Estimating the size-selectivity of fishing gear by conditioning on the total catch: the SELECT (Share Each Lengthclass’s Catch Total) model

by
Russell B. Millar
Science Branch
Dept of Fisheries and Oceans
P.O. Box 5667, St John’s,
Newfoundland, A1C 5X1, Canada.

ABSTRACT

A conditional maximum likelihood model is used to estimate the size-selectivity of trawls, gillnets and hooks when the data are obtained by simultaneous fishing with different size meshes or hooks. Size-selectivity is expressed here by the selection curve, \( r(l) \), the probability that a fish of length \( l \), if encountering the gear, will be retained. In most applications \( r(l) \) is either fitted by eye, by heuristic means, or by improper application of generalized linear models, and so it is not possible to evaluate the fit of \( r(l) \), or to make other statistical inferences. It is shown here that by conditioning on the total catch, selectivity data can be modelled as binary data or polytomous data for interval scales. Because the essence of this approach is to determine the proportion of the total catch of each lengthclass that is expected from each of the different size gears it is called the SELECT (Share Each Lengthclass’s Catch Total) model. Application of the model to trawl and hook data demonstrates that selection curves can be fitted using generalized linear models which may require non-standard link functions or link functions with parameters.
1. INTRODUCTION

Knowledge of the size specific selectivity of fishing gear is vital to the proper management of a fishery. When information on the growth, maturity and fecundity of the species is available then production models can be used to determine the strategy for optimizing the yield from the fishery (Gülland 1983). This strategy includes specification of fishing intensity and the size at which fish should become susceptible to capture by the gear being used. Thus it is essential to know what size of fish is targeted by different types and sizes of fishing gear. The size-selectivity knowledge also provides a useful assessment technique since it allows the size distribution of the population to be inferred from the size distribution of the catch. From this the next step taken is often to estimate the age structure of the population.

In seeking a functional relationship between size and selectivity it would seem appropriate to quantify size by fish girth in mesh selection experiments, and to use gape of mouth for hook selection experiments: However, due to its relative ease of measurement and almost universal use as a measure of fish size, selectivity is most often expressed as a function of length, and this is assumed here. A selectivity experiment is called direct if the length distribution of the population being fished is known. Such knowledge can be difficult to obtain and in practice many selectivity studies are performed indirectly by comparing catches from different sizes of the same gear type. This paper addresses the problem of analysing indirect studies, where no knowledge of the population length distribution is assumed.

The last few years have seen a resurgence of interest in gear selectivity, particularly that of trawls where radical changes to construction, such as inclusion of escape “windows” (Galbraith and Main 1989) or rigging of the mesh in square rather than the traditional diamond configuration, have been considered (Isaksen and Valdemarsen 1986, Robertson and Stewart 1988, Walsh et al. 1989, Isaksen and Valdemarsen 1990, Suuronen 1990). Deployment of selectivity experiments has become more sophisticated and experimental trawls are now often monitored by underwater camera. Statistical analysis of the data (e.g. Beverton and Holt 1957, Holt 1963, Pope et al. 1975) has not kept pace with the technological advances and the “analyses” performed are ad-hoc and incapable of contributing to the understanding of the data. Not surprisingly, most selection curves are still fitted by hand.

Section 2 describes three commercially important types of fishing gear (trawls, hooks and gillnets) and the nature of the selectivity associated with them. Section 3 presents notation and the simple conditioning argument that leads to a new general methodology for analysing data from indirect selectivity experiments. It is applied in Section 4.

2. THREE TYPES OF FISHING GEAR

Trawl gear consists of a conical shaped net towed behind a vessel at a speed that is typically similar to walking pace. The mouth of the trawl is held open by the flow
of water against the "otter boards" rigged to the trawl warps on each side. Bottom
trawls are used for ground fish (e.g. cod, flounder, hake, halibut) and midwater
trawls are used for pelagic species such as capelin and herring. Fish encountering
the trawl are eventually overtaken by it and find themselves in the rear portion
of the net, the codend. Selectivity of trawls is determined primarily by the size
of the mesh openings in the codend, though some recent studies have investigated
modifying selection prior to the codend (Galbraith and Main 1989). The selection
curve for any particular codend is assumed to be a monotone non-decreasing function
of fish length (i.e., the larger the fish, the smaller its chances of wriggling through
the codend meshes) with an upper asymptote at unity. Codend performance is often
summarized by the lengths of 25%, 50% and 75% retention probability.

A gillnet is a rectangular grid of meshes, buoyed at the top and weighted below.
The gillnet hangs passively and operates by entangling fish that swim into it, usually
trapping them at the gills. Fish that are too small pass through the meshes and
fish that are too large do not penetrate sufficiently far into the mesh to become
entangled. Thus the selection curve is often assumed to be bell shaped. Fish that
are rough bodied may be snagged at points other than the gills, in which case a
selection curve that is skewed or multi-modal may be more appropriate (Hamley
1975).

The usual commercial application of hooks is on a longline - a long length of line
with leaders and baited hooks or lures attached at regularly spaced intervals. Very
little is known about the selectivity of hooks (Ralston 1990), but it is believed that
hooks have very broad selection curves (Pope et al. 1975). The typical scarcity of
large fish in a commercial fishery makes it difficult to estimate the right-hand limb
of the curve and consequently both monotone curves and unimodal curves have been
used.

For gillnets and hooks the height of the selection curves are expressed on a
relative basis. Different sizes of the same construction of gillnet or hook are usually
assumed to have equal maximum fishing efficiency (Holt 1963, Pope 1975), that is,
selection curves of the same maximum height. This assumption may be questionable
in some situations. In a gillnet selectivity study on walleye (Stizostedion vitreum
vitreum) Hamley and Regier (1973) conclude that large meshes are more efficient.
However, in a 1987 herring (Clupea harengus harengus) selectivity study, Winters
and Wheeler (1990) found the smaller meshes to be more efficient. Both of these were
direct studies (Hamley and Regier created a known population of tagged walleye,
and Winters and Wheeler used data from acoustic surveys).

Indirect studies are based on the comparative catch from two or more sizes of the
same gear type fished simultaneously and usually with equal effort. For example,
a longline can be rigged so that the hooks alternate in size and gillnets can be
constructed of several panels, each of a different size mesh. The order of the panels
can be changed on each day of fishing to avoid any systematic preference by the
fish for any particular part of the net. In Atlantic Canada trawl selectivity studies
are presently being conducted using the trouser trawl (Figure 1) which fishes a net with two codends, each constructed from different size and/or orientation of mesh. The vertical separator panel separates fish at the trawl mouth, hopefully before they can detect any difference between the two codends. Variants of trouser trawl type experiments include use of split trawls, twin trawls and the alternate haul method whereby the two codends are fished separately in alternate hauls.

The obvious trawl selectivity experiment is the covered codend method, where a small mesh cover is attached to the outside of the codend to capture all fish that pass through the codend mesh. However, this method has been criticized because the presence of the cover is suspected of influencing net performance and fish behaviour (Pope et al 1975, p. 9). Stewart and Robertson (1985) used underwater camera to monitor covered codend trawls and suggested methods of construction to minimize any effect of the cover.

It is often the case that although the different size gears are fished with equal effort they do not fish with equal efficiency. There are several possible explanations, I) there is evidence to suggest that larger gears operate more efficiently II) the gears may have fished different concentrations of fish - especially in the case of alternate hauls where the pair of hauls may be hours apart III) the experimental gear may not have operated as expected (due to gear construction or weather conditions, water currents etc) and one size may have enjoyed an advantage over others. Unequal fishing efficiencies can not be formally modelled in the traditional analyses, but they are permitted in the model described below.

3. THE SELECT MODEL

The length scale is partitioned into \( n \) length-classes, with mid-points \( l_1, \ldots, l_n \). If the relative fishing efficiencies of the \( k \) sizes of gear are denoted \( (p_1, \ldots, p_k) \) where \( \sum p_i = 1 \) then the number of length \( l_i \) fish encountering size gear \( j \) can be modelled as Poisson with rate \( p_j l_i \). Here \( l_i \) can be considered the overall rate at which lengthclass \( i \) fish encounter the combined (across sizes) gear. For schooling species of fish (e.g. herring) an over-dispersed Poisson would be expected. Note that it is assumed that the relative fishing efficiencies are constant across all lengthclasses. Denoting the selection curves for the \( k \) sizes of gear as \( r_j(l), j = 1, \ldots, k \), the catch of size \( l_i \) fish in gear \( j \) is Poisson with rate \( r_j(l_i)p_j l_i \). The actual catch will be denoted \( y_{ij} \) and the total catch of length \( l_i \) fish by \( y_{i+} \).

If each selection curve belongs to a common parametric family then \( r_j(l) \) can be denoted \( r(l; \beta_j), j = 1, \ldots, k \). For lengthclass \( i \) the parameters defining the model are \( \theta = (\beta_1, \ldots, \beta_k, \lambda_i) \equiv (\psi, \lambda_i) \) say. The parameters \( \lambda_i, i = 1, \ldots, n \) reflect the concentration of fish over the duration of the experiment. As such, they are not of interest in a selectivity study and can be considered nuisance parameters. For fixed \( \psi \), \( y_{i+} \) is sufficient for \( \lambda_i \) and complete. The conditional distribution of \( y_{ij}, j = 1, \ldots, k \)
given $y_{i+}$ is multinomial with $y_{i+}$ trials and cell probabilities

$$\phi_j(l_i; \psi) = \frac{p_jr(l_i; \beta_j)}{\sum_{a=1}^{k} p_ar(l_i; \beta_a)} \quad j = 1, ..., k. \quad (1)$$

Note that $\phi_j(l_i; \psi)$ is the expected proportion of the total catch of length $l_i$ fish expected in gear $j$. Under this model, analysis of data from indirect selectivity experiments is put into the form of analysis of binary or polytomous data. The next Section shows that in practical application the techniques of generalized linear models can be used, though the link function may not be of a standard form.

4. APPLICATIONS

Trawls

Here the SELECT model is applied to a data set taken from the literature. It has previously been applied in studies of the trawl selectivity of American plaice (Millar and Walsh 1990) where further details, including formula for calculating the standard errors of the estimated retention lengths, can be found.

Table 1 gives the catch of haddock (Melanogrammus aeglefinus) from an alternate haul study (from Pope et al. 1975, p. 48). A total of four one hour hauls were performed, two with 35mm diamond mesh codends and two with a codend of 87mm diamond polypropylene mesh. The small mesh codend is used because it is assumed to be non-selective over the range of lengths considered. It is the selectivity of the 87mm mesh codend that it of interest here.

The first step of the traditional analysis of such data is to adjust the small mesh catch if it appears that the two codends did not fish equally. That is clearly the case here since the 87mm diamond mesh codend caught at least as many fish as the small mesh codend for every lengthclass above 30cm. The small mesh catch is scaled by the ratio of large mesh to small mesh catch, calculated over the larger lengthclasses which are above the range of selectivity of the large mesh. For lengthclasses 32cm and above Pope et al. (1975) calculated this ratio as $682/531 \approx 1.28$.

The selection curve is then fitted under the premise that the small mesh catch (after possible adjustment) of each lengthclass gives the number of fish that entered the large mesh codend. A selection curve was fitted to this haddock data by eye and the length of 50% retention was estimated to be 30cm. It is common in more recent studies to fit a curve by logit or probit analysis (e.g. Walsh et al. 1989, Simpson 1989). When smaller than the large mesh catch, the small mesh catch is set equal to the large mesh catch, or that lengthclass is ignored. The assumptions of the underlying binomial model are of course not satisfied.

The SELECT model is applied without manipulating the data in any way. If the 87mm diamond mesh selection curve is logistic and $p$ denotes its fishing efficiency (proportion of fish encountered over the four hauls that encountered the large mesh...
codend hauls) then the conditional probability that a length $l$ fish was caught in the large mesh given that it was caught, is (from (1))

$$\phi(l) = \frac{pr(l)}{(1 - p) + pr(l)} = \frac{p \exp(a + bl)/(1 + \exp(a + bl))}{(1 - p) + p \exp(a + bl)/(1 + \exp(a + bl))}$$

$$= \frac{p \exp(a + bl)}{(1 - p) + \exp(a + bl)},$$

where the small 35mm mesh codend was assumed to retain all fish entering it.

Equation (2) can be represented within a generalized linear model as the inverse of the link function $g(\phi) = \log((1 - p)\phi/(p - \phi))$ containing the parameter $p$. When equal split ($p = 0.5$) of fish into the two codends is assumed the link function is $g(\phi) = \log(\phi/(1 - 2\phi))$.

The maximum likelihood fit of $\phi(l)$ to the observed proportions of catch in the large mesh codend is summarized in Table 2. The maximization was implemented in Splus using the general optimization function `nlm`. The equal split model was also fitted but the likelihood ratio test shows that there is strong evidence ($p < 0.001$) against the 50:50 split hypothesis. The unequal split model shows no lack of fit or over-dispersion and the fitted curve and plot of deviance residuals are shown in Figure 2. The deviance residual at each lengthclass has magnitude equal to the square root of twice the difference between full model and current model likelihood for that lengthclass (McCullagh and Nelder 1989, p. 39).

The split was estimated to be 57:43 (1.33:1) in favour of the large mesh codend. This compares closely to the 1.28:1 ratio calculated from lengthclasses 32cm and above, particularly since that value is probably under-estimated due to selectivity of the large mesh codend for lengths in the 32 to 34cm range (Figure 3).

**Hooks and Gillnets**

The trawl experiment in the previous Section made use of a codend with sufficiently small mesh as to be non-selective. Indirect hook and gillnet studies are complicated by the lack of such non-selective catch data. This experimental situation is also true for trawls in the case where two large mesh codends of slightly different size are deployed rather than a large mesh codend and a small mesh codend. Analysis of these data is very dependent on accurate specification of the shape of the selection curve.

Hook selection curves are suspected of being very broad and both monotone and unimodal curves have been fitted (Myhre 1969, Pope et al. 1975). Thus, by analysing hook selectivity we also cover the analysis of gillnet selectivity (Gaussian density function curve) and of trawls without small mesh codends (logistic curve). Holt (1963) and Pope et al. (1975) refer to an unpublished manuscript (Holt and Thomas 1957, unpubl.) that compares longline catches of cod to (non-selective) purse seine catches and which concludes that the hook selection curve is unimodal,
right skewed and may be modelled by the log-normal density function. However, no such application of skewed selection curves has appeared in the literature.

It is assumed that two or more different sizes of the same hook type are fished with equal effort. For example, Ralston (1990) collected catch data on four species of snapper (lutjanidae) using two different sizes (#20 and #28) of circle hook. The catch numbers for one of these species (Pristipomoides zonatus) are given in Table 3. For each hook size an equal number of hooks and same bait were used. The historical selection curve is fitted by "modelling" the ratio of catches in each lengthclass. Gaussian selection curves for different sizes of the same gear are typically assumed to have common spread and height (equal maximum fishing efficiency) and center proportional to the size of the gear. In linear dimension the #28 hook is approximately 40% larger than the #20, so if the selection curve for the #20 hook is parametrized by \( r_1(l) \equiv r(l; \mu, \sigma) = \exp(-(l - \mu)^2/2\sigma^2) \) then the curve for the #28 hook is \( r_2(l) = r(l; 1.4\mu, \sigma) \). Then,

\[
\frac{r_1(l)}{1 - r_1(l)} = \exp(0.48(\mu/\sigma)^2 - 0.4\mu l/\sigma^2) \equiv \exp(a + bl).
\]

Parameters \( a \) and \( b \) are traditionally estimated by an unweighted least squares fit of the log of the observed catch ratio (if defined) versus length (Holt 1963). The scarcer lengthclasses are usually omitted due to the extreme variability of the catch ratio. In the case of logistic selection curves, unweighted non-linear least squares has been used to fit \( r_1(l)/(1 - r_1(l)) \) to the observed catch ratios (Kimura 1978).

The SELECT approach provides a natural model for this type of data. For example, in the Gaussian curve case

\[
\frac{\phi_1(l)}{1 - \phi_1(l)} = \frac{r_1(l)/(r_1(l) + r_2(l))}{1 - r_1(l)/(r_1(l) + r_2(l))} \equiv \exp(a + bl)
\]

where \( \phi_1(l) \) is the proportion of the total lengthclass \( l \) catch that is caught on the small hook. Thus the analysis becomes a standard generalized linear fit using the logit link function. This gives \( \hat{a} = 0.9845 \) and \( \hat{b} = -0.0353 \), or \( \hat{\mu} = 23.23, \hat{\sigma} = 16.22. \) Figure 4 shows the fit of \( \phi_2(l) = 1/(1 + \exp(a + bl)) \) to the observed proportion of catch on the large hook, and the deviance residuals. The model fit appears to be good and the model deviance is only 9.9. The deviance residuals possibly show some lack of fit at the extremes, but these residuals are based on very few observations and are small in absolute value.

If the selection curve of the #20 hook is logistic and that of the #28 is a location or scale shifted version of it, then the #20 hook will have higher retention probability for all sizes of fish. From Table 3 it is clear that this is not the case since the #28 hook has higher catch for all lengthclasses above 30cm. The model confirms this since fits of logistic selection curves have model deviance of 116 for both the location and scale shifted options.
It is important to note that adequate model fit indicates only that \( \phi(l) \) is well modelled, and it can not by used to imply that the assumed form of \( r(l) \) is reasonable because the mapping between \( r(l) \) and \( \phi(l) \) is not one-to-one. The fitted Gaussian selection curves are given in Figure 5. They may be realistic over the range of lengthclasses represented in the data (20-50cm) but are clearly not plausible for smaller fish since they give a high relative probability of capture for zero length fish. This suggests that a selection curve passing through the origin may be more appropriate.

Scale families of the gamma and lognormal density functions (scaled to have unit height) were fitted to Ralston’s data. The unit height gamma selection curve is

\[
r_\gamma^2(l; \alpha, \beta) = \left( \frac{l}{(\alpha - 1)\beta} \right)^{(\alpha-1)} \exp(\alpha - 1 - l/\beta)
\]

and \( r_\gamma^2(l) = r_\gamma^2(l; \alpha, 1.4\beta) \). Then

\[
\logit(\phi_\gamma^2(l)) = (\alpha - 1) \log(1.4) - 2l/7\beta \equiv a + bl
\]

so the logit fit used to estimate the Gaussian selection curves also gives the estimated parameters for the gamma selection curves. For \( \hat{a} \) and \( \hat{b} \) from above this gives \( \hat{\alpha} = 3.926, \hat{\beta} = 8.091 \).

The unit height lognormal selection curve is

\[
r_\ln^4(l; \mu, \sigma) = \exp(\mu - \sigma^2/2 - (\log(l) - \mu)^2/2\sigma^2)/l
\]

and with \( r_\ln^4(l) = r_\ln^4(l; \mu + \log(1.4), \sigma) \) this gives

\[
\logit(\phi_\ln^4(l)) = (\log(1.4)/\sigma^2)(\sigma^2 - \mu - \log(1.4)/2 + \log(l)) \equiv a + b\log(l)
\]

This model can be fitted by logit analysis after transforming length to the log scale. This gives \( \hat{a} = -4.238, \hat{b} = 1.265 \), corresponding to \( \hat{\mu} = 3.447 \) and \( \hat{\sigma} = 0.5157 \). The deviance from this fitted model was 8.9. The three selection curves (Gaussian, gamma and lognormal) are overlaid in Figure 6.

The Gaussian and gamma are obtained by the same fit to \( \phi_1(l) \) and the lognormal provides a very similar fit. (For two of the three other snapper species caught in Ralston’s experiment the Gaussian and gamma selection curves fitted better than the lognormal. The difference in model deviance was never more than 0.13.) It does not appear that verification of one (if any) of these selection curves as an adequate representation of hook selectivity in snapper is possible from these data. One could argue that there may be some possible inference from the curves because over the range 20 to 44cm the three selection curves for the #20 hook are very similar. Nonetheless, this is assuming that one of the three curves provides a reasonable model of selectivity and at present there is not sufficient direct evidence to support this assumption.
When three or more different sizes of gear are fished simultaneously then the model becomes an application in analysis of polytomous data on the interval scale (McCullagh and Nelder 1989, p. 150) with the scale given by the relative gear sizes. In this case the Gaussian (location shifted) and gamma (scale shifted) selection curves will be distinguishable. This is particularly applicable for gillnets where experimental "gangs" of several different sizes are usually deployed. It is then also possible to fit a term quantifying the possible change in fishing efficiency for the different size meshes. This work is in progress. Preliminary results suggest that it is still difficult to distinguish between types of selection curve and that estimation of different fishing efficiency is sensitive to specification of the selection curve.

5. DISCUSSION

In indirect selectivity experiments no knowledge of relative abundance of different lengths in the population being fished is assumed and the total catch of each lengthclass is a sufficient statistic for \( \lambda_i \) - the Poisson rate at which fish in length-class \( i \) encounter the gear. The conditional maximum likelihood (SELECT) model presented above uses the familiar technique of conditioning on these Poisson totals (the total catch of each lengthclass) to obtain a binomial or multinomial distribution. Covered codend selectivity experiments can also be considered indirect. These have the advantage of simpler analysis because the expected proportion of catch in the (large mesh) codend of lengthclass \( l_i \) fish is simply \( r(l_i) \) whereas in trouser trawl studies this proportion is given by (1). However, practical problems with the covered codend (e.g. the possibility of the cover collapsing on the codend) have prompted many researchers to use the trouser trawl method or variants of it.

Direct selectivity experiments assume that \( \lambda_i \) is known, at least to a common constant. An interesting blend of direct and indirect experiments is discussed by Boy and Crivelli (1988) in a study where the length distribution of each ageclass of fish is known and so the population length distribution is a mixture of these age specific distributions.

For each of the gear types presented here (trawls, hooks and gillnets) there are fundamental questions of great practical importance that need to be addressed. For trawls these include quantifying the effect on selectivity of variations in gear design (e.g. codend mesh size and shape, tension of codend supporting ropes, use of escape windows, number of meshes circumference of codend) and of catch rate and haul duration. An appropriate family of selection curves has not yet been demonstrated for hooks. The question of increased fishing efficiency with increased mesh size is important to both trawl and gillnet studies. The SELECT model provides a better understanding of indirect selectivity experiments and will be a useful tool to answer some of these problems. It has also demonstrated that answers to certain problems, such as specification of a suitable hook selection curve, may not be practically possible from indirect studies.
Many research institutes worldwide are conducting indirect trawl selectivity experiments, but with selection curves fitted by free hand or ad-hoc methods it is difficult to assess the legitimacy of the conclusions. This would compromise any attempt at a combined assessment (or meta-analysis) of these results, which may be the route required to obtain sufficient information to truly understand the size-selectivity of fishing gear.

REFERENCES


Table 1. Catch of haddock from an alternate haul study (Pope et al 1975, pg 48).
Two hauls were completed with each mesh size. The small mesh is 35mm diamond.

<table>
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Table 2. Fit of logistic selection curve to 87 mm diamond mesh codend. Parameter estimates are given for both the equal \((p = 0.5)\) and unequal fishing efficiency assumptions. Values in parentheses are standard errors. The likelihood ratio test statistics for the goodness of fit hypothesis and equal fishing efficiency hypothesis are also given.

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\(H_0: \) model

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\(H_0: p = 0.5\)

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Table 3. Catch of snapper (*Pristipomoides zonatus*). Data from Ralston (1990).

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Fig. 1. Diagram of a trouser trawl with a vertical separator panel.

Fig. 2. Plot of the observed and expected proportions of total haddock catch in the large (87mm) meshed codend and the associated deviance residuals.

Fig. 3. Estimated logistic selection curve for haddock in an 87mm diamond mesh codend.

Fig. 4. Plot of the observed and expected proportions of total snapper (*Pristipomoides zonatus*) catch on the large (#28) hook and the associated deviance residuals.

Fig. 5. Estimated Gaussian selection curves for snapper (*Pristipomoides zonatus*) on #20 and #28 circle hooks.

Fig. 6. Estimated Gaussian, gamma and lognormal selection curves for snapper (*Pristipomoides zonatus*) on #20 and #28 circle hooks.
Propn in large mesh codend

Residual plot

Fig 2
87mm diamond mesh haddock selection curve

Retention probability

24 26 28 30 32 34 36 38 40 42 44 46

Length (cm)
Gaussian selection curves for #20 and #28 hooks

Relative selectivity

length (cm)
Selection curves for P. zonatus, #20 hook

Selection curves for P. zonatus, #28 hook