Implications of Multipurpose Fleets and Mixed Stocks for Control Policies[1]

D. D. HUPPERT

National Marine Fisheries Service, Southwest Fisheries Center, La Jolla, CA 92038, USA

HUPPERT, D. D. 1979. Implications of multipurpose fleets and mixed stocks for control policies. J. Fish. Res. Board Can. 36: 845–854.

Management of harvests from mixed stocks and multipurpose fleets requires the use of concepts not discussed in single species fishery models. Optimum harvest of a group of mixed stocks implies that an aggregate objective pertaining to the multispecies catch is maximized. This usually prohibits the attainment of the maximum sustained yield or the maximum economic yield for each individual stock. Operation of a multipurpose fleet is economically justifiable when there are significant annual or seasonal fluctuations in fish stock abundance. A simple linear model is developed in this paper to demonstrate how the multipurpose fleet can be a necessary part of rational management.

Key words: economics, management, multispecies

HUPPERT, D. D. 1979. Implications of multipurpose fleets and mixed stocks for control policies. J. Fish. Res. Board Can. 36: 845–854.

Pour gérer la récolte de stocks mixtes par des flottilles polyvalentes, on doit faire appel à des concepts qui ne sont pas examinés dans des modèles de pêcheries d'espèces uniques. La récolte optimale d'un groupe de stocks mixtes suppose que l'on porte au maximum un objectif composite par rapport à des captures de plusieurs espèces. Pour cette raison, il est ordinairement impossible d'atteindre le rendement maximal soutenu ou le rendement économique maximal pour chaque stock. Il est économiquement justifiable d'exploiter une flottille polyvalente quand il y a d'importantes fluctuations annuelles ou saisonnières d'abondance des stocks. Nous élaborons dans cet article un modèle linéaire simple démontrant la façon dont une flottille polyvalente peut être partie nécessaire d'une gestion rationnelle.

Received October 16, 1978
Accepted April 4, 1979

Reçu le 16 octobre 1978
Accepté le 4 avril 1979

FISHERIES management science has not adequately addressed the problems associated with mixed biological stocks and multipurpose vessels. Both situations influence the economic and biological analyses required for optimization of the harvest. In the case of mixed stocks, the concept of maximum yield must be adapted to a multispecies aggregate rather than being applied on a stock-by-stock, or species-by-species basis. Economically desirable harvest rates for mixed stocks depend upon relative prices of the species caught and upon the costs of altering the species mix. In the first section below I review recent literature on mixed stock management and summarize the conclusions for fisheries policy.

Multipurpose vessels shift from fishery to fishery in response to seasonal fish abundance, closures by management, or fluctuations in prices and costs. Any economic or biological factors that cause economic returns to fluctuate can induce vessel operators to diversify in an attempt to improve long run earnings potential or to decrease annual variations in income. Although economically irrational management methods may often be responsible for the appearance of multipurpose fleets, there are many situations in which investment in multipurpose vessels is justifiable. The examination of conditions favorable to multipurpose fleets and the determination of optimum size for a multipurpose fleet are the main subjects of the second part of the paper.

In developing an analysis of mixed stocks and multipurpose fleets, it was necessary to abstract from some of the more detailed problems of fishery regulations. Companion papers in this symposium by Adasiak (1979), Crutchfield (1979), Fraser (1979), and Scott (1979) draw more attention to the problems of regulating fisheries than I do. In particular, the cost minimization in the traditional economic efficiency approach to management requires that capital investment in fishing capability be limited. This requirement is often identified with license limitation programs, and I adopt this position in the discussion of optimum multipurpose fleet. The overinvestment may be transformed, however, from a problem of too many vessels to one of vessels that are too big or heavily equipped.

[1]This paper forms part of the Proceedings of the Symposium on Policies for Economic Rationalization of Commercial Fisheries held at Powell River, B.C., August 1978.

Printed in Canada (J5410)
Imprimé au Canada (J5410)

Fraser is especially concerned that license limitation, and even restrictions on the total tonnage of the fleet, will not satisfactorily constrain the investment in fishing vessels and gear. Rather than repeat the arguments presented elsewhere, I refer the reader to the other papers in the symposium. In general, the whole spectrum of regulatory methods discussed in these other papers is applicable, with modification, to multiple stocks and multipurpose fisheries.

Management of Mixed Stocks

Several investigations of mixed stock fisheries have appeared in recent years. Among these are Anderson (1975, 1977), Clark (1976), Hilborn (1976), Hobson and Lenarz (1977), and Paulik et al. (1967). The papers by Hilborn and Paulik et al. treat the specific problems associated with mixed stocks of salmon. Conditions characterizing the salmon management problem are (1) the thorough mixing of many substocks of economically identical fish at sea, (2) the inability of fishing vessel operators to avoid the contemporaneous harvest of fish from more than one stock, and (3) the lack of biological interactions which affect the productivity of the individual stocks. All the other authors identify several categories of mixed stock fisheries. Hobson and Lenarz (1977) seem to have the most comprehensive taxonomy of mixed stock fisheries. Fish stocks may be ecologically interactive or not, and fishing gear utilized in the fishery may be flexible or inflexible.

The first characteristic, degree of interaction among stocks, depends upon the relationship of species in a food web. Stocks of predator fish may be food limited, thus implying a positive relationship between the number of predators and the size of the prey stocks. Two species may compete for food, in which case the size of one stock may be inversely related to the size of the competing stock. Finally, the several stocks being exploited may be neither competing for a common food source nor preying on each other.

The flexibility of the gear in targeting upon a single species or a subgroup of species depends upon both the physical characteristics of the gear and upon the spatial and behavioral attributes of the fish. When fish from several stocks are essentially identical as in the salmon fishery, the fishermen may realistically be assumed to have no practical means of discriminating among the several stocks available at a given time and place. Fishing gear that sweeps a given area is generally less selective among fish species or stocks than gear that requires that a target species have a particular physical or behavioral attribute. Trawl nets are perhaps the archetypical example of sweeping gear. Pacific halibut, for example, are taken in conjunction with a variety of other flatfish species by bottom trawlers. Longline gear, on the other hand, can discriminate against the smaller flatfish species because a larger hook prevents smaller fish from being caught.

Adding to this complexity is the great variability in species mix that any given gear type can achieve by selection of temporal and spatial deployment. At different times of day or in different seasons of the year, the species available to trawl gear differ radically. Also, a given species can mix with another species during certain life stages but not during others. In all of the published papers on management of mixed stocks, this richness of detail is sacrificed to the analytical tractability of the models. Those generalizations that I find promising for mixed stock management policy are discussed under the following two headings: (1) optimum harvest rates and (2) the incidental catch problems.

Optimum Harvest Rates

Existing analyses all seem to agree on one important aspect of the joint harvest problem. When the fishing gear used to harvest one or more mixed stocks is incapable of targeting upon single stocks, it is agreed that (1) the maximum harvest rate for the aggregate of stocks will be less than the sum of the theoretical maxima of the individual stocks, and (2) the less productive stocks will have to be reduced to levels that cannot support their individual maximum yields, and the more productive stocks will be exploited at rates close to, but generally less than, the individual stock maxima. Some stocks may even be driven to extinction by an aggregate sustained yield maximizing policy. This result leans heavily on two key assumptions: (1) that maximum physical yield is the objective, and (2) that the gear is inflexible. Different objectives and more flexible gear lead to different conclusions.

Preservation of genetic diversity, for instance, may be an important consideration. This particularly concerns biologists studying the effects of heavy exploitation of salmon stocks. From an economic standpoint, genetic diversity may have great value if it preserves future options and acts to increase overall productivity over time. Another major consideration is the relative economic values of the mixed species. For salmon this may not be of critical importance, but in groundfish harvests there are often high-valued species of relatively low productivity or great vulnerability mixed with larger stocks of lower-valued species.

Both Anderson (1975) and Clark (1976) derive conditions necessary for the economic optimization of mixed stocks. The value to be maximized is the aggregate sales value of the mixed catch minus the harvest cost. Just as in the single species models popularized by Gordon (1954) and Schaefer (1957), the economic optimum is examined by converting the physical yield curve into a value curve measured in dollars. When a two-species harvest is introduced, the economic value curve has two local maxima. The annual net economic yield is maximized when the marginal cost of fishing just equals the marginal sales value of the mixed catch. Since there will generally be two rates of harvest satisfying this condition, the overall economic optimum occurs at the point that has the higher total net value. From a theoretical standpoint this is all that is needed. In practice, however, the aggregate biological yield is difficult to determine, especially when the two stocks being harvested interact biologically. Also, unlike the "biological" maximum, the economic optimum will not necessarily sacrifice the less productive stock to fully exploit the more abundant stock. If the smaller, more vulnerable stock has an extremely high value relative to the more abundant stock, the economic optimum may well dictate a low rate of exploitation which protects the small stock and leaves the large stock relatively underexploited

Flexibility of the gear in targeting on individual species may provide a means to avoid retarding the development of a larger fishery to protect a small, high-valued stock. Flexibility implies that the relative harvest rates of mixed stocks can be adjusted by gear modification or targeting, while overall exploitation rate is controlled, as usual, by the total amount of fishing. For each possible relative rate of harvest of two species there will be a theoretical economic yield curve with two peaks. If it is assumed that the unregulated fishing vessels adopt those fishing methods that yield the greatest net revenue, then any alteration in fishing methods will result in an apparent reduction in earnings or increase in costs. But a regulated modification of relative harvest rates may result in a long-term increase in total sustainable economic yield. An optimal adjustment of relative harvest rates requires that the rate of increase in fishing costs be balanced at the margin against the rate of increase in equilibrium value of harvest.

Incidental Catch Problem

Among the most difficult and frequently occurring problems in fisheries management is the incidental, or by-catch problem. The general approach to mixed stock management discussed above does not include any mention of incidental catches simply because we assume that managers accept the mixed catch and optimize over the range of possible relative and aggregate rates of fishing. Under the multiple species approach, incidental catch is not a problem or nuisance. In what sense, then, can an "incidental catch problem" occur? It seems to me that the problem has two sources: (1) institutional or political inflexibility in setting objectives, and (2) technological and enforcement shortcomings.

If managers are committed to manage on a species-by-species basis, then each fishery management unit may become a proponent for the particular group of fishermen and gear types that specialize on its species. Each species management group will want to promulgate as many direct controls (gear regulations, season and area restrictions, and incidental catch allowances) as are necessary to protect its species and to maximize the yield from its species. Under this sort of management institution it will be very difficult for any central authority to adopt a rational aggregate approach to the mixed stocks. Not only will the scientists studying each species develop a narrow viewpoint, but the operators in each separate group are likely to become a political force supporting the continuation of the enforced separation of fisheries. There will be no special interest group to protest the onerous economic costs that such a system will impose on society as a whole.

It must be admitted, however, that appropriate mixed-stock management procedures will not necessarily accomplish the ideal relative harvest rates without imposing incidental catch regulations. It is possible, for instance, that catch of some depleted but high-valued species should be prohibited. If this conclusion is economically rational, it is implied that there is some technological means of avoiding the prohibited species at reasonable cost. Economists often recommend the use of tax incentives to encourage desired behavior or discourage undesired behavior. When the behavior (or fishing technology) occurs outside the manager's observation range, however, it may be impossible for a tax or fee system to work. Obviously, the incidental catch can be discarded at sea while the economic rewards and/or penalties are applied at the point of landings. Control over fish landings, therefore, is unlikely to provide adequate protection to a prohibited species.

Once it is concluded that landings regulations or taxes cannot enforce the desired fishing rates, other direct regulations may be considered. The imposition of any kind of gear requirement, or season or area restrictions, should be preceded by a demonstration that the long-run increase in potential catch value exceeds the increase in harvest costs. In conclusion, the problem of regulating incidental catches can arise in rational mixed-stock management programs, but the frequency of such problems would probably be greatly reduced if multiple species management approaches were adopted.

Management of Multipurpose Fleets

Despite its relevance to fisheries management, multipurpose vessel operation has been subject to few penetrating analyses. Meany (1977) has recently written one of the few overviews of the pertinent issues. Five reasons for fishermen to invest in multipurpose capability are identified by Meany. These are (1) changes in relative abundance of different species, (2) changes in relative prices of species, (3) seasonal factors, (4) differential changes in gear costs, and (5) personal preference of the skippers. Like any successful businessman, the fishing vessel owner must periodically assess the profitability of various production methods. When conditions change, the profitability of fishing changes, and the fishermen must adapt.

Meany goes on to develop a hypothetical scenario involving successive imposition of limited entry to four interrelated fisheries. All vessels with historical participation in a given fishery are issued licenses to fish in that fishery. Over time this results in unequal treatment of newcomers who can fish only in the less-developed fisheries. As more fisheries become heavily exploited, they are put under license limitation programs. Eventually, a bewildering array of single and multiple fishery licenses emerges. Under this system of limited entry there is far too much potential effort for some species (due to the inclusion of all past participants), while at the same time some vessels have too little flexibility in fishing methods to survive the inevitable failures of recruitment in individual stocks. The system, in other words, protects neither fish stocks nor fishermen. Meany's conclusions for fishery management are (1) multipurpose fleets should be managed as a unit by limiting access to the multi-species group of fisheries; (2) the optimum number of vessels in the group should be determined in accordance with maximum sustainable yield, maximum profit, or some other socially acceptable objective; (3) changing conditions imply changes in the optimum fleet size and managers should be prepared to increase or decrease the fleet size; (4) differential license fees should be introduced for each fishing method to shift effort from the more heavily exploited to the less heavily exploited fisheries; and (5) licensing regulations can be supplemented, if necessary, by gear restrictions and other forms of catch regulation. Under this recommended system, fishermen are free to decide (subject to fees and gear restrictions) which of the fisheries they will enter during any given year.

Implementation of an economically rational management program of the type that Meany recommends will depend crucially upon the ability of the managers to determine the optimum fleet size. This will be true regardless of which regulatory methods are adopted. To examine how one might accomplish this task, I have developed a simple two-stock model. I assume that the two essential aspects of economic rationalization, regulation of the catch and regulation of long-term commitment of resources to fishing and processing capital, are separable. Although optimum extraction rates and optimum capital stock can be derived formally from a single optimizing model (see Clark 1977; Anderson 1975; Smith 1969), separation of the two problems has practical value. Rates of exploitation will often be determined through intensive interaction among biologists, economists, fishermen, and managers. Any proposals for further regulation aimed at cost minimization will be developed largely by economists. Controls on fleet size, therefore, are in practice often appended to some preexisting plan for controlling catch.

The discussion of optimum fleet size is developed in two parts. In both, the annual allowable catches are assumed to be interpreted as fishing quotas which are enforced through season closures. Under Case I, it is further assumed that the annual quotas are fixed and recurring year after year. Case II examines the implications of random variation in the fish stocks which is reflected in annual variation in the two quotas.

Case I — Fixed Annual Quotas

The two fish stocks may be potentially available to the fishing fleet throughout most of the year or they may be available in two discrete seasons due to natural variations in availability. In either case the development of a two-stock fishery can be examined by reference to Fig. 1. A fuller algebraic development of the model is contained in the Appendix. Only a verbal explanation will be attempted in the main text. In both panels of Fig. 1 the number of vessels in the fleet is measured along the horizontal axis.

In the upper panel the curve labeled R represents the level of revenue minus operating costs earned per vessel. As the number of vessels is increased the net operating revenue, R, proceeds through three stages. As N increases from zero up to the number required to fully utilize the quota of the more profitable stock (assumed to be stock 1), the profit per vessel remains constant. If the two stocks are available all the time, then until the number of vessels exceeds N^*, no vessels fish the less profitable stock. Only stock 1 is fished because the quota is taken at a slow enough rate to allow full utilization of the fleet. If the fishing vessels are earning sufficient profits to attract additional fishermen into the fishery for stock 1, however, the fleet will continue to expand. As the number of vessels expands beyond N^*, the net revenue per vessel declines because each vessel must stop fishing for the more profitable stock 1 when the quota is reached. An increasing fraction of the available fishing capacity will be devoted to the less valuable second stock.

With free access to the hypothetical fishery the eventual size of the fleet is determined by the prospective profits and the capital costs associated with owning a fishing vessel. It is usually realistic to assume that additional fishing vessels will be built to enter the fishery until the prospective net earnings (revenue minus operating costs) are just balanced by the annual capital costs. The line labeled I_1 in Fig. 1 represents a level of capital cost that implies an eventual fleet size of N_1. If capital costs are at the lower level represented by the line I_2, the fleet will expand further to N_2. When the number of vessels reaches N^{**}, both quotas will be taken in a full fishing year. And further expansion of the fleet beyond N^{**} causes all vessels to remain idle for the remainder of the year. Clearly, this simple model could be expanded to allow for a third or fourth fishery which would be entered successively as the fleet grows and fishing seasons for the more profitable stocks become shorter and shorter.

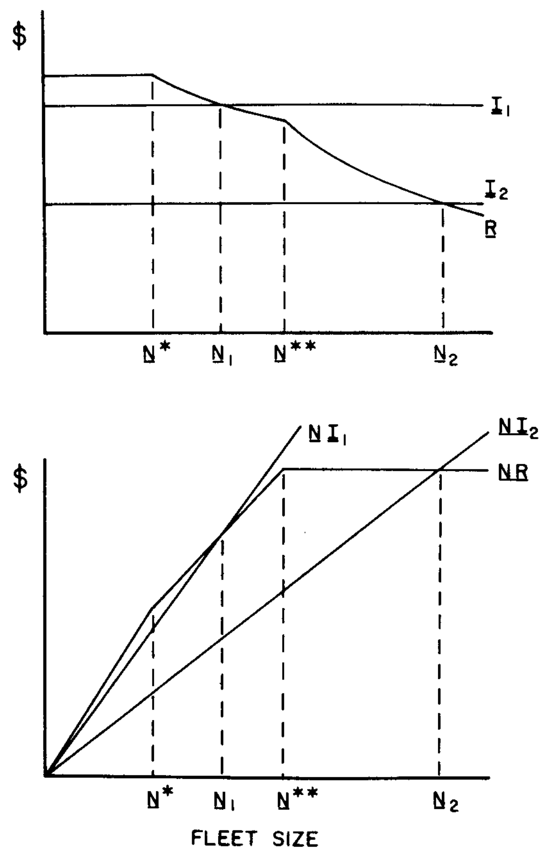

FIG. 1. Theoretical relationship between fleet size (N) and net earnings per vessel (*lower panel*), and between fleet size and total profits (*upper panel*), for two stocks of fish.

The economically rational fleet size depends upon the total net earnings of the fleet and the total commitment of capital. The relevant diagram for this examination is in the lower panel of Fig. 1. The curve labeled NR represents the total fleet earnings in excess of operating costs, and the two lines NI_1 and NI_2 represent the total capital costs corresponding to per vessel capital costs I_1 and I_2. The maximum net earnings of the fleet in excess of capital costs occurs at the fleet size that obtains the greatest vertical distance between NR and NI. For capital cost I_1 the optimum fleet size is N^*, a fleet just large enough to fully exploit the more profitable stock. With the lower capital cost, NI_2, the optimum fleet, N^{**}, is just large enough to take both of the quotas. The simple logic of this is that an economically rational management program cannot allow the fleet to expand further after the incremental increase in capital cost exceeds the incremental increase in net earnings.

Suppose the management program begins to seek economic efficiency only after the fishery has already reached the free-access equilibrium fleet size. If the capital cost curve NI_1 applies, then the fleet size will be N_1, and an excess number of vessels, equal to N_1 minus N^*, will be already in the fishery. Unless the vessels can be transferred into an alternative, underdeveloped fishery, however, it will not be desirable to initiate a licensing program for only N^* vessels. Unlicensed vessels either will go bankrupt or will suffer a capital loss. A similar conclusion holds if the capital cost per vessel is I_2.

In the fully developed free-access fishery it will be apparent that vessels must participate in more than one fishery to earn a satisfactory return on investment. But it is also clear that the fleet may not need to be multipurpose if it were not overbuilt. This is certainly the case if the two fisheries are not seasonal. The vessels become multipurpose only after the fleet is larger than necessary to fish stock 1. With capital cost I_1, the fleet need be no larger than N^*, and no vessels need to shift into stock 2. With capital cost I_2 the fleet needs to be no larger than N^{**}, and the manager can create two separate fleets that specialize on the two stocks. Thus, without seasonality in the fisheries, none of the reasons for diversification identified by Meany (1977) exist. By licensing two separate fleets, the management program can ensure that each fishing season is as long as possible, thus decreasing the costs of processing and storage facilities onshore.

If the two stocks have natural seasons, however, and the capital cost is low enough to justify full exploitation of both quotas, the manager may as well license all of the N^{**} vessels to fish both stocks. This is true at any rate if the cost of building an optimum size multipurpose fleet does not exceed the cost of building two specialized fleets. With a multipurpose fleet, none of the vessels will be forced to spend part of the year in idleness. Thus, the economic rationality of multipurpose fleet with fixed prices, costs, and annual quotas depends upon whether the fish stocks are seasonally available and whether the cost of building multipurpose capability into the vessels is excessive.

The main management implications to be gleaned from the fixed quota model are summarized as follows:

1) A multipurpose fleet is economically efficient if it is just large enough to fully exploit all stocks that yield sufficient net revenue to cover capital costs on an annual basis.

2) If the two stocks can support separate fishing fleets by virtue of year-around availability of fish, then it may be preferable to maintain two distinct fleets through regulation. It should also be recognized that all vessels licensed to fish only for the less profitable stock will be unhappy with this circumstance.

3) If only one stock is profitable enough to support a separate fleet in specialized fishing, then it is economically optimal to have a fleet just large enough to fully exploit one stock. This may appear wasteful or

paradoxical to those who wish to see every fish stock fully utilized.

4) If the fisheries must occur during separate seasons and if it is reasonably inexpensive to outfit vessels for multipurpose operation, then the fleet should be licensed to fish both stocks. Since the full utilization of one of the quotas is likely to require fewer vessels than the other, the multipurpose fleet will have excess fishing capability. But if economic conditions dictate that both stock quotas be fully utilized, the appearance of excess capability is not wasteful.

Under the conditions of the two-stock, fixed quota model, there are only two reasons for having a multipurpose fleet rather than one or two specialized fleets. First, a multipurpose fleet is more economical when the fisheries are naturally seasonal in character. And second, economic rationalization of an already overcapitalized fleet may allow for continued operation of multipurpose vessels to maintain their economic viability as private businesses. This second rationale is not a long-term policy, but rather a condition to be countenanced during a transitional period. The length of the transitional period depends upon the life of the capital equipment in the fishery. As vessels depreciate to the point of nonprofitability, they should be retired.

Case II — Variable Annual Quotas

Environmental influences can cause uncontrolled variations in stock sizes which in turn elicit annual variations in catch rates and quotas. Assuming that prices and fishing costs are fixed, the variations in catch rates translate directly into variations in net revenue earned per day of fishing. The relative profitabilities of two stocks will switch occasionally. Thus each of the following four circumstances may occur in some years: (1) each stock yields some positive net revenue to fishermen, (2) neither stock yields net revenue, (3) fish stock 1 is sufficiently abundant to yield net revenue but stock 2 is not, and (4) fish stock 2 yields net revenue but stock 1 does not. Since neither of the stocks can be relied upon to support a fishing fleet every year, it is natural to suspect that a multipurpose fleet would be more profitable than two specialized fleets.

To illustrate how the optimum fleet size may be affected by variability of quotas and catch rates, I have developed a numerical example the pertinent characteristics of which are listed in Table 1. It is assumed that each stock has five possible annual quotas that occur with known frequencies. One tenth of the time, for instance, the annual quota for stock 1 is zero; 24% of the time the quota is 10 000; 32% of the time the quota is 20 000; and so forth. Similar conditions are specified for stock 2. Fish from stock 1 are sold for a price of $10, while fish from stock 2 bring a price of $20. A day of fishing is assumed to cost $70/d regardless of which stock is being fished.

To complete the example, I assume that each vessel is able to fish 200 d/yr and that the annual capital cost per vessel is $8 thousand. Given the relative frequencies and net daily earnings corresponding to the various quotas listed in Table 1, the expected annual net revenue per vessel and expected annual fleet profits can be computed for any given fleet size. The computations were performed for each stock assuming that no vessels are allowed to change fisheries. Table 2 summarizes the results.

If the two stocks of fish are to be harvested by two separate fleets, then expected net earnings before capital cost per vessel falls in each fishery as fleet size increases. This relationship is comparable to that derived in Case I for a fixed annual quota. As indicated in Table 2, the average net annual earnings per vessel falls to about $8 thousand when each fleet expands to 14 vessels. Thus

Table 1. Characteristics of the 2-stock multipurpose fleet model with variable annual quotas and catch rates.

	Quota	Catch rate	Relative frequency	Net revenue/d fishing
Stock 1	0	10.0	0.1	—
	10 000	12.5	0.24	55
	20 000	15.0	0.32	80
	30 000	17.5	0.24	105
	40 000	20.0	0.1	130
Stock 2	0	15.0	0.1	—
	20 000	22.5	0.24	42.5
	40 000	30.0	0.32	80.0
	60 000	37.5	0.24	117.5
	80 000	45.0	0.1	155.0

Table 2. Relationship between expected annual profits and fleet size for two separate fishing fleets.

	Stock 1		Stock 2	
Fleet size (*N*)	Vessel net earnings (*R*)	Fleet profits (*NR*)	Vessel net earnings (*R*)	Fleet profits (*NR*)
4	15.4	29.6	15.9	31.6
5	14.9	34.8	15.7	38.6
6	14.7	40.0	15.5	44.7
7	14.2	43.1[a]	15.0	48.8[a]
8	13.2	41.9	14.1	48.6
9	12.3	38.9	12.8	43.4
10	11.3	33.5	11.5	35.4
11	10.3	25.5	10.5	27.4
12	9.5	17.5	9.6	19.4
13	8.7	9.5	8.9	11.4
14[b]	8.1	1.5	8.2	3.4
15	7.6	−6.5	7.7	−4.6

[a]Maximum expected fleet profits.
[b]Maximum fleet size which returns, on the average, the annual capital costs.

a free access fishery might stabilize at 14 vessels per fishery, or 28 vessels overall. I say might because vessel owners will not necessarily evaluate the probabilities of earnings the way that an "objective" fishery manager does. Defining an optimum fleet as one that maximizes the expected annual profit earned, the optimum fleet size for stock 1 is seven, and for stock 2 is seven. The aggregate profit earned on the average from both stocks is $91.9 thousand and is generated by a total fleet of 14 vessels.

To investigate the economic consequences of the alternative policy of allowing vessels to shift from one stock to the other whenever profitable, the probabilities of encountering combinations of stock quotas must be specified. Three alternative bivariate relative frequency (or probability) distributions are introduced for this purpose. The first assumes statistical independence of the two stocks. This requires that the probability of encountering any given combination of two quotas be equal to the product of the probabilities of each quota. Thus the probability that both quotas will be zero in any year is $0.1 \times 0.1 = 0.01$. By constructing the joint probabilities in this fashion, the marginal probability of any single quota is the same as specified for the separate quotas in Table 1. Comparability of the multipurpose and specialized fleet examples is thus preserved.

It is assumed that each vessel fishes the more profitable stock until the quota is reached. If the other stock is also profitable, then each vessel switches fishing modes and continues fishing until either (1) 200 d of fishing accumulate, or (2) the second quota is reached. The expected annual net revenue per vessel is calculated by multiplying each of the 25 possible net revenues by the corresponding probability from the joint probability matrix. Expected annual profit equals the expected net revenue minus the capital cost. Additional details regarding the computation of expected net revenue, including a listing of the probability matrix, are in the Appendix. The results of the expected value computations are displayed in Table 3.

The optimum fleet size for statistically independent stocks is 13 vessels. The corresponding fleet profit is $105 thousand. In comparison to separate fleets, the multipurpose fleet is smaller, thus saving capital costs, and achieves a greater average net revenue per vessel. This result depends upon the fact that multipurpose vessels can fish stock 2 when stock 1 is low, and stock 1 when stock 2 is low. It should be expected, therefore, that the economic advantage of multipurpose vessels should depend upon the assumed relationship between the two stocks. If the two stocks are negatively correlated, there should be greater opportunity to shift from stock to stock. If the two stocks are positively correlated, less economic advantage will be enjoyed because when one quota is large the other is also likely to be large.

The expected annual fleet profits with positive and negative correlation between stocks are listed in columns 4 and 5 of Table 3. The optimum fleet size is smaller when stocks are negatively correlated, just as expected, and the multipurpose fleet is more profitable. With positive correlation between stocks a larger fleet is required to maximize profits, but, perhaps surprisingly, the multipurpose fleet is still more profitable than separate fleets. In general, therefore, the greater the negative correlation between stocks, the more attractive is the use of a multipurpose fleet.

If the price of fish from stock 2 in the numerical example is reduced from $5 to $3, then the expected annual net return from a separate fishery on stock 2 becomes negative. In this situation it is not possible to maintain a separate fleet for stock 2, but it is still useful to allow the fleet fishing stock 1 to fish for stock 2. With the lower price for stock 2, the optimum fleet for a separate stock 1 fishery is 7 vessels yielding an average of $43 thousand in profits annually. In contrast, a multipurpose fleet would be 9 vessels with an aggregate expected profit of $58 thousand. It is conceivable that a fleet could thrive on a group of fluctuating stocks, no one of which yields a positive expected annual profit. Limited entry for a single stock under such conditions would be inappropriate, because no specialized fleet would be economically viable.

Other important considerations not introduced in the example are (1) the cost of specialized gear and/or the cost of shifting from one stock to the other, (2) enforcement or monitoring costs associated with multipurpose fleets, and (3) the economic loss associated with shorter fishing seasons under multipurpose fleets. Any one of these three could, upon incorporation in the analysis of optimum fleet size, reverse the decision in favor of multipurpose fleets. In the numerical example, the multipurpose fleet was expected to earn $14.1 thousand more in annual profits than could separate, specialized fleets when the stocks are sta-

TABLE 3. Relationship between multipurpose fleet size and annual profits earned from the fishery.

Fleet size (N)	Annual fleet profits with: Independent stocks	Negatively correlated stocks	Positively correlated stocks
	(1000's)		
4	48	52	43
6	71	78	63
8	91	101	80
10	101	112	90
11	103	114	93
12	104.7	114.9[a]	96
13	105.3[a]	114.6	98.1
14	104.0	111	98.4[a]
15	102	107	97.6
16	98	100	95

[a]Profit maximum.

tistically independent. If it costs more than $14.1 thousand to outfit 14 vessels for multipurpose fishing rather than for specialized fishing, then specialized fishing is preferable. Also, it is conceivable that enforcement of regulations, when vessels shift from stock to stock during a year, could be more expensive or cumbersome than when vessels are specialized. If enforcement costs are to be considered in the design of management programs, separation of vessels into specialized fleets may be economically desirable. Before this conclusion is reached for any specific case, hard data and analysis should demonstrate that enforcement costs with multipurpose fleets exceed benefits. Simple administrative ease should not be taken as a compelling case for separate licensing by species or by geographical area.

As noted in the discussion of the fixed annual quotas, fishing seasons may be longer with specialized fleets than with a multipurpose fleet. This would be true if the multipurpose vessels deploy solely on the more profitable species first and then shift to less profitable species. In some cases (salmon runs being one example), the time period over which the fish are available to the fleet may be very short in any case. Nevertheless, some fisheries can be unnecessarily forced into a short time span by the operation of a multipurpose fleet. An examination of the processing and storage costs should serve to determine whether these costs exceed the potential benefits of multipurpose fleet operation.

Management implications of the variable annual quota model are

1) Multipurpose fleets are an economically rational response to economic and environmental variability. The ability to shift from species to species is beneficial to vessel owners and can be important to the economic optimization of a fishery.

2) Since profits per vessel fluctuate, any fees charged to inhibit entry or to extract rents for the public treasury should be flexible. Annual license fees, for instance, should not be fixed at a level that causes hardship to vessel owners in years of poor fishing. Large fixed fees could be replaced by landings taxes or royalties that fluctuate with the fishery.

3) With multipurpose fleet management, there will be apparent excess effort for at least one of the stocks in most years and excess effort for all stocks together in some years. Management of harvest rates must rely upon annual quotas or some other control besides fleet size. Limited access simply provides some long-run average control over effort.

This last point is of particular interest because it suggests the real problems that will crop up in any attempt to identify overcapitalized fisheries or to measure the degree of overcapitalization. Examination of economic data from 1 or a few years may be insufficient to determine whether overcapitalization has occurred. As a corollary, rapid changes in limited entry policies are unlikely to be correctly evaluated. None of this, however, weakens the basic conclusion that free-access fisheries will tend to overinvest in vessels and gear, and that economic efficiency will occur only under a management scheme that limits investment.

Conclusions

Several implications for economically rational control of mixed stocks and multipurpose fleets were developed. It was concluded that mixed stock management requires that individual species objectives be abandoned in favor of aggregate yield objectives. Optimum harvest rates must be developed with full accounting of the revenue and cost effects on all species being harvested. Regulation of fishing methods or gear will influence the relative harvest rates of two or more mixed stocks. Thus, incentives such as differential landings taxes, or standards such as gear or area restrictions may appear prominantly in the list of regulatory tools for mixed stock management. Although it is suspected that a multispecies management approach will largely avoid the creation of "incidental catch problems," it is difficult to reach any general conclusions. More detailed investigation of specific cases will undoubtedly reveal conditions under which combinations of regulatory controls will be optimal.

Multipurpose vessels are shown to be a reasonable response to variations in underlying biological or economic conditions. A vessel capable of fishing in several discrete fisheries is like a diversified portfolio; it is exposed to less financial risk. Furthermore, when two or more fluctuating fish stocks can be harvested by a common fleet, economic efficiency may require that the fleet be managed as a multipurpose fleet. Specialized fleets are efficient with stable, year-round fisheries, but few fisheries fit this description. Thus, the presumption is that license limitation on a species-by-species basis is to be avoided. As a consequence, short-term regulation of harvest rates must be achieved by more flexible methods such as landings taxes, quotas, season or area closures. Management of investment in fleet capacity simply provides the necessary long-term control over capital costs.

Both the biological and economic conditions underlying multispecies fisheries present vast problems for future research. Ecological models for fishery management may need to specify more precisely the effects of predator–prey linkages or competition for food among stocks. An alternative approach suggested by Dickie (1973) is to develop more aggregated models that emphasize harvesting fish of a given size or at a given trophic level rather than individual species. Economic analyses required to make a multispecies model operational include studies of market pricing, processing requirements and costs, gear flexibility, and fishing cost functions. Although it suggests some important concepts for management, the multipurpose fleet analysis developed above must be considered provisional and incomplete. Clearly, many vessels operate in several fisheries; it will be difficult in practice to isolate a fixed fleet of vessels fishing a closed set of stocks. Because of differences in cost, varying seasonal and market conditions, and discontinuities in stock abundances, the appropriate grouping of species will be different at different times and places. Extension of the multipurpose fishery model to include complex overlapping species groups may prove useful. It is hoped that this paper encourages further research along these lines.

ADASIAK, A. 1979. Alaska's experience with limited entry. J. Fish. Res. Board Can. 36: 770–782.

ANDERSON, L. G. 1975. Analysis of open-access commercial exploitation and maximum economic yield in biologically and technologically interdependent fisheries. J. Fish. Res. Board Can. 32: 1825–1842.

1977. The economics of fisheries management. Johns Hopkins Univ. Press, Baltimore, Md. 214 p.

CLARK, C. W. 1976. Mathematical bioeconomics. John Wiley & Sons, New York, N.Y. 352 p.

CRUTCHFIELD, J. A. 1979. Economic and social implications of the main policy alternatives for controlling fishing effort. J. Fish. Res. Board Can. 36: 742–752.

DICKIE, L. M. 1973. Management of fisheries; ecological subsystems. Trans. Am. Fish. Soc. 2: 470–480.

FRASER, G. A. 1979. Limited entry: experience of the British Columbia salmon fishery. J. Fish. Res. Board Can. 36: 754–763.

GORDON, H. S. 1954. The economic theory of a common-property resource: the fishery. J. Polit. Econ. 62: 124–142.

HILBORN, R. 1976. Optimal exploitation of multiple stocks by a common fishery: a new methodology. J. Fish. Res. Board Can. 33: 1–5.

HOBSON, E., AND W. LENARZ. 1977. Report of a colloquium on the multispecies fisheries problem, June 1976. U.S. Dep. Comm. Mar. Fish. Rev. 39: 8–13.

MEANY, F. 1977. License limitation in a multipurpose fishery. Aust. Fish. 36(11): 8–19.

PAULIK, G. J., A. S. HOURSTON, AND P. A. LARKIN. 1967. Exploitation of multiple stocks by a common fishery. J. Fish. Res. Board Can. 24: 2527–2537.

SCHAEFER, M. B. 1957. Some considerations of population dynamics and economics in relation to the management of commercial marine fisheries. J. Fish. Res. Board Can. 14: 669–681.

SCOTT, A. D. 1979. Development of economic theory on fisheries regulation. J. Fish. Res. Board Can. 36: 725–741.

SMITH, V. L. 1969. On models of commercial fishing. J. Polit. Econ. 77: 181–198.

Appendix

The following notation is adopted for the model:

- P_1, P_2 Market prices for the two species.
- C_1, C_2 Daily fishing costs per vessel when fishing for species 1 and species 2.
- T Amount of fishing time per year per vessel (e.g. 200 d).
- I Annual capital cost per vessel.
- t_1, t_2 Number of days that vessels fish for species 1 and 2, respectively (note: $t_1 + t_2 \leq T$).
- Q_1, Q_2 Annual quotas for the two species.
- X_1, X_2 Daily catch rates for species 1 and 2.
- N Number of multipurpose vessels in the fleet.

The net daily operating revenue per vessel in each fishery is

$$r_i = (P_i X_i - C_i), \quad \text{for} \quad i = 1 \text{ or } 2. \tag{1}$$

Annual net operating revenue per vessel is

$$R = r_1 t_1 + r_2 t_2; \tag{2}$$

and the annual profit per vessel is simply net revenue minus annual capital cost, i.e.

$$\pi = R - I. \tag{3}$$

Quotas are enforced by season closures. Thus the maximum amount of time that a fishing season can be open is determined by the prevailing catch rate and fleet size as follows.

$$t_i^* = Q_i/(NX_i) \tag{4}$$

The term, NX_i, represents the total daily rate of withdrawal from stock i when the fleet is fishing. This rate of catch, divided into the annual quota, determines the length of the open fishing season. Clearly, the more vessels fishing, the shorter the season will be.

FIXED ANNUAL QUOTAS

If there are no natural seasonal variations in fish availability, profit-maximizing vessel operators will fish solely in the most profitable fishery as much of the time as possible. If the fleet size is greater than (Q_1/X_1T), however, the season for species 1 closes before the vessels have exhausted their fishing capabilities. If the fleet size is greater than (Q_1/X_1T) but less than $(Q_1/X_1T) + (Q_2/X_2T)$, the vessels will be fully utilized in fishing first for species 1 and then for species 2. If the fleet is greater than $(Q_1/X_1T) + (Q_2/X_2T)$, both fishing seasons will be closed and the vessels will be idle part of the year. Annual net revenue per vessel is a function of fleet size:

$$R = \begin{cases} r_1 T & \text{if} \quad N \leq Q_1/X_1T \\ r_1 \dfrac{Q_1}{X_1N} + r_2\left(T - \dfrac{Q_1}{X_1N}\right) & \text{if} \quad \dfrac{Q_1}{X_1T} < N < \dfrac{Q_1}{X_1T} + \dfrac{Q_2}{X_2T} \\ r_1 \dfrac{Q_1}{X_1N} + r_2 \dfrac{Q_2}{X_2N} & \text{if} \quad N > \dfrac{Q_1}{X_1T} + \dfrac{Q_2}{X_2T} \end{cases} \tag{5}$$

If the two fish stocks are naturally available in two discrete periods of the year (T_1 and T_2), each vessel will seek to fish in both fisheries as much time as possible. Net revenue per vessel is, again, a function of fleet size in three discrete segments. Assuming that stock 1 is the first to be fully exploited,

$$R = \begin{cases} r_1T_1 + r_2T_2 & \text{if} \quad N \leq \dfrac{Q_1}{X_1T_1}, \quad N \leq \dfrac{Q_2}{X_2T_2} \\ r_1 \dfrac{Q_1}{X_1N} + r_2T_2 & \text{if} \quad N > \dfrac{Q_1}{X_1T_1}, \quad N \leq \dfrac{Q_2}{X_2T_2} \\ r_2 \dfrac{Q_1}{X_1N} + r_2 \dfrac{Q_2}{X_2N} & \text{if} \quad N > \dfrac{Q_1}{X_1T_1}, \quad N > \dfrac{Q_2}{X_2T_2} \end{cases} \tag{6}$$

These two equations correspond to curve R in Fig. 1.

Regardless of whether equation (5) or (6) is the appropriate net revenue function, the fleet's total profit is expressed as

$$V = N \cdot (R - I). \tag{7}$$

Assuming that both fisheries yield net revenue ($r_1, r_2 > 0$), the fleet size maximizing V is easily found. If $(r_1T - I)$ is greater than zero for the nonseasonal fishery, then total profit is increased by expanding the fleet up to $N^* = (Q_1/X_1T)$. If the second stock is also profitable, i.e. $(r_2T - I) > 0$, then the fleet should be expanded to $N^{**} = (Q_1/X_1T) + (Q_2/X_2T)$. Any further expansion of the fleet would increase the investment cost but not the net revenue, thus decreasing the profits.

For the case of consecutive natural seasons, if $(r_1T_1 + r_2T_2) > 0$, profits are increased as the fleet expands up to size $N^* = (Q_1/X_1T)$. When the second stock is profitable, i.e. $(r_2T - I) > 0$, the total profit continues to increase until $N^{**} = (Q_2/X_2T_2)$. Expansion of the fleet beyond the size needed to fully exploit the second stock causes a reduction in profits.

Variable Annual Quotas

The numerical example in the text is based upon the algebraic model developed above and the following specific assumptions:

(1) $P_1 = 10, P_2 = 20$;
(2) $C_1 = C_2 = 70$;
(3) $I = 8000$;
(4) $T = 200$ d;
(5) $X_{1j} = 10 + .00025\, Q_{1j}, X_{1j} = 15 + .000375\, Q_{2j}$.

where X_{1j} is the daily catch rate for stock 1 with annual quota level j.

The annual quotas have probability distributions listed in Table 1 of the main text.

Letting f_j represent the probability of quota level j, the expected value of net earnings for a vessel fishing solely stock i is

$$E(R) = \sum_j f_j T^* r_{ij}, \tag{8}$$

where $T^* = T$ for $N \leq Q_{ij}/X_{ij}T$,

and $T^* = Q_{ij}/X_{ij}$ for $N > Q_{ij}/X_{ij}T$.

This formula was used to compute the expected vessel earnings in columns 2 and 4 of Table 2. Fleet profits, columns 3 and 5 of Table 2, are simply $N \cdot (E(R) - I)$.

In extending the example to multipurpose vessels, it is assumed that each vessel fishes whichever stock is most profitable until the quota is reached. Once the first quota is reached, the fleet shifts to the less profitable stock. Letting f_{jk} represent the probability that quota level j for stock 1 and quota level k for stock 2 will occur in the same year, the expected net revenue is calculated as follows:

$$E(R) = \sum_{j=1}^{5} \sum_{k=1}^{5} f_{jk}[T_1^* r_{1j} + T_2^* r_{2k}] \tag{9}$$

where

(a) $T_1^* = T$, $T_2^* = 0$ for $N \leq (Q_{1j}/X_{1j}T)$

(b) $T_1^* = Q_{1j}X_{1j}$, $T_2^* = (T - T_1^*)$ for $(Q_{1j}/X_{1j}T) < N < (Q_{1j}/X_{1j}T) + (Q_{2k}/X_{2k}T)$

(c) $T_1^* = Q_{1j}/X_{1j}$, $T_2^* = Q_{2k}/X_{2k}$ for $N > (Q_{1j}/X_{1j}T) + (Q_{2k}/X_{2k}T)$

To permit comparison of the results for different kinds of stock interactions, equation (9) was evaluated over the range of fleet sizes from 4 to 15 vessels and for three different joint probability distributions. The first distribution representing independent stocks follows the rule that Prob (X,Y) = Prob (X) Prob (Y) for X and Y independent. Probabilities for each quota level are the same as those given in Table 1. Competitive stocks are represented by the probability distribution in Table 4, having a negative correlation of −0.53. The joint probability distribution with positive correlation is created by rotating the probability matrix in Table 4 one-quarter turn.

TABLE 4. Joint probability distribution for two stock quotas. Correlation coefficient = −0.53.

	Quota 1				
Quota 2	0	10 000	20 000	30 000	40 000
0	0.00	0.01	0.03	0.04	0.02
20 000	0.01	0.02	0.05	0.12	0.04
40 000	0.03	0.05	0.16	0.05	0.03
60 000	0.04	0.12	0.05	0.02	0.01
80 000	0.02	0.04	0.03	0.01	0.00