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Selective haddock (*Melanogrammus aeglefinus*) trawling: Avoiding cod (*Gadus morhua*) bycatch

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ABSTRACT

The critical condition of the North Sea cod stocks has resulted in restrictions on not only cod, but also haddock and other species that are caught together with cod. Thus full exploitation of the haddock stock is unachievable unless cod can be excluded from the haddock catch. We designed a selective trawl based on the behavioral differences between haddock and cod as they enter a trawl, i.e., cod stay close to the seabed whereas haddock rise above it. The trawl's fishing line is raised ~60 cm above the seabed to allow cod to escape beneath the trawl while haddock are retained. To collect the escapees, three sampling bags were attached beneath the raised fishing line. The selective haddock trawl reduced the total catch of cod by 55% during the day and 82% at night, and 99% of the marketable haddock was caught during the day and 89% at night. Cod escape rates were highly length dependent: smaller cod escaped the trawl in greater numbers than did larger individuals. Whiting, saithe, lemon sole, and plaice were included in the analysis.

1. Introduction

The majority of towed fishing today occurs in a multispecies setting, where to a large extent the trawl catch reflects the species diversity present in the trawl's path. In general, these multispecies fisheries are not able to adjust their catch composition to stock fluctuations and other management concerns. Thus, the protection of one species in a multispecies fishery can affect the exploitation of other species and reduce the total cost efficiency of the given fishery.

In recent years, North Sea cod (*Gadus morhua*) stocks have been at a critical level, in contrast to the species such as haddock (*Melanogrammus aeglefinus*), which today is classified as having full reproductive capacity and is being harvested sustainably (ICES, 2008). Since 2000, the North Sea cod stock has been in such a bad state that ICES advised the closure of all fisheries in which cod is caught (ICES, 2002). At the same time, the North Sea haddock stock was at its highest level in 30 years. Nonetheless, because haddock is taken mostly with cod, ICES advised that "Unless ways to harvest haddock without bycatch or discards of cod can be demonstrated fishing for haddock should not be permitted" (ICES, 2002). Thus, a strong biological and economic incentive exists to solve this classic mixed-species fishery problem: how can we restrict fishing on cod without restricting fishing on haddock taken in the same fishery?

Mechanical sorting of haddock and cod based on size is difficult due to the morphological similarities between the two species. Caddy and Agnew (2003) suggested that restoring both the age structure of the population and the stock biomass is an appropriate approach to rebuild groundfish (e.g., cod) stocks. They warned that focusing solely on improving juvenile survival through a supplementary mesh size increase or using minimum sizes in a recovery plan based on quotas might increase the pressure on the few remaining large and fertile spawners.

Using behavioral differences among species is another approach to address this problem. Species-specific behavioral differences exist between cod and haddock as they enter the trawl mouth: haddock rise from the seabed whereas cod maintain a position close to the seabed (Main and Sangster, 1981). Their follow-up study reported that the best separation of cod and haddock occurred when the separator panel was placed 75 cm over the seabed (Main and Sangster, 1982). Several other studies have tried to utilize this behavioral difference to separate cod and haddock and other species in demersal trawls (Main and Sangster, 1985; Galbraith and Main, 1989; Engås et al., 1998; Ferro et al., 2007). These trials demonstrated a separation by which the majority of haddock enter the top compartment and the majority of cod enter the lower compartment. In the North Sea demersal fisheries several other species, such as plaice (*Pleuronectes platessa*), lemon sole (*Microstomus kitt*),

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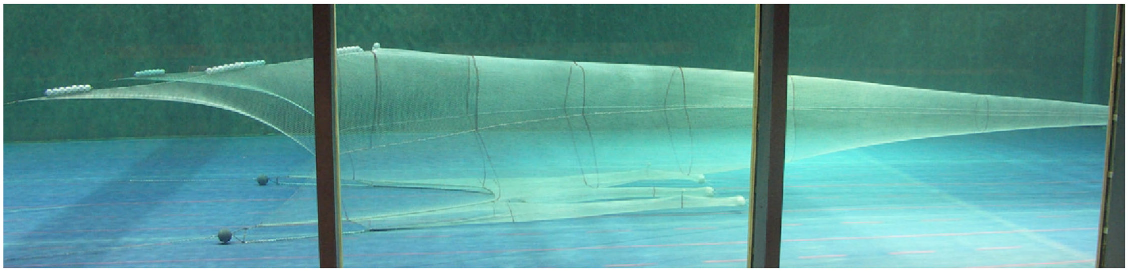

Fig. 1. Model (scale = 1:8) of the selective haddock trawl in the Hirtshals flume tank. Note the three lower collecting bags.

dab (*Limanda limanda*), witch (*Glyptocephalus cynoglossus*), monkfish (*Lophius piscatorius*), rays (*Raja* spp.), and *Nephrops* (*Nephrops norvegicus*), enter the lower part of the trawl along with cod (Main and Sangster, 1982, 1985; Ferro et al., 2007). This diverse group of species represents different sizes, morphological shapes, and minimum landing sizes (MLS), and the species therefore are difficult to separate mechanically from cod.

This study describes the development and commercial testing of a selective haddock trawl in which the fishing line is raised above the seabed. Fish and other marine organisms that pass beneath the raised fishing line escape the trawl (in contrast to separator trawls designs) with a minimum of contact with the fishing gear. During the experiment, we used small mesh collecting bags to quantify the escapement of fish beneath the raised fishing line. The consistency in the vertical separation of haddock and cod over length and between day and night was estimated. We also evaluated the gear design's commercial applicability to reduce the catch of cod in the haddock fishery.

2. Materials and methods

2.1. Flume tank experiments

Danish fishermen in the North Sea and Skagerrak typically target haddock with a high opening two-panel modified version of a Scottish haddock trawl known in Denmark as a Jackson trawl. Thus, this trawl (with 750 160 mm meshes in the fishing circle) was selected for this study and a 1:8 scale model was built and tested in the Hirtshals flume tank (Fig. 1). The fishing line was raised to the equivalent of 75 cm by a large danleno bobbin. Three collecting bags were made following the design described in Ingolfsson and Jørgensen (2006) to quantify the escapement beneath the raised fishing line. The headline height of the trawl was equal to 8 m and the spread of the upper wings to 22 m and of the lower wings to 20 m; towing speed was equal to three knots. The total width of the three collecting bags equaled about 15 m (i.e., the width of each bag, perpendicular to the towing direction, was about 5 m). A float equivalent to a 20 cm float was attached to each of the three collecting bag codends to keep them off of the bottom.

2.2. Commercial testing

A full-scale experimental trawl was built according to the scale model. The collecting bags and the main codend were constructed of 40 mm mesh size (full mesh) made of 1.4 mm nylon twine. The position to the raised fishingline relative to the colleting bags and main trawl body is illustrated in Fig. 2. Before the sea trials, a row of 20 meshes from each codend was measured with an ICES spring-loaded mesh gauge set at 4 kg. The ground gear was made of 18 cm rock hopper discs in the centre section and 13 cm rock hopper discs in the wing sections, both with 30 cm intervals. In the fisheries, heavy rock hopper gears with about 50 cm discs normally are used. The smaller rock hopper discs used in this study were chosen to minimize the escapement of fish beneath the collecting bags. It is assumed that all fish in the path of the trawl are caught. However, fishing with small discs restricts fishing to areas with a relatively smooth bottom compared to the grounds that can be fished with heavy rock hopper gears. A 53 cm bunt bobbin was connected to an 80 cm butterfly by a crowfoot made of 19 mm chain (8.5 kg/m). The false fishing line was made of a 19 mm chain (8.5 kg/m), and the raised fishing line was made of a 13 mm chain (3.8 kg/m). The trawl was rigged with 163 m sweeps and 55 m bridles and was spread with a set of Thyborøn V doors each weighing 1799 kg. The sea trails were conducted onboard the commercial vessel HM 128 *Borkumrif* (28 m and 728 kW) from 7 to 17 October 2006. Fishing was conducted in the southwestern part of the Skagerrak along *Jyske rev* (ICES area 44).

2.3. Catch measurement

Fourteen successful tows were taken the days and nights. Day tows were conducted from an hour after sunrise to an hour before sunset, and the night tows were conducted between an hour after sunset to an hour before sunrise. The towing time was 30 min at about 3 knots; the short towing time was due to the high density of fish and the small mesh size used in both the collecting bags and in the main codend. Haddock, cod, whiting, saithe, plaice, and lemon sole were collected and measured. In some hauls, haddock, whiting, and saithe were subsampled due to large catches in the main codend. A representative sample was taken by measuring 2–3 30 l baskets of whiting, 8–10 baskets of haddock, and 12–15 baskets of saithe. These numbers of baskets correspond to about 500 fish measured per species in each tow when subsampling was conducted. The weight of subsamples and the total catches of the respective species were determined and raising factors estimated. The total

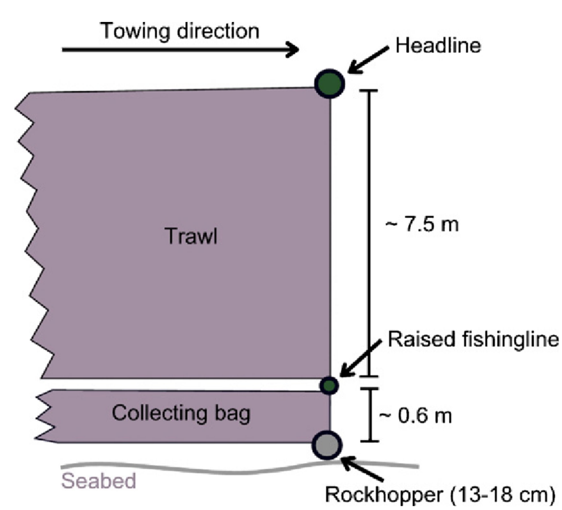

Fig. 2. Schematic side view of the collecting bags, raised fishing line and main trawl body.

Table 1
Operational conditions and gear performance.

	Depth (m)	Door-spread (m)	Headline height (m)	Speed (knt)	Wind (m/s)
Average	94.77 ± 10.1	123.5 ± 6.28	8.04 ± 0.2	3.16 ± 0.1	5.21 ± 3.0
Min–max	77–111	104–139	7.1–9.0	3.0–3.3	1.0–12.0

catch of cod, plaice, and lemon sole were measured in all hauls. All fish were measured, rounded down to the nearest centimeter below and 0.5 cm was added in the subsequent analysis.

2.4. Data analysis

Data for haddock, cod and whiting were included in the model because these species were caught in sufficient numbers throughout the experiment. The data are categorical, with response categories represented by the four compartments from which the fish that entered the gear were finally collected. Furthermore, the sampling scheme forms a cluster structure, with cluster units represented by the hauls in which the gear was tested. This naturally leads to a generalized linear mixed model. We fit the model in a two-stage framework well known from previous selectivity studies (e.g., Madsen et al., 1999; Revill and Holst, 2004). The first stage summarizes data from individual hauls into maximum likelihood estimates that are assumed to be approximately multivariate normal. This stage typically employs some variant of the SELECT model (Millar, 1992) that has been adapted to model the specific experiment in question. The second stage uses Fryer's model of between-haul variation (Fryer, 1991). This stage is well described elsewhere, thus here we concentrate on issues specific to this application. First we describe the fixed effects model applicable to a single haul. We then extend the model to cover random effects.

In the following we consider a single haul and therefore omit references to the haul identifier. The catch of length l fish in compartment MC (main codend), S (starboard), M (middle), and P (port) is denoted n_{MCl}, n_{Sl}, n_{Ml}, and n_{Pl}, respectively. The conditional distribution of the catch of length l fish in the four compartments, given the total catch, is a multinomial:

$$(n_{MC\,l}, n_{S\,l}, n_{M\,l}, n_{P\,l} | n_{+,l}) \sim m(n_{+,l}; \pi_{MC,l}, \pi_{S,l}, \pi_{M,l}, \pi_{P,l})$$

where $n_{+l} = n_{MCl} + n_{Sl} + n_{Ml} + n_{Pl}$ and the $\pi^{*}, {}_{l}$'s are the probability parameters. Because we were interested in both the vertical and the horizontal distributions among the compartments, a baseline logit model using the *LM* compartment as the baseline category was considered appropriate. For ease of exposition, we assume the probabilities depend only on the length of the fish and are thus given by:

$$\pi_{C\,l} = \begin{cases} \dfrac{\exp(\eta_{C\,l})}{1+\exp(\eta_{MC\,l})+\exp(\eta_{S\,l})+\exp(\eta_{P\,l})}, & \text{for } C = MC, S, P \\ \dfrac{1}{1+\exp(\eta_{MC\,l})+\exp(\eta_{S\,l})+\exp(\eta_{P\,l})}, & \text{for } C = M \end{cases}$$

where $\eta_{Cl} = \beta_{C0} + \beta_{C1} l$ and $C = MC, S, P$. The β parameters are best interpreted by looking at the probabilities on a logit scale. For example, logit $(\pi_{MC1}) = \log(\pi_{MC1}/\pi_{M1}) = \beta_{MC0} + \beta_{MC1} l$ means that β_{MC1} gives the increase in log-odds by one unit increase in length l of being caught in the upper compartment (*MC*) versus being caught in the baseline compartment (*M*).

The model is readily extended to include other covariates (fixed effects) as well as random effects to account for latent variables associated with the hauls. The general expression for the linear predictor for a length l fish caught in compartment C during haul h is $\eta_{hC\,l} = x_{hl}^{T}\beta_C + z_{hl}^{T} b_{hC}$, where $x_{h\,l}$ and $z_{h\,l}$ are column vectors of fixed and random covariates respectively and the β_Cs are the parameter vectors of interest. Finally, we assume that the b_{hC} s are independent multivariate normals $b_{hC} \sim \text{MVN}(0,\text{D})$.

The model described above is fairly general and may be fitted by various tools. In a two-stage approach, the "multi-

Table 2
Proportions of the total catches in the main codend and the three lower collecting bags. The different species MLS's are: haddock (HAD) = 30 cm, cod (COD) = 35 cm, whiting (WHG) = 23 cm, saithe (POK) = 35 cm, lemon sole (LEM) = 26 cm, and plaice (PLE) = 27 cm.

Collecting bag			Day tows (%)				Night tows (%)		
		No. of total	No. of total	No. < MLS	No. > MLS	No. of total	No. of total	No. < MLS	No. > MLS
Port	HAD	131	0.33	0.65	0.03	678	2.70	3.94	2.45
	COD	493	9.81	10.31	6.57	455	15.95	16.61	11.72
	WHG	151	3.43	5.13	2.93	154	4.56	5.92	4.50
	POK	0	0.00	0.00	0.00	37	0.98	7.14	0.92
	LEM	14	11.57	12.50	10.20	2	7.41	5.56	11.11
	PLE	11	25.00	0.00	25.00	1	25.00	0.00	25.00
Middle	HAD	2,344	5.99	11.32	0.86	2,095	8.35	17.38	6.55
	COD	1,666	33.14	36.47	11.49	1,326	46.49	48.34	34.64
	WHG	888	20.17	36.82	15.31	550	16.30	31.58	15.58
	POK	1	0.19	0.00	0.20	66	1.76	21.43	1.53
	LEM	53	43.80	54.17	28.57	12	44.44	50.00	33.33
	PLE	18	40.91	0.00	40.91	0	0.00	0.00	0.00
Starboard	HAD	204	0.52	0.98	0.08	534	2.13	3.06	1.94
	COD	647	12.87	14.05	5.22	567	19.88	19.85	20.05
	WHG	136	3.09	5.84	2.29	132	3.91	4.61	3.88
	POK	0	0.00	0.0	0.0	9	0.24	2.38	0.22
	LEM	11	9.09	12.50	4.08	4	14.81	16.67	11.11
	PLE	7	15.91	0.00	15.91	2	50.00	0.00	50.00
Main codend	HAD	36,446	93.15	87.04	99.04	21,776	86.82	75.62	89.06
	COD	2,221	44.18	39.18	76.72	504	17.67	15.19	33.59
	WHG	3,228	73.31	52.21	79.47	2,539	75.23	57.89	76.05
	POK	512	99.81	100.00	99.80	3,645	97.02	69.05	97.34
	LEM	43	35.54	20.83	57.14	9	33.33	27.78	44.44
	PLE	8	18.18	0.00	18.18	1	25.00	0.00	25.00

Table 3
Significant effects for haddock, cod, and whiting using the middle compartment as a baseline for the statistical comparisons between compartments. Day was used as the baseline for day/night comparisons.

Species	Parameters		Estimate (S.E.)	df	*P*
	Compartment	Effect			
Haddock	Port	Intercept	−2.62 (0.39)	160	<0.001
	Main	Intercept	−2.31 (0.33)	160	<0.001
	Starboard	Intercept:length	−0.18 (0.06)	160	0.001
	Main	Intercept:length	0.2 (0.01)	160	<0.001
	Starboard	Night	−3.3 (1.06)	160	0.002
	Main	Night	1.55 (0.51)	160	0.003
	Starboard	Night:length	0.24 (0.09)	160	0.006
	Main	Night:length	−0.11 (0.02)	160	<0.001
Cod	Starboard	Intercept	−0.93 (0.19)	163	<0.001
	Port	Intercept	−1.3 (0.27)	163	<0.001
	Main	Intercept	−3.01 (0.34)	163	<0.001
	Main	Intercept:length	0.11 (0.01)	163	<0.001
	Main	Night	−1.24 (0.36)	163	<0.001
Whiting	Main	Intercept	−7.48 (1.11)	168	<0.001
	Main	Intercept:length	0.32 (0.05)	168	<0.001
	Starboard	Night	−3.34 (1.05)	168	0.002
	Port	Night	−2.51 (1.02)	168	0.015
	Main	Night	4.78 (1.6)	168	0.003
	Main	Night:length	−0.15 (0.06)	168	0.023

nom" procedure in the R package (R Development Core Team, 2004) "nnet" can be used for fitting the model for individual hauls. The second stage can be fitted using the ECWEB software (http://www.constat.dk/ecwebsd/).

3. Results

3.1. Sea trials

The chain in the raised fishing line was polished during the first two test tows, indicating that the fishing line was not raised above the seabed. This premise was supported by very little catch in the three collecting bags, in contrast to the large catches of fish in the main codend and the presence of benthic species such as sea stars and sea urchins in the main codend. The first two tows were omitted and not included in the analysis. Therefore, four 28 cm and eight 20 cm floats were attached to the raised fishing line. Drop chains were placed in the centre of the middle collecting bag to estimate the height of the raised fishing line based on polish. Based on polish from the drop chain, the additional floats raised the fishing line about 60–70 cm above the seafloor and opened the three lower collecting bags. Benthic invertebrate species such as sea stars were thereafter caught only in the three lower collecting bags. Average mesh sizes of the four compartments were 42.51 mm with a standard deviation of 1.10 mm. The trawl geometry used during the 28 valid tows was stable in terms of headline height and door-spread (Table 1).

3.2. Vertical species separation

Relatively high and consistent catch rates were obtained for haddock, cod, and whiting throughout the experiment (Table 2). Therefore, these three species were included in the statistical modeling. The middle compartment was used in the modeling as the baseline for comparison with the other compartments (starboard, port, and main codends). Saithe, plaice, and lemon sole were also caught but in fewer hauls and in lower numbers (Table 2).

In general, regardless of species, day or night, a clear preference for entering either above or beneath the raised fishing line was found. During the day 93% of the haddock (total numbers) and 99% of marketable haddock (above MLS) were caught in the main codend (Table 2); at night the values for the main codend catch were 87% and 89%, respectively. During the day, 44% of cod (total numbers) and 77% of marketable cod (above MLS) were caught in the main codend; at night the values were 15% and 34%, respectively (Table 2). The separation of cod, haddock, and whiting into the lower compartments beneath the raised fishing line was significantly higher ($P < 0.001$) at night than during the day (Table 3). The separation into the main codend was in general reduced during the night tows for cod, haddock, and whiting.

The vertical separation between the lower middle compartments in the centre of the ground gear and the main codend was significantly different ($P < 0.001$) for haddock, cod, and whiting (Table 3). The length dependency of the vertical separation was significantly different ($P < 0.05$) between day and night for haddock, cod, and whiting (Table 3). A larger proportion of the smaller individuals were caught in the lower compartments at night compared to during the day (Figs. 3 and 4). The vertical separations estimated confidence bands (95%) for the day tows compared to the night tows are narrower, which indicates a higher haul-to-haul variation during the night tows (Fig. 4). Furthermore, the estimated slope of the vertical separation for haddock and whiting was steeper during the day than at night.

The total number of haddock caught per haul varied between 77 and 5848 with a median at 3492 haddock. Explorative plots of fish distribution between different codends with different fish densities did not indicate density dependency in the distribution of haddock.

3.3. Horizontal species separation

The three lower compartments were about equal in size. A large proportion of the fish caught in these compartments was caught in the middle codend (Table 2). This suggests that most fish enter the trawl at the centre of the ground gear. This is also where most of the escapement beneath the raised fishing line occurs. For haddock caught in the lower compartments during the day, the middle codend caught significantly more fish of all sizes ($P < 0.05$) compared to the starboard and port codends (Fig. 3). At night, the difference in catch among the three lower compartments was significant only ($P < 0.05$) for small haddock below 20 cm long. For cod, the difference in catch among compartments was significant ($P < 0.05$) for fish below 30 cm long at night and below 20 cm long during the day. The catch proportions in the lower port and starboard codends were quite similar (Table 2); this indicates that

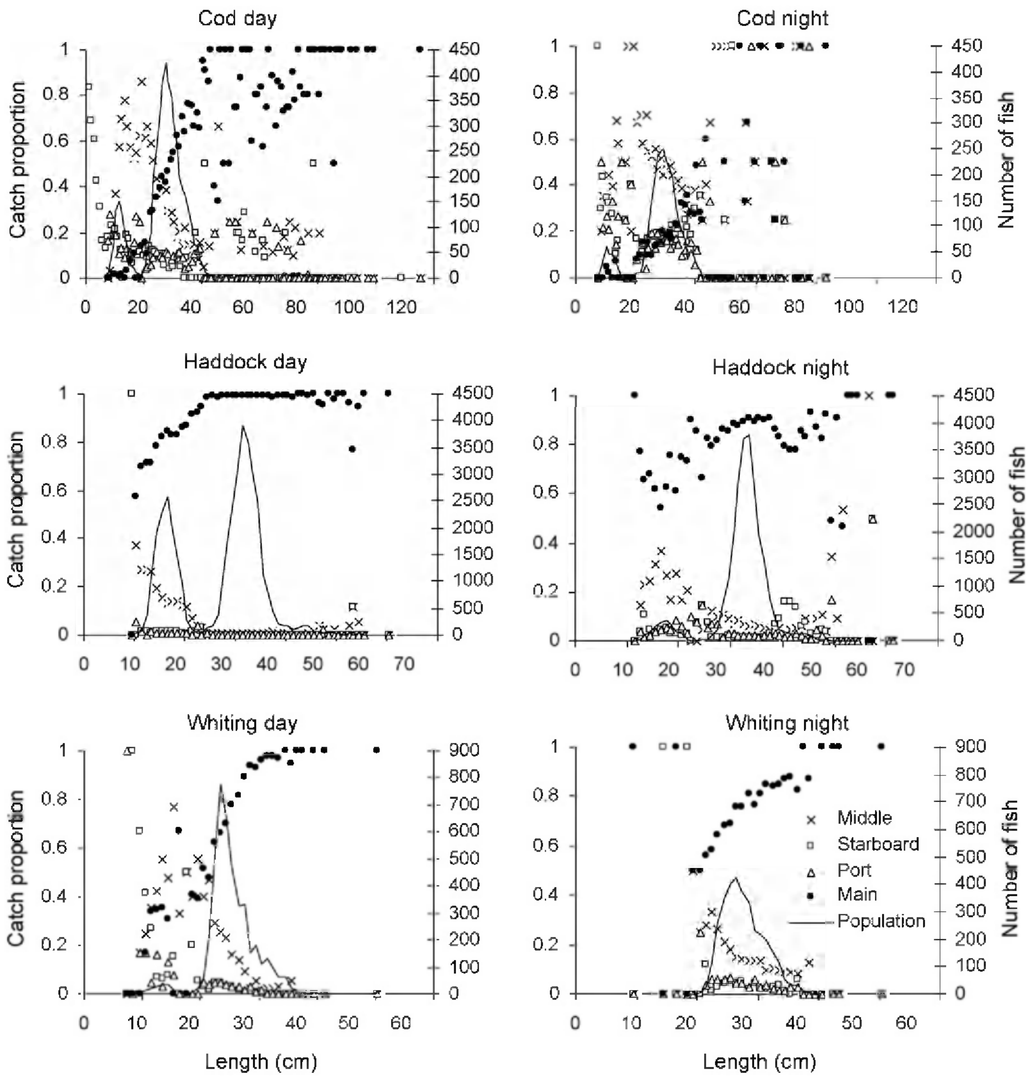

Fig. 3. Proportion of cod, haddock, and whiting caught in the four different codends by length and number of fish caught.

the trawl was operating without systematic differences during the experiment.

3.4. Discussion

This experiment showed that the bycatch of cod, including large cod, in haddock-directed fisheries can be substantially reduced by raising the fishing line above the seabed; this change will make the exploitation of haddock and cod more independent of one another. The bycatch of cod can be substantially reduced from the fishery, but not completely removed because especially larger cod still are caught. With our trawl, whiting and saithe will be caught efficiently along with haddock, whereas flatfish will escape beneath the trawl. The loss of flatfish is expected to be acceptable to the industry as catches of flatfish normally are low in this fishery and therefore irrelevant for the total catch value.

The length dependency and the diurnal effect on the vertical separation on gadoids and flatfish can cause variation in the separation of species. Fish reaction to fishing gear is based primarily on vision (Glass and Wardle, 1995), thus changes in the physical parameters that affect fish vision can affect the behavioral response and introduce variation into the separation success. The total separation success also will be affected by the size structure in the exploited population and by the time of day during which fishing is conducted. The escapement beneath the raised fishing line will be high in a population that consists primarily of small cod and lower if the population consists of larger individuals. The diurnal effect observed in our study, where more cod went under the raised fishing line in the selective haddock trawl during the night than during the day, is in contrast to Ferro et al. (2007), in which significantly more cod entered the lower compartment during the day.

The separation success of the selective haddock trawls is encouraging compared to results for cod selection obtained with selective devices such as square mesh panels that currently are used (Krag et al., 2008). Recent experiments in which the separation of cod and haddock were stimulated using black tunnels (see Glass and Wardle, 1995) in the trawl extension caught 90% of the haddock in the upper compartment along with 60% of the cod (He et al., 2008).

Results of experiments using separator trawls exhibit a relatively consistent and high separation of haddock into the upper compartment even though these designs range from relatively low headline trawls (Main and Sangster, 1982, 1985) to higher headline designs (Engås et al., 1998; Ferro et al., 2007). The separation success for cod, however, is not so conclusive. Engås et al. (1998) reported a length dependency by which larger cod preferred the lower compartment, whereas Ferro et al. (2007) found no evidence of a systematic effect of cod length. One explanation for the differences in length dependency between the two studies could be

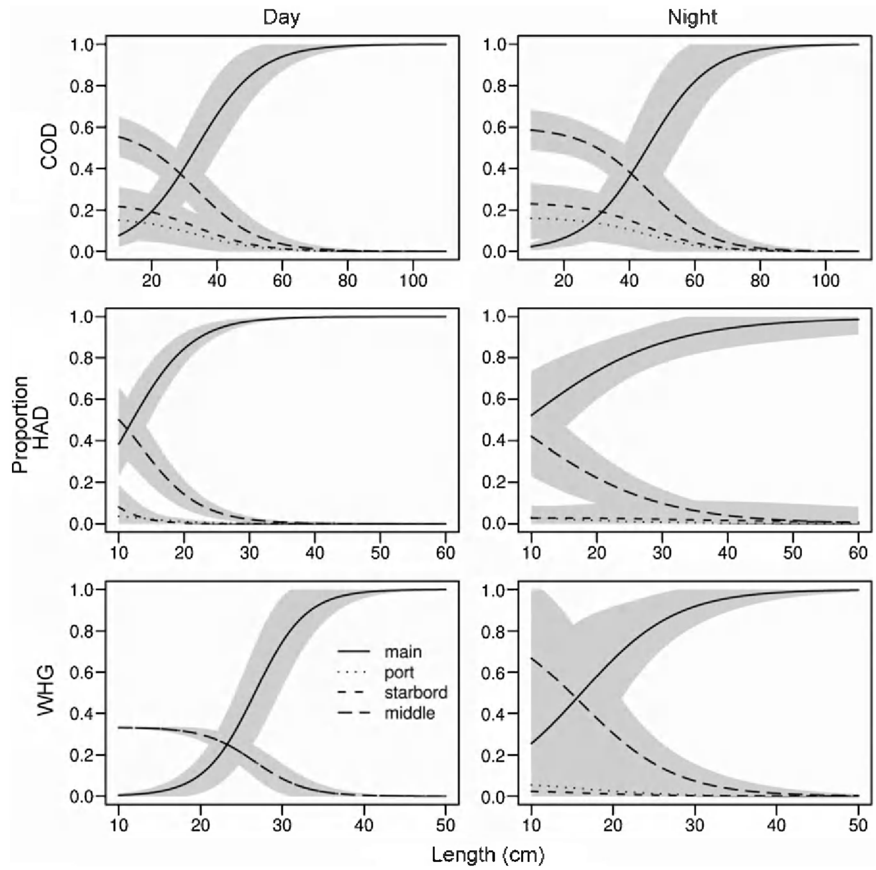

Fig. 4. Estimated catch proportion at length for cod, haddock, and whiting. Confidence limits (95%) are indicated with grey bands for the four codends; main codend = —, starboard codend = - - -, port codend = ·····, and middle codend = ———.

that Ferro et al. (2007) used a small meshed panel while Engås et al. (1998) used larger meshes which allowed fish to penetrate through the panel. An alternative explanation for these differing results could be that the vertical distribution of species differs among areas (Engås et al., 1998). The escapement of fish beneath a ground gear of a survey trawl (Walsh, 1991) and a commercial fish trawl (Ingolfsson and Jørgensen, 2006) exhibited contrasting length dependencies to the separator trawl experiment reported by Engås et al. (1998) as primary small fish escaped the trawl beneath the ground gear. The length dependency by which small fish enter the trawl closer to the seabed compared to larger fish also has been found for American plaice (*Hippoglossoides platessoides*) and yellowtail flounder (*limanda ferruginea*) (Walsh, 1992). This may indicate that small individuals of demersal fish species in general enter a trawl closer to the seabed than do larger individuals. The size structure of the catch retained in the main codend may therefore be affected by the separation height. Ferro et al. (2007) suggested that light level and water clarity also influence the height at which fish enter the net mouth. In general, the experiments conducted with separator trawls have obtained a good separation of haddock and cod, but they have not provided a solution to reduce the number of cod, including larger specimen, in the catches.

Experiments have shown that fish that escape late in the catching process are more exposed to the consequence of injuries and exhaustion (Ryer, 2004). A major advantage of the selective haddock trawl is that unwanted bycatch will escape the gear with little or no physical contact with the gear. Moreover, benthic invertebrate marine species and rocks will pass beneath the raised fishing line and will not be mixed with the haddock catch, thereby potentially improving the quality of the catch. In a commercial version of the selective haddock trawl, the main fishing line would be raised above the traditional rock hopper ground gear and the three lower collecting bags would be removed. A lighter ground gear (e.g., with only a few large discs) could also be used to reduce the seabed impact and the towing resistance, as good bottom contact is not required to catch haddock, saithe, and whiting efficiently.

More fish passed below the centre of the raised fishing line (middle compartment) than along the wings (starboard and port compartment), which is consistent with results reported by Walsh (1992) and Ingolfsson and Jørgensen (2006). This aggregation of fish in front of the centre part of the ground gear is due to the herding process described in Wardle (1993). The centre section of the ground gear is therefore where species separation devices in the trawl mouth should be focused.

Holst and Revill (2009) reported a high reduction in the numbers of cod caught in their experiments using the Eliminator trawl in the North Sea mixed-species fishery. The Eliminator trawl has large meshes in the forward part of the trawl which gradually decreases towards the codend. These results indicate that the reduction of cod obtained with the selective haddock trawl could be further improved with large meshes in the lower belly section of the trawl.

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