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A game of two halves: Bycatch reduction in *Nephrops* mixed fisheries

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ABSTRACT

Trawlers that target *Nephrops norvegicus* and a range of demersal fish species need gear options to reduce bycatch and address European Union landing obligation requirements. We demonstrated how this can be achieved by using inclined panels to separate fish species into an upper codend with 90 mm T90-mesh, and *Nephrops norvegicus* into a lower codend with 80 mm diamond-mesh. A nested mixed effects model was developed to compare proportional catch at length of key species retained in test or control trawls, and based on this, the conditional probability of retention in the upper and lower test trawl codends. Haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) < minimum conservation reference size (MCRS) were significantly reduced, while haddock ≥ MCRS, *Nephrops*, cod (*Gadus morhua*), monkfish (*Lophius piscatorius*), and commercial flatfish catches were generally maintained in the test trawl. Model outputs demonstrated effective separation of *Nephrops* into the lower codend, and size dependent separation of haddock and whiting into the upper codend. Strong performance of this catch separation device facilitates alternative selectivity measures depending on landing obligation requirements. Additional benefits such as improved catch quality and reduced catch sorting times, but also the need for further incentives to encourage industry uptake are discussed.

1. Introduction

Sustainable fishing practices are required to curb overexploitation from the increasing demand for seafood (Watson et al., 2013). Fisheries bycatch and discarding pose a major threat to sustainability by negatively impacting biodiversity, fish populations, ecosystems, and contributing to overfishing. In addition, discarding is considered a waste of resources, unethical and a loss of scientific information (Crowder and Murawski, 1998; Diamond and Beukers-Stewart, 2011; Hall et al., 2000). Recent global discard estimates range from 7.3 to 10 M t and 8 to 10% of total fish catches with demersal trawl fisheries accounting for > 50% of total discards (Kelleher, 2005; Zeller et al., 2018). Regionally, discards of 1.3 M tonnes have been estimated for demersal trawlers in the Northeast Atlantic, the majority attributed to fisheries in European Union waters (Kelleher, 2005).

Discard bans have been implemented to address the bycatch issue e.g. in North America, New Zealand, and Scandinavia (Condie et al., 2014), and more recently in the EU (EU, 2013). By 2019, the EU 'landing obligation' (LO) will restrict discarding of most species subject to catch limits, or minimum sizes in the Mediterranean Sea. Catches below minimum conservation reference size (MCRS) must generally be landed, deducted from quotas and cannot be sold for human consumption. In addition, vessels may be subject to an early cessation of fishing effort or "choking" once a quota for an individual species is reached. This catch-based approach to management is designed to encourage fishers to avoid such unwanted catches.

Nephrops norvegicus (henceforth, *Nephrops*) is a commercially important species distributed throughout the North East Atlantic and Mediterranean Sea. Total landings of 66,500 t in 2010 were mainly attributed to demersal trawlers operating in the North East Atlantic (FAO, 2010; Ungfors et al., 2013). With a total value of €322 M, *Nephrops* was the highest value demersal trawl species landed by EU vessels in 2011 (Borrello et al., 2013). Landings of 8000 t worth €55 M occurred in 2017 making it the highest value demersal fisheries species in Ireland (BIM, 2018). Fisheries targeting *Nephrops* also catch gadoid species such as whiting (*Merlangius merlangus*), haddock (*Melanogrammus aeglefinus*) and cod (*Gadus morhua*), and numerous other commercial and non-commercial species. Consequently, such fisheries can be termed "*Nephrops* mixed fisheries". Much of the fish catch can be undersized or over-quota (Alverson et al., 1994; Catchpole and Revill,

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2008; MI and BIM, 2011; Ungfors et al., 2013). Aside from the impact on stock status, if unresolved, such catches will likely have major operational impacts under the LO. For example, *Nephrops* fisheries in ICES sub areas IV and VII which landed ~27,000 t of *Nephrops* in 2015 (MI, 2016) are categorised as 'very high risk' in terms of potential non-compliance with the LO due to the level of bycatch and stock status of gadoid species (Anon, 2015). Hence, vessels targeting *Nephrops* could face intense scrutiny from a control perspective and reduced fishing opportunities through choking, while the broader industry could suffer from reduced fishing opportunities through inefficient utilisation of fish quotas.

A variety of gear modifications have been developed which reduce fish while maintaining *Nephrops* catches (Catchpole and Revill, 2008). For example, sorting grids generally reduce catches of all fish species across all size classes, and essentially aim to provide a single species fishery for *Nephrops* (e.g. Catchpole et al., 2006; Cosgrove et al., 2016a; Nikolic et al., 2015; Valentinsson and Ulmestrand, 2008). Such an approach may be justified where: management measures require protection of fish species, e.g. the EU cod management plan (EC, 2008); fish species represent a relatively small component of the catch value; quotas for certain fish species are low, e.g. towards the end of a quota management period and there is a risk of choking. Vessels operating in mixed *Nephrops* fisheries are, however, generally entitled to catch fish species which can make a major contribution to catch value (Catchpole et al., 2006; Catchpole and Revill, 2008; Catchpole et al., 2007) so measures that improve fish selectivity are also needed. Square-mesh panels can improve selectivity in whitefish trawls (Fryer et al., 2016). However, there is no clear fish size selection pattern for such devices in *Nephrops* trawls with a number of studies reporting escapement of bigger fish, fish of all sizes (Catchpole and Revill, 2008) or no fish escapement (Nikolic et al., 2015). Hence, a need exists for gear modifications that optimise size selectivity of fish species while maintaining *Nephrops* catches in *Nephrops* mixed fisheries.

Separation of *Nephrops* and fish catches into two independent codends (e.g. Graham and Fryer, 2006; Hillis, 1983; Main and Sangster, 1985) could assist in addressing this issue. Here, we conducted a catch comparison experiment using a novel gear design which employs inclined panels to separate *Nephrops* and fish catches into 'two halves' or codends where different selectivity measures are applied. Two outcomes from this process were of interest: (1) the difference in catches between the test and control trawl and hence, the effectiveness of the test trawl in reducing unwanted catches; (2) species separation between the upper and lower codends in the test trawl to better understand gear performance and potential applications to different catch compositions. In relation to the latter, a direct comparison between upper and lower codends was not possible given differences in mesh size and orientation. To deal with this, we implemented a nested mixed effects model, which accounted for the probability of key species being retained in the test versus control trawl and based on this, the conditional probability of retention in the upper or lower codends in the test trawl. The broad-ranging benefits but also the need for practical management measures to encourage industry uptake of this gear are discussed.

2. Materials and methods

2.1. Fishing gear and operations

The trial was conducted on board the MFV Stella Nova, a 23.5 m trawler which employed quad-rig trawling (Browne et al., 2017a) to target *Nephrops* and a range of demersal fish species. Hauls were conducted under normal commercial fishing conditions over a five-day period commencing 8th October 2016 on the "Smalls" fishing ground, ICES Division VIIg in the Celtic Sea. Standard *Nephrops* trawls were towed using a three-warp system with a 900 kg roller centre clump and spread using Thyboron Type II otter boards. The trawls were fished using 50 m single combination sweeps and 20 m double bridles giving an overall sweep-line length of 70 m. Catch comparison was restricted to two of the vessels four trawls with control and test trawls deployed on the vessel's starboard side.

The control trawl comprised a standard two-panel codend, where each panel was constructed using 50 × 60 meshes (length × width) of 80 mm (nominal mesh size, henceforth mesh sizes are nominal unless obtained with an Omega gauge) diamond-mesh. Codend circumference was 120 meshes in the control codend. The test trawl comprised an adapter section, a four-panel separator section with inclined or guiding panels, two extension pieces, and two two-panel codends (net plan available in supplementary material). The intention of this design was to guide actively swimming fish species along the panels into the upper codend while *Nephrops* passed through the panel into the lower codend (Fig. 1).

The adapter section was ~9.3 m long. This length was needed to incorporate a long-wedge section and facilitate a smooth transition between the trawl's two-panel belly and the four-panel separator sections. The separator section was also ~9.3 m long to facilitate the angle of attack and placement of the two inclined panels between the adapter section and the extension pieces. The inclined panels formed an apex, eight meshes from the top panel. The location of the apex was designed to assist fish contact with a square-mesh panel, should one be required to comply with technical measures regulations. The anterior inclined panel comprised 32 × 8 meshes of 300 mm square-mesh, constructed with 4 mm ø single polyethylene (PE) twine and fixed at ~30°. This mesh size was chosen as previous work demonstrated that a 300 mm inclined panel provided a reasonably good balance between separation of fish catches and *Nephrops* retention compared with a 200 or 400 mm inclined panel (Coull and Birnie, 2017). The 30° anterior panel was based on previous research which demonstrated successful species separation in a *Nephrops* trawl with that angle of attack (Rihan et al., 2009). The posterior panel was 56 × 60 meshes of 80 mm diamond-

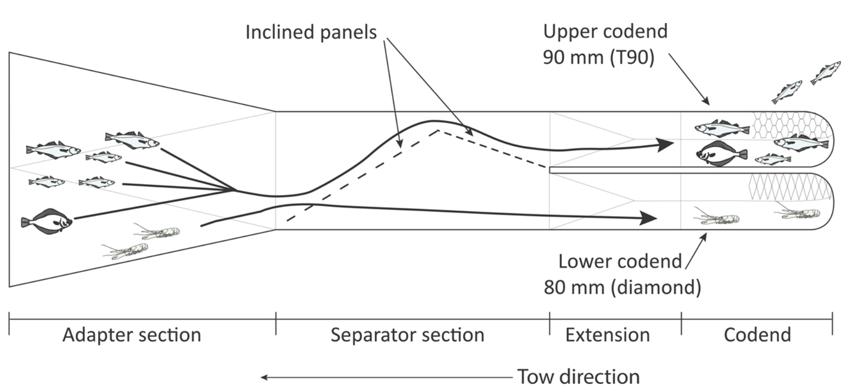

Fig. 1. Illustration of the test trawl including the likely behaviour of fish passing over the inclined panels into the upper codend, and *Nephrops* passing through the inclined panel into the lower codend.

mesh constructed with 2 mm ø single PE twine and fixed at ~18°. The extension pieces comprised two ~4.5 m sections that were used to join the four-panel separator section to the two-panel codends.

The lower test codend was constructed using 50 × 60 meshes of 80 mm diamond-mesh. The 80 mm mesh size was chosen based on previous research which demonstrated a 45% reduction in *Nephrops* < MCRS of 25 mm carapace length (CL) and increased vessel profitability compared with a minimum legal requirement of 70 mm (Cosgrove et al., 2015a). Codend circumference was 120 meshes round in the lower test codend.

The upper test codend was constructed using 60 × 40 meshes of 90 mm T90-mesh (i.e. diamond-mesh turned 90°). T90 was chosen for the top codend based on a previous finding of a 60% reduction in whiting < MCRS (27 cm) by using 80 mm T90 in a demersal trawl fishery targeting that species (Browne et al., 2016). A larger 90 mm T90-mesh size was employed in the top codend with a view to maximising reductions of haddock < MCRS (30 cm), a major potential choke species in the Celtic Sea (CEFAS, 2014; Cosgrove et al., 2015b). Codend circumference was 80 meshes round in the top codend.

Using the protocol from Fonteyne et al. (2007), codend mesh sizes of 87 mm for the two diamond-mesh codends and 90 mm for the T90-mesh codend were obtained with an Omega gauge. Single 6 mm ø twine was used in all codends.

Catch comparison was restricted to two of the vessels four trawls deployed on the vessel's starboard side. The complex arrangement of the test trawl restricted us to one gear rotation to take account of potential differences in fishing power with the inner trawl moved to the outer position and vice versa approximately half way through the trial.

2.2. Sampling and analysis

Total catches were sorted and weighed at haul level for commercial species and the non-commercial species lesser-spotted catshark (*Scyliorhinus canicula*), because it formed a relatively major catch component. Black (*Solea solea*) and lemon sole (*Microstomus kitt*), megrim (*Lepidorhombus whiffiagonis*), European plaice (*Pleuronectes platessa*), and turbot (*Scophthalmus maximus*) were combined and categorised as flatfish due to low catches. We combined non-commercial species such as European flounder (*Platichthys flesus*), pouting (*Trisopterus luscus*), small pelagic species and crabs as 'other species'. Random representative subsamples were weighed and measured for commercial species. These were measured to the nearest cm below while *Nephrops* CL was measured to the nearest mm below.

Statistical modelling of catch at length focussed on haddock, whiting and *Nephrops* because these commercial species were caught in sufficient numbers throughout the trial. The experimental setup comprised two trawls and three compartments: a control trawl (one compartment), and a test trawl that was sub-divided into upper and lower codends (two compartments) (Fig. 1). Given the test trawl's sub-division and different mesh types, a probabilistic description of the experimental data comprises two levels: 1) the probability of retention in the combined test trawl versus the control trawl and 2) the conditional probability of retention in either of the test compartments given retention in the test trawl. The model we propose for analysing such data is a nested model that allows for inference at both levels (test versus control trawl, and upper versus lower test compartment) within a single model. We first present the probabilistic assumptions, followed by the distributional assumption and inclusion of covariates. Let $P(C)$ be the probability of being retained in the control trawl given capture (i.e. conditional on capture); the probability of retention in the test trawl given capture is therefore $P(T) = 1-P(C)$. The probability of retention in the lower compartment $P(T_L) = P(T)P(T_L|T)$, where is the conditional probability of retention in the lower compartment given retention in the test trawl. Similarly, the probability of being retained in the upper compartment is $P(T_U) = P(T)P(T_U|T)$, note that $P(T_L|T) + P(T_U|T) = 1$, which facilitates modelling at this conditional level.

The response $y_{h,i,j}$ was the count of a given species in haul h, length-class i and compartment $j \in (C, L, U)$ (control, lower and upper compartments). At level 1 (test versus control), the counts retained in the test trawl for a given haul and length were modeled with a binomial probability mass function:

$$P(y_{h,i,T}|N_{h,i}, p_{h,i,T}) = \frac{N_{h,i}!}{y_{h,i,T}!(N_{h,i}-y_{h,i,T})!} p_{h,i,T}^{y_{h,i,T}} (1-p_{h,i,T})^{N_{h,i}-y_{h,i,T}} \tag{1}$$

where: $y_{h,i,T}$ is the count of fish in the test compartment; $N_{h,i}$ is the total count of fish in all three compartments; and $p_{h,i,T}$ is the probability of retention in the test compartment. The probability of retention in the test trawl is modeled as a logistic function of the fish length with random haul-level intercepts and a sub-sampling offset included:

$$p_{h,i,T} = \frac{e^{\alpha_1+\delta_1 n_h+u_{h,0,1}+s_1(L_i)+u_{h,1,1}L_i+o_{h,1}}}{1+e^{\alpha_1+\delta_1 n_h+u_{h,0,1}+s_1(L_i)+u_{h,1,1}L_i+o_{h,1}}} \tag{2}$$

where: α_1 is the baseline log-odds; $\delta_1 n_h$ is a baseline night-time effect where $n_h = 1$ if haul$h$ was at night-time and 0 otherwise; $s_1(L_i)$ is an overall penalised smooth function of length using a cubic B-spline, 40 equidistant knots over the length range and a second-order smoothness penalty (Eilers and Marx, 1996); $u_{h,0,1}$ and $u_{h,1,1}$ are haul-specific random effects on the baseline log-odds and length effects, respectively; these random effects allow for haul-specific differences in the baseline log-odds and linear deviations from the overall length effects by haul. A bivariate normal distribution was assumed for the random effects ($\boldsymbol{u}_{h,1} \sim N(0, \boldsymbol{\Sigma}_1)$), where 0 is a column vector of two zeros and $\boldsymbol{\Sigma}_1$ is an unstructured covariance matrix (Durbán et al., 2005) with covariance $\rho_1\sigma_{u_{0,1}}\sigma_{u_{1,1}}$; and $o_{h,1}$ is a sub-sampling offset (see Supplementary Material for details of the level 1 sub-sampling offset).

The same approach was adopted for level 2 (upper versus lower test compartment), where the probability of retention in the upper compartment was given by:

$$p_{h,i,U} = p_{h,i,U|T}\, p_{h,i,T} \tag{3}$$

where $p_{h,i,U|T}$ is the conditional probability of retention in the upper compartment given retention in the test trawl. The level 2 conditional probability ($p_{h,i,U|T}$) was again modeled as an overall smooth function of length with random haul-level baseline log-odds and length effects, along with a night-time effect and a sub-sampling offset (refer to Eq. (2) for level 1 analogue).

Conditional on the random effects, the log-likelihood of the parameters θ for a given haul and length was given by:

$$\begin{aligned} \ln L(\theta|N_{h,i}, y_{h,i,T}, y_{h,i,U}, n_h, L_i, o_{h,1}, o_{h,2}, \boldsymbol{u}_{h,1}, \boldsymbol{u}_{h,2}) \\ = \ln\binom{N_{h,i}}{y_{h,i,T}} + y_{h,i,T}\ln p_{h,i,T} + (N_{h,i}-y_{h,i,T})\ln(1-p_{h,i,T}) + \ln\binom{N_{h,i}}{y_{h,i,U}} \\ + y_{h,i,U}\ln p_{h,i,U} + (N_{h,i}-y_{h,i,U})\ln(1-p_{h,i,U}) \end{aligned} \tag{4}$$

The marginal likelihood was obtained by integrating the joint log-likelihood (including the random effects distributions at both levels and penalized random effects on the level-specific splines, not presented for simplicity in Eq. (4)) over the random effects using Laplace approximation. Given the two-levels of the model, requirement for flexible splines and random effects, we developed specific code to fit the model using Template Model Builder (TMB) (Kristensen et al., 2015) and R (R Core Team, 2015). Code for running the nested mixed effects model is stored at: https://github.com/mintoc/epif/tree/master/nested.

Model selection was conducted by first checking the saturated model fits with all parameters estimated. Where variance parameters tended to zero or there were any issues of estimation/identifiability, we set these parameters to zero. We then selected the best fitting model via likelihood ratio tests on models with or without night-time effect (at both levels). We avoid R^2 summary measures as they do not show goodness of fit in this setting and logistic regression versions have been shown to be biased low (Hosmer and Lemeshow, 2000). Calculated via

Table 1
Total species catches (kg) with mean ± standard error (SE) in brackets for the control and test trawls and upper and lower compartments of the test trawl.

Species	Test		Upper		Lower		Control	
	(kg)	(mean, SE)	(kg)	(mean, SE)	(kg)	(mean, SE)	(kg)	(mean, SE)
Haddock	362.5	(27.88, 6.54)	300.2	(23.09, 5.58)	62.3	(4.79, 1.29)	368.8	(28.37, 5.74)
Whiting	1039.6	(79.97, 13.14)	885.3	(68.10, 11.08)	154.3	(11.87, 2.76)	2402.1	(184.78, 19.81)
Nephrops	2436.5	(187.42, 30.32)	205.3	(17.11, 3.55)	2231.2	(171.63, 30.11)	2602.7	(200.20, 29.23)
Cod	176.6	(13.59, 2.42)	162.0	(12.46, 2.26)	14.6	(2.09, 0.95)	148.8	(11.45, 2.51)
Monkfish	171.2	(13.17, 2.75)	168.1	(12.93, 2.79)	3.1	(1.03, 0.24)	128.7	(9.90, 2.05)
Mixed flatfish	63.6	(4.89, 0.93)	53.1	(4.09, 0.84)	10.5	(0.81, 0.23)	59.9	(4.61, 1.12)
Hake	19.04	(1.47, 0.44)	15.4	(1.54, 0.50)	3.6	(0.52, 0.16)	35.5	(2.96, 0.64)
Lesser spotted catshark	1339.4	(103.03, 28.07)	894.9	(74.58, 18.22)	444.5	(34.19, 11.71)	1434.3	(110.33, 24.07)
Other species	750.9	(57.76, 10.06)	423.5	(32.58, 8.03)	327.4	(25.18, 6.87)	1217.4	(93.65, 31.76)
Bulk (total)	6359.37	(489.18, 57.06)	3107.8	(239.07, 27.23)	3251.5	(250.12, 38.37)	8398.3	(646.02, 61.69)

the delta-method approximation, resulting catch-ratio plots include pointwise confidence intervals on the predicted proportions. The null hypothesis of equal catch efficiency between trawls and compartments was rejected for a given length-class *i*, when the confidence limits associated to the punctual prediction on length-class *i* did not overlap the reference value of 0.5 (50% catch probability). Model outputs also included random effects plots, and plots of the predicted proportions by haul and level. To accompany overall catch-ratio outputs, we presented model estimates for a specific reference length class. We did this by reporting the probability (and uncertainty) of species at MCRS occurring in the test versus control trawl and upper versus lower compartment. We also report the odds ratio (p/(1-p), and uncertainty therein) as an intuitive measure representing how much more likely a fish is to be found in one gear over another.

3. Results

3.1. Catch and operational data

Nephrops, whiting, lesser-spotted catshark, and haddock were the main species encountered during the trial (Table 1). Total whiting catches (kg) were lower in the test compared with the control trawl, with relatively small differences in catches for the other main species. Although it formed a relatively minor catch component, hake catches were also lower in the test trawl (Table 1). Larger quantities of all fish species and fewer *Nephrops* were observed in the upper compared with the lower compartment of the test trawl (Table 1). Data on fishing operations and catch data (total numbers and sampling ratios) for modeled species are presented in Table 2. A total of 13 hauls were conducted with a mean haul duration and fishing depth of 300 min and 106 m. Five hauls were carried out during night-time with all species subsampled in some hauls.

3.2. Best fitting models

A significant night-time effect was only found for level 1 *Nephrops* with a negative coefficient (see Supplementary data) indicating reduced proportions in the test gear during the night. The best fitting model for haddock had no random length effects at level 2 (i.e., the constant fixed effect of the spline was sufficient across hauls) (Table 3, Fig. 2). Haddock displayed the largest amount of between-haul variability at level 1, however (Table 3, Fig. 2). This was largely driven by hauls 1–3 that displayed different trends to the other hauls (Fig. 3). A similar model structure was found to fit best for whiting except the second-order penalty on the level 2 spline was found to be close to zero (Table 3). This implies that a linear effect of length on the logit scale is sufficient for describing the change in proportion over length for whiting at level 2 (Figs. 3 and 4)

The best fitting *Nephrops* model included similar baseline variability at both levels except for haul 12 at level 2, which had virtually no individuals < 40 mm in the upper codend (i.e. almost perfect separation) (Fig. 3). A small amount of spline variability (indicating a high penalty towards a linear effect on the logit scale) was estimated for *Nephrops* at level 2 (Table 3, Fig. 4). In contrast to the other species, *Nephrops* displayed variability in the length effects at level 2 driven by some hauls having a different trend (e.g. level 2, haul 11 in Fig. 3).

For all species and levels, the correlation of the random baseline and length effects was found to be very high (Table 3). Haul-level departures were adequately captured within the model. For example, in the test versus control (level 1) hauls 1, 2, 3 and 10, *Nephrops* had a decreasing proportion retained over length compared to a flat or increasing trend in the others (Fig. 3).

3.3. Test versus control trawl

Significant reductions in proportions of haddock approximately (∼) < 27 cm and whiting ∼ < 36 cm occurred in the test compared with the control trawl. No significant differences were observed for proportional catches above these lengths given that the 95% confidence limits crossed the 50% catch probability line in all cases (Fig. 4). Narrow confidence intervals on the whiting proportions reflect the consistency of the effects across all hauls (Fig. 3) as well as the large number of individuals caught. Separated day/night proportions clearly show significant reductions in *Nephrops* caught in the test trawl during night and no significant reduction in Nephrops caught during day hauls. There were 8 day and 5 night hauls so the overall points were closer to the predicted day curve (Fig. 4).

At MCRS, the overall proportions of haddock and *Nephrops* in the test gear was close to 0.5 (0.47, Table 4) with the upper confidence interval spanning 0.5. Reflecting this, the odds ratio (odds that a species at MCRS is found in the test gear over the odds that it is found in the control gear) is close to even with confidence intervals spanning equal odds in both cases. These results indicate no significant difference in the catches between the test and control trawls for haddock and *Nephrops* at MCRS. For whiting, the probability of being in the test gear at MCRS is well below 0.5 (∼ 0.15) with an odds ratio of ∼ 0.2 indicating that whiting at MCRS were ∼ five times less likely to occur in the test than control the trawl.

3.4. Upper versus lower compartment in the test trawl

The level 2 analysis showed significantly greater catches of haddock and whiting ∼ > 27 cm, and significantly fewer *Nephrops* (over all lengths) in the upper compartment compared with the lower compartment of the test trawl (Fig. 4, Table 3). Separation of haddock and whiting was clearly size dependent with bigger fish more likely to be retained in the upper compartment. Proportionally less whiting and haddock ∼ < 27 cm occurred in the upper compartment. This was not significant for haddock, however, due to wide confidence limits associated with few individuals occurring at this length (Fig. 4). The

Table 2
Fishing operation and catch information comprising the total number of individuals (N) and sampling ratio (q) for the three modeled species in the control and test trawls and upper and lower compartments of the test trawl. Test and control nets were rotated on the starboard side of the quad rig.

Haul No.	Depth	Duration	Day/night	Species	Test[b]	Upper		Lower		Control[a]	
	(m)	(min)			N	N	(q)	N	(q)	N	(q)
1	102	225	Night	Haddock	56	29	(1)	27	(1)	157	(1)
				Whiting	115	76	(1)	39	(1)	1172	(0.17)
				Nephrops	5108	395	(1)	4713	(0.07)	6219	(0.05)
2	109	315	Day	Haddock	98	77	(0.50)	21	(1)	82	(0.50)
				Whiting	220	177	(0.50)	43	(1)	849	(0.20)
				Nephrops	14,323	494	(0.50)	13,829	(0.02)	14,103	(0.02)
3	111	315	Day	Haddock	99	78	(1)	21	(1)	58	(1)
				Whiting	269	202	(0.50)	67	(1)	348	(0.33)
				Nephrops	19,199	1080	(0.25)	18,119	(0.02)	9040	(0.03)
4	101	315	Night	Haddock	55	49	(1)	6	(1)	43	(1)
				Whiting	163	127	(1)	36	(1)	688	(0.25)
				Nephrops	3326	624	(0.50)	2702	(0.07)	5280	(0.06)
5	102	270	Day	Haddock	40	28	(1)	12	(1)	57	(1)
				Whiting	151	120	(1)	31	(1)	818	(0.20)
				Nephrops	18,394	1043	(0.25)	17,351	(0.02)	25,643	(0.01)
6	101	330	Day	Haddock	16	13	(1)	3	(1)	21	(1)
				Whiting	293	263	(0.50)	30	(1)	716	(0.20)
				Nephrops	13,331	2085	(0.14)	11,246	(0.02)	21,122	(0.01)
7	104	255	Night	Haddock	12	8	(1)	4	(1)	14	(1)
				Whiting	228	214	(0.50)	14	(1)	845	(0.14)
				Nephrops	4624	514	(0.50)	4110	(0.07)	8865	(0.03)
8	105	330	Day	Haddock	31	27	(1)	4	(1)	43	(1)
				Whiting	581	515	(0.20)	66	(1)	1196	(0.13)
				Nephrops	22,931	1000	(0.20)	21,931	(0.01)	19,626	(0.02)
9	108	340	Day	Haddock	19	16	(1)	3	(1)	29	(1)
				Whiting	379	327	(0.33)	52	(1)	1488	(0.10)
				Nephrops	10782	1332	(0.17)	9450	(0.03)	11,035	(0.02)
10	111	150	Night	Haddock	4	2	(1)	2	(1)	3	(1)
				Whiting	97	90	(1)	7	(1)	156	(1)
				Nephrops	1376	156	(1)	1220	(0.25)	2419	(0.13)
11	110	390	Night	Haddock	167	161	(0.50)	6	(1)	213	(0.50)
				Whiting	331	303	(0.33)	28	(1)	932	(0.14)
				Nephrops	4563	914	(0.33)	3649	(0.07)	6975	(0.04)
12	105	315	Day	Haddock	48	36	(1)	12	(1)	28	(1)
				Whiting	338	262	(0.33)	76	(1)	1017	(0.13)
				Nephrops	11,512	155	(1)	11,357	(0.02)	8516	(0.03)
13	110	330	Day	Haddock	126	79	(1)	47	(1)	263	(0.50)
				Whiting	617	617	(0.20)	0	(–)	987	(0.14)
				Nephrops	9230	1594	(0.14)	7636	(0.03)	9253	(0.03)

[a] Hauls 1–7: outer starboard side; hauls 8–13: inner starboard side.
[b] Hauls 1–7: inner starboard side; hauls 8–13: outer starboard side.

proportion of *Nephrops* retained in the upper codend was consistently low up to ~40 mm, after which it increased but again, the confidence limits were wider in association with fewer individuals (Fig. 4).

The probability of haddock being caught in the upper compartment at MCRS was approximately 0.8 and the lower confidence interval did not overlap 0.5 (Table 4). The odds ratio was approximately 3.5 (Table 4) indicating that a haddock of length 30 cm was over 3 times more likely to occur in the upper compartment than the lower compartment. Whiting separation was demonstrated by odds of 2.5 of whiting at MCRS occurring in the upper compared with the lower compartment. *Nephrops* separation was even stronger with the odds ratio indicating that *Nephrops* at MCRS were ~12 times (odds ratio of 0.083) more likely in the lower compartment.

4. Discussion

Study results highlight the test trawl's effectiveness in achieving substantial reductions in haddock and whiting < MCRS while generally maintaining other catches. The reduction in whiting ≥ MCRS of 27 cm was expected given the mesh size and orientation used in the upper test codend. Reduced catches of whiting and hake could be addressed by using smaller 80 mm T90-mesh (Browne et al., 2016). Alternatively, larger mesh sizes could also be used to improve selectivity of other species such as cod (Herrmann et al., 2013). Hence, depending on which species are the most quota limited, this gear provides a range of options for vessels in mixed *Nephrops* fisheries to postpone choking and comply with the LO.

Demonstration of effective separation of commercial fish species from *Nephrops* in the test trawl could potentially permit removal of the top codend to allow such species to escape from the trawl when fish quotas are very low. Removing the top codend would likely affect the performance of the inclined panels and the trawl, and would need to be tested and possibly further developed. If successful, this would further enhance this gear's ability to effectively deal with a range of LO quota scenarios. Using this modification as a fish exclusion device may be preferable to using a rigid sorting grid which can be subject to handling difficulties when hauling on a vessel's net drum and power block (Graham and Fryer, 2006). However, *Nephrops* separated in to the upper codend would be lost if the codend was removed. A drop-down section made up of large square-mesh in the posterior separator panel might allow *Nephrops* to pass back into the lower codend and improve the viability of the gear in this manner.

Juvenile gadoids such as cod and whiting are known to be less responsive to selectivity devices such as large-mesh escape panels and grids (Tyndall et al., 2017; Valentinsson and Ulmestrand, 2008) which could explain the size dependent separation of haddock and whiting.

Table 3
Parameter estimates (95% confidence intervals in parenthesis) from the best fitting model by species. For a given level, the parameters are: α baseline log-odds; δ night-time effect; σ_s second-order spline coefficient penalty; $\sigma_{u,0}$ standard deviation of the baseline haul-level random effects; $\sigma_{u,1}$ standard deviation of the haul-level random length effects; ρ correlation of the haul-level random effects.

Parameter	Haddock	Whiting	*Nephrops*
	Level 1 (Test vs *control)*		
α_1	−0.264 (−1.14, 0.612)	−0.403 (−0.832, 0.026)	−0.374 (−0.795, 0.047)
δ_1			−0.529 (−0.836, −0.222)
σ_{s1}	0.038 (0.012, 0.124)	0.028 (0.008, 0.095)	0.046 (0.014, 0.154)
$\sigma_{u0,1}$	3.621 (2.277, 5.757)	2.939 (1.873, 4.612)	1.279 (0.818, 2.001)
$\sigma_{u1,1}$	0.119 (0.075, 0.19)	0.081 (0.051, 0.129)	0.038 (0.024, 0.061)
ρ_1	−0.992 (−0.998, −0.969)	−0.994 (−0.999, −0.976)	−0.982 (−0.995, −0.934)
	Level 2 (Upper vs *lower)*		
α_2	1.065 (0.229, 1.901)	4.289 (3.255, 5.323)	−2.133 (−2.563, −1.703)
σ_{s2}	0.07 (0.019, 0.252)	0	0.009 (0.001, 0.059)
$\sigma_{u0,2}$	0.592 (0.245, 1.431)	1.115 (0.671, 1.852)	1.911 (1.217, 2.999)
$\sigma_{u1,2}$	0	0	0.04 (0.023, 0.068)
ρ_2	0	0	−0.972 (−0.995, −0.844)

The absence of a significant effect of time of day on separation of whiting and haddock catches into the upper codend bodes well for the effectiveness of the test trawl regardless of operational time of day, and is generally in agreement with previous research (Fryer et al., 2017; Krag et al., 2010). The reason for significantly fewer *Nephrops* in the test trawl at night is unknown as this species is generally thought to move passively along the trawl's aft section (Catchpole and Revill, 2008). Further in situ observations with underwater video might assist in elucidating this issue.

Results from this study compare well with previous studies focussed on optimising separation of fish species and *Nephrops* into two codends. A series of separator trials conducted in the early 1980's aimed to maximise whiting and *Nephrops* separation into two codends: *Nephrops* separation was reduced with longer haul duration with a panel draped over the lower codend, and with guiding ropes leading to the upper codend (Hillis, 1983, 1984). The best results were obtained with a separator trawl (Hillis, 1985). Separator trawls employ a horizontal panel running up to the entire trawl length. They are effective in separating haddock and whiting from *Nephrops* but ineffective for cod and flatfish, and relatively complex and expensive to fit (Catchpole and Revill, 2008; Graham and Fryer, 2006; Main and Sangster, 1985). Krag et al. (2009) reported separation rates of up to 95% for whiting and 87% for haddock but lower rates for cod (up to 67%) and flatfish species (~50%) using rigid separator frames. Using a rigid sorting grid to separate catches into two codends, Graham and Fryer (2006) achieved separation rates of 60–80% for haddock and 30–75% for dab (*Limanda limanda*) but also 40–70% for *Nephrops* > 50 mm CL into the top codend. In comparison with previous studies, the test trawl achieved a good balance between *Nephrops* separation into the lower codend, and separation of all fish species into the top codend, while also avoiding potential handling difficulties associated with rigid sorting devices.

The implemented model provides a framework for hypothesis testing of the influence of catch, environmental, or technological covariates at haul level on the performance of the gear. Conditional probability theory allowed for inference at both levels of the trial. Ultimately, the catches were counted in the three codends but two were joined while the third acted as a control. Using conditional probability allows for these effects to be modelled together. The degree of flexibility of the spline is penalised via a second-order penalty. Such an

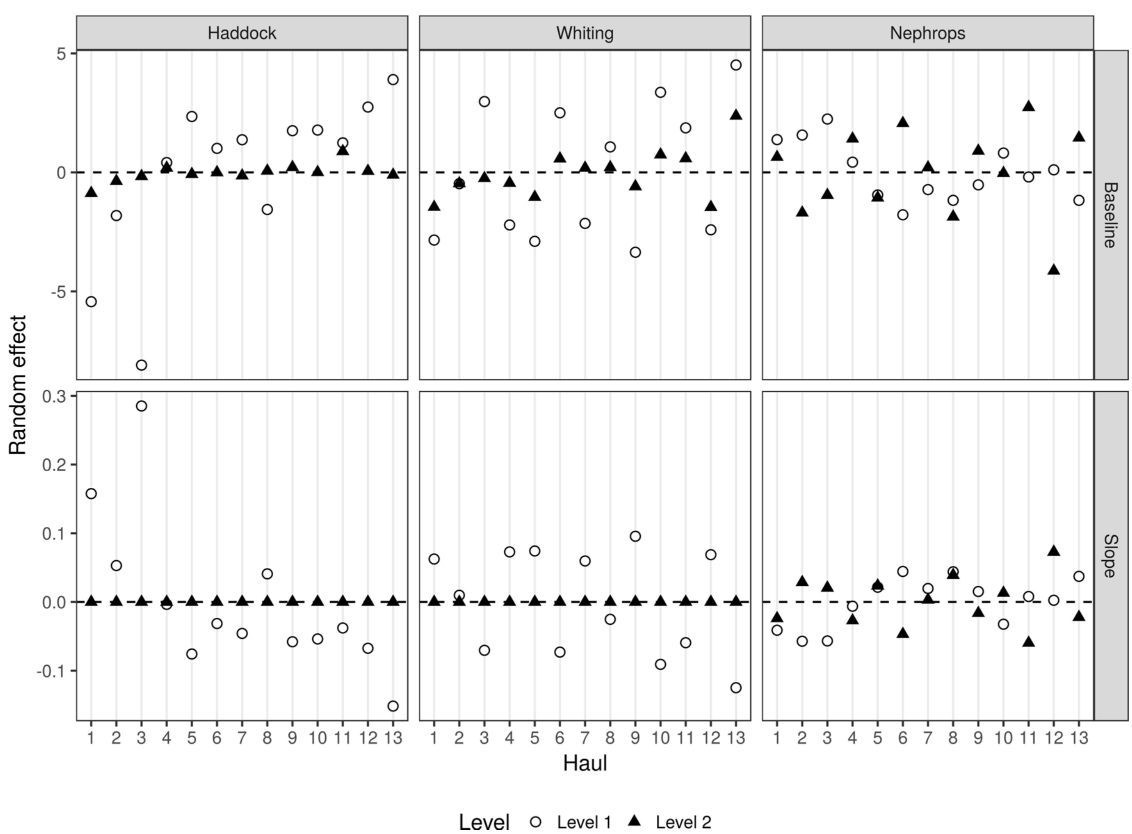

Fig. 2. Haul-level random effects at the test versus control trawl (white circles) and upper versus lower compartment (black triangle) levels. Top row represents the predicted difference in the baseline log-odds by haul, whereas the bottom row represents the predicted difference from the overall length effect by haul.

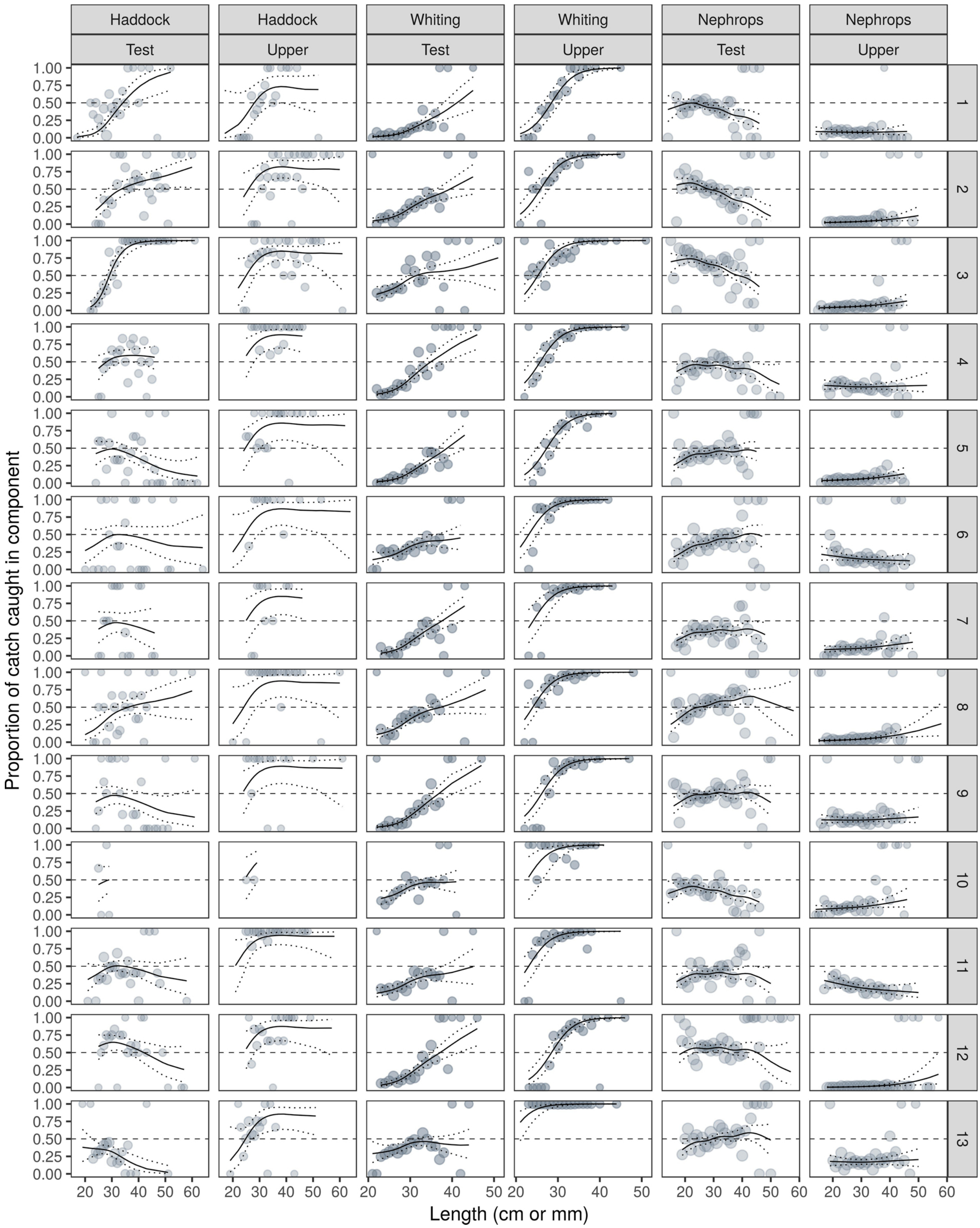

Fig. 3. By-haul proportion of catch per length-class of haddock, whiting, and *Nephrops* for level 1 - test over test plus control trawl ('Test'), and level 2 - upper over upper plus lower compartment of the test trawl ('Upper'). Points represent the empirical raised proportions by haul with point sizes proportional to the raised counts. Haul-specific fitted curves (solid) and 95% confidence intervals (dotted) come from the nested model with covariates set to those recorded for each haul (i.e. represents the actual fit to the data on the inverse logit scale). Haddock and whiting lengths are in cm and *Nephrops* in mm.

approach is useful for modelling catch comparison data and the ability to estimate spline penalties may offer advantages over local smoothers where the bandwidth must be chosen via sensitivity analysis (Fryer et al., 2003). While it may also be possible to model the deviations away from the average curve via splines, we opted for linear random effects for simplicity. These provided adequate fits to the haul-level data (Fig. 3) without an overly complex modelling burden. We note however some wiggle in the spline for overall proportions for level 1 *Nephrops*. This could be improved by allowing smooth departures from the overall curve at the haul level (Ruppert et al., 2003).

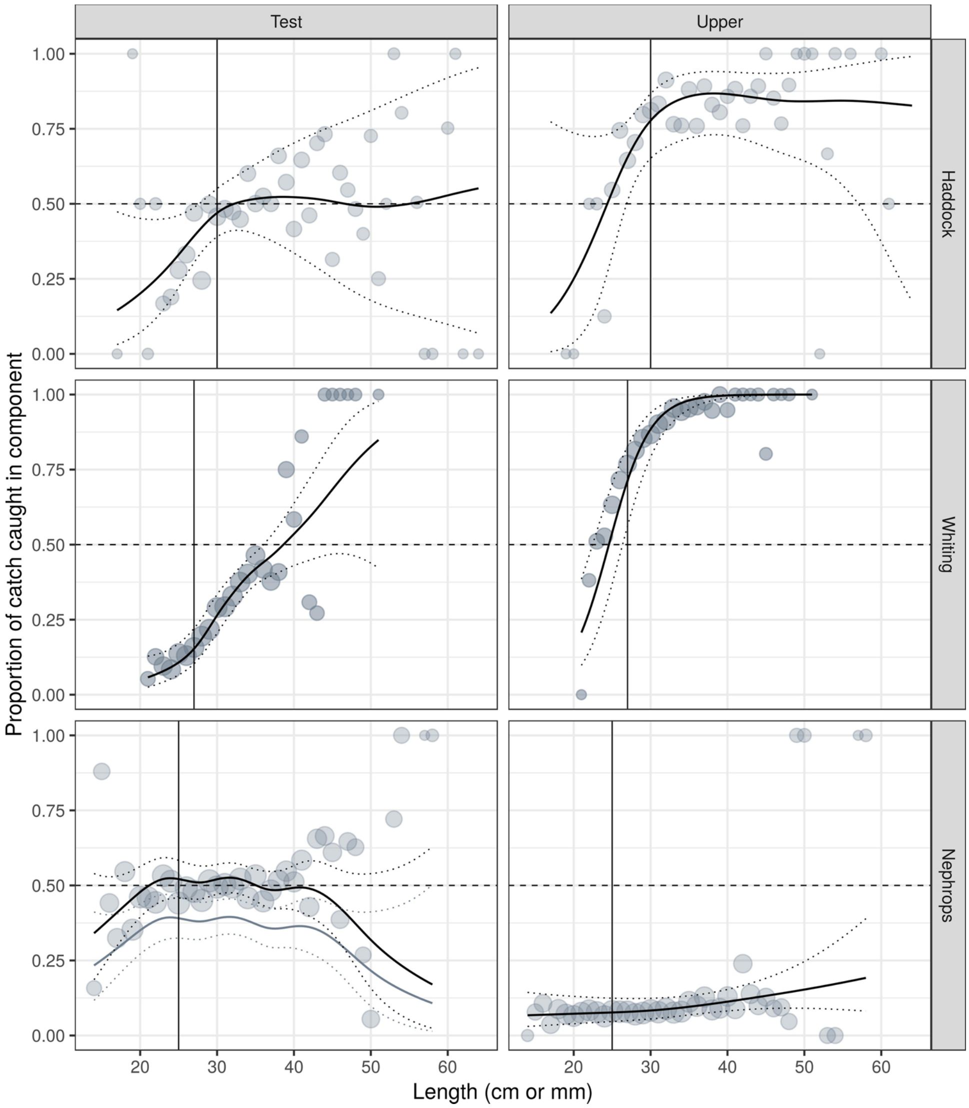

Fig. 4. Overall proportion of catch per length-class of haddock, whiting, and *Nephrops* for level 1 - test over test plus control trawl (left column), and level 2 - upper over upper plus lower compartment of the test trawl (right column). Points represent the empirical raised proportions over all hauls with point sizes proportional to the raised counts. Fitted average (solid) and 95% confidence intervals (dotted) come from the nested model. For *Nephrops* level 1, the black and grey curves predict *Nephrops* during day (8 hauls) and night (5 hauls) respectively. Vertical lines represent the minimum conservation reference size per species in the area. Haddock and whiting lengths are in cm and *Nephrops* in mm.

Table 4
Model predicted catch and odds ratios (95% confidence intervals in parenthesis) in relation to a reference catch at length of minimum conservation reference size (MCRS) for each species.

Species	MCRS	Compartment	Proportion	Odds
Haddock	30 cm	Test	0.47 (0.39, 0.551)	0.886 (0.635, 1.234)
Haddock	30 cm	Upper	0.777 (0.651, 0.867)	3.49 (1.846, 6.6)
Whiting	27 cm	Test	0.153 (0.103, 0.221)	0.18 (0.114, 0.286)
Whiting	27 cm	Upper	0.713 (0.562, 0.828)	2.483 (1.264, 4.879)
Nephrops	25 mm	Test	0.47 (0.415, 0.526)	0.888 (0.706, 1.116)
Nephrops	25 mm	Upper	0.077 (0.046, 0.124)	0.083 (0.048, 0.143)

We assumed normally distributed random effects to explore and account for haul-level variability. More advanced approaches such as non-parametric random effects (Aitkin et al., 2009) may be useful to avoid given haul effects inflating the variability of the random effects (e.g. haddock level 1 hauls 1–3, Fig. 2). A delta-method approximation was used to approximate standard errors and confidence intervals on the predictions (Kristensen et al., 2015); it would be useful to compare the coverage properties of these intervals against a parametric bootstrap commonly used for mixed effect models (Bates et al., 2015). In addition, estimation of simultaneous confidence bands for inference over all lengths, as opposed to inference at given lengths (e.g., MCRS) would be a fruitful area for future development (Ruppert et al., 2003).

Apparent bias between the model and empirical raised proportions exists for level 1 *Nephrops* and level 2 whiting (Fig. 4). The significant night effect and the different number of hauls conducted during day and night can partly explain the *Nephrops* bias. For whiting, the bias at level 2 is persistent and unrelated to whether random effects are used or not. The subtle effect of sub-sampling ratios likely contributes to the bias for both *Nephrops* and whiting but we have dealt with this using a standard approach (Holst and Revill, 2009). Further work is required on sub-sampling ratios in this setting.

The test trawl has a number of potential benefits aside from reduced catches of undersize fish. Effective separation of *Nephrops* and fish species can greatly reduce catch sorting times, enhance catch quality and value, and improve discarded *Nephrops* survivability. From 2019, vessels targeting *Nephrops* will generally be required to grade all catches subject to catch limits by species and by MCRS category. The test trawl could be of major benefit in this regard. Separation of spinous *Nephrops* and fish species in the trawl's aft section significantly improves the quality of fish species potentially leading to increased catch value (Karlsen et al., 2015). Furthermore, T90-mesh in the upper codend can further improve fish catch quality and value compared with diamond-mesh (Browne et al., 2017b; Digre et al., 2010). Reduced contact with fish, in particular the rough skinned lesser-spotted catshark, may also improve *Nephrops* quality. The LO does not apply to species for which scientific evidence demonstrates high survival rates.

High survivability exemptions have been granted for *Nephrops* caught with specified selective gears which substantially reduce fish catches and boost post-capture survival of *Nephrops* in ICES Sub area IV and Division IIIa (EU, 2016). Scope exists, therefore, for a high survivability exemption for *Nephrops* caught with the test trawl. These broad ranging benefits of the test trawl can greatly assist vessels in complying and dealing with operational impacts of the LO, while optimising utilisation and value of quota allocations.

The benefits of the test trawl have been well publicised through trade press articles, an industry report (Cosgrove et al., 2016b) and a series of Irish LO workshops in 2016 and 2017. In spite of this, minimal progress on uptake of this gear by the Irish fishing industry has been achieved. Experience shows that additional incentives to fish more selectively and avoid unwanted catches are needed to make discard bans work (Catchpole et al., 2008; Condie et al., 2014). Under the EU common fisheries policy, Member States are encouraged to incentivise more selective fishing through allocation of fishing opportunities (EC, 2008). The Irish '*Nephrops* scheme' seeks to implement that policy by providing an enhanced share of the national *Nephrops* quota in return for a commitment to using a selective gear to reduce unwanted catches (DAFM, 2018). The Irish fishing industry was consulted through a dedicated workshop, and a quota management advisory committee made up of industry representatives and officials from the Irish government Department of Agriculture, Food & the Marine, who also administer the scheme. There is "no one size fits all" gear modification and any attempt to improve selectivity must be appropriate for the season, fishing area, and individual vessel (Condie et al., 2014). Hence, the scheme is operated on a voluntary basis and vessel owners can pick from a range of selective gears including the test trawl over a rolling three-month period. The scheme provides a 20% increase in *Nephrops* quota for up to 10 vessels. If successful, places on the scheme will increase which will greatly assist in reducing unwanted catches and developing a culture of compliance with the LO. In the longer term, the scheme has major potential to boost stock status of fish species avoided by *Nephrops* trawls. Indeed, major scope exists to develop similar schemes for vessels targeting fish species, and to tailor quota allocations accordingly. Such an approach would make optimal use of quotas and likely lead to further reductions in unwanted catches of non-target species. Although still in its genesis, the transition from a 'first half' landings to a 'second half' catch-based approach to management combined with quota-based incentives, potentially provides a powerful driver for uptake of more selective gears and the gradual elimination of discards in EU fisheries.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2018.09.019.

This consists of: A net plan of the test trawl; details of level-one (control versus test trawl) sub-sampling; a table on significance of night-time effects; raised length frequency counts for modeled species by haul.

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