LINEAR PROGRAMMING SIMULATIONS OF THE EFFECTS OF BYCATCH ON THE MANAGEMENT OF MIXED SPECIES FISHERIES OFF THE NORTHEASTERN COAST OF THE UNITED STATES

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ABSTRACT

We evaluated the results of using historic bycatch (incidental catch) ratios in adjusting fishing regulations by linear programming techniques. We used both 1971 and 1973 bycatch ratios separately to assess the sensitivity of the results to the reported changes in bycatch ratios in estimating the total 1975 catch of countries fishing in the northwest Atlantic. For 4 of the 11 countries for which data were examined, the difference between the percentage of a country's species total allowable catches (i.e., those catches allowed a country by regulation) using the 1971 and 1973 bycatch ratios, was at least 20%. Only four countries were predicted to catch at least 80% of their species total allowable catches. The predicted total catches of all countries and all species was only 60% of the total species quotas. The simulated directed fisheries constituted only 70% of the total catch using 1971 bycatch ratios and only 73% using 1973 bycatch ratios. Examination of the reported 1975 catches indicated that the total allowable catches for herring were most frequently limiting a country's catch. Except for U.S.S.R., the differences between reported and simulated catches were less than 50 metric tons, with the difference less than 10 metric tons for 6 of the 11 countries. There was little difference in reported versus simulated catches between the schemes using the 1971 and 1973 bycatch ratios.

The control of fishing mortality by means of individual species catch quotas is difficult in a mixed fishery, i.e., where a significant proportion of the fishing mortality on a given species is generated as a result of the incidental catch, or bycatch, of that species in fisheries directed toward other species. Moreover, if a country is allowed to catch a specified amount of a given species by means of a directed fishery for that species, the total species catch may exceed that amount because of the associated bycatch of that species in the other fisheries.

The International Commission for the Northwest Atlantic Fisheries (ICNAF) modified its regulatory measures several times in attempts to account for bycatches of species under quota restrictions. The initial haddock quota regulations (Subarea 5 and Division 4X, Figure 1) stated that the directed fishery should cease when the accumulated catch (directed catch plus bycatch) reported to ICNAF biweekly reached 80% of the quota, anticipating that the catch after closure (a bycatch by definition) would be 20% of the quota (ICNAF 1969). When yellowtail flounder was added to the list of species under quota, the closure procedures were changed. The Assessments Subcommittee of ICNAF estimated the expected monthly bycatch after closure of directed fisheries and the decision to cease directed fishing was then made when the accumulated total catch reported to ICNAF on a biweekly basis plus the expected bycatch during the remainder of the year equalled the quota (ICNAF 1970). With the introduction of national quota allocations in 1972, the procedure again changed, requiring each country to control its directed fishery so that the sum of its directed catch and the estimated bycatches would not exceed its quota allocation (ICNAF 1972a).

The bycatch problem was acknowledged by ICNAF in its decision to establish a TAC (total allowable catch, i.e., that catch allowed a country by regulation) for all species combined that was less than the sum of the individual species TAC's for 1974 and 1975 (ICNAF 1974a). Linear programming simulations utilizing bycatch ratios from directed fisheries for all countries combined substantiated this policy (Brown et al. 1973; Anthony and Brennan 1974).

Since 1974, TAC's were set for all species (either singly or in groups) and for national catches (ICNAF 1974a, 1975a). Under this regime, it was possible to utilize linear programming more realistically to investigate the extent to which the

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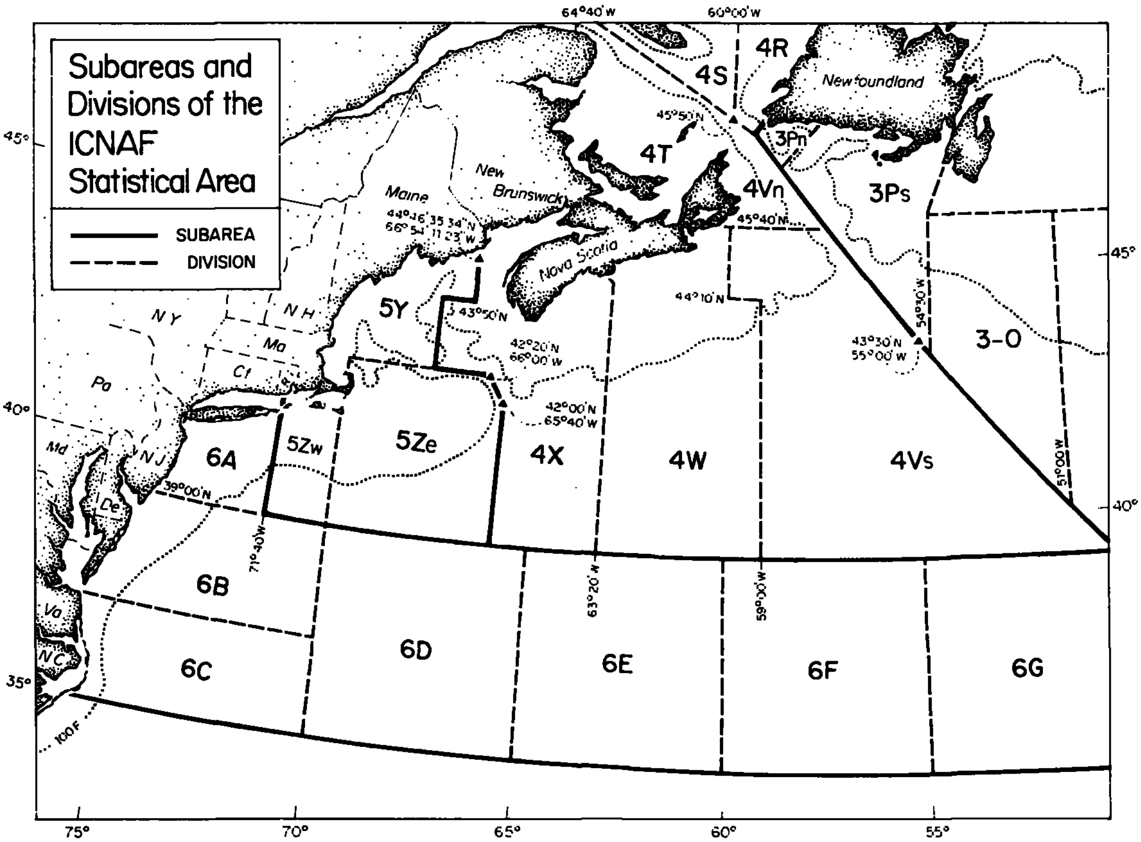

FIGURE 1.—Northwest Atlantic Ocean partitioned into ICNAF areas.

regulations in ICNAF were adequate to account for the bycatch. Simulations of 1975 catches were made utilizing bycatch ratios from both 1971 and 1973 to assess the sensitivity of the technique to differences in historic bycatch ratios. Brennan (1975) found little evidence of a decline in bycatch ratios when examined on a country-gear level over the years 1970-73. We compared the simulated catches and the reported catches on a species basis and on a country basis and examined the results to determine for which countries and species the simulations were successful.

METHODS AND MATERIALS

Data Base

Almost all countries fishing in Subarea 5 and Statistical Area 6 (Figure 1) submitted data on nominal catch (i.e., that reported landed (adjusted to live weight) by the country, not necessarily that actually caught—it is the term used in the ICNAF Statistical Records following standard United Nations Food and Agricultural Organization procedures) and effort for main species (or a species) sought. These data are published each year in tables 4 and 5 in the annual ICNAF Statistical Bulletins. The data of 1971 and 1973 (ICNAF 1972b, 1975b) were the sources of the bycatch ratios. Data of these years were reported according to the species categories given in Table 1. The nominal catches do not include fish caught and discarded at sea.

The nominal catch and effort (days fished) for 1971 and 1973 for finfish were summed over months for each target fish of the fishery (the "main species sought") categories reported in tables 4 and 5 of the ICNAF Statistical Bulletin (1972b and 1975b, respectively). Catches made with fixed gear as well as catches of Atlantic menhaden, Atlantic halibut, and large pelagic fishes, i.e., tunas, billfishes, and sharks (other than dogfishes), were excluded. Most of these were not covered by the regulations and have <1 t (metric ton) per 100 t of directed species caught. In instances where no "main species sought" category was indicated or where landings were attributed to a mixed fishery, the monthly landings by vessel classification and gear were assigned to "species sought" categories according to the species which formed a simple plurality of the catch. The United States of America often reported mixed fisheries on groundfish species. The Union of Soviet Socialist Republics (U.S.S.R.), Poland, Japan, and German Democratic Republic (G.D.R.) typically reported their pelagic and/or squid fishery catches as mixed.

The term "fishery" as used in this paper refers to the vessels and associated catch on these "main species sought" categories. The term "species" refers to both individual species and species groups. All reported landings were thus identified by two factors: species and fisheries. Such tabulations were prepared for all nations for which data were available. For Romania, which has had an Atlantic herring fishery but did not report a directed Atlantic herring fishery in 1973, bycatch ratios for 1972 (ICNAF 1974b) were used for that species fishery. The only countries with an allocated national quota for which 1971 and 1973 data were not available and thus could not be analyzed were Italy (1971 and 1973) and France (1971).

In this paper, all catch restrictions described below will all be referred to as "quotas." To apply linear programming techniques to the bycatch problems restraints on the total catches for each species by country need to be set. For countries and for species categories reported in ICNAF Statistical Bulletins, we used restraints in linear programming (ICNAF 1974a). For countries and/or species for which ICNAF had not set specific quota allocations (but for which the quota was included in, say, "other countries" under ICNAF regulations—a country not given a specific catch quota could fish in competition with other similar countries from an "other country" allocation or "other flounder" category), we estimated these restraints by the following procedures. These were chosen so that the categories of quota allocations matched the species categories (Table 1) by which the catches were reported. We proportioned the "others" allocation category for each individual species to countries based on the 1973 nominal catch for each particular species and the catch of that species of all of the countries that did not have a national quota for the species. We proportioned the quota for "other groundfish" and "other pelagic" from the "other fish" TAC for each country. The quotas for American plaice and witch flounder were subtracted from the "other flounder" TAC for each individual country. Since the quota for pollock was set by ICNAF for Division 4VWX plus Subarea 5, national quota allocations were estimated as an average percent of the nominal pollock catches during 1971, 1972, and 1973 in Subarea 4VW and 5.

TABLE 1.—Species categories as reported to ICNAF, 1971 and 1973.

1971	1973	1973
Atlantic cod	Atlantic cod	Yellowtail flounder
Haddock	Haddock	Other flounder
Redfish	Redfish	Atlantic herring
Atlantic halibut	Silver hake	Atlantic mackerel
Silver hake	Red hake	Other pelagic
Atlantic herring	Pollock	Other groundfish
Other pelagic	American plaice	Other fish
Other groundfish	Witch flounder	Squids
Other fish plus squids		

Analysis Methods

Linear programming is a optimization method for which the effectiveness of an allocation scheme distributed over several variables is measured by the maximum or minimum value of some linear function of those variables, when those variables are subject to linear constraints. The problem considered here was to determine $X = (x_1, x_2, \ldots, x_n)$ such that

$$z = \sum_{i=1}^{n} c_i x_i \tag{1}$$

is maximized, where for each i, c_i was the weighting coefficients of the variable x_i. In the present context,

x_i = catch of species i to be taken in directed fishery for species i,

c_i = catch of species i in all fisheries divided by catch of species i taken in directed fishery for species i ($c_i \geq 1.00$),

n = number of directed fisheries considered, and

z = total catch of all species.

Solutions $(x_1, x_2, \ldots, x_n)$ of Equation (1) were subject to the constraints for each i

$$\sum_{i=1}^{n} \hat{a}_{ij} x_i \leq b_j \tag{2}$$

$$x_i \geq 0 \quad (3)$$

where $\hat{a}_{ij}$ = catch of species j taken in directed fishery for species i/catch of species i in directed fishery for species i

b_j = constraint on total catch of species j, for $j = 1 \ldots m$.

The estimates of $\hat{a}_{ij}$ for each country for 1973 are presented in Appendix Table 1. Analogous tables for the 1971 data are in Brown et al. (1973).

The solution used in this paper was devised by using the Simplex Algorithm (Hadley 1963:132f) which was computed by using a Honeywell[2] computer program LINPRO; a description of this use of linear programming is given in appendix II of Brown et al. (1973). In this analysis the linear constraints were that no country would exceed its national allocation for any species (b_j). The output of the LINPRO program includes the vector X of directed catches of the species along with the resultant total catches of the species and the overall total catch.

RESULTS AND DISCUSSION

The results of each country's simulation are given in Appendix Table 2. In each case the sum of the species quota allocations exceeded the country's maximum possible catch (without violating single species constraints) as determined by the linear programming model. Table 2 lists the ratios of the simulated catches to the TAC's using 1973 and 1971 bycatch ratios. For 4 countries (Bulgaria, Canada, G.D.R., and Japan) of the 11, the percentages derived from 1971 bycatch ratios differed from those derived from 1973 fishing patterns by at least 0.20. More detailed reporting of catches (i.e., by species rather than groups) in 1973 than in 1971 and, therefore, in the analysis contributed to this change. Poland, United States, France, and Federal Republic of Germany (F.R.G.) were the only countries which could have taken >80% of the sum of their species TAC's based on 1971 or 1973 bycatch rates. The United States, however, has a significant discard of fish which is not taken into consideration in this analysis. Of the other countries considered, the effect of unreported discard would be expected to be greatest in the Spanish squid fisheries.

[2]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

TABLE 2.—Comparison of maximum catches from linear programming simulation using 1971 and 1973 bycatch ratios, with sum of species "quotas" for the ICNAF area.

Country	Maximum catch—sum of species quota using: 1973 bycatch ratios	1971 bycatch ratios
Bulgaria	0.64	0.83
Canada	.54	.78
France	.52	—
Federal Republic of Germany	.97	.82
German Democratic Republic	.40	.64
Japan	.57	.17
Poland	.94	.93
Romania	.08	.05
Spain	.72	.72
U.S.S.R.	.25	.35
United States	.90	.93

Closer inspection of Appendix Tables 2 and 3 reveals the species which were the limiting factors in a country's inability to take the sum of its species quotas at present. These are the species which were caught in significant amounts as bycatch and directed catch and for which a species quota was met. The species whose catch was most frequently limiting was herring, when either 1971 or 1973 bycatch ratios was used. The next major species using 1973 ratios were pollock and "other pelagic" and using 1971 ratios were "other fish," "other pelagic," and haddock. Pollock was less limiting when 1971 ratios were used because it was combined with the "other groundfish" category, which had not been limiting.

The sum of the linear programming estimates over countries using 1971 and 1973 data are presented in Tables 3 and 4, respectively. In each case the sum of the expected maximum catches determined by the linear programming runs was only about 60% of the sum of the species quota. The simulated directed fisheries catch levels composed only 70% using 1971 bycatch ratios and 73% of the

TABLE 3.—Sum of individual country's linear programming simulation of 1975 catches in the ICNAF area, maximizing total catch (1,000 t) and using 1971 bycatch ratios. Catches of France assumed to be those using 1973 bycatch ratios.

Species sought	Total allowable catch restraint	Directed catch	Total catch
Atlantic cod	45.00	1.7	18.53
Haddock	6.00	0.0	5.23
Redfish	25.00	6.60	22.20
Silver hake	175.00	43.65	62.68
Flounders	41.00	1.32	36.25
Other groundfish	152.00	64.08	84.49
Atlantic herring	175.00	140.14	176.69
Other pelagic	311.90	189.07	210.48
Other fish plus squids	127.40	26.08	67.25
Total	1,058.30	482.64	683.81

TABLE 4.—Sum of individual country's linear programming simulation of 1975 catches, maximizing total catch (1,000 t), and using 1973 bycatch ratios for the ICNAF area.

Species sought	Total allowable catch restraint	Directed catch	Total catch
Atlantic cod	45.00	16.39	31.48
Haddock	6.00	0.00	5.25
Redfish	25.00	18.24	22.25
Silver hake	175.00	74.69	85.72
Red hake	65.00	11.83	26.51
Pollock	21.30	9.57	20.28
American plaice	2.70	—	1.15
Witch flounder	4.30	—	1.70
Yellowtail flounder	16.00	11.02	15.06
Other flounder	18.00	—	6.54
Other groundfish	65.70	27.38	40.96
Atlantic herring	175.00	107.38	120.01
Atlantic mackerel	285.00	127.51	150.60
Other pelagic	26.90	16.97	26.45
Other fish	56.40	9.33	33.35
Squids	71.00	25.93	40.30
Total	1,058.30	456.24	626.75

total using 1973 bycatch ratios, the rest being taken as bycatch. The highest percentage of TAC's, which were caught in directed fisheries, were for other pelagics (90%), Atlantic herring (79%), other groundfish (76%), and redfish (75%) using 1971 bycatch ratios, and for Atlantic herring (89%), silver hake (87%), Atlantic mackerel (85%), and redfish (82%) using 1973 bycatch ratios.

Referring to the individual country linear programming output tables in the Appendix, it is obvious that under 1971 and 1973 bycatch ratios, national patterns ran the gamut from almost a total mixed fishery by the U.S.S.R., and to a somewhat lesser extent by the G.D.R., to very specific fisheries of the F.R.G. and Poland.

As noted earlier, the species which was most frequently limiting to the total reported 1975 catch was Atlantic herring (6 out of 11 countries), and the countries which had the most limiting species TAC's were United States (5) and U.S.S.R. (4). Except for the catches of U.S.S.R., United States, G.D.R., and Poland, there was little difference in reported total catch minus simulated reported catch, when 1971 and 1973 bycatch ratios were used. Moreover, only for U.S.S.R were these differences > 50,000 t, and for six of the countries the differences were < 10,000 t for both schemes. The species for which the simulated and reported total catches differed most varied by country. Atlantic herring and Atlantic mackerel were the species most frequently differing in simulated vs. reported catches, but Atlantic mackerel and silver hake contributed most in metric tons to the differences. In general, and in view of the findings of Brennan (1975), the differences between schemes using 1971 and 1973 bycatch ratios were minimal, and more likely due to the different grouping of the data.

A summary of the 1975 TAC's, the 1975 reported catches, and the linear program estimates of total catch by country, is presented in Table 5. It is obvious that the overall TAC of 850,000 t for 1975 would not be attained without exceeding certain species TAC's unless bycatch was reduced, according to the simulations. The expected catches of 626,750 t using 1973 bycatch ratios and of 681,050 t using 1971 bycatch ratios are only 74% and 80%, respectively, of the 1975 total TAC. On a country basis, and using the results derived from the 1973 bycatches, it can be seen that the country total TAC's were set for 1975 at approximately appropriate levels for France and Spain (based on

TABLE 5.—Comparison of linear programming estimates of maximum total catch by overall country's total allowable catches (TAC's) in the ICNAF area. Figures in 1,000 t.

Country	1973 nominal catch of species regulated by the total TAC	Sum of species TAC's for 1975	1975 total TAC	Linear programming estimate of total catch: 1973 bycatch ratios	Linear programming estimate of total catch: 1971 bycatch ratios	Actual 1975 nominal catch of species regulated on total TAC
Bulgaria	37.29	34.40	24.65	22.22	28.74	24.69
Canada	16.80	26.32	26.00	14.24	20.51	14.00
France	3.62	5.29	2.95	2.76	2.76	3.36
Federal Republic of Germany	38.28	30.89	24.85	30.05	25.31	25.10
German Democratic Republic	150.85	100.98	82.85	40.52	64.17	82.74
Italy	3.92		4.15	(1)	(1)	4.40
Japan	32.90	45.35	21.25	26.05	7.59	20.84
Poland	190.55	153.94	129.25	144.87	144.37	127.05
Romania	7.14	5.71	3.85	0.46	0.27	1.80
Spain	22.20	20.98	14.80	15.06	15.10	14.65
U.S.S.R.	449.04	366.64	301.80	93.10	127.02	313.78
United States	203.09	262.37	211.60	237.42	245.21	221.04
Total	1,155.68	[2]1,052.87	[3]850.00	626.75	[4]681.05	853.45

[1]No estimate available.
[2]Six thousand metric tons of other species not prorated to other species.
[3]Includes 2,000 t allocated to others.
[4]Due to the absence of bycatch ratios for 1971 data, estimate of France's total catch is derived from the 1973 bycatch ratios.

reported statistics), too low for the F.R.G., Japan, Poland, and United States, and too high for the other countries. In fact, summing the national total TAC's rather than the linear program estimates of country catch, when the former are limiting, to obtain an overall estimated catch, results in an expected total catch of 575,000 t, only 68% of the overall TAC. The analogous expected total catch derived from 1971 bycatch ratios was 627,470 t, only 74% of the overall TAC. Bycatch may be reduced through actions initiated by fishing fleets or by regulations such as the closure to bottom trawling by larger vessels in the southern New England, Middle Atlantic, and Georges Bank areas (ICNAF 1975) for 1975 and by the similar closure on Georges Bank for 1976. The reduction of the overall TAC to 650,000 t in 1976 (ICNAF 1976) and 525,000 t in 1977 (ICNAF 1977) was designed to reduce the bycatch problem.

It should be noted, however, that despite the above potential for change as well as the inadequacies of the reporting to ICNAF, which may combine more than one directed fishery under a mixed category, there were other factors which worked in the opposite direction. The first was the inadequate recording of bycatch noted during international inspections. Some of this was discarded and not reported, and some was apparently utilized but not accurately reported on logbooks. Both the lack of reporting and any underestimates of bycatch can cause the bycatch ratios used in this analysis to be underestimated.

In mixed species fisheries, bycatch must be considered in the allocation of quotas to species and to elements of the fishery (in this example the elements are countries, but under different circumstances they could be otherwise—e.g., ports). Lack of attention to attendant bycatch may result in an unexpected overharvest of selected species or conversely the wastage of large quantities of protein depending on whether or not the directed fishery ceased when a small amount of bycatch had been taken. Linear programming provides a suitable technique for examing this problem. However, to have a refined analysis, accurate statistics as to main species sought and the composition of the bycatch including discards must be available. Lacking these, the inferences as in this paper, are directional. The specific individual estimates can be interpreted for policy decisions only when the user has the understanding of the fishery to qualitatively account for the appropriate reporting inadequacies.

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APPENDIX TABLE 1.—1973 nominal landings by country (ICNAF Subarea 5 and Statistical Area 6), expressed as ratios of bycatch to main species sought within fisheries. See text for explanation.

	Species caught															
Species sought	Atlantic cod	Haddock	Redfish	Silver hake	Red hake	Pollock	American plaice	Witch flounder	Yellowtail flounder	Other flounders	Other groundfish	Atlantic herring	Atlantic mackerel	Other pelagic	Other fish	Squids
BULGARIA																
Herring	0.006	—	0.064	0.060	0.050	—	—	—	0.010	—	—	1.000	0.243	0.049	—	—
Mackerel	0.001	—	—	0.048	0.011	—	—	—	0.003	—	0.007	0.039	1.000	0.007	0.026	0.013
CANADA																
Cod	1.000	0.214	0.009	—	—	0.081	0.003	0.002	0.004	0.011	0.125	—	—	—	—	—
Haddock	0.549	1.000	0.002	—	—	0.126	0.015	0.004	0.001	0.004	0.059	—	—	—	—	—
Other groundfish	1.087	0.700	0.027	—	—	3.472	0.012	0.005	—	0.019	1.000	—	—	—	—	—
Herring	—	—	—	—	—	—	—	—	—	—	—	1.000	0.006	—	—	—
Other pelagic	—	—	—	—	—	—	—	—	—	—	—	—	—	1.000	—	—
FRANCE																
Atlantic herring	—	—	—	—	—	—	—	—	—	—	—	1.000	—	—	—	—
Squids	—	—	—	—	—	—	—	—	—	—	0.023	—	—	—	—	1.000
FEDERAL REPUBLIC OF GERMANY																
Pollock	0.005	—	—	0.027	—	1.000	—	—	—	—	0.065	—	—	—	—	—
Other groundfish	—	—	—	—	—	—	—	—	—	—	1.000	—	0.083	—	—	0.500
Atlantic herring	—	—	—	—	—	—	—	—	—	—	—	1.000	0.010	0.008	0.010	—
Atlantic mackerel	—	—	—	—	—	—	—	—	—	—	—	—	1.000	0.094	—	0.080
Squids	—	—	—	0.001	—	—	—	—	—	—	0.463	—	0.178	0.084	0.005	1.000
GERMAN DEMOCRATIC REPUBLIC																
Pollock	0.004	—	0.002	—	—	1.000	—	—	—	—	—	0.042	0.009	—	—	—
Atlantic herring	0.001	—	0.001	0.003	—	0.001	—	—	—	—	—	1.000	0.008	—	0.211	0.005
Atlantic mackerel	—	—	—	0.001	—	—	—	—	—	—	—	0.031	1.000	0.003	0.010	—
Other fish	0.011	—	—	0.006	—	0.006	—	—	—	—	0.001	0.204	0.225	0.006	1.000	—
JAPAN																
Other groundfish	—	—	—	—	—	—	—	—	—	0.044	1.000	—	—	—	—	0.067
Atlantic herring	—	—	0.015	0.011	—	—	—	—	—	0.001	—	1.000	—	0.057	0.038	0.012
Atlantic mackerel	—	—	—	—	—	0.813	—	—	—	—	—	—	1.000	0.813	0.062	0.875
Other pelagic	—	—	0.015	0.020	—	—	—	—	—	0.003	0.003	0.007	0.017	1.000	0.055	0.334
Other fish	0.005	—	—	0.012	—	—	—	—	—	—	0.002	0.025	—	0.407	1.000	0.447
Squids	—	—	—	0.020	—	—	—	—	—	0.002	0.008	0.001	0.023	0.215	0.071	1.000
POLAND																
Red hake	—	—	—	—	1.000	0.031	—	—	—	—	—	0.047	—	0.172	0.031	—
Pollock	—	—	—	—	—	1.000	—	—	—	—	—	—	—	—	0.250	—
Atlantic herring	0.004	—	—	—	—	—	—	—	—	—	0.012	1.000	0.258	0.034	0.039	0.024
Atlantic mackerel	0.003	—	—	0.001	—	—	—	—	—	—	0.012	0.075	1.000	0.006	0.056	0.027
Other pelagic	—	—	—	—	0.142	0.025	—	—	—	—	0.039	0.025	0.352	1.000	0.167	—
Other fish	—	—	—	0.092	0.167	—	—	—	—	—	0.017	0.033	0.317	0.125	1.000	—
Squids	—	—	—	0.034	—	—	—	—	—	—	0.057	0.080	0.231	0.144	0.197	1.000

APPENDIX TABLE 1.—Continued.

Species sought	Species caught: Atlantic cod	Haddock	Redfish	Silver hake	Red hake	Pollock	American plaice	Witch flounder	Yellowtail flounder	Other flounders	Other groundfish	Atlantic herring	Atlantic mackerel	Other pelagic	Other fish	Squids
ROMANIA																
Herring	—	0.007	0.007	0.020	—	—	—	—	0.016	—	—	1.000	0.223	0.035	—	—
Mackerel	—	—	—	0.008	—	—	—	—	—	—	0.064	0.051	1.000	0.058	0.010	0.026
SPAIN																
Atlantic cod	1.000	0.065	—	—	0.001	0.134	—	—	—	—	0.008	—	—	—	—	—
Squids	—	—	—	—	—	—	—	—	—	—	0.003	—	—	—	—	1.000
U.S.S.R.																
Silver hake	0.005	0.001	0.034	1.000	0.236	0.003	0.001	0.001	0.002	0.004	0.062	0.069	0.303	0.006	0.188	0.073
Red hake	0.020	—	0.019	0.410	1.000	0.009	0.003	0.004	0.007	0.011	0.117	0.118	0.237	0.002	0.107	0.032
Other groundfish	0.494	—	—	0.571	0.101	—	0.002	0.012	0.035	0.058	1.000	0.164	0.148	0.036	0.031	—
Atlantic herring	0.011	—	—	0.187	0.140	—	0.003	0.002	0.004	0.007	0.100	1.000	0.227	0.001	0.110	—
Atlantic mackerel	0.010	0.005	0.017	0.147	0.094	0.017	0.002	0.003	0.001	0.005	0.051	0.301	1.000	0.003	0.082	0.017
Other pelagic	—	—	—	0.092	0.299	—	—	—	—	—	—	—	0.055	1.000	0.061	0.001
Other fish	0.068	0.003	0.010	0.147	0.245	0.126	0.024	0.026	0.006	0.056	0.675	0.099	0.250	0.020	1.000	0.059
UNITED STATES																
Atlantic cod	1.000	0.075	0.013	0.002	—	0.052	0.009	0.004	0.035	0.088	0.056	—	—	—	0.001	—
Haddock	0.343	1.000	0.006	—	—	0.087	—	0.006	0.056	0.045	0.017	—	—	—	—	0.003
Redfish	0.039	0.006	1.000	0.001	—	0.066	0.005	0.007	—	—	0.046	—	—	—	—	0.001
Silver hake	0.054	0.003	0.010	1.000	0.022	0.010	0.007	0.006	0.004	0.016	0.058	0.014	0.002	0.008	0.009	0.025
Red hake	0.023	—	—	0.241	1.000	—	—	—	0.148	0.132	0.357	0.011	0.001	0.096	0.216	0.077
Pollock	0.168	0.054	0.045	0.028	0.008	1.000	0.007	0.021	0.007	0.004	0.130	0.001	—	—	0.001	0.005
Yellowtail flounder	0.091	0.014	0.001	0.001	—	0.001	0.010	0.020	1.000	0.053	0.004	—	—	0.001	—	0.003
Other flounder	0.492	0.074	0.003	0.013	0.003	0.014	0.125	0.230	0.423	1.000	0.072	—	—	0.003	0.005	0.002
Other groundfish	0.344	0.108	0.063	0.197	0.088	0.188	0.019	0.033	0.070	0.148	1.000	0.023	0.003	0.017	0.069	0.041
Atlantic herring	0.001	—	—	—	—	—	—	—	—	—	—	1.000	0.002	0.006	—	—
Atlantic mackerel	—	—	—	0.018	0.014	0.018	—	—	0.004	0.016	0.148	0.059	1.000	0.087	0.024	0.164
Other pelagic	0.003	—	—	0.125	0.003	—	—	—	0.003	0.006	0.030	—	0.064	1.000	0.107	0.189
Other fish	0.010	—	—	—	—	—	—	0.010	—	—	—	—	—	0.160	1.000	—
Squids	—	—	—	0.015	0.002	—	—	—	—	0.091	0.110	—	0.005	0.025	0.005	1.000

APPENDIX TABLE 2.—Linear programming simulation by country in ICNAF Subarea 5 and Statistical Area 6, 1975 catches to maximize total catch (1,000 t). Simulated using 1973 bycatch ratios. Actual directed and total catches are included also.

Species sought	Total allowable catch constraint	Simulated		Actual	
		Directed catch	Total catch	Directed catch	Total catch
BULGARIA					
Atlantic cod	0.07	—	0.03	—	—
Redfish	0.50	—	0.03	—	—
Silver hake	2.00	—	0.92	1.02	1.92
Red hake	5.41	—	0.23	—	0.03
Yellowtail flounder	0.14	—	0.06	—	<0.01
Other groundfish	0.65	—	0.13	—	0.34
Atlantic herring	1.20	0.47	1.20	—	0.42
Atlantic mackerel	18.75	18.64	18.75	18.47	18.75
Other pelagic	0.75	—	0.15	—	0.39
Other fish	2.60	—	0.48	—	2.63
Squids	1.70	—	0.24	—	0.21
Total	34.40		22.22		24.70
CANADA					
Atlantic cod	4.82	0.55	1.31	1.10	1.93
Haddock	1.20	—	0.60	0.44	1.44
Redfish	0.50	—	0.02	0.01	0.06
Pollock	2.46	—	2.46	4.13	4.74
American plaice	<0.01	—	<0.01	—	0.02
Witch flounder	<0.01	—	<0.01	—	0.01
Yellowtail flounder	0.02	—	<0.01	—	0.01
Other flounder	0.03	—	0.02	—	0.05
Other groundfish	0.78	0.70	0.76	0.30	0.66
Atlantic herring	9.00	9.00	9.00	5.08	5.08
Atlantic mackerel	7.50	—	0.06	—	<0.01
Other pelagic	0.01	0.01	0.01	—	—
Total	26.32		14.24		14.00
FRANCE					
Other groundfish	0.02	—	0.02	—	—
Atlantic herring	1.87	1.87	1.87	3.34	3.34
Squids	3.40	0.87	0.87	—	—
Total	5.29		2.76		3.34
FEDERAL REPUBLIC OF GERMANY					
Atlantic cod	0.09	—	0.01	—	0.02
Silver hake	0.50	—	0.04	—	0.04
Pollock	1.60	1.60	1.60	0.10	0.15
Other groundfish	0.90	0.48	0.90	—	0.02
Atlantic herring	24.50	24.50	24.50	22.99	23.01
Atlantic mackerel	1.40	0.99	1.40	0.08	0.47
Other pelagic	0.51	—	0.35	—	1.46
Other fish	0.39	—	0.25	—	—
Squids	1.00	0.68	1.00	—	0.03
Total	30.89		30.05		25.20
GERMAN DEMOCRATIC REPUBLIC					
Atlantic cod	1.30	—	0.03	—	0.03
Redfish	0.63	—	0.02	—	0.01
Silver hake	3.10	—	0.06	—	0.04
Pollock	3.50	3.49	3.50	<0.01	0.10
Other groundfish	<0.01	—	—	—	0.07
Atlantic herring	31.90	13.00	13.75	27.00	30.90
Atlantic mackerel	56.25	20.00	20.14	47.95	48.34
Other pelagic	0.06	—	0.06	—	0.06
Other fish	2.94	—	2.90	0.12	2.18
Squids	1.30	—	0.06	—	0.90
Total	100.98		40.52		82.63
JAPAN					
Atlantic cod	0.05	—	—	—	—
Redfish	0.50	—	0.12	—	0.02
Silver hake	7.30	—	0.35	—	<0.01
Red hake	0.03	—	—	—	<0.01
Pollock	0.25	—	0.25	—	—
Other flounder	0.06	—	0.04	—	—
Other groundfish	0.10	—	0.10	0.33	1.13
Atlantic herring	1.16	1.09	1.16	1.88	1.88
Atlantic mackerel	0.80	0.31	0.65	0.08	0.20
Other pelagic	9.30	6.71	9.30	2.65	3.62
Other fish	1.50	0.37	1.50	—	—
Squids	24.30	9.89	12.58	13.25	13.99
Total	45.35		26.05		20.84
POLAND					
Atlantic cod	0.49	—	0.37	—	0.48
Redfish	0.40	—	—	—	<0.01
Silver hake	5.30	—	0.13	0.24	0.38
Red hake	2.20	2.12	2.20	—	—
Pollock	0.35	0.28	0.35	—	0.02
Other groundfish	1.40	—	1.40	—	1.11
Atlantic herring	38.40	32.14	38.40	33.05	38.46
Atlantic mackerel	90.00	81.45	90.00	68.45	74.28
Other pelagic	2.20	0.15	2.20	0.17	3.77
Other fish	6.40	0.34	6.40	—	1.71
Squids	6.80	0.45	3.42	3.25	6.84
Total	153.94		144.87		127.05
ROMANIA					
Haddock	0.01	—	<0.01	—	—
Redfish	0.34	—	<0.01	—	0.01
Silver hake	0.50	—	<0.01	—	0.12
Yellowtail flounder	0.01	—	<0.01	—	—
Other groundfish	0.15	—	0.01	—	<0.01
Atlantic herring	0.20	0.20	0.20	1.54	1.54
Atlantic mackerel	3.75	0.05	0.10	—	0.07
Other pelagic	0.13	—	0.13	—	—
Other fish	0.02	—	0.02	—	—
Squids	0.60	—	<0.01	—	0.05
Total	5.71		0.46		1.79
SPAIN					
Atlantic cod	7.09	1.49	1.49	4.07	4.07
Haddock	0.30	—	0.10	—	0.07
Red hake	0.07	—	<0.01	—	0.01
Pollock	0.42	—	0.42	—	0.10
Other groundfish	0.10	—	0.05	—	0.42
Squids	13.00	13.00	13.00	9.90	9.90
Total	20.98		15.06		14.57
U.S.S.R.					
Atlantic cod	2.50	—	0.24	—	2.43
Haddock	0.05	—	0.05	—	0.01
Redfish	1.44	—	1.44	—	1.37
Silver hake	113.30	40.20	41.22	71.38	88.88
Red hake	44.40	—	11.18	4.50	26.12
Pollock	1.26	—	0.20	—	0.19
American plaice	0.20	—	0.05	—	0.18
Witch flounder	0.20	—	0.05	—	0.20
Yellowtail flounder	0.84	—	—	—	0.08
Other flounder	0.60	—	0.20	—	0.56
Other groundfish	16.70	—	2.79	—	2.86
Atlantic herring	42.10	1.91	5.28	37.08	40.95
Atlantic mackerel	101.25	1.96	14.80	99.91	106.31
Other pelagic	4.40	4.15	4.40	—	0.68
Other fish	28.90	—	8.20	5.99	34.08
Squids	8.50	—	3.00	3.53	8.94
Total	366.64		93.10		313.84
UNITED STATES					
Atlantic cod	28.00	14.35	28.00	12.46	23.41
Haddock	4.50	—	4.50	0.86	5.09
Redfish	20.62	18.24	20.62	7.07	8.96
Silver hake	43.00	34.49	43.00	17.79	20.59
Red hake	12.90	9.71	12.90	0.11	2.43
Pollock	11.50	4.19	11.50	3.80	8.06
American plaice	2.50	—	1.10	0.26	2.19
Witch flounder	4.10	—	1.65	0.36	2.03
Yellowtail flounder	15.00	11.02	15.00	14.99	19.32
Other flounder	17.30	—	6.28	11.81	19.39
Other groundfish	44.88	26.20	34.80	10.34	19.11
Atlantic herring	24.65	23.20	24.65	35.76	36.09
Atlantic mackerel	4.70	4.11	4.70	0.54	1.65
Other pelagic	9.52	5.95	9.52	19.61	23.40
Other fish	13.60	8.62	13.60	17.02	27.65
Squids	5.60	1.04	5.60	0.21	1.67
Total	262.37		237.42		221.04

APPENDIX TABLE 3.—Linear programming simulation by country in ICNAF Subarea 5 and Statistical Area 6 of catches to maximize total catch (1,000 t). Simulated using 1971 bycatch ratios. Actual directed and total catches are included also.

Species sought	Total allowable catch constraint	Simulated		Actual	
		Directed catch	Total catch	Directed catch	Total catch
BULGARIA					
Atlantic cod	0.70	—	0.01	—	—
Haddock	0.01	—	0.01	—	—
Redfish	0.50	—	—	—	—
Silver hake	2.00	0.88	1.82	1.02	1.92
Flounders	0.14	—	0.14	—	<0.01
Other groundfish	6.06	0.78	1.76	—	0.37
Atlantic herring	1.20	—	1.20	—	0.42
Other pelagic	19.50	18.39	19.50	18.47	19.15
Other fish + squids	4.30	—	4.30	—	2.84
Total	34.41		28.74		24.70
CANADA					
Atlantic cod	4.82	—	0.75	1.10	1.93
Haddock	1.20	—	0.37	0.44	1.44
Redfish	0.50	—	0.05	0.01	0.06
Flounders	0.05	—	0.05	—	0.09
Other groundfish	3.24	2.78	2.78	4.43	5.40
Atlantic herring	9.00	9.00	9.00	5.08	5.08
Other pelagic	7.51	7.51	7.51	—	<0.01
Total	26.32		20.51		14.00
FEDERAL REPUBLIC OF GERMANY					
Atlantic cod	0.09	—	—	—	0.02
Silver hake	0.50	—	—	—	0.04
Other groundfish	2.50	—	0.27	0.10	0.17
Atlantic herring	24.50	24.50	24.50	22.99	23.01
Other pelagic	1.91	—	0.54	0.08	1.93
Other fish + squids	1.39	—	—	—	0.03
Total	30.89		25.31		25.20
GERMAN DEMOCRATIC REPUBLIC					
Atlantic cod	1.30	—	—	—	0.03
Redfish	0.63	—	—	—	0.01
Silver hake	3.10	—	—	—	0.04
Other groundfish	3.50	0.54	3.50	<0.01	0.17
Atlantic herring	31.90	30.63	31.90	27.00	30.90
Other pelagic	56.31	20.23	24.53	47.95	48.40
Other fish + squid	4.24	—	4.24	0.12	3.08
Total	100.98		64.17		82.63
JAPAN					
Atlantic cod	0.05	—	0.01	—	—
Redfish	0.50	—	0.01	0.12	0.02
Silver hake	7.30	—	0.03	0.35	0.01
Flounders	0.06	—	0.01	0.04	—
Other groundfish	0.38	—	0.38	0.35	1.13
Atlantic herring	1.16	1.15	1.16	1.88	1.88
Other pelagic	10.10	4.49	4.50	2.73	3.82
Other fish + squids	25.80	—	1.51	13.24	13.99
Total	45.35		7.59		20.84
POLAND					
Atlantic cod	0.49	—	0.14	—	0.48
Redfish	0.40	—	0.09	—	<0.01
Silver hake	5.30	—	0.09	0.24	0.38
Other groundfish	3.95	—	0.25	—	1.13
Atlantic herring	38.40	26.01	38.40	33.05	38.46
Other pelagic	92.20	85.90	92.20	68.62	78.05
Other fish + squids	13.20	1.48	13.20	3.25	8.55
Total	153.94		144.37		127.05
ROMANIA					
Haddock	0.01	—	<0.01	—	—
Redfish	0.34	—	—	—	0.01
Silver hake	0.50	—	0.01	—	0.12
Flounders	0.01	—	0.01	—	—
Other groundfish	0.15	—	<0.01	—	<0.01
Atlantic herring	0.20	—	0.04	1.54	1.54
Other pelagic	3.88	0.14	0.15	—	0.07
Other fish + squids	0.62	—	0.06	—	0.05
Total	5.71		0.27		1.79
SPAIN					
Atlantic cod	7.09	1.71	1.71	4.07	4.07
Haddock	0.30	—	0.30	—	0.07
Redfish	0.07	—	—	—	—
Other groundfish	0.52	—	0.09	—	0.53
Other fish + squids	13.00	13.00	13.00	9.90	9.90
Total	20.98		15.10		14.57
U.S.S.R.					
Atlantic cod	2.50	—	0.38	—	2.43
Haddock	0.05	—	0.05	—	0.01
Redfish	1.44	—	1.44	—	1.37
Silver hake	113.30	10.00	17.73	71.38	88.88
Flounders	1.84	—	1.84	—	1.02
Other groundfish	62.36	0.14	6.14	4.50	29.17
Atlantic herring	42.10	34.46	42.10	37.08	40.95
Other pelagic	105.65	39.85	47.33	99.91	106.99
Other fish + squids	37.40	—	10.01	9.52	43.02
Total	366.64		127.02		313.84
UNITED STATES					
Atlantic cod	28.00	—	15.54	12.46	23.41
Haddock	4.50	—	4.50	0.86	5.09
Redfish	20.62	16.59	20.62	7.07	8.96
Silver hake	43.00	32.77	43.00	17.79	20.59
Flounder	38.90	1.32	34.20	27.42	42.93
Other groundfish	69.28	59.84	69.28	14.25	29.60
Atlantic herring	24.65	10.65	24.65	35.76	36.09
Other pelagic	14.22	12.56	14.22	20.15	25.05
Other fish + squids	19.20	9.86	19.20	17.23	29.32
Total	262.37		245.21		221.04