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Estimating and accounting for fish losses under the footrope of a survey trawl: The case of northern shelf anglerfish

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ABSTRACT

Anglerfish, or, monkfish, (*Lophius piscatorius* and *L. budegassa*) are two of the most valuable commercial fish species in northern Europe. The stock which occupies the northern European shelf is monitored by an annual bottom trawl survey which aims to estimate absolute abundance. This estimation includes corrections for herding by the trawl gear but also requires an estimate of the capture efficiency of the net. To determine the latter, losses of fish under the footrope were quantified by 1 cm length class using trawls fitted with sub-footrope collection bags. The results demonstrate clear length dependency with the smallest fish being the most likely to escape under the gear. Overall, approximately 27 % of the anglerfish were lost under the footrope, with approximately 77 % of those below 30 cm being found in the ground gear collection bags. A length-based retention model for the gear was fitted here with a day-night effect, following appropriate model selection. This estimated higher proportions of fish escapes at night than during the day. The model was then used to estimate total stock numbers at length using data from the 2006 monkfish survey data to examine their impact on the stock estimates. As expected, this demonstrated a significant increase in the abundance of smaller recruiting fish when escapement under the footrope is accounted for. The estimates at length and age will provide better inputs for future developments of an age- or length-based analytical stock assessment which in turn will contribute to better stock management.

1. Introduction

Fish stock assessments and forecasts provide necessary information for decision makers to manage fish stocks using an informed management plan (Hilborn and Walters, 1992). These are usually supported by survey data providing either a relative or absolute stock estimate. The International Council for the Exploration of the Sea (ICES) categorises stocks according to the varying kinds and quantities of data available for use in their assessment and management advice (ICES, 2012). Those stocks that have an age- or length-based assessment approved which leads to absolute estimates of fishing mortality and stock size are considered as being more data rich (Categories 1 and 2) than those with only relative indices or catch and landings data available (Categories 3–5). Relative stock indices examine trends over time and assume that the stock size will change at a proportional rate to the survey estimates (Pennington, 1985). It is, therefore, vital that the performance of these surveys remains consistent so that they do not diminish the ability to make valid comparisons with previous years. However, estimating the stock size in absolute terms is often more desirable for a stock assessment because specific reference points can then be derived and absolute catch limits set in relation to what might be considered sustainable rates of fishing.

Surveys used to obtain absolute estimates must ensure that the survey covers the entire stock area. However, in most cases, concerns also exist that there may be inaccuracies in absolute survey estimates due to differences in the specifications of the fishing gear or issues associated with the efficiency of the gear (Van Zile, 2003). The gear specification must be consistent and appropriate for the species, and any bias associated with catchability and gear efficiency must be accounted for. The efficiency of the gear is known to be affected by a number of factors including the gear design, fish swimming ability and fish behaviour in response to the gear (see review by Fraser et al., 2007), in addition to the

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habitat and time of day in which the trawl occurs (Somerton et al., 1999; Ryer et al., 2010). The three primary components of this gear efficiency are considered as horizontal herding, vertical herding and escapement under the footrope (Somerton et al., 1999). Experiments can be conducted for each component to estimate efficiency coefficients (e.g. for herding, see Reid et al., 2007). These coefficients for efficiency may then be used to scale the relative index into absolute abundance (Dean et al., 2021).

Anglerfish (*Lophiidae*), also known as monkfish, represent a useful example with which to investigate the efficiency component of escapement under the footrope. These fish have significant commercial importance and were worth approximately €271.01 million to the EU fishery in 2019, with 51,394 tonnes landed (European Market Observatory for Fisheries and Aquaculture Products EUMOFA, 2021). The anglerfish stock on the northwest European Shelf (ICES Division IIIa, Sub-area IV and Sub-area VI) is used here as a case study for examining and accounting for fish losses under the footrope. This stock refers to the two species of anglerfish *Lophius piscatorius* and *L. budegassa* that occur in this area. The white bellied monkfish (*L. piscatorius*) is much more abundant in this stock, while the black bellied monkfish (*L. budegassa*) is found in much smaller numbers and accounts for approximately 6 % of the catch (Laurenson et al., 2008).

Prior to 2003, the northern shelf anglerfish stock was assessed with an analytical length-based model. This was abandoned due to the uncertainty associated with the provenance of the catch data (Dobby, 2002). An updated length-at-age assessment model was proposed, however, little further progress has been made in developing this model due to concerns over the age reading (ICES, 2009). The reliability of the age data has been questioned due to difficulties in the interpretation of growth cycles and comparability of the two calcified structures used, the otoliths and illicia (Woodroffe et al., 2003). The stock is now currently supported by the industry-science anglerfish survey (SIAMISS), conducted by Marine Scotland Science (MSS) and the Marine Institute (MI), Galway, Ireland with the aim of producing an absolute estimate of abundance each year. Despite this, the stock is currently designated as a category 3 data limited stock (ICES, 2012). This defines it as a stock that uses survey indices to indicate trends but lacks a quantitative assessment with the ability to forecast. It has been considered that additional work may be necessary to develop a more appropriate assessment that can account for the uncertainty and potential bias associated with the fishing industry catch data (ICES, 2019).

The SIAMISS survey is currently regarded as providing the most appropriate indicator available for use to manage this stock. As such, the biomass index values it produces are used in the '2 over 3 method' used to form the basis of the stock catch advice (ICES, 2019). This involves the comparison between the average of the two most recent values with the previous three. As a data limited stock, an uncertainty cap and precautionary buffer must also be considered and implemented if appropriate. This uncertainty cap ensures that the recommended total allowable catch does not exceed a 20 % increase from the previous year's advice. The precautionary buffer acts to reduce the catch advice by 20 %, although it may not be applied in cases where stock indices consistently indicate a trend of increasing abundance or decreasing fishing pressure.

The anglerfish survey uses a trawl that was specifically designed in consultation with anglerfish fishing industry (Reid et al., 2007). Various components of the catch efficiency of anglerfish in this trawl are considered for the survey estimate (Somerton et al., 1999). Horizontal herding by the sweeps and bridles was investigated and shown to be relatively small, with approximately 4 % of the fish that encounter the sweeps and bridle being likely to be caught (Reid et al., 2007). This is equivalent to a herding coefficient of 0.017 and is currently incorporated into the stock estimate (Fernandes et al., 2007). Vertical herding would act to increase the effective sampling height of the trawl as fish dive into the path of the gear as part of an avoidance response to the survey vessel. This is unlikely to occur due to the very benthic nature of the fish: it is therefore not accounted for.

In this study the component of efficiency corresponding to escapement of fish under the footrope was estimated. This effect was quantified using a set of experimental trials carried out in 2006 and 2007 by MSS (then Fisheries Research Services) using a number of small collection bags positioned just behind the footrope of the main trawl. Footrope retention probability was modelled as a function of fish length, using a number of alternative candidate selectivity models and included the potential effect of day and night. The modelling results were then applied to stock estimates.

2. Material and methods

2.1. Trawl gear and collection bags

The trawl used in the anglerfish surveys is based on the style of commercial gear used by the fishing industry to target anglerfish and was designed as a result of discussions between MSS and industry representatives. The main gear specifications are summarised by Reid et al. (2007). The ground gear is 45.7 m in length and has a 'ballooned' top sheet to stop anglerfish from escaping over the headline after being disturbed by the (19 mm) tickler chain. The mesh size in the lower wings is 120 mm to ensure that the smaller anglerfish are caught. It also uses 400 mm diameter rockhoppers in the centre of the ground gear, rigged on a 19 mm chain.

For the purposes of this experiment, the trawl gear was modified with the addition of sub-footrope collection bags. The initial design concept for the ground gear collection bags was similar to a rig developed by the Institute of Marine Research, Bergen, Norway (Ingólfsson and Jørgensen, 2006). The design incorporated three separate bags consisting of a port, starboard and centre bag (Fig. 1). Each bag was similar to a small low opening trawl with their headlines rigged to the fishing line of the anglerfish survey trawl (Fig. 2). The centre bag was intended to collect escapees from under the trawls bosom ground gear section. The port and starboard bags aimed to collect escapees going under the quarter sections of the ground gear.

Flume tank model tests were used to refine the design of the collection bags (at the Seafish Flume tank, Hull, in June 2006). Model trawls and collection bags were scaled to 1/15. The mesh size used in the

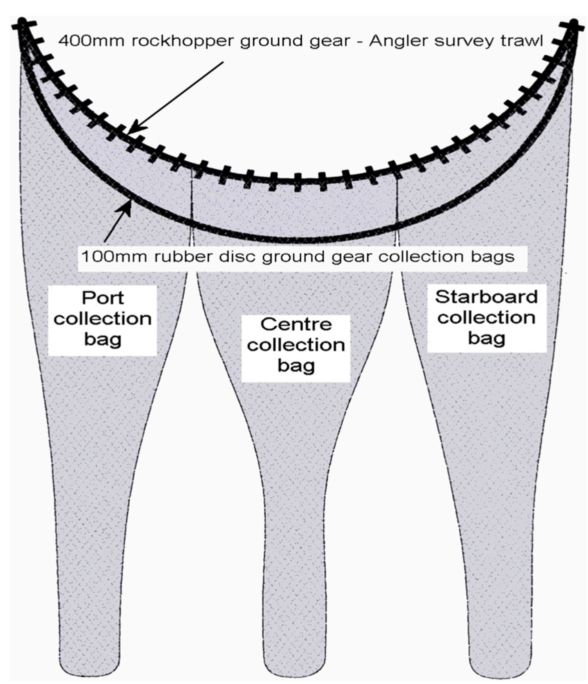

Fig. 1. Collection bags used in the 2006 and 2007 anglerfish (*Lophius piscatorius* and *L. budegassa*) gear selectivity trials.

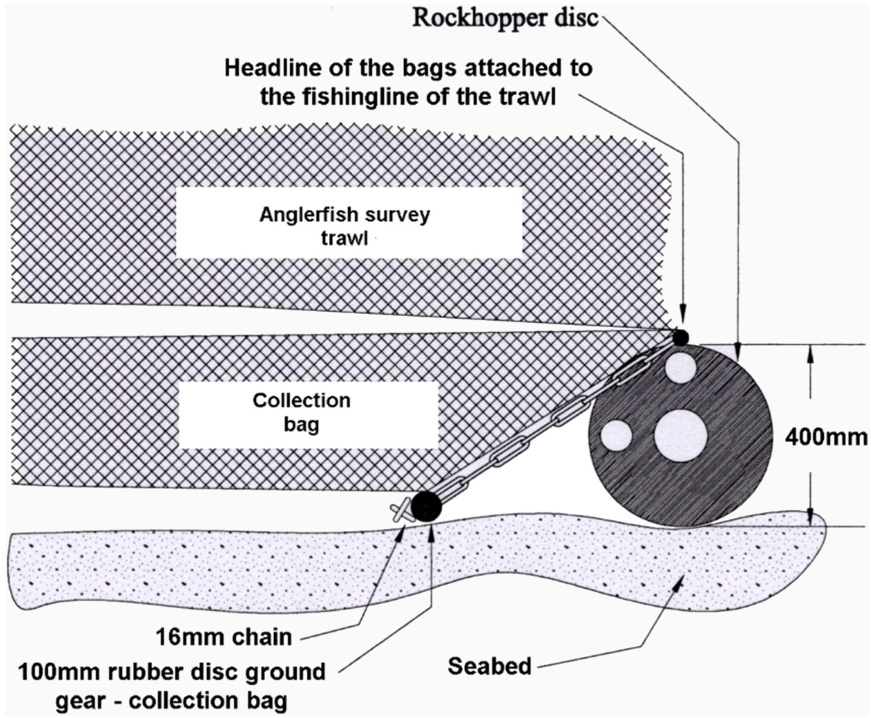

Fig. 2. Side elevation of the trawl used in the 2006 and 2007 anglerfish (*Lophius piscatorius* and *L. budegassa*) gear selectivity trials, showing the mouth of the collection bag and lower part of the main survey trawl.

construction of the bags was scaled to 100 mm full-scale. On observation of the initial design the side panels were found to have too many meshes, causing slack netting to hang down around the belly netting. It was further noted that the cut used in the top sheet wing panels of the outer bags did not follow the trawls fishing line correctly causing the bags to fall back and become tangled with the centre bag. After minor modifications, the bags were then found to be orientated correctly with no slack netting observed down the side panels and all three fishing symmetrically.

The full-scale collection bags were constructed from 100 mm × 4 mm single high tenacity polyethylene (PE) twine with all leading edges strengthened with sections of double twine. The collection bag codends were constructed from 2 mm single PE twine and rigged with strengthening bags. The ground gear was constructed from 100 mm rubber discs on 20 mm combination rope with 16 mm chain tacked along its full length to give added weight and ensure good contact with the seabed. The headline of each bag was laced to the fishing line of the anglerfish trawl. A 2 m bridle rope was used to attach the wing tips of both port and starboard wing bags to the trawls rockhopper ground gear. This allowed the tension in the wing bags to be adjusted by increasing or decreasing the length of the bridle rope. It should also be noted that the codend on the main gear was 100 mm mesh constructed from double 6 mm braid, while the codend mesh in the collection bags was 50 mm, single 2.8 mm twisted braid.

2.2. Data collection

The trials were carried out on the MSS research vessel MRV Scotia from 19th to 27th October 2006 and 19th to 24th October 2007. The annual anglerfish survey is currently conducted in April where the daily duration of sunlight is greater, than in October. Therefore, we used the presence of sunlight, rather than the time of day, to determine day-night here. Day and night were delineated by sunrise and sunset which were defined based on the top edge of the sun appearing above the horizon and then disappearing below the horizon. The trawls were taken in the northern North Sea off the south-west tip of the Shetland Islands, south of the Scalloway deeps. The locations of the trials were based on information provided by the fishing industry and were selected with the aim of producing clean tows with good expected catches of anglerfish, at a range of depths. The tow speed was approximately 4 knots (2.06 m s^{-1}) and tow duration between 30 and 60 min. In the 2006 experiment, a total of 29 tows were completed, with the ground gear collection bags deployed on 21 tows and recovered undamaged on 14 tows. In the 2007 experiment, a total of 24 tows were completed, with the ground gear bags deployed and recovered undamaged on all 24 tows. Six of the 36 hauls that caught anglerfish were taken in the hours of darkness (considered here as ‘night’), four in 2006 and two in 2007. The modified gear was monitored during trawling using gear mensuration equipment (Scanmar) to ensure that its performance was comparable with the SIAMISS survey, although these data were not recorded. Performance metrics included depth, bottom contact, headline height, bridle angle, door spread, wing spread and average speed over the ground. Anglerfish catches were recorded separately for the main trawl codend and the sub-footrope collection bags, with the length, weight and sex recorded for all fish. The species of anglerfish caught was not recorded and so the catches in these trials may contain both *Lophius piscatorius* and *L. budegassa*. As these two species are morphologically similar, there is not expected to be any significant difference in their response to the trawl gear.

2.3. Footrope retention estimation

Those individuals that were caught in the codend of the gear were assigned a retention value of 1, while those caught in the sub-footrope collection bags received a value of 0. The escapement under the footrope component of catchability was then modelled as follows. For any haul h carried out at daylight level d (where day = 1 and night = 0), let $y_{h,l,d}$ be the number of fish caught at length l, in the codend, and $n_{h,l,d}$ be the number of fish caught in total in the haul (in both the codend and the ground collection bags). Then $y_{h,l,d}$ is assumed to have a binomial distribution: $y_{h,l,d} \sim Bi(n_{h,l,d}, r_{l,d})$ where $r_{l,d}$ is the footrope retention probability, i.e. the probability that a fish of length l does not escape under the footrope and is, therefore, retained in the codend at daylight level d. The footrope retention probability was modelled as a function of length (binomial smoother) and daylight (factor, with the two time periods, day or night), using a generalised additive model (GAM):

$$r_{l,d} \quad = \quad \left(\frac{\exp(\beta_0 + \beta_1 X_d + f(X_l))}{1 + \exp(\beta_0 + \beta_1 X_d + f(X_l))}\right) \tag{1}$$

where β_0 is the intercept, β_1 is the coefficient of the effect of daylight, f represents the regression function and X_d and X_l are the variables of daylight and fish length. A generalised linear model (GLM), Richards curve (Richards, 1959) and generalised linear mixed model (GLMM) were also fitted for comparison. The generalised linear model produces a curve that is symmetrical around the point of inflection and was fitted in the form of:

$$r_{l,d} = \left(\frac{\exp(\beta_0 + \beta_1 X_d + \beta_2 X_l)}{1 + \exp(\beta_0 + \beta_1 X_d + \beta_2 X_l)}\right) \tag{2}$$

where β_2 is the coefficient of the effect of length. The Richards curve or generalised logistic model is an extension of the logistic function that allows for asymmetry in the curve and is commonly used to fit gear efficiency (e.g. Millar, 2010; Dean et al., 2021). This took the form of:

$$r_{l,d} = (1 - \beta_0 \exp(\beta_1 X_d - \theta \quad \beta_2 X_l))^{\frac{-1}{\theta}} \tag{3}$$

where θ is a variable which fixes the point corresponding to the asymptotic maximum length. The generalised linear mixed model was created as follows, with a random effect of the different hauls included as:

$$r_{l,d} \quad = \quad \left(\frac{\exp(\beta_0 + \beta_1 X_d + \beta_2 X_l + Z_h u)}{1 + \exp(\beta_0 + \beta_1 X_d + \beta_2 X_l + Z_h u)}\right) \tag{4}$$

where Z_h represents the model matrix for the random effect of hauls u.

The models were fitted with the statistical software R version 3.4.1 (R Core Team, 2020). The GLM and Richards curve were fitted by maximum likelihood (with standard R functions); the GAM was fitted by an un-biased risk estimator (UBRE) using the mgcv package, version 1.8-28 (Wood, 2011); and the GLMM using lme4 version 0.999375-32 (Bates et al., 2015). A graphical analysis of the residuals of these models was carried out to investigate model validation. Model fits were also compared using Akaike's Information Criterion (AIC: Akaike, 1973). The effect of these models on the existing 2006 stock estimate, calculated using an adapted version of the methods outlined in Fernandes et al. (2007), was then investigated. This was based on estimations of density from individual trawl swept-areas using a Horvitz-Thompson-like estimator (Horvitz and Thompson, 1952) to estimate abundance. The proportion of anglerfish within the area swept by the net (trawl wings) that were caught was estimated by the footrope retention model.

3. Results

During the 2006 experiment a total of 245 angler fish were caught, with 163 in the main trawl codend and 82 in the sub-footrope collection bags. In 2007 186 angler fish were caught, with 151 in the main trawl

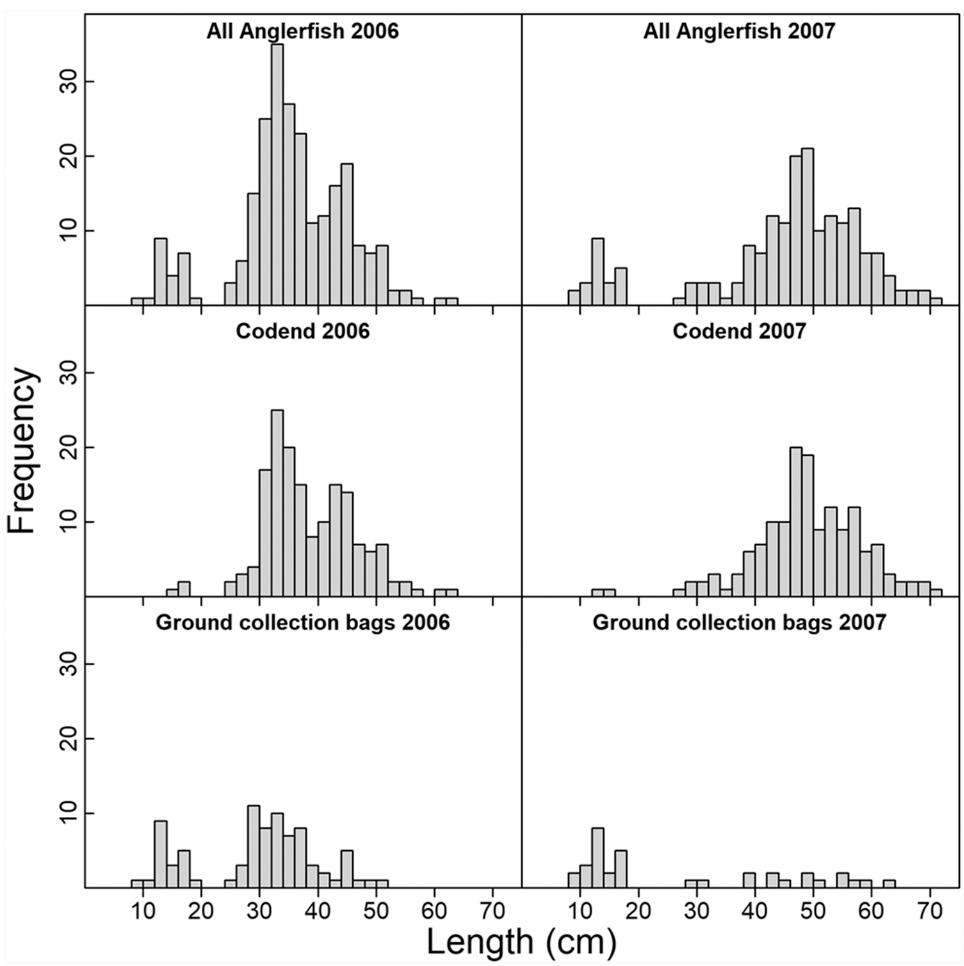

Fig. 3. Length distributions for those anglerfish (*Lophius piscatorius* and *L. budegassa*) caught during the two separate trials (2006 and 2007), both overall and by codend and ground collection bags.

codend and 35 in the sub-footrope collection bags. This was an overall retention rate of approximately 73 %, with 27 % lost under the footrope. For the main gear in 2006, this represented a catch rate of approximately 18 fish per hour, which was comparable with commercial catch rates in the same area. However, the numbers in each haul were low with only two hauls catching more than 22 fish, half the hauls catching less than 10 fish, and approximately 12 being caught on average.

The length distributions of the fish ranged from 9.5 to 62.5 cm in 2006 and 9.5 to 71.5 cm in 2007 (Fig. 3). The overall length distributions of the fish for the two experimental trials have similar features: a mode between 10 and 20 cm; very few fish caught between 20 and 25 cm; and two modes at around 30–35 and 45–50 cm in each year; with the largest mode at approximately 33 cm in 2006 and 48 cm in 2007, indicating a large year class moving through the population. This was confirmed by the surveys in those years. The distributions for the codend and collection bags were quite distinct, with 88 % of the smallest group of fish (10–20 cm) escaping the main trawl and being caught in the collection bags. Approximately 28 % of fish between 30 and 40 cm and 11 % of fish between 40 and 50 cm also escaped under the footrope. Age length keys from commercial samples indicate that the 10–20 cm fish are 0-group fish, while those in the largest age class were likely of age 1–3 years as they moved through 2006 and 2007 (Landa et al., 2013).

The efficiency of the gear was found to differ between night and day with 75 % of the fish being caught in the main trawl during the day and 65 % during the night. This difference in fish escapement was greater for the larger fish (over 40 cm), for which approximately 91 % of the fish were caught during the day and 84 % at night. This effect was lower for those smaller fish (under 40 cm), for which approximately 56 % of the fish were caught during the day and 52 % at night. The effect of day-night was found to be significant ($\alpha = 0.05$) and so it was included in all of the models. Accounting for the effect of day-night resulted in a higher proportion of fish being lost under the footrope at night than during the day for all of the models fitted (Fig. 4).

Selectivity data is commonly fitted using mixed models (Fryer et al., 2003; Holst and Revill, 2009), allowing between-haul variation to be modelled as a random variance component. However, the low numbers of anglerfish caught in many of the hauls in these trials resulted in unrealistic variance estimates of approximately zero or correlations of one. The GLMM was, therefore, excluded from further analyses.

The GAM allowed a smooth with a maximum 10 degrees of freedom (df), however, using generalised cross validation (GCV) resulted in a smooth with approximately 2 effective degrees of freedom. This had a steeper selection curve than that implied by the GLM, with lower retention probability at lengths less than 24 cm for day and 27 cm for night, while tailing off slower at longer lengths greater than 45 cm for day and 43 cm for night (Fig. 4). The Richards curve was similar to the GAM but produced even smaller proportions of fish caught at shorter lengths, whilst similarly to the GLM tailed off more quickly to reach approximately 100 % retention, demonstrating the reduced flexibility of the Richards curve and GLM compared to the GAM (Fig. 4). The L50 (the length at which 50 % of fish are caught) was approximately 26 cm for day and 31 cm for night for all models, and the retention was almost 100 % by 100 cm in all cases, with the GLM and Richards curve achieving this within the range of the data, at approximately 80 cm. Model validation did not raise any significant concerns, with the models producing relatively comparable residuals that were sufficiently evenly distributed across the range of values (Fig. 5). Goodness of fit statistics were similar across all models (Table 1), with the GAM explaining slightly more deviance (25.7 %) and a higher R^2 (30.7 %) than the other models, whilst using the same number of parameters as the Richards

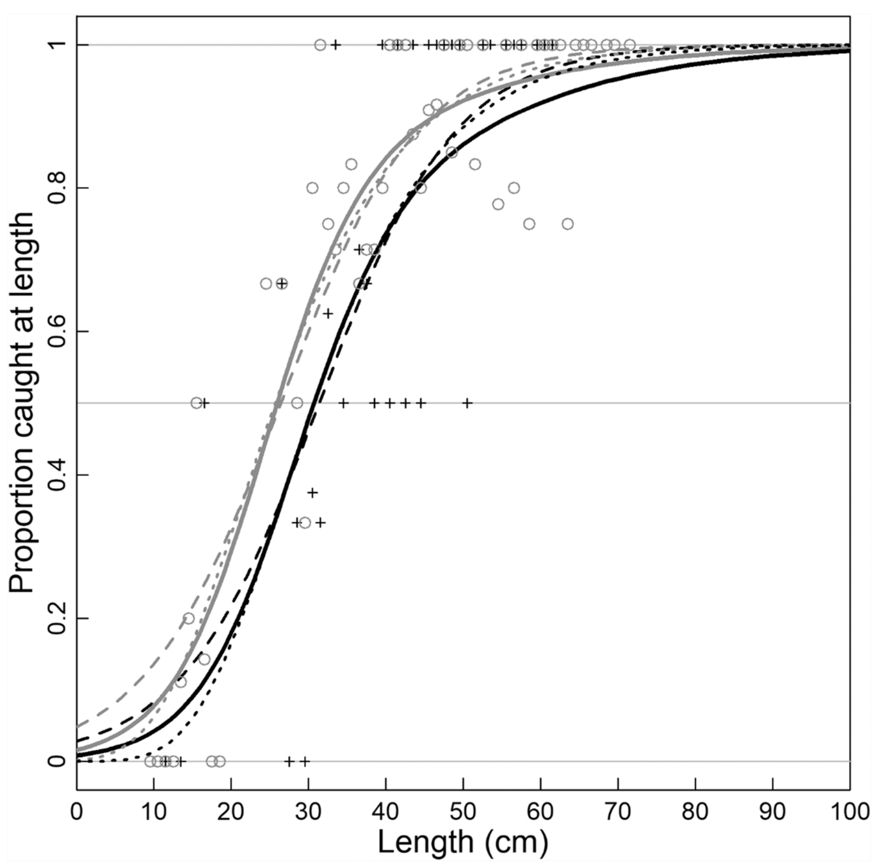

Fig. 4. The overall proportion of anglerfish (*Lophius piscatorius* and *L. budegassa*) caught in the codend for each 1 cm length class during the day (circles) and night (crosses). The grey lines display the model for day, while the black line displays night for the generalised additive model (solid), Richards curve (dotted) and generalised linear model (dashed). The horizontal line shows the L50 (the length at which 50 % of fish are caught).

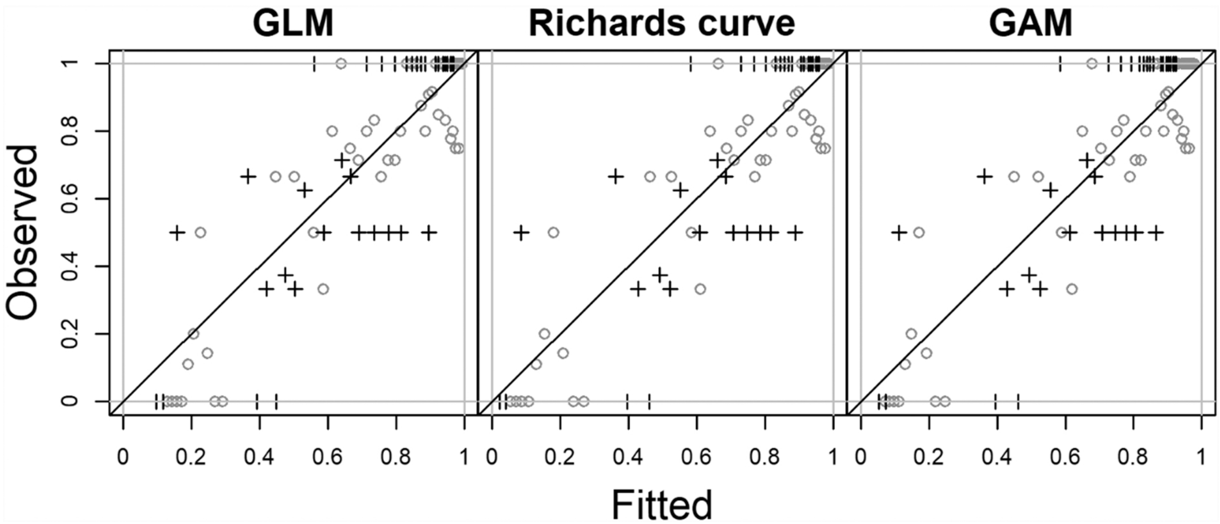

Fig. 5. The observed proportions of anglerfish (*Lophius piscatorius* and *L. budegassa*) caught in the codend plotted against the fitted values produced by the different models explored for the escapement of anglerfish (*Lophius piscatorius and L. budegassa*) under the footrope of the survey trawl during the day (circles) and night (crosses). The solid line displays a 1:1 relationship.

Table 1
Comparison of the model goodness of fit statistics for the different footrope escapement models for anglerfish (*Lophius piscatorius and L. budegassa*) explored.

Model	Deviance (residual)	Deviance explained (%)	Adjusted R^2	df (residual)	AIC
GAM	374.2	25.7	0.307	427	382.3
Richards	376.2	25.4	0.305	427	384.0
GLM	380.5	24.5	0.300	428	386.5

model, and just one parameter more than the GLM, resulting in a lower AIC than both the other two models. The comparison of the model AICs displayed the GAM as producing the lowest value and so providing the best fit (Table 1). Using the approach of Burnham and Anderson (2004) which proposes that candidate models with an AIC with a difference of less than 2 from the AIC of the best model has substantial support, whilst a model with an AIC difference of more than 4 from the best model has less support, the Richards model could be considered similarly parsimonious to the GAM, with the GLM being less parsimonious. On the basis of the model AICs and visual inspection of graphical model diagnostics (Figs. 4 and 5) the GAM (Table 2) was selected as the most appropriate model.

The GAM was incorporated into the estimation of the stock abundance and biomass for 2006 where it produced an abundance estimate of 29.962 million fish and a biomass estimate of 42.144 kt (Table 3).

This estimate of abundance is significantly higher than when escapement under the footrope is not considered which provides an estimate of 19.792 million individuals (no overlap of the 95 % confidence intervals of the estimates). The effect on the estimated stock abundance at length, when this footrope retention model is incorporated, was clear, with abundance increasing the most for smaller fish lengths (Fig. 6). The inclusion of escapement increased the estimates most notably for fish smaller than approximately 50 cm (ages 0–3). The biomass estimate is also considerably higher, albeit not statistically significantly so, than the biomass estimate which did not account for escapement of fish under the footrope (36.277 kt).

4. Discussion

This study has demonstrated clear evidence that anglerfish, particularly smaller ones, are able to escape under the footrope of the trawl, avoiding capture in the gear. The effect is clearly length dependent,

Table 2
Summary of the model analyses of the generalised additive model (GAM), generalised linear model (GLM) and Richards curve for the escapement of anglerfish (*Lophius piscatorius and L. budegassa*) under the footrope of the survey trawl. Here β_0 is the intercept, β_1 the coefficient of the effect of daylight, β_2 the coefficient of the effect of length, f represents the regression function and θ is a variable which fixes the point corresponding to the asymptotic maximum length.

GAM			
Parametric term	**Estimate**	**Std.Error**	***p***
β_0	0.756	0.241	0.002
β_1	0.643	0.279	0.021
Smooth term	**Estimated df**	**Refined df**	***p***
f	2.044	2.572	< 0.001
GLM			
Parametric term	**Estimate**	**Std.Error**	***p***
β_0	-3.533	0.509	< 0.001
β_1	0.557	0.276	0.044
β_2	0.113	0.013	< 0.001
Richards curve			
Parametric term	**Estimate**	**Std.Error**	***p***
β_0	-0.344	0.213	0.107
β_1	-0.461	0.215	0.032
β_2	2.988	1.447	0.039
θ	0.030	0.015	0.038

which is similar to previous findings for other species such as cod and haddock (Godø and Walsh, 1992; Walsh, 1992; Ingólfsson and Jørgensen, 2006; Brinkhof et al., 2017). A significant effect of day-night on the footrope retention probability was also found. This effect of day-night on fish escapes under the ground gear has also previously been reported for haddock (Larsen et al., 2018). This may be a due to a reduced response by the fish to the gear which may result from reduced visual herding by the gear during the night when detection by the fish is lower (Ryer et al., 2010). A reduced response may allow the fish to pass under the gear in a more passive manner rather than an active process of rising from the seabed above the footrope of the gear when seeking to escape. It has been found with flounder that those individuals that are not stimulated to leave the seabed are not caught by the gear (Underwood et al., 2015). In the case of cod, it has also previously been suggested that, although herding may be equally efficient during day and night, the distribution of fish in the trawl mouth was affected by light levels, with fish being located closer to the seabed as they enter the trawl

Table 3
Comparison of abundance and biomass stock estimates for anglerfish (*Lophius piscatorius* and *L. budegassa*) when escapement of fish beneath the footrope of the trawl gear is accounted for (using the generalised additive model) with when no escapement is accounted for. Displayed with the 95 % confidence intervals of the estimates.

Model	Abundance (million)	Lower 95 % C.I	Upper 95 % C.I	Biomass (kt)	Lower 95 % C.I	Upper 95 % C.I
Escapement	29.962	25.538	34.385	42.144	36.399	47.890
No Escapement	19.792	16.914	22.669	36.277	31.004	41.550

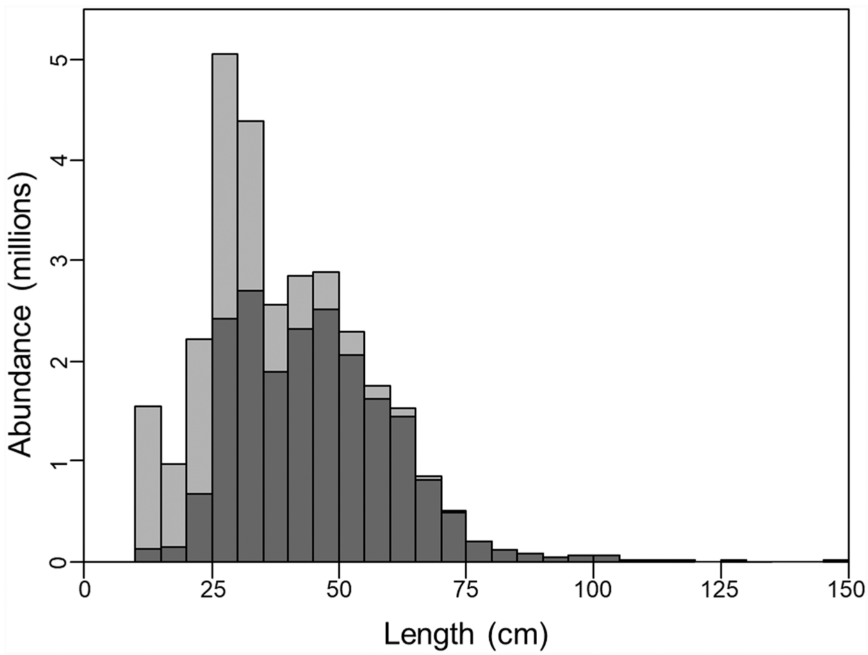

Fig. 6. Comparison of the numbers of fish at length for anglerfish (*Lophius piscatorius* and *L. budegassa*) produced for 2006 by the stock estimate model using the generalised additive model for footrope escapement developed here (light grey), as well as when escapement under the footrope is not accounted for (dark grey).

mouth at night (Engås and Ona, 1990). This may be due to the fish relying more on non-visual methods to detect the gear, leading to greater losses under the footrope. Conversely, retention may be lower at night as a result of a behavioural response, with anglerfish having been found to be more vertically active at night than during the day (Ofstad et al., 2022). These vertical activities may be due to the anglerfish making short horizontal movements, feeding or spawning (Hislop et al., 2000). This increased level of activity at night may result in a more active response, and so a higher number of losses under the footrope as the fish seek to escape the gear. However, anglerfish activity has also been shown to persist into the day, occurring predominantly between midnight and noon (81 %), with peaks of movement being found at 3 a. m. and 10 a.m. (Rountree et al., 2008). Ex situ experiments of the visual response and swimming behaviour of anglerfish under differing light levels would likely be needed to further examine this effect. Catch rates have been reported as higher during the day for a number of species, such as cod, haddock, herring, redfish, whiting and dab (Engås and Soldal, 1992; Korsbrekke and Nakken, 1999; Petrakis et al., 2001). Yet it should be considered that in some cases this may be due to the diel vertical migration that they exhibit, rather than differences in escapement. This can result in a larger proportion of those fish being present near the seabed and within the path of the net during the day than at night (Gauthier and Rose, 2005).

The GAM is considered here to be the most parsimonious model on the basis of its AIC value. However, none of the models resulted in a statistically significant change to the stock biomass estimate for 2006 and this is not expected to differ for the rest of the time series. The practical use of these models in the stock estimation process should also be considered. The GAM contains a smoothing factor that must be stored and recalled, unlike the GLM and Richards curve which may be implemented using simple numerical parameters to calculate the retention probabilities. The GLM and Richards curve therefore have greater ease of use than the GAM. There appear to be small trade-offs between the models examined in terms of model fit and practicality. However, the ease of use associated with the GLM and Richards model was not deemed sufficient to warrant selecting either of those models over the better fit provided by the GAM.

When the loss of fish under the footrope is not included in the estimate it is shown to result in a lower value of abundance. This is because the model assumes that all of the fish that are within the path of the net are caught. This assumed lack of escapement results in a significant underestimate of the numbers of fish at length (Fig. 6), most notably for those smaller fish (< 40 cm). The failure to account for this escapement would therefore portray a stock trend of fewer young fish and produce a population age distribution that would be biased. Including this element of gear efficiency is therefore likely to make it possible to more effectively propagate back year classes, making them more apparent at younger ages/smaller lengths and improving forecasting power. It will assist in producing recruit estimates, which are required for determining a stock-recruitment relationship for use in a management strategy evaluation. This, in turn, is needed to estimate key management parameters such as the fishing mortality that provides the maximum sustainable yield (F_{MSY}) and the maximum sustainable yield biomass trigger (MSY $B_{trigger}$) which represents the lower bound of the spawning-stock biomass fluctuation when fishing at F_{MSY}. The total stock abundance estimate for 2006 is significantly higher when escapement under the footrope is accounted for. This emphasises the need to include these models in the estimates, even in cases where they do not result in a significant change to the biomass estimate, as seen here for the 2006 estimate. Although the uncertainty associated with this model was not propagated through into the stock estimates, this could be achieved through bootstrapping methods to simulate the regression coefficients (Yuan, 2012). In the absence of this it must be considered that any estimates of survey uncertainties are likely underestimates.

It should be considered that the size range of fish caught in these trials did not include some larger sizes typically caught during the annual SIAMISS survey. The sizes obtained in 2007 were notably higher than those in 2006, however, the overall distribution from both years contained few lengths over 60 cm. The largest fish recorded in the trials was 71.5 cm, while the largest in the collection bags reached 63.5 cm. The estimated footrope retention probability produced by the models was high for these larger fish, reaching almost 100 % by 100 cm for all models. However, as there are a greater number of larger fish being caught in the annual survey (up to 146 cm in 2006) it may be important to confirm this retention probability for these large fish and ensure that the model is representative across the length range. The collection bag catches also included smaller fish sizes than those seen in the main trawl cod end of the trials or the SIAMISS survey (Approx. 9–12 cm: Fig. 3). This was likely a result of those smaller fish being more likely to escape underneath the footrope of the gear. For those smallest fish it may also be due to differences in mesh selection as a result of the 50 mm codend in the collection bags compared to the 100 mm in the main trawl codend.

During the 2007 experiment only two hauls were carried out at night which represented a small proportion of the total number of successful hauls and as a result it was not possible to model the effect of day-night on footrope retention using only this year. Despite this, the model L50s appeared relatively robust, with the those for the GAM being the same for the day when using both trial years and using only the 2006 trial in the model creation. Similarly, the L50 for night when using the 2006 data alone was approximately only 1 cm larger than with both trials. However, there were more significant differences in the tails of the models with those based solely on the 2006 trials reaching 100 % retention much sooner and retention being notably higher for the smaller lengths. There would likely be benefit in conducting a larger proportion of hauls in the hours of darkness in any future experiments to provide a greater number of data points to explore this effect of day-night.

The seabed substrate types over which these trials were conducted must also be considered. The collection bags used in this study were relatively fragile compared to the main net. As a result, all the successful tows with the collection bags were carried out in an area characterised by smooth, fine sand. Similar tows were attempted in other substrates which resulted in damage to the collection bags. The ground gear used on the net is a Rockhopper design, allowing the gear to ride over obstructions. In the trial tows, the seabed was relatively flat, and the gear tended to dig into the soft substrate, so the bottom contact was good throughout the tows. Given that the SIAMISS survey will likely have a significant proportion of the survey conducted on rougher seabed than these experiments, the net may be operating at a lower efficiency. These estimates of fish loss under the footrope, which assumed no escapement beneath the sub-footrope collection bags and were carried out in optimum conditions during the trials, could therefore be considered as a minimum level.

It was important to ensure that the modification of the gear with the addition of the sub-footrope collection bags does not affect the gear performance, which was a previous conclusion (Dahm, 2000). In the current case, this was mitigated using the model gear tests prior to the construction of the gear and Scanmar monitoring during the experiment trawls. The data from these trawl sensors indicated that the gear behaved in a consistent and similar manner to that during the survey.

Although experiments with collection bags represent a widely used method of estimating gear efficiency, other approaches using mathematical and statistical methods have also been developed. These mathematical approaches often use depletion methods which quantify the impact of repeated catches in a given area on the catch rate for that population (Bez et al., 2006; Rago et al., 2006; Walter et al., 2007). This is not appropriate for many stocks which do not exhibit a depletion trend. A method using exclusively statistical modelling with survey catch length data and commercial catch and discard data has also been explored (Walker et al., 2017). This involves the estimation of catch-ratios which can then be re-scaled and used to fit gear efficiency. The study more broadly categorised gear types, within which the gear may be rigged and operated differently, however, this method may also present a useful means of assessing gear efficiency. Although they are often more resource intensive, the use of collection bag trials for the estimation of escapement under the footrope and ultimately gear efficiency, represents an effective method which relies on fewer assumptions than many of the mathematical and statistical approaches. Although the results are specific to anglerfish, the experimental approach may also be appropriate (using species appropriate gear) to produce estimates of retention at length for other species.

This study provides evidence that small anglerfish are lost under the footrope of the trawling gear. This effect can be quantified using the modified gear trials described here, with the footrope retention probability being demonstrated as length dependent with an effect of day-night. Although, statistically, the GAM model was selected as the most appropriate one here, others were very similar and have advantages in being simpler to apply in the estimation process. The resulting retention probability at length can then be used to modify the length data for the survey estimates correcting for the fish that were lost under the footrope. Changes in diel catchability have been found to result in higher catches during the day for some species and lower catches for others (Benoît and Swain, 2003). Regardless of whether the diel variation for a given species results in an increase during the day or night, there is likely significant benefit in including the effect in any calculations of catchability. This may assist a survey in becoming more robust to any annual variation in the proportions of fishing activity carried out during the hours of daylight and darkness.

CRediT authorship contribution statement

Rufus E. Danby: Formal analysis, Writing – original draft, Visualization. **Elizabeth D. Clarke:** Supervision, Methodology, Writing – review & editing. **Robert J. Kynoch:** Investigation. **David G. Reid:** Supervision, Writing – review & editing. **Paul G. Fernandes:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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