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ARTICLE

Performance of the Nordmøre Grid in Shrimp Trawling and Potential Effects of Guiding Funnel Length and Light Stimulation

Roger B. Larsen*

UiT, The Arctic University of Norway, Brevika, N-9037 Tromsø, Norway

Bent Herrmann

*UiT, The Arctic University of Norway, Brevika, N-9037 Tromsø, Norway; and
SINTEF Fisheries and Aquaculture, Brattørkaia 17C, N-7010 Trondheim, Norway*

Manu Sistiaga

SINTEF Fisheries and Aquaculture, Brattørkaia 17C, N-7010 Trondheim, Norway

Jesse Brinkhof and Ivan Tatone

UiT, The Arctic University of Norway, Brevika, N-9037 Tromsø, Norway

Lise Langård

Norwegian Directorate of Fisheries, Postbox 185 Sentrum, 5804 Bergen, Norway

Abstract

The introduction of the Nordmøre grid to shrimp trawls has reduced the issue of bycatch to that of small-sized species and juveniles that are able to pass through the grid and enter the small-meshed cod end together with the targeted shrimp. This study estimated the size- and species-selective performance of the Nordmøre grid in the configuration most often applied by fishermen and made a preliminary exploration of the effects of reducing the length of the guiding funnel in front of the grid and mounting light-emitting diodes (LEDs) around the escape exit. Experimental fishing trials were conducted in the Barents Sea to assess the size-selective properties of a 19-mm bar spacing Nordmøre grid, mandatory in this Norwegian trawl fishery targeting deepwater shrimp *Pandalus borealis* (also known as northern shrimp), and its potential improvement. Results were obtained for the target species and four bycatch species: redfish *Sebastes* spp., Haddock *Melanogrammus aeglefinus*, Atlantic Cod *Gadus morhua*, and American Plaice *Hippoglossoides platessoides*. In general, very few deepwater shrimp were found to escape through the escape exit, although the quantity increased slightly at larger sizes. Between 80% and 100% of the bycatch species up to a species-specific size passed through the grid and entered the cod end. A short guiding funnel decreased this for Haddock significantly by increasing the fraction of small Haddock seeking the escape exit. Further, adding LEDs around the escape exit significantly negated this effect. For the other bycatch species, the results indicated similar trends but were not statistically significant. However, considering that

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*Corresponding author: roger.larsen@uit.no

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only a few fishing hauls were conducted using the short guiding funnel with or without mounting LEDs calls for some caution when attributing these changes to the configuration of the Nordmøre grid, and these preliminary results should be followed up by further testing before definitive conclusions are made.

The deepwater shrimp *Pandalus borealis* (also known as the northern shrimp) is a commercially important species that has been fished since the beginning of the 20th century along the Norwegian coast and more widely in deep water since the late 1960s off Norway and in other countries. However, the international trawl fishery in the Barents Sea is often associated with juvenile fish bycatch problems. This is related to the small mesh size used in the shrimp trawl and cod end, with a minimum of 35-mm mesh being permitted. When the density of juveniles in the fishing grounds is large, the catches of juveniles of various fish species can be large. The Nordmøre grid (Figure 1) has been proven to be efficient at excluding bycatch fish species during shrimp trawling (Isaksen et al. 1992). With the introduction of the requirement for its use in the Norwegian fishery in 1991 and internationally in 1993, the bycatch problem of larger-sized fish was eliminated because they are unable to pass through the grid and into the trawl cod end. However, small-sized fish such as the juveniles of various fish species are still able to pass through the 19-mm bar spacing grid and enter the cod end together with the targeted shrimp. The Nordmøre grid mainly consists of a guiding funnel, a 40–50° inclined grid, and an escape exit in the upper panel just in front of the grid (Figure 1).

Current northeastern Atlantic Ocean shrimp fishery regulations allow the retention of low numbers of juveniles of regulated fish species. For example, fishing areas are closed if catches of 10 kg of deepwater shrimp contain more than 8 Atlantic Cod *Gadus morhua*, 20 Haddock *Melanogrammus aeglefinus*, 3 redfish *Sebastes* spp., or 3 Greenland Halibut *Reinhardtius hippoglossoides* (Norwegian Directorate of Fisheries 2011). These relatively strict bycatch rules have led to frequent closures of large shrimp fishing grounds in the northeastern Atlantic Ocean over the last few years. The

closures can last for weeks or months and cause significant operational problems and increased costs for the fishing fleet (i.e., the distances between the potential fishing grounds become larger with increased area closures). Bycatches of juvenile fish are also associated with practical problems related to sorting the catch onboard the fishing vessels.

Some small-sized fish may avoid entering the cod end by seeking the escape exit in the upper panel in front of the Nordmøre grid without first making contact with the grid. In addition to changing the grid bar spacing, other alterations to the grid section design may affect the ratio of juvenile fish that seek the escape exit without contacting the grid at all. These types of changes can affect the size and species selectivity of the Nordmøre grid without changing the characteristics of the grid itself. One factor that can affect this contact ratio is the length of the guiding funnel, which is intended to ensure that the majority of the targeted deepwater shrimp make contact with the Nordmøre grid and are sorted into the cod end. Grimaldo et al. (2015) showed that guiding fish to a size-selective sorting grid by means of a guiding panel is essential for achieving satisfactory selectivity results for species such as Atlantic Cod. Other species such as flatfish (order Pleuronectiformes), which are similar to Atlantic Cod in that they tend to stay low down inside the trawl, can also pose a challenge when it comes to facilitating their escape through exits placed in the upper panel of the gear.

Another measure that can affect fish behavior is stimulation with light emitting diodes (LEDs). Different studies have shown the potential of this measure to influence the selective properties of a gear. Rose and Hammond (2014), for example, showed that attaching green Lindgren-Pitman Electralume LEDs to the footrope of a survey trawl increased the escape of Rock Sole *Lepidopsetta bilineata*. The study of Hannah

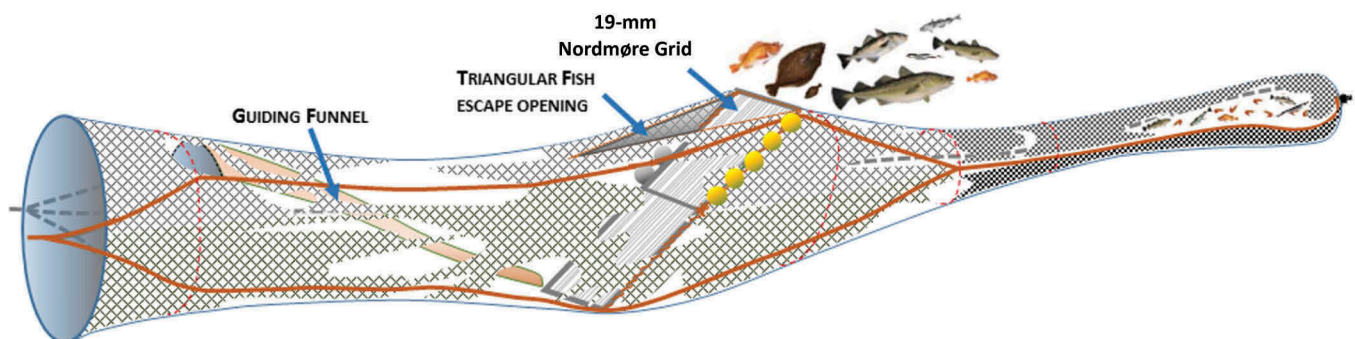


FIGURE 1. Selective system used in shrimp trawling consisting of a Nordmøre grid followed by a cod end. The Nordmøre grid mainly consists of a guiding funnel, a 40–50° inclined grid, and an escape exit in the upper panel just in front of the grid.

et al. (2015) is another example in which the same lights, attached to shrimp trawl footgear and illuminating the escape path under the net, resulted in a fish bycatch reduction of up to 90% for some species and well above a 50% reduction for others.

The current study investigated the size- and species-selective performance of the Nordmøre grid with the configuration mostly applied by trawlers targeting deepwater shrimp in Norway. In addition, a preliminary investigation of the potential effects of shortening the guiding funnel and mounting LEDs around the escape exit were conducted. Experimental fishing trials were carried out in the Barents Sea, and the size-selective properties of the 19-mm bar spacing of the Nordmøre grid, which is mandatory in this fishery, were assessed in detail. This included estimating the probability of fish seeking the escape exit in front of the grid without prior contact with the grid.

METHODS

Experimental design.—The fishing trials were performed on board the research trawler RV *Helmer Hanssen* (63.8 m length overall and 4,080 hp) during February 16–28, 2016. The fishing grounds chosen for the tests are located in the north of the Barents Sea (Hopen Banken; 76°00'N, 32°00'E). The fishing trials were carried out using a Campelen 1800# trawl built entirely of 80 40-mm diamond meshes (2-mm polyethylene twine). The trawl doors employed were of the type Thyborön T2 (6.5 m² and 2,200 kg), and a 2-m-long restrictor rope was linked between the warps 80 m in front of the doors, which kept the distance between the doors constant at 48–52 m, independent of fishing depth and towing speed. Apart from a pair of Scanmar distance sensors, we used a Scanmar height sensor to control the height of the trawl, which is a good indicator that it is functioning well. The typical height for a Campelen 1800# trawl ranges between 4.5 and 4.8 m. The design used 40-m

double sweeps and 19.2-m-long rockhopper gear built of three sections with 46-cm rubber discs.

The trawls were equipped with four-panel Nordmøre grid sections that were equivalent in dimension and construction to the two-panel standard Nordmøre grid section previously used by the Norwegian coastal fleet targeting deepwater shrimp. The Nordmøre grid is made of stainless steel and is 1,510 mm high and 1,330 mm wide. The grid in both sections used was mounted so that it would be maintained at an angle of 45° (SD, 2.5) while fishing. The fishing trials were carried out with a selection system comprising a Nordmøre grid followed by a cod end. The mean ± SD bar spacing in the Nordmøre grid, measured with a caliper, was 18.8 ± 0.4 mm. The escape exit on the top panel of the grid section was cut as a 35-mesh long, 70-mesh wide triangle.

For the collection of the fish and deepwater shrimp escaping through the escape exit ahead of the grid, a small meshed cover (mean ± SD mesh size, 18.9 ± 1.2 mm) was mounted over the escape exit (Figure 2). To collect the fish and deepwater shrimp that passed through the grid, the cod end contained a small, low-hanging inner net mesh (mean ± SD mesh size, 18.5 ± 0.9 mm) to prevent fish and deepwater shrimp from escaping through the cod end.

Three different configurations were attached to the same trawl, one at a time (Figure 3):

1. A long guiding funnel that ends 0.5 m in front of the grid (i.e., the long funnel configuration). This is the minimum length legislated and the preferred configuration by fishermen.
2. A short guiding funnel that ends 1 m in front of the grid.
3. A short guiding funnel that ends 1 m in front of grid, with five LEDs (i.e., green Lindgren-Pitman Electralume) attached around the escape exit (LEDs configuration).

As the primary objective of the study was to quantify in detail the size-selective performance of the Nordmøre grid in the

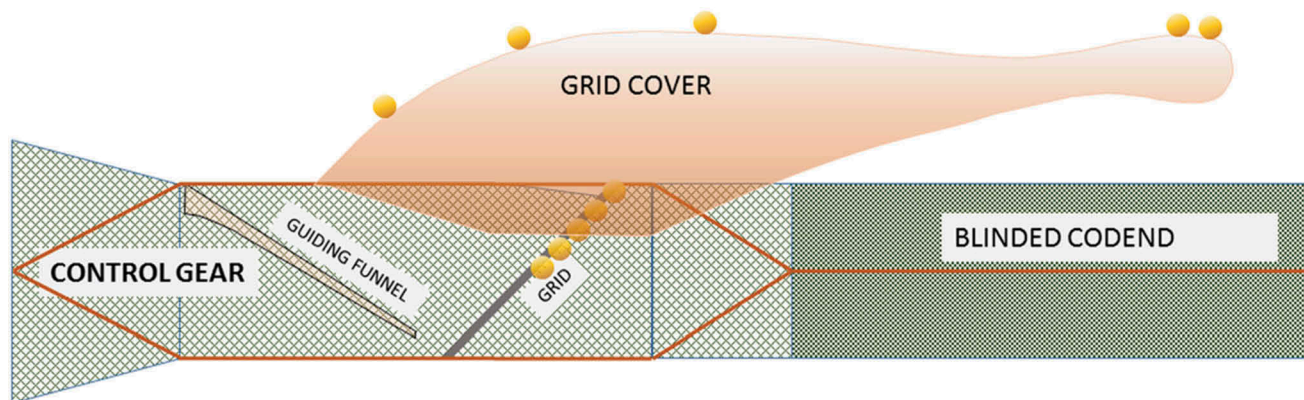


FIGURE 2. Experimental setup for the Nordmøre grid section. A cover was installed over the escape outlet in the upper panel and an inner net was installed in the cod end.

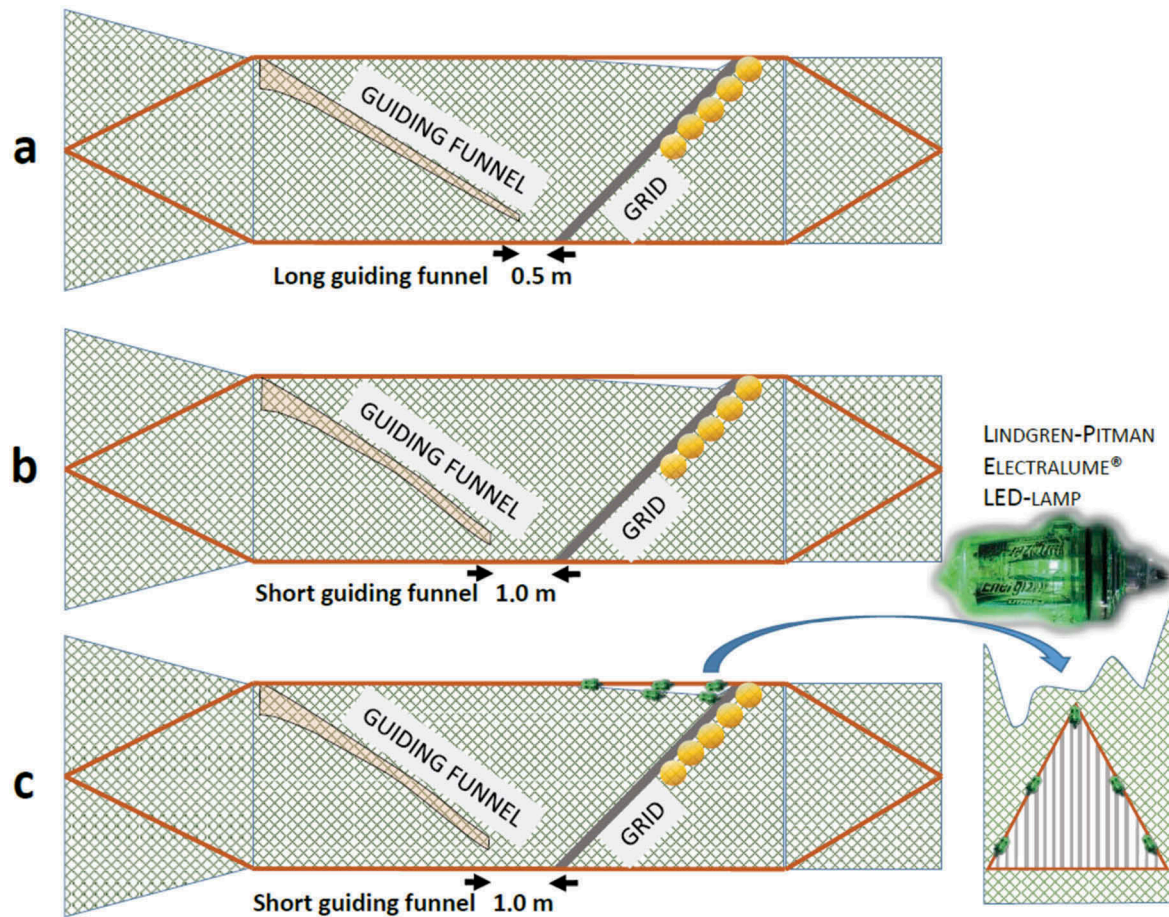


FIGURE 3. The three configurations tested, including (a) the long guiding funnel configuration, (b) the short guiding funnel, and (c) the short guiding funnel with five green Lindgren-Pitman Electralume LED lamps mounted around the escape outlet.

configuration mostly used in the fishery today, the majority of hauls were conducted with the long guiding funnel. Therefore, the two other configurations were only tested to the extent that the total vessel time available allowed it after first collecting an extensive data set for the first configuration with the long guiding funnel.

The catch from the different compartments in the gear was kept separate at all times. The catch in each compartment was sorted by species, and all the fish bycatch species were measured to the nearest centimeter below. No subsampling was carried out for any of the fish species, but as measuring all shrimp in the catch was not possible, we subsampled the shrimp catch in all compartments and hauls. From the shrimp catch in each compartment we separated a portion of approximately 1 kg. This portion was a random portion of the total catch, so that it should be representative of the size distribution of the shrimp in that specific compartment. The carapaces of the shrimp were measured using a caliper.

Size selection models.—The size selection system used during the trials consisted of a Nordmøre grid, which the shrimp and fish need to pass through to enter the cod end.

The purpose of the grid is to let shrimp of all sizes pass through toward the cod end, while all individuals of all bycatch species are prevented from passing through. Individuals that do not pass through the Nordmøre grid are released through the triangular escape exit in the upper panel. For a shrimp or fish to pass through the grid, two conditions need to be fulfilled: (1) they need to contact the grid and (2) they morphologically need to be able to pass through the grid, which is dependent on their size and orientation when they come in contact with the grid. It must be considered that some shrimp and fish might not contact the Nordmøre grid at all or that they do so with such a poor orientation that they will not have any length-dependent chance of passing through the grid. This is modeled by the length-independent parameter C_{grid} , which has a value in the range 0.0–1.0. An estimated C_{grid} value of 1.0 means that every individual of that species contacts the grid in a way that gives them a length-dependent chance of passing through the grid. For an individual contacting the grid with sufficient orientation for a length-dependent probability of passing through grid ($pc[l]$), the following logit model was used (Krag et al. 2017):

$$\begin{aligned}
 p_C(l, L50_{grid}, SR_{grid}) &= 1.0 - \frac{\exp\left(\frac{\ln(9)}{SR_{grid}} \times (l - L50_{grid})\right)}{1.0 + \exp\left(\frac{\ln(9)}{SR_{grid}} \times (l - L50_{grid})\right)} \\
 &= \frac{1.0}{1.0 + \exp\left(\frac{\ln(9)}{SR_{grid}} \times (l - L50_{grid})\right)}
 \end{aligned} \tag{1}$$

Model (1) considers that the probability that an individual will be able to pass through the grid, under the condition that it contacts the grid and that passage is length dependent and decreases for larger individuals. In the equation, l denotes the length of the individual, $L50_{grid}$ denotes the length with a 50% probability of being prevented from passing through, and the selection range (SR_{grid}) describes the difference in length between individuals with a 75% and 25% probability of being prevented from passing through the grid.

Based on the above, the following model was used for the size-dependent probability of a shrimp or fish being able to pass through the Nordmøre grid and enter the cod end ($p[l]$):

$$p(l, C_{grid}, L50_{grid}, SR_{grid}) = \frac{C_{grid}}{1.0 + \exp\left(\frac{\ln(9)}{SR_{grid}} \times (l - L50_{grid})\right)} \tag{2}$$

The escape probability through the escape exit in front of the Nordmøre grid was therefore modeled as follows:

$$e(l, C_{grid}, L50_{grid}, SR_{grid}) = 1.0 - p(l, C_{grid}, L50_{grid}, SR_{grid}) \tag{3}$$

Models (2) and (3) combined are a so-called structural model because they are based on modeling the individual elements involved in the size selection process. One advantage of applying such a structural model compared with an empirical-based model is that once the values of the parameters in the model are estimated, they can be directly interpreted. Three parameters need to be estimated to be able to describe the size selection in the Nordmøre grid: C_{grid} , $L50_{grid}$, and SR_{grid} .

The term C_{grid} loosely models the contact probability with the grid for modes of orientation that result in a length-dependent probability for an individual's being able to pass through the grid, which is known as selectivity contact (Larsen et al. 2016). If all individuals contact the grid with a reasonable mode of contact, then the value for C_{grid} should be 1.0. However, this is not necessarily the case, and some individuals may even escape through the escape exit in front of the Nordmøre grid (Figure 1) without contacting the grid first. Other individuals may be so poorly oriented when they meet the grid that the probability of their passing through will be similar to that of individuals not contacting the grid at all. This means that they would not have made selectivity contact

(Larsen et al. 2016), which will also be reflected in the value of C_{grid} . For the shrimp or fish that contact the grid with a reasonable mode of orientation, $L50_{grid}$ and SR_{grid} describe the probability of their passage based on model (1). A larger bar spacing will result in a higher $L50_{grid}$ value. For small individuals that would pass through if they made contact with the grid, the value $1 - C_{grid}$ can loosely be interpreted as the fraction of fish that would be able to seek and subsequently escape through the escape exit without contacting the grid. A small SR_{grid} value would indicate a well-defined grid contact orientation, with all those individuals making contact doing it with a similar orientation. In contrast, a large SR_{grid} value would indicate that the contact is more disordered, with many different orientations involved. As different species have different morphologies and behaviors, the values of the parameters C_{grid} , $L50_{grid}$, and SR_{grid} will, for the same selective system, be species-specific. Therefore, the analysis needs to be applied separately for deepwater shrimp and different bycatch species.

Since this study was interested in how each of the Nordmøre grid configurations tested performed on average over the hauls conducted, the analysis included data summed over j hauls. The analysis was conducted separately for each Nordmøre grid configuration based on the data from the hauls with the specific configured cod end and separately for each species. Therefore, function (4) was minimized, which is equivalent to maximizing the likelihood for the observed data in the form of the length-dependent number of individuals retained in the cod end (n_{Cj}) versus those collected in the Nordmøre grid cover (n_{Gj}):

$$\begin{aligned}
 & - \sum_{j=1}^m \sum_l \left\{ \frac{n_{Cjl}}{qC_j} \times \ln(p(l, C_{grid}, L50_{grid}, SR_{grid})) \right. \\
 & \left. + \frac{n_{Gjl}}{qG_j} \times \ln(e(l, C_{grid}, L50_{grid}, SR_{grid})) \right\},
 \end{aligned} \tag{4}$$

where qC_j and qG_j are the sampling factors for the fraction of individuals measured in the cod end catch and grid cover catch, respectively. The sampling factors comprise a value in the range 0.0–1.0 (1.0 if all individuals are measured for length). The outer summation in function (4) comprises the hauls conducted with the specific Nordmøre grid configuration and the inner summation over length-classes in the data.

Evaluating the ability of models (2) and (3) to describe the data sufficiently was based on calculating the corresponding P -values. In the case of poor fit statistics ($P < 0.05$), the residuals were inspected to determine whether the poor result was due to structural problems when modeling the experimental data (models 2 and 3) or to overdispersion in the data (Wileman et al. 1996).

To account for both within- and between-haul variations in selectivity (Fryer 1991) when estimating the uncertainty for the average size-dependent grid passage probability, we

applied a double bootstrap method using the facilities in the software tool SELNET (Herrmann et al. 2012). For each species analyzed, 1,000 bootstrap repetitions were conducted to estimate the 95% confidence limits (Efron percentiles) for the model parameters (C_{grid} , $L50_{grid}$, and SR_{grid}) and for the grid passage probability curve (Herrmann et al. 2012). The effects of shortening the guiding funnel and adding LEDs were evaluated based on plotting the estimated grid passage probability curve with confidence intervals for each of these “configurations” against the equivalent baseline configuration curve for the design mostly applied in the fishery.

RESULTS

Collected Data

During the trials, a total of 24 hauls were performed (Table 1): 16 hauls with the long funnel (which has the minimum distance to the grid required by law and is the configuration preferred by fishermen), 4 hauls with the short guiding funnel configuration, and 4 hauls with the short guiding funnel and LED lamp configuration (Figure 4). The trawling time was intended to be kept constant and ranged between 60 and 63 min. The data were sampled continuously in the same area within 2 weeks in February 2016. We conducted the experiments at a latitude where the sun was below the horizon, which made light levels at fishing depths similar for all hauls. The lengths of 11,600 shrimp were measured during the cruise. Regarding the number of bycatch fish species, a total of 9,090 redfish, 1,529 Haddock, 1,158 Atlantic Cod, and 15,206 American Plaice *Hippoglossoides platessoides* were measured (Table 1). This means that the study is based on a total of 38,583 shrimp and fish measurements (25,624 of which were from the configuration most often applied in the fishery), while 8,752 and 8,509 measurements were taken for the short funnel and short funnel + LED configurations, respectively (Table 1). Other important bycatch species in the fishery, such as Greenland Halibut and Polar Cod *Boreogadus saida* (known as Arctic Cod in North America), were not caught in sufficiently high numbers to be included in the study. We applied models (2) and (3) to estimate the selectivity parameters and fit statistic results for all species (Table 2).

Size Selectivity and Grid Passage Probability for Shrimp

For deepwater shrimp, the Nordmøre grid passage probability was very high for the three configurations tested (Figure 5). This was also manifested in the C_{grid} values that we obtained, which were estimated to be 100, 94, and 100% for the long funnel configuration, the short funnel configuration, and the short funnel + LEDs configuration (Table 2), respectively. These slight differences were not significant because the confidence intervals for this parameter overlapped between the configurations. This was also reflected in the overlapping confidence intervals for the grid passage

probabilities (Figure 5). While the grid passage probabilities were high, they all demonstrated a significant decrease with an increase in the size of the shrimp. The fit statistics showed that, for deep-water shrimp, models (2) and (3) were capable of describing the experimental data well for the long guiding funnel configuration as the P -value was estimated to be above 0.05 (Table 2). For the two other configurations, the P -value was very low. However, since there was no clear pattern in the deviations between data points and the fitted grid passage probability curves, the result was considered a case of overdispersion. This overdispersion was probably created by the heavy subsampling necessary in the shrimp data collection process (Table 1). Therefore, models (2) and (3) could be confidently applied for the description of the length-dependent grid passage probability (Figure 5).

Size Selectivity and Grid Passage Probability for Redfish

For redfish, the fit statistics showed that models (2) and (3) were capable of describing the experimental data collected with the three configurations well. The P -values were estimated to be between 0.67 and 0.77 for the three configurations, which meant that the deviation between the experimental results obtained and the fitted model could well be coincidental in all three cases (Table 2). The grid contact values were significantly below 100% for all three configurations tested, which offers evidence of some redfish escaping through the escape exit without contacting the Nordmøre grid at all. This phenomenon was also clear from the length-dependent grid passage probability curves, which showed a horizontal plateau well below 1.0 (100% contact) for sizes of redfish up to 10 cm long. The value for C_{grid} ranged from 63% with the short funnel configuration to 74% and 80% for the LEDs + short funnel configuration and the long funnel configuration, respectively. This indicates that the majority of small redfish would make selectivity contact with the Nordmøre grid and that all individuals with a length below 10 cm will then pass through the grid into the cod end. This is due to the fact that the grid bar spacing begins to restrict the passage probability gradually with the increasing size of the redfish. The effect is quantified by model (1), with $L50_{grid}$ values between 13.6 and 14.0 cm and SR_{grid} values between 2.7 and 3.3 cm for the three configurations. These parameters did not differ significantly between the three cases. The values for C_{grid} , $L50_{grid}$, and SR_{grid} together provided the characteristic selectivity pattern shown in Figure 6, with the aforementioned plateau; there was a high and constant grid passage probability for redfish up to 10 cm long. After this size, the retention gradually decreased to zero for sizes of redfish above 18 cm. The two alternative configurations did not improve the situation. They indicated a reduction in contact but the confidence intervals for the parameter estimation between the three cases overlapped, meaning that the differences observed were not significant (Table 2). The C_{grid} values obtained were significant and below 100% for all three configurations investigated; this

TABLE 1. Numbers of fish and shrimp measured for length in the hauls carried out during the trials. The values in parentheses represent the sampling factors. For the fish species there was no subsampling. Abbreviations are as follows: G = grid cover, C = cod end; asterisks indicate that data were not collected because the shrimp were crushed, making measurement impossible.

Haul number	Configuration	Deepwater shrimp		Redfish		Haddock		Atlantic Cod		American Plaice	
		G (% measured)	C (% measured)	G	C	G	C	G	C	G	C
1	Long funnel	123 (72.31)	160 (1.63)	56	36	13	23	21	11	208	177
2	Long funnel	120 (58.14)	153 (1.95)	143	37	20	10	17	8	238	182
3	Long funnel	163 (7.47)	173 (1.16)	404	169	112	113	58	9	438	187
4	Long funnel	108 (9.60)	171 (1.20)	184	86	36	38	12	7	265	156
5	Long funnel	144 (40.54)	160 (1.91)	108	20	22	15	28	9	321	121
6	Long funnel	169 (100.00)	175 (2.02)	68	34	10	12	8	12	206	150
7	Long funnel	208 (22.74)	169 (1.02)	187	94	52	42	12	12	391	287
8	Long funnel	189 (21.12)	190 (0.73)	164	120	33	72	18	12	327	301
9	Long funnel	123 (9.34)	412 (4.10)	242	68	16	18	34	20	424	196
10	Long funnel	133 (100)	482 (4.22)	174	92	15	16	43	21	417	320
11	Long funnel	100 (39.16)	515 (2.42)	149	180	26	62	30	18	378	396
12	Long funnel	*	*	381	172	36	74	35	23	402	413
13	Long funnel	144 (30.58)	521 (2.68)	216	66	15	20	34	21	302	204
14	Long funnel	112 (40.00)	394 (2.23)	204	55	16	19	20	23	347	294
15	Long funnel	175 (22.76)	462 (1.92)	189	143	36	98	27	8	304	295
16	Long funnel	138 (8.70)	458 (4.13)	309	27	4	4	17	14	426	312
17	Short funnel	149 (6.84)	441 (3.66)	368	46	3	8	22	12	429	300
18	Short funnel	129 (12.66)	428 (2.97)	542	67	17	8	49	29	496	276
19	Short funnel	124 (23.26)	453 (3.82)	440	70	13	6	51	23	394	281
20	Short funnel	188 (8.67)	517 (1.95)	473	147	71	88	44	21	552	452
21	LEDs + short funnel	131 (15.63)	492 (2.78)	401	132	49	116	49	20	394	412
22	LEDs + short funnel	179 (13.22)	439 (2.93)	454	72	12	12	42	23	378	311
23	LEDs + short funnel	137 (71.73)	470 (3.17)	352	51	4	10	30	41	234	387
24	LEDs + short funnel	117 (53.76)	462 (3.98)	807	91	5	9	38	22	207	318



FIGURE 4. Underwater photo from inside the grid section as used during the selectivity experiments with five green Lindgren-Pitman Electralume LED lamps mounted around the escape outlet.

demonstrates the necessity of using a model such as models (2) and (3) to infer the size selectivity of a Nordmøre grid. This is because this model explicitly accounts for the fact that not all fish will make selective contact with the grid.

Size Selectivity and Grid Passage Probability for Haddock

The size structure in the data collected for Haddock is concentrated in a narrow span of length classes between 11 and 18 cm (Figure 7). This calls for some caution when estimating the size selectivity for Haddock based on these data. However, a clear size selection process is seen for Haddock within this size range. The fit statistics showed that for Haddock models (2) and (3) were capable of describing the experimental data well for the short funnel and short funnel + LEDs configurations, as the P -values were estimated to be above 0.05 (Table 2). For the long funnel configuration, the P -value was slightly below 0.05. However, since there was no clear pattern in the deviations between data points and the fitted grid passage probability curve, this was considered a case of overdispersion in the data. Therefore, there was a high level of confidence in applying models (2) and (3) to describe the length-

TABLE 2. Size selectivity parameters and fit statistic results for deepwater shrimp, redfish, Haddock, Atlantic Cod, and American Plaice based on fitting models (2) and (3) to the experimental data. The values given in parentheses are the 95% confidence intervals.

Species	Parameter	Long guiding funnel	Short guiding funnel	Short guiding funnel and LEDs
Deepwater shrimp	C_{grid}	1.00 (0.97–1.00)	0.94 (0.88–1.00)	1.00 (0.98–1.00)
	$L50_{grid}$ (mm)	39.55 (31.87–47.76)	32.24 (26.77–51.40)	50.70 (33.09–83.50)
	SR_{grid} (mm)	13.40 (6.13–20.72)	6.78 (0.10–28.27)	21.17 (6.06–48.45)
	df	18	18	17
	Deviance	18.95	59.06	46.81
	P -value	0.3947	<0.0001	<0.0001
Redfish	C_{grid}	0.80 (0.70–0.90)	0.63 (0.55–0.77)	0.74 (0.67–0.87)
	$L50_{grid}$ (cm)	13.95 (13.31–14.51)	13.57 (12.72–14.16)	14.01 (13.30–14.75)
	SR_{grid} (cm)	3.28 (2.81–3.86)	2.85 (2.37–3.45)	2.72 (2.20–3.20)
	df	28	26	31
	Deviance	24.05	22.29	25.05
	P -value	0.6786	0.6729	0.7655
Haddock	C_{grid}	1.00 (0.71–1.00)	0.55 (0.48–0.67)	0.96 (0.75–1.00)
	$L50_{grid}$ (cm)	14.85 (14.14–17.33)	16.33 (15.54–16.92)	16.36 (15.03–17.18)
	SR_{grid} (cm)	4.32 (2.49–8.89)	0.84 (0.10–2.31)	1.62 (0.73–3.96)
	df	8	6	22
	Deviance	15.92	0.82	11.37
	P -value	0.0436	0.9914	0.9691
Atlantic Cod	C_{grid}	0.89 (0.74–1.00)	0.73 (0.52–1.00)	0.87 (0.59–1.00)
	$L50_{grid}$ (cm)	18.40 (17.05–19.85)	19.04 (15.85–21.49)	19.05 (16.27–21.27)
	SR_{grid} (cm)	4.94 (2.84–6.69)	3.58 (0.10–6.28)	4.21 (0.82–7.07)
	df	29	28	28
	Deviance	15.15	9.35	6.48
	P -value	0.9838	0.9996	1
American Plaice	C_{grid}	1.00 (0.99–1.00)	0.99 (0.86–1.00)	1.00 (0.99–1.00)
	$L50_{grid}$ (cm)	18.23 (17.48–18.83)	16.66 (15.96–17.88)	18.99 (17.43–20.15)
	SR_{grid} (cm)	8.26 (7.65–8.99)	8.92 (7.16–10.56)	8.30 (7.36–8.99)
	df	44	43	41
	Deviance	46.40	52.83	36.52
	P -value	0.3736	0.1448	0.6697

dependent grid passage probability for Haddock (Figure 7). Using the long guiding funnel configuration, which is the one preferred by fishermen, and thereby forcing the fish closer to the lower panel and the grid before exiting the funnel, seemed to prevent any small Haddock from utilizing the escape exit without encountering the grid first (grid contact was estimated to be 100%; Figure 7; Table 2). For Haddock, the sizes at risk for passing through the grid were up to approximately 18 cm (Figure 7). The grid contact value for the short funnel configuration was estimated to be significantly below 100%, which implies that there is evidence of some Haddock escaping through the escape exit without contacting the Nordmøre grid for this configuration. This phenomenon was also clear from the length-dependent grid passage probability curve that shows a horizontal plateau well below 1.0 (100% contact) for sizes of Haddock up to 14 cm (Figure 7). The C_{grid} value with the short funnel configuration was 55%, implying that as many as 45% of the small Haddock would escape through the escape exit without

contacting the grid. However, no Haddock below 11 cm were caught during the few hauls conducted with this configuration, and therefore we should be very careful about inferences regarding Haddock and especially those below this size limit. Adding LEDs around the escape exit for the short funnel configuration significantly increased the value of C_{grid} to 96% (CI = 75–100%). This shows that with this configuration only 4% of the Haddock would seek the escape exit directly. This result demonstrates that the LEDs around the escape exit greatly discouraged small Haddock from seeking it. The predicted significant difference in the grid passage probability of small Haddock is also clear from Figure 7, where the passage probabilities between the configurations are compared.

Size Selectivity for Atlantic Cod

For Atlantic Cod, the power in the experimental data was weaker than for the other species investigated, as fewer

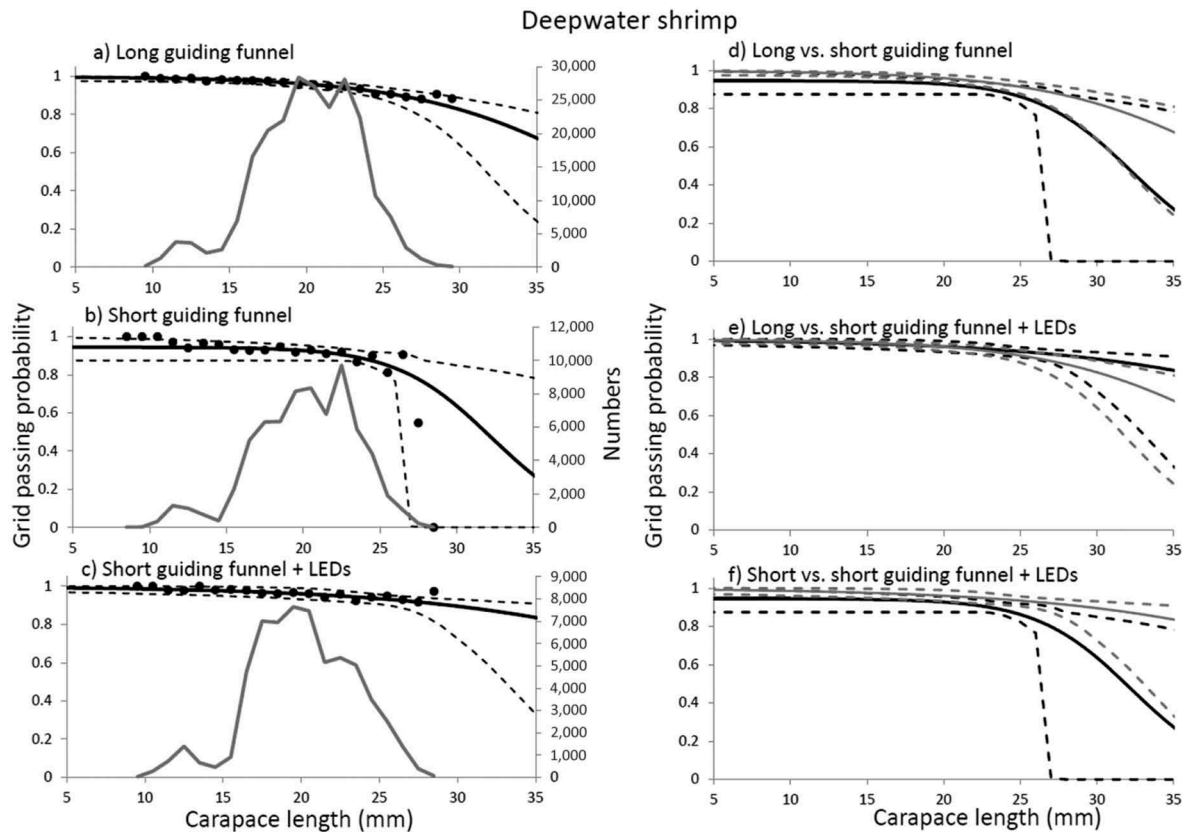


FIGURE 5. Grid passage probability and length-frequency distribution for deepwater shrimp using different funnel and LED configurations, including (a) a long guiding funnel configuration, (b) a short guiding funnel configuration, and (c) a short guiding funnel + LED lamp configuration. Panel (d) shows a comparison between a long guiding funnel (gray) and a short guiding funnel (black) configuration, panel (e) a comparison between a long guiding funnel (gray) and a short guiding funnel + LED lamp (black) configuration, and panel (f) a comparison between a short guiding funnel (black) and a short guiding funnel + LED lamp (gray) configuration. The dots represent experimental rates, the solid curves indicate the fitted model, and the dashed curves indicate the 95% confidence bands for the curve.

individuals were caught (Table 1). This resulted in wider confidence bands, which made inferences for Atlantic Cod difficult. This is particularly the case for the two configurations with the short guiding funnel, which was only tested in a very few hauls (Table 1). It was estimated that 89, 73, and 87% of the Atlantic Cod made selectivity contact with the Nordmøre grid, corresponding to 11, 27, and 13% seeking the escape exit in front of the grid without contacting the grid for the long guiding funnel, short guiding funnel, and short funnel + LEDs configurations, respectively (Table 2). These results show the same tendency regarding the effect of the configurations investigated as those of both redfish and Haddock, although Atlantic Cod appeared to react to a lesser extent than Haddock. Since the confidence intervals overlapped for both the model parameters and the grid passage probability curves for all three configurations, there were no significant differences detected between the three configurations tested based on the data collected (Figure 8). Although data were weaker for Atlantic Cod than for the other species, when

considering the confidence intervals estimated it is possible to conclude that at least 74% of the Atlantic Cod up to approximately 15 cm would pass through the grid into the cod end if the long guiding funnel is applied. With the short funnel configuration, the risk is reduced to 50%. Mounting LEDs to the short funnel configuration increases this risk to at least 60%. For Atlantic Cod above 15 cm, the grid passage probability gradually decreases with increasing length and reaches zero for Atlantic Cod above 25 cm. The fit statistics showed that models (2) and (3) were capable of describing the experimental data well for all three configurations, as the *P*-values were above 0.05 in every case (Table 2).

Size Selectivity for American Plaice

For American Plaice, the fit statistics showed that models (2) and (3) described the experimental data well because the *P*-values were above 0.05 for all three configurations investigated (Table 2) and because the fitted curves followed the trends in the experimental data well (Figure 9). The values

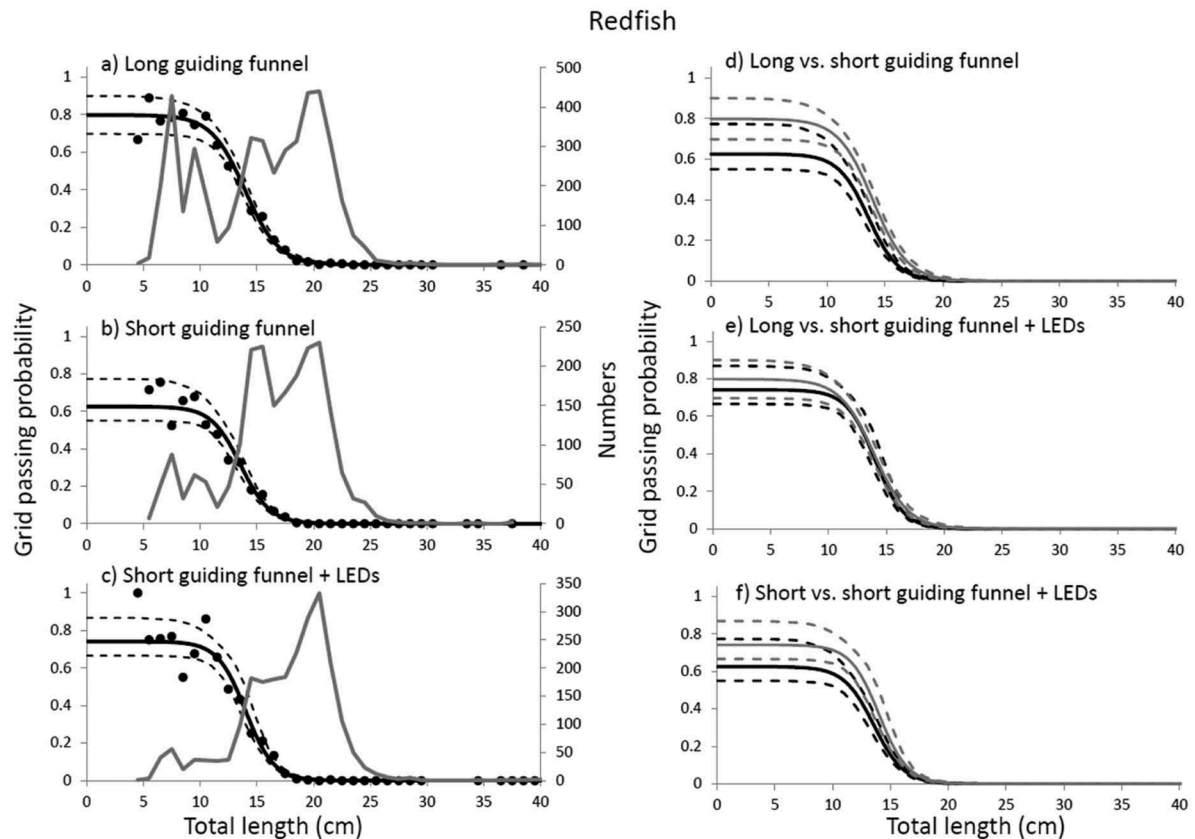


FIGURE 6. Grid passage probabilities, length-frequency distributions, and gear comparisons for redfish using different funnel and LED configurations. See Figure 5 for additional details.

for C_{grid} were very high, 99–100%, corresponding to only 0–1% of the American Plaice that entered the gear seeking the escape exit without contacting the grid. The value of C_{grid} did not differ significantly between the three configurations tested (Table 2). Almost all of the smallest American Plaice passed through the Nordmøre grid, with the passage probability decreasing continuously to zero at around lengths of 32 cm (Figure 9). Therefore, American Plaice of up to approximately 32 cm in length have a high risk of being caught in a trawl using a Nordmøre grid with 19-mm bar spacing. The estimated $L50_{grid}$ values combined with the high C_{grid} values estimated imply that approximately 50% of the American Plaice entering the trawl will pass through the Nordmøre grid and into the cod end. The estimated SR_{grid} values were 45–50% of the $L50_{grid}$ value and therefore relatively large (Table 2).

DISCUSSION

This study investigated the performance of the Nordmøre grid in the gear configuration most often used by fishermen

targeting deepwater shrimp in the Barents Sea. It further made a preliminary exploration on the effect of shortening the guiding funnel length and mounting LEDs around the escape exit on the performance of the Nordmøre grid. Experimental fishing trials were conducted in the Barents Sea to assess the size-selective properties of the Nordmøre grid with 19-mm bar spacing, which is mandatory for all vessels targeting deepwater shrimp in the northern trawl fishery. The study focused on selectivity data obtained for the target species and four bycatch species. The results obtained were based on a sampling effort that yielded a total of 38,583 length measurements (Table 1). As 25,624 of these measurements were taken within the 16 hauls carried out with the most popular configuration, the results provide a solid experimental base with which to quantify the current situation in the fishery regarding Nordmøre grid selectivity, which was the main objective for the study. The remaining eight hauls included in the study utilized two other configurations, four hauls with the short funnel and four with the short funnel + LEDs configuration. This resulted in a weaker experimental base for those results, which is reflected in the

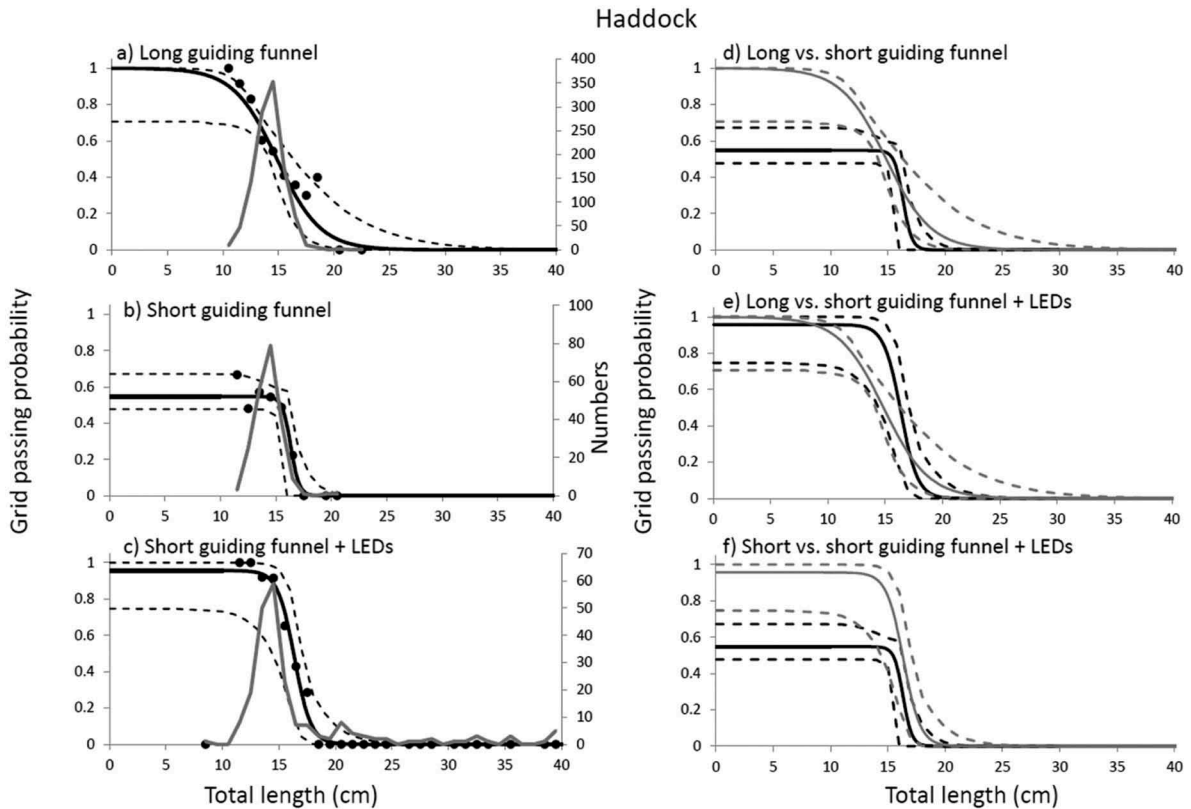


FIGURE 7. Grid passage probabilities, length-frequency distributions, and gear comparisons for Haddock using different funnel and LED configurations. See Figure 5 for additional details.

wider confidence bands for the size selection curves obtained. The number of hauls with these configurations was lower than we would normally recommend for making definitive conclusions. Therefore, our results for these designs should to some extent be considered as preliminary, but still relevant. These trials should, however, be followed up by new trials with more hauls specifically conducted with the objective of quantifying the effects of such design changes before definitive conclusions are made. However, as the confidence bands obtained were calculated using a well-established double bootstrapping method that accounts correctly for within-haul (uncertainty due to the finite numbers of fish in individual hauls) and between-haul variation in the size selection process (Millar 1993; Herrmann et al. 2013), the concern should be reduced as to whether the hauls for the three different configurations were on average subjected to the same conditions regarding factors that could affect their size selectivity. In this respect we did our utmost to keep conditions similar with respect to factors like towing time, area, and daylight. The latter factor, in particular, raises some concern, as one of the configurations used LEDs. However, fishing was conducted far north in the winter, with no daylight at the fishing depth. Based on these circumstances, we considered it of value to make the comparison

between the performances of the three configurations, but with a caution about drawing inferences as noted above.

One aspect that in general improved our experimental sampling was that we were able to avoid subsampling for all bycatch species, which increases the precision of the estimations made and eliminates the risk for bias from potentially obtaining no representative samples. Subsampling was only necessary for deepwater shrimp due to catch amounts. However, 11,600 shrimp were measured for length altogether (Table 1). The increased uncertainty due to subsampling was accounted for in the bootstrapping procedure for the estimation of uncertainties. However, the subsampling raises the question whether we managed to take a representative subsample from the shrimp catch. The procedure we applied in the laboratories on board was conducted very carefully following standard protocols, and we expect that the samples taken were representative for the size distribution in the catch.

The results that we obtained showed that between 80% and 100% of the bycatch species up to a species-specific size passed through the grid and entered the cod end. With the caveats noted above, our results showed that a short guiding funnel significantly increased the fraction of small Haddock seeking the escape exit. Further, the preliminary results showed that adding LEDs around the escape exit to the short

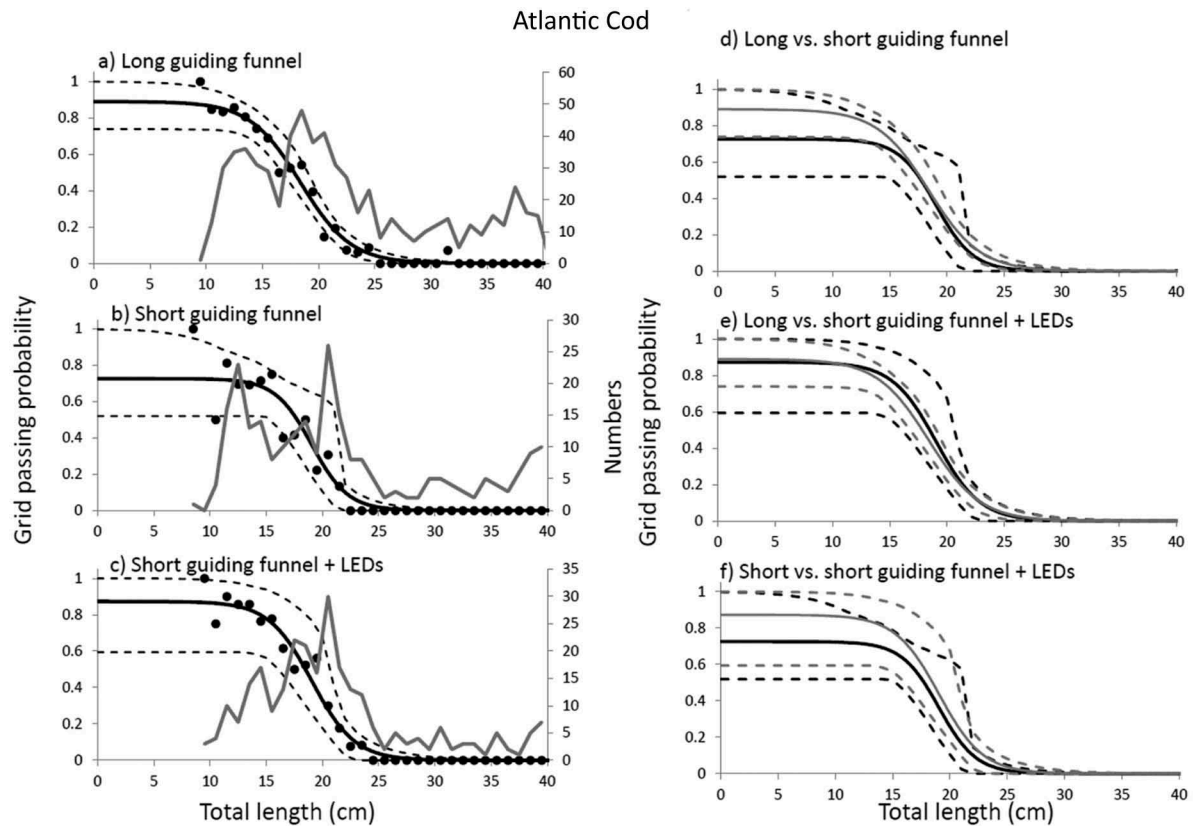


FIGURE 8. Grid passage probabilities, length-frequency distributions, and gear comparisons for Atlantic Cod using different funnel and LED configurations. See Figure 5 for additional details.

funnel configuration significantly negated this effect. The results for the other bycatch species were similar to those for Haddock but not statistically significant. In accordance with the results obtained by Hannah et al. (2015), our results indicate that it might be possible to change the performance of the Nordmøre grid by utilizing LED technology. However, placing LEDs around the escape exit was ineffective at stimulating fish escape through the grid escape exit. Based on the results obtained, it appears that LEDs discourage fish from getting close to the area where they are placed, which agrees with the results of Parsons et al. (2012) and seems to apply especially to species such as Haddock, whose escape behavior is known to be directed upwards (Winger et al. 2010; Sistiaga et al. 2016). Therefore, placing the LEDs at the lower part of the Nordmøre grid could be a better option, as it can direct the fish toward the escape exit without contacting the grid first.

In addition, turning the grid section upside down, with the escape exit facing downwards and LEDs placed at the top of the grid, could increase escape without contacting the grid for species known to seek an escape route downwards, such as Atlantic Cod and various species of flatfish (Rose and Hammond 2014; Sistiaga et al. 2016). The use of a long guiding funnel similar to the one

used in the Norwegian shrimp trawl fishery tended to allow a lower fraction of small bycatch fish species to escape through the escape exit than was the case with a short guiding funnel. Therefore, since a short guiding funnel shows advantages in terms of bycatch reduction compared with a long funnel, the latter should be avoided if the former does not imply an increase in shrimp loss. Silva et al. (2011) tested several configurations of the Nordmøre grid in an artisanal shrimp trawl fishery. They found only minor changes in selectivity for more than 40 species of crustaceans and teleost fish when the guiding panel was removed. To our knowledge, in the northern hemisphere all fisheries for species like deepwater shrimp and Pacific pink shrimp *P. jordani* use a guiding funnel (or guiding panel) in front of the Nordmøre grid. The justification for this is the anxiety by fishermen that a larger fraction of the target species may be excluded if the guiding device is removed. They claim that when fishing with twin or triple trawl configurations a trawl with a damaged or broken guiding funnel always catch less shrimp.

Our results imply that to avoid catches of redfish using a 19-mm bar spacing Nordmøre grid it would be necessary to use a cod end construction that would release all redfish below 10 cm and preferably up to around the estimated $L50_{grid}$ range

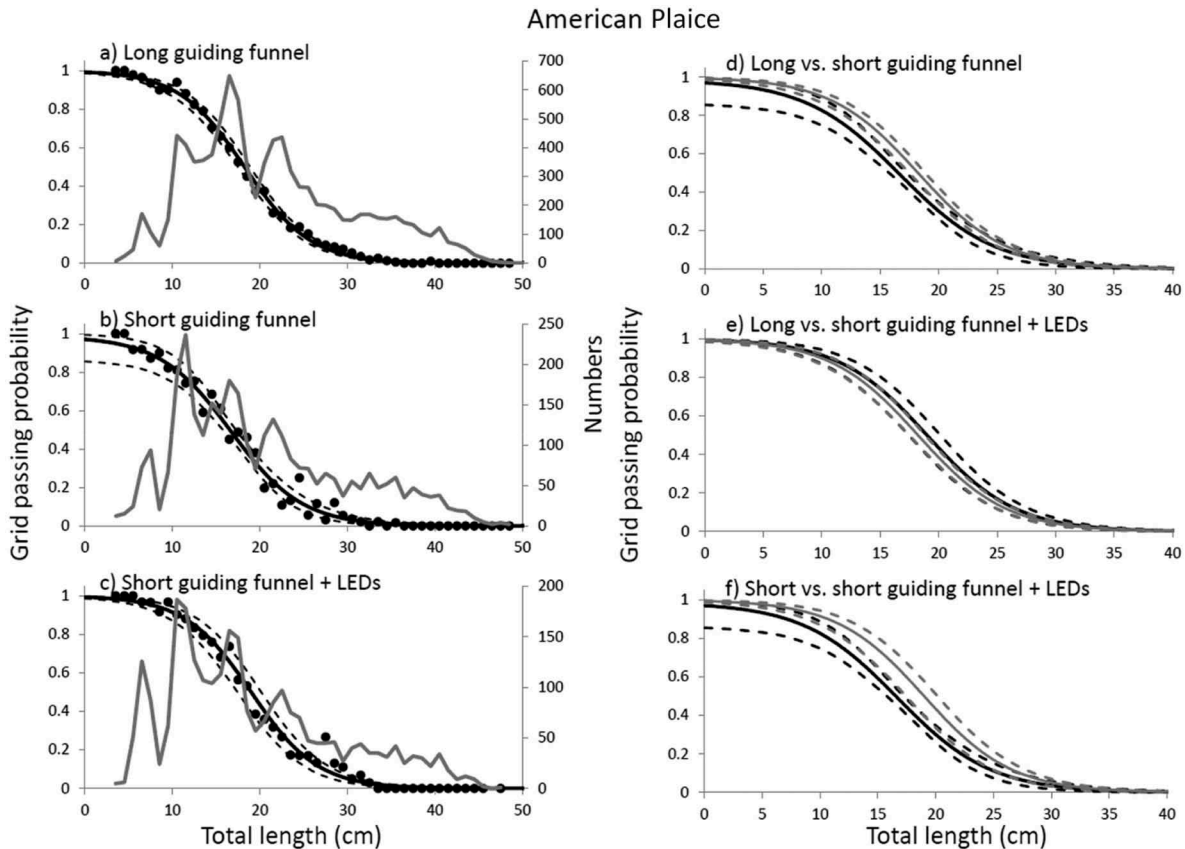


FIGURE 9. Grid passage probabilities, length-frequency distributions, and gear comparisons for American Plaice using different funnel and LED configurations. See Figure 5 for additional details.

of 13.6–14.0 cm. As this would likely create difficulties retaining the targeted deep-water shrimp in the cod end, a better strategy for reducing the redfish catch would be to use constructions that in connection with the Nordmøre grid would reduce the value of C_{grid} as much as possible without lowering it for deepwater shrimp.

The behavior of American Plaice can explain the results for this species. It is expected that flatfish will have a preference for staying down in the gear, and therefore the length-dependent grid passage probability does not have the characteristic plateau with constant values for sizes up to a certain size, as seen for other species. The estimated SR_{grid} values were 45–50% of the $L50_{grid}$ value and therefore relatively large (Table 2). This is likely due to the fact that the grid contact size selection provides many different ways for the flatfish to make contact with the grid. This phenomenon would explain the low slope of the grid passage curve. This type of process has previously been invoked to explain the size selection of Greenland Halibut in fish sorting grids (Herrmann et al. 2013), and a similar process is expected for American Plaice. When one is using a relatively small sorting grid, there is a certain risk that the relatively large densities of American Plaice in the northeast Barents Sea can clog the grid face (Figure 10). If this happens,

fish and deepwater shrimp escape would increase notably. In general, very few shrimp escaped through the escape exit in the present study, although escape increased slightly for the larger sizes. The results indicate that a short guiding funnel slightly increased the escape of deepwater shrimp through the escape exit, while adding LEDs seem to restore it to its previous level. However, these effects were not significant, so further testing is necessary before making definitive conclusions.

A demand for improved selectivity in any type of bottom trawl has been expressed in Norwegian–Russian legislation for northern fisheries. The fishing fleet, supported by fisheries managers, constantly seeks solutions that could improve the selectivity of the gear. The findings from this study provide new and important knowledge for the fishing industry. The results for the baseline configuration itself are important because they quantify to what extent and at what size fish are at risk of being caught together with the shrimp if they are abundant in the fishing grounds. This is important for fisheries managers, who can decide between closing those fishing grounds for a certain period or enforcing the use of cod ends that enable the release of most of the sizes at a high



FIGURE 10. The Nordmøre grid during a normal tow with several American Plaice on and in the vicinity of the grid face.

risk of passing through the grid. The first mitigation option may have significant consequences for the operational possibilities of the fleet, but it is simpler to apply. In contrast, the latter mitigation strategy needs to be carefully considered, taking into account the cod end size selection of the targeted shrimp species.

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