A LINEAR PROGRAMMING APPROACH TO DETERMINING HARVESTING CAPACITY: A MULTIPLE SPECIES FISHERY

ROBERT A. SIEGEL,[1] JOSEPH J. MUELLER,[2] AND BRIAN J. ROTHSCHILD[3]

ABSTRACT

The U.S. Fishery Conservation and Management Act of 1976 (P.L. 94-265) requires that fishery management plans specify the capacity of a fishing fleet. However, the Act does not provide a definition of capacity. This paper considers some of the problems of defining and measuring capacity in the harvesting sector of the fishing industry and suggests an estimation procedure. A linear programming model is used to estimate the economic capacity of a fishing fleet. The model provides estimates of the expected output in a multiple species fishery.

Measurement of capacity in the U.S. fishing industry has become of increasing importance as a result of the passage of the Fishery Conservation and Management Act of 1976 (FCMA). The FCMA requires (Section 303 (a) (4) (A)) fishery management plans prepared by Regional Fishery Management Councils or the Secretary of Commerce to: "assess and specify . . . the capacity and the extent to which fishing vessels of the United States, on an annual basis, will harvest the optimum yield . . . ."

The FCMA, however, does not provide a functional definition of capacity that can be used in the preparation of fishery management plans. This raises operational difficulties since "capacity" can be based on economic or physical concepts. For example, physical capacity can be measured in terms of the hold space of a fishing vessel, although this generally exceeds the catch. An economic measure would simply be past catches (assuming these reflect equilibrium conditions), but this does not necessarily provide an accurate indication of future catches.

It is apparent that the hold space or past catches are only "first" approximations to "capacity" and that better indicators are needed in order to have meaningful estimates of the expected catch of the fleet. Since estimates of capacity are of obvious importance in determining U.S.-foreign allocations, it is essential that the measurements of capacity and expected catch be accurate. Thus, a major effort must be made to develop meaningful estimates of capacity that are consistent and to indicate what these measures are designed to represent.

Analysis of the capacity problem must address four issues:

1) development of a definition and measure of capacity, at least initially, relevant to the harvesting sector of the fishing industry;
2) development of appropriate methods of estimating capacity;
3) estimation of what the fleet will catch under a set of economic and environmental conditions (it will be suggested that the expected domestic catch is indeed the appropriate notion of "capacity" in the short run); and
4) the time frame for the analysis.

This paper will consider some of the problems of measuring capacity in the harvesting sector of the fishing industry and suggest possible estimation procedures. Section I focuses on economic and technical concepts of capacity. Section II presents a linear programming model which can be used to estimate the output of a fishing fleet in a multispecies fishery. Section III contains an example problem which shows the applicability of this model to a multispecies fishery such as the New England otter trawl fleet. Section IV provides a summary of the paper and briefly describes areas of further research.

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[1] National Marine Fisheries Service, Office of Resource Conservation and Management, Washington, DC 20235.

[2] National Marine Fisheries Service, Federal Building, 14 Elm Street, Gloucester, MA 01930.

[3] National Oceanic and Atmospheric Administration, Office of the Administrator, Washington, DC 20230.

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CONCEPT OF CAPACITY: FISHING INDUSTRY

General Capacity Characteristics

In general, a firm's productive capacity refers to the quantity of output that can be produced during a given time with existing plant and equipment. This definition is characterized by physical and time dimensions. The physical dimension requires that output be specified in terms of a measurable quantity. The time dimension reflects what "can be produced" during the period of operation of the plant. An important aspect of the time dimension centers on the interpretation of "what can be produced." For example, plant and equipment can be used to produce a certain quantity of output if operated continuously 24 h a day, for 7 days a week, assuming no resource input constraints; and another quantity of output if operated 8 h a day, 5 days a week, taking into account the most economical combination of inputs. Because of these characteristics and the variability of output given different economic and environmental conditions, there does not appear to be a unique number for capacity.

Fishing Fleet Capacity Measures

Technical Capacity

While it may not be possible to define the concept of capacity in precise detail, a distinction can be made between technical and economic capacity. A technical interpretation can be formulated in terms of the following question: how much fish can be caught by a given vessel on each trip, utilizing the entire physical hold space and with no constraints on resource abundance? Capacity in this context is associated with the physical hold space of a fishing vessel. It represents an upper limit on the physical capabilities of the vessel, assuming no input constraints. However, a technical definition of capacity as described above has limited applicability under the FCMA because the capacity problem is to determine the amount of fish the fleet can be expected to catch during a given time period. In other words, the physical notion relates to "assess the capacity" but does not provide any guidance on the "extent to which" this capacity will be utilized.

Economic Capacity of a Fishing Fleet

Economic theory contains several different concepts of capacity. These are briefly described as follows:

1) the output that can be produced at minimum average cost in a competitive model (Klein and Preston 1967);
2) the production flow associated with the input of fully utilized manpower, capital, and labor, and other relevant factors of production (Klein 1960);
3) the maximum sustainable level of output the industry can attain within a very short time if the demand for its product were not a constraining factor, when the industry is operating its existing stock of capital at its customary level of intensity (Klein and Summers 1966);
4) the greatest level of output that a plant can achieve within the framework of a realistic work pattern (U.S. Bureau of the Census 1976).

The first concept has generally been used in theoretical discussions about capacity. The other concepts have been applied in the measurement of capacity in the manufacturing sectors of the economy. In addition, there are several concepts pertaining to agricultural capacity, although none of these have gained universal acceptance (Spielmann and Weeks 1975). After reviewing these concepts and taking into account the specific requirements of the FCMA, it is nevertheless possible to develop a concept of capacity applicable to the harvesting sector of the fishing industry.

Harvesting Capacity Under the FCMA

The FCMA requires that estimates be made of U.S. harvesting capacity which are clearly short run in nature. This is due to the fact that, in a particular year, total allowable catch constraints are established, and the problem then is to determine the catch of the U.S. fleet under different economic conditions. In the short run, economic capacity is related to the quantity of fish that can be caught with a fishing vessel in order to maximize profits or other objectives during a specified period of time. The concept of capacity in this context reflects the behavior of the vessel in the short run corresponding to the level of output that can be produced as determined by market conditions, input prices, technology, vessel hold space, and a normal fishing pattern. In effect, economic capacity, other things being equal, moves with price. If prices rise, capacity or output of those vessels already in the fishery will be expected to increase. If prices drop, it will fall.[4]

Conversely, if the catch per unit effort increases, and factor costs and output prices remain unchanged, then capacity rises. The important point to note about the economic concept of capacity is that it is not necessarily the full utilization of the hold space of a fishing vessel. If there are changes in cost conditions, market prices, and stock abundance, then capacity output will also change. Thus, the technical notion of capacity described what can be produced based on the physical characteristics of a fishing vessel and the fleet. This concept, however, does not incorporate constraints on output or the quantity of landings because of economic or environmental factors. In contrast, the economic concept of capacity describes what will be produced given technical relationships, factor prices, and product price information, and it is essentially what is implied in the FCMA regarding the "extent to which the (physical) capacity will be utilized."

The definition of fleet capacity used hereafter in this report is as follows: Capacity is the amount of fish that the fleet is expected to harvest during a specified period with the existing stock of capital (vessels and gear) and technology, given catch quotas, processing capabilities, and market conditions. Clearly, the expected domestic catch is synonymous with the "extent to which" notion contained in the Act, and both of these are synonymous with the notion of short run economic capacity as defined above.

SPECIES ALLOCATION OF CAPACITY USING A LINEAR PROGRAMMING (LP) FRAMEWORK

This section outlines an approach that can be used to estimate short-run capacity (output) in a multispecies fishery.

The LP Problem for a Multispecies Fishing Fleet

A complete generalization of the problem of estimating the "extent" or the expected catch of the fleet is to determine the allocation of resources (over species, vessel category, fleet capacity, fishing area, and time period) that maximizes a stated objective. The following LP model is based on a model formulated by Mueller.[5]

The statement of the objective function and the associated constraints of the model are presented below:

$$\text{Maximize} \quad Z = \sum_{i,j,t} P_{ijt}L_{ijt} - \sum_{i,j,t} C_{ijt}L_{ijt} \qquad (1)$$

$$\text{or} \quad Z = \sum_{i,j,t} L_{ijt}\,(P_{ijt} - C_{ijt})$$

where Z = net revenue received at the harvesting level

L_{ijt} = pounds of species i in area j landed in a directed fishery for that species during period t

P_{ijt} = revenue realized per pound of species i landed in a directed fishery for species i in area j during period t (includes value of bycatch)

C_{ijt} = cost associated with catching a pound of species i (and its associated bycatch) in area j during period t in a directed fishery for species i.

Equation (1) is the objective function to be maximized. It shows the number of pounds of each species that should be caught in a directed U.S. fishery in each area during a particular time period in order to maximize net revenues. These net revenues include the value of the target species and the associated bycatch. In this LP problem formulation, the price per pound landed and cost per pound landed are invariant with the quantity of output.[6] However, these can be allowed to vary.

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[4] This assumes that there is no entry or exit in a fishery during a given fishing season. If prices rise, vessels may shift from other fisheries; but it is not clear whether the shift will occur in the current or following season.

[5] Mueller, J. J. 1976. A linear programming discussion model for maximizing the net revenues from a multiple species fishery. Unpubl. manuscr., 13 p. National Marine Fisheries Service, Federal Building, 14 Elm Street, Gloucester, MA 01930.

[6] An alternative formulation of the objective function could involve substitution of a demand function for a given price in each time period. In addition, instead of the assumption of a constant average cost per pound of fish landed, costs could be allowed to vary with the quantity of fish landed and with the

Total Allowable Catch Constraint

Presumably there will be a year's total allowable catch (TAC) set for each species for each area. However, because of the bycatch problem, if the number of pounds of each species taken in a directed fishery equaled the TAC for each species, then all of the TAC's would be exceeded. To deal with this problem the following constraint is formulated:

$$\sum_{i,t} A_{mijt}\, L_{ijt} \leqslant T_{mj} \tag{2}$$

where A_{mijt} = number of pounds of species m caught per pound of species i in a directed fishery for species i in area j during period t. It is assumed that these A_{mijt} are the same for all vessel categories.

T_{mj} = TAC for species m in area j for all periods.

Processing Capacity

Generally there exists an upper bound on the total amount of species processing capacity available during a particular time period. To reflect this situation the following constraint was formulated:

$$\sum_{i,j} b_{ijt}\, L_{ijt} \leqslant B_t \tag{3}$$

where b_{ijt} = the number of pounds of processing capacity required when a pound of species i is caught in a directed fishery for species i in area j during period t

B_t = the number of pounds of processing capacity available during period t.

Harvesting Capacity

The final restriction used in this model is a physical upper limit on the amount of fish that can be caught by the fleet in a particular time period or season. To address this problem, the following constraint was formulated:

$$\sum_{i} d_{ijt}\, L_{ijt} \leqslant FC_{jt} \tag{4}$$

where d_{ijt} = the number of units of physical harvesting capacity required when a pound of species i is caught in a directed fishery for species i in area j during period t.

FC_{jt} = the total number of pounds of fish that a fleet consisting of a specified number of vessels (given technology and gear) is physically capable of catching in area j during a particular time period t.

AN APPLICATION TO THE NEW ENGLAND OTTER TRAWL FLEET

New England Otter Trawl Fishery

The fishery to be studied is the otter trawl fishery in New England. The output consists of landings by vessels using otter trawls in Maine, Massachusetts, and Rhode Island during the 1955-74 period (Table 1). In the late 1950's landings in this fishery averaged more than 304,000 metric tons (t). However, by 1972 landings had declined sharply to about 126.8 thousand t.

The catch per gross registered ton (CGRT) reached a maximum value of 9.03 t in 1957 (Table 2). The total associated catch in 1957 also peaked at 318.5 thousand t. By 1973 both CGRT and landings sharply declined to 3.45 t and 127.4 thousand t, respectively. This decrease can be generally attributed to a lower stock abundance of target

TABLE 1.—Landings (metric tons) of fish by otter trawl vessels in Maine, Massachusetts, and Rhode Island. (Sources: U.S. Department of Commerce 1971-77, U.S. Fish and Wildlife Service 1957-69.)

Year	Maine	Massachusetts	Rhode Island	Total
1955	51,341	208,495	39,470	299,306
1956	49,920	207,514	53,281	310,715
1957	44,200	224,436	49,827	318,463
1958	49,525	213,007	42,066	304,598
1959	50,769	198,544	40,846	290,159
1960	46,438	179,805	15,417	241,660
1961	46,094	180,201	23,151	249,446
1962	43,473	190,430	26,550	260,453
1963	40,454	184,294	25,837	250,585
1964	42,167	180,006	11,090	233,263
1965	42,788	177,877	15,435	236,100
1966	45,634	162,307	25,361	233,302
1967	41,716	136,194	29,648	207,558
1968	42,709	127,465	27,494	197,668
1969	34,774	105,859	35,644	176,277
1970	31,872	103,152	26,288	161,312
1971	29,154	96,984	24,838	150,976
1972	24,485	79,457	22,954	126,896
1973	22,049	77,309	28,044	127,402
1974	17,766	72,263	27,051	117,080

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fishing area. If these changes were incorporated into the LP model, they would certainly make the problem more realistic. However, the purpose of this was to initially formulate a simple problem and then to develop more complex models in future research. A drawback to this assumption of a given price in each time period is that the quantity landed would be expected to influence price. At the time of this analysis, appropriate demand functions had not been estimated.

TABLE 2.—Estimates of potential output (capacity) based on prices, costs, and stock abundance.

Year	Gross registered tons (GRT)	Catch per gross registered ton (t)	Potential capacity (t) 1957 abundance	Abundance index (Clark and Brown 1977)	Potential capacity (t) adjusted for abundance
1955	37.472	6.93	338,820	1.000	338,820
1956	36.362	8.42	323,335	1.000	323,335
1957	35,269	9.03	318,463	1.000	318,463
1958	35,192	8.66	317,762	1.000	317,762
1959	34,786	8.34	314,099	1.000	314,099
1960	39,280	6.15	354,469	1.000	354,469
1961	36,833	6.77	332,571	1.000	332,571
1962	38,677	6.73	349,226	1.000	349,266
1963	38,839	6.45	350,691	1.000	350,691
1964	39,155	5.96	353,557	1.000	353,557
1965	39,256	6.01	354,503	0.3639	128,984
1966	42,216	5.53	381,212	0.7315	278,848
1967	42,237	4.91	381,316	1.0561	402,787
1968	37,698	5.24	340,217	0.8741	297,548
1969	40.629	4.38	363,456	0.5761	211,353
1970	40,093	4.02	361,734	0.7011	253,818
1971	39,452	3.83	356,071	0.3844	136,936
1972	39,383	3.43	333,933	0.3739	132,957
1973	36,918	3.45	333,512	0.4923	164,116
1974	39.016	3.00	352,283	0.3693	130,098
[1]1975	38,972	3.54	351,901	0.2693	94,767
[1]1976	38,972	3.54	351,901	0.4041	142,203

[1]Based on 1970-74 average.

species in the otter trawl fishery resulting from the entry of foreign effort in these fisheries in the late 1950's and early 1960's.

The LP model formulated in the previous section required data on species, prices, harvesting costs, bycatch ratios, and physical capacity estimates for both the harvesting and processing sectors. Data are generally available for these items except for harvesting costs. In the absence of harvesting cost data, the objective function in the model was specified to only maximize gross revenues. Because of this, the solution variables would probably be overestimates of actual expected catches.

In this report the method of incorporating cost factors is to deflate the peak CGRT by an index of relative species abundance (Clark and Brown 1977). The index of stock abundance is being used to adjust the expected level of catch for changes in cost conditions for the 1955-77 period. Since the level of catch is, among other factors, a function of abundance, any declines in abundance would be expected to result in a lower level of catch (other things being equal). Reductions in abundance, therefore, would be expected to result in declining CGRT and increased costs per unit of output. A more realistic measure of factor productivity would be catch per unit of effort; this information was not available.

Data in Table 2 indicate that GRT has not changed significantly since 1955 for this otter trawl fishery. The assumption was made that the number of days fished per GRT has not changed.[7] The year 1957 was chosen as the base year because CGRT reached a maximum value and stock abundance was probably relatively high. Table 2 also shows an index of stock abundance for the International Commission for the Northwest Atlantic Fisheries (ICNAF) designated subarea 5 and statistical area 6 for finfishes and squids.

In order to develop a measure of expected output relative to 1957, it is noted that catch in subsequent years will vary as a function of fishing effort and stock abundance. If the catchability coefficient relative to GRT can be assumed to be the same, at least as a first approximation for each year, then the catch in any year is:

$$\frac{T_i}{T_0} \times C_0$$

where T_i is the GRT in the ith year, and T_0 and C_0 are, respectively, the GRT and catch for the year 1957.[8] Furthermore, it is assumed that catch would depend on the abundance of the stock and, therefore, the catch in any year should be modified by:

$$A_i/A_0$$

where A_i denotes the abundance in the ith year and A_0 the abundance in the base year (1957).

Thus, an estimate of expected output relative to the base year is:

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[7]Data are not available to verify this assumption.

[8]Using this approach, it is necessary to choose a base year. As a result, physical capacity and economic capacity were identical for 1957.

$$\frac{T_i}{T_0} \times \frac{A_i}{A_0} \times C_0 .$$

An underlying feature of this simple index (A_i/A_0) is that while catches should rise and fall with effort (T_i's), they should also increase and decrease with abundance. Consequently, abundance is a factor influencing output or capacity when the other inputs, except for effort (GRT), are fixed.

Example Problem

An example problem is presented below utilizing the model formulations in the previous section. In this problem it is assumed that there are: 1) 11 species, 2) 1 vessel category (all otter trawlers), 3) 1 time period (1 yr), and 4) 1 area. The objective of the problem is to maximize the gross revenues to the otter trawl fleet assuming the 1977 catch restrictions, the most recent bycatch ratios, and an estimated U.S. deflated harvesting capacity as developed in the previous section.[9]

The species that were used and their associated bycatch ratios are in Table 3. The interpretation of the entries in the table is as follows: when a pound of cod is sought in a directed fishery for cod, 1 lb of cod, 0.059 lb of haddock, 0.012 lb of redfish, etc., are caught.[10] The total pounds caught when seeking to catch a pound of cod in a directed fishery for cod is 1.344.

Table 4 presents the total gross revenue realized for each species when attempting to catch that species in a directed fishery. For example, when attempting to catch a pound of cod in a directed fishery, the total of 1.344 lb of fish actually caught is worth a total of 35.2 cents and includes the value of the cod and the value of the bycatch. Table 5 presents the amount of processing capacity required per pound of each species caught in a directed fishery and includes the bycatch requirement. Cod, haddock, and pollock are the only species of those listed that are landed drawn and a loss of 15% by weight is assumed. A total processing capacity of 500 million pounds (226,796 t) was assumed.

Estimates of Landings Adjusted for Abundance

Estimates of adjusted landings (incorporating cost factors) were made (Table 2) using the ap-

TABLE 4.—Gross revenue per pound in a directed fishery. (Source: U.S. Department of Commerce 1976.)

Species	Total revenue per pound caught in a directed fishery (includes value of bycatch) (¢/lb)
Atlantic cod	35.2
Haddock	52.7
Redfish	16.6
Silver hake	16.2
Red hake	20.3
Pollock	22.6
Yellowtail flounder	46.4
Other flounders	55.6
Other finfish	28.7
Atlantic mackerel	13.3
Squid	10.0

TABLE 3.—United States otter trawl bycatch ratios in 1974 for ICNAF areas. (Source: Northeast Fisheries Center, National Marine Fisheries Service, NOAA, Woods Hole, Mass.)

	Species caught (pounds)											
Species sought	Atlantic cod	Haddock	Redfish	Silver hake	Red hake	Pollock	Yellowtail flounder	Other flounder	Other finfish	Atlantic mackerel	Squid	Total
Atlantic cod	1.0	0.059	0.012	0.002	0	0.07	0.041	0.108	0.052	0	0	1.344
Haddock	0.214	1.00	0.022	0.027	0	0.027	0.038	0.049	0	0	0	1.377
Redfish	0.04	0.011	1.0	0.002	0	0.059	0	0.001	0.046	0	0	1.159
Silver hake	0.051	0.003	0.004	1.0	0.081	0.005	0.061	0.073	0.106	0.009	0.04	1.433
Red hake	0.021	0	0	0.496	1.0	0	0.054	0.082	0.360	0.001	0.098	2.112
Pollock	0.213	0.032	0.035	0.009	0.022	1.0	0.003	0.003	0.073	0.001	0.085	1.476
Yellowtail flounder	0.101	0.015	0	0.001	0	0.003	1.00	0.058	0.004	0	0.004	1.186
Other flounders	0.266	0.036	0	0.054	0.005	0.007	0.296	1.0	0.170	0.002	0.112	1.948
Other finfish	0.313	0.078	0.06	0.152	0.048	0.153	0.07	0.124	1.0	0.019	0.046	2.063
Atlantic mackerel	0.009	0	0	0.024	0	0.012	0	0	0.042	1.0	0.051	1.138
Squid	0	0	0	0	0	0	0	0.001	0.002	0	1.0	1.003

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[9] For the purpose of this problem, gross revenues were used in the objective function since the separable costs of catching these species has not yet been determined. The costs of traveling to and from the fishing grounds should also be included in the objective, but these are not available at present.

[10] The bycatch ratios used in the LP problem were not converted from pounds to metric tons. The basic data for the computations in the LP problem were specified in pounds.

TABLE 5.—Processing requirements per pound of each species in a directed fishery. (Source: National Marine Fisheries Service, Statistics Branch, Gloucester, MA 01930.)

Species	Processing requirement
Atlantic cod	1 1745
Haddock	1.19085
Redfish	1 1425
Silver hake	1.42415
Red hake	2.10885
Pollock	1.2895
Yellowtail flounder	1.1911
Other flounders	1.8935
Other finfish	1.98135
Mackerel	1.3485
Squid	1.003

proach outlined in the previous section.[11] In 1976, for example, the deflated estimate of landings was 142,000 t under current conditions of abundance. Another way of explaining this figure is as follows: if we assume that the relationship between aggregate production prices and aggregate factor costs have been unchanged since 1957, then we would expect that 142,000 t of fish would be landed by the otter trawl fleet (given the current level of abundance). It should be noted that in 1965 and 1971 the actual catch was larger than the estimated potential catch adjusted for abundance. These discrepancies could be due to reasons such as increased fishing intensity or possibly large sampling errors given the stochastic nature of the stocks.

Estimates of undeflated catch are also provided in Table 2. These indicate what could be caught if 1957 productivity conditions prevailed. However, these estimates are not particularly meaningful since they do not reflect changes in stock abundance and cost conditions.

The estimate of 142,000 t for 1976 also could be modified to take into consideration the changes in technology of the fleet. The changes include, among others, the utilization of stern trawlers, pair trawls, improved loran, and increase in horsepower. It is assumed for this example that these changes account for an estimated 5,000 t of additional harvesting capacity under current conditions of abundance. Table 6 shows the simplex tableau for the LP calculations for the base model.

RESULTS

The base model computations are presented in Table 7. Column 2 (Directed catch) shows the catches of each of the species in the directed fisheries. Column 3 (Bycatch) presents the resultant incidental catches of each of the species that are implied by the directed catches in column 2. The total gross revenues that would accrue to the otter trawl fleet by employing this fishing strategy, as predicated on the optimal LP solution, would be $68.5 million. This is the maximum gross revenue that the fleet could obtain given the assumptions of the LP model. In other words, there is no other fishing strategy (allocation of harvesting capacity) that would result in a larger level of gross revenues.

The FCMA requires that foreign fishing be allowed on those stocks for which surpluses have been identified. This LP model can be used to estimate foreign surpluses. Column 4 (Total catch) presents the estimated total U.S. catches of each of the species. Column 5 (Quota) indicates the recommended quotas for 1977. Column 6 (Estimated surplus) shows the resultant surplus or the excess of each species quota over the probable U.S. catch of the particular species as identified by the model.

TABLE 6.—Basic computational form or simplex tableau for LP calculations.

	Decision variables										
[illegible]	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	Constraints
[illegible]	0.214	0.04	0.051	0.021	0 213	0.101	0.266	0.313	0.009	0	55,125,000
[illegible]	1.0	0.011	0.003	0.0	0.032	0.015	0.036	0.078	0	0	13,230,000
[illegible]	0 022	1.0	0.004	0	0.035	0	0	0 060	0	0	19,845,000
[illegible]	0.027	0.002	1 0	0.496	0.009	0.001	0 054	0 152	0.024	0.0	264,600,000
[illegible]	0	0	0.081	1.0	0.022	0	0.005	0.048	0	0	97,020,000
[illegible]	0.027	0.059	0.005	0	1.0	0.003	0.007	0.153	0.012	0	66,150,000
[illegible]	0.038	0	0.061	0.054	0.003	1.0	0.296	0.07	0	0	30,870,000
[illegible]	0.049	0.001	0.073	0 082	0.003	0.058	1.0	0.124	0	0.001	44,100,000
[illegible]	0	0.046	0.106	0.360	0.073	0.004	0.170	1.0	0.042	0.002	269,000,000
	0	0	0 009	0.001	0 001	0	0 002	0.019	1.0	0	165,375,000
	0	0	0 040	0 098	0.085	0.004	0 112	0 046	0.051	1.0	174,195,000
[illegible]	1.377	1.159	1.433	2.112	1 476	1.186	1.948	2.063	1.138	1.003	325,000,000
[illegible]	1.19085	1.1425	1 42415	2 10885	1 2895	1.1687	1 8935	1.98135	1.150	1 003	500,000,000
	0.527	0.166	0.162	0 203	0.226	0.464	0.556	0.287	0.133	0.1004	Objective function

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[11] Data on catch per gross registered ton were not available for 1975-76. The estimates of deflated capacity in 1976 for this example were based on 1973 data on catch per GRT and the 1976 index of abundance (A_t/A_0). It is interesting to note that the 1974 forecast was within 5% of the actual 1974 catch by otter trawls.

TABLE 7.—Results of the base model showing estimated U.S. catches and surpluses in the otter trawl fisheries in ICNAF Areas 5 and 6. Harvesting capacity = 325 million pounds (147,565 t); gross revenues = $68,605,600.

Species	Directed catch	Bycatch	Total catch	Quota	Estimated surplus	Actual surplus
	Millions of pounds					
Atlantic cod	27	28	55	55	—	0
Haddock	8	5	13	13	—	0
Redfish	17	3	20	20	—	0
Silver hake	—	4	4	265	261	188
Red hake	—	2	2	97	95	77
Pollock	62	4	66	66	—	0
Yellowtail flounder	18	13	31	31	—	0
Other flounders	40	4	44	44	—	0
Other finfish	—	16	16	269	253	132
Atlantic mackerel	61		61	165	104	152
Squid	—	13	13	174	161	94
Total	233	92	325	1,199	874	643

The results of the model (Table 7) indicate that all of the cod, haddock, redfish, pollock, yellowtail flounder, and other flounders be allocated for exclusive U.S. exploitation since the sum of the directed catches and the bycatches for these species are equal to the quotas.

The results from the model did identify the existence of surpluses for silver and red hake, Atlantic mackerel, squid, and other finfish. Coincidentally, the species or species groupings for which surpluses were identified in the Preliminary Management Plans (PMP's) for the Fishery Conservation Zone in the northwest Atlantic were for these same species identified by the model. All of the surpluses, except for Atlantic mackerel, are larger than the actual surpluses specified in the PMP's. (These surpluses appear in column 7 of Table 7.) This would be expected since the model only considered the otter trawl fleet capacity in New England and did not include harvesting capacity by other gear types in New England and in the Mid-Atlantic area.

An important implication of the optimal solution for the LP model was the calculation of shadow prices for certain species for which the constraints were binding (i.e., there were zero surpluses).[12] The optimal solution indicates that the quotas for Atlantic cod, haddock, redfish, pollock, yellowtail flounder, and other flounders were harvested. In addition, the entire harvesting capacity was utilized. Therefore, all of these species quotas were binding constraints and the resources had positive shadow prices in the optimal solution. Furthermore, harvesting capacity was also a binding constraint. Shadow prices are shown in Table 8. For the species in excess supply (as evidenced by surpluses) there are no shadow prices. This is to be expected since the corresponding shadow price is zero because the excess supply is of no value to the U.S. fleet if it cannot be harvested and sold.

TABLE 8.—Shadow prices for binding constraints.

Resource	Shadow price ($/lb)
Atlantic cod	0.14
Haddock	0.32
Redfish	0.02
Pollock	0.01
Yellowtail flounder	0.30
Other flounders	0.19
Harvesting capacity	0.12

In this particular problem, the shadow price for cod can be interpreted as follows: if the Atlantic cod quota was increased by 1 lb, the objective function would increase by 14 cents. This 14 cents includes the imputed value of Atlantic cod (shadow price) and the other species caught as bycatches with cod less the value of a pound of lower valued species that the new mix replaces. As can be seen from Table 8, the shadow prices vary since the exvessel prices shown in the simplex tableau (Table 6) are different. In the optimal solution, the shadow price for harvesting capacity is lower than most of the other species in Table 8. This is because if the harvesting capacity was increased by 1 lb, the only species available to harvest are the lower valued species.

Shadow prices play an important role in the development of resource management strategies. For example, a decision to rebuild the stock for a particular species could be based on the shadow price that indicates the greatest return when a constraint is increased by one unit. The LP model in this paper, given the shadow prices from the optimal solution, shows that in the multispecies otter trawl fishery, cod, haddock, and yellowtail

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[12] Shadow prices show the changes in the objective function for a unit change in the constraint (see column RHS in Table 6).

flounders would be likely candidates for rebuilding.

An area of further interest in this model is to determine how sensitive the optimal solution (Table 7) is to changes in the prices, bycatch ratios, and quotas. If the optimal solution is not particularly sensitive to changes in these parameters, this means that it may not be necessary to be overly concerned with very precise estimates of technical parameters. Consequently, the bounds on the technical parameters in the LP model may not result in a large impact on changes in the objective function. A sensitivity analysis was not performed for this LP model, but the implication for future research is that estimates of certain technical parameters may not have to be as precise as researchers believe before there is a significant change in the optimal solution to the LP problem.

SUMMARY

The purpose of this paper was to discuss alternative approaches used to measure capacity, to develop a definition of capacity for the harvesting sector of the commercial fishing industry, and to present a model that could be used to estimate this capacity in a multispecies fishery. We have argued that the concept of capacity contained in the FCMA is identical to short-run economic output. We feel the suggested methodology and the model presented in this paper can be used to address the issue of capacity in a multispecies fishery. The model can be used to examine other scenarios than presented here, by incorporating seasonal quotas, alternative mesh sizes, and stock rebuilding considerations.

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