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Estimates of Gear Selectivity From Multiple Tagging Experiments

by

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ABSTRACT

A new method is introduced for estimating selectivity of fishing gear from tagging data in which data from many experiments are combined. We apply this method to 126 tagging experiments on Atlantic cod (*Gadus morhua*) conducted from 1954 to 1990. We show that the selectivity of otter trawls changed from the 1960's to the 1980's; during the earlier time period maximum probability of capture occurred at 55 cm and declined for older fish whereas now the maximum probability is approximately 60 cm and remains constant for longer fish. Gillnet selectivity at length decreased from the 1960's to the 1980's; the peak gillnet maximum probability of capture declined from approximately 75 to 60 cm. for gillnets. We discuss how selectivity estimates can be used to improve stock assessments.

Introduction

Determining the selectivity of fishing gear for fish of different sizes is a key component of fisheries assessment. For example, during the late 1980's all Canadian cod stocks were assessed using the assumption that the selectivity of the commercial fishing gear, primarily otter trawls, decreased at older ages (Myers and Cadigan 1995b). This assumption turned out not to hold up under statistical analysis (Myers and Cadigan 1995b) and resulted in the spawning biomass being overestimated. This overestimation of spawner abundance may have played a major role in the collapse of the cod stocks in Eastern Canada (Myers et al. 1996).

The most direct method for estimating selectivity is to tag or mark a large number of fish and determine the proportion caught in each size category. This is readily accomplished in small lakes (Hamley and Regier 1973); however, it is rare that single tagging experiments release enough tagged fish in large lakes or the ocean to enable selectivity to be well determined. An exception is Anganuzzi et al. (1994) who estimated selectivity from two experiments in which over 55,000 fish were tagged.

The purpose of this paper is to present a simple method that allows selectivity of fishing gear to be estimated in a rigorous way using data from many separate tagging experiments.

We make use of the theory of generalized linear models (McCullagh and Nelder 1989) and this allows us to perform the calculations using standard statistical software such as GLIM and SAS. A generalized linear model has three features: 1) a linear function of the explanatory variables, 2) a link function (usually nonlinear) relating the expected value of a dependent variable to the linear combination of explanatory variables, and 3) an error structure in the exponential family of statistical distributions. Common examples of generalized linear models are probit and logit models and log-linear (multiplicative) models.

We will briefly mention two alternative approaches to estimating selectivity. First, if the commercial catch-at-age is known, then age-structured models, e.g. virtual population analysis (VPA), can be used to estimate selectivity of the commercial fishing gear. Statistical catch-at-age models can be formulated in a variety of ways; many formulations depend upon the selectivity of the independent survey or commercial catch rate series being known, at least for older ages. This may cause a fundamental indeterminacy in many formulations because the estimated selectivity of the gear that is being used to calibrate the VPA depends upon assumptions in the fishery (Myers and Cadigan 1995a,b).

A second approach is to compare the catch rates of different size fish in two or more gear types. This is known as indirect estimation of selectivity (Millar 1992). However, Millar (1995) has recently shown that the functional form of selectivity from such a comparative approach cannot be determined from comparative catch data alone using two types of gear. It remains an open statistical problem whether selectivity can be effectively estimated when more than two gear types are used. It is possible to construct experiments in which two gear types can be directly compared, e.g. by constructing a trawl with two different types of cod ends (Hamley and Regier 1973; Millar 1992). Although these experiments are very valuable their results are limited, e.g. they only determine the selectivity of fish that enter the trawl, because small or larger fish may avoid entering the trawl by various avoidance behaviors (Millar 1992).

Methods

Consider a tagging experiment, i, in which $N_{i,l}$ fish of length l are tagged and released. We will examine tag returns for a relatively brief time after tagging, e.g. less than a year, in which growth and natural mortality should be minimal. The exploitation rate on the size group most vulnerable to gear type g in experiment i is $U_{i,g}$. The selectivity of gear type g is $S_{g,l}$, where the selectivity will be scaled so that the largest selectivity over all lengths will be 1. We construct a simple model in which the selectivity will be constant over several experiments. The expected value of the reported catch of tagged fish, $E[C_{i,g,l}]$, is

$$E[C_{i,g,l}] = N_{i,l} R_{i,g} U_{i,g} S_{g,l}$$

where $R_{i,g}$ is the product of the proportion of fish that survives tagging, the proportion of tags that are not lost (shed), and the proportion of recovered tags that is reported from experiment i in gear type g. $R_{i,g}$ is assumed to be constant over lengths of fish. Note that we have assumed that tagging mortality, natural mortality, tag loss, and tag reporting rate are independent of the length of fish for each gear type (but not necessarily constant from experiment to experiment). Also we have assumed that natural mortality is small enough to be ignored during the analysis.

If the capture probability is the same for all fish of a given length, and the captures occur independently and at random, then the capture probability of a tagged fish will be

$$\pi_{i,g,l} = R_{i,g} U_{i,g} S_{g,l},$$

and the probability of observing $C_{i,g,l}$ recaptures is binomial:

$$Prob(C_{i,g,l}) = \begin{pmatrix} N_{i,l} \\ C_{i,g,l} \end{pmatrix} (\pi_{i,g,l})^{C_{i,g,l}} (1 - \pi_{i,g,l})^{N_{i,l} - C_{i,g,l}}.$$

The likelihood follows immediately from the above probabilities. The deviance, $d_{i,l,s}$, is defined to be twice the difference between the maximum likelihood achievable in a full model, in which there is one parameter fit per observation, and that achieved by the model under investigation. In the data considered, all estimates were within the feasible range.

An over-dispersed binomial model may be more appropriate if only a few schools of fish were tagged, and the fish in these schools were captured (Fryer 1991, Millar 1992). In this case over-dispersion is easily modeled using a scale factor for the variances (McCullagh and Nelder 1989, p. 126).

The simplest model for the capture probabilities is a multiplicative model. Letting lower case letters represent the log of a value, e.g., $s_{g,l} = \log(S_{g,l})$, we have

$$\log(\pi_{i,g,l}) = r_{i,g} + u_{i,g} + s_{g,l}.$$

Note that $r_{i,g}$ and $u_{i,g}$ are completely confounded in the above equation. This does not matter because we treat the sum, $r_{i,g} + u_{i,g}$, as a nuisance parameter and we do not require separate estimates of each. For the above model to make sense, $r_{i,g} + u_{i,g}$ and $s_{g,l}$ must be less than or equal to 0.

In the framework of a generalized linear model (McCullagh and Nelder 1989), the above equation predicts the log of the proportion of tagged fish captured at length should have a binomial sampling error with a mean that is dependent upon $r_{i,g} + u_{i,g}$, which is a nuisance parameter, and $s_{g,l}$, which is the parameter of interest. Statistical tests and estimation were carried out using a binomial error assumption and a log link function. Differences in selectivity among length groups were tested using standard likelihood ratio tests. A length effect was estimated for each tagging experiment with length class entered as factors in hierarchical tests. This procedure is similar to a standard analysis of variance method but is appropriate for binary data such as in a mark-recapture experiment.

The selectivities for each gear type estimated using this method are relative. We have standardized the data display so that the selectivity for the length class with the maximum selectivity is equal to one for each gear type. There will be no standard error associated with this selectivity.

There are several alternative definitions of generalized residuals for generalized linear models (McCullagh and Nelder 1989); we examine the Pearson χ^2 residual, which is defined as

$$r_P = \frac{y_k - \mu_k}{\sqrt{V(\mu_k)}}$$

and the deviance residual, which is defined as

$$r_D = \text{sign}(y_k - \mu_k)\sqrt{d_k}$$

where y is the observed catch, μ_k is the predicted mean of the k^{th} observation, $V(\mu_k)$ is the variance of the binomial for predicted mean, d_k is the deviance, and "sign(x)" is the 1 if $x > 0$ and -1 then $x < 0$.

Data

We examine 137 tagging experiments conducted from 1954 to 1991 in which approximately 179,000 cod were tagged and released (Fig. 1). Cod were captured for tagging by baited hooks, traps, or trawls of short tow duration; only fish in excellent condition were released. Each tagging episode typically took a week. An experiment refers to a single release of fish in a relatively small area (typically within 20 nautical miles) over a period of a week. Tag loss was initially approximately 10%, and about 2% after that (Barrowman and Myers in press). Fig. 1 near here

In 1954 and 1955, there were 13 tagging experiments (Templeman 1974). About half of the tags were internal tags and half were external tags made of vinylite or celluloid (Templeman 1963). For the 1950's data, the median number of fish released per experiment we analyzed was 880 and the median number of returns was 213. Between 1962 and 1966, and after 1978, the tagging experiments we examined were conducted using Petersen disk tags attached posterior or anterior to the dorsal fins (Templeman 1977; Lear 1984). For the 1960's data, the median number of fish released per experiment was 672 and the median number of returns was 191. For the data after 1978, the median number of releases per experiment was 978 and the median number of returns was 105. Taggart et al. (1995) provide a summary of the historical tagging data in the Newfoundland region. We used all available data, but there were periods in which no tagging was carried out.

We considered the six major fishing gear types used in the Newfoundland region for cod fishing: 1) cod traps with diamond mesh size usually of 89 mm (3.5 inches), 2) otter bottom trawls usually with diamond mesh of 130 mm since 1974 (mesh size of 76 mm or smaller were used before 1957, at which time minimum mesh size increased to 114 mm) (Pinhorn and Halliday 1990), 3) longlines, which are long lines of baited hooks (usually "number 15 15 Mustad J hooks") spread along the ocean floor, 4) hand lines, a line with a weight and baited hook (usually "number 15 Mustad J hooks"), 5) jiggers, which are lure-like hooks attached to a line that is moved up and down in a series of short movements to snag fish, and 6) bottom gill nets which have a diamond mesh of 140 mm mm (larger meshes were previously used).

The type of gear used varied among fishermen. For example, small mesh "liners" are often illegally used to increase the catch rates of otter trawls (Palmer and Sinclair 1996). Our purpose here is to describe the selectivity of the gear actually used by fishermen.

We divided data into 5 cm length groups. For each commercial fishing gear investigated, we used data from experiments in which recaptures occurred in at least two length classes.

Results

We initially analyzed the data on releases from 1954 to 1966 separately from the releases after 1977 (Table 1). We compare how the selectivity has changed over time. For each of the gear types, we fit the models with separate selectivities for each time period, and used a likelihood ration test to determine if the hypothesis that they were equal could be rejected (last 3 columns in table 1). The selectivity of otter trawls drastically changed from the pre-1969 data to the post-1977 data (likelihood ratio test, see Table 1); the selectivity for longer cod is less than for cod around 55 cm during the early period whereas in the latter period selectivity does not decline with increasing size (Fig. 2 and 3). During the early period most otter trawls were side, as opposed to stern, deployed. These older stern trawlers towed nets slower, the nets were smaller, vertical openings were lower, and smaller mesh was used. These factors evidently allowed larger cod to escape. .

Table. 1 near here

Fig. 2 and 3 near here

There is no significant decrease in the selectivity of cod at longer lengths for the post-1978 data. A linear relationship was fit to selectivity at length for lengths greater than 50 cm using the binomial errors assumed above and a factor for every experiment; the slope was not significant, (likelihood ratio test, $\chi^2 = 1.4$, df=1, p= 0.094).

The change in gill net selectivity was significant during the two time periods (likelihood ratio test, Table 1). Capture probability peaks at intermediate lengths, which is typical of gill nets (Hamley and Regier 1973). Before 1969, the peak was around 75 cm, while after 1978 the peak declined to 60 cm. This corresponds to a decrease in mesh size of gill nets from 178 to 203 mm (before 1970) to 140 mm in the 1980's (Hutchings and Myers 1995).

There was no statistically significant difference between the selectivity of codtraps, line trawls, handlines, and jiggers during the two time periods.

In general the fits were good. There appeared to be very little evidence of overdispersion in our data; i.e. the observed variance of the data around the predicted means was approximately that expected under the binomial assumption. A common method to adjust for overdispersion is to calculate a scale parameter to adjust the statistics, e.g. estimated standard errors (McCullagh and Nelder 1989). This scale parameter for the binomial is the square root of the deviance divided by the degrees of freedom. In our case, the scale parameter suggests that we had underdispersion, i.e. in all cases the deviance is less than the degrees of freedom (Table 1).

Some experiments have very small capture probabilities; this may cause the apparent underdispersion in Table 1, i.e. the estimated deviance is less than the degrees of freedom. We do not believe this represents underdispersion because the asymptotic approximation used to determine underdispersion breaks down when the estimates are close to a constraint, i.e. the capture probability must be greater than or equal to zero.

We examined the χ^2 and deviance residuals with respect to length of the fish and experiment. We examined changes of selectivity over time by plotting the residuals for each length class and year (Fig. 4). We found some indications of slight differences in selectivity in different years, but these were not great; nor were they statistically significant. The longer length classes often show all negative residuals; this is usually because there were no returns in that length class. This happened particularly in later years when there were very few longer fish available to be tagged (Fig. 5).

Robustness and Violations of Model Assumptions

The most important limitation of our approach is that it is critically dependent upon the assumption that apart from differences in selectivity, tags are returned *independently of the length of the fish*. This assumption could be violated if smaller fish were discarded before they could be examined for tags or if smaller fish suffered higher mortality because of tagging.

The smallest size acceptable for plants salting fish was 45 cm, while plants processing cod for the fresh or frozen market accepted fish greater than 40 cm (Mercer and Brothers 1984). For this reason, we restricted our analysis to fish greater than 40 cm; however, we believe that the selectivity for the 40-45 cm length group is underestimated.

Fish will grow during the period between release and recapture. Although there is clearly substantial measurement error in the length data, it is possible to estimate the average growth during the period of release (Fig. 6). On average, the fish grew about 2 cm while at liberty and the amount of growth was not highly dependent on initial length (slope of regression of length at recapture on length at tagging = 0.98). In the range of sizes where catchability increases with length there will be a positive bias in the estimates of catchability and, likewise, where catchability decreases with length there will be a negative bias.

A limitation of our approach is that selective catch taken by one gear may change the availability of fish to be caught by other gear. This effect is minimal when the total fraction of tagged fish recovered is low; in practice one may need to limit the returns to one year, or even a fraction of the year. To investigate this possibility, we considered the returns from only the first six months after release, and obtained similar results to that using a full year.

We also tried different criteria for selecting the data to analyze. We estimated the model parameters using the following alternative selection criteria for experiments: : (1) at least one fish was recaptured, (2) recaptures occurred in at least 4 length categories, and (3) recaptures occurred in at least 6 length categories. In no case were the estimates very different under these conditions.

Discussion

Our results show that selectivity of commercial fishing gear can be effectively estimated by combining results from many tagging experiments. Selectivity is crucial for the management of fish populations and there are fundamental statistical difficulties in estimating it indirectly, e.g. without a known or tagged population (Millar 1992). The analysis of historical and ongoing tagging programs should be carried out. For example, we have detected large shifts to lower sizes in the gillnet selectivity that have occurred over the last 30 years. During this time, smaller mesh sizes were introduced in response to a reduction in the size of cod because of increased fishing pressure. Not all changes in selectivity were so simple: the functional form of otter trawl selectivity changed drastically over the same period.

We have shown that the assumption that the largest fish are much less vulnerable to otter trawls than fully vulnerable sizes is not valid in recent years. The selectivity of otter trawls is almost constant for fish over 45 cm. This is very different from the assumptions used in Eastern Canada for many cod assessments (Myers and Cadigan 1995a) in which the fishing mortality on the oldest age, e.g. 12, was assumed to be half of the average fishing mortality on ages 7 to 9 in each year. Myers and Cadigan (1995a) constructed a statistical model to test this assumption using the commercial catch-at-age data and research survey estimates of abundance and found that the best model fit was one in which the fishing mortality on the oldest ages did not decrease. Their statistical test was relatively weak and depended upon the assumption that the research survey selectivities were constant for older ages, an assumption that could not be tested.

Our analysis of the post-1979 otter trawl data are consistent with estimates of selectivity at length from experiments using paired tows, covered codends, and trouser trawls (reviewed by Halliday and White 1989). Halliday and White (1989) estimate that capture probability does not decrease at length for these experiments, and their selectivity is similar to the ones we estimate. This suggests that avoidance by cod over 40 cm of modern, fast-moving stern trawls does not depend upon length.

Our results differ from those obtained using most models of selectivity (Fryer 1992, Suuronen and Miller 1992, Millar 1992) and tagging (Cormack and Skalski 1992) in that we find no evidence of overdispersion, i.e. variance greater than that predicted from the binomial assumption. We believe that the reason for this is that it was rare for more than one tagged fish from a given experiment to be caught in the same deployment of the gear. The tagging usually took more than a week, so that more than one school of fish were tagged. This differs from selectivity experiments in which overdispersion can be created by the existence of individual schools of fish which the trawl encounters, or tagging experiments from hatcheries in which all releases in a given year may have the same tag type.

The Use Of Improved Tagging Models For The Assessment Of Marine Fish Populations

Tagging studies can be used to estimate gear selectivity by size, identify substocks and movement patterns, quantify movement rates, and estimate total mortality rate and exploitation rate by size group and substock. Tagging studies can be thought of as comprising two types: designed studies and post-hoc analyses. In the former, the investigator plans the study in order to estimate certain parameters. In the latter, the investigator attempts to make inferences from an existing tag data base.

Best results are obtained when the investigator has control over the design of the tagging programs. In this case, the investigator may wish to release fish in multiple years in order to make use of Brownie models (Brownie and Pollock 1985) to estimate total mortality. If a catch sampling program, or a variable reward tagging study, is implemented it is possible to estimate tag reporting rate which, in turn, makes it possible to estimate exploitation rates (Pollock et al. 1991). It may also be necessary to estimate tag shedding rates by a double tagging study (see Barrowman and Myers, in press) and to estimate tag-induced mortality with cage or pen holding studies.

We have found that much useful information can be gained from the post-hoc analysis of existing tag data bases. In the present case, we were able to estimate selectivity of various gear types. This is particularly important because it sheds light on a controversy that arose in the tuning of the virtual population analyses for these stocks: whether the partial recruitment (or selectivity) vector should be monotonically increasing or dome-shaped. The change in trawl selectivity over time noted in our analysis implies that it is inappropriate to use models which require selectivity to be constant over time. In addition, we have shown that total mortality rates could be estimated for subcomponents of these populations (Myers et al. 1995, 1996). A comprehensive analysis of the movement patterns and stock structure remains to be done.

We conclude that use of tagging data deserves far greater consideration than it is given at present. All assessment methods, including virtual population analysis (Myers and Cadigan 1995a), are subject to a variety of biases. Analysis of tagging data can be used to provide independent estimates of mortality, to check on assumptions required for other method, and to provide necessary auxiliary information such as on gear selectivity.

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TABLE 1. The deviance values and the respective degrees of freedom for the six gear types for the two time periods as well as the difference in deviance, ΔDeviance, degrees of freedom, Δdf, and probability, P, that selectivity at length is equal, between a model that assumes the selectivity is the same during the two time periods from one that assumes that it is different.

	1954-1966		1979-1990				
Gear	Deviance	df	Deviance	df	ΔDeviance	Δdf	P
codtrap	415.9	404	374.2	485	7.5	7	0.37
gillnet	358.9	380	553.4	585	35.1	8	2.6×10^{-5}
handline	287.6	326	264.8	299	6.9	8	0.54
jigger	295.3	360	193.2	268	5.7	8	0.68
longline	386.9	399	303.0	343	6.9	8	0.54
otter	424.4	434	533.7	560	45.2	8	3.4×10^{-7}

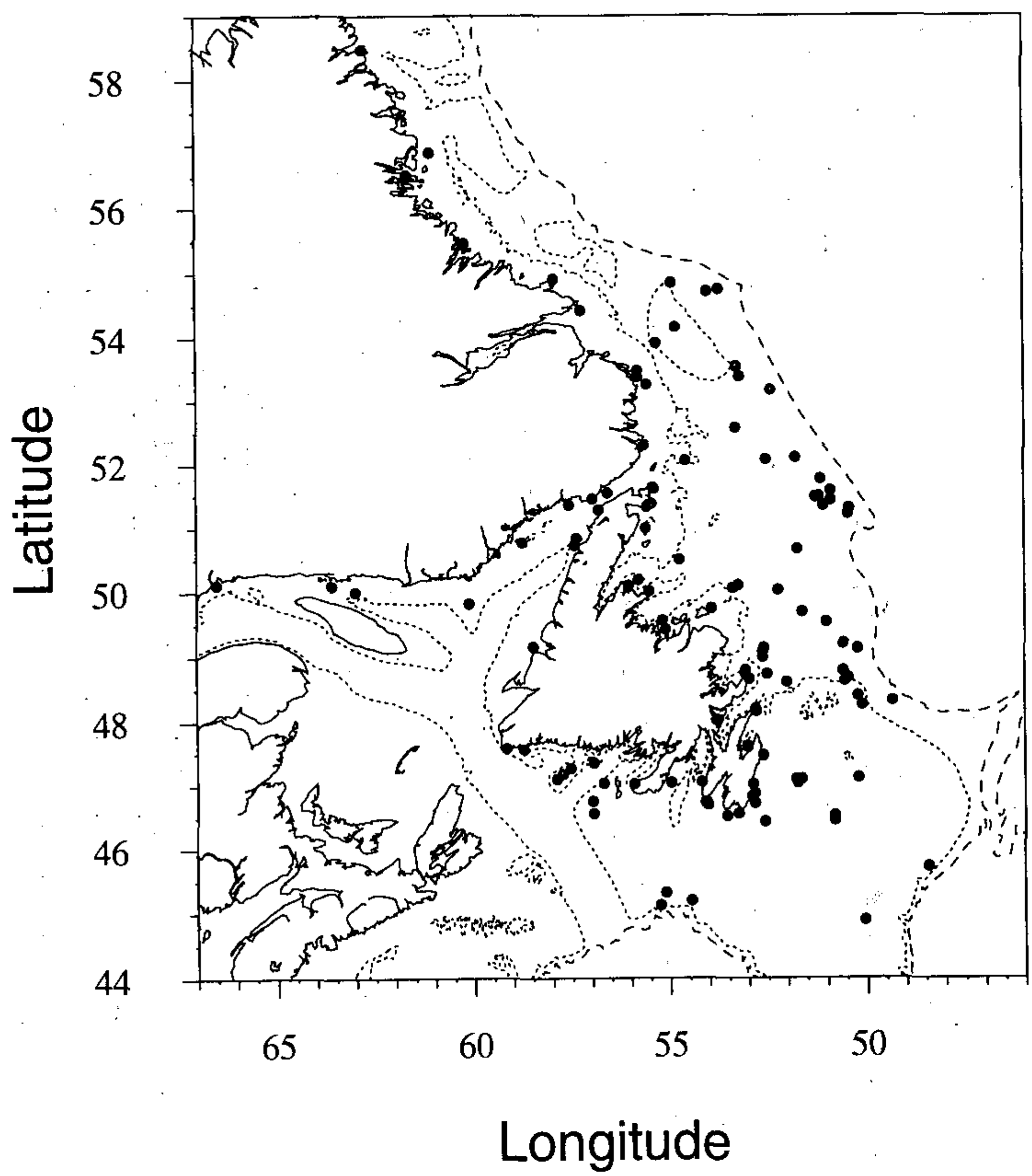


Fig. 1. Locations of tagging experiments. The dotted line is the 200 m isobath and the dashed line is the 1000 m isobath.

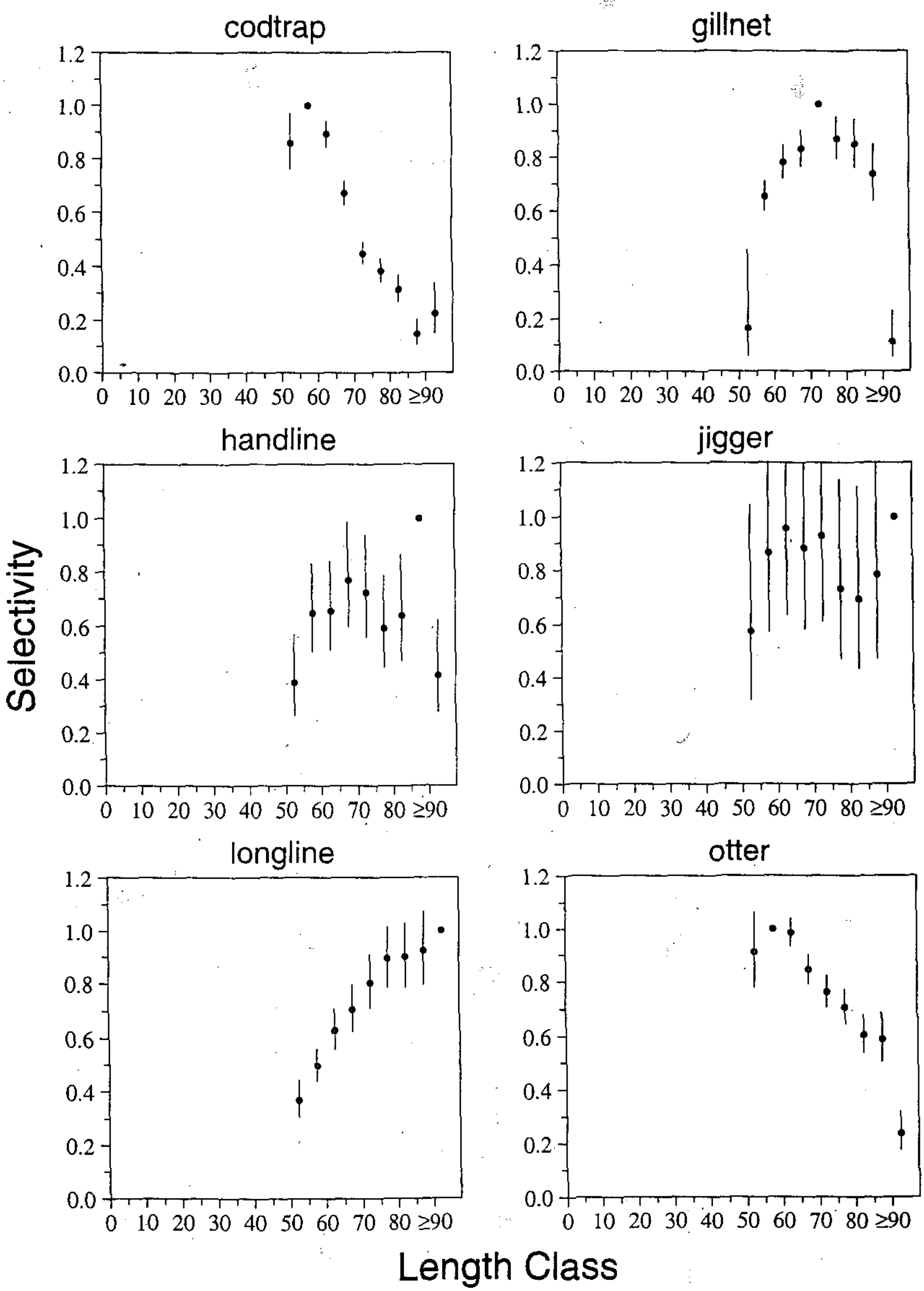


Fig. 2. Estimates and S.E.'s of selectivity from 1954 to 1964. We have standardized the data display so that the selectivity for each gear type is standardized so that the length class with the maximum selectivity is equal to one. There will be no standard error associated with this selectivity. Data for fish longer than 90 cm have been pooled.

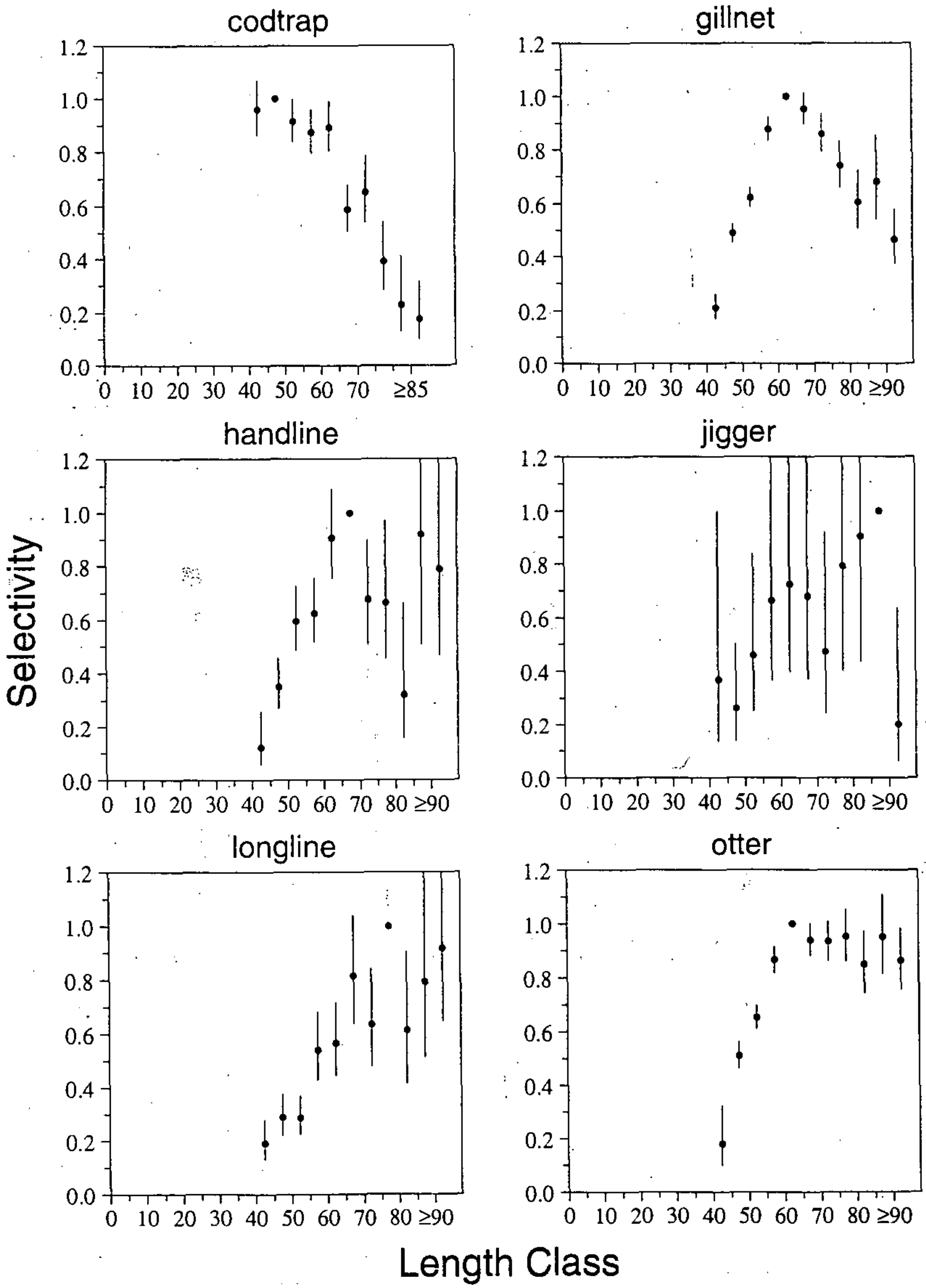


Fig. 3. Same as Fig. 2 except for data from 1979 to 1990. For cod traps we combined all data over 85 cm because there were very few returns for cod longer than 85 cm.

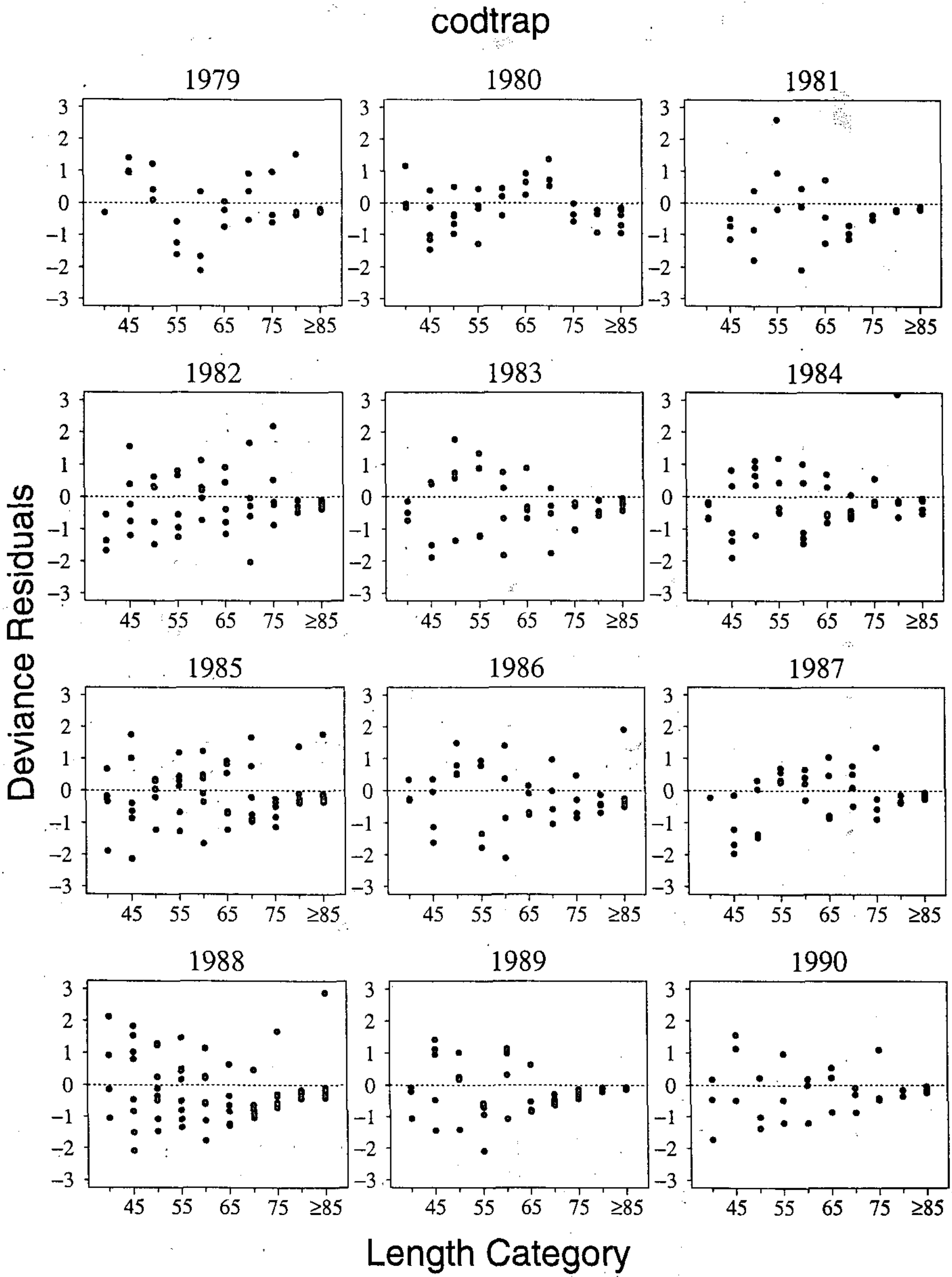
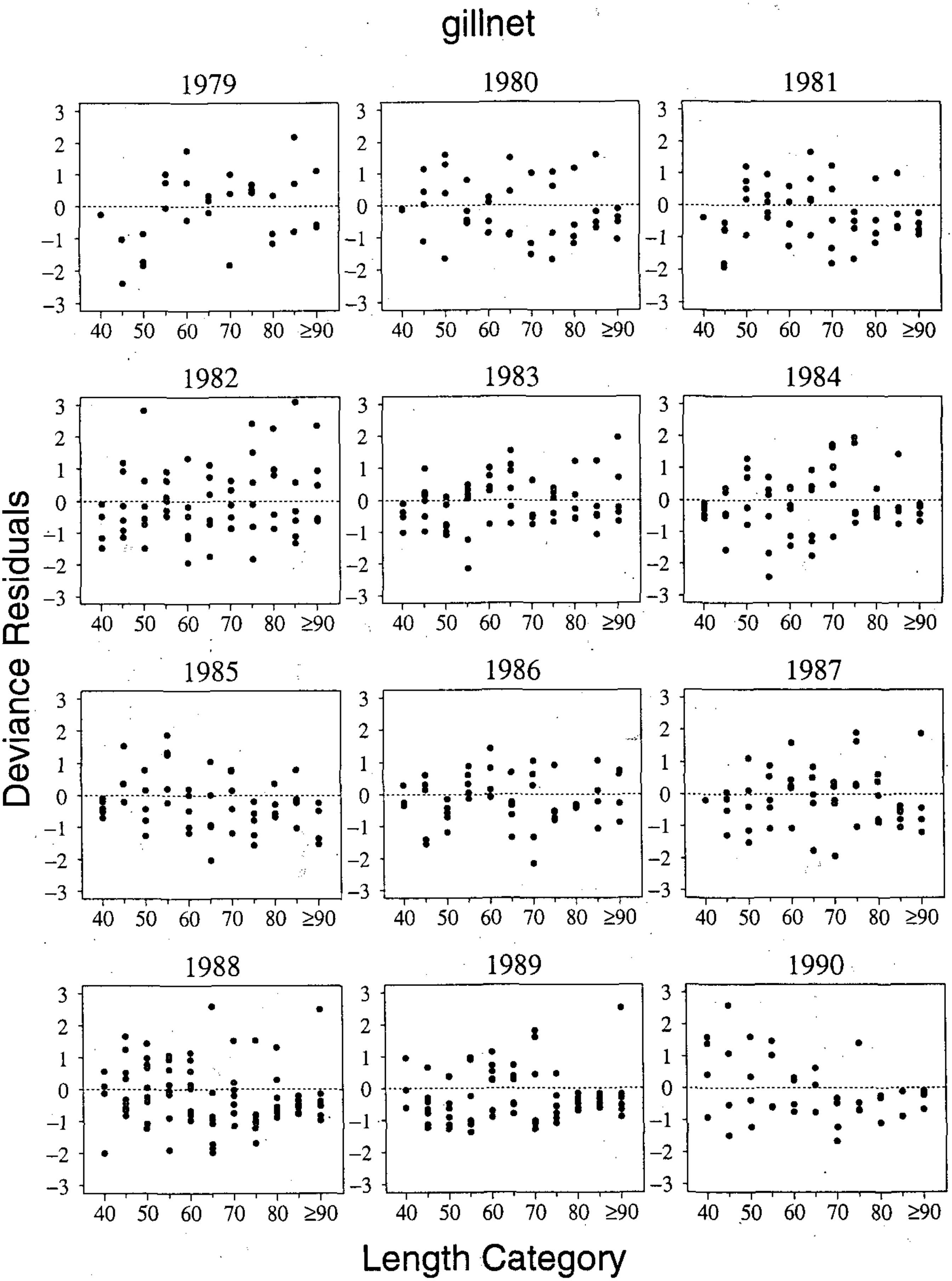


Fig. 4. Deviance residuals for gill nets, otter trawls, longlines, and traps for the post-1978 data with respect to length and year of release.



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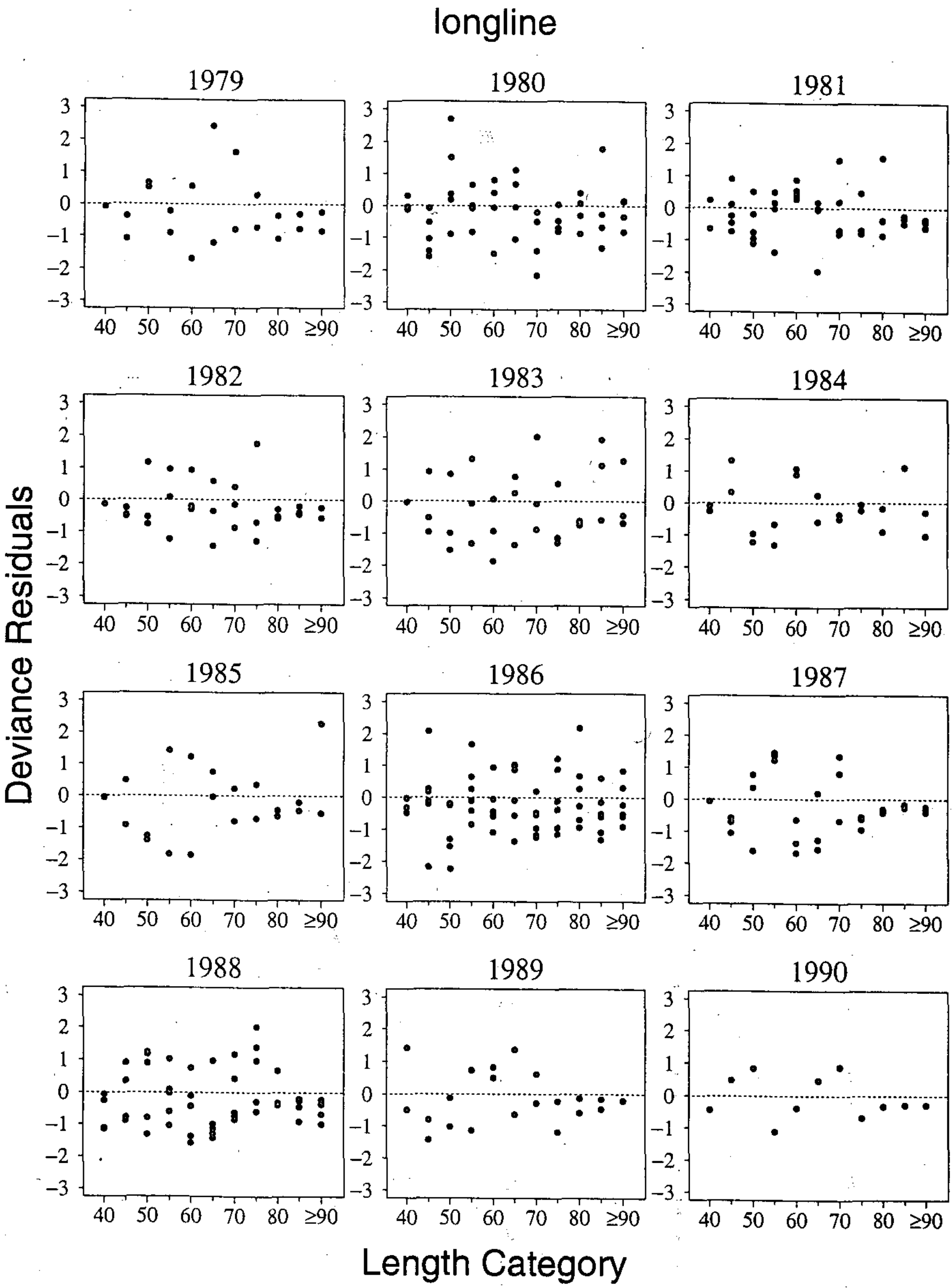

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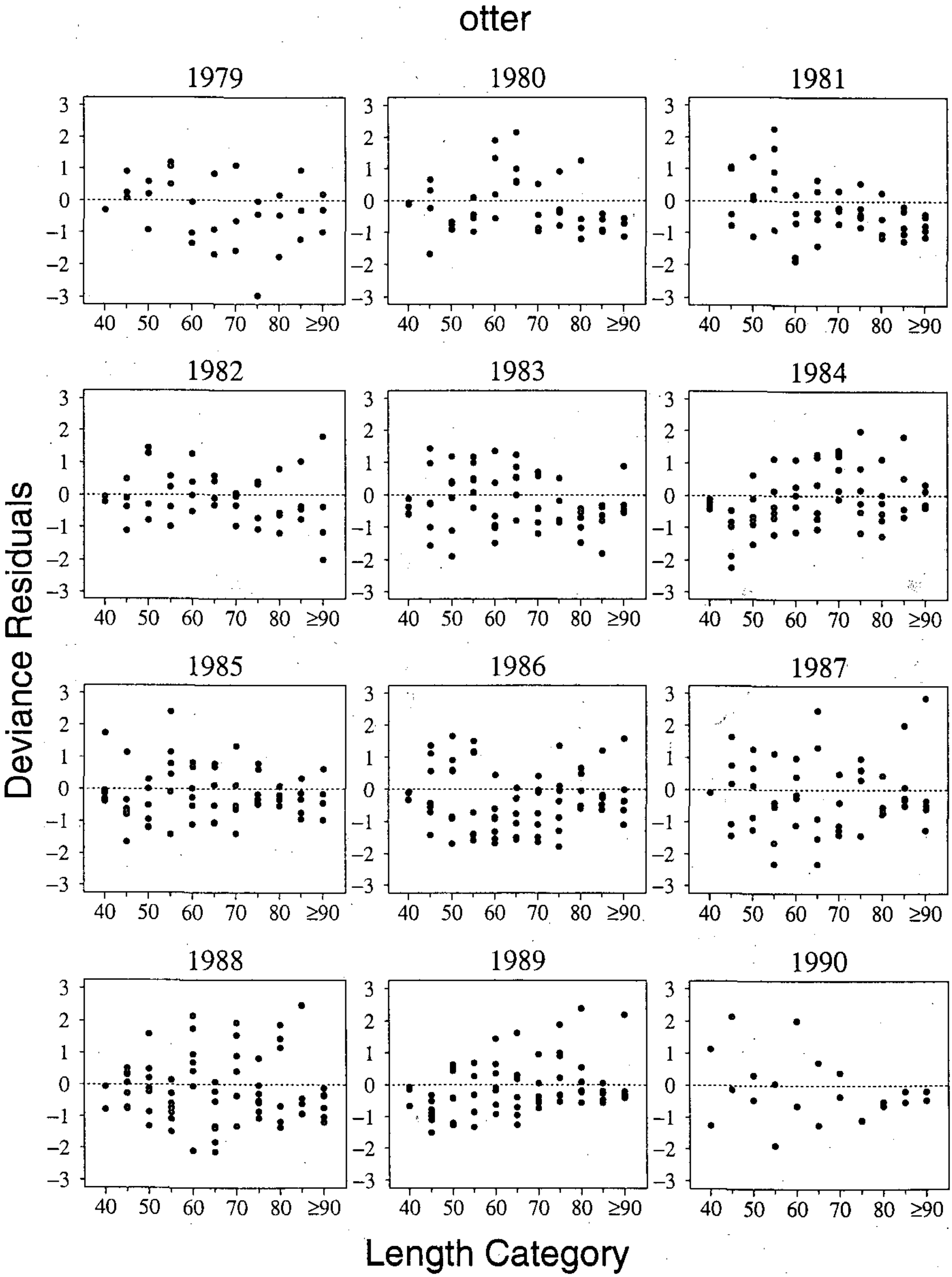

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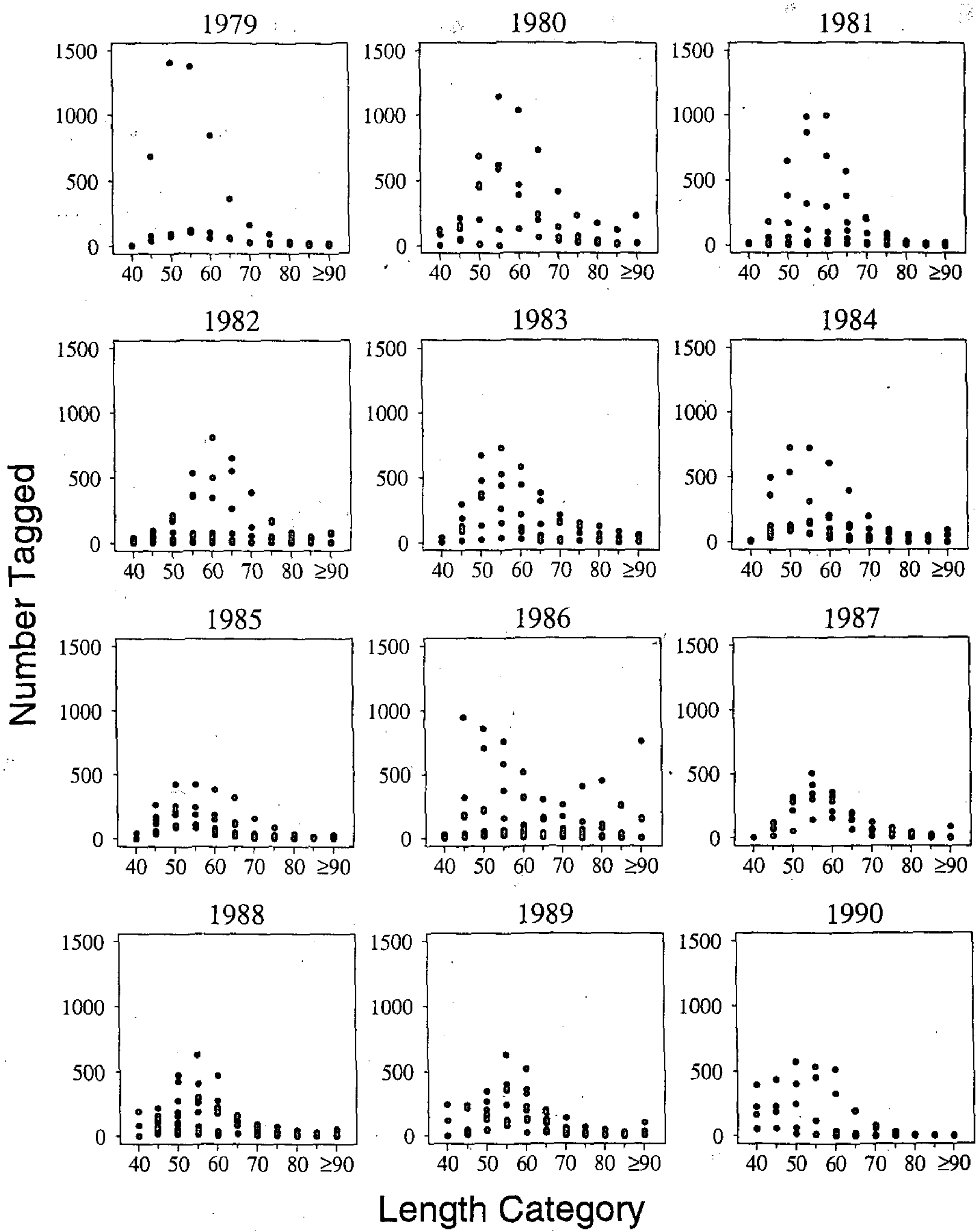

Fig. 5. Number of cod tagged and released during the 1978 to 1990. Each point represents a different experiment/length class.

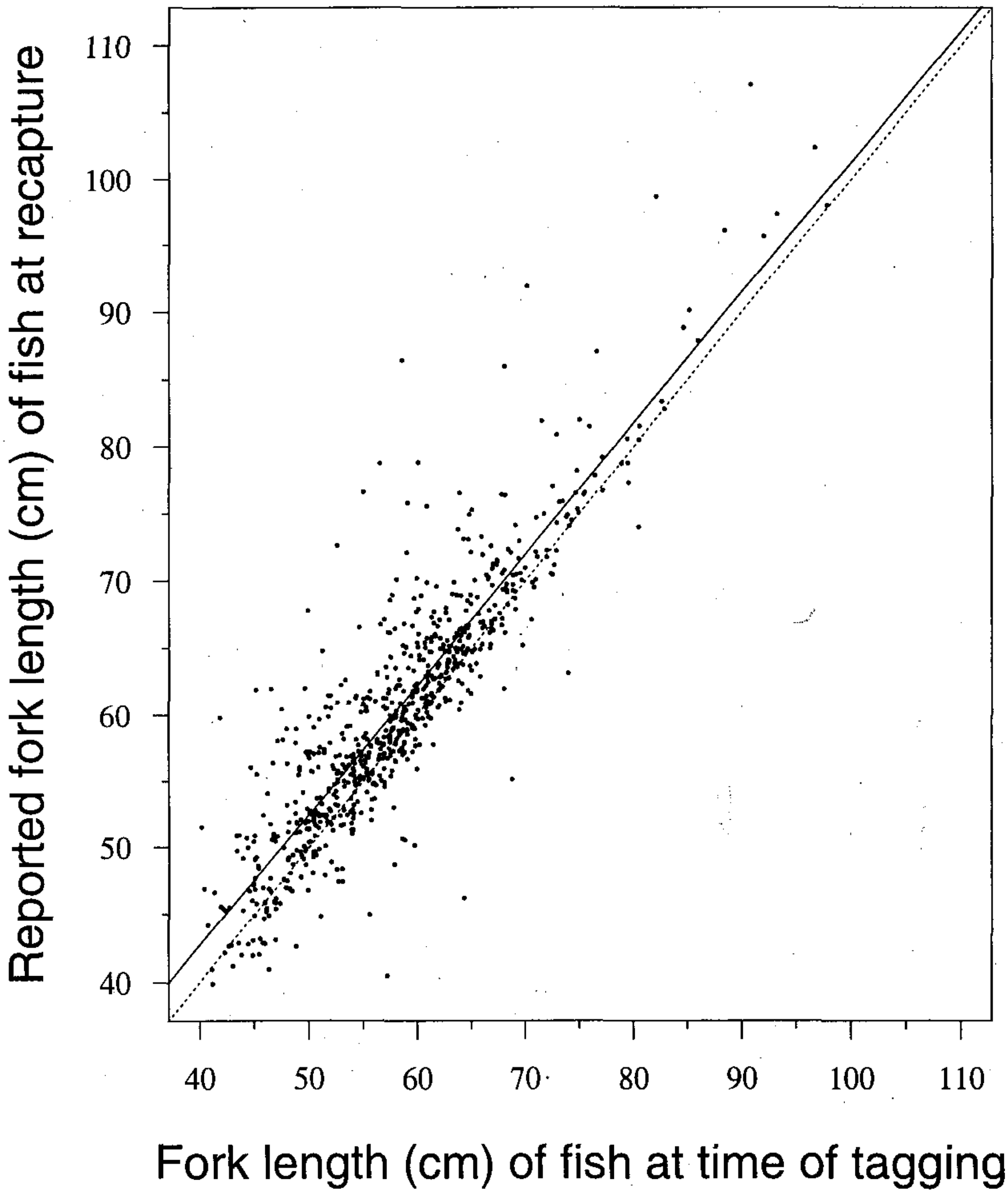

Fig. 6. The estimated length at recovery during the first year after release versus the length at release for the 1978 to 1990 data for fish greater than 40 cm. The solid line is the least squares regression ($y = 3.64 + 0.98x$, $R^2 = 0.80$). The dotted line is the one-to-one line.