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Models of Codend Selection

by

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Abstract

Different models relating codend selectivity to net variables such as mesh size, extension length and codend diameter often fit experimental data almost equally well. The choice of an appropriate model must then be determined by other considerations. This is particularly important when, for management reasons, it is necessary to extrapolate outside the range of the experimental data. Two families of codend selectivity models were considered. One family was developed using empirical fits to data. The other was developed using arguments about the physical and biological mechanisms which underlie selectivity; this family provides plausible prior selectivity models which might be useful for extrapolation. The fit to experimental data and the extrapolatory behaviour of each model was investigated. Although an 'empirical' model often provided the best fit, this sometimes resulted in unrealistic predictions outside the range of experimental data and such models should not be used for extrapolation. When a plausible prior model gives the best fit to the data, its use is generally recommended. When this is not the case, procedures are suggested for balancing the advantages of a plausible prior model with the empirical evidence for an alternative model.

Gear Selectivity/Technical Interactions Symposium

1 Introduction

Recent investigations of codend selection have stressed the importance of using appropriate statistical methods in fitting models to data (Fryer, 1991; Millar, 1992; Millar and Walsh, 1992) and of taking into account factors other than mesh size, such as codend diameter and the length of the extension piece (Reeves *et al.*, 1992; Galbraith *et al.*, 1994). However, relatively little attention has been given to the most appropriate functional form to be fitted. The use of a logistic curve relating retention probability to length is now commonplace in the field (Pope *et al.*, 1975), although recently, various asymmetric models (Millar, 1991) and nonparametric models (Millar and Naidu, 1993) have been used. Reeves *et al.* (1992) show that the parameters of the logistic curve can vary with factors such as mesh size, codend diameter *etc.* and that these relationships can be expressed in a number of different ways. These various alternatives may fit the data almost equally well and a choice amongst them may have to be guided by other considerations (see *eg* the discussion by Reeves *et al.* (1992) about the choice between their equations (5) and (7)).

The differences between alternative models may only become apparent when they are extrapolated beyond the range of the data fitted. Formally, of course, such extrapolation is undesirable. Regrettably, however, it is often unavoidable in practice; for example, when considering the effect of an increase in mesh size beyond that used in selectivity trials to date. In such circumstances, the known dangers of extrapolation may be reduced by using only models which are 'robust' to extrapolation, in the sense that they give 'sensible' predictions which are consistent with whatever understanding of the underlying physical and biological mechanisms are available. Indeed, models robust to extrapolation may well be preferred to other candidate models, even when their fit to experimental data is marginally worse, if the purpose is prediction outside the range of the data. A well known situation in which this occurs is in fitting polynomial regression models; such models are often useful for describing trends in data, but should rarely be used for extrapolation. The selection of appropriate families of models rarely receives the attention it deserves; Gilchrist (1984) gives a useful discussion of the issues involved.

This paper considers five models of codend selection. The first two, which we will loosely call 'empirical' models, were used by Reeves *et al.* (1992) and Galbraith *et al.* (1994) to demonstrate the effect of mesh size, codend diameter and extension length on selectivity, using experimental data. The remaining models, which we call 'structural' models, are developed using arguments about the underlying physical and biological mechanisms of codend selection and are more directly based on the traditional treatment of selectivity data in terms of selection factors and ranges. These models are plausible and internally consistent ***a priori*** and therefore should provide reasonable, feasible predictions. Sections 2 and 3 describe the empirical and structural models respectively. Section 4 investigates the fit of each model to four sets of selectivity data. Section 5 considers the interpretation and application of each model, with particular emphasis on extrapolation. Finally, section 6 considers the management implications of model selection.

2 Empirical Models

Reeves *et al.* (1992) and Galbraith *et al.* (1994) describe selectivity trials for haddock, whiting and cod using

- two seine nets and a single boat trawl with mesh sizes of approximately 80 - 100 mm, extension lengths of 0 - 13 m and codend diameters of 2 - 4 m.
- a pair trawl with mesh sizes of 80 - 110 mm, codend diameters of 2 - 4 m, and a constant extension length of about 11 m.

Using these data, they investigated models of the form

Model E1: $$\log\left(\frac{p}{1-p}\right) = \alpha_1 + \alpha_2 m + \alpha_3 e + \alpha_4 c + (\alpha_5 + \alpha_6 m + \alpha_7 e + \alpha_8 c)\, l$$

where p, l, m, e, c are retention probability, fish length, mesh size, extension length and codend diameter respectively and where α_1, α_2, ... α_8 are unknown parameters which are species / net dependent. Further, they found two simplifications of this model,

Model E2: $$\log\left(\frac{p}{1-p}\right) = \alpha_1 + \alpha_2 m + \alpha_3 e + \alpha_4 c + \alpha_5 l$$

Armstrong Model
& length varies linearly.

Model E3: $$\log\left(\frac{p}{1-p}\right) = \alpha_1 + \alpha_3 e + \alpha_4 c + (\alpha_5 + \alpha_6 m)\, l$$

which both adequately described the selectivity data for all species / net combinations over the range of experimental mesh sizes, extension lengths and codend diameters. Full details are given in the references above. For comparative purposes, we also consider here the null model

Model EN: $$\log\left(\frac{p}{1-p}\right) = \alpha_1 + \alpha_5 l.$$

Fixed L50 + Sel Range.
∴ Stupid.

3 Structural Models

The traditional parameterisation of a logistic curve for a particular mesh size m (and any other relevant variables) is in terms of the 50% retention length l_{50} and the selection range $SR = l_{75} - l_{25}$. It has also been traditional to express the 50% retention length in scaled form, as the selection factor $SF = l_{50}/m$. It has not been so common to express the selection range in the equivalent scaled form, as the range factor $RF = SR/m$, but we shall find this useful also. Such non-dimensional scaling is a common procedure in physics and engineering and (although sometimes merely a matter of convenience) often reflects fundamental properties of the system under discussion. This leads to the powerful technique confusingly known as dimensional analysis, much used in fluid dynamics (see, for example, Fender, 1957).

The problem of mesh selection is essentially geometrical. Selectivity can be thought of as the passage of rather similarly shaped objects of various sizes (fish) through square or diamond shaped (but somewhat deformable) holes. Given a particular net, and a certain size composition of some species of fish, what would happen if the size of mesh and the sizes of all the fish were doubled (or halved)? If we were dealing with ball bearings and rigid round holes, the answer would be obvious; the same fraction of balls would pass through the holes. In the case of fish and fishing nets, the answer is not so clear. Both fish and net are somewhat deformable and fish can force their way through in a tight squeeze. Nevertheless, this only affects fish whose escape is borderline. For those which are substantially too large or too small, the outcome will be the same in the re-scaled situation. Thus, on very general grounds, the probability of escape should be similar.

These scaling and dimensional arguments suggest that a selectivity model in which l_{50} is directly proportional to mesh size, or equivalently SF is constant, should be a good first approximation. This gives

$$l_{50} = f(\underline{x})m,$$

where $f(\underline{x})$ is a (dimensionless) function of net variables other than mesh size, such as extension length and codend diameter.

Approximations based on such geometrical arguments are just what are needed for plausible prior models. However, they must be tempered by a number of considerations. For example, although mesh size may be doubled, a 50 cm haddock is not exactly double a 25 cm haddock, either in girth, or in its wriggling power. Secondly, such geometrical arguments assume that other variables affecting selectivity remain unchanged. However, in practice, changes in mesh size require changes in other net variables, so that the net continues to function properly. For example, keeping a constant codend diameter is attained by reducing the number of mesh sizes round the codend. This point is discussed further later.

Given that l_{50} is of the form $f(\underline{x})m$, and that a logistic selectivity curve is appropriate for any particular set of net variables, some simple algebra shows that the selectivity model must be of the form

$$\log\left(\frac{p}{1-p}\right) = g(\underline{x})m^{1-\delta} + h(\underline{x})lm^{-\delta}$$

where $g(\underline{x})$ and $h(\underline{x})$ are functions of net variables other than mesh size and where δ is an unknown parameter. The selection range for this model is then

$$SR = 2\log(3)m^{\delta}/h(\underline{x}).$$

Geometrical arguments can again be used to suggest that SR should also be directly proportional to mesh size and that an appropriate prior value for δ is therefore 1. Such arguments are less compelling for SR than for l_{50}. Whereas the relationship between l_{50} and mesh size is determined mainly by changes in girth with fish length, the relationship between SR and mesh size is determined mainly by how the deformity of the net changes with mesh size and how the deformity of fish and variation in girth change with fish length. Nevertheless, it is quite reasonable that SR increases with mesh size at a rate close to linear, suggesting that an appropriate value for δ is close to 1.

A fairly general model of this form, incorporating extension length and codend diameter, is

$$\log\left(\frac{p}{1-p}\right) = (\alpha_1 + \alpha_2 e + \alpha_3 c)m^{1-\delta} + (\alpha_4 + \alpha_5 e + \alpha_6 c)lm^{-\delta}$$

It turns out that, for the selectivity data described earlier, profile likelihood intervals for δ, although wide, generally contain unity (Table 1), suggesting that if l_{50} is directly proportional to mesh size, then SR is also directly proportional to mesh size. This gives

Model S1: $$\log\left(\frac{p}{1-p}\right) = (\alpha_1 + \alpha_2 e + \alpha_3 c) + (\alpha_4 + \alpha_5 e + \alpha_6 c)lm^{-1}.$$

Similar to models E2, E3 and EN, we also consider

Model S2: $$\log\left(\frac{p}{1-p}\right) = (\alpha_1 + \alpha_2 e + \alpha_3 c) + \alpha_4 lm^{-1}$$

Model S3: $$\log\left(\frac{p}{1-p}\right) = \alpha_1 + (\alpha_4 + \alpha_5 e + \alpha_6 c)\, lm^{-1}$$

Model SN: $$\log\left(\frac{p}{1-p}\right) = \alpha_1 + \alpha_4 lm^{-1}.$$

which are nested within model S1.

These models are interpreted as follows:

S1: Both the selection factor *SF* and the range factor *RF* depend on the gear variables other than mesh size (*ie* codend diameter and extension length), but in different ways,

S2: *RF* is constant but *SF* depends on the other gear variables,

S3: Both *SF* and *RF* depend on the other gear variables, but in the same way,

SN: Both *SF* and *RF* are constant. [illegible]

Note that a model in which *SF* is constant and *RF* depends on the other gear variables can be formulated as

Model S4: $$\log\left(\frac{p}{1-p}\right) = (\alpha_1 + \alpha_2 e + \alpha_3 c) \times (1 + \alpha_4 lm^{-1})$$

but this model is not considered further here.

4 Model Fits to Data

The empirical and structural models described above were fitted to the haddock, whiting and cod selectivity data of Reeves *et al.* (1992) and Galbraith et *al.* (1994), using the fixed and random effects model of Fryer (1991). Note that the general quality of the data was good for haddock, reasonable for whiting and poor for cod, and so poor for cod / single boat trawl that no model could be fitted to these data. Thus, the results for haddock should be the most 'reliable' and haddock has always been used below for illustrative purposes.

All the models revealed the same qualitative effect of mesh size, extension length (where appropriate) and codend diameter on selectivity and gave broadly similar fitted values within the range of experimental data. No model was perfect. For example, all models could be improved by the inclusion of quadratic terms; however, as these terms were not consistent between nets and / or species and as the improvements in fit were not large, more complicated models have not been considered.

A formal comparison of the model fits is not straightforward because the number of parameters varies between models and because the empirical and structural models are not nested. A useful model selection criterion is Akaike's Information Criterion (*AIC*) (Akaike, 1973, 1974), which is defined to be

AIC = - 2 (maximised log-likelihood) + 2 (number of estimated parameters). Models within two units of the lowest *AIC* are considered to be plausible 'best' models, and of these, the model with the fewest parameters is usually selected (Jones, 1993). Table 2 gives the *AIC* for each model / species / net, scaled so that the minimum ***AIC*** is zero.

No model is consistently the best. However, on the basis of *AIC*, one of the empirical models usually provides the best fit, and of these, model E3 would appear to be a good general choice, since it has comparatively few parameters and performs reasonably for all the data sets. In most cases, one of the structural models also fits reasonably, with the notable exception of seine 1.

5 Interpretation and Application of Model Fits

Expressions for l_{50} and *SR* for each model are given in Table 3. By construction, l_{50} and *SR* are directly proportional to mesh size for the structural models. A variety of behaviours is possible for model E1, depending on the values of the parameters $\underline{\alpha}$. However, for E2, l_{50} varies linearly with (but is not generally directly proportional to) mesh size and *SR* is independent of mesh size and for E3, both l_{50} and *SR* vary as the inverse of a linear function of mesh size.

Figure 1 shows how estimates of l_{50} for haddock depend on the selectivity model as mesh size increases from 80 - 150 mm. Throughout, an extension length of 9 m (11 m for the pair trawl) and a codend diameter of 3 m have been assumed. These are roughly the average values used in the selectivity trials and explain why the estimates of l_{50} for the structural models are so similar; real differences between these models only appear at different values of extension length and codend diameter. There is reasonable agreement between the two sets of models within the range of mesh sizes used in the selectivity trials (80 - 100 mm for seine 1, seine 2 and the single trawl and 80 - 110 mm for the pair trawl). However, extrapolating outside the range of experimental mesh sizes causes the estimates of l_{50} to diverge. In particular, the estimates of l_{50} from models E1 and E3 rapidly increase due to the inverse linear relationship between l_{50} and mesh size. For the data sets considered here, the estimates of l_{50} from model E2 increase faster with mesh size than those for the structural models, although this need not necessarily be the case.

Figure 2 shows how the estimates of selection range for haddock depend on the selectivity model as mesh size increases from 80 - 150 mm. Again, there is reasonable agreement within the range of mesh sizes used in the selectivity trials, but the estimates of *SR* diverge outside this range. Again, estimates of *SR* based on models E1 and E3 increase rapidly with mesh size.

6 Management Implications

The choice of an appropriate selectivity model depends on the purpose for which it is to be used. For example, all the models considered here demonstrate the effect of mesh size, extension length and codend diameter on the selectivity of the four experimental nets. Further, if the aim is to estimate selectivity curves within the range of experimental mesh sizes, extension lengths and codend diameters, then a sensible strategy would be to use the 'best' model as determined, for example, by *AIC*. Indeed, for the selectivity trials considered here, all the models would give 'similar' estimates.

However, other considerations become important when extrapolating outside the range of experimental data. For example, although model E3 often provided the best fit to the experimental data, extrapolations using this model are highly inconsistent with our intuitive ideas on how a net should behave (see Figures 1 and 2), so model E3 should not be used for extrapolation. The same applies to the more general model E1 unless the value of the parameter α_6 is negligible.

Further, consider the case of haddock / seine 1. Here, the empirical models fit much better than the structural models. However, some judicious model construction reveals a structural model with a comparable fit; namely

$$\log\left(\frac{p}{1-p}\right) = (\alpha_1 + \alpha_2 e + \alpha_3 n) + \alpha_4 l m^{-1}$$

where n is the number of meshes round the codend, (highly correlated with the codend diameter). This model suggests that doubling the mesh size, whilst keeping the extension length and the number of meshes round the codend fixed, would double l_{50}. However, suppose that $n = 120$ and that mesh size is doubled from 80 to 160 mm. Although $n = 120$ and $m = 80$ mm represent a practical net configuration, $n = 120$ and $m = 160$ would create considerable 'ballooning' of the codend, leading to quite unpredictable selection behaviour and extrapolations from this model should be viewed with caution.

Despite such cautionary tales, the need to extrapolate remains. In general, the use of a structural model would be recommended when it provides the best fit to the data. However, an appropriate choice is less clear when, for example, model E2 provides a better fit than any of the structural models, since it is then necessary to balance the advantages of a geometrically consistent prior model with the empirical evidence. A wishy-washy solution would be to present results from both sets of models. If these are close, the extrapolations are insensitive to the choice of model and one can proceed with confidence using either prediction. If the extrapolations differ greatly, then the potential dangers arising from uncertainty over the choice of model are clear and an informed decision can be made based on whether one is an empiricist or a structuralist and on any other relevant considerations.

For example, suppose we wish to reduce haddock discards from pair trawls by increasing l_{50} to 40 cm, say, by an appropriate increase in mesh size. From Table 2, models E2 and E3 are competing 'best' models because they are within two units of the minimum *AIC*. Model E2 is preferred to model E3 for extrapolation and suggests an l_{50} of 40 cm would be achieved by increasing the mesh size to 118 mm (with an approximate 95% confidence interval, conditional on model E2 being correct) of 114 - 126 mm. Model S2 also has a pretty good fit and gives a target mesh size of 130 mm with a 95% confidence interval of 125 - 136 mm. The two predictions do not completely conflict, given that the confidence intervals overlap. A general estimation method would be to take a weighted average of the two estimators where the weights are based on the strength of our prior preference for a structural model and the difference in the empirical fits of the two models. However, the question of an appropriate weighting function immediately arises. A more satisfactory solution would be to look at the short and long term implications of each model choice, assuming it to be correct model, and under mutual model misspecification. That is, what are the biological, social and economic consequences of an increase in mesh size to 130 mm when l_{50} increases to 40 cm as predicted by model S2 or to 46 cm as predicted by model E2? Similarly, what would be the effect of an increase in mesh size to 120 mm? Such an approach falls naturally into the philosophy of risk analysis which is being increasingly used in fisheries management.

When extrapolation is necessary, a good principle is to choose models which are asymptotically sensible (*ie* do not yield infeasible results in any limiting situation). On this principle, structural models will often be preferred, since, except in special cases, extrapolation using empirical models can lead to unrealistic estimates of l_{50} and *SR* for mesh sizes within a reasonable range.

References

Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. Second International Symposium on Information Theory, (B.N. Petrov and F. Csaki, Eds), Budapest. Akademia Kaido, 267-281.

Akaike, H. 1974. A new look at statistical model identification. IEEE Trans. on Automatic Control, AC-19, 716-723.

Fender, D.H. 1957. General physics and sound. English Universities Press.

Fryer, R.J. 1991. A model of between-haul variation in selectivity. ICES J. Mar. Sci., 48: 281-290.

Galbraith, D.K., Fryer, R.J. and Maitland, K.M.S. 1994. Demersal pair trawl cod-end selectivity models. Fish. Res., **: ***-***.

Gilchrist, W. 1984. Statistical modelling. John Wiley and Sons, New York.

Jones, R.H. 1993. Longitudinal data with serial correlation: a state-space approach. Chapman and Hall, London.

Millar, R.B. 1991. Estimation of asymmetric selection curves for trawls. ICES C.M./B:56.

Millar, R.B. 1992. Estimating the size-selectivity of fishing gear by conditioning on the total catch. J. Amer. Stat. Assoc., 87: 962-968.

Millar, R.B. and Naidu, K.S. 1993. Nonparametric estimation of selection curves: letting the data speak for themselves. Fishery Bulletin, 91(3): ***-***.

Millar, R.B. and Walsh, S.J. 1992. Analysis of trawl selectivity studies with an application to trouser trawls. Fish. Res., 13: 205-220.

Pope, J.A., Margetts, A.R., Hamley, J.M. and Akyuz, E.F. 1975. Manual of methods for fish stock assessment. Part 3 - selectivity of fishing gears. FAO Fish. Tech. Pap., 41, Rev. 1.

Reeves, S.A., Armstrong, D.W., Fryer, R.J. and Coull, K.A. 1992. The effects of mesh size, cod-end extension length and cod-end diameter on the selectivity of Scottish trawls and seines. ICES J. Mar. Sci., 49: 279-288.

Table 1 Maximum likelihood estimates and 95% profile likelihood intervals for δ

	Seine1	Seine2	Single Trawl	Pair Trawl
Haddock	1.7 (1.1, 2.3)	1.1 (0.4, 1.7)	1.3 (0.5, 2.1)	1.3 (0.5, 2.2)
Whiting	1.4 (0.6, 2.2)	1.2 (0.6, 1.8)	0.1 (<0, 1.1)	0.2 (<0, 1.8)
Cod	1.7 (1.8, 2.5)	1.2 (0.6, 1.9)	-	-

Table 2 Akaike's Information Criterion for each model / species / net scaled so that the minimum *AIC* is zero.

	Seine1	Seine2	Single Trawl	Pair Trawl
Haddock, Model EN	275.2	96.4	119.4	48.2
Model SN	202.6	60.6	83.4	21.3
Model E1	2.9	1.6	0.0	1.8
Model E2	11.2	19.4	11.9	1.7
Model E3	0.0	0.0	4.1	0.0
Model S1	69.0	4.0	5.5	5.3
Model S2	65.8	5.6	16.1	3.5
Model S3	90.0	5.8	48.9	5.7
Whiting, Model EN	124.0	88.4	96.6	31.9
Model SN	88.6	50.4	73.2	18.6
Model E1	5.0	19.4	3.2	2.3
Model E2	9.8	35.2	0.0	0.0
Model E3	0.0	16.0	9.8	2.9
Model S1	1.4	0.0	17.8	3.3
Model S2	18.0	20.2	16.8	3.1
Model S3	3.8	10.0	33.4	1.3
Cod, Model EN	216.0	109.2		23.5
Model SN	152.8	58.8		13.6
Model E1	0.0	5.7		1.9
Model E2	10.0	21.0		6.1
Model E3	2.0	0.0		3.8
Model S1	66.6	11.2		0.0
Model S2	66.4	9.0		2.6
Model S3	85.4	29.0		7.7

Table 3 Expressions for l_{50} and SR for each model

	l_{50}	SR
Model EN	$-\dfrac{\alpha_1}{\alpha_5}$	$\dfrac{2\log(3)}{\alpha_5}$
Model E1	$-\dfrac{\alpha_1 + \alpha_2 m + \alpha_3 e + \alpha_4 c}{\alpha_5 + \alpha_6 m + \alpha_7 e + \alpha_8 c}$	$\dfrac{2\log(3)}{\alpha_5 + \alpha_6 m + \alpha_7 e + \alpha_8 c}$
Model E2	$-\dfrac{\alpha_1 + \alpha_2 m + \alpha_3 e + \alpha_4 c}{\alpha_5}$	$\dfrac{2\log(3)}{\alpha_5}$
Model E3	$-\dfrac{\alpha_1 + \alpha_3 e + \alpha_4 c}{\alpha_5 + \alpha_6 m}$	$\dfrac{2\log(3)}{\alpha_5 + \alpha_6 m}$
Model SN	$-\dfrac{\alpha_1}{\alpha_4} m$	$\dfrac{2\log(3) m}{\alpha_4}$
Model S1	$-\dfrac{(\alpha_1 + \alpha_2 e + \alpha_3 c) m}{\alpha_4 + \alpha_5 e + \alpha_6 c}$	$\dfrac{2\log(3) m}{\alpha_4 + \alpha_5 e + \alpha_6 c}$
Model S2	$-\dfrac{(\alpha_1 + \alpha_2 e + \alpha_3 c) m}{\alpha_4}$	$\dfrac{2\log(3) m}{\alpha_4}$
Model S3	$-\dfrac{\alpha_1 m}{\alpha_4 + \alpha_5 e + \alpha_6 c}$	$\dfrac{2\log(3) m}{\alpha_4 + \alpha_5 e + \alpha_6 c}$

m = const. prop'ty fact.

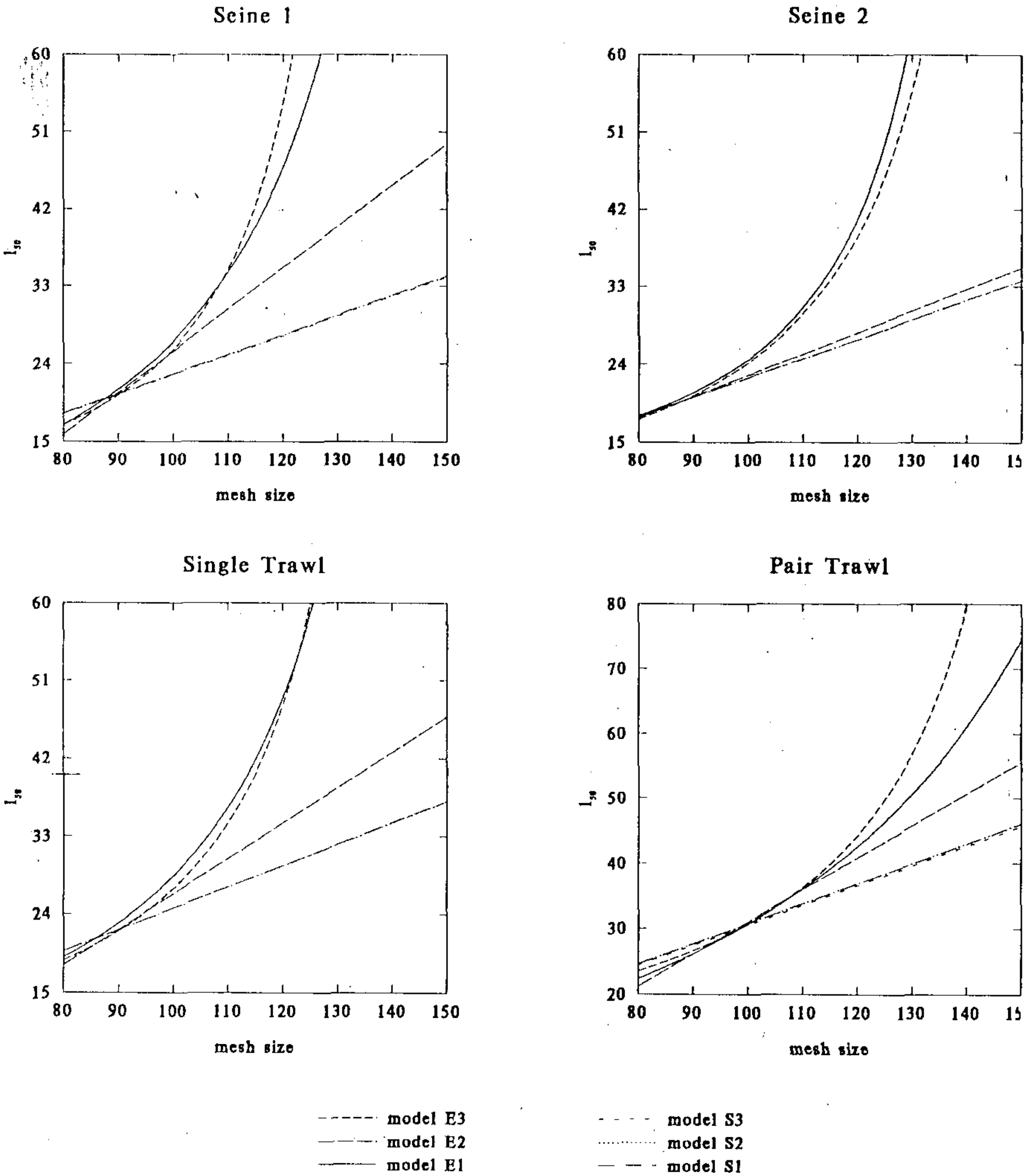

Figure 1. Haddock l_{50}s for mesh sizes between 80 and 150 mm predicted from models E1-3 and S1-3.

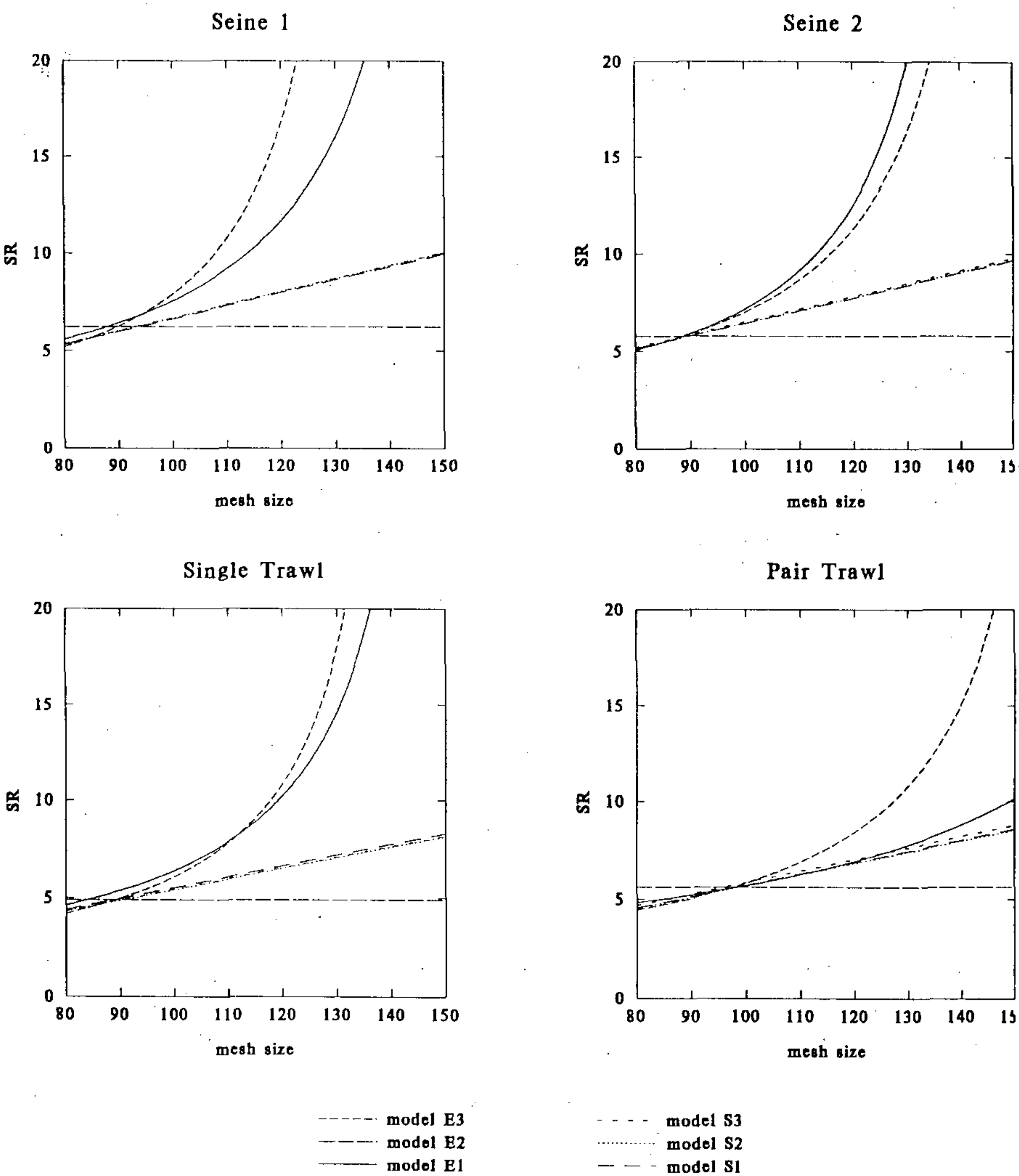

Figure 2. Haddock *SRs* for mesh sizes between 80 and 150 mm predicted from models E1-3 and S1-3.