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A meta-analysis of plaice size-selection data in otter trawl codends

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Abstract

The influence that mesh size, the number of open meshes around the circumference, twine thickness and catch size have on the size-selection of plaice (*Pleuronectes platessa*) in otter trawl codends is investigated by synthesising the data from 164 hauls using 25 gear configurations during 9 trips.

All these variables have an effect on selection. The 50% retention length (L50) increases by 1.9 cm for every 10 mm increase of mesh size and decreases by 0.24 cm for every doubling of catch. The selection range decreases by 3.8 % for each increase of 10 open meshes and increases by 12.3 % for each 1 mm increase of twine thickness. The mesh size and twine thickness effects have strong support from the data. The open meshes and catch size effects have less support and should be treated with some caution.

There is good correspondence between the predictions of the analysis presented here and the L50 estimates of beam trawl codend selectivity trials, which is noteworthy given the many operational differences between the two fishing methods.

Keywords: plaice size selectivity, otter trawl, meta analyses, mesh size, twine thickness, meshes in circumference

Introduction

The Landing Obligation is a key component of the recently reformed European Union (EU) Common Fisheries Policy (Karp et al., 2019). It aims to eliminate discards of species that are subject to quota restrictions in the European Atlantic fisheries and that have minimum landing sizes in the European Mediterranean fisheries. Minimum conservation reference sizes (MCRS) have been set for these species and fish caught below their MCRS can neither be discarded nor sold for human consumption. They must be brought ashore, and consequently there can be additional storage, handling and onshore disposal costs. In the European Atlantic quota fisheries, these fish are counted against quota and hence, their capture is a direct economic loss (Karp et al., 2019). Furthermore, in mixed fisheries, fishing operations may have to stop if a species, whose quota is exhausted, cannot be avoided. Such species have been termed ‘choke species’, and the North Western Waters Advisory Council has identified haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), Atlantic cod (*Gadus morhua)*, European plaice (*Pleuronectes platessa*), hake (*Merluccius merluccius*) and sole (*Solea solea*) as being at moderate or high risk of being choke species, depending on the fishery (NWWAC, 2018; Fitzpatrick et al., 2019).

One way of addressing the Landing Obligation is to reduce the capture of unwanted species and sizes by improving the selectivity of fishing gears. Such an approach has long been used as a management measure to promote the sustainability of commercial fisheries worldwide (O’Neill et al., 2019, Broadhurst, 2000; Graham 2010). Attention has generally been directed at the main target species and often, relatively little is known about the secondary target and/or other bycatch species. In North Western European Waters there have been many studies of the selective performance of demersal otter trawls in relation to haddock, cod and *Nephrops* (*Nephrops norvegicus*), and of how codend design parameters such as mesh size, number of open meshes in circumference, twine thickness, mesh shape etc. affect the selectivity of these species (Fryer et al, 2016, 2017; Madsen, 2007; ICES, 2007). By comparison there are few studies of the selection of species such as whiting, plaice, hake, saithe (*Pollachius virens*), sole, megrim (*Lepidorhombus whiffiagonis*) and monkfish (*Lophius piscatorius* and *Lophius budegassa*) (Vogel et al., 2017a; Vogel et al., 2017b; Pol et al., 2016). With the onset of the Landing Obligation, it has become increasingly important to better understand the selection of these species so that (i) unmarketable individuals can be avoided where they are a target and (ii) they do not choke a fishery where they are a bycatch.

In this paper, we focus on the selectivity of plaice in demersal otter trawl fisheries. Plaice is a target species in some Danish otter trawl fisheries and an important bycatch species in many others in North Western European waters (Fonteyne and M'Rabet, 1992; Bayse et al. 2016). There have not been many studies of the selectivity of plaice in otter trawl codends and here, in order to get a better overview, we synthesise and combine size-selection data across trials and develop empirical models over a broader range of gear variables and values than is possible with individual trials. In particular, we combine seven studies which all used the covered codend method (Wileman et al., 1996) and for which we have the raw data, allowing the effect of gear variables to be explored using conventional size-selection statistical models. We develop models for the 50% retention length (L50) and selection range (SR) and compare model predictions with point estimates from other otter trawl trials which could not be included in the analysis, beam trawl trials and a seine net trial.

Data

We carried out searches of Google Scholar (http://scholar.google.com); ICES historical Conference and Meeting (CM) documents (www.ices.dk); and Web of Science (https://apps.webofknowledge.com/) and identified 7 studies of plaice size-selection by diamond mesh codends fished by demersal otter trawls conducted using the covered codend method (Table 1). We also identified one study that used the twin trawl method (Frandsen et al., 2009), but excluded it from the analysis because of the difficulties of combining data collected with different methods. The covered codend studies comprised 164 hauls using 25 different gear configurations over the course of 9 trips. Most gear configurations corresponded to different codends, since the studies typically investigated the effect of codend variables such as mesh size and twine thickness. However, the six gears in trip 9 corresponded to three codends, each fished with two sweep angles. Numbers of plaice at length retained in the test codend and the cover with the corresponding sub-sampling fractions were available for all hauls.

In most trips, gears were fished independently of each other. However, trips 3 and 5 tested two gears simultaneously (both with covers), fishing them as a twin trawl. There were 14 and 5 paired hauls in trips 3 and 5 respectively giving 28 and 10 ‘individual’ hauls for estimating codend selection (Table 1). For simplicity, the ‘individual’ hauls from each pair were treated as independent in the analysis below. This can justified to some extent by the fact that a generalised linear mixed model estimate of the within-pair covariance in selection was, though moderate numerically, non-significant statistically ($p = 0.15$). However, we also explore the robustness of our results to this assumption (see Methods).

The explanatory variables considered were:

- Mesh size: the inside codend mesh size (mm). All gears had diamond mesh.

- Meshes around: the number of open meshes around the codend circumference.
- Twine thickness: the nominal codend twine thickness (mm). All but 5 gears (on trips 6 and 7) had double twine. Single twine thickness was converted to a double twine equivalent through the formula double = single × $6^{-0.25}$ (Fryer et al, 2016).
- Catch: the total catch bulk in the codend (kg).
- Panel: the presence of a square mesh panel. Three gears (trips 3 and 5) had a square mesh panel on the bottom of the extension.

A scatterplot matrix of these variables is presented in Figure 1. There were only three gears with a square mesh panel and these had the largest number of meshes around. To avoid confounding the two variables in model selection, panel was excluded from further consideration. This choice was also motivated by the absence of a significant panel effect on plaice selection in the original study (Frandsen et al, 2011).

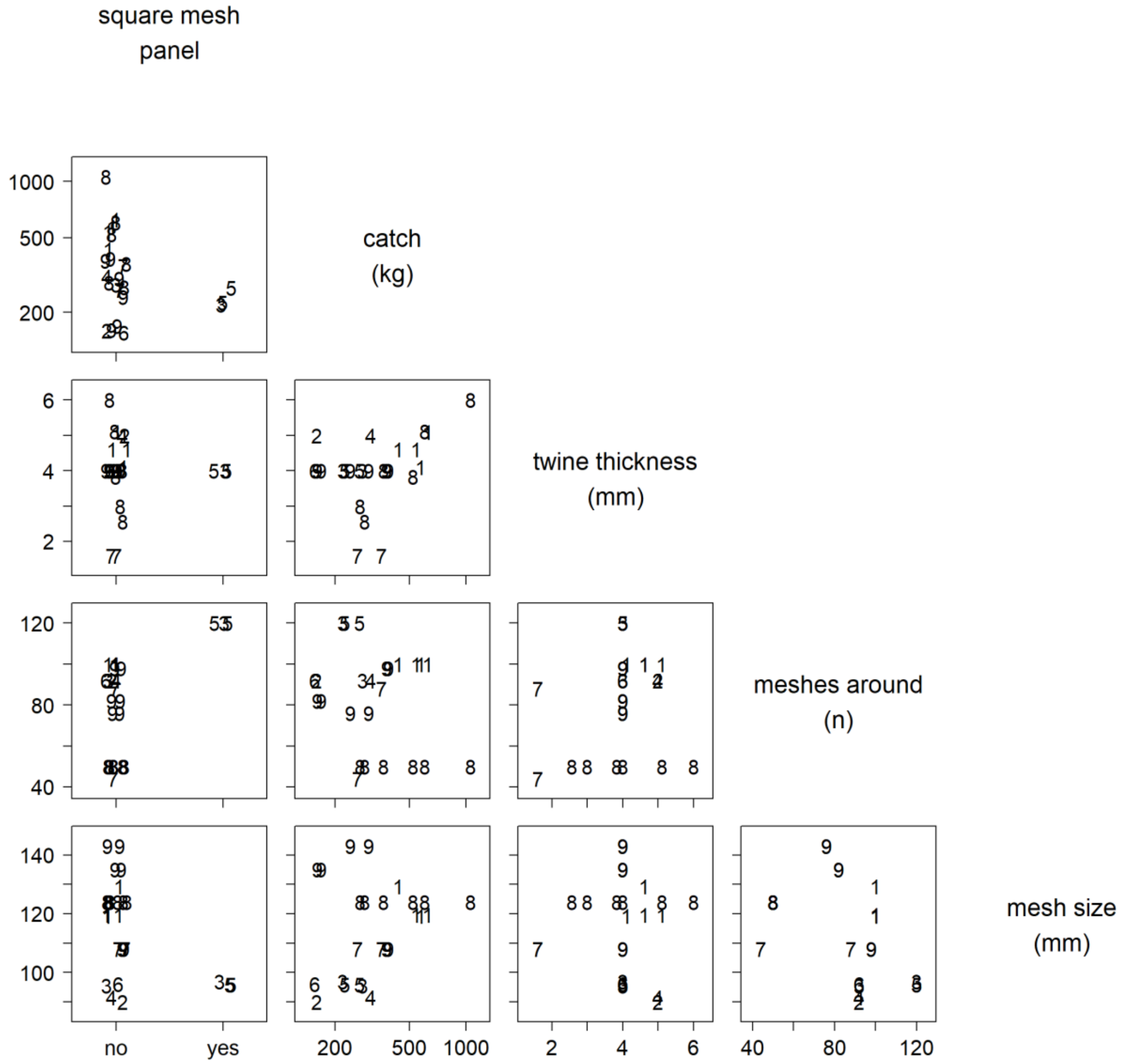

Figure 1. Scatterplot matrix of the explanatory variables. Each point corresponds to a different gear and is labelled by the trip it comes from (Table 1). For catch, the median value for each gear has been plotted on the log scale. The points are jittered slightly to reduce overlay.

Methods

The effect of the explanatory variables on selection was investigated using generalized nonlinear mixed models, extending the approach used by O'Neill et al (2016) by including more random effects. In essence, selection was assumed to be a linear logistic function of length, with the slope and intercept varying randomly from haul to haul about mean values which depend on the explanatory variables (Fryer, 1991).

However, for easier interpretation, the fixed component of the model was constructed by assuming that the L50 and log SR were linear functions of the explanatory variables. The mean intercept and slope were thus nonlinear functions of the explanatory variables. The log scale was used for the SR relationship to ensure predicted values of SR were positive.

The models were formally specified as follows. Let n_{hl1} and n_{hl2} be the numbers of fish of length l in haul h counted in the codend and cover respectively and let q_{hl1} and q_{hl2} be the corresponding sub-sampling fractions. It was assumed that

$$n_{hl1} \sim \text{Binomial}\left(n_{hl1} + n_{hl2},\ \phi_{hl}\right)$$

where

$$\text{logit}\ \phi_{hl} = \alpha_h + \beta_h l + \log\left(q_{hl1}/q_{hl2}\right) \tag{1}$$

(Millar and Fryer, 1999). The parameters α_h and β_h defined the selection curve for haul h and were assumed to have a bivariate normal distribution with mean values $\alpha(\mathbf{x}_h)$ and $\beta(\mathbf{x}_h)$ which depend on $\mathbf{x}_h$, the values of the explanatory variables for haul h. The L50 and log SR of the mean selection curve were assumed to be linearly related to the explanatory variables

$$\text{L50}(\mathbf{x}_h') = \mathbf{x}_h'\gamma\ ; \quad \log \text{SR}(\mathbf{x}_h') = \mathbf{x}_h'\delta \tag{2}$$

where γ and δ are parameters that controlled the linear relationship. Thus, $\alpha(\mathbf{x}_h)$ and $\beta(\mathbf{x}_h)$ were nonlinearly related to the explanatory variables through

$$\alpha(\mathbf{x}_h) = -\frac{\log(9)\,\text{L50}(\mathbf{x}_h)}{\text{SR}(\mathbf{x}_h)}; \quad \beta(\mathbf{x}_h) = \frac{\log(9)}{\text{SR}(\mathbf{x}_h)}$$

Following preliminary investigation of the data, three variance components were included to account for random variation in selection between trips, between gears (within trips) and between hauls. Specifically,

$$\alpha_h = \alpha(\mathbf{x}_h) + \zeta_{trip(h)} + \zeta_{gear(h)} + \zeta_h; \quad \beta_h = \beta(\mathbf{x}_h) + \xi_{trip(h)} + \xi_{gear(h)} + \xi_h \tag{3}$$

where *trip*(h) and *gear*(h) denote the trip and gear corresponding to haul h, and the random effects $\left(\zeta_{trip(h)},\ \xi_{trip(h)}\right)$, $\left(\zeta_{gear(h)},\ \xi_{gear(h)}\right)$ and $\left(\zeta_h,\ \xi_h\right)$ had bivariate normal distributions with zero means and variances D_{trip}, D_{gear} and D_{haul} respectively. A fourth variance component was included to account for residual within-haul overdispersion by extending equation (1) to give

$$\text{logit}\ \phi_{hl} = \alpha_h + \beta_h l + \log\left(q_{hl1}/q_{hl2}\right) + \epsilon_{hl} \tag{4}$$

where the ϵ_{hl} were independent and normally distributed with zero mean and variance σ^2. The validity of the variance structure was assessed using standard residual plots and biplots of the estimated random effects.

The relationship between L50, log SR and the explanatory variables was investigated by first fitting a 'full' model in which:

L50 ~ 1 + mesh size + meshes around + twine thickness + log catch

log SR ~ 1 + mesh size + meshes around + twine thickness + log catch

Here, 1 denotes an intercept and mesh size, meshes around, twine thickness and log catch denote linear terms in these explanatory variables. Catch was log transformed to reduce the effect of skewness. All sub-models were then fitted and the final model chosen was that with the lowest Akaike Information Criterion (AIC). All models were fitted by maximum likelihood in the R statistical environment (R Core Team, 2017) building on the functions in the lme4 package (Bates et al, 2015).

To ensure no single trip was driving the results, the final model was refitted excluding each trip in turn and the parameter estimates and their significance were reassessed. The final model was also refitted excluding the three gears with a panel (trip 5 and half of trip 3), which provides a data set (and fit) in which there were no paired hauls.

The parameters γ and δ, which determine the linear relationship between L50 and log SR and the explanatory variable through equation (2), were estimated explicitly by the maximum likelihood routines, with their covariance matrix obtained from the Hessian matrix. Predictions of L50 and log SR for different gear configurations, with corresponding standard errors, were then obtained from equation (2) using standard linear theory. However, these standard errors do not include the uncertainty in the estimates of the variance components D_{trip}, D_{gear} and D_{haul} and σ^2.

Results

The final model was

L50 ~ 1 + mesh size + log catch

log SR ~ 1 + meshes around + twine thickness

Parameter estimates are given in Table 2 and the estimated effects are plotted in Figure 2. The L50 increased by 1.9 cm for every 10 mm increase in codend mesh size (95% confidence limits 1.6, 2.2 cm). The L50 decreased by 0.24 cm for every doubling of catch (although the 95% confidence limits suggest that a decrease of 0.51 cm or an increase of 0.02 cm are also compatible with the data). Back-transforming from the log scale, SR decreased by 3.8 % for each increase of 10 meshes around the codend (95% confidence limits 1.6, 6.0 %) and increased by 12.3 % for each 1 mm increase in twine thickness (95% confidence limits 6.9, 18.0 %). Of the eight models within two units of the minimum AIC (Table 3), mesh size appears in all the L50 models and log catch in six of them. Meshes around and twine thickness appear in all the log SR model.

Figure 2 also shows the point estimates of L50 and log SR from the twin-trawl trials (Frandsen et al., 2009) that could not be included in the analysis. The L50 estimates show good agreement when plotted against mesh size and are compatible with the scatter of the other L50 estimates when plotted against catch size. One of the SR estimates shows good agreement; the other (5.11) had a large standard error (2.25) so the discrepancy is not surprising.

The mesh size and twine thickness effects are robust, in the sense that they remain highly significant ($p < 0.001$) if any single trip is removed from the data set, with parameter estimates typically within two standard errors of the estimates in Table 2. The one exception is the mesh size estimate which becomes markedly larger (0.235) if trip 9 is removed. However, the meshes around and catch size effects must be treated with some caution. For meshes around, although the point estimates from the single trip deletions are always within two standard errors of the estimate in Table 2, the effect is driven by trip 9 and the significance level of the term reduces markedly if this trip is removed ($p = 0.15$) or if the gears with a panel are removed ($p = 0.10$). There is only weak evidence of a catch size effect ($p = 0.063$) even when based on the full data set, with the significance level reducing to $p = 0.30$ if trip 6 is removed. The impact of the single trip deletions is not surprising given that there are only nine trips in the study and the between-trip variance dominates the estimates of the random effects (Table 4).

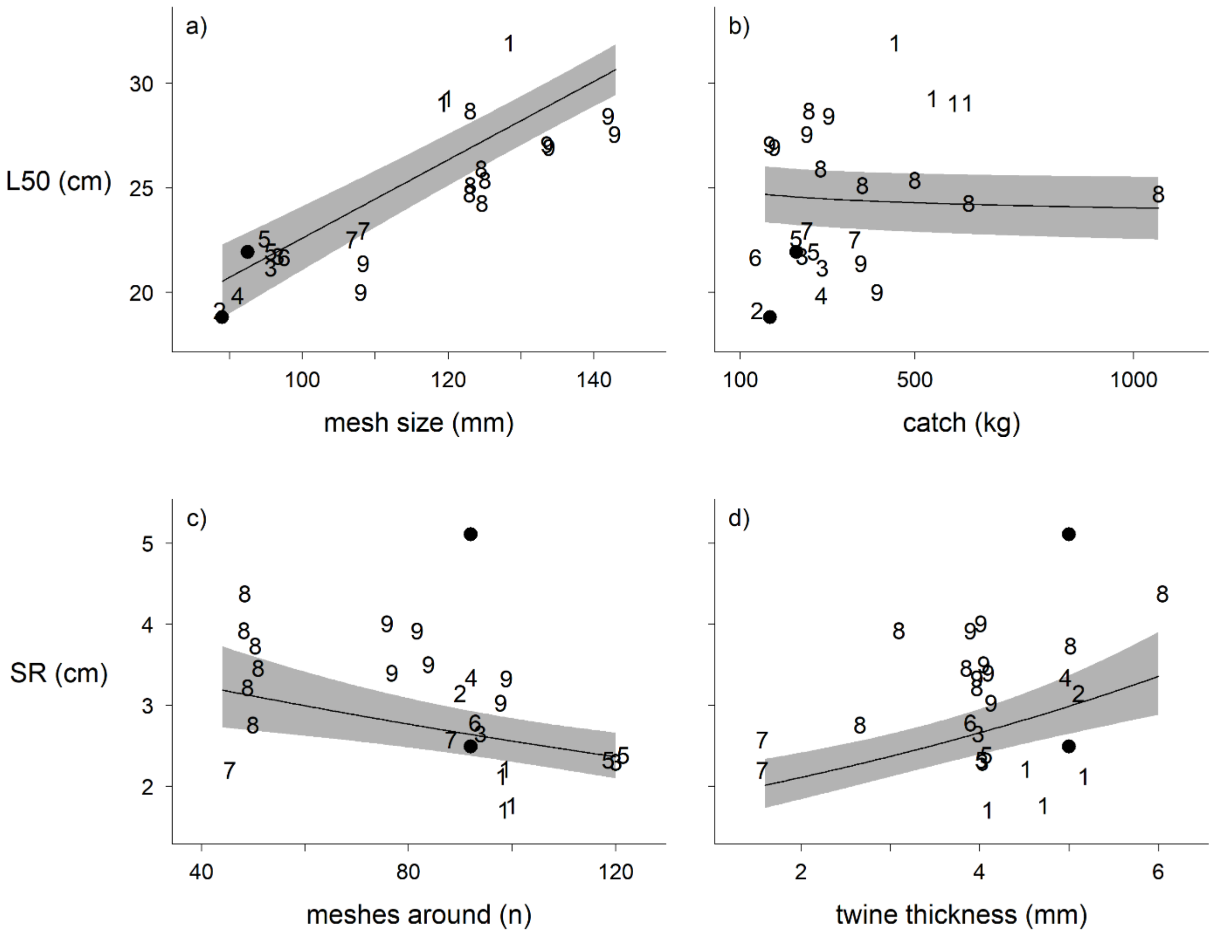

Figure 2. Predicted values (solid lines) with pointwise 95% confidence bands (grey shaded areas) of a) L50 plotted against mesh size (with catch fixed at 300 kg); b) L50 plotted against catch (with mesh size fixed at 110 mm) c) SR plotted against number of meshes around (with twine thickness fixed at 4 mm); d) SR plotted against twine thickness (with number of meshes around fixed at 90). The points are the estimates of L50 or SR for each gear, labelled by trip (Table 1), and jittered slightly to reduce overlap. These were obtained by fitting a generalised linear mixed model with a separate selection curve for each gear and between-haul and overdispersion random effects. The solid circles are the estimates from Frandsen et al. (2009).

Discussion

Based on 9 trips with 25 gear configurations and 164 hauls, we have found strong evidence that the selection of plaice in otter trawl codends depends on the mesh size and twine thickness, and weaker evidence that it also depends on the number of meshes in circumference and the catch size. Specifically, the

L50 increases by an estimated 1.9 cm for every 10 mm increase of codend mesh size and decreases by 0.24 cm for every doubling of catch, and the SR decreases by 3.8 % for each increase of 10 open meshes and increases by 12.3 % for each 1 mm increase of twine thickness. The estimated dependence of L50 on mesh size is a good representation of the underlying data (Figure 2) and the increase of SR with an increase of twine thickness reflect the results of O'Neill et al. (2016) and Herrmann et al. (2013). While it is not surprising that our results support the conclusions of the individual studies from which the data were sourced, the advantage of our analysis is that it incorporates results from multiple trials, where typically only one or two parameters are tested. Hence, we are able to produce empirical models that predict selection across a wider range of gear parameters and over a broader range of their values, leading to a better understanding of their relative influence.

There is weak evidence that plaice L50 reduces with increased catch sizes ($p = 0.063$). This contrasts with the analysis of Fryer at al. (2016) who find a weak ($p = 0.057$) increasing dependence of haddock L50 with catch size. Both sets of results, however, are consistent with a mechanistic interpretation of the selection process, where, as the catch size increases, the lateral opening of the meshes immediately ahead of the catch increases, thus facilitating more suitable escape opportunities for the wider roundfish and fewer for the oblate and narrower flatfish (O'Neill and O'Donoghue, 1997; Broadhurst et al., 2006; Tosunoğlu, 2007).

By the same token, we would have also expected twine thickness to influence L50. Although it does for three of the models within two units of the minimum AIC, it is not in the final model (Table 3). Several studies have shown that, as the thickness increases, the L50 of roundfish species such as haddock decreases (Herrmann and O'Neill, 2006; O'Neill et al, 2016) which may be because, for a given twine material, thickness is correlated with bending stiffness. O'Neill and Priour (2009) show that the lateral mesh opening reduces as twine bending stiffness increases, which should make it more difficult for roundfish to escape, but easier for flatfish. Likewise, we would have expected the reduction of lateral mesh opening associated with having more meshes around to have increased L50. However, we didn't find a dependence of L50 on either twine thickness or number of meshes around and it may be that any potential benefit of a more slender mesh hape is offset by the greater visual barrier of more closed meshes or netting made from thicker twine (Glass et al., 1993).

It is difficult to explain the negative dependence of SR on twine thickness and number of meshes around. It may be that as twine thickness increases and the number of meshes around decreases there is more scope for variation in the lateral mesh opening, permitting fish with a more variable range of morphological characteristics to escape, leading to an increase of SR (Fryer et al., 2016).

In a meta-analysis of haddock size-selection data, Fryer et al (2016) show that haddock codend selection also depends on mesh size, number of meshes around and twine thickness. They estimate that the codend l50 increases by 3.39 cm for each 10 mm increase in codend mesh size, decreases by 1.27 cm for each extra 10 codend meshes around, and decreases by 1.40 cm for each 1 mm increase in codend twine thickness. Further, the codend SR increases by 11 % for each 10 mm increase in codend mesh size and decreases by 8 % for each 1 mm increase in codend twine thickness. These results are interesting as they indicate that simple design changes can be used to alter the selection of haddock and plaice differently. For instance, decreasing the meshes around will increase the haddock L50 but have little effect on plaice L50; whereas a decrease in twine thickness will lead to a sharper selection of haddock but a broader one for plaice. While these types of differential effects may have different biological consequences (Vasilakopoulos et al., 2016) they are likely to be useful in the context the Landing Obligation of the EU Common Fisheries Policy and in other jurisdictions where there are economic or management imperatives that limit the capture of one species but not of another.

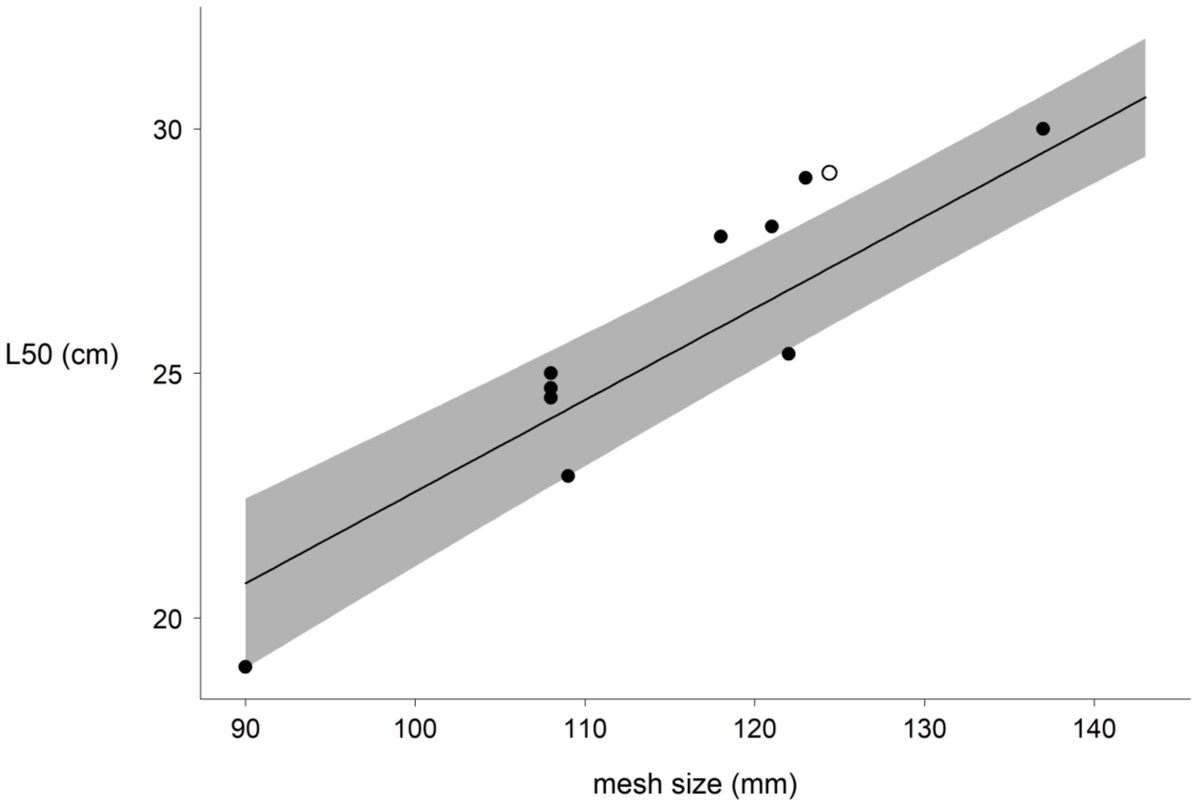

Figure 3. Beam trawl L50 estimates from van Beek et al (1983) (solid dots) compared with the otter trawl predictions from our analysis (solid line). The open circle shows the L50 estimate from the Danish seine study of Noack et al (2017). The grey shaded area shows pointwise 95% confidence bands on the otter trawl predictions.

Although our focus here has been on plaice selection in otter trawls, the majority of plaice caught in the North Sea and Skagerrak (53 %) are caught by beam trawls (ICES, 2018). Van Beek et al (1983) present the results of beam trawl codend selection trials carried out on two vessels in 1981. While we must be cautious making comparisons, as there are many differences between the experimental and statistical methods employed, there is nevertheless a good correspondence between their l50 estimates and the results of our analyses over a wide range of mesh sizes (Figure 3). This suggests the selection of plaice in otter and beam trawls might be fairly similar, which would be noteworthy given the many operational differences between the two fishing methods. Plaice are also targeted by Danish seiners in the North Sea and Skagerrak and Noack et al (2017) estimate their l50 in a 124 mm Danish seine codend to be 29.1 cm.

Knowledge of codend selection is often limited to key species in specific fisheries. In many cases, little is known about the selection of species that may be important commercially, but are not the primary target.

Where sufficient data exist, there is a need to extend the type of analysis carried out here to these other species. Where there is insufficient data, alternative approaches will need to be considered. It may be possible to explore empirical correlations between species, or to further develop predictive models that are based on morphology, mesh geometry and fish behaviour (O'Neill and Herrmann, 2007, Herrmann et al., 2009).

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Table 2. Parameter estimates, standard errors and significance (based on likelihood ratio tests) for each term in the final model. For numerical stability, the explanatory variables were centred before model fitting so the intercepts correspond to a mesh size of 110 mm, a catch of 300 kg, 90 meshes around, and a twine thickness of 4 mm.

model component	parameter	estimate	standard error	significance
L50	intercept	24.46	0.68	< 0.0001
	mesh size	0.187	0.015	< 0.0001
	log catch	-0.35	0.19	0.063
log SR	intercept	0.979	0.052	< 0.0001
	meshes around	-0.0039	0.0011	0.0012
	twine thickness	0.116	0.025	< 0.0001

Table 3. Models within two units of the minimum AIC. The first two columns give the models for L50 and log SR respectively. The number of fixed effect parameters and the difference between the AIC and the minimum AIC (ΔAIC) are also given.

L50	log SR	parameters	ΔAIC
1 + mesh size + log catch	1 + meshes around + twine thickness	6	0.0
1 + mesh size + twine thickness + log catch	1 + meshes around + twine thickness	7	0.4
1 + mesh size + log catch	1 + meshes around + twine thickness + mesh size	7	1.1
1 + mesh size + twine thickness	1 + meshes around + twine thickness	6	1.2
1 + mesh size + twine thickness + log catch	1 + meshes around + twine thickness + mesh size	8	1.3
1 + mesh size	1 + meshes around + twine thickness	5	1.4
1 + mesh size + log catch	1 + meshes around + twine thickness + log catch	7	1.7
1 + mesh size + meshes around + log catch	1 + meshes around + twine thickness	7	1.9

Table 4. Estimated variances of the random effects. The rows show the hierarchy of the random effects structure. The columns show the variance of the random effect as it relates to the intercept α and slope β of the selection curve through equation (3) or, in the case of the overdispersion term, to ϕ through equation (4). $D_{trip,1,1}$ and $D_{trip,2,2}$ are the diagonal elements of D_{trip}, and similarly for D_{gear} and D_{haul}.

random effect	intercept α		slope β	
	parameter	estimate	parameter	estimate
between trip	$D_{trip,1,1}$	2.96	$D_{trip,2,2}$	0.0163
between gear	$D_{gear,1,1}$	0.11	$D_{gear,2,2}$	0.0001
between haul	$D_{haul,1,1}$	0.37	$D_{haul,2,2}$	0.0186
within haul (overdispersion)	σ^2	0.11		

375 Table 1 A summary of the covered codend studies of plaice size-selection, broken down by trip, giving the year, month and vessel and method, the number of gears and hauls, the presence of a square mesh panel, and the range of each explanatory variable (with a single value denoting that the variable was fixed during the trip). The range across all trips is given at the bottom of the table.

trip	year	month	vessel	gears	hauls	mesh size	meshes around	twine thickness	panel	catch	reference
1	2003	October	Carina	4	29	119, 129	100	4.1, 5.1	no	267, 979	O'Neill et al. (2016)
2	2006	September	Canopus	1	14	90	92	5.0	no	85, 541	Frandsen et al. (2010)
3	2007	June	Mette Amalie	2	28	96, 97	92, 120	4.0	no, yes	80, 1020	Frandsen et al. (2011)
4	2007	August	Mette Amalie	1	6	92	92	5.0	no	180, 355	Frandsen et al. (2010)
5	2007	September	Mette Amalie	2	10	96	120	5.0	yes	158, 275	Frandsen et al (2011)
6	2007	September	Mette Amalie	1	15	96	92	4.0	no	91, 466	Madsen et al. (2012)
7	2010	March	Solea	2	12	108	44, 88	1.6	no	154, 726	Hermann et al (2015)
8	2011	March	Solea	6	19	124	50	2.6, 6.0	no	180, 1266	Hermann et al (2013)
9	2012	November	Solea	6	31	108, 143	76, 98	4.0	no	20, 633	Mieske (2012)
	overall			25	164	90, 143	44, 120	1.6, 6.0		20, 1266	