Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 10:493–507, 2018

ISSN: 1942-5120 online
DOI: 10.1002/mcf2.10048

ARTICLE

Catch Efficiency of Groundgears in a Bottom Trawl Fishery: A Case Study of the Barents Sea Haddock

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Abstract
The catch efficiency of two types of groundgear—a conventional rockhopper and a new type of groundgear called the semicircular spreading gear (SCSG)—was investigated through experimental fishing for Haddock *Melanogrammus aeglefinus* conducted in the Barents Sea. A retainer bag was attached behind the footrope of the trawl, and the number of fish that were overrun by the trawl was compared with the catch in the trawl cod end. The catch efficiency increased slightly for larger Haddock for both groundgears. The SCSG was found to have a significantly higher catch efficiency than the conventional rockhopper groundgear. The estimated improvement in catch efficiency varied between 4.5% and 12.3%, with an equivalent reduction in escape rate underneath the groundgear of more than 70%. The rockhopper groundgear can have a catch efficiency as low as 76%, corresponding with values reported in previous studies. Average catch efficiency for the rockhopper gear was significantly lower during the night in comparison with the daytime. No such difference was found with the SCSG. The SCSG is more efficient for catching Haddock, and it is lighter than the rockhopper groundgear. Both are important factors in reducing seabed impact and fuel consumption.

Subject editor: Patrick Sullivan, Cornell University, Ithaca, New York

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Received January 12, 2018; accepted August 7, 2018

When compared to results of a similar study on Atlantic Cod *Gadus morhua*, we found that in general, both groundgears had a greater catch efficiency for Haddock, which accords with differences in behavior between the two species.

The Haddock *Melanogrammus aeglefinus* is an important commercial species in several fisheries, including the Norwegian bottom trawl fishery in the Barents Sea (northeast Atlantic). The main purpose of the footrope (groundgear) in a bottom trawl is to maintain continuous contact with the seabed and ensure that the trawl runs smoothly over the ground without damaging the fishing line or the netting panels of the lower wings and belly. For the last 25–30 years, the rockhopper groundgear, a dense and tight line of rubber discs attached along the fishing line, has been commonly used in Norwegian bottom trawl fisheries. The rockhopper was shown to increase seabed contact, thus improving groundgear catch efficiency for bottom-dwelling species like Atlantic Cod *Gadus morhua* and Haddock, in comparison with the previous bobbin groundgear (Engås and Godø 1989).

During bottom trawling, demersal species like Haddock are herded into the path of the trawl net. The initial herding action starts from the otter boards, while the effect created by the sweeps aggregates the fish in front of the trawl mouth (Winger et al. 2010). Once the fish reach the trawl mouth area, they change their swimming direction, trying to maintain a constant position in front of the trawl; this optomotoric response was described by Wardle (1993). The behavior of fish in front of the trawl mouth influences capture efficiency and is species dependent. Ambient light intensity is an important factor influencing the behavioral pattern of fish in the vicinity of the trawl mouth. Both the distribution of fish in the trawl mouth (Engås and Ona 1990) and their reactions due to the visual appearance of the gear are affected by light intensity (Kim and Wardle 1998; Winger et al. 2010). At high light intensities, fish swim in ordered patterns using the optomotoric response. However, this response ceases at low light intensities, resulting in fish swimming in different directions toward the approaching gear, colliding with other fish and gear components (Glass and Wardle 1989; Walsh and Hickey 1993). In situ observations have shown that at night, Haddock do not detect or respond to the approaching gear until it is within 1–2 m (Wardle 1993). This often results in fish colliding with the groundgear and subsequently being overrun due to high reaction thresholds and short reaction distances (Winger et al. 2010). Some species, like Atlantic Cod, tend to actively seek an escape route close to the seabed under the fishing line and between the rockhopper discs, a behavior that is both species and size dependent (Engås and Godø 1989; Ingólfsson and Jørgensen 2006; Winger et al. 2010). Haddock tend to attempt to escape upwards when they feel threatened (Engås and Ona 1990; Wardle 1993; Winger et al. 2010). However, Ingólfsson and Jørgensen (2006) estimated that approximately 23% of Haddock escape beneath the groundgear, implying that the gear is inefficient.

Based on conflicting observations that Haddock rise when seeking escape and the reported loss of Haddock beneath the groundgear, we investigated the groundgear catch efficiency of Haddock (1) with the rockhopper groundgear; (2) with a new type of groundgear termed the semicircular spreading gear (SCSG; Grimaldo 2014; Brinkhof et al. 2017); and (3) during nocturnal and diurnal conditions with the rockhopper and the SCSG.

METHODS

To assess the catch efficiency of the rockhopper gear and the SCSG, we used the method applied by Brinkhof et al. (2017), which allowed potential catch efficiency differences between these two groundgears to be investigated. This method consists of an experimental design for collecting data during fishing trials and an analysis method to quantify the groundgear catch efficiency based on the collected data. The following sections briefly describe the methodology; a detailed description is provided by Brinkhof et al. (2017).

Trawls and Groundgears

Two identical, two-panel, Alfredo number 3 trawls were used, made of 80-mm mesh from 3-mm-diameter polyethylene (PE) twine (810 meshes in circumference). One trawl was equipped with a rockhopper gear, while the other trawl had an SCSG. A 12-m-long cod end made of 8-mm-diameter PE (80 meshes in circumference) and with a nominal mesh size of 135 mm was attached to the aft part of the extension of the trawls. The trawls had a 36.5-m-long headline equipped with 170 floats (20 cm in diameter) and a fishing line length of 18.9 m.

The trawls were rigged with a set of Injector bottom trawl otter boards (each 8.0 m^2 and weighing 3,100 kg) that had 3-m-long backstraps, which were linked to the sweeps by a 7-m-long, 19-mm-diameter connector chain. We inserted a 53-cm steel bobbin in the middle of both 60-m-long sweeps to protect the sweeps from abrasion. The 46.9-m-long groundgear consisted of an 18.9-m groundgear in the center, with 14-m-long, 19-mm-diameter chain equipped with three 53-cm, steel bobbins on each side (Figure 1). The geometry of the trawls was monitored by a set of Scanmar HC4-110/144 door sensors, an HC4-TS-156 height sensor, and an HC-8585 catch sensor (Scanmar AS, Åsgårdstrand, Norway) that provided information on the distance between the otter boards, the trawl height, and the catch size.

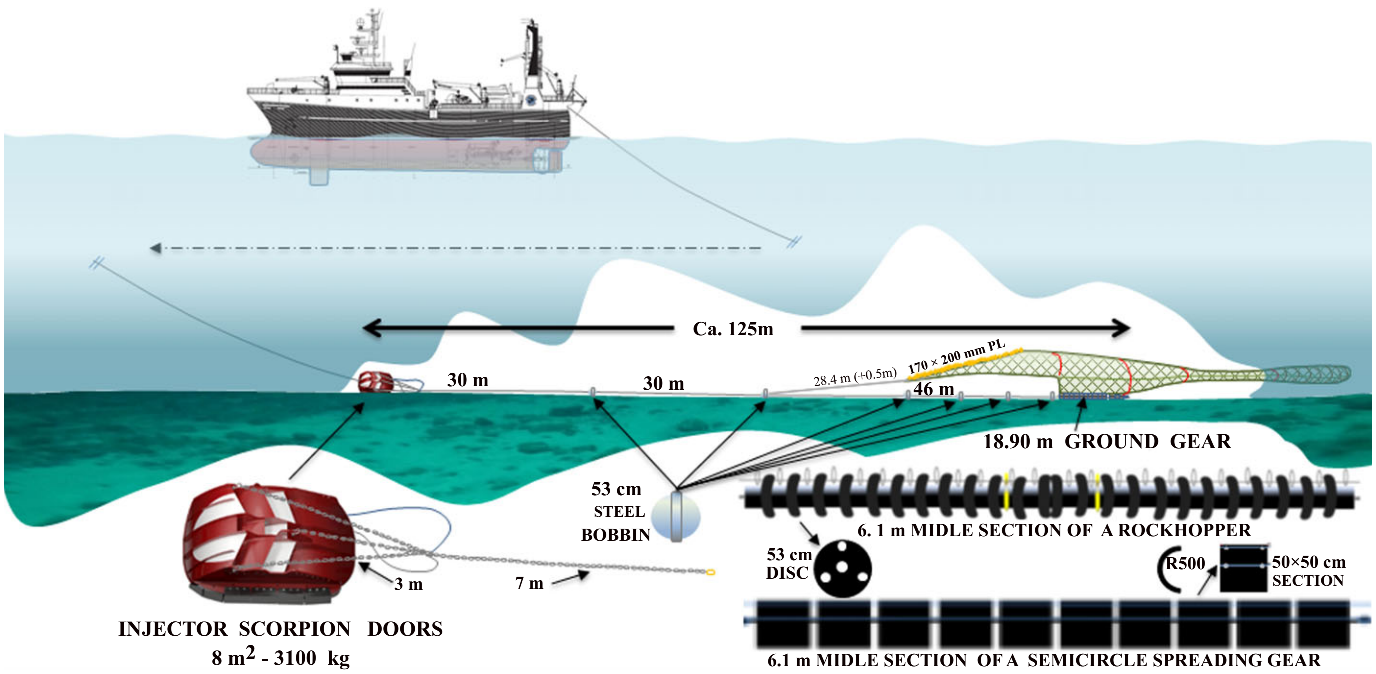

FIGURE 1. The main components (and their dimensions) of the trawl system combined with an Alfredo number 3 trawl as used in our experiments (PL = plastic floats).

The groundgear comprised either standard rockhopper discs of 53 cm or 51-cm SCSG units (Brinkhof et al. 2017). The 18.9-m rockhopper was built of three equal, 19-mm-diameter chain sections (6.1 m each) connected with hammerlock links. The 18.9-m-long SCSG consisted of three equal sections, each built entirely on a 19-mm chain and connected to the fishing line with steel rings attached to a 16-mm-diameter wire. The SCSG was made from 50-cm-long, 3.4-cm-thick, half-moon-shaped sections (51 cm in diameter) of high-density PE, with a distance of 8 cm between them. The weight in air of the rockhopper gear was approximately 1,730 kg, while the SCSG weighed about 570 kg in air. Details of these groundgears are shown in Figure 2.

Retainer Bag

To collect fish that would otherwise have escaped, a retainer bag was mounted underneath the trawl, as described by Brinkhof et al. (2017). The retainer bag was equipped with a small groundgear along the 6.6-m-long fishing line and had the same mesh size as the trawl cod end (135-mm nominal mesh size). The construction of the retainer bag is shown in Figure 3. After each tow, the groundgear was visually inspected to see whether it was polished, which indicated proper contact with the seabed. In addition, the retainer bag was inspected for damage. If any damage or other anomaly was detected, the haul was discarded.

Fishing Ground and Operations

Sea trials were carried out onboard the 63.8-m-long R/V *Helmer Hanssen* (4,080 hp) during February 17–27, 2015. The fishing grounds were located in the north Norwegian coast (southern Barents Sea) between 70°50′–70°45′N and 31°05′–30°43′E. The trawls were fished in a pairwise pattern, and the towing speed varied between 7.22 and 7.78 km/h (between 3.9 and 4.2 knots). Towing time was restricted to a maximum of 90 min; tow duration was shorter if the catch sensor revealed catches higher than approximately 3 metric tons. The catch from the retainer bag and the catch from the cod end were kept in separate bins onboard, and length measurements were recorded for all Haddock caught. Measurements were rounded down to the nearest centimeter.

Underwater Observations

Underwater video recordings were made during the trials. These recordings enabled (1) observation of Haddock behavior in relation to the groundgear and (2) evaluation of the performance of the groundgear and the retainer bag. GoPro Hero 4 black edition HD camera systems (GoPro, Inc., Riverside, California) were used for the underwater video recordings, which were made in shallow fishing grounds (60–75 m deep) under natural light conditions to avoid a negative impact from artificial light (Weinberg and Munro 1999). The cameras were attached inside the upper

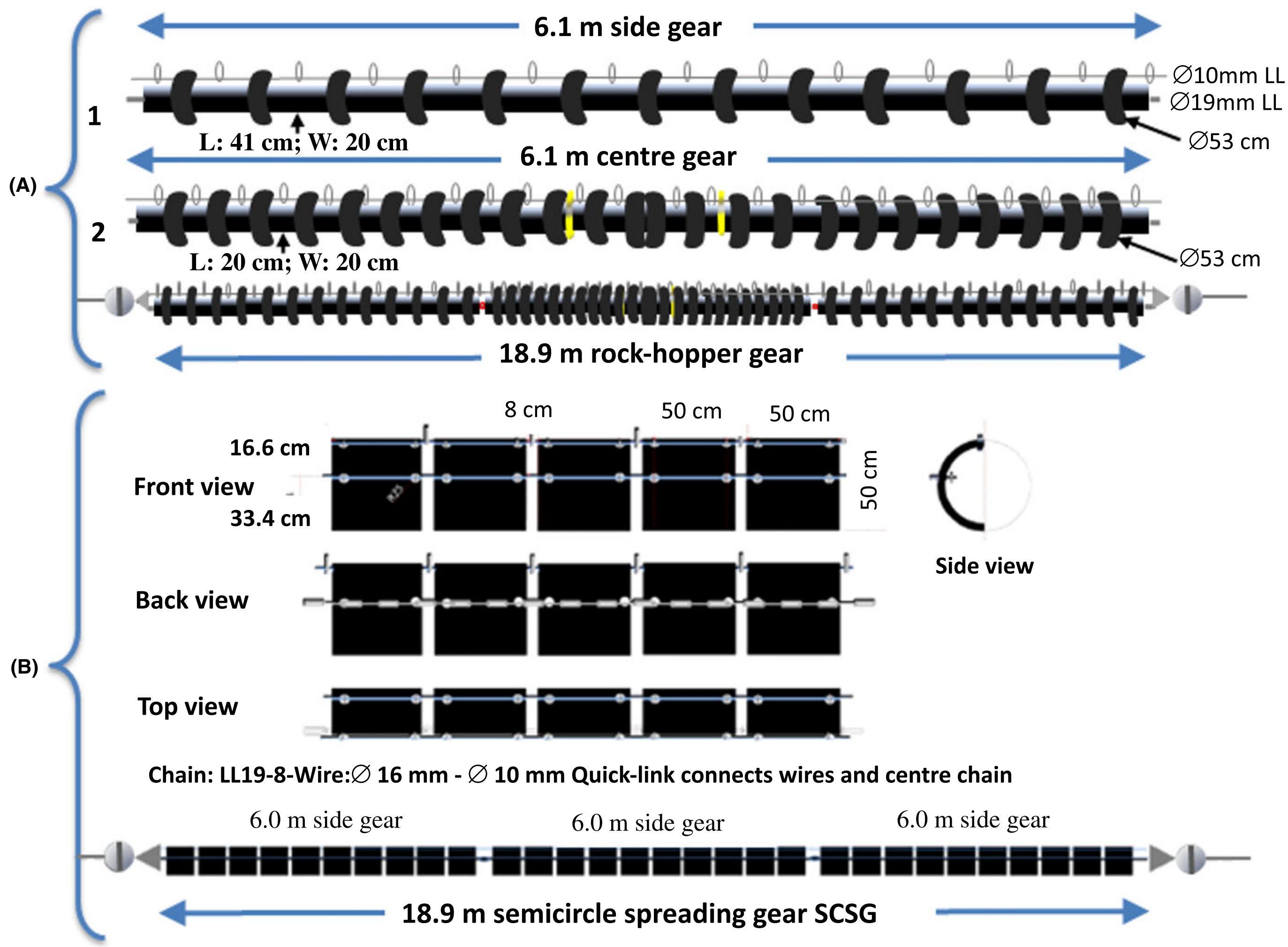

FIGURE 2. Design of **(A)** the rockhopper gear and **(B)** the semicircular spreading gear (SCSG; Ø = diameter value; LL = long link steel chain).

panel of the trawl facing downwards, thereby giving a view over the central part of the footrope (groundgear).

Data analyses

Comparing relative catch efficiency of groundgears.— The experimental catch comparison rate R_l for Haddock of length-class l from the cod end catch nc_l and the retainer bag catch nr_l (in terms of the number of Haddock) was quantified by

$$R_l = \frac{nc_l}{nc_l + nr_l}. \quad (1)$$

Ideally, R_l should be close to 1.0 for all sizes l, which would imply that few Haddock escaped under the central part of the groundgear and entered the retainer bag. In the current study, the total catch comparison rate is of greater interest than R_l, as it accounts for the fact that the retainer bag did not sample all fish escaping underneath the fishing line. Because the retainer bag covered only the central zone of the groundgear (Figure 4), it did not necessarily catch all of the fish that escaped underneath the groundgear. Specifically, it only collected fish that escaped underneath the fishing line in the central part of the groundgear. Brinkhof et al. (2017) demonstrated how this can be accounted for in the analysis by considering two scenarios differing in the fraction of fish that would be herded into the center zone of the groundgear before coming into contact with it. In the first scenario, no fish were herded into the central zone before contact (herding efficiency $hf = 0.0$); in the second scenario, all fish were herded into the central zone before contact ($hf = 1.0$). The same analysis approach was employed in the current study, as it provided lower and upper limits for groundgear catch efficiency.

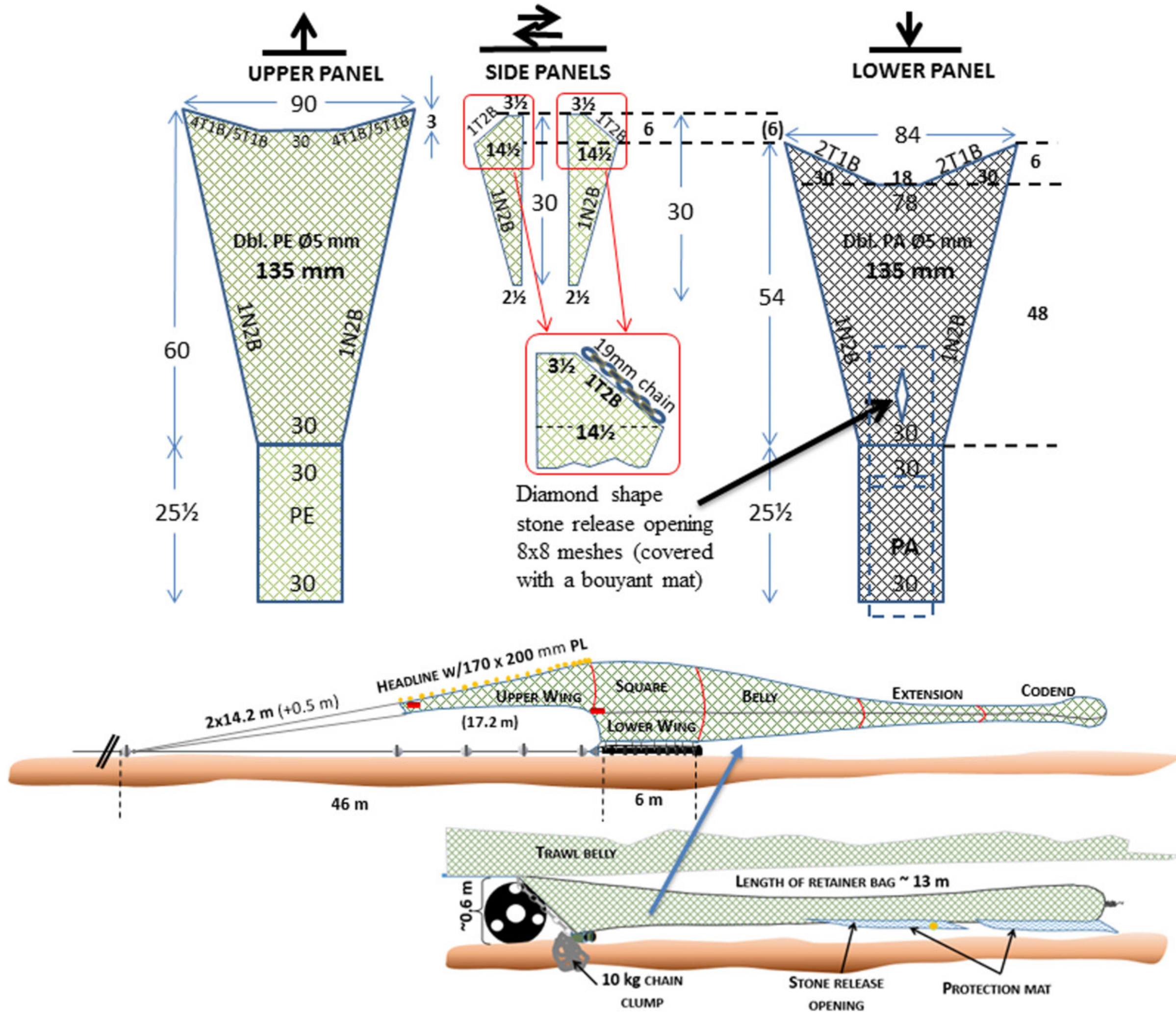

FIGURE 3. Construction drawing of the retainer bag and a sketch illustrating how it was mounted under the trawl to catch escaping Haddock (Ø = diameter value; Dbl. PE = double polyethylene; Dbl. PA = double polyamide [nylon]).

Similar size selection is assumed between the equal-mesh-sized retainer bag and cod end. Under this assumption, Brinkhof et al. (2017) showed that the influences of size selection in the retainer bag and the cod end, respectively, cancel each other out in the equation relating to groundgear catch efficiency GG(l) and the observed catch comparison rate $R(l)$. In this case, the only size selection in the trawl that influences the relationship between GG(l) and $R(l)$ is in the 80-mm-mesh trawl body (Brinkhof et al. 2017). Therefore, in the current study, the investigation of groundgear catch efficiency was restricted to Haddock of a size above which size selection can occur in the 80-mm-mesh trawl body. In the present case, the relationship between GG(l) and $R(l)$ only depends on the fraction q of the total amount of fish escaping under the groundgear that is collected in the retainer bag (Brinkhof et al. 2017). Brinkhof et al. (2017) also showed how q is related to the total width of the groundgear, the width of the retainer bag, and the groundgear herding efficiency $hf(l)$. Using this information from Brinkhof et al. (2017), we arrived at the following relationship between $R(l)$ and GG(l):

$$\mathrm{GG}(l) \approx \frac{hf + 0.61}{1.61 - (1.0 - hf) \times R(l)} \times R(l). \qquad (2)$$

The constants 0.61 and 1.61 in equation (2) are based on the specific groundgear width and the retainer bag width used in the experimental sampling (Figure 4). Equation (2) is therefore only valid for that specific setup, and the deduction of it is detailed in the Appendix. As in Brinkhof et al. (2017), the FISHSELECT methodology (Herrmann et al. 2009) was used in the current study to estimate the size limit at which Haddock cannot escape

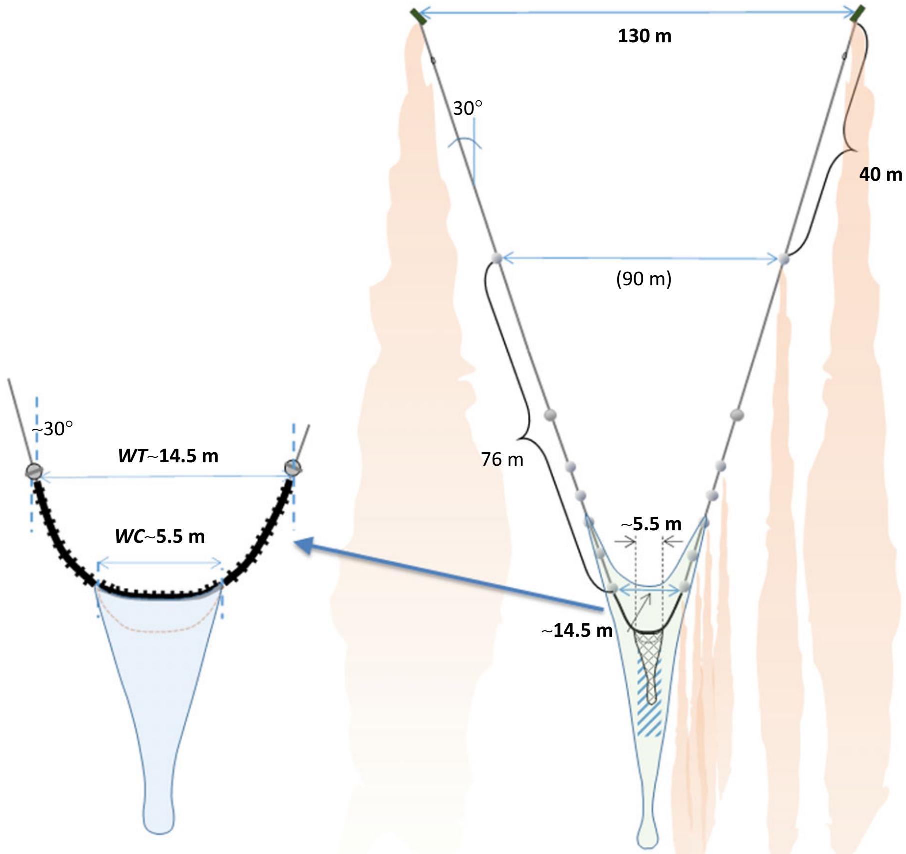

FIGURE 4. Sketch of the trawl with the retainer bag mounted underneath, showing the area covered by the groundgear of the trawl (WT) and the area covered by the retainer bag (WC).

through the 80-mm-mesh trawl body based on fish morphology. We used this to define the size limit, from which we can apply equation (2) to estimate GG(l) from $R(l)$. To achieve this, morphological data and models for Barents Sea Haddock from Sistiaga et al. (2011) were used to produce a size limit estimate of 33 cm.

To use equation (2), the functional form $R(l)$ of the observed catch comparison rate from the experimental data must be estimated.

Size-dependent catch comparison analysis.— The observed size-dependent catch comparison rate and subsequent inferences of groundgear efficiency were established by analyzing the catch data. Catch data included numbers and sizes of Haddock retained in the cod end and the retainer bag separately for the group of hauls belonging to the respective cases investigated via the procedure described below. The method applied is identical to that used by Brinkhof et al. (2017). It is based on fitting a flexible model to the experimental data consisting of binominal count data for the different length-groups (1-cm intervals). It uses these data to estimate the curvature of a model for $R(l)$ averaged over hauls for the specific case investigated using maximum likelihood estimation. The method accounts for multiple competing models to describe the data, and it employs a double bootstrapping procedure to account for the different sources of uncertainty in the estimation of confidence limits for $R(l)$ and subsequently for GG(l) (Brinkhof et al. 2017). The ability of the model to describe the experimental data was assessed based on the P-value, which expresses the likelihood of obtaining at least as large a discrepancy as that observed between the fitted model and the experimental data by coincidence. Therefore, for the combined model to be a candidate model, the P-value should not be less than 0.05 (Wileman et al. 1996). In cases with poor fit statistics (P-value <0.05; deviance $\gg$ df), the deviations between the experimental observed GG(l) points and the fitted curve were examined to determine whether they were due to structural problems in the description of the experimental data with the combined model or due to overdispersion in the data.

The average value for R_l, integrated over all lengths above the size limit (33 cm) where any selection was caused solely by groundgear efficiency, was estimated using the method described by Brinkhof et al. (2017).

All analyses were performed using the software tool SELNET (Herrmann et al. 2012). The results were exported to R version 3.0.2 (R Core Team 2013) for graphical presentation.

Analysis of groundgear diel differences.— Overall, 42 hauls were conducted, 14 of which were performed with various camera riggings that allowed for observations of fish behavior and gear performance. The recordings were made during daylight to avoid the use of artificial light, which is believed to affect fish behavior (Mueller et al. 2006). During the study period, it was light between the hours of 0700 and 1500 hours local time, and there was total darkness for almost 14 h per day. The difference in light intensity between day and night allowed us to investigate how diurnal variability would potentially affect catch efficiency.

To investigate each of our research questions, hauls belonging to each of the following six groundgear efficiency cases were analyzed separately by following the procedure described in the previous section: (1) rockhopper; (2) SCSG; (3) rockhopper day; (4) rockhopper night; (5) SCSG day; and (6) SCSG night. To determine any potential differences in groundgear efficiency between the cases, the efficiency curves of each case were plotted pairwise along with their 95% confidence intervals (CIs). Length-classes without overlapping CIs were then identified to determine whether significant differences could be detected based on the collected data.

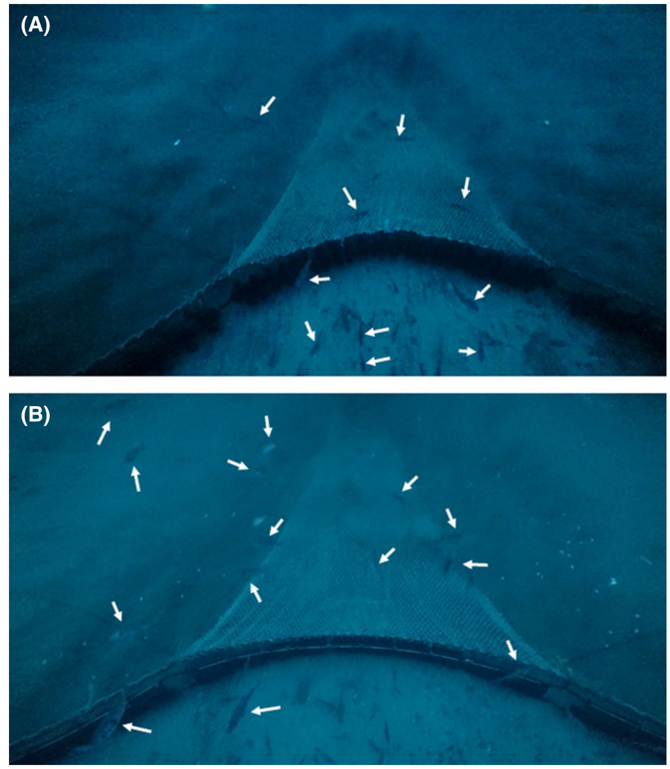

FIGURE 5. Photos grabbed from underwater video recordings made at approximately 65-m depth in natural light on February 25, 2015, showing the behavior of Haddock in the mouth of the trawl with **(A)** rockhopper gear and **(B)** semicircular spreading gear. The white arrows indicate the positions of Haddock in front and over the footrope. The visible net behind the center section of the footrope belongs to the retainer bag.

RESULTS

Data Collection and Underwater Recordings

The video recordings clearly showed that Haddock were evenly distributed when entering the trawl mouth (Figure 5). The fish swam for a short period in front of the central section of the fishing line, and the majority entered the trawl by rising well over the fishing line while alternating their swimming direction, swimming into the trawl but against the towing direction.

The video recordings revealed considerably larger mud clouds behind the rockhopper gear in comparison with the SCSG due to differences in gear design and weight. We examined the trawl performance during tows with and without the retainer bag attached and found no difference in the door spread and trawl height.

Of the 28 hauls conducted without video recordings, 26 were considered valid and were included in the statistical analyses (13 hauls conducted with the rockhopper gear and 13 hauls conducted with the SCSG). A summary of the number of Haddock caught in the cod end and in the retainer bag for each haul is presented in Table 1. In total, 1,682 Haddock were caught and measured from all valid hauls. Most of the Haddock were of a length larger than the established size limit of 33 cm.

Figure 6 shows the size structure of Haddock caught during the study for hauls using the rockhopper groundgear and the SCSG, respectively. It can be seen from Figure 6 that most of the Haddock caught were between 45 and 65 cm. Less than 10 Haddock were recorded in the remaining length-classes when summed over hauls for the rockhopper gear and SCSG. Based on this, the subsequent analysis of the data was restricted to Haddock within the 45–65-cm length range, which is well above the established size limit of 33 cm. Therefore, the initial 33-cm size limit for analysis was replaced by a 45-cm size limit.

Groundgear Catch Efficiency Curves

Figure 7 shows the experimental catch comparison rate and the catch frequency of each Haddock length-class (within the 45–65-cm length range) for the rockhopper gear and the SCSG for all hauls conducted during both day and night. The modeled catch comparison curves

TABLE 1. Details of bottom trawl hauls conducted during the cruise (February 17–27, 2015), including the type of groundgear used (SCSG = semicircular spreading gear), the number of Haddock caught and measured in the cod end and in the retainer bag, and the light conditions during each haul. The 14 hauls with underwater camera observations are not included here.

			Number of Haddock	
Haul	Groundgear type	Light conditions	Cod end	Retainer bag
1	SCSG	Twilight	13	0
2	Rockhopper	Diurnal	33	2
3	Rockhopper	Diurnal	77	1
4	SCSG	Diurnal	41	1
5	SCSG	Twilight	36	5
6	Rockhopper	Twilight	59	6
7	Rockhopper	Nocturnal	65	3
8	SCSG	Nocturnal	61	0
9	SCSG	Nocturnal	83	1
10	Rockhopper	Nocturnal	92	13
11	Rockhopper	Nocturnal	136	10
12	SCSG	Diurnal	174	0
13	SCSG	Diurnal	64	2
14	Rockhopper	Twilight	43	5
15	Rockhopper	Nocturnal	33	2
16	SCSG	Nocturnal	42	1
17	SCSG	Nocturnal	40	0
18	Rockhopper	Twilight	62	3
19	Rockhopper	Diurnal	90	4
20	SCSG	Diurnal	61	0
21	SCSG	Diurnal	62	2
22	Rockhopper	Twilight	30	4
23	Rockhopper	Nocturnal	63	2
24	SCSG	Nocturnal	35	2
25	SCSG	Nocturnal	54	2
26	Rockhopper	Nocturnal	53	9

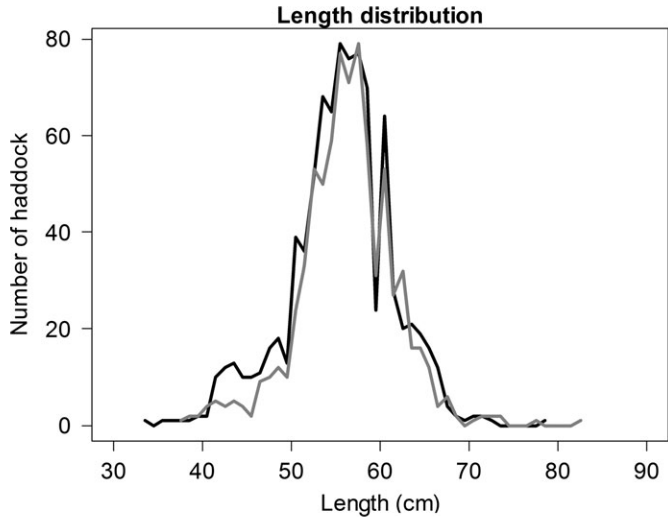

FIGURE 6. Size structure of Haddock caught during experimental fishing with the rockhopper gear (black line) and semicircular spreading gear (gray line). Data are pooled for all valid hauls conducted.

follow the main trends of the experimental points, which is supported by the fit statistics presented in Table 2. For the rockhopper data, the *P*-value less than 0.05 could suggest problems describing the experimental data, but an inspection of the deviance residuals did not indicate any patterns. Therefore, it seemed that the data were overdispersed, and the model could be applied to describe the experimental observed catch comparison rate in this case. The lack of patterns in the deviation between the model and experimental data is also clear from Figure 7A.

Based on the estimated catch comparison curves, equation (2) was used to estimate the corresponding groundgear catch efficiency curves (including their 95% CIs) for the two extreme *hf* values ($hf = 0.0$ and $hf = 1.0$) to provide lower and upper limits for groundgear catch efficiency (Figure 8).

As shown in Figure 8, the estimated groundgear catch efficiency was found to be only slightly length dependent. Comparing the catch efficiency between the gears, there was a slightly higher catch efficiency for the SCSG than for the rockhopper gear, but no significant difference was detected (Figure 8).

The average catch efficiency with $hf = 1.0$ for the rockhopper gear and 45–65-cm Haddock was calculated as 93.8% (95% CI = 91.7–95.8%), significantly lower than the catch efficiency with the SCSG, which was calculated as 98.2% (95% CI = 96.1–99.4%). The average catch efficiency for $hf = 0.0$ was only slightly lower than the values presented above (Table 3). The estimated improvement in efficiency with the SCSG was between 4.5% and 10.8% for Haddock in the 45–65-cm size range. This corresponds to a decrease of more than 70% in the number of escapees underneath the groundgear (Table 3).

Effect of Diel Variability on Groundgear Catch Efficiency

Exclusion of hauls conducted during dusk and dawn resulted in relatively few hauls (Table 1) and fish (Figures 9A, B, and 10A, B) for this comparison. For the rockhopper gear, there was a significant difference (Figure 9C, D) in catch efficiency between nighttime hauls and daytime hauls. For 45–65-cm Haddock with $hf = 1.0$, the average groundgear catch efficiency for the hauls conducted under diel conditions was calculated as 97.7% (95% CI = 97.2–100%), whilst average groundgear catch efficiency under nocturnal conditions was significantly lower at 92.2% (95% CI = 89.5–94.8%). For the SCSG

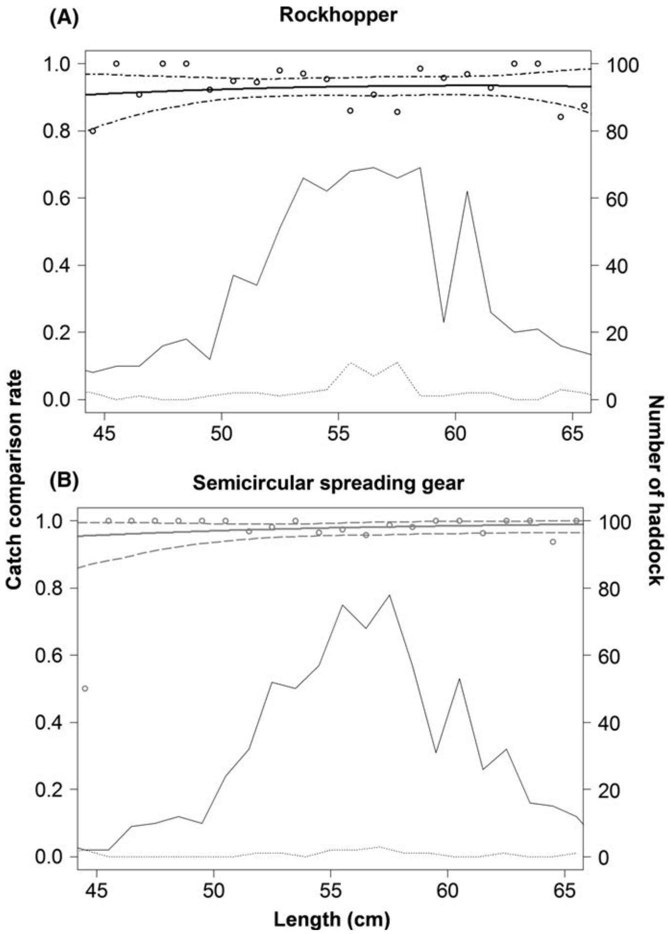

FIGURE 7. Experimental catch comparison rates (circles), estimated catch comparison curves (solid curves) with 95% confidence intervals (dashed curves), and Haddock length distributions in the cod end (thin lines) and retainer bag (dotted lines) for the **(A)** rockhopper gear and **(B)** semicircular spreading gear.

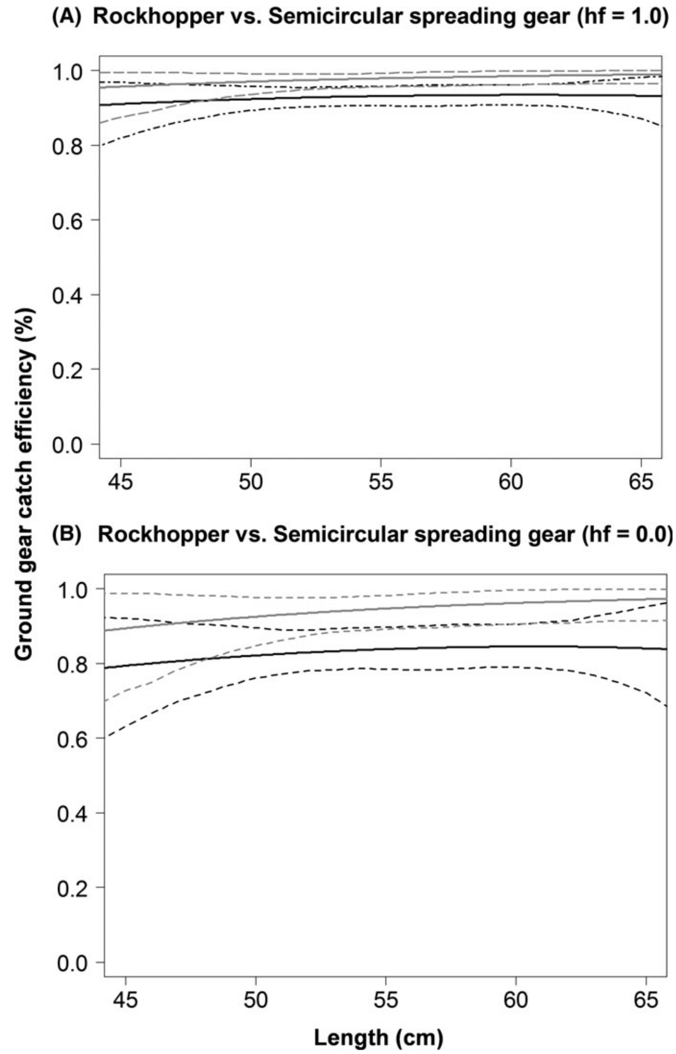

FIGURE 8. Comparison of groundgear catch efficiency between the rockhopper gear (black solid curve) and the semicircular spreading gear (gray solid curve) with 95% confidence intervals (dashed curves) for Haddock at two herding efficiency (*hf*) values: **(A)** $hf = 1.0$ and **(B)** $hf = 0.0$.

TABLE 2. Fit statistics for the modeled catch comparison rate of Haddock in hauls conducted with rockhopper gear or semicircular spreading gear (SCSG).

Groundgear type	*P*-value	Deviance	df
Rockhopper	0.019	54.45	35
SCSG	0.773	26.69	33

(Figure 10C, D), no significant difference in groundgear catch efficiency was found between the hauls conducted under nocturnal versus diurnal conditions. The fit statistics given in Table 4 indicate that the model described the data sufficiently well, with the exception of hauls conducted under nocturnal conditions with the rockhopper gear. Investigation of the deviance residuals did not show any pattern, thus suggesting that the data were overdispersed (Table 5).

DISCUSSION

Due to discrepancies between previous qualitative and quantitative studies (Wardle 1993; Ingólfsson and Jørgensen 2006), the aim of this study was to investigate the catch efficiency for Haddock with two different groundgears. Although the length-dependent evaluation did not detect any significant difference in catch efficiency between the two groundgears, the evaluation of the average catch efficiency revealed a significant improvement for the SCSG compared to the rockhopper gear. Additionally, the average catch efficiency for the rockhopper gear was found to be significantly lower during the night than during the daytime. No such difference was found for the SCSG. Because the

TABLE 3. Average groundgear catch efficiency (%) and groundgear escape rates (%) caused solely by the groundgear selection process (SCSG = semicircular spreading gear) for 45–65-cm Haddock at two herding efficiency (*hf*) values (*hf* = 0.0 or 1.0). Values in parentheses are 95% confidence limits.

Groundgear type	Average groundgear catch efficiency (%)		Average groundgear escapement (%)		Improvement in groundgear catch efficiency (%)		Reduction in groundgear escapement (%)	
	$hf = 1.0$	$hf = 0.0$	$hf = 1.0$	$hf = 0.0$	$hf = 1.0$	$hf = 0.0$	$hf = 1.0$	$hf = 0.0$
Rockhopper	93.8 (91.7–95.8)	85.1 (80.7–89.6)	6.2 (4.2–8.3)	2.4 (1.6–3.3)				
SCSG	98.2 (96.1–99.4)	95.4 (90.3–98.4)	1.8 (0.6–3.9)	0.7 (0.2–1.5)	4.5	10.8	71.0[a]	70.8[b]

[a]71% = 100 × (6.2 − 1.8)/6.2.
[b]70.8% = 100 × (2.4 − 0.7)/2.4.

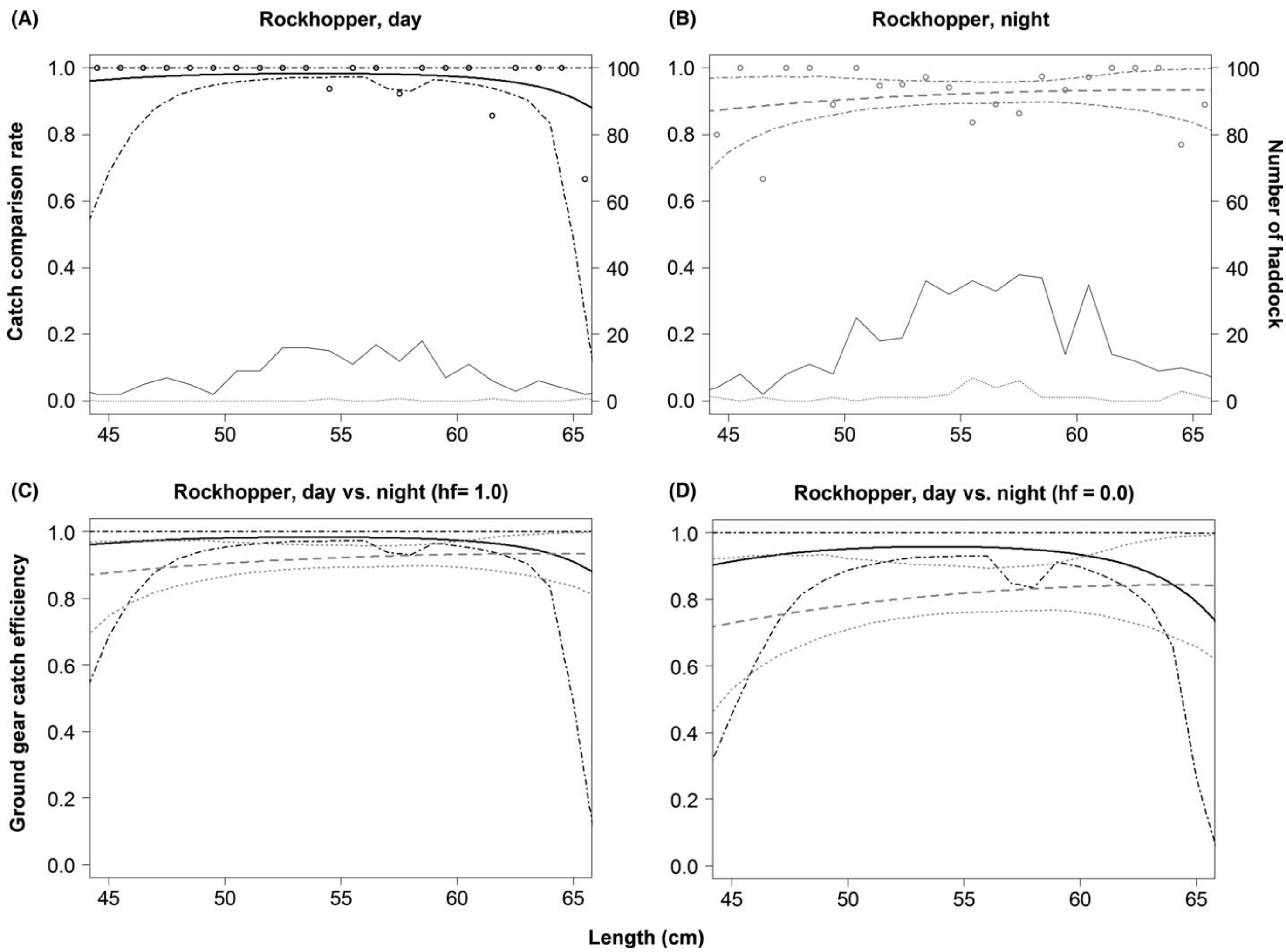

FIGURE 9. Catch comparison rate curves for Haddock in hauls conducted with rockhopper gear under **(A)** diurnal conditions (black curve) and **(B)** nocturnal conditions (gray curve); and groundgear catch efficiency curves compared for rockhopper gear during daytime versus nighttime at two herding efficiency (*hf*) values: **(C)** *hf* = 1.0 and **(D)** *hf* = 0.0. Circles represent the experimental catch comparison rates, solid curves represent the estimated curves, and dashed curves represent 95% confidence intervals. Panels (A) and (B) also depict the length distribution of Haddock caught in the cod end (thin solid line) and the retainer bag (dotted line).

fishery often operates during a period of the year with little or no daylight, use of the SCSG could significantly improve catch efficiency.

Limitations in the experimental setup in the current study were identified and considered in the analyses. First, due to possible size selection in the cod end, trawl body,

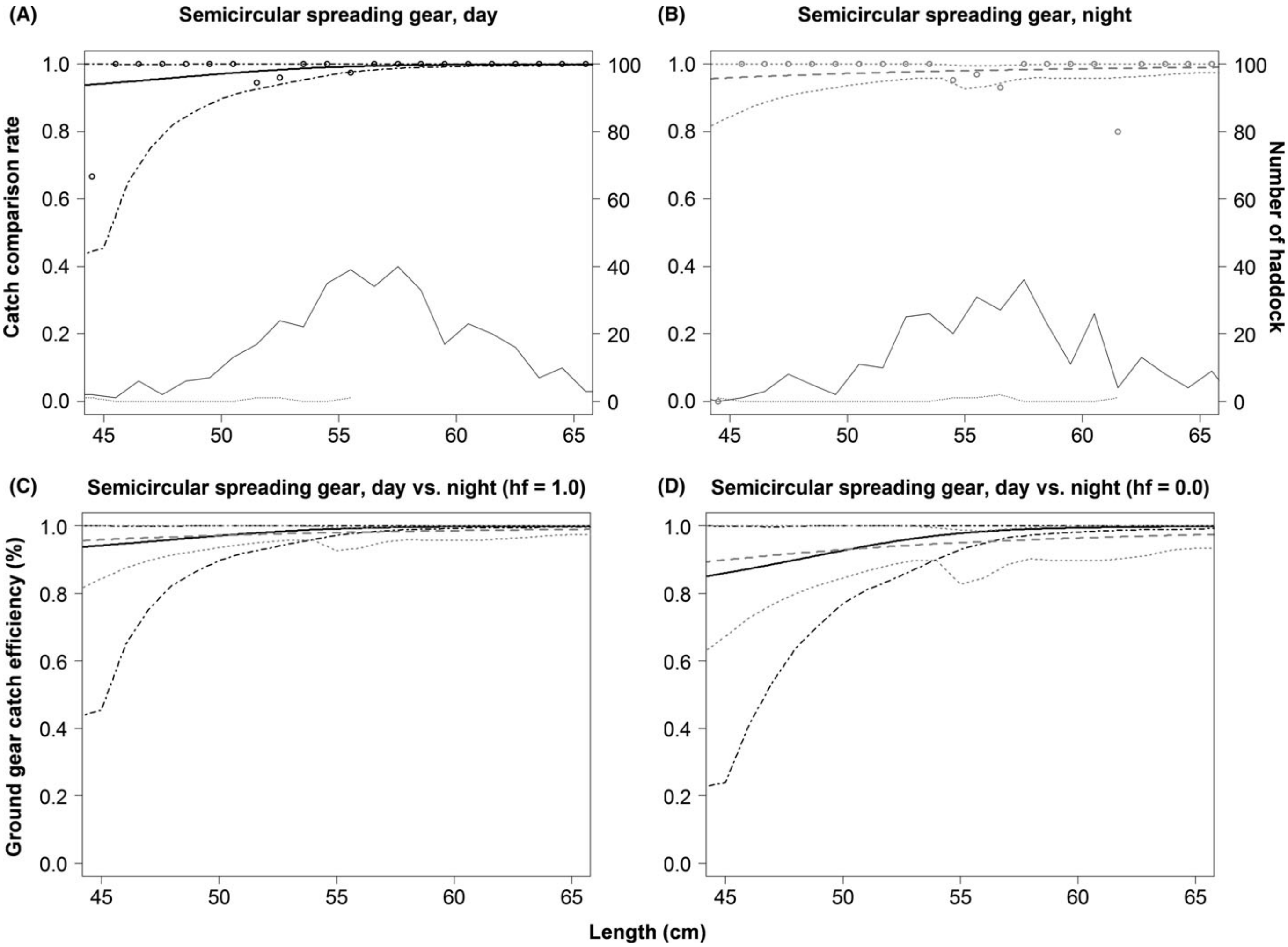

FIGURE 10. Catch comparison rate curves for Haddock in hauls conducted with semicircular spreading gear (SCSG) under **(A)** diurnal conditions (black curve) and **(B)** nocturnal conditions (gray curve); and groundgear catch efficiency curves compared for SCSG during daytime versus nighttime at two herding efficiency (*hf*) values: **(C)** *hf* = 1.0 and **(D)** *hf* = 0.0. Circles represent the experimental catch comparison rates, solid curves represent the estimated curves, and dashed curves represent 95% confidence intervals. Panels (A) and (B) also depict the length distribution of Haddock caught in the cod end (thin solid line) and the retainer bag (dotted line).

TABLE 4. Fit statistics for the comparison of groundgear catch efficiency for Haddock in hauls conducted with rockhopper gear or semicircular spreading gear (SCSG) under diurnal and nocturnal conditions.

Groundgear type, light conditions	*P*-value	Deviance	df
Rockhopper, day	0.833	19.95	27
Rockhopper, night	0.032	45.92	30
SCSG, day	0.920	14.64	28
SCSG, night	0.603	22.57	25

or retainer bag for Haddock given the large mesh size, a size limit of 33 cm was established (justified by Brinkhof et al. 2017). Any selection above this limit is solely caused by groundgear selection, whereas selection below the limit could possibly be influenced by selection in the cod end, trawl body, or retainer bag. Second, the retainer bag only covered the central part of the fishing line. This was accounted for by considering two extreme scenarios regarding the proportion of the total amount of fish that could escape underneath the trawl and be collected in the retainer bag. The underwater recordings indicated that most fish escaped in the central section of the fishing line, which means that the *hf* would be closer to 1.0 than to 0.0. This value implies that groundgear catch efficiency could be closer to the least conservative estimate—an observation that is corroborated by other studies reporting the same behavior (Main and Sangster 1981; Walsh 1992; Krag et al. 2010). Nevertheless, Ingólfsson and Jørgensen

TABLE 5. Average groundgear catch efficiency and groundgear escape rate for 45–65-cm Haddock in hauls conducted with rockhopper gear or semicircular spreading gear (SCSG) under diurnal and nocturnal conditions at two herding efficiency (*hf*) values (*hf* = 0.0 or 1.0). Values in parentheses are 95% confidence limits.

Groundgear type, light conditions	Average groundgear catch efficiency (%)		Averaged groundgear escapement (%)		Improvement in groundgear catch efficiency (%)		Reduction in groundgear escapement (%)	
	hf = 1.0	*hf* = 0.0	*hf* = 1.0	*hf* = 0.0	*hf* = 1.0	*hf* = 0.0	*hf* = 1.0	*hf* = 0.0
Rockhopper, day	98.4 (97.8–100)	95.9 (94.4–100)	1.6 (0.0–2.2)	0.6 (0.0–0.8)				
Rockhopper, night	93.1 (90.5–95.9)	83.6 (78.3–89.9)	6.9 (4.1–9.5)	2.7 (1.6–3.8)	5.4	12.8	76.8[a]	77.8[b]
SCSG, day	99.2 (97.9–100)	97.9 (94.6–100)	0.8 (0.0–2.1)	0.3 (0.0–0.8)				
SCSG, night	98.3 (97.1–99.4)	95.6 (92.7–98.4)	1.7 (0.6–2.9)	0.7 (0.2–1.1)	0.9	2.3	52.9[c]	57.1[d]

[a]76.8% = 100 × (6.9 − 1.6)/6.9.
[b]77.8% = 100 × (2.7 − 0.6)/2.7.
[c]52.9% = 100 × (1.7 − 0.8)/1.7.
[d]57.1% = 100 × (0.7 − 0.3)/0.7.

(2006) reported that some fish escaped under both side sections of the groundgear, indicating that the more conservative estimate for catch efficiency may be more appropriate (*hf* = 0.0). Finally, a major assumption when investigating groundgear catch efficiency is that the trawl and retainer bag are 100% effective and that no fish escape underneath the retainer bag. Thorough effort was put into investigating the performance of the retainer bag to ensure that no secondary escape occurred.

Previous studies have reported that fish escape is highly length dependent (Engås and Godø 1989; Walsh 1989, 1992; Dahm and Wienbeck 1992; Godø and Walsh 1992; Ingólfsson and Jørgensen 2006; Krag et al. 2010; Brinkhof et al. 2017). It is reasonable to assume that the overall escape rate would be considerably higher under circumstances with more abundant small fish than found in the current study. Therefore, it is important to emphasize that groundgear efficiency averaged for all length-groups above the established size limit (Table 3) is specific to the population structure encountered during a given trial period or area and should not be extrapolated to other scenarios. Furthermore, although no significant difference was detected for size-dependent groundgear catch efficiency (Figure 8), the lower confidence limit for the SCSG and the upper confidence limit for the rockhopper gear were equal for Haddock between 52 and 62 cm. More robust data (with narrower 95% CIs) and/or sampling conditions where other extrinsic factors could influence the results, such as water temperature and season, could potentially result in a statistically significant improvement in the catch efficiency for the SCSG or vice versa.

In the Barents Sea bottom trawl fishery, Atlantic Cod and Haddock are often caught simultaneously. Therefore, to conduct a comparison between the two species, the catch efficiency estimated for Haddock in this study was compared with the catch efficiency for Atlantic Cod presented by Brinkhof et al. (2017). Groundgear catch efficiency was significantly higher for Haddock than for Atlantic Cod (Figure 11). The difference was significant for fewer length-groups with the SCSG (Figure 11B) relative to the rockhopper gear (Figure 11A), which implies that groundgear catch efficiency was improved with the SCSG.

The discrepancy in groundgear catch efficiency between Atlantic Cod and Haddock (Figure 11) shows that catch efficiency is species dependent in addition to being length dependent, which accords with the findings of previous studies (Engås and Godø 1989; Ingólfsson and Jørgensen 2006; Winger et al. 2010). The observed behavioral differences from the underwater recordings (Figure 5) confirm the differences between Atlantic Cod and Haddock as described by the estimated groundgear efficiency curves (Figure 11) and are supported by previous studies (Engås and Ona 1990; Wardle 1993; Winger et al. 2010).

The improved efficiency (i.e., reduced levels of escape) with the SCSG compared to the rockhopper gear can be explained by two factors. First, the design of the SCSG does not allow for any escape between the elements of the gear (a distance of just 8 cm between elements; Figure 2), in contrast to what often is observed with the rockhopper gear, where fish escape between the discs. The only space where fish can escape in the SCSG is underneath the elements themselves and through the two openings between the section quarters of the groundgear. Furthermore, the water flow and hydrodynamic forces around the two gear types differ. It is possible that the rockhopper gear allows a relatively high flow of water between the discs, which have large spaces between them.

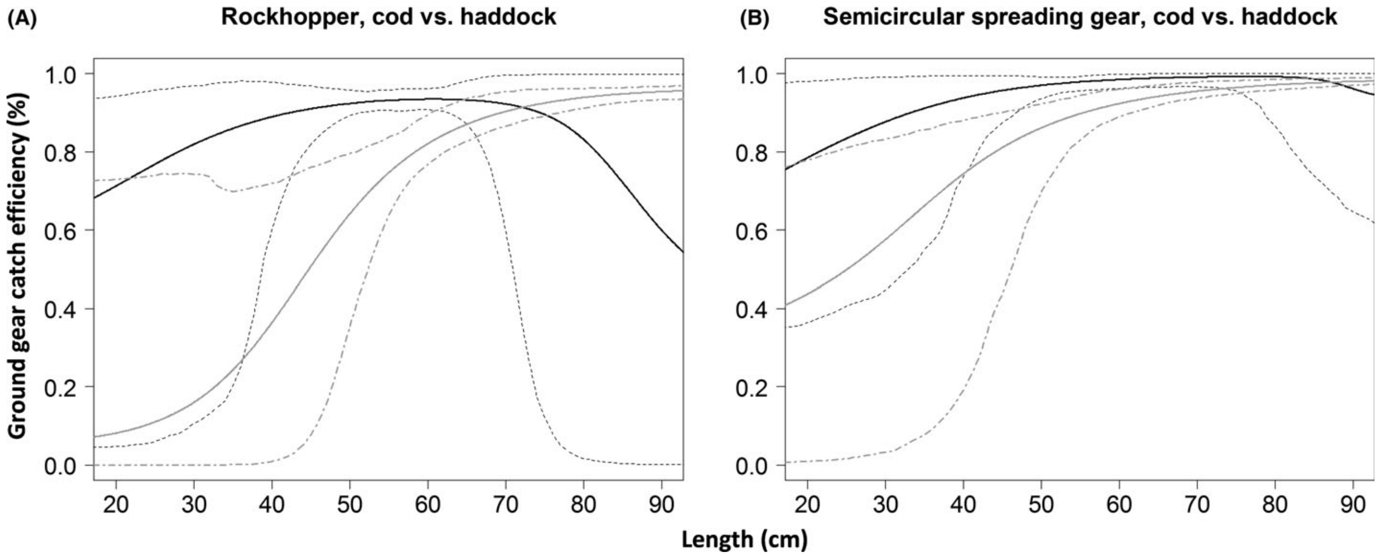

FIGURE 11. Comparison of groundgear catch efficiency for Haddock (black solid curve) and Atlantic Cod (gray solid curve) in hauls conducted with the **(A)** rockhopper gear and **(B)** semicircular spreading gear. Dashed curves represent the 95% confidence intervals.

The drag and turbulence behind the rockhopper gear were clearly visible on underwater recordings as large mud clouds directly behind the groundgear. In contrast, the design of the SCSG reduces water flow between the elements, and water is pushed either over or under the elements. The mud clouds observed behind the SCSG appeared to be much smaller than those observed with the rockhopper gear. We believe that a substantial fraction of the water is directed into the trawl mouth with the SCSG, which enables fish to enter over the groundgear and fishing line more easily than for the rockhopper gear. Another factor that could contribute to the difference in the size of the mud clouds is the heavier weight of the rockhopper gear. Accounting for the specific gravity/density of the different materials in water, the weight of the SCSG is only 30% of the rockhopper gear's weight and is thought to have a reduced impact on the seabed. The underwater video recordings also show that after passing obstacles, such as rocks, the SCSG re-establishes seabed contact faster than the rockhopper gear.

Ingólfsson and Jørgensen (2006) reported a high incidence of external and internal injuries to fish that were overrun by the rockhopper gear. The fate of injured escapees is not known, but it is generally believed that there will be some mortality due to behavioral impairment, increased risk of predation, and disease susceptibility caused by contact with the groundgear (Chopin and Arimoto 1995; Ryer 2004). It would therefore be beneficial for fishery management to limit the loss of Haddock below the fishing line during the capture process, thereby reducing potential mortality. In addition to the significant improvement in catch efficiency provided by the SCSG, the lighter SCSG likely results in less bottom friction, which could lead to reduced fuel consumption and subsequent reductions in CO_2 and NO_x emissions. Hence, the introduction of the SCSG should be of interest to the fishing industry due to increased catch per unit time, potential reduction in fuel consumption, and reduced seabed impact.

ACKNOWLEDGMENTS

We thank the Arctic University of Norway, the Norwegian Directorate of Fisheries, and the Research Council of Norway (Project Number 216423/O70) for assistance in providing necessary permits and financial support. We appreciate the two anonymous reviewers whose valuable comments improved the manuscript considerably. We are also grateful to the crew of the R/V *Helmer Hanssen* for their valuable help during the sea trials. Roger B. Larsen, Bent Herrmann, and Jesse Brinkhof contributed equally to this work. There is no conflict of interest declared in this article.

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Appendix: Derivation of the Relationship between Groundgear Catch Efficiency and Observed Catch Comparison Rate

Here, we describe how equation (2) (i.e., the relationship between the groundgear catch efficiency and the experimental observed catch comparison rate) was derived. Because the retainer bag covered only the center zone of the groundgear (Figure 4), it did not necessarily catch all of the fish that escaped underneath the groundgear. Specifically, it only collected the fish that escaped underneath the fishing line in the center part of the groundgear.

The experimental observed catch comparison rate R_l for a Haddock in length-class l between the cod end catch nc_l and the catch in retainer bag nr_l in terms of the number of Haddock is quantified by equation (1). However, instead of being interested in R_l, we are interested in the total catch comparison, RT_l, which would account for the fact that the retainer bag did not sample all fish escaping underneath the fishing line. Assuming that the retainer bag sampled fraction q of the total number of fish escaping underneath the fishing line, the experimental RT_l can be expressed as (from Brinkhof et al. 2017)

$$\mathrm{RT}_l = \frac{nc_l}{nc_l + \frac{nr_l}{q}}. \tag{A.1}$$

Combining equations (1) and (A.1) yields

$$\mathrm{RT}_l = \frac{q \times R_l}{q \times R_l + (1.0 - R_l)}. \tag{A.2}$$

Based on equation (1), we can obtain R_l from the experimental data; based on equation (A.2), we can use R_l to obtain RT_l. However, we need an estimate for the retainer bag sampling fraction q. Based on geometrical consideration using Figure 4, we developed the following formula for determining q (see Brinkhof et al. 2017 for details):

$$\begin{aligned} q &= \frac{\mathrm{WC} + (\mathrm{WT} - \mathrm{WC}) \times hf}{\mathrm{WT}} \\ &= \frac{5.5 + (14.5 - 5.5) \times hf}{14.5} \approx 0.3793 + 0.6207 \times hf, \end{aligned} \tag{A.3}$$

where *hf* is the assumed size-independent herding coefficient, which quantifies the fraction of fish that enter the zone of the fishing line outside the center part (area covered by the retainer bag [WC]) but that first make contact with the fishing line after being herded into the center part (WT = area covered by the groundgear of the trawl). Thus, *hf* is constrained to the interval 0.0–1.0. A value of 0.0 would mean that there is no herding effect toward the center part in the groundgear zone. A value of 1.0 would mean that no fish escape underneath the fishing line outside the center zone.

From Brinkhof et al. (2017), it follows that the groundgear catch efficiency can be approximated directly by RT_l for sizes of Haddock above which size selection can occur in the trawl body. Therefore, we have the following functional description after using equations (A.2) and (A.3),

$$\begin{aligned} GG(l) \approx RT(l) &= \frac{q \times R(l)}{q \times R(l) + [1.0 - R(l)]} \\ &= \frac{(0.3793 + 0.6207 \times hf) \times R(l)}{(0.3793 + 0.6207 \times hf) \times R(l) + [1.0 - R(l)]} \\ &= \frac{hf + 0.61}{1.61 - (1.0 - hf) \times R(l)} \times R(l), \end{aligned} \quad (A.4)$$

which is identical to equation (2).