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Factors Influencing By-Catch and Discard Rates: Analyses From Multispecies/Multifishery Sea Sampling

by

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Abstract

Factors associated with the species composition and magnitude of bycatch and discarding were evaluated, based on multifishery sea sampling data. Data used were from the mixed species otter trawl fisheries of the Georges Bank-Southern New England sampled during 1989-1992. A total of 4,533 otter trawl tows were sampled. General linear models of main effects related discard rates, total catch and indices of species richness, diversity and evenness to temporal, spatial and operational variables associated with the fishing process (year, month, statistical area, primary species sought, cod-end mesh size, vessel size, tow duration, total catch, total discards, depth). Discarding rates (proportion of the catch discarded) varied significantly both for individual species and for aggregate species by year, area, month, and target species. The effects of cod-end mesh size were variable, and confounded with year class strength, particularly in the case of yellowtail flounder. Flounder fisheries generally exhibited higher overall discard rates than fisheries directed to small pelagics. The species composition and diversity of catches was a significant function of categorical variables as well as mesh size and tow duration.

Gear Selectivity/Technical Interactions Symposium

Introduction

Bycatch and discarding are fast becoming critical fishery management issues worldwide (Schoning et al. 1992). Emphasis on these issues stems from the increasing recognition of the economic and ecological implications of wasteful harvesting practices (Murawski 1993). Contemporary fishery science has come to recognize the complexity of interactions among resources and their fisheries that determine mixed fisheries (Murawski 1991), and it is this complexity that belies easy solutions to the bycatch problem. Management of mixed species fisheries is, by necessity, a compromise among regulatory strategies optimal for individual species and métiers comprising a multifishery system. Often these compromises involve selecting regulated gear types or mesh sizes that result in optimal size at entry for some species, and sub-optimal-sized catches for others. The selection of gear mesh size appropriate for individual métiers is usually based in part on gear selection experiments, directed at evaluating the relationship between mesh size and percent retention at length of one or more important constituent species.

Gear selection experiments are usually directed to individual target species of interest and are conducted under an experimental design that attempts to fix or at least randomize all factors except the control variable of interest. Thus, for example, mesh size alternatives are tested one at a time for their effects on the size composition of the target species of interest. Where species catches are highly mixed, the results of mesh selection studies can be ambiguous, manifested as wide confidence limits around estimates of lengths at retention by the gear. Mesh retention studies can yield useful insights into the nature of the selection process, particularly for individual species of interest. However, because of the interactions among the various species caught, and fishing practices, the relations between mesh size, discarding and bycatch are complex and confounded.

In this paper I present multivariate analyses of mixed fishery sea sampling data. The intent of these studies is to relate aspects of bycatch and discarding to spatial, temporal and operational characteristics of the fishing process. Data used for the study were derived from a directed sea sampling program initiated by the Northeast Fisheries Science Center in 1989 (Anderson 1992). The program has covered a wide variety of otter trawl, gill net and dredge fisheries. Given the wide variety of mesh sizes, target species, years, and variations in species abundance, analyses of these data may yield useful insights into the interactions among factors influencing bycatch and discarding and serve as an important compliment to and aid in designing directed gear retention experiments and in developing regulatory schemes to reduce the magnitude of discarding.

Approach and Data

Exploratory analyses of the factors influencing bycatch and discarding were undertaken using the sea sampling database of the Northeast Fisheries Science Center. These analyses were restricted to the otter trawl fisheries of the Georges Bank and Southern New England regions (Statistical reporting areas 521-613, inclusive; Figure 1). Although a wider variety of gears and areas are covered by the sea sampling program, this subset was chosen for illustration purposes, and critical discarding problems have been identified for these fisheries (Murawski 1993).

Data collection and archival for the sea sampling program are described in Anderson (1992). Briefly, scientific observers determine the species composition, amount and disposition (kept or discarded) of all species or species groups caught on a tow-by-tow basis. Length frequency and other biological sampling occurs, and the sampler determines location and gear variables. At the beginning of the trip, the captain is asked to identify the primary species (or group) sought. A large number of vessel and gear variables are also evaluated (Anderson 1992).

The subset of variables describing attributes of each trawl tow and the resulting catch used in statistical analyses is described in Table 1. The designations of primary species sought contained in the analyzed subset are given in Table 2. The species catch for each tow was aggregated into 6 species groupings: (1) yellowtail flounder, (2) winter flounder, (3) skates, (4) other groundfish species, (5) other species, and (6) all species combined. The kept and discarded portions were evaluated separately for each of the six species groups. These groupings were made so as to illustrate both single- and multispecies responses, and to evaluate the aggregate responses of broad species groups of economic or ecological importance.

A total of 4,533 vessel tows was contained in the sub-set of information. These tows were disproportionate over the years, areas, months and primary species sought. Apart from the species groupings made from the tow catches, a number of descriptive variables were computed describing the degree of mixture of the tow-by-tow catches:

Indices of Species Richness, Diversity and Evenness

An important question in designing mitigation measures for bycatch and discard is the extent to which various operating characteristics may influence the catch of non-target species. By limiting directed fishing to times, places etc. where resources are segregated, then the quantity of unintended catch could be reduced. Murawski (1991) noted that factors such as tow duration may act to integrate patchy distributions of more-or-less segregated resources into what appear to be mixtures of species. Thus, the implication is that shorter tow times may result in less diverse catches, and perhaps a higher proportion of target species. In order to evaluate the factors associated with the degree of species co-occurrence, a series of statistics evaluating the species richness, diversity and evenness (Ludwig and Reynolds 1988) were calculated from individual catch data on a tow-by-tow basis:

Richness:

$N0 = S$ (number of species)

A number of other richness indices are available, but have been developed for species numbers rather than weight indices.

Diversity:

A wide variety of diversity indices are available; each variant is sensitive to different aspects of the catch:

N1 = exp(H') where H' is Shannon's diversity index:

$$H' = -\sum_{i=1}^{S} (p_i \ln p_i)$$ [p_i is the proportion of species i in the sample]

H' ranges from 0 if there is only one species in the sample , and is maximum when all S species are equally represented. N1 gives the number of species that would, if each were equally common, produce the same H' as the sample.

N2 = 1/λ where λ is Simpson's diversity index:

$$\lambda = \sum_{i=1}^{S} p_i^2$$ [p_i is the proportion of species i in the sample]

Simpson's diversity index (varying from 0 to 1) is the probability that two individuals drawn at random belong to the same species. Diversity is low if the index is high. The inverse (1/λ) is commonly used since lower numbers imply lower diversity.

Evenness:

Evenness indices measure the extent to which species catch is distributed over the species present in the sample. If all species are equally abundant, evenness is maximum.

E1 = H'/ln(S)

E2 = exp(H')/S

E3 = exp(H')-1/S-1

Indices E1-E3 are sensitive to the number of species in the sample. Indices E4 and E5 (below) are effectively independent of sample size and the numbers of species:

E4 = 1/λ÷exp(H')

E5 = (1/λ)-1÷exp(H')-1

E4 can be thought of as the ratio of very abundant to abundant species and tends towards 1 as one species becomes dominant, whereas E5 approaches 0 as a single species becomes dominant, thus E5 is a preferred measure (Ludwig and Reynolds 1988). The above indices were evaluated as linear functions of the categorical and continuous independent variables describing location, time and fishing operations.

General Linear Models

A series of general linear models (GLMs) were fitted using the dependent and independent variables described in Table 1. These GLMs used a combination of categorical and continuous variables. In all cases only main effects were tested, although it is known that significant interaction effects occur. The choice to test only main effects was due to the wide range of exploratory analyses undertaken. In some cases, additional analyses of interaction effects were performed, when specific questions of interpretation of model results arose. All models were fitted using SAS proc GLM. Type II-IV sums of squares were used in hypothesis testing, owing to the unbalanced nature of the data. For main effects modeling with all cells filled, types I-IV SS are identical.

Results for a number of the GLMs performed are summarized in Table 3. For each model fitted, the following data are given: (1) total R^2 from the model fit (in all cases the models were significant, owing to the very large sample sizes), (2) significance and F-values associated with the categorical independent variables, and (3) significance and estimated model coefficients associated with continuous independent variables. The F-statistics for significant main effects were used to compare in a relative way the importance of various factors to the dependent variables tested. Likewise, for categorical variables, estimates of relative model coefficients for each level (i.e., year, month, area, etc.) were determined. It should be noted that only a small portion of the potential variety of models that could have been estimated from the data are summarized herein, but the examples presented represent several of the key hypotheses.

Results and Discussion

Results of GLMs and their interpretations are summarized in Table 3 and Figures 2-9. For each GLM fit, the overall model and all categorical independent variables (year, month, area, primary species sought) were statistically significant. This was due to the very large sample sizes, and the wide contrasts among the various levels of the categorical variables. The model fits explained between 7 and 48% of the tow-by-tow variation in the dependent variables. Given the large variation inherent in tow-by-tow data, the overall amount of variation explained by some models was surprising.

Model fits 1-3 evaluated the effects of independent variables on discard rates of yellowtail flounder, winter flounder, and all species taken. A significant portion of the sea sampling program has been devoted to evaluating yellowatil flounder discarding over the four years. A total of 1,948 sea sampled tows contained yellowtail catch data. The overall discard rate was 27%, but the rate varied significantly by year (Figure 2). The decline in yellowtail discarding over the four years was due to the recruitment of a strong 1987 year class, followed by very weak cohorts. For yellowtail discard rate, the Year effect was dominant, followed by area and month (Figure 3). Surprisingly, the effect of mesh was non-significant in the main effects GLM. The mesh sizes contained in the samples ranged from 4.1 to 6.1 inches (4.5, 4.7, 4.8, 5.0, 5.5, 5.6, 5.7, 5.8, 6.0, and 6.1 inches). The lack of significant mesh size effects in the initial model was no doubt due to the interaction among year and mesh. Since a strong cohort was moving through the fishery, large amounts of discard occurred in the early years, with all mesh sizes (Figure 4). A second GLM incorporating year and mesh main effects and a Year*Mesh interaction indicated a significant Year*Mesh effect (Figure 3).

The effects of cod-end mesh size on discard rates are illustrated in Figures 4 and 5. The mesh effect for yellowtail was non-significant at the 5% level ($P>0.06$), but is nevertheless illustrated. The all-species discard rate was significantly negatively related to cod-end mesh size (Table 3). These data indicate a general negative effect on discard rates as the cod-end mesh is increased from 4.5 to 6.1 inches. It should be noted, however, that cod end mesh sizes were not measured on sea sampled tows, and in some cases liners were used, which are not accounted for in these summaries. Nevertheless, the overall pattern is clear.

Results summarized in Figure 6 are the estimated coefficients relating all species discard rate to the principal species sought. Several patterns emerge. In all cases, flatfish fisheries produce proportionally greater discards, and fisheries for slender bodied groundfish (e.g., silver hake) and pelagics produce relatively lower discard rates. The differences are thought to be due to the fact that otter trawl fisheries for pelagics and silver hake produce lower species mixtures, and higher quantities of target species, than do the flatfish fisheries. The directed skate fishery also produces relatively low discard rates. In general, however, skates are discarded in quantity in most trawl fisheries: the overall discard rate for skates was 89%. The main factors influencing the all species discard rate were year, primary species sought, mesh size, and tow duration. The effect of tow duration was negative (longer tows resulting in lower discard rates), which is probably an artefact of interactions with other main effects.

The main factors associated with the total catch (landings + discards) were primary species sought, and the gross registered tonnage of the vessel. Other factors were minor, including tow duration.

Variation in species diversity was primarily related to tow duration (Figure 8). The effect was positive. In general, the effects of mesh size were significant and negative, implying that larger mesh sizes resulted in lower species diversity. Although categorical effects were significant in determining species richness, diversity and evenness, there effects were modest, and overall amounts of variance explained in these model fits was much lower than for discard rates. In general tow duration was positively related to evenness (Table 8; Figure 9), and shallower depths produce more even distributions of catches over the species.

These exploratory models identify some potentially important relationships among fishing practices and the seasonal, annual and temporal patterns in the availability of species. The significant effects of year class size (aliased as a year effect) on discard rate are well documented (Anonymous 1985; Reeves 1990). The effects of mesh size, minimum size and discard rate are generally appreciated, but the effect of mesh size on multispecies discard rates has not been heretofore evaluated. The effects of mesh size and tow duration on discard rates and species diversity/richness may have some utility in designing strategies to reduce overall bycatch and discarding. One tendency resulting from lower overall groundfish and flounder catch rates off the Northeast USA has been an increase in overall tow duration. If tow duration is indeed positively related to diversity, then bycatch levels for the fleet will increase with lower catch rates. This is generally consistent with the anecdotal observation of less single species targeting in the otter trawl fisheries, and more effort being directed to 'target mixtures'. The relationship between tow time and overall discard rate was clearly positive for yellowtail flounder, but negative for all species catches. Clearly, the confounding influences of other main effects in the GLM models need to be evaluated in more detail. The strong area and month effects in all models imply that season/area effects could potentially be exploited in an overall strategy to reduce discard/bycatch.

These preliminary analyses have significant implications for the design of future mesh retention studies. Given the association of catch levels, discard rates and operational characteristics (such as tow time and mesh size), the interactions of these factors may negate the benefits expected from a mesh change. Future mesh studies should account for variations among operational characteristics (e.g., tow time) and variations in the biological community being fished in a factorial experimental design, and the analysis of mesh retention should be considered in a multivariate framework.

References

Anderson, J. 1992. Sea sample database system (SSDBS) users manual. National Marine Fisheries Service, Northeast Fisheries Science Center, Woods Hole, Massachusetts 02543 (unpublished mimeo).

Anonymous. 1985. Report of the working group on methods of fish stock assessments, 20-26 November, 1985, Copenhagen. ICES C.M. 1985/Assess:10.

Ludwig, J.A. and J.F. Reynolds. 1988. Statistical ecology, a primer on methods and computing. John Wiley & Sons. New York. 337 pp.

Murawski, S.A. 1991. Can we manage our multispecies fisheries? Fisheries (Bethesda) 16(5):5-13.

Murawski, S.A. 1993. Opportunities in bycatch mitigation. In: R. Stroud (ed). Conserving U.S. Fisheries: A national symposium on the Magnuson Act. (in press).

Reeves, S.A. 1990. Linear modeling of discard data from Scottish demersal fisheries. ICES C.M. 1990/G:53. (mimeo).

Schoning, R.W., R.W. Jacobsen, D.L. Alverson, T.H. Gentle and J. Auyong (eds.). 1992. Proceedings of the National Industry Bycatch Workshop, February 4-6, 1992, Newport, Oregon (available from Natural Resources Consultants, 4055 21st W., Seattle, WA 98199).

Table 1. Summary of variables utilized in computing general linear models of factors influencing discard and bycatch, based on sea sampled otter trawl fishing trips in the Georges Bank, Southern New England area, 1989-1992. Total number of trawl tows summarized is 4,533.

Variable	Description	Comments
Year	Year trawl tow was sampled	89, 90, 91, 92
Month	Month trawl tow was sampled	
Tons	Gross Registered Tonnage of Vessel	
Mesh	Cod-end mesh size of trawl	not measured
Dur	Tow duration in tenths of hours	
Area	3-digit statistical area	Figure 1
Lat	Latitude (DDMM) of tow	
Lon	Longitude (DDMM) of tow	
Prime	Primary species sought by trip	Table 2
Dep	Depth of tow (average)	
Totc	Total catch of all species	in pounds
Totd	Total discards of all species	in pounds
Totl	Total landings of all species	in pounds
Ytd	Total yellowtail flounder discards	in pounds
Ytl	Total yellowtail flounder landings	in pounds
Wfd	Total winter flounder discards	in pounds
Wfl	Total winter flounder landings	in pounds
Skd	Total skate discards	in pounds
Skl	Total skate landings	in pounds
Ogfd	Total other groundfish[1] discards	in pounds
Ogfl	Total other groundfish[1] landings	in pounds
Osd	Total other species[2] discards	in pounds
Osl	Total other species[2] landings	in pounds

Additionally, the following statistics were computed for each tow:

N0	Total number of species caught
Simp	Simpson's diversity index (λ)
H'	Shannon's diversity index
N1	exp(H')
N2	$1/\lambda$
E1	Eveness index : H'/ln(N0)
E2	Eveness index : N1/N0
E3	Eveness index : N1-1/N0-1
E4	Eveness index : N2/N1
E5	Eveness index : N2-1/N1-1

[1] Other groundfish species are cod, haddock, pollock, summer flounder, American plaice, witch, Acadian redfish and windowpane

[2] Other species include everything not explicitly mentioned above

Table 2. Designations of primary species sought (Prime) in vessel captain's interviews aboard sea sampling trips in the Georges Bank-Southern New England otter trawl fisheries, 1989-1992.

Species/Group Sought	Coded value
Atlantic cod	01
Haddock	02
Silver hake	04
Pollock	06
Witch flounder	11
Yellowtail flounder	12
Winter flounder	14
Summer flounder	15
Flatfishes (not specified)	19
Groundfish (not specified)	29
Atlantic mackerel	31
Butterfish	32
Tuna	42
Pelagic fish (not specified)	49
Skates	54
Finfishes (not specified)	59
American Lobster	70
Squid	81
Species not identified	99

Table 3. Description of general linear models relating aspects of discarding and bycatch (dependent variables) in the Georges Bank-Southern New England otter trawl fisheries to categorical and continuous independent variables. Independent variables are described in Table 1. For each general linear model (GLM), the total R^2 explained by the model is given, along with the significance (Probability > F) of each main effect. The second line for each model gives the F -values relating to categorical variables, and the estimated model coefficients for continuous variables. Variables not included or not estimated for each model are blank.

		Independent Variables										
		Categorical				Continuous						
Dependent Variable	R^2	Year	Month	Area	Prime	Mesh	Tons	Dur	Totc	Totd	Dep	Skate d+l
YT Discard Rate	0.44	0.00	0.00	0.00	0.00	N.S.	N.S.	0.02	0.00	0.00	0.01	N.S.
[F-values/Coefficients]		54.6	12.0	18.6	8.8	-	-	1.79	-0.001	0.004	0.136	
WF Discard Rate	0.48	0.00	0.00	0.00	0.00	N.S.	0.00	N.S.	N.S.	0.00	N.S.	0.00
[F-values/Coefficients]		43.8	8.83	26.2	13.7	-	-0.03	-	-	0.004	-	-0.003
Total Discard Rate	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
[F-values/Coefficients]		48.6	6.8	15.0	31.5	-5.64	0.019	-6.36				
Total Catch	0.51	0.00	0.00	0.00	0.00	0.05	0.00	N.S.				
[F-values/Coefficients]		5.6	4.7	10.2	202.4	411.5	4.35	-				
Number of Species (N0)	0.25	0.00	0.00	0.00	0.00	0.01	0.00	0.00			0.01	
[F-values/Coefficients]		14.5	16.6	10.7	17.5	-0.82	-0.003	0.65			0.004	
Simpson's Diversity	0.22	0.00	0.00	0.00	0.00	0.01	N.S.	0.00			0.00	
[F-values/Coefficients]		4.5	12.3	8.8	11.0	0.03	-	-0.04			0.0003	
Shannon's Diversity	0.23	0.00	0.00	0.00	0.00	0.00	N.S.	0.00				
[F-values/Coefficients]		7.5	14.4	10.0	13.4	-0.13	-	0.09				
N1 Diversity [exp(H')]	0.21	0.00	0.00	0.00	0.00	0.00	N.S.	0.00				
[F-values/Coefficients]		10.3	15.4	11.7	13.3	-0.55	-	0.34				
N2 Diversity [1/λ]	0.19	0.00	0.00	0.00	0.00	0.00	N.S.	0.00			N.S.	
[F-values/Coefficients]		8.1	11.6	11.9	11.0	-0.31	-	0.25			-	
E1 Evenness [H'/ln(N0)]	0.24	0.00	0.00	0.00	0.00	0.01	N.S.	0.00			N.S.	
[F-values/Coefficients]		10.2	10.3	8.8	10.3	-0.03	-	0.02			-	
E2 Evenness [N1/N0]	0.18	0.00	0.00	0.00	0.00	N.S.	0.03	N.S.			0.02	
[F-values/Coefficients]		13.5	5.8	11.6	10.6	-0.02	8.8e-5	-			-0.0002	
E3 Evenness [N1-1/N0-1]	0.21	0.00	0.00	0.00	0.00	0.02	0.04	0.00			0.00	
[F-values/Coefficients]		12.9	8.3	10.5	10.2	-0.03	8.7e-5	0.01			-0.003	
E4 Evenness [N2/N1]	0.07	0.00	0.00	0.04	0.00	0.01	N.S.	N.S.			0.00	
[F-values/Coefficients]		5.5	3.5	1.7	4.3	0.02	1.4e-5	-			-0.0002	
E5 Evenness [N2-1/N1-1]	0.13	0.01	0.00	0.00	0.00	N.S.	0.05	0.00			0.00	
[F-values/Coefficients]		4.0	7.2	5.8	5.6	-	7.3e-5	0.02			-0.0005	

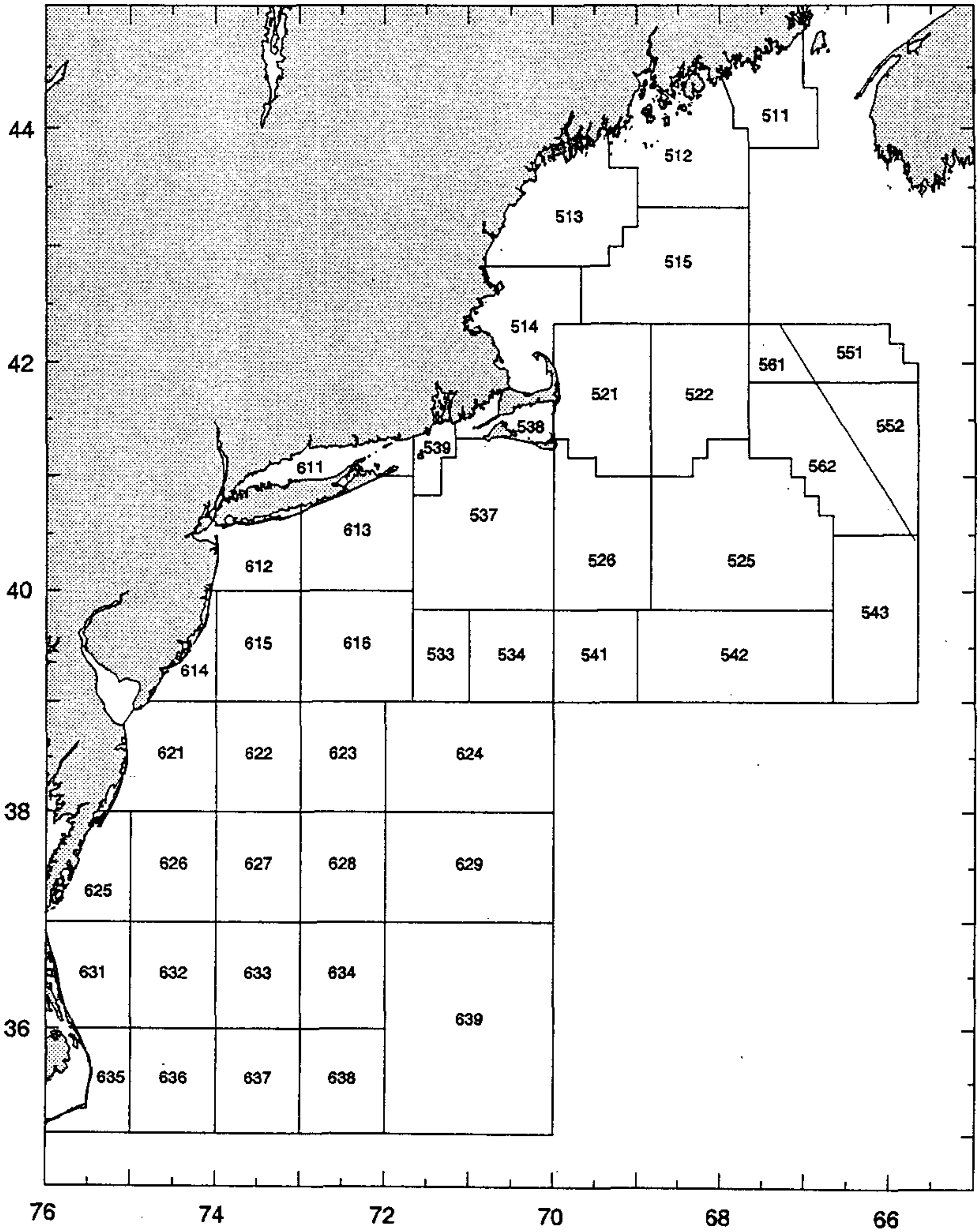

Figure 1. Three-digit statistical reporting areas off the Northeast USA and Southeast Canada. Analyses of sea sampling data conducted herein used data from areas 521-613, inclusive.

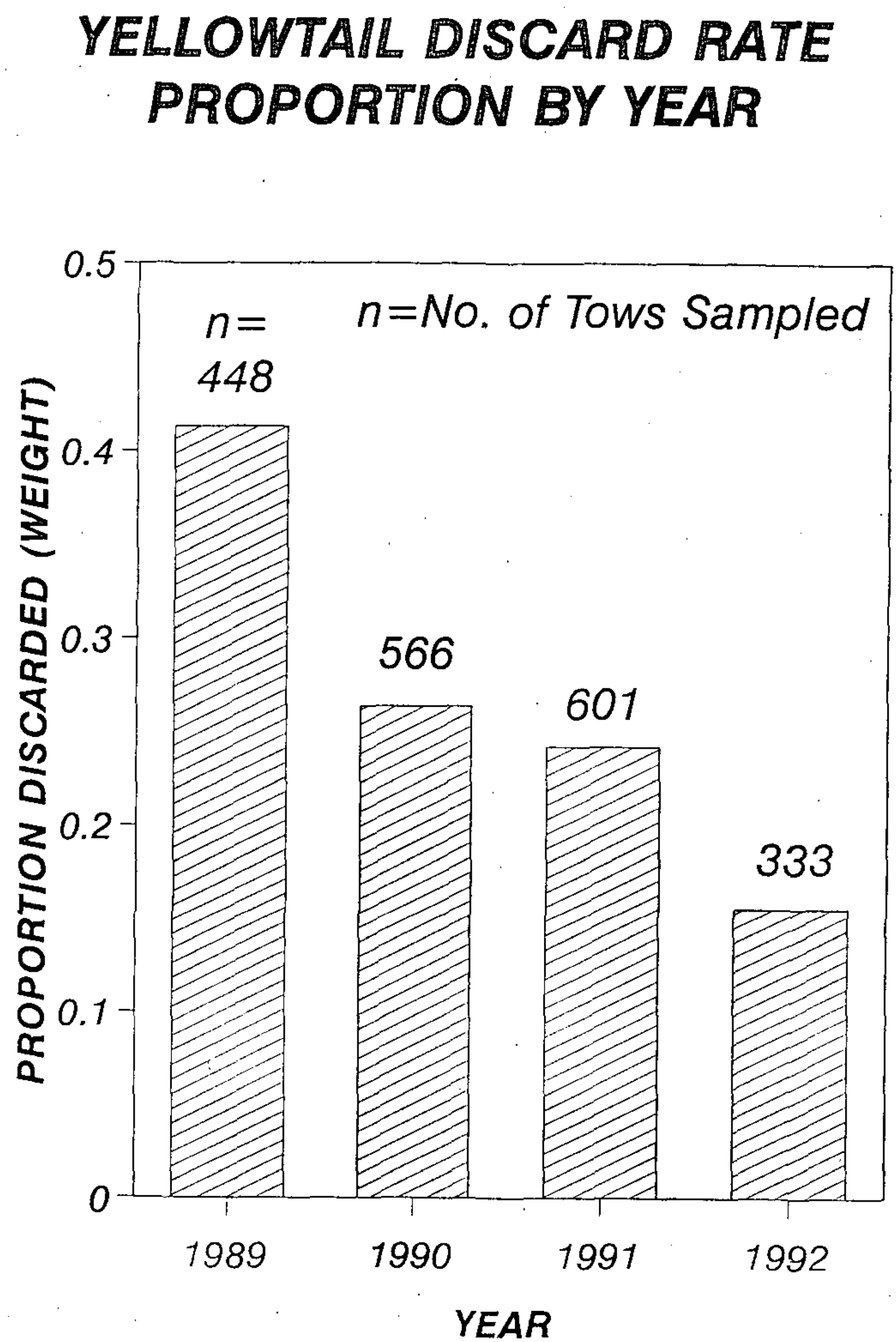

Figure 2. Discard rate (pounds discarded/landed+discards) of yellowtail flounder sampled aboard commercial otter trawlers, 1989-1992. Data are mean discard rates for given numbers of tows sampled at sea.

YELLOWTAIL DISCARD RATE F-VALUES BY FACTOR

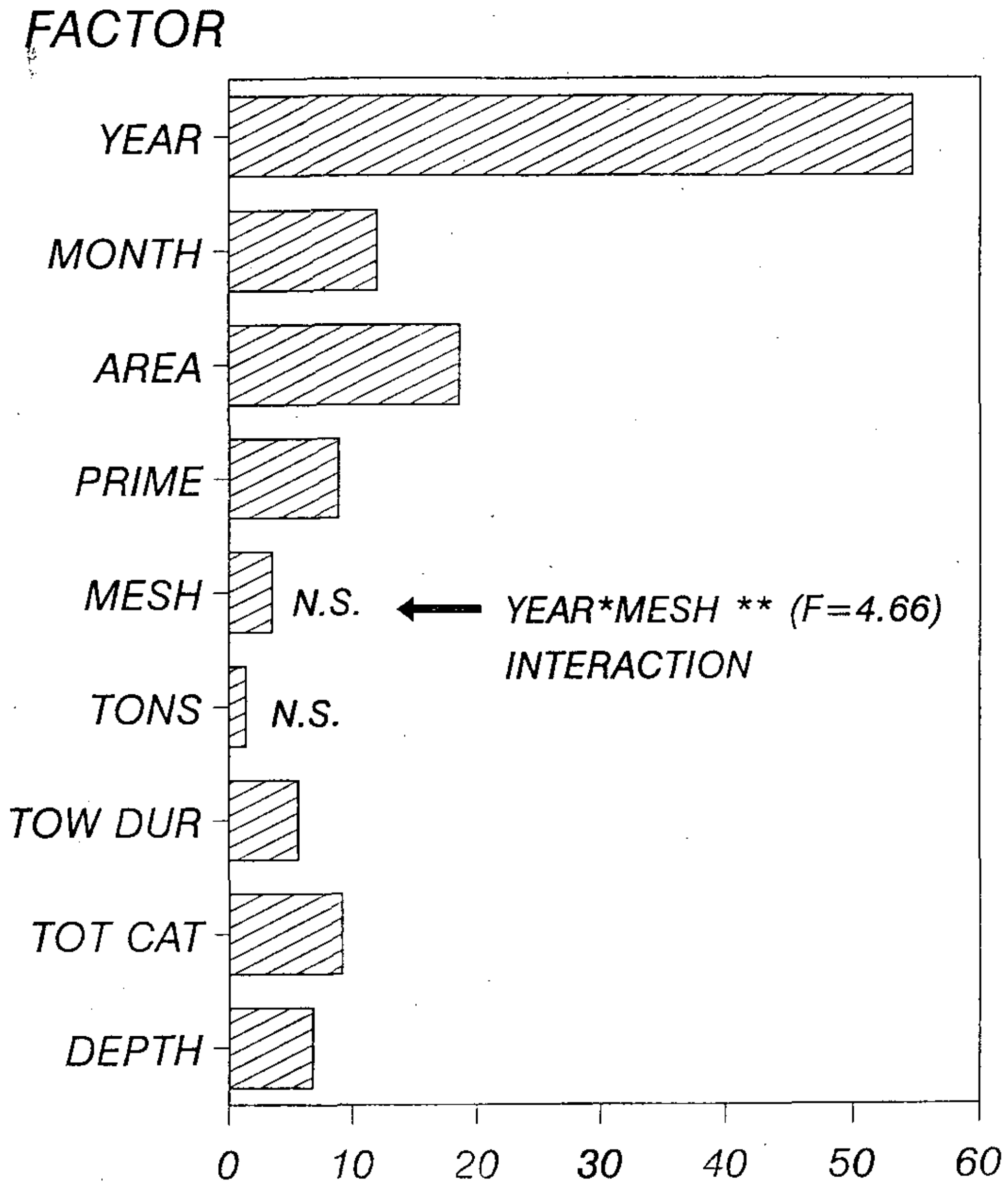

Figure 3. F-ratios from general linear models fitted to sea sampling data collected from otter trawl fisheries off the Northeastern USA, 1989-1992. Dependent variable is yellowtail flounder discard rate. N.S., indicates non-significant ($P>0.05$) factor. In the case of year and mesh factors, a second model was fitted including a year*mesh interaction factor, that was highly significant ($P<0.01$).

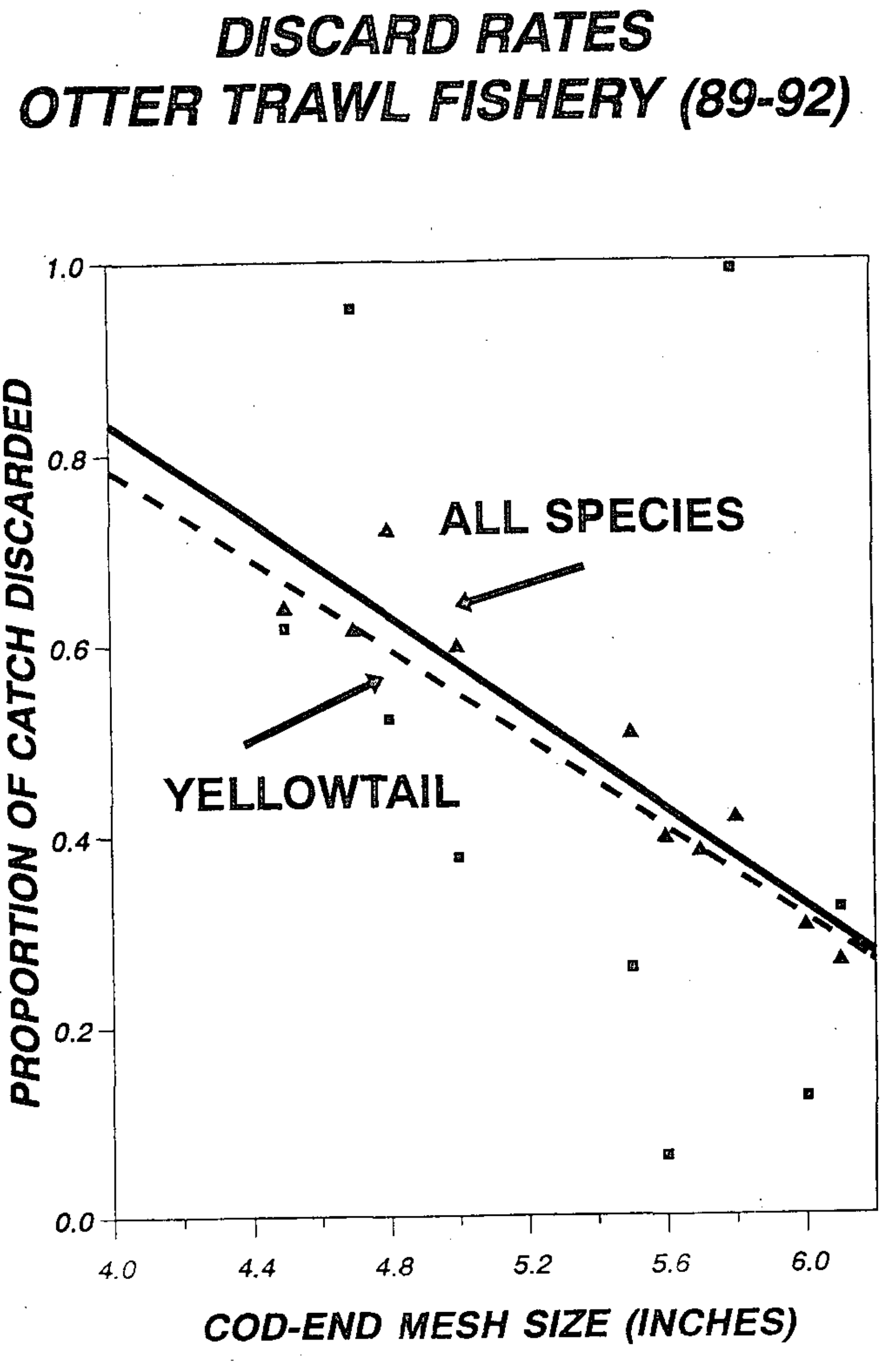

Figure 4. Effects of cod-end mesh size on the proportion of trawl tow catch discarded, for all species caught, and for yellowtail flounder. Data are from otter trawl fishery sea sampling off the Northeast USA, 1989-1992.

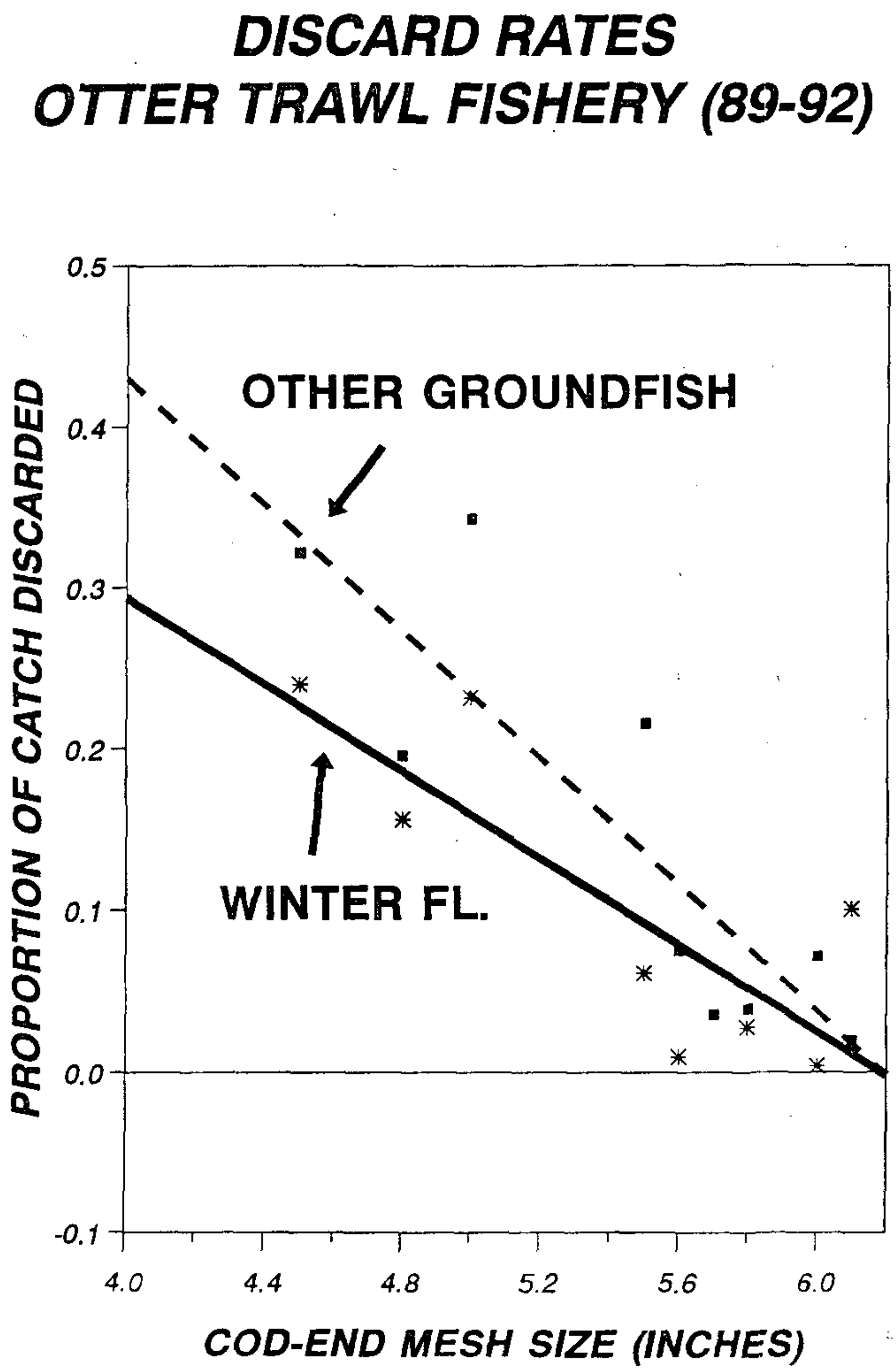

Figure 5. Effects of cod-end mesh size on the proportion of trawl tow catch discarded, for other groundfish species (see Table 1), and for winter flounder. Data are from otter trawl fishery sea sampling off the Northeast USA, 1989-1992.

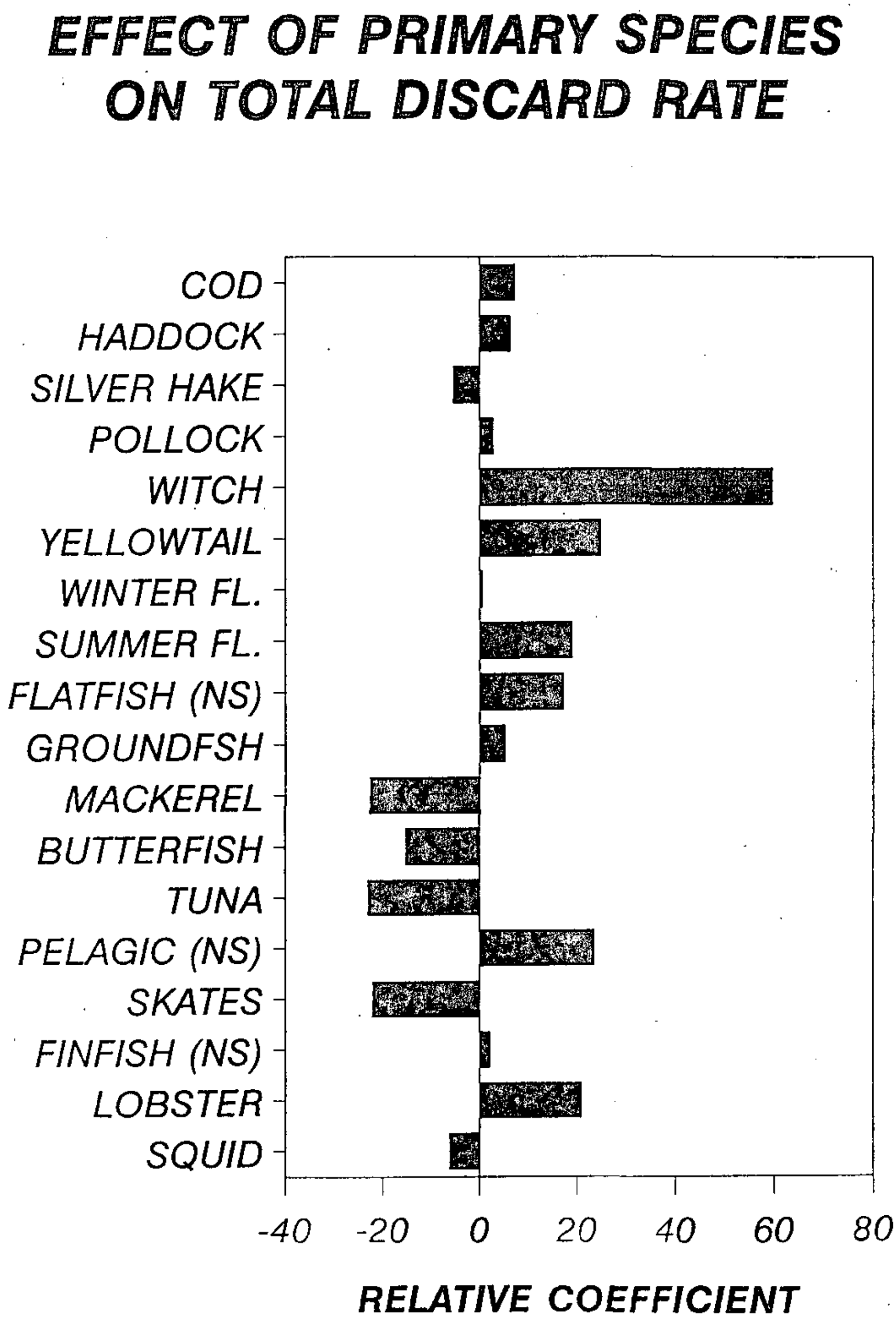

Figure 6. Estimated relative coefficients for each primary species category, with respect to its effect on total (all species) discard rate. Coefficients are scaled relative to a coefficient of 0.0 for primary species = other species caught (code=99).

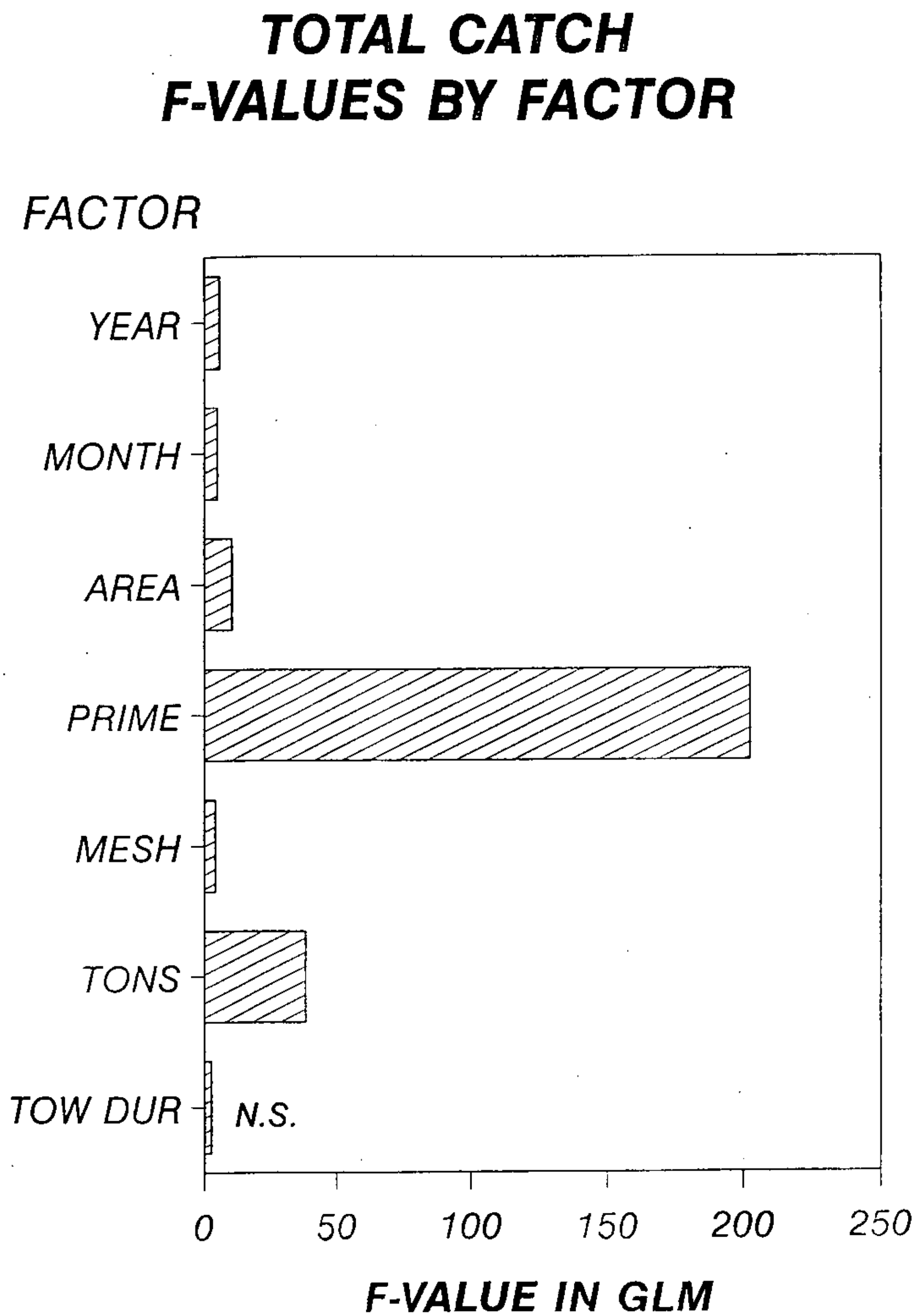

Figure 7. F-ratios from general linear models fitted to sea sampling data collected from otter trawl fisheries off the Northeastern USA, 1989-1992. Dependent variable is total (all species) catch. N.S. indicates non-significant (P>0.05) factor.

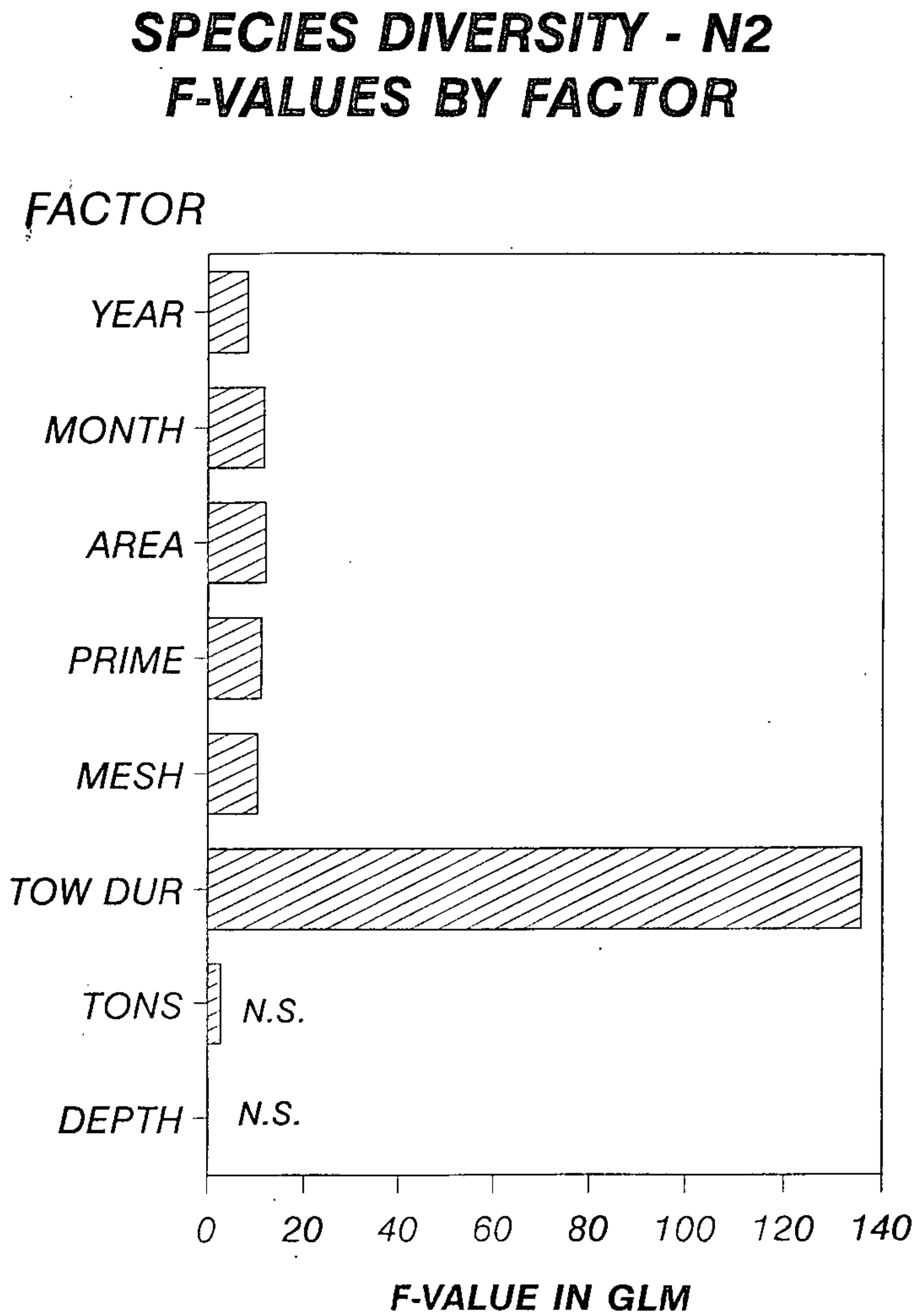

Figure 8. F-ratios from general linear models fitted to sea sampling data collected from otter trawl fisheries off the Northeastern USA, 1989-1992. Dependent variable is species diversity (N2 index, see Table 1). N.S. indicates non-significant ($P>0.05$) factor.

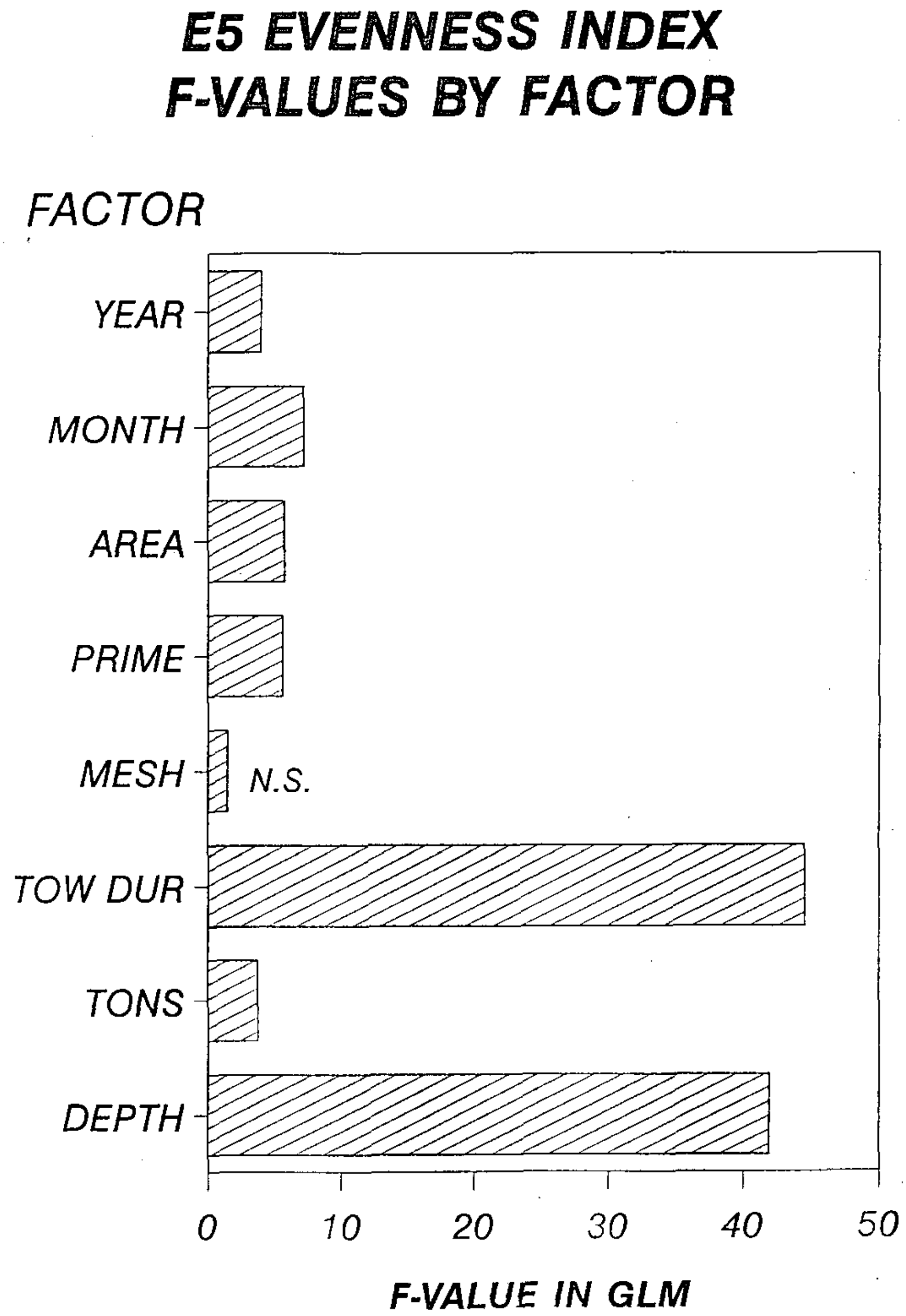

Figure 9. F-ratios from general linear models fitted to sea sampling data collected from otter trawl fisheries off the Northeastern USA, 1989-1992. Dependent variable is species evenness (E5 index, see Table 1). N.S. indicates non-significant ($P > 0.05$) factor.