.5 times meal produced) we get a "value per ton landed" equation

$$v = 86.9 - 3.795 \times 10^{-5}\,y \tag{10}$$

where y is annual landings. Although a more comprehensive study of the market demand would undoubtedly yield a more precise valuation procedure, Equation 10 provides a useful, rough estimate of the market value of reduction fishery harvests.

The industry structure in southern California is characterized by buyer and seller concentration in the raw fish sector, and by rigorous competition in the product markets. That is, the fishing fleet is organized by two unions—Fishermen's and Allied Workers Union (ILWU) and Fishermen's Union of America

(AFL-CIO)–and a vessel owners cooperative–the Fishermen's Cooperative Association of San Pedro. Fishermen in Monterey (or Moss Landing) are also represented by a chapter of the Fishermen's Union of America, but the few vessels landing at Port Hueneme apparently operate without benefit of a special organization. Buyers of anchovies for reduction are distributed as follows: one in Moss Landing, one in Port Hueneme and two in Los Angeles harbor. Competition in the fish meal and oil markets is assumed due to the large numbers of buyers and the plethora of alternative sources of both fish meal and other protein meals.

Because of the close-knit structure of the fishery/processor sector in all the reduction fishing ports, prices and wages are not a competitive market solution. Instead, the net value of the intermediate products sold is distributed to the various participants (reduction plant operators, fishing vessel owners, and crew members) through negotiated pricing and crewshare agreements. As is typical in marine fisheries, the crew members are paid a share of the landed value of the catch less direct operating expenses. Current arrangements call for a 58% share of the net landed value to be split among the 12-man crew.[12] The crewshare is negotiated between the Fishermen's Cooperative and the unions. Similarly, the Fishermen's Cooperative (with active guidance by the unions) negotiates a pricing formula for anchovy landings. The 1978 formula was

$$p_f = \begin{cases} 25 + (p_m/65 - 3) \times 7.5 & \text{if } p_m/65 \geqslant 3 \\ 25. & \text{if } p_m/65 < 3 \end{cases} \tag{12}$$

where p_f is price per ton of fish and p_m is price of fish meal quoted in the Department of Agriculture's *Feed Market News* (Los Angeles, California). Thus a meal price of $390/ton results in a fish price of $47.50/ton. This pricing agreement is analogous to the contingent contracts commonly signed by labor unions (see, e.g., Hall and Lilien [1979]). In this regard it is noteworthy that the minimum price of $25 is just above the estimated minimum average cost of $24.58/ton harvested. This strongly suggests that the ex-vessel fish price is related to the opportunity costs of fishing.

Processing of anchovies is estimated to cost $23.30/ton of fresh fish landed (D. Cukierman, personal communication). This cost is, of course, dependent on the rate of flow through the reduction plant to some minor extent, but this fact will be ignored in subsequent discussions. Combining this constant processing cost, the fishing cost (Equation 8), and the gross market value (Equation 10), the net economic profit for the consolidated fishing/processing sector is expressed as

$$NV = (63.6 - 3.795 \times 10^{-5} y)y - (10315B^{-0.4})y \tag{13}$$

where capital costs of plant and vessels are not yet introduced.

The economic parameters and functional relationships described here are used in the following section on applications of economic theory to anchovy management. Table III presents a summary of these. Clearly, however, the broader economic concerns of nonreduction fishing and the ecological function of anchovies are as important as the quantified reduction fishery. The economic description of the fishery focused on the reduction fishery because the harvest for reduction is the major use of anchovies commercially, and because the data and analyses needed to quantitatively consider the other uses for anchovy are not available. As management analysts, however, economists must avoid the tendency to emphasize the importance of those things that are quantified to the neglect of those that are not.

THEORY AND ANALYSIS OF ECONOMIC ISSUES

Each of the five issues discussed in the second section above can be examined from the viewpoint of economic theory. The two issues which are most extensively and satisfactorily treated are those regarding optimum (i.e., economically efficient) reductions harvest rates and optimum investment in fishing capacity. Because these two issues are closely linked in the theoretical model they are combined in the first part of this section. Following this, the discussion turns

Table III. Economic Parameters and Functions for the Anchovy Reduction Fishery

1. Inverse demand equation for processed products:

$$v = 86.9 - 3.795 \times 10^{-5} q_f$$

where v is value per ton of fish landed and q_f is tons of fish landed.

2. Average variable cost per ton landed:

$$c_1 = 10315\ B^{-0.4}$$

where B is stock biomass

3. Capital cost of fishing fleet:

$$c_2 = 425{,}000\ N$$

where N is number of fishing vessels in the fleet.

4. Cost of processing per ton landed:

$$c_3 = 23.30\ q_f$$

to the allocation issue. Both the allocation of anchovies to the live-bait fleet and to the enrichment of the ecosystem are important aspects. A brief discussion of regulatory mechanisms for managing the fishery precedes the final section which presents an economic approach to determining the "best" level of precision to attempt in measuring the stock size. Where data and/or appropriate theory are lacking the deficiencies are noted.

Optimum Harvest Strategies and Fleet Size

The term optimum harvest *strategy* emphasizes the need for a contingency plan, that is, for a harvest plan which adapts to the unpredictable variations in fish stock size brought about by oceanographic and ecological events. A substantial portion of existing theory assumes a deterministic world in which biological and economic relationships are known and predictable. Even the more recent dynamic optimization theorists [Brown 1974; Clark 1976; Quirk and Smith 1970] examine the characteristics of the long-run steady-state in great detail, while treating very briefly the problem of approaching a steady-state, and ignoring entirely the need for adaptive control in a fluctuating environment. This is not to criticize the development of dynamic, capital-theoretic analysis of fisheries, because substantial gains in understanding have resulted from these developments. But recent papers by operations researchers and mathematicians have explored the theory and solution methods for stochastic optimizing models (cf. Walters [1975]; Walters and Hilborn [1976]; Reed [1979]; Mendelssohn [1980]). These focus on the derivation of optimum harvest strategies with uncertain biological production parameters. The consequences of market uncertainty, measurement error and social aversion to variability have yet to be adequately examined in the fisheries context.

The first step in applying an optimization method is, of course, the adoption of a management objective. Ignoring for the moment the nonreduction uses and ecological linkages important to anchovy management, we define an economically optimal harvest strategy as one which sets the harvest annually to maximize the expected discounted value of the fishery. In any year the net value of the fishery equals the net profit to the fishing industry plus any consumer's surplus obtained by those purchasing the fish meal, oil and solubles. Profit to the fishing industry was examined above, but the existence of surplus is less transparent because the usual notion of consumer's surplus applies only to markets for final consumption goods. Fortunately, Just and Hueth [1979] have shown that under certain conditions the overall welfare effect of a change in quantity of an intermediate good is represented by the usual "area under the demand curve" associated with consumer's surplus. The intermediate good must be in a vertical chain of markets none of which has a perfectly elastic demand curve.[13] An acceptable procedure, therefore, is to combine the area under the demand curve but above the current market price with the industry profits to obtain an overall economic value. Based on Equation 13 the resulting algebraic expression is:

$$NEV(y,B) = (63.6 - 1.8975 \times 10^{-5}y)y - (10315B^{-0.4}y) \qquad (14)$$

where we ignore capital costs for now.

The long-run objective, the net present value (NPV) of the anchovy fishery over a period of T years, is computed by the usual formula:

$$NPV(y,B) = \sum_{t=o}^{T} NEV(y_t,B_t)\,(1/1 + d)^t \qquad (15)$$

where d is a discount rate and $(1/1{+}d)^t$ is the discount factor applied to a monetary return occurring t years in the future. To introduce the random variability exhibited by the anchovy stock, the stock transition equation is multiplied by a lognormal error term ϵ.

$$B_{t+1} = g(y_t,B_t)\epsilon \qquad (16)$$

where ϵ has a mean value equal to one.[14] The function g( ) is the mean or expected stock transition function. Assuming that the public decision-maker is not averse to risk per se, the objective can be reexpressed as the expected net present value,

$$EPV = E(\sum_{t=o}^{T} NEV(y_t, B_t)\,(1/1 + d)^t) = \sum_{t=o}^{T} E\,(NEV(y_t, B_t)\,(1/1 + d)^t) \qquad (17)$$

The problem of maximizing the EPV subject to a stochastic stock transition equation can be decomposed into a sequence of annual decisions, each of which requires that the EPV be maximized for all future years, given the current stock biomass, B_t. Thus in year 1 the problem is to maximize

$$EPV_1 = NEV(y_1, B_1) + E(\sum_{i=2}^{T} NEV(y_i, B_i)\,(1/1 + d)^i) \qquad (18)$$

It is most practical to solve this sort of problem with stochastic dynamic programming methods. The reader is referred to Hillier and Lieberman [1967] for a thorough introduction to the mathematics, but a common sense interpretation of the process is attempted here.

Equation 18 indicates that there are two ways to utilize the available biomass in any year. One is to harvest the fish, thus enjoying an immediate economic return. The other is to leave the fish in the ocean to contribute to the stock available in future years, thus increasing the potential future economic value. The current value of harvesting fish is subject to diminishing returns, and is dependent also on the current fish stock biomass, since unit harvesting costs are lower with greater biomass. The diminishing marginal value of catch discourages any tendency to harvest all the fish at once, and the decrease in harvesting costs resulting from larger biomasses provides one incentive for maintaining a larger fish stock. In addition, the expected percentage rate of growth in the fish stock grows as the stock declines, thus increasing the incentive to "invest" in the stock rather than to "liquidate" it when the stock is small. These various incentives are countervailing to some extent. Larger biomass means lower harvesting costs, but also lower percentage returns to investment in the stock. Thus the optimum policy must choose a trade-off between current and future returns which properly accounts for the impact of current harvests on the future. At the optimum current year harvest, the marginal value of additional catch just equals the marginal decrement to expected discounted value from future years.

Since the current value of a given level of harvest is enhanced by increased biomass, and since the percentage rate of growth in the stock is negatively related to biomass, we should expect larger current year biomass levels to be associated with greater current year harvests in the optimal program. That is, the optimum harvest strategy (optimum harvest as a function of, or contingent upon biomass) has a positive slope. A second common sense result is that there may be a biomass level below which the marginal value of current harvest is less than the expected contribution of increased biomass to future return for *any* positive level of harvest. That is, below some minimum biomass the optimum decision is to harvest none at all.[15]

The optimal harvest strategy for the anchovy reduction fishery, assuming no fishing capacity constraint and no other users of the resource, is displayed as Strategy I in Figure 4. This optimal strategy was computed assuming a discount rate of 0.04,[16] and a standard deviation of 0.3 for the proportional random error term in the stock transition equation.[17] To facilitate an interpretation of this harvest strategy, the expected yield curve from Figure 2 is reproduced on Figure 4. According to this optimum strategy, when biomass is below 1.1 million tons, the potential future return from investment in the stock exceeds the current net economic value of even a small harvest. At biomass levels between 1.1 million and 2.6 million tons, the optimum harvest is less than the expected growth in the stock, thus reflecting investment in a larger stock. Above a biomass of 2.6 million tons the optimum strategy calls for a drawing down of the stock, or dis-investment in biomass.

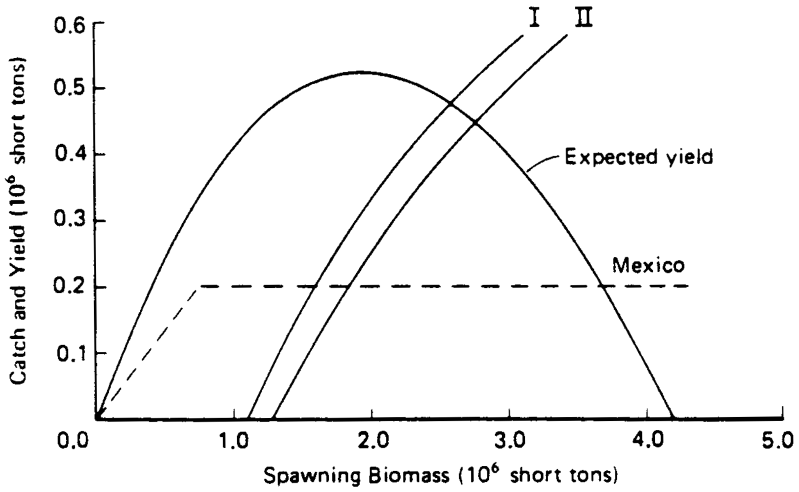

Figure 4. Optimal harvest strategies for the U.S. reduction fishery. Curve I is for fishery without Mexican competition. Curve II assumes Mexico takes an amount represented by the broken line.

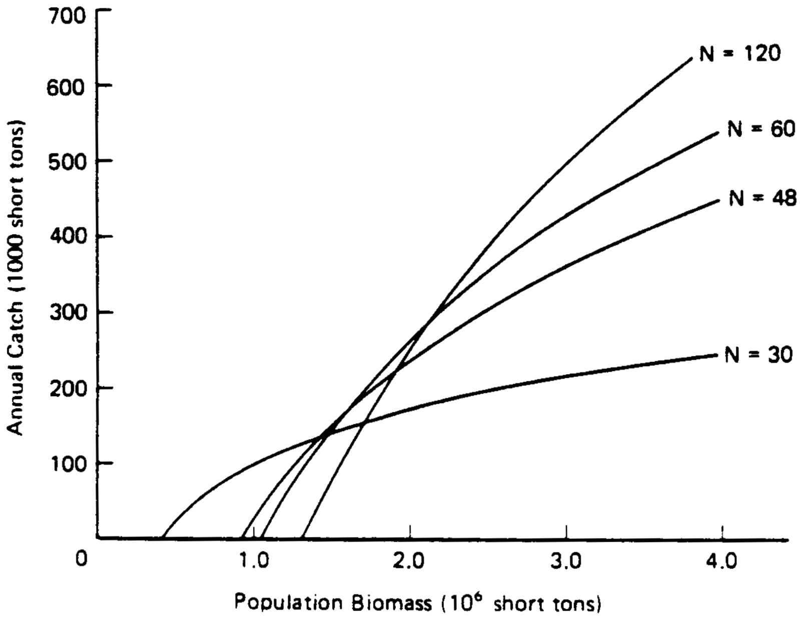

Figure 5. Optimum harvest strategies for the U.S. reduction fishery with fleet size constraints ranging from 30 vessels to 120 vessels. (Still assume Mexican harvest is as depicted in Figure 4.)

As explained earlier, the Mexican fishery for anchovy reduction at Ensenada expanded to an annual harvest of around 200,000 tons, most of which is from the central subpopulation of anchovies. If we assume that Mexico will continue to take 200,000 tons per year, the optimum U.S. harvest strategy is altered. Since reduced stock size would affect the Mexican fishery, we assume that no more than 90% would be taken of the 30% of the stock below the U.S./Mexican border. Given this admittedly arbitrary assumption, the U.S. strategy calls for a lower U.S. catch at every stock size (approximately 50,000 ton/yr lower than without the Mexican fishery), and an increase in the fishery cut off level of biomass from 1.1 to 1.3 million tons. Additional consideration of international strategies for harvesting the jointly fished stock along lines outlined by Anderson [1975] may be useful, but this requires economic data regarding the Mexican fishery that are unavailable to the author.

In deriving harvest strategies I and II in Figure 4, only the operating costs for fishing vessels and reduction plants were subtracted from the gross value in computing NEV. This is equivalent to assuming that fishing effort is unlimited. But the capacity for catching anchovies is limited by both the number of vessels and the stock abundance. Assuming each vessel fishes 144 days per year, the amount of nominal fishing effort available per year is $N \times 144 = f_{max}$, where N represents number of homogeneous anchovy fishing vessels. Inserting this and the estimate value for the parameter "a" into Equation 7 yields the following capacity constraint:

$$y_{max} = 26.78\ N\ B^{0.4} \tag{19}$$

The existence of such a constraint will alter the optimum strategy if some of the potential harvest rates along the unconstrained strategy curve (Strategy curve I in Figure 4) require more than the available fishing effort. With a fishing fleet of 48 vessels, for example, harvest strategy I exceeds the capacity output when biomass exceeds 2.57 million tons.

Optimum U.S. harvest strategies for a range of fleet sizes (and, again, assuming that Mexico harvests 200,000 tons) are displayed in Figure 5. As shown, diminishing fleet size dictates a falling harvest cutoff level and a lower peak catch level. For any one of these strategy curves the variations in biomass due to natural, unpredictable events will cause the fishery to harvest different amounts in different years. A frequency distribution of annual catches will be generated for any strategy and underlying error distribution in the biomass transition equation. Since the capacity constraint limits annual catch, it truncates the frequency distribution of catches on the righthand tail. A larger capacity, therefore, permits the fishery to take the larger catch consistent with large biomasses. But since the optimum strategy, with no capacity constraint, has an equilibrium harvest of around 470,000 tons (at an equilibrium biomass of 2.6 million tons), a capacity to take, say, one million tons might not be economical. A huge capacity would be used very infrequently; hence, the marginal expected value of an additional vessel must become very small for fishing fleets very much larger than that needed to take 470,000 tons.

One could define the optimum fleet size as that number of vessels which maximizes the net discounted value of the fishery minus the capital cost of building the fishing fleet. The curve labeled NPV in Figure 6 is the maximum net present value of the U.S. anchovy reduction fishery as related to fleet size. Each point represents NPV over a 25-year period. Only operating costs are considered in NPV, so the investment needed to build a fleet of N vessels is represented separately by the line labeled "capital cost." This line assumes each new vessel costs $425,000. It is easy to see that the maximum net difference between NPV and fleet capital cost occurs at a fleet size of about 48 vessels.

Assuming the absence of any recreational, ecological or income distributional concerns in the anchovy fishery, the economically efficient U.S. harvest strategy is the one labelled "N = 48" in Figure 5, and the optimum fleet size is 48. While this result is by no means conclusive (note the many qualifications in the previous statement), it provides a useful quantitative assessment of how economic considerations cause optimum yield to deviate from maximum sustained yield. Despite further modifications to incorporate noncommercial and noneconomic considerations into the optimum harvest strategy, two points will continue to be essential. First, the optimum harvest strategy is a contingency plan (or feedback control) which adapts current harvests to current stock levels for longer-term objectives. And, second, the optimum fleet size must be determined in a stochastic context which recognizes that all vessels will be fully utilized only infrequently.

Some of the key deficiences in the foregoing economic analysis are (1) the lack of multifishery interactions considered in the single-species optimizing framework; (2) the lack of market uncertainty in the model; and (3) the crudeness of estimated economic parameters such as those in the unit harvesting cost function, the demand function and the capacity relationship. Fishery interactions are particularly important for the southern California purse seine fleet as illustrated by the catch data in Table II. Since the capacity to fish is not specific to anchovy fishing, neither is the capital cost of the fleet. Furthermore, the opportunity costs of not fishing for, say, bonito or mackerel may frequently be greater than the current net return from anchovy fishing for many vessels. Thus the optimum rate of anchovy harvest ultimately depends on many other biological and market conditions. Before better multifishery models can be implemented, however, I think that additional serious theoretical development must ensue, possibly along lines suggested by Huppert [1979] or Anderson [1980]. More precise data on the fishing fleet economic parameters are needed, since the optimality of the given policies depends so critically on these values and the existing information is partly dependent upon extrapolations and secondary sources.

Allocation Among End-Uses

In a sense the allocation of fish among uses should be a part of the optimum harvest strategy. Any harvest by the reduction fishery clearly preempts some other use of the fish, and this is properly done only after comparison of the reduction fishery value to the opportunity costs associated with other uses. A

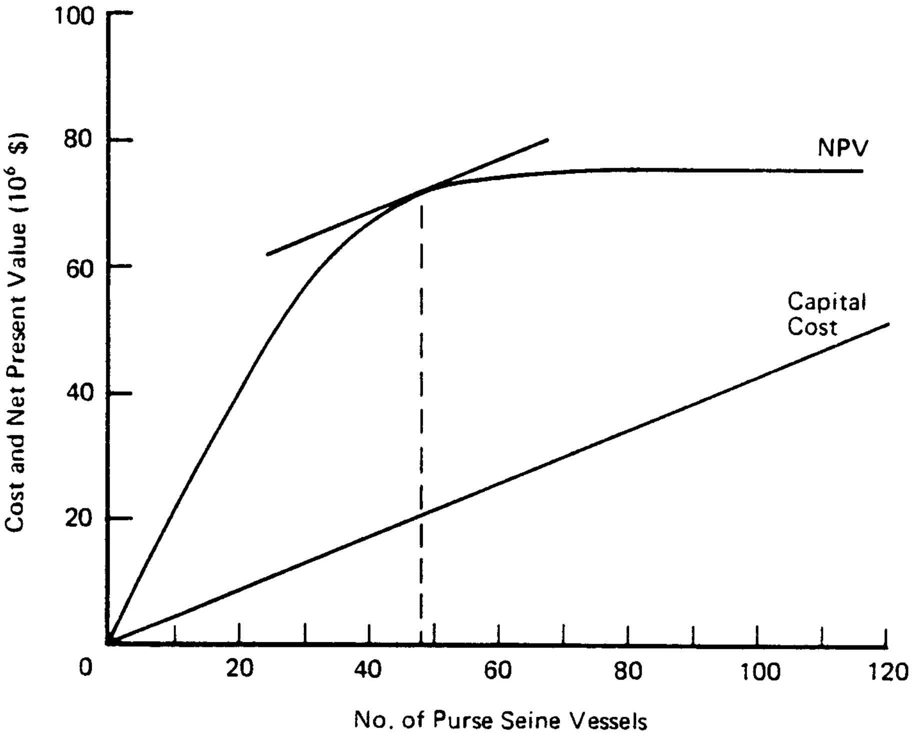

Figure 6. Net present value of the U.S. reduction fishery versus capital cost of the fleet.

more complete derivation of optimum harvests, therefore, would involve a more complicated economic value equation containing separate components for each end-use, and an additional constraint requiring the sum of the harvests to equal the total withdrawal from the population. An optimum harvest strategy with two end uses, for instance, would maximize the sum of two value expressions, NEV_1 and NEV_2. In most circumstances one would expect the optimum strategy to occur with an allocation of catch between the two uses such that the marginal values of fish in the two uses are equal.[18] In considering the allocation of anchovy harvest between reduction and live bait, however, no such analysis was performed.

To implement the theoretical model several additional pieces of information would be needed: (1) a demand curve for live-bait; (2) the costs of fishing for live-bait and holding the fish live; and (3) the physical relationship between reduction and live-bait fishing in the ocean. Available information suggests that such a formal analysis may be unnecessary. First, with respect to the third point, much of the live-bait fishing takes place nearshore during the late spring, summer and early fall. The "availability" of anchovy schools in the narrowly circumscribed baiting areas seems to determine the success of the live-bait operators in meeting contractual commitments to partyboats and in supplying the general public. The little evidence available does not suggest that the success of live-bait fishing is related to the anchovy stock size. If bait supply does not depend directly on the biomass and indirectly on the reduction fishery harvests, the need for treating the two fisheries as two competing users in an analysis of optimum harvesting strategy is negated. Furthermore, the small size of the live-bait harvests means that there is no detectable impact directly on the fish stock and indirectly on the reduction fishery. Given this perception of the situation, the arbitrary assignment of a portion of the overall harvest quota to the live-bait fishery (which is essentially the procedure followed in the Anchovy Fishery Management Plan) may be a perfectly acceptable resolution to the problem.

The other form of allocation, between harvest of anchovies and forage for higher-level predators, is not so easily dispensed with, but is even less amenable to analysis with existing empirical knowledge. Again, the theoretical format for determining an optimal harvesting program would have to be extended to include other sources of economic value. Since anchovies are preyed on by many commercial and recreational fish, the number of values would be great. The problem is further compounded by the fact that the recreational values are difficult to measure and the ecological models available are only suggestive of the structure of the interspecies relationships, not useful, predictive tools of analysis. In a general, qualitative sense, however, an optimum harvest strategy recognizing the ecological-cum-commercial and recreational value of anchovies as forage would harvest the stock more conservatively than the strategies without such recognition.

Choice of Regulatory Tools

There are several good surveys of fishery regulations. Crutchfield [1961; 1979], Anderson [1977], and Clark [1980] are particularly complete. The usual array of management methods includes annual fishery quotas, individual fisherman quotas, limitations on the kinds of gear used, limitation of the numbers of fishermen or vessels licensed, restriction of the fishery to certain areas or seasons, taxes or royalties on fish landings, and license fees. A few generalizations can be gleaned from the literature. First, in the face of severe fish stock depletion under open competition, any aggregate limitation on total annual withdrawals from the fish stock is beneficial if it enables the fishery to sustain a much higher harvest level. More consumer's surplus is generated even if no further efforts are directed toward productive efficiency (cost minimization). Second, a complex set of physical restrictions on fishing activities (such as gear, season, area and size limit regulations) may maximize the physical yield of the fishery, but so long as other dimensions of fishing effort are open to manipulation (at a cost) a competitive fishing industry will be unlikely to achieve a high degree of economic efficiency. To approach the socially optimal configuration of productive factors in the fishery as well as the ideal harvest rate requires either (1) an infinite degree of control over the individual fishing operations, or (2) a set of rules and conditions which elicits fishermen behavior consistent with economic efficiency. A variety of taxing schemes and altered property rights regimes have been proposed in order to meet this second condition.

In the Anchovy Plan a great variety of regulations were proposed. These included (1) the establishment of a harvest strategy curve for the California fishery, (2) a size limit of five inches on the reduction fishery, (3) closure of nearshore areas to reduction fishing, (4) closure of the reduction fishery during the peak summer recreational fishing season and during the peak anchovy spawning season (February/March), (5) allocation of the quota to nonreduction fishermen and among reduction fisheries north and south of Pt. Buchon, (6) adjustment of the annual quota in response to imbalances in the ratio of male and female fish in the harvest, and (7) license limitation in the reduction fishery. Of these, only the last two were rejected by the Pacific Fishery Management Council. Economic analysis gave some support to the harvest strategy curve, but the fact that the curve finally adopted was nearly identical to the existing California state plan leaves open the possibility that inertia was the dominant factor. And the license limitation proposal which was motivated explicitly by the economic efficiency rationale found little support, ostensibly due to the absence of a hugely overcapitalized fleet The slight support given the license limitation scheme came, ironically, from both the commercial and recreational groups. The commercial interests were presumably intrigued by the possibility of forming a closed shop, and the recreationists were willing to opt for any regulation limiting the size of the commercial fishery. Economic efficiency considerations, in other words, held little sway in the decision-making process.

The analysis of alternative kinds of economic regulations in the anchovy fishery suffers from fundamental defects stemming from inadequacies in the existing theory. Even the primary motivation for regulating the fishery could be given further attention. The usual argument is that a freely competitive fishery will overfish the stock, if not biologically then at least economically. But, as Scott [1955] pointed out, a sole owner would operate the fishery efficiently. And more recently Clark and Munro [1979] have suggested that a monopsonist fish processor may also run an economically efficient fishery. In the anchovy fishery we have neither a sole owner nor a true monopsonist fish buyer, but the number of participants in harvesting and processing is small enough to make one wonder whether the negotiating game among the few might not achieve a reasonable degree of commercial efficiency even without public regulations. Thus a satisfactory model of the industrial structure and behavior of the reduction fishery might have serious implications for management.

The biggest remaining difficulty, of course, is that a commercial fishery will be efficient only producing what it can sell. Recreation and enhancement of other fish stocks might require protection by a government agency even if overcapitalization and depletion in the usual sense is not threatened. Under the postulated condition of efficient execution of commercial fishing, but with too great an annual take, a quota system may very well be found to be an efficient management device. This line of reasoning bolsters my long-held belief that almost any kind of regulation can be efficient in some situation, and that the real need is for much more comprehensive empirical work which specifies the true situation and feasible set of alternatives.

Another of the basic weaknesses in the existing literature on fisheries regulation is that it is mostly based on a static model of the fishery (except for Clark [1980]), and always assumes a deterministic world. The unrealistic conditions assumed in the theory can lead to distortions in the conclusions regarding optimal regulatory policy. Weitzman [1978] shows that if the cost of deviating from a regulatory target (like not achieving the ideal harvest or fleet size) is a quadratic loss function, then the optimal selection of quantitative standards (like a quota) and pricing-type regulations (like royalities and license fees) generally includes a mix of both types. Presumably the regulatory analyst has some model of firm behavior which allows him to forecast the response of firms to new rules. To the extent that the behavioral model errs in predicting behavior, pricing-type regulations will result in missing the target. Quantitative rules may more reliably achieve targets in some circumstances. Whether reliance on quantity regulations is preferable to pricing depends on the cost of missing the target as well as the accuracy with which behavior can be predicted. If, for instance, a slight deviation is very costly (the weight attached to the squared term in the quadratic loss function is large), and firm behavior is predicted with large errors, quantitiative restrictions on firms are preferable to price incentives. On the other hand, if the value of the regulated industry is fairly linear about the target and the regulator's model of the industry behavior is accurate, optimum regulations may rely heavily on price incentives.

Although this quick sketch does not reveal the full implications of Weitzman's work, and the results are not directly applicable to fisheries anyway, it does suggest some new directions for investigation. In particular, the seemingly vast gulf between adherents of the traditional quota/season-type regulations and the proponents of taxes and royalities may be partly bridged by a theory embedded in a world of uncertainty and stochastic decision-making. Both kinds of regulation may be optimal under some conditions, and a mix of regulations is probably called for in most situations. The ideal mix of regulations for the anchovy fishery have almost certainly not been found. To make much progress we need further conceptual thinking and data gathering. Until more is known about the system being managed and better management alternatives are devised, a rigorous case for different regulations in the anchovy fishery will not be developed.

Analysis of Management Information

Collection and analysis of management information is a continuing need under any kind of management program. It is needed to support law enforcement activities and regular changes in regulations and to enable the managing agencies to periodically assess the performance of the regulations and initiate significant reforms. Because the FCMA provides broad definitions and regulatory options, there is now increased pressure on fisheries managers to husband great masses of economic, social and ecological data along with the more traditional stock assessments. All this is, of course, essential if enlightened fishery policy is to address the wide range of issues required by law. But enlightenment is costly, and at some point the marginal cost of more information must exceed its marginal value. To determine the optimum amount of information-gathering in all the various fields of inquiry is a prodigious task. But some routine data-gathering activities having a clear purpose and a calculable impact can be evaluated with the help of decision theory and the economic theory of information.

Generally speaking, any decision-maker must continually choose among a variety of options based on more or less imperfect information. An important component of the uncertainty inherent in decision-making is uncertainty about objective facts, i.e., uncertainty about the "state of the world." Assuming that different decisions are optimal under different states, better decisions will be made when more precise information about pertinent aspects of the world is available. Decision theory provides a rational framework for using imperfect information, and, consequently, suggests a way to place an economic value on specific kinds of information.

To give an example from anchovy management, consider the annual quota decision which, according to the anchovy plan [Department of Commerce 1978], follows the rule

$$Q = \begin{cases} 0.333(B - 1{,}000{,}000) & \text{if } (B - 1{,}000{,}000) > 0 \\ 0. & \text{if } (B - 1{,}000{,}000) \leqslant 0. \end{cases}$$

where Q is the annual quota and B is the estimated biomass. Since B is a statistical estimate based on ichthyoplankton surveys, it is at best correct on average. When biomass is over- or underestimated the assigned quota deviates from the level intended, and the expected economic value of the fishery presumably suffers. To evaluate the amount of information collection which is warranted on economic grounds, we need to demonstrate two relationships: (1) the relationship between the expected monetary value (EMV) of the fishery and the quantity of data collected; and (2) the correspondence between cost of data and quantity of data.

A rough, but illustrative, application of this approach can be developed by assuming that some elementary sampling theory applies to anchovy biomass estimation. First, we assume that the standard deviation of the biomass estimate about the true value is inversely related to the square root of the sample size. As the sample size gets larger the standard error of the estimate shrinks. This corresponds to collecting more data to get more precision. Table IV, columns 1 and 2 show the postulated relationship. Second, the cost of making the biomass estimate is assumed to be proportional to the sample size needed. (See Table IV, column 3.) Finally, the expected monetary value of the fishery is calculated as the annual average NEV defined as in Equation 14 above. The procedure for calculating these expected values involves a simulation program which is explained in detail by Huppert et al. [1980b]. As we should expect, the EMV (Table IV, column 5) for the fishery fall with decreasing accuracy of the estimate.

The payoff associated with increased data collection (i.e., larger sample size) for this example can be evaluated by comparing increased EMV with increased cost at successive levels of precision. The pertinent computations are given in Table IV, column 5. When the sample size is increased from 125 to 163, for instance, the cost of sampling grows from $139,000 to $181,000, while the EMV increases from $3.787 to $3.838 million for a net increase of $39,000. As is indicated in the table, collecting more than 222 samples may not be justified by the economic gain.

A more careful and thorough analysis is needed before reaching a final conclusion here, because nonreduction fishery values were not incorporated, and because an increased year-to-year variability in the quotas accompanies the decreased precision in estimation. An aversion to instability in the fishery would shift more emphasis onto the precision factor. Evaluation of other types of management information may be approached with the techniques outlined above.

SUMMARY AND RECOMMENDATIONS

A rich variety of economic issues and analytical techniques has been discussed or mentioned in the foregoing sections of the chapter. Existing applications to the anchovy fishery were summarized, deficiencies were identified and directions for improvement were suggested. Insufficient data are

Table IV. Evaluation of Biomass Estimates for the Anchovy Reduction Fishery Management Program

Standard Error of the Estimate[a]	Sample Size[b]	Total Cost	Expected Monetary Value (EMV)	Increase in EMV minus Increase in Cost
			($1000)	
0.05	8000	8896	4155	-6647
0.10	2000	1113	4130	-1200
0.15	889	989	4095	-384
0.20	500	556[c]	4046	-141
0.25	320	356	3987	-71
0.30	222	247	3916	+12
0.35	163	181	3838	+39
0.40	125	139	3757	-

[a] Represents a proportional, not additive, error.

[b] Based on the assumption that 500 plankton samples yield a standard error of 0.2. Other values are computed by the use of the formula: $\sigma = \sqrt{s^2} / \sqrt{N}$

[c] This is the estimated cost for annual survey in Department of Commerce (1978).

perhaps the commonest kind of problem, but this mainly affects the precision of certain estimated parameters and not the structure of the economic analysis or the kinds of management options evaluated. The methodological weaknesses, however, stem from more fundamental defects in applied fisheries economics. Three areas in particular need of further development are (1) the valuation of indirect impacts of commercial fishing and unpriced outputs; (2) a theory of multiple-use fishing vessels which addresses the problem of optimizing a mix of harvests under conditions of biological and market uncertainty; and (3) an investigation of the industry structure with implications for management strategy.

Obvious components of the first area of investigation are the extension of ecosystem models to predict interspecies effects of anchovy harvests, and development of recreational fishery evaluations to determine the importance of changes in angler success rates. The specification of predictive ecosystem models may be a distant goal, but current efforts in the area of recreational economics give some reason for optimism. Unless the impact of the anchovy fishery on recreationists can be assessed, however, the recreational economics work may not contribute significantly to management practice.

It is clear enough that a single species fishery with a single-purpose fishing fleet is an unrealistic abstraction. I think it is equally clear that the unpredictability of catch rates and the variability of fish prices provide sufficient motivation for the observed level of flexibility designed into the multipurpose southern California purse seine fleet. To manage adequately the harvest of any one target species in this situation has unavoidable implications for the others. A useful line of research, therefore, is one which seeks to capture the essential features of the fleet's economic strategies and to approach the fishery management question within a multidimensional model.

Behavior of the fishing industry is all too often assumed to be perfectly competitive. Cooperative behavior (or competition among a few participants) yields different conclusions regarding the need for public intervention, especially if a reasonable degree of control can be exercised by the industry over total fishery withdrawals. Externalities and indirect effects not valued by the commercial fishery may still justify public participation in fishery management, but industry behavior may be anticipated to solve some of the requirements for economic efficiency. Thus, the kinds of regulatory mechanisms proposed might reasonably avoid addressing many internal industry efficiency problems. A thorough examination of industry structure and market behavior along traditional lines could, depending on the finding, lead to a significant simplification in the kinds of regulations economists need examine.

NOTES

[1] Participating in the analysis of the anchovy fishery were, in addition to the author, Dr. G. D. Stauffer, A. MacCall and J. McMillan.

[2] The causes were natural in the sense that direct fishery-induced mortality was not responsible. The rapid growth of the stock in the early 1960s may have been partly due to the sardine stock collapse which may be attributable to the sardine fishery.

[3] A coefficient of variation equals the standard deviation divided by the mean.

[4] Although the presence of larvae is clear evidence of adults, there is some indication that anchovy schools tend to move farther north in the summer and south in the winter. Since the major spawning activity occurs during February-April, the larva distribution may be farther south than the average adult fish distribution.

[5] Gulland's method for estimating potential yield requires an estimate of unfished biomass. Since the anchovy stock biomass ranged from 2.6 to 4.0 million tons during the 1968-1972 period, the potential yield was given as a range of 1.5 to 2.4 million tons (MacCall et al. [1976], p. 7). Clearly, the unfished stock of anchovies was far smaller in the early 1950s than it was in later years.

[6] Radovich and MacCall [1979] was first presented at the 1976 CalCOFI Conference. Thus it predates MacCall [1980] and Department of Commerce [1978].

[7] The statistical test is of the hypothesis $H_0\!:E(R/B) = \bar{R}$. The following table from Huppert et al. [1980b] summarizes the results for both recruitment models in Figure 3.

Analysis of Variance for Recruitment Models
(Total sum of squares equals 14.078)

	Model A (logistic)	Model B
Variance		
Explained (df)	4.506 (1)	3.875 (1)
Unexplained (df)	9.572 (13)	10.203 (13)
Mean Square		
Explained	4.506	3.875
Unexplained	0.736	0.785
F-statistic	6.12	4.94
Approximate probability	0.028	0.045

[8] The alternative recruitment model, B, was generated during a discussion of density-dependence at the Pacific Fishery Management Council's Scientific and Statistical Committee meeting in La Jolla, California on July 8, 1980. Below a biomass of 1.225 million tons the per capita recruitment is "density-independent" (i.e., not affected by the biomass of spawning fish), and above 1.225 million tons the absolute value of recruitment is density-independent. This model is a compromise between two extreme positions; one holding total recruitment to be completely independent, and the other holding recruitment to be strictly dependent via the logistic growth model.

[9] Green's estimated total predation was 3.5 times the estimated small school fish available to predators. The gap between these two figures illustrates the crude state of existing quantitative ecosystem models.

[10] The origin of the term "wetfish" is disputed among experts, but throughout this paper it stands for a group of fish species landed "wet" (i.e., in fresh seawater, without freezing) by purse seine vessels. These species include anchovy, jack mackerel, Pacific mackerel, Pacific bonito, bluefin tuna, Pacific sardine and squid. The "wetfish fleet" is that group of purse seiners which land these species *and* are smaller and less mobile than the tropical tuna vessels.

[11] An earlier unpublished paper by Fox [1974] precedes MacCall's work and the summary discussion by Gulland [1977] of the variable catchability model.

[12] The $24.58/ton average cost of fishing anchovies which was quoted earlier would correspond to an approximate $18,900/year wage per crew member. This assumes 48 weeks of fishing five days per week at 78.1 tons catch per day, direct operating costs of 15% of cost and 58% crew share for a 12-man crew.

[13] Strictly speaking, the Just and Hueth result applies only to a vertically structured competitive sector of an economy where each industry in the sector produces a single product using one major variable input produced within the sector and other variable inputs originating in other sectors of the economy. Since both the fishing fleet and the processing firms produce nonanchovy products, this use of their welfare measurement is not completely legitimate.

[14] Equation 15 can be derived from the stock transition Equation 4 and the catch Equation 5. Although we cannot algebraically solve Equation 5 for fishing mortality, F, as a function of y_t and B_t, there is a one-to-one correspondence between F and y_t and B_t which can be computed numerically and can be expressed as

$$F = f(y_t, B_t),\ y, B > 0$$

with $$\frac{\partial f}{\partial y} > 0, \frac{\partial^2 f}{\partial y^2} > 0, \frac{\partial f}{\partial B} < 0, \frac{\partial^2 f}{\partial B^2} = 0$$

Substituting this function into Equation 4 yields

$$B_{t+1} = B_t K/(H + B_t) - B_t e^{-(M - G)} (1 - e^{-f(y_t, B_t)})$$

or $$B_{t+1} = g(y_t, B_t).$$

[15] More formal derivation of these qualitative results proceeds as follows. The deterministic optimization problem is to maximize the following Lagrangian

$$L = \sum_{t=0}^{T} NEV(y_t, B_t)\left(\frac{1}{1+d}\right)^t - Z_t\,[B_{t+1} - g(y_t, B_t)]$$

Necessary conditions for an interior maximum are

$$\frac{\partial L}{\partial y_t} = \left(\frac{1}{1+d}\right)^t \frac{\partial NEV}{\partial y_t} + Z_t \frac{\partial g}{\partial y_t} \leqslant 0 \qquad (1)$$

$$\frac{\partial L}{\partial B_t} = \left(\frac{1}{1+d}\right)^t \frac{\partial NEV}{\partial B_t} - Z_{t-1} + Z_t \frac{\partial g}{\partial B_t} \leqslant 0 \qquad (2)$$

$$\frac{\partial L}{\partial Z_t} = B_{t-1} - g(y_t, B_t) = 0 \qquad (3)$$

$$y, B > 0$$

If $\frac{\partial L}{\partial y_t} < 0$ for all $y > 0$, the nonnegativity constraint is effective, i.e., the optimum y is $y = 0$. Note that Z_t is the discounted value of having one more unit of biomass in year $t + 1$. If B_t is not so low as to require a zero harvest, Condition 1 must be an equality. An interpretation of this is that the marginal contribution of catch in year t to the discounted return must just equal the marginal contribution of leaving an additional unit (i.e., catching one unit less). The second term on the right side of Equation 1 equals marginal contribution of an additional unit of stock next year times the marginal effect of this year's catch on next year's stock.

[16] Choice of an appropriate discount rate involves several theoretical nuances that are not of great concern here, but which have occupied the journal literature [Baumol 1968]. The 4% rate of discount reflects the typical yield on Moody's corporate AAA Bonds during the relatively non-inflationary 1950-1965 period.

[17] A sample standard error of about 0.6 was computed for the residuals of the growth model [Huppert et al. 1980b]. A smaller standard deviation is assumed here because much of the variability in the fitted residuals appears to be due to the less accurate biomass estimates of the early 1960s which were based on far fewer plankton samples than are current estimates. It seems reasonable that at least half of the original standard error could be attributed to variability in the stock's real growth response.

[18] Using the terminology of note 15 and substituting the relationships,

$$NEV\,(y_t, B_t) = V_1\,(y_{1t}, B_t) + V_2\,(y_{2t}, B_t)$$

$$y_{1t} = S_1 y_t$$

$$y_{2t} = (1 - S_1) y_t$$

into the Lagrangian expression, the necessary conditions for an optimum include the following:

$$\frac{\partial L}{\partial y_t} = \frac{\partial V_1}{\partial (S_{1t} y_t)} y_t - \frac{\partial V_1}{\partial (1 - S_{1t}) y_t} y_t \leqslant 0$$

In case this condition is satisfied as an equality, the marginal value of harvest in use 1 must equal the marginal value in use 2.

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