A general catch comparison method for multi-gear trials: application to a quad-rig trawling fishery for *Nephrops*

D. Browne[1], C. Minto[2], R. Cosgrove[1], B. Burke[2], D. McDonald[1], R. Officer[2], and M. Keatinge[1]

[1]*Irish Sea Fisheries Board (BIM), New Docks, Galway, Ireland*
[2]*Marine and Freshwater Research Centre, Galway-Mayo Institute of Technology (GMIT), Dublin Road, Galway, Ireland*

Corresponding author: tel: +353 91539360; fax: +353 91568569; e-mail: browned@bim.ie

Browne, D., Minto, C., Cosgrove, R., Burke, B., McDonald, D., Officer, R., and Keatinge, M. A general catch comparison method for multi-gear trials: application to a quad-rig trawling fishery for *Nephrops*. – ICES Journal of Marine Science, doi:10.1093/icesjms/fsw236.

Expeditious uptake of quad-rig trawling in the economically important Irish fishery for *Nephrops norvegicus* outpaced technical understanding of this newly introduced gear. The main driver for its introduction is increased catch rates of *Nephrops*. Higher *Nephrops* discard rates associated with quad-rig trawling are likely to be problematic under the landing obligation unless size selectivity can be improved. Catch comparison methods are suitable for assessing the performance of fishing gear modifications to reduce discards. Utilizing a quad-rig potentially increases the number of gears that can be included in a catch comparison study to four but current modeling methods are limited to two gears. Our study provides a new general multinomial mixed effects modeling framework that can be applied to two or more gears, elucidates how case-specific and choice-specific covariates may influence catch at length, and facilitates discussion on appropriate gear based management measures. Application of the method to catches from four different cod-end mesh sizes revealed significant effects of carapace length, catch weight and net position, on the numbers of *Nephrops* retained in each cod-end. Results suggest that management measures which specifically address different catch profiles associated with different numbers of trawling rigs are required to optimize *Nephrops* size selectivity.

Keywords: catch comparison, cod-end mesh size, landing obligation, mixed logit, multinomial mixed effects, multi-rig, *Nephrops norvegicus*

Introduction

Nephrops norvegicus is a commercially important species distributed throughout the North East Atlantic and Mediterranean Sea. Total landings of 66 500 tonnes in 2010 were predominantly attributed to the United Kingdom (58.1%) followed by Ireland (11.7%) and various other European Union (EU) countries operating in Atlantic and Mediterranean waters (FAO, 2010). More than 95% of EU *Nephrops* landings are taken by single or multi-rig trawlers which target *Nephrops* in mixed species fisheries (Ungfors *et al.*, 2013). The high value of Irish *Nephrops* landings at the first point of sale (estimated at €44.5M in 2014) make it the most commercially important demersal species in Ireland (Cosgrove *et al.*, 2015). The simultaneous use of four trawls, known as quad-rig trawling (Figure 1), is practiced in shrimp trawl fisheries in the United States of America and Australia (e.g. Eayrs, 2012; Broadhurst *et al.*, 2013) and commenced in the Irish *Nephrops* fishery in October 2012. By the end of 2014, quad-rigs accounted for $\sim$ 80% of *Nephrops* landings by the Irish fleet (unpublished data, Marine Institute, Ireland).

The main driver for increased uptake of quad-rig trawling is increased catch rates of *Nephrops* which are likely to result from a wider swept area of seabed compared with single or twin-rig trawling (Montgomerie, 2015). *Nephrops* catch weights were observed to increase by at least 50% in the North Sea and Celtic

Sea in studies comparing quad with twin-rig trawling (Revill et al., 2009; BIM, 2014a). Such increases in efficiency may be beneficial in terms of improving operational performance but could lead to increases in the 15% discard rate of *Nephrops* below minimum legal or market size in Irish waters (BIM, 2014b; MI, 2014). Bycatch of undersized and non-targeted fish species is also a major issue in *Nephrops* trawl fisheries (e.g. Catchpole et al., 2005; Catchpole and Revill, 2008; Ungfors et al., 2013; Nikolic et al., 2015). New requirements to restrict discarding of demersal species under Article 15 of EU regulation 1380/2013, the landing obligation, are likely to have negative impacts on the economics of *Nephrops* fisheries unless species and size-selectivity can be improved.

Gear modifications to reduce bycatch are generally assessed using either selectivity (e.g. Millar, 1992; Millar and Walsh, 1992; Millar and Fryer, 1999; McClanahan and Mangi, 2004) or catch comparison experiments (e.g. Sangster and Breen, 1998; Holst and Revill, 2009; Krag et al., 2014; van Marlen et al., 2014). Practical advantages of the catch comparison method include commercial-like performance and handling of the gear. In addition, the ease with which results of catch comparison experiments can be reported and interpreted (Holst and Revill, 2009) is likely to be of particular assistance to the fishing industry in addressing challenges posed by regulation of their catch composition, for example the EU landing obligation. While a limitation of the latter approach is that results can only be used for comparison of the gears included in a given experiment (Frandsen, 2010), utilizing a quad-rig increases the number of gears that can be evaluated in the experiment to four. This facilitates assessment of more concurrent experimental settings and provides substantially more information than twin or single-rig catch comparisons. Development of a Generalized Linear Mixed Model (GLMM) approach to catch comparison provided a statistical comparison of catch at length by two fishing gears, improving the power of catch comparison analyses (Holst and Revill, 2009). Binomial GLMMs are, however, limited to experiments with two response categories. Multinomial logit models generalize binomial logistic regression to multi-category response problems (McCullagh and Nelder, 1989), i.e. those with two or more fishing gears.

Here, we develop and test the potential benefits of applying a multinomial modelling approach to a comparison of *Nephrops* catches in a quad-rig trawl fishery. Our goals are to provide a general statistical framework that incorporates the multivariate response; elucidates how covariates may influence catch at length; and facilitates discussion on appropriate gear-based management measures.

Materials and methods
Experimental design
Data were collected from a catch comparison experiment conducted in the western Irish Sea, ICES sub-area VIIa, between 18 July 2015 and 21 July 2015. The trial vessel quad-rig trawled using a triple warp and centre clump arrangement with 4 identical nets each fitted with a diamond mesh cod-end with nominal mesh sizes of 70, 80, 90, or 100 mm (mesh size descriptors used henceforth). Cod-ends were constructed with single braided 6 mm (nominal) diameter polyethylene twine and were fitted with strengthening bags and lifting straps as is typical in this fishery. Cod-end mesh size was measured with the Omega gauge using the protocol of Fonteyne (2005). Mean cod-end mesh size values
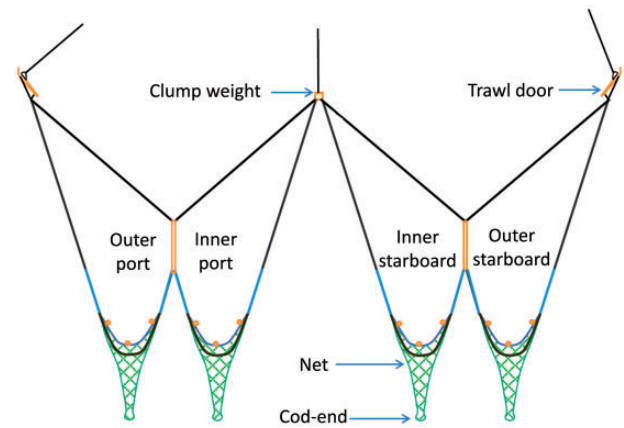

Figure 1. Outline of quad-rig gear including net position in relation to the vessel. Reproduced and edited from Seafish (2010) with permission from Seafish.

Table 1. Details of fishing vessel and gear.

Vessel	Our Lass II (DA261)
Vessel Length Overall (m)	21.7
Engine power (kW)	484
Home port	Howth, Ireland
Trawl type	Quad-rig for *Nephrops*
Trawl manufacturer	Pepe Trawls Ltd., Ireland
Otter board manufacturer/type	Dunbar 7′6″
Fishing circle (mm)	380 x 80
Door weight (kg)	492
Clump weight type/weight (kg)	Roller/680
Average door to clump spread (m)	34.4
Sweep length (m)	50 + 20

(with standard error in brackets) were the following: 70.8 (0.3), 80.8 (0.3), 92.6 (0.2), and 103.0 (0.3) mm. Codend circumference was 120 (70 mm), 120 (80 mm), 100 (90 mm), and 100 (100 mm) meshes which complies with the legal maxima under Regulations (EC) nos. 850/98 and 2602/2001 and conforms to normal fishing practice. Nominal mesh size in the main trawl body was 80 mm, while mesh size in the upper wing ends was 160 mm. Corresponding to the normal fishing practices in the area, square mesh panels of 120 mm mesh size were mounted 9–12 m from the cod-line. Here, "net" describes the whole trawl body. Net positions in relation to the vessel were fixed while cod-end positions were rotated daily to account for potential differences in fishing power without confounding cod-end mesh size and net position effects (Figure 1). Each cod-end was deployed on each net for 3 hauls which equates to one out of four fishing days, with data from 12 consecutive hauls analysed. Further information on the vessel and gear used in the trial is presented in Table 1. Fishing operations approximating normal commercial fishing practice were carried out with haul duration, towing speed, and depth of ground fished averaging: 04:47 h, 3.1 kn, and 48 m respectively.

Sampling
Random representative subsamples were obtained to estimate *Nephrops* catch at length for each codend mesh size. *Nephrops* carapace length was recorded to the nearest mm below using

digital callipers connected to a wireless recording system (Cosgrove *et al.*, 2015). Catch weight is known to influence the opening of cod-end meshes and affect cod-end size selection for a range of fish species (e.g. Robertson and Stewart, 1988; Campos *et al.*, 2003; Herrmann and O'Neill, 2005; Herrmann *et al.*, 2006) and the crustacean *Aristeus antennatus* (Campos *et al.*, 2003). Hence, the total catch weight in each cod-end, "catch weight per cod-end", was obtained for inclusion as a covariate in the model to determine its potential effect on *Nephrops* selectivity.

Model development

In the quad-rig trial, the response $Y_{h,i,j}$ was the count of *Nephrops* in a given haul ($h = 1, \ldots, 12$), carapace length-class ($i = 1, \ldots, l_h$, where l_h is the maximum number of length classes in haul h) and cod-end mesh size ($j = 70$ mm, 80 mm, 90 mm, 100 mm). For example, for the 30 mm carapace length bin in haul 5, the response was $Y_{h=5,i=30mm} = 24, 12, 19,$ and 20 denoting that 24 *Nephrops* were counted in the 70 mm cod-end, 12 in the 80 mm, 19 in the 90 mm, and 20 in the 100 mm.

The response data are multivariate counts for which interest lies in describing how the relative proportions retained per length-class in each of the cod-ends varies as a function of the cod-end mesh size and other explanatory variables. When trials result in counts per category (cod-end), a starting distribution is the multinomial (Agresti, 2002) with probability mass function

$$p(n_1, n_2, n_3, n_4) = \frac{N!}{n_1! n_2! n_3! n_4!} \pi_1^{n_1} \pi_2^{n_2} \pi_3^{n_3} \pi_4^{n_4} \tag{1}$$

where n_j is the count in the jth cod-end and $N = \sum_j n_j$; and π_j is the probability of outcome j,

$$\sum_j \pi_j = 1.$$

Covariates

With a multivariate response, covariates can be either case-specific, which are common across categories or alternative-specific (also termed "choice-specific"), which differ for each category (MacFadden, 1973).

Case-specific covariates

Carapace length is the only case-specific covariate included in the model. A common model for case-specific covariates is the multinomial logit, where the probability of a given outcome depends on values of the case-specific explanatory variables for the h, ith observation:

$$\pi_{h,i,j} = \frac{e^{\alpha_j + \beta_j CL_i}}{\sum_{k=1}^{4} e^{\alpha_k + \beta_k CL_i}}, \tag{2}$$

where CL_i is the carapace length. Note that α_1 and β_1 are fixed at zero so that the first cod-end (70 mm control gear here) is set to the baseline (Greene, 2000).

Alternative-specific covariates

For a given haul, both catch weight per cod-end and net-position differ by cod-end mesh size and are, therefore, considered alternative-specific covariates. Parameters for alternative specific

covariates can be either generic, i.e. common across cod-ends or alternative-specific, i.e., differing across cod-ends (Croissant, 2012). For example, the effect of catch weight per cod-end $W_{h,j}$ could differ by cod-end mesh size. We, therefore, allowed the effect of catch weight to either differ by cod-end: $W_{h,j}\gamma_j$ or be the same across cod-ends: $W_{h,j}\gamma$. Net position effects (port inside PI, starboard inside SI and starboard outside SO; port outside being the baseline) were modelled using generic coefficients, as to model them with cod-end-specific coefficients would require four parameters per net position, which would use excessive degrees of freedom from a relatively small number of hauls.

We thus use a mixture of case-specific and cod-end-specific covariates leading to the fixed effects model (with cod-end-specific weight effects):

$$\pi_{h,i,j} = \frac{e^{\alpha_j + \beta_j CL_i + W_{h,j}\gamma_j + \delta_{PI} PI_{h,j} + \delta_{SI} SI_{h,j} + \delta_{SO} SO_{h,j}}}{\sum_{k=1}^{4} e^{\alpha_k + \beta_k CL_i + W_{h,k}\gamma_k + \delta_{PI} PI_{h,k} + \delta_{SI} SI_{h,k} + \delta_{SO} SO_{h,k}}}, \tag{3}$$

where, for example, $PI_{h,j} = 1$ if mesh j was in the port inside position in haul h and $PI_{h,j} = 0$ otherwise.

Two interactions were included in the model: catch-weight per cod-end and carapace length $\rho_j W_{h,j} CL_i$; and net-position and carapace length (e.g., $\varphi_{PI} PI_{h,j} CL_i$). The interaction between catch weight per cod-end and carapace length may capture changes in selectivity owing to mesh opening; whereas the interaction between net position and carapace length may reflect different selectivity over length caused by the whole net excluding the cod-end. Interaction coefficients and variables are not included in (4) for presentation purposes.

All continuous covariates were scaled to have mean zero and standard deviation of one prior to fitting, which we found improves hessian matrix estimation.

Subsampling offset

As the counts are sub-sampled, it is also necessary to include an offset for the proportion of the catch in each cod-end sampled. In a twin-rig (two category) trial the offset is given by $\ln(q_t/q_c)$ where q_t and q_c are the proportions of the catch sampled in the test and control, respectively (Holst and Revill, 2009). In the quad-rig trial with the proportion $q_{h,j}$ of the jth cod-end in the hth haul sampled, the vector of offsets is given by $O_{h,j} = \left(0, \ln\left(\frac{q_{h,2}}{q_{h,1}}\right), \ln\left(\frac{q_{h,3}}{q_{h,1}}\right), \ln\left(\frac{q_{h,4}}{q_{h,1}}\right)\right)$, where the first zero comes from $\ln\left(\frac{q_{h,1}}{q_{h,1}}\right)$.

The offset is incorporated as

$$\pi_{h,i,j} = \frac{e^{\alpha_j + \beta_j CL_i + W_{h,j}\gamma_j + \delta_{PI} PI_{h,j} + \delta_{SI} SI_{h,j} + \delta_{SO} SO_{h,j} + O_{h,j}}}{\sum_{k=1}^{4} e^{\alpha_k + \beta_k CL_i + W_{h,k}\gamma_k + \delta_{PI} PI_{h,k} + \delta_{SI} SI_{h,k} + \delta_{SO} SO_{h,k} + O_{h,k}}}. \tag{4}$$

Multinomial random effects

Counts for category j in a multinomial have an expected mean $\mathrm{E}[n_j] = \pi_j N$ and variance $\mathrm{Var}[n_j] = \pi_j N(1 - \pi_j)$. However, there is often more variability in the counts than the mean-variance (and covariance) allows for, which is termed overdispersion (Hinde and Demétrio, 1998). This may reflect uncaptured variability or clustering, in particular haul-level variability not accounted for when the observations are treated as independent multinomials.
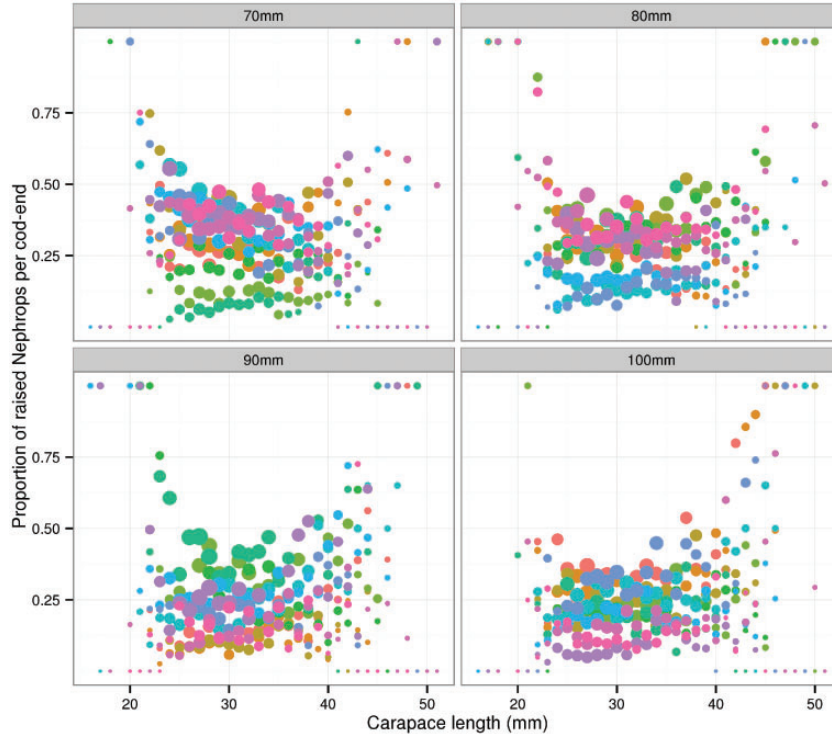
Figure 2. Proportion of *Nephrops* retained per length-class by diamond mesh size. Hauls are coloured to demonstrate the haul effects. The diameter of the points is proportional to the log base 10 of the raised counts to illustrate where the distribution of the counts.

Given that the observations are clustered by hauls, the approach we focus on for accounting for extra-multinomial variability is to include random effects in the model. Multinomial random effects include the baseline category logit random effects model (Hartzel *et al.*, 2001). This model has a multinomial response distribution with the addition of random effects that more explicitly capture the variability attributable to hauls. The random effects multinomial model we test is an extension of (4) given by

$$\pi_{h,i,j} = \frac{e^{\alpha_j + \beta_j CL_i + W_{h,j}\gamma_j + \delta_{PI} PI_{h,j} + \delta_{SI} SI_{h,j} + \delta_{SO} SO_{h,j} + O_{h,j} + u_{h,j}}}{\sum_{k=1}^{4} e^{\alpha_k + \beta_k CL_i + W_{h,k}\gamma_k + \delta_{PI} PI_{h,k} + \delta_{SI} SI_{h,k} + \delta_{SO} SO_{h,k} + O_{h,k} + u_{h,k}}} \quad (5)$$

where the random effects per haul have a multivariate normal distribution $u_h \sim \text{MVN}(\mathbf{0}, \boldsymbol{\Sigma})$, where $\boldsymbol{\Sigma}$ is the covariance matrix of the random effects. The baseline category random effect is again set to zero, resulting in a trivariate normal distribution for u_h. An arbitrary (six parameter) covariance matrix structure, as recommended in Hartzel *et al.* (2001) was implemented. The random effect structure we implemented introduces a random intercept for each cod-end and haul log-odds ratio.

The model contained conditional logit, multinomial logit, and random effects, which does not facilitate model naming. For simplicity, we refer to the model as a "multinomial mixed effects model".

Model selection and prediction
We define the full model as including the main effects (5) and the interactions between: catch-weight per cod-end and carapace length; and net position and carapace length. We fit all valid sub-models of this model with weight effects treated as either generic or cod-end-specific. As the models are estimated via maximum likelihood, we report both Akaike's Information Criterion (AIC) and the Bayesian Information Criterion (BIC). With a large number of samples (which is here the sum of the length bins per haul across all hauls: 338 rows) AIC can tend towards models of increasing complexity whereas BIC penalizes the number of parameters more severely. As the actual number of hauls is limited (12), we selected our final model using a pragmatic compromise between both information criteria.

Overall predictions were obtained by setting the net position values in the predicted model matrix to $1/4$ (Fox and John, 2003). Catch weight per cod-end in the overall predictions was set to the mean per cod-end.

Estimation
The estimation of the multinomial random effects model necessitates integrating over the random effects to estimate the marginal likelihood. We did not find readily available software to fit Equation (7) we therefore wrote an estimation routine in Template Model Builder (TMB) (Kristensen *et al.*, 2015) and R (R Core Team, 2015). Code for running the multinomial mixed effects model is stored at: https://github.com/mintoc/epif/tree/master/multinomial.

Results
A total of 15 443 *Nephrops* were measured during the experiment. Most of the carapace length measurements were in the range of 20–45 mm (Figure 2). Considerable between-haul variability was observed in the proportions retained at length with some hauls

Table 2. Multinomial mixed effects model fit summaries.

Model	CL	NP	W	WxCL	NPxCL	W alternative	Log likelihood	Model df	AIC	BIC
1							−2106.85	9	4231.7	4318.51
2	+						−2084.61	12	4193.22	4308.97
3		+					−2075.63	12	4175.26	4291.01
4			+				−2080.57	10	4181.14	4277.6
5	+	+					−2053.3	15	4136.6	4281.29
6	+		+				−2058.25	13	4142.5	4267.9
7		+	+				−2067.25	13	4160.5	4285.9
8	+	+	+				−2044.49	16	4120.98	4275.32
9	+	+			+		−2021.92	18	4079.84	4253.47
10	+		+	+			−2039.97	14	4107.94	4242.99
11	+	+	+		+		−2013.11	19	4064.22	4247.5
12	+	+	+	+			−2026.28	17	4086.56	4250.54
13	+	+	+	+	+		−2009.69	20	4059.38	4252.3
14			+			+	−2072.33	13	4170.66	4296.06
15	+		+			+	−2049.76	16	4131.52	4285.86
16		+	+			+	−2056.11	16	4144.22	4298.56
17	+	+	+			+	−2033.1	19	4104.2	4287.48
18	+		+	+		+	−2021.58	20	4083.16	4276.08
19	+	+	+		+	+	−2001.13	22	4046.26	4258.47
20	+	+	+	+		+	−2004.9	23	4055.8	4277.66
21	+	+	+	+	+	+	−1990.62	26	4033.24	4284.04

Explanatory variables are abbreviated: carapace length (*CL*); net positions (*NP*); catch weight per cod-end (*W*). *W alternative* denotes whether the catch weight effects were alternative specific (i.e., differ by cod-end), which are those models below the horizontal line. A "+" sign denotes inclusion in the model. The model degrees of freedom (*Model df*) includes 6 parameters parameterizing the trivariate covariance matrix of the random effects for all models. Final selected model is shaded.

Table 3. Best fitting model (model 13) parameter estimates table.

Parameter	70 mm	80 mm	90 mm	100 mm
Intercept α_j	0	0.01 (0.078)	−0.079 (0.105)	−0.071 (0.093)
Carapace length $\beta_{CL,j}$	0	0.094 (0.046)	0.196 (0.05)	0.21 (0.048)
Port inside δ_{PI}		−0.498 (0.091)		
Starboard inside δ_{SI}		−0.16 (0.071)		
Starboard outside δ_{SO}		−0.036 (0.084)		
Cod-end weight γ		0.204 (0.058)		
PI x CL φ_{PI}		0.195 (0.058)		
SI x CL φ_{SI}		−0.029 (0.046)		
SO x CL φ_{SO}		0.165 (0.045)		
W x CL ρ		−0.075 (0.029)		

Standard errors are in parentheses. Intercept and baseline carapace length effects pertains to the port outside net position.

displaying consistently lower or higher retention across carapace lengths (Figure 2). The observed proportions at the extremes of the length distribution were more variable as they were derived from fewer observations (e.g. zero or unity proportions in Figure 2). Total *Nephrops* catch weights were 2093, 1837, 1642, and 1662 kg in the 70, 80, 90, and 100 mm cod-ends, respectively. *Nephrops* accounted for approximately 40% of the total catch weight across all hauls with the remainder of the catch primarily consisting of flatfish and gadoid species.

Separate inclusion of each of the main effects (carapace length, net positions, and catch weight per cod-end) resulted in decreases in both the information criterion relative to a model with fixed proportions (Table 2, models 2–4). Model 10 included the main effects of carapace length and catch weight per cod-end and their interaction had the lowest BIC, whereas model 13 including, in addition, net position effects and the interaction between net position and carapace length had the lowest AIC of those models

treating the catch weight per cod-end effect as generic (Table 2, models 1–13). Including catch weight per cod-end effects as cod-end specific was not supported in any of the models, as judged by BIC (Table 2, models 14–21). The most complicated model was chosen by AIC (model 21). However, the model required 26 degrees of freedom from 12 hauls, which was deemed excessive. In addition, the parameter estimates of the catch weight per codend by carapace length effects for this model did not make sense. We, therefore, decided to treat the catch-weight per cod-end effect as generic and chose model 13 as the "best fitting" model used for inference.

Case-specific parameter estimates were the log-odds ratios relative to the 70 mm (Table 3, rows 1 and 2). The baseline position was the port outside position and the intercept parameters implied that at mean catch weight per cod-end and mean carapace length, similar proportions of *Nephrops* were found across the cod-ends in the port outside position (Table 3, intercept).

The log-odds carapace length slopes increased across cod-end mesh sizes reflecting that, for example, a bigger difference in the proportions retained between the 100 mm and the 70 mm than the 80 mm and the 70 mm (Table 3, row 2). The port inside effect was significantly negative (Table 3, row 3) implying a lower fishing power for this position in this trial. The starboard inside position also fished lower than the port outside position (Table 3, row 4), whereas the starboard outside had a similar retention to the port outside position (Table 3, row 5).

The main effect of catch-weight per cod-end was positive (Table 3, row 6). This effect was not surprising in that there was a strong correlation (0.75) between the *Nephrops* catch weight per cod-end and (total) catch weight per cod-end. The interaction between catch weight per cod-end and carapace length was, however, negative (Table 3, row 10) indicating that the carapace length slope decreases with increasing catch weight per cod-end.

The interactions between net position and carapace length (Table 3, rows 7–9) indicated that retention increased over carapace length in the port inside and starboard outside positions. Given the finding that the port inside had overall lower retention (Table 3, row 3), the interaction implied that this net retained lower numbers of smaller *Nephrops*, whereas the starboard inside net had lower retention over all lengths, and the starboard outside had increased retention over length relative to the port outside.

From the best fitting model the estimated covariance and correlation matrices of the random effects were

$$\hat{\Sigma} = \begin{pmatrix} 0.06 & 0.07 & 0.06 \\ 0.07 & 0.11 & 0.06 \\ 0.06 & 0.06 & 0.08 \end{pmatrix} \text{ and}$$

$$\hat{\text{corr}}(\boldsymbol{u}) = \begin{pmatrix} 1 & 0.81 & 0.88 \\ 0.81 & 1 & 0.63 \\ 0.88 & 0.63 & 1 \end{pmatrix}, \text{ respectively.}$$

The magnitude of the variance of the random effects (e.g., $\hat{\Sigma}_{1,1} = 0.06$) implied that having accounted for the fixed effects of carapace length, net position, and catch weight per cod-end (Table 3), the expected proportions varied in extremes by $\pm 12\%$ by haul (inverse logit of 95% intervals $-0.5, +0.5$). Typically the variability was lower than this (Figure 3). The relatively low inter-haul variability estimated together with the model comparisons (Table 2) highlighted that a considerable amount of between-haul variability was captured by the fixed effects of net position and catch-weight per cod-end though some inter-haul variability remains, which was captured by the random effects (Figures 3 and 4). Dropping the random effects from model 13 resulted in a large decrease of the log likelihood to -2161.12, which when tested on a Chi-squared distribution with 6 degrees of freedom (random effect covariance matrix parameters) was highly significant in favour of the inclusion of the random effects.

The by-haul predictions fitted the data well in both the fixed effects and random effects models (Figure 4), although the random effects models expectedly fitted some haul and mesh combinations better (e.g., 70 mm and 80 mm in hauls 3 and 5). Overall predictions showed a higher proportion of small *Nephrops* retained in the 70 mm, with a decrease in the proportion of smaller *Nephrops* retained as cod-end mesh size increases (Figures 5 and 6). In addition, the slope of the proportion

retained over length classes went from negative in the 70 mm and the 80 mm to positive in the 90 mm and the 100 mm (Figure 5). Higher proportions of larger *Nephrops* were retained in the 90 mm and 100 mm cod-ends (Figure 5).

The estimated confidence intervals on the mean proportions were narrow (Figure 5) reflecting the number of observations contributing to the mean with the considerable between-haul variability accounted for via the fixed and random effects (Figure 4). Note that confidence intervals on proportions should not be interpreted separately as the proportions at a given length retained in the four test cod-ends sum to one. Based on Bonferonni corrections to the confidence intervals, the catch ratios between the pairs of cod-ends (inter-mesh odds ratios) showed: uncertain differences of the 70–80 mm, no difference between the 90 mm and the 100 mm and larger differences among the others (Figure 6). The uncertain differences observed between the 70 mm and the 80 mm could be further investigated by removing non-significant parameter estimates from the best fitting model (Table 3).

Discussion

Our study developed a multinomial mixed effects model that included case-specific and alternative-specific covariates, cod-end specific sub-sampling, and multivariate random haul effects. The method is generally applicable to multi-gear catch comparison studies, as demonstrated in our analyses of a quad-rig trawling *Nephrops* fishery. Here, we discuss the model developments, main findings of the quad-rig application and fishery implications.

Model developments

Examples of the application of multinomial models to fisheries include analysis of egg stages (Stratoudakis *et al.*, 2006; Ibaibarriaga *et al.*, 2007), comparisons of age-length keys (Gerritsen *et al.*, 2006), fleet behaviour (Ward and Sutinen, 1994), and discard survivability (Benoit *et al.*, 2010). We extended the traditional multinomial logit model to include the specific requirements of a catch-comparison trial such as alternative-specific covariates (e.g. catch weight per cod-end) multiple sub-sampling ratios and haul-level random effects (to account for over-dispersion). The method is applicable to other catch comparison situations where multiple gears are tested concurrently. By incorporating these effects, we have developed a general multinomial modelling framework with applications beyond the field of fisheries science. Hartzel *et al.* (2001) conceptually develop the baseline logit multinomial random effects model but, to our knowledge, no readily available open source code exists for fitting this model. The use of TMB greatly facilitated model development as it converges quickly for the relatively complicated mixed effects models implemented here.

Strong correlations observed in the random effects may result from the order the nets are hauled aboard for this trial but would require further investigation. The estimated random effects were odds ratios relative to the baseline 70 mm cod-end (Figure 3). Using another mesh-size baseline would imply different random effects and covariance matrices but the model would structurally be the same, given the implementation of an unconstrained covariance matrix (Hartzel *et al.* 2001).

Future model developments

A linear carapace length effect was fitted (Table 2). However, this assumption may result in an over-influence of smaller and
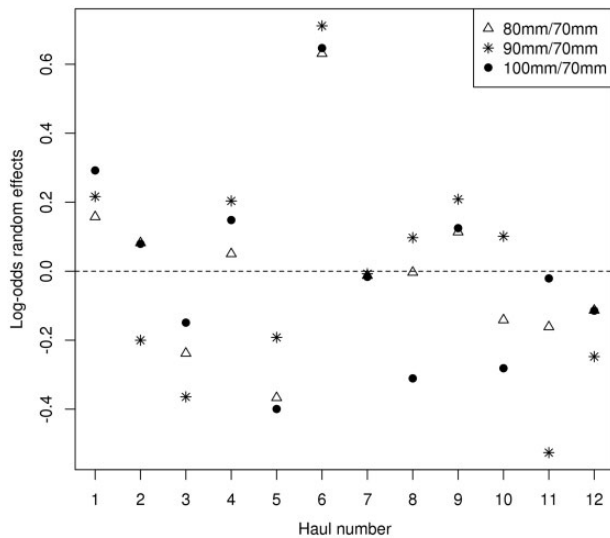
Figure 3. Estimated trivariate random effects (log-odds ratios to the baseline 70 mm case: u_h in (6) by haul.

medium carapace lengths on the proportions retained at larger lengths. Quadratic effects (results not shown) did not improve the model fit but they may not be supported at larger lengths simply because there are fewer observations. As a result, the fits for larger lengths should not be over-interpreted. Alternative approaches such as fixing the proportions above a certain carapace length to be equivalent or implementing smooth non-parametric curves could be used to address local changes more adequately (Fryer *et al.*, 2003).

The random effects implemented are additive random intercepts on the linear predictor scale, which alters the baseline proportion for each haul and cod-end mesh size (Figures 3 and 4). It is common in other settings to include random effects on additional parameters, e.g. carapace length effect. These can be incorporated into the present framework by implementing a 6×6 covariance matrix with the top-left 3×3 block representing the intercept and the bottom right 3×3 block representing the carapace length random effects covariance. A completely unconstrained covariance matrix would require 12 additional parameters (18 covariance parameters in total). However, it may be useful to only allow for covariance in the random intercept and random slope for a given odds ratio, restricting the intercept and slope random effects for different odds ratios to be independent. With each additional random parameter, the number of unconstrained covariance parameters triples relative to a single random parameter; therefore, care needs to be taken on what parameters are allowed to vary given the logistical constraints on the number of hauls in a trial.

Using a Dirichlet-multinomial distribution (Thorsén, 2014) offers an alternative method for modelling count data with a response with two or more categories. The Dirichlet-multinomial model is a multivariate extension of the beta-binomial distribution and is used in cases where data exhibit variance greater than expected in a multinomial. Over dispersion in the Dirichlet-multinomial is accounted for by an additional set of parameters for the baseline category, allowing for an additional variability in the response counts (Mosimann, 1962; Thorsén, 2014). We chose to develop the multinomial mixed effects model rather than apply the

Dirichlet-multinomial model, as a key component of over-dispersion here is likely at the haul-level. A combined Dirichlet-multinomial mixed effects model could be developed in the future.

Covariate effects

Carapace length, catch weight per cod-end and net position significantly affected the numbers of *Nephrops* retained in the different cod-end mesh sizes (Table 2). The significant effect of carapace length, and fewer smaller *Nephrops* retained as mesh size increased (Figures 5 and 6), corroborates the results of previous studies in the Irish Sea and Bay of Biscay (Briggs *et al.*, 1999; Nikolic *et al.*, 2015). This is also consistent with previous findings that increases in diamond cod-end mesh size do not generally affect the selection range of *Nephrops*, but do affect *Nephrops* catch at length (Catchpole and Revill, 2008).

The significant negative interaction between catch weight per cod-end and carapace length confirms the influence of this covariate on retention of *Nephrops norvegicus*. The negative interaction is consistent with a moderation of the effect of catch weight per codend on carapace length as catch weight increases. *Nephrops* escapement is known to take place along the entire length of the trawl (Hillis and Earley, 1982). Catch weight is likely to affect mesh openings and *Nephrops* escapement in the codend, but may also affect whole-trawl *Nephrops* selectivity. Whatever the underlying process, the significant effect of catch weight on catch at length highlights the importance of accounting for this covariate in designing experiments or developing management measures for vessels targeting *Nephrops* with different gears and different catch profiles.

Net position was an important variable explaining a considerable amount of inter-haul variability (Table 2). Position effects within a quad-rig likely result from differences in fishing power caused by variable net geometry associated with asymmetry of warps, sweeps, and doors. Net geometry is assumed to govern gear performance and fishing mortality for *Nephrops* (Sangster and Breen, 1998; Eigaard *et al.*, 2011). Failure to address this issue could result in confounding mesh effects with position effects. We found that the simplest way to deal with these effects is to rotate the gears so that each gear has multiple opportunities to fish in each position. Logistical constraints limit the number of rotations but we found a rotation each night to be a feasible compromise between logistics and position mitigation. Assessment of position effects on quad-rigs using data from gear monitoring sensors (Sangster and Breen, 1998) or side-scan sonar (Lucchetti and Sala, 2012) could further assist in understanding this issue.

The model allows for additional covariates to be included. Variables we did not incorporate in the model include haul duration, time of day, cod-end circumference, and other measurements of gear geometry, and environmental parameters such as depth, tidal effects, sea state, among others. The effects of these variables will be captured to some extent by the random effects estimated in the model (Figure 3). They could also be included as fixed effects but the number of covariates that can be included is limited by the number of tows and meshes in the trial (i.e. available degrees of freedom).

Fishery implications

The finding that catch weight influences codend catch at length for *Nephrops* has important implications for the development of gear specific management measures in *Nephrops* fisheries. Reductions in total catches of up to 61% of cod, 38% of haddock,
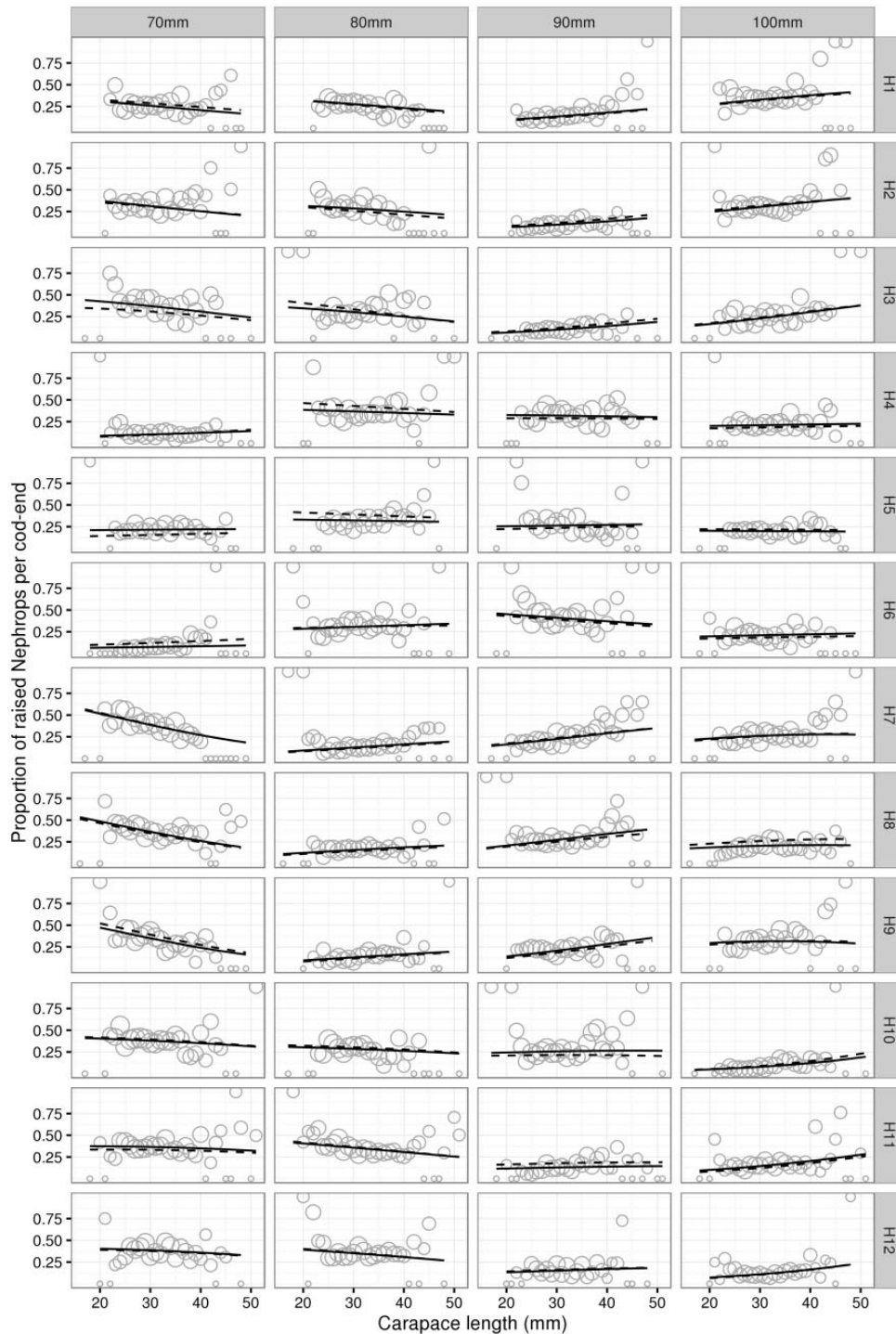
Figure 4. Fitted multinomial mixed effects proportions by haul. Solid and dashed lines represent the predictions from the best fitting model with and without random effects respectively.

and 59% of whiting were observed in trials which compared catches in quad and twin-rig trawls in the Celtic and North Seas. These reductions could be associated with lower headline height and altered sweep arrangements (Revill *et al.*, 2009; BIM, 2014a). Significantly increased proportions of small *Nephrops* and cod were retained in the quad-rig compared with the twin-rig in the

Celtic Sea study (BIM, 2014a). Results of the current and aforementioned studies suggest that lower catch weight associated with reduced fish catches in quad-rig trawling is likely to increase retention of smaller *Nephrops* compared with single or twin-rig trawling. Hence, management measures which consider the different catch profiles of single, twin, and quad rig trawling are
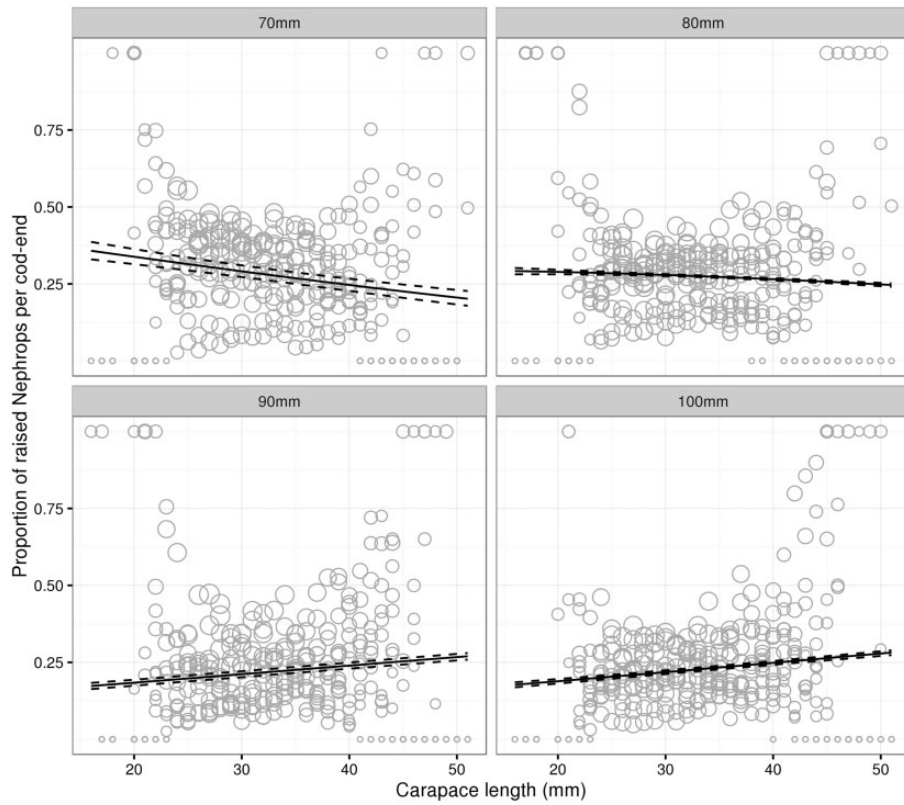
Figure 5. Overall predicted proportions at length. Solid and dashed lines represent the mean and 95% confidence intervals on the mean respectively (see text for discussion on confidence intervals in this setting).
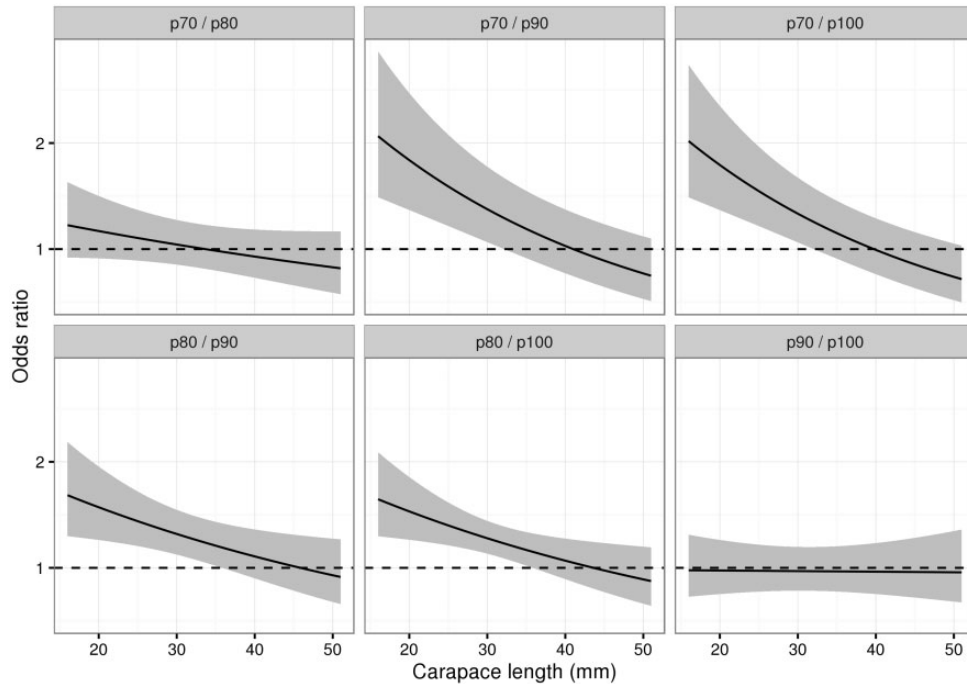

Figure 6. Pairwise odds ratios obtained by setting cod-end mean weights and equal position effects. 95% confidence intervals are pointwise Bonferroni corrected for the six comparisons made.

required in *Nephrops* fisheries to optimize bycatch reduction and quota utilization under the EU landing obligation.

An increase in minimum cod-end mesh size would make sense economically and biologically. In the context of the landing obligation, economic modelling of an increase in minimum cod-end mesh size from 70 mm to 80 mm on a quad-rig vessel, demonstrated that reduced catches of small *Nephrops* in the larger mesh size provided more opportunity to catch increased quantities of larger more valuable *Nephrops*. This lead to marginal increases in vessel profitability over the course of a fishing season (Cosgrove *et al.*, 2015). Our finding that larger cod-end mesh sizes retained fewer small *Nephrops* provides firm biological justification for a mesh size increase. The confirmed effect of catch weight on codend catch at length for *Nephrops* suggests that any increase in minimum cod-end mesh size should take account of the different catch profiles associated with different numbers of trawling rigs. Such an approach would effectively reduce catches of undersize *Nephrops*, boost sustainability of the *Nephrops* stock, assist fishers in meeting EU landing obligation requirements, and optimize economic returns from the *Nephrops* fishery.

Acknowledgements

References
Agresti, A. 2002. Categorical Data Analysis. John Wiley & Sons, Inc., Hoboken, NJ.

Benoit, H. P., Hurlbut, T., and Chasse, J. 2010. Assessing the factors influencing discard mortality of demersal fishes using a semi-quantitative indicator of survival potential. Fisheries Research, 106: 436–447.

BIM. 2014a. Catch comparison of Quad and Twin-rig trawls in the Celtic Sea Nephrops fishery, BIM Gear Technology Report. 4 pp.

BIM. 2014b. Catch comparison of Quad and Twin-rig trawls in the Celtic Sea Nephrops fishery. Irish Sea Fisheries Board (BIM), Fisheries Conservation Report. 4 pp.

Briggs, R., Armstrong, M., and Rihan, D. 1999. The consequences of an increase in mesh size in the Irish Sea Nephrops fishery: an experimental approach. Fisheries Research, 40: 43–53.

Broadhurst, M. K., Sterling, D. J., and Millar, R. B. 2013. Progressing more environmentally benign penaeid-trawling systems by comparing Australian single- and multi-net configurations. Fisheries Research, 146: 7–17.

Campos, A., Fonseca, P., and Erzini, K. 2003. Size selectivity of diamond and square mesh cod ends for four by-catch species in the crustacean fishery off the Portuguese south coast. Fisheries Research, 60: 79–97.

Catchpole, T., Frid, C., and Gray, T. 2005. Discards in North Sea fisheries: causes, consequences and solutions. Marine Policy, 29: 421–430.

Catchpole, T., and Revill, A. 2008. Gear technology in Nephrops trawl fisheries. Reviews in Fish Biology and Fisheries, 18: 17–31.

Cosgrove, R., Browne, D., McDonald, D., Curtin, R., and Keatinge, M. 2015. Assessment of an increase in cod-end mesh size in the Irish Sea Nephrops fishery. Irish Sea Fisheries Board (BIM), Fisheries Conservation Report. 16 pp.

Croissant, Y. 2012. Estimation of multinomial logit models in R: The mlogit Packages. R package version 0.2-2. URL: http://cran. r-project.org/web/packages/mlogit/vignettes/mlogit.pdf.

Eayrs, S. 2012. Comparative Testing of Bycatch Reduction Devices in Tropical Shrimp-trawl Fisheries—A Practical Guide. FAO, Rome. 122 pp.

Eigaard, O. R., Rihan, D., Graham, N., Sala, A., and Zachariassen, K. 2011. Improving fishing effort descriptors: modelling engine power and gear-size relations of five European trawl fleets. Fisheries Research, 110: 39–46.

FAO. 2010. Landing data for Nephrops norvegicus in 1955–2010 using FAO programme and database FishStatJ. http://www.fao.org/fishery/statistics/software/fishstatj/en (last accessed 1 December 2015).

Fonteyne, R. 2005. Protocol for the use of an objective mesh gauge for scientific purposes, ICES Cooperative Research Report No. 279, 8 pp. ISBN 87-7482-044-3.

Fox, J., and John, F. 2003. Effect displays in R for generalised linear models. Journal of Statistical Software, 8: 27.

Frandsen, R. P. 2010. Reduction of discards in the Danish Nephrops (Nephrops norvegicus) directed trawl fisheries in Kattegat and Skagerrak. Aalborg University, The Faculty of Engineering and Science, Department of Biotechnology, Chemistry and Environmental Engineering. Ph.D., 135 pp.

Fryer, R., Zuur, A. F., and Graham, N. 2003. Using mixed models to combine smooth size-selection and catch-comparison curves over hauls. Canadian Journal of Fisheries and Aquatic Sciences, 60: 448–459.

Gerritsen, H. D., McGrath, D., and Lordan, C. 2006. A simple method for comparing age – length keys reveals significant regional differences within a single stock of haddock (Melanogrammus aeglefinus). ICES Journal of Marine Science: Journal Du Conseil, 63: 1096–1100.

Greene, W. H. 2000. Econometric Analysis. Prentice Hall, Upper Saddle River, NJ.

Hartzel, J., Agresti, A., and Caffo, B. 2001. Multinomial logit random effects models. Statistical Modelling: An International Journal, 1: 81–102.

Herrmann, B., and O'Neill, F. G. 2005. Theoretical study of the between-haul variation of haddock selectivity in a diamond mesh cod-end. Fisheries Research, 74: 243–252.

Herrmann, B., Priour, D., and Krag, L. A. 2006. Theoretical study of the effect of round straps on the selectivity in a diamond mesh cod-end. Fisheries Research, 80: 148–157.

Hillis, J., and Earley, J. 1982. Selectivity in the Nephrops trawl. ICES CM, 1982/B19: 1–11.

Hinde, J., and Demétrio, C. G. B. 1998. Overdispersion: models and estimation. Computational Statistics & Data Analysis, 27: 151–170.

Holst, R., and Revill, A. 2009. A simple statistical method for catch comparison studies. Fisheries Research, 95: 254–259.

Ibaibarriaga, L., Bernal, M., Motos, L., Uriarte, A., Borchers, D. L., Lonergan, M. E., and Wood, S. N. 2007. Characterization of stage-classified biological processes using multinomial models: a case study of anchovy (Engraulis encrasicolus) eggs in the Bay of Biscay. Canadian Journal of Fisheries and Aquatic Sciences, 64: 539–553.

Krag, L. A., Herrmann, B., and Karlsen, J. D. 2014. Inferring fish escape behaviour in trawls based on catch comparison data: model development and evaluation based on data from Skagerrak, Denmark. PLoS One, 9: e88819.

Kristensen, K., Nielsen, A., Berg, C., and Skaug, H. 2015. TMB: Automatic Differentiation and Laplace Approximation. Journal of Statistical Software, 70: 1–21.

Lucchetti, A., and Sala, A. 2012. Impact and performance of Mediterranean fishing gear by side-scan sonar technology. Canadian Journal of Fisheries and Aquatic Sciences, 69: 1806–1816.

McClanahan, T. R., and Mangi, S. C. 2004. Gear-based management of a tropical artisanal fishery based on species selectivity and capture size. Fisheries Management and Ecology, 11: 51–60.

McCullagh, P., and Nelder, J. A. 1989. Generalized Linear Models, 2nd edn. Chapman and Hall, London, UK. 512 pp.

MI. 2014. The Stock Book 2014: Annual Review of Fish Stocks in 2014 with Management Advice for 2015. Galway, Ireland, 624 pp.

Millar, R. B. 1992. Estimating the size-selectivity of fishing gear by conditioning on the total catch. Journal of the American Statistical Association, 87: 962–968.

Millar, R. B., and Fryer, R. J. 1999. Estimating the size-selection curves of towed gears, traps, nets and hooks. Reviews in Fish Biology and Fisheries, 9: 89–116.

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

Montgomerie, M. 2015. Basic fishing methods, a comprehensive guide to commercial fishing methods. 106 pp.

Mosimann, J. E. 1962. On the compound multinomial distribution, the multivariate β-distribution, and correlations among proportions. Biometrika, 49: 65–82.

Nikolic, N., Diméet, J., Fifas, S., Salaün, M., Ravard, D., Fauconnet, L., and Rochet, M. J. 2015. Efficacy of selective devices in reducing discards in the *Nephrops* trawl fishery in the Bay of Biscay. ICES Journal of Marine Science, 72: 1869–1881.

Revill, A., Course, G., and Pasco, G. 2009. More prawns and fewer cod caught in trials with multi-rig prawn trawl, CEFAS. 3 pp.

Robertson, J., and Stewart, P. 1988. A comparison of size selection of haddock and whiting by square and diamond mesh codends. ICES Journal of Marine Science, 44: 148–161.

Sangster, G. I., and Breen, M. 1998. Gear performance and catch comparison trials between a single trawl and a twin rigged gear. Fisheries Research, 36: 15–26.

Seafish. 2010. Research & Development Catching sector Fact Sheet. 8 pp.

Stratoudakis, Y., Bernal, M., Ganias, K., and Uriarte, A. 2006. The daily egg production method: recent advances, current applications and future challenges. Fish and Fisheries, 7: 35–57.

Thorsén, E. 2014. Multinomial and Dirichlet-multinomial modeling of categorical time series. Mathematical Statistics, Stockholm University. Bachelor Thesis 2014:6, 33 pp.

Ungfors, A., Bell, E., Johnson, M. L., Cowing, D., Dobson, N. C., Bublitz, R., and Sandell, J. 2013. *Nephrops* fisheries in European waters. In Advances in Marine Biology, pp. 247–314. Ed. by L. J. Magnus and P. J. Mark. Academic Press (Chapter 7).

van Marlen, B., Wiegerinck, J. A. M., van Os-Koomen, E., and van Barneveld, E. 2014. Catch comparison of flatfish pulse trawls and a tickler chain beam trawl. Fisheries Research, 151: 57–69.

Ward, J. M., and Sutinen, J. G. 1994. Vessel entry-exit behaviour in the gulf of Mexico shrimp fishery. American Journal of Agricultural Economics, 76: 916–923.

Handling editor: Finbarr O'Neill