Fisheries Research 167 (2015) 164–173

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Effect of lifting the sweeps on bottom trawling catch efficiency: A study based on the Northeast arctic cod (*Gadus morhua*) trawl fishery

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ARTICLE INFO

Article history:
Received 23 April 2014
Received in revised form 31 October 2014
Accepted 30 January 2015
Handling Editor P. He

Keywords:
Catch efficiency
Demersal trawl fishery
Herding
Sweeps
Cod
Catch comparison

ABSTRACT

Fuel consumption and environmental concerns have led bottom trawlers fishing for cod (*Gadus morhua*) in the Barents Sea to use semi-pelagic doors. However, this change may affect fish herding and consequently the catch efficiency of the gear. In this study we compared the catch efficiency of two different setups where the sweep length with bottom contact was different. This setup also enabled us to estimate the herding efficiency of the sweeps on the seabed. The data for this study were collected using the alternate haul method and analyzed using a new method for unpaired data. We estimated that the setup with the lifted sweeps captured on average 33% fewer cod than the setup that kept the sweeps at the seabed. The loss of catch for cod was length independent and significant for a length span between 41 and 104 cm. When sweeps were lifted above the seabed, herding was negatively impacted and fish were lost; in contrast, when on the seabed, the sweeps were able to herd (on average) 45% of the cod into the catch zone of the gear. Lifting the trawl doors from the seabed is touted as a positive development for this fishery. However, our results show that lifting the doors and consequently the sweeps can lead to substantial catch losses. Finally, the study highlights the importance of carefully evaluating the positive and negative potential consequences of introducing changes in a fishing gear.

1. Introduction

In trawl fisheries, fish herding is associated with three components of the trawl gear: the trawl doors, the sweeps, and the ground gear (Winger et al., 2010). The doors and sweeps are the first parts of the gear to interact with the fish. The doors spread the gear and the sweeps connect the doors to the trawl, and they also herd the fish towards the trawl mouth. Once in the trawl mouth, species like cod (*Gadus morhua*) and other gadoids swim in the trawl direction until they cannot keep up with the trawl speed and then fall back into the trawl net. Other species can react differently and swim in different directions in the trawl mouth area. When the fish pass the trawls mouth area and enter the trawl net, they are further gathered until they are finally collected in the codend.

In practically every otter trawl design used to fish cod in the Barents Sea, the distance between the doors is substantially greater than the distance between the lower wings of the trawl (from ∼3 to ∼7 times greater depending on the type of doors used and factors such as the fishing depth, trawling speed, etc.) (Engås and Godø, 1986; Jørgensen et al., 2006). Thus, sweeps are thought to play a key role in the herding process, as they are designed to keep target fish within the trawl path (Winger et al., 2010). The herding properties of the sweeps may be of particular importance when fishing with semi-pelagic doors, as the lack of contact between the doors and the seabed means that no sand cloud is created by the sweep section to contribute to the herding. The position of the target species in the water column with regard to the doors and sweeps also is a factor in herding efficiency. Bottom sweeps, for example, are known to be very effective for herding benthic species such as skates and flatfish (Ryer, 2008). Several researchers have documented how the herding ability of the sweeps varies depending of their length, their angle with respect to the towing direction, and the towing speed (e.g., Strange, 1984; Engås and Godø, 1989; Winger et al., 1999). For a given angle, a larger area is swept as the length of the sweeps increases. Increasing the angle with respect to the towing direction and increasing the towing speed also increase the area swept per unit of time. However, because the swimming ability or endurance of different fish species and different sizes of the same species can differ (Beamish, 1966; He, 1991; Videler, 1993; Winger et al., 1999),

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http://dx.doi.org/10.1016/j.fishres.2015.01.015
0165-7836/

increasing the area swept does not necessarily increase the amount of fish herded into the catch zone of the trawl. Increasing the sweep angle and the towing speed can result in lowered efficiency because the herded fish fail to keep up the pace and fall back over the sweeps before they reach the catch zone of the net (the area between the lower wings of the trawl).

Although efficient pelagic and semi-pelagic fisheries exist, trawling for cod has traditionally been carried out using bottom trawls. In recent years, however, bottom trawling has become increasingly controversial due to the large volume of diesel consumed per kilo of fish harvested (Ziegler and Hansson, 2003; Schau et al., 2009) and the seabed impact of the ground gear, sweeps, and bottom trawl doors (Jones, 1992; Løkkeborg, 2005; Valdemarsen et al., 2007). In addition to these environmental concerns, the high price of diesel has made it increasingly difficult for trawl vessel owners to make a profit from their quotas. Thus, modern trawlers have started to consider alternative trawl gear to target benthic species. In Norway, 30 vessels of over 40 m of total length fish cod with bottom trawls (Norwegian Fisheries Directorate, 2013). By the beginning of 2013, at least seven of these trawlers fished permanently and three fished partially using semi-pelagic trawl doors, which are more fuel efficient than standard bottom-tending gear. When semi-pelagic trawl doors are used, sweeps can be lifted (at least partially) off the seabed. Especially in harsh sea conditions, the skipper might have difficulties keeping the doors at a constant position in the water column. Lifting the doors and sweeps from the seabed would have direct consequences on herding, but the potential loss in catch efficiency of the gear due to loss in herding efficiency is poorly documented. Thus, in this study we investigated whether there is a loss in catch efficiency for cod when the sweeps are partially lifted from the seabed.

The reaction of a roundfish individual to an approaching trawl door and the subsequent parts of the trawl gear has been studied and thoroughly described by several authors in recent decades (Hall et al., 1986; Wardle, 1993; Winger et al., 2010). Furthermore, several studies have evaluated changes in the fishing efficiency of trawl gear when the properties of the individual components of the gear are altered. When fishing with semi-pelagic trawls doors, there is a built-in risk of lifting the sweeps from the seabed due to lack of control of the position of the doors in the water column. Although the effect of changing the sweep angle and length of trawl gear has been evaluated in previous studies (Engås and Godø, 1989; Strange, 1984), to our knowledge the difference in catch efficiency created by lifting the sweeps from the seabed has not been documented.

In the present study, we compared two nearly identical trawl setups using semi-pelagic doors. The aim of the study was to quantify the potential loss in fishing efficiency by lifting part of the sweeps from the seabed, which simulates a semi-pelagic trawling scenario with lack of control over the position of the doors in the water column. In addition, we estimated herding efficiency based on the geometrical parameters of the trawl and the catch rates. We used a newly developed method to analyze unpaired data collected with the alternate haul method (see Wileman et al. (1996) for further information on the alternate haul method).

2. Materials and methods

2.1. Gear and data collection

The data included in this study were collected onboard the R/V Helmer Hanssen (63.8 LOA and 4080 HP) from 9–24 November, 2013. The trials were carried out in the Barents Sea in the fishing grounds off the Hopen Island (N 75°05′–74°36′ and E 32°09′–31°14′). In this period of the year there is barely any daylight at this latitude as the sun does not rise over the horizon. Thus, the trials were carried out almost in total darkness. The starting setup (length of the sweeps, etc.) was chosen based on earlier experience with the gear and a preliminary test carried out with the gear in March 2013. The gear used consisted of a pair of Injector XF9 (6.5 m^2 and 2200 kg each) high aspect ratio semi-pelagic doors, 15.9 m backstrops, 3 m backstrop extensions, 30 + 45 m steel sweeps (30 mm diameter), and an Alfredo n°3 trawl (Fig. 1). The trawl was built entirely of 80 mm meshes constructed of 3 mm PE twine (the solidity of the trawl was the same as that of the commercial version of the trawl) and had a headline of 36.5 m and a fishing line of 19.2 m. A 130 mm mesh size (nominal) codend was attached to the extension piece in the aft part of the trawl. The codend was made of 8 mm PE twine (Polar Gold), was 70 meshes long and 70 meshes around, and was entirely blinded with a 12 m long inner-net (160 meshes around) constructed of 52 mm meshes. The 46 m ground gear was composed of 8 steel bobbins of 21″ and an 18 m (3 × 6 m sections) rockhopper constructed of 21″ rubber discs. We used a 19 mm chain for the whole ground gear section except for the section between the last two bobbins before the rockhopper; the chain in that section had a diameter of 32 mm. To avoid the trawl losing contact with the seabed, an 8 m chain piece (38 mm) weighing 210 kg was attached to the 32 mm chain section on each side of the ground gear (part “e” in Fig. 1). Between the sweeps and between the sweeps and the trawl gear we inserted 4 m of 19 mm chains with two locks that allowed us to attach the two 450 kg clumps used during the experiments (Fig. 1). The clumps were composed of 16 m steel chains (35 mm in diameter) that were linked together to act as a weight pushing the sweeps towards the seabed where it was placed. The clump position closest to the trawl was defined as setup 1 and the clump position closest to the trawl doors was defined as setup 2. During the trawling, we alternated setup 1 and setup 2 (Table 1).

We used two sets of distance sensors, a set of door sounders, a trawl height sensor, and a catch sensor to monitor the gear. The two sets of distance sensors (Marport MFX, Marport deep sea technologies Inc., Iceland) operated at 110 and 144 kHz, so there was no interference between their signals. The sensors were placed at the doors and the lower wings because the distance at these two points was considered most important for estimating the bridle geometry of the trawl. Because the door and wing distances were important for the study and the Marport sensors were relatively new, their readings were checked using a set of similar Scanmar sensors (Scanmar AS, Norway). The Marport door sounders were placed at the doors and just underneath the distance sensors (close to the midpoint of the doors). These sounders were used to determine the height of the doors over the seabed. If necessary, the height was adjusted changing the warp length. Good control of the height of the doors over the seabed was key to ensuring that the two different setups were working as planned. A trawl height sensor (Scanmar HC4-HT60) was placed in the center of the headline of the trawl to monitor headline height and ensure standard operating values were maintained (between 4 and 6 m), implying constant contact between the rockhopper gear and the seabed. Finally, the Scanmar SS4 catch sensor was placed 20 meshes from the codline and was used to make sure the catches during the trials were restricted. We wanted the towing duration to be as long as possible so that the potential differences in herding between the two setups would be as large as possible, but within restricted catches up to 3 tons/tow due to the limited fish processing capacity at the research vessel. We tried to keep the towing time for contiguous hauls conducted using the two different setups as similar as possible. The aim was that the overall towed times for each of the setups during the cruise were as similar as possible. Using the data from the different sensors, we manually registered the distance between the doors, the distance between the lower wings of the trawl, the height of the doors over the seabed, water temperature at depth (registered from

Table 1
Operational data for the 32 hauls conducted during the sea trials. Trawl time represents the time the trawl was at the seabed. Depth, catch rate, catch size, wind speed and sampling factor for each haul are also provided. The door distance, wing distance, door distance over the seabed and the headline height represent the geometry of the trawl in each haul. Finally, the temperature at depth is shown for each tow. For these parameters both the mean and standard deviation values are provided.

Haul Nr.	Trawl time	Depth (m)	Wind speed (m/s)	Lodd position	Fish measured	Sampling factor	Catch size (kg)	Door dist. (m)		Wing dist. (m)		Door dist. over seabed (m)		Headline height (m)		T (°C)	
								Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
6	59	272.3	11.4	Setup 1	89	0.49	373.0	99.75	26.39	15.2	0.47	9.5	1.9	5.34	0.35	0.83	0.36
7	61	273.4	11.8	Setup 2	263	0.51	1065.9	132.37	36.27	16.2	0.57	5.7	1.3	4.85	0.60	0.26	0.05
8	62	272.5	13.7	Setup 2	315	0.52	1317.0	106.65	29.48	18.0	9.40	5.9	1.9	5.48	0.43	0.23	0.08
9	60	276.6	11.3	Setup 1	257	0.50	990.6	109.92	31.34	15.6	0.53	9.7	2.5	5.54	0.43	0.45	0.08
10	65	271.6	12.0	Setup 1	226	0.54	922.6	121.39	42.35	16.4	8.51	9.2	4.4	5.03	2.88	0.50	0.27
11	62	284.5	12.2	Setup 2	564	0.52	2219.5	106.63	48.86	15.6	8.34	6.7	3.52	5.21	2.56	0.32	0.28
12	45	280.1	12.3	Setup 2	321	0.38	1162.4	123.53	36.74	16.2	0.59	5.5	0.725	5.37	0.81	0.43	0.12
13	46	283.0	11.3	Setup 1	258	0.38	990.3	120.54	33.30	16.1	0.82	11.0	3.41	–	–	0.34	0.08
14	93	281.3	14.4	Setup 1	206	0.78	715.4	133.1	34.30	16.9	0.36	9.0	3.618	4.64	0.48	0.64	0.05
15	89	261.0	9.5	Setup 2	731	0.74	2647.9	122.27	34.15	16.2	0.29	6.1	2.818	4.88	0.29	0.77	0.15
16	88	261.1	13.5	Setup 2	478	0.73	1703.3	121.16	31.89	16.28	0.71	5.37	0.977	5.46	0.80	0.64	0.07
17	88	263.1	10.7	Setup 1	477	0.73	1630.7	106.63	27.68	15.45	0.73	10.92	1.929	5.45	0.47	0.93	0.20
18	93	262.0	6.1	Setup 1	458	0.78	1524.6	124.3	32.89	15.93	1.76	11.37	3.949	5.27	0.64	0.99	0.22
19	93	278.5	2.8	Setup 2	521	0.78	1789.1	118.53	36.40	16.7	1.66	5.2	0.845	4.89	0.34	0.64	0.25
20	90	258.2	3.3	Setup 2	573	0.75	1902.3	106.65	32.35	16.25	0.92	5.71	1.585	5.08	0.31	0.80	0.04
21	92	276.4	12.5	Setup 1	485	0.77	1608.7	122.58	29.97	16.37	0.68	8.29	2.961	5.18	0.47	1.12	0.67
24	74	269.8	4.5	Setup 2	533	0.62	1718.8	110.99	29.40	15.96	0.59	5.16	0.0	5.38	0.43	0.95	0.04
25	90	282.0	4.0	Setup 1	329	0.75	1157.8	109.44	29.58	15.68	0.63	11.37	2.34	5.63	0.29	0.96	0.05
26	90	269.0	2.4	Setup 1	480	0.75	1650.8	95.67	24.68	15.67	1.06	12.82	3.3	5.67	0.24	1.00	0.00
27	90	289.4	6.5	Setup 2	340	0.75	1094.3	119.05	28.78	16	0.61	6.2	2.0	5.52	0.32	0.97	0.00
28	91	279.1	4.0	Setup 2	398	0.76	1157.5	105.04	24.69	15.63	0.53	5.32	0.5	5.39	0.33	1.00	0.07
29	97	279.6	13.7	Setup 1	186	0.81	517.9	143.48	32.71	16.75	0.55	13	4.4	5.47	0.30	0.90	0.05
32	59	275.7	6.6	Setup 2	353	0.49	1211.5	121.72	32.49	16.27	0.26	6	1.4	—	—	0.80	0.00
33	61	272.2	12.5	Setup 1	322	0.51	1137.5	114.53	24.47	15.8	0.40	11.47	4.2	5.49	0.48	1.76	0.35
34	75	259.1	8.9	Setup 1	208	0.63	730.1	138.26	32.00	16.42	0.66	15.19	3.2	5.42	0.49	1.23	0.12
35	60	272.7	11.8	Setup 2	642	0.50	2336.9	105.93	25.63	16.04	0.51	5.43	0.8	5.19	0.27	1.00	0.00
36	44	263.4	6.8	Setup 2	359	0.37	1346.0	121.63	30.30	16.14	0.45	6.89	1.7	4.88	0.33	1.00	0.00
37	47	276.4	4.7	Setup 1	443	0.39	1714.7	110.33	23.98	15.82	0.57	13.35	4.6	5.76	0.52	1.50	0.00
38	62	264.6	2.9	Setup 1	152	0.52	602.7	130.77	27.05	16.47	0.50	13.12	2.4	5.46	0.28	1.36	0.09
39	41	272.9	17.7	Setup 2	520	0.34	1966.7	121.19	28.07	15.78	0.39	6.73	2.3	5.24	0.34	1.50	0.00
40	43	302.4	18.5	Setup 2	371	0.36	1452.8	127.35	31.17	16.22	0.80	5.5	0.7	4.77	0.67	1.80	0.00
41	85	271.4	18.1	Setup 1	919	0.71	3486.1	102.08	21.75	16.58	1.68	7.6	2.9	5.42	0.38	—	—

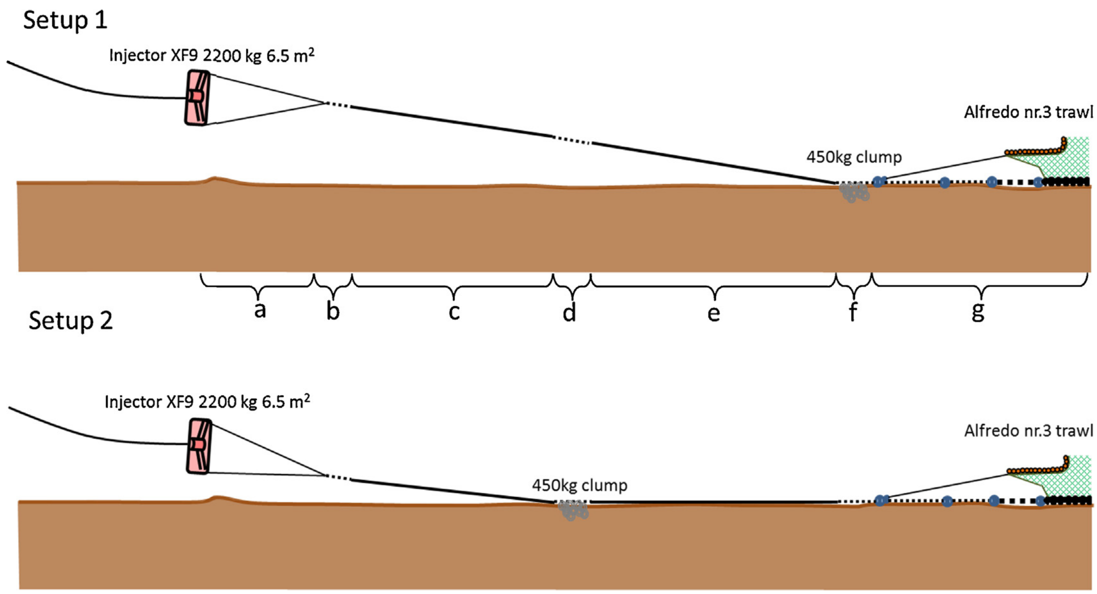

Fig. 1. Schematic view of the gear used during the sea trials. (a) 15.9 m backstrop, (b) 3 m backstrop extension, (c) 30 m of 30 mm sweep, (d) 4 m of 19 mm chain (attaching position for the clumps), (e) 45 m of 30 mm sweeps, (f) 4 m of 19 mm chain (attaching position for the clumps), (g) 45 m of ground gear composed of 19 mm chain (32 mm chain closest to the rockhopper), and the rockhopper.

the Marport MFX sensor), trawl height, water depth (registered from the echo sounder of the vessel), and towing time every fifth minute during trawling.

Once the catch came onboard the vessel, the total length of all cod above 30 cm in length were measured to the nearest centimeter.

2.2. Data analysis

All the data analyses carried out in this study were performed using the software SELNET (Sistiaga et al., 2010; Eigaard et al., 2011; Frandsen et al., 2011; Herrmann et al., 2012).

2.2.1. Catch comparison

We used a catch comparison analysis developed at Krag et al. (2014) to estimate the relative change in length-dependent catch efficiency as we were interested in estimating the mean difference in catch rates between the two setups over all hauls. These values provided information about how catch efficiency varied on average when using setup 1 compared to setup 2 in the fishery. We assumed that the relative catch performance for the groups of hauls conducted with each setup was representative of how these setups would perform in the commercial fishery. In the experimental procedure, setups 1 and 2 were alternated, meaning that the catch data for the two setups were not collected concurrently. Hence, to estimate the functional form of the average catch comparison rate (the experimental being expressed by Eq. (2)) between setups 1 and 2, the raised length frequency data from the hauls conducted using setup 1 were combined and compared with the combined data from the hauls conducted using setup 2 by minimizing the following equation:

$$-\sum_{l}\left\{\frac{1}{a}\sum_{i=1}^{a}\left\{\frac{n1_{li}}{q1_{li}}\right\}\times\ln(CC(l,\boldsymbol{v}))+\frac{1}{b}\sum_{j=1}^{b}\left\{\frac{n2_{lj}}{q2_{lj}}\right\}\times\ln(1.0-CC(l,\boldsymbol{v}))\right\} \tag{1}$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l, \boldsymbol{v})$, $n1_{li}$ and $n2_{lj}$ are the number of fish measured in each length class l, and $q1_{li}$, and $q2_{lj}$ are the fraction of fish measured with respect to the total number of fish in the codend (sampling factor) for each length class, respectively, for setups 1 and 2. All hauls were standardized to have the same towing time as the haul with the longest duration. For example, for a haul with a towing time that was half that of the haul with the longest towing time and for which 25% of the cod in the codend were measured, the sampling factor would be calculated as $0.25 \times 0.5 = 0.125$. The standardization procedure was carried out to compensate for differences in catch size caused by differences in towing time. Without this standardization, the assessment of the catch comparison would be biased. In Eq. (1), a and b are the number of hauls conducted with setups 1 and 2, respectively, and the inner summations in the equation represent the summations of the data from these hauls. The outer summation in Eq. (1) is the summation over the length classes (l).

The experimental averaged catch comparison rate, CC_l, where l denotes the fish length, is given by:

$$CC_l=\frac{\frac{1}{a}\sum_{i=1}^{a}\left\{\frac{n1_{li}}{q1_{li}}\right\}}{\frac{1}{a}\sum_{i=1}^{a}\left\{\frac{n1_{li}}{q1_{li}}\right\}+\frac{1}{b}\sum_{j=1}^{b}\left\{\frac{n2_{lj}}{q2_{lj}}\right\}} \tag{2}$$

The experimental CC_l is often modeled by the function $CC(l)$, which has the following form (Krag et al., 2014):

$$CC(l,\boldsymbol{v})=\frac{\exp(f(l,q_0\ldots q_k))}{1+\exp(f(l,q_0\ldots q_k))} \tag{3}$$

where f is a polynomial of order k with coefficients q_0 to q_k so $\boldsymbol{v} = (q_0, \ldots, q_k)$. Thus, $CC(l, \boldsymbol{v})$ expresses the probability of finding a fish of length l in the gear when fished with setup 1 given that it is found when fished with one of the two setups. A value of 0.5 for $CC(l, \boldsymbol{v})$ would mean that the likelihood of finding a fish of length l in any of the two setups is equal, implying that changing from one setup to the other would not have any effect on the catch efficiency. The values of the parameters $\boldsymbol{v}$ describing $CC(l, \boldsymbol{v})$ are estimated by minimizing Eq. (1). We considered f up to an order of 4 with parameters q_0, q_1, q_2, q_3, and q_4. Leaving out one or more of the parameters $q_1 \ldots q_4$ led to 31 additional models that were also considered as potential models for the catch comparison $CC(l, \boldsymbol{v})$ between the two riggings of the gear. Selection of the best model for $CC(l, \boldsymbol{v})$ among the 32 competing models was based on a comparison of the Akaike

Information Criterion AIC values for the models. The model with the lowest AIC value was selected (Akaike, 1974). We restricted the analysis to length classes for which the total number of estimated cod captured for both setups was at least 20 (starting at the lowest and highest length classes where 20 individuals were present).

To test the goodness of fit of the model describing the data, we calculated the model deviance, D, as follows:

$$D = 2 \times \operatorname{sign}(y_l - ym_l) \times \sum_l \left\{ nt_l \times \ln\left(\frac{y_l}{ym_l}\right) + nc_l \times \ln\left(\frac{1-y_l}{1-ym_l}\right) \right\} \tag{4}$$

where

$$\begin{aligned} y_l &= \frac{n1_l}{n1_l + n2_l} \\ ym_l &= \frac{q1_l \times CC(l,\boldsymbol{v})}{q1_l \times CC(l,\boldsymbol{v}) + q2_l \times (1 - CC(l,\boldsymbol{v}))} \\ n1_l &= \sum\nolimits_{i=1}^{a} n1_{li} \\ n2_l &= \sum\nolimits_{j=1}^{b} n2_{lj} \\ q1_l &= \frac{n1_l}{\sum_{a}^{i=1}\left\{\frac{n1_{li}}{q1_{li}}\right\}} \\ q2_l &= \frac{nc_l}{\sum_{b}^{j=1}\left\{\frac{n2_{lj}}{q2_{lj}}\right\}} \end{aligned} \tag{5}$$

The selected model's ability to describe the experimental data was based on the p-value, which was calculated based on the model deviance and the degrees of freedom (Wileman et al., 1996).

The confidence limits for the catch comparison curve were estimated using a double bootstrapping method. The procedure accounted for between-haul variation by selecting a hauls with replacement from the pool of hauls carried out with setup 1 and b hauls with replacement from the pool of hauls carried out with setup 2 during each bootstrap loop. Within-haul variability was accounted for by randomly selecting fish with replacement from each of the selected hauls. The number of fish selected from each haul was the same as the number sampled in that haul. These data were then raised and combined as described above, and the catch comparison curve was estimated. We performed 10,000 bootstrap iterations to estimate 95% confidence limits for the catch comparison curve (Efron, 1982). We accounted for additional uncertainty due to model selection by incorporating an automatic model choice based on the lowest AIC model into each of bootstrap iteration.

2.2.2. Catch ratio

We could not use the catch comparison rate $CC(l, \boldsymbol{v})$ to quantify directly the ratio between the catch efficiencies for a fish of length l when using setup 1 compared to setup 2. Instead, we used the catch ratio $CR(l, \boldsymbol{v})$. For the experimental data, the average catch ratio is written as follows:

$$CR_l = \frac{\frac{1}{a}\sum_{i=1}^{a}\left\{\frac{n1_{li}}{q1_{li}}\right\}}{\frac{1}{b}\sum_{j=1}^{b}\left\{\frac{n2_{lj}}{q2_{lj}}\right\}} \tag{6}$$

Simple mathematical manipulation yields the following general relationship between catch ratio and catch comparison:

$$CR_l = \frac{CC_l}{1 - CC_l} \tag{7}$$

and the same relationship exists for the functional form:

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{1 - CC(l,\boldsymbol{v})} \tag{8}$$

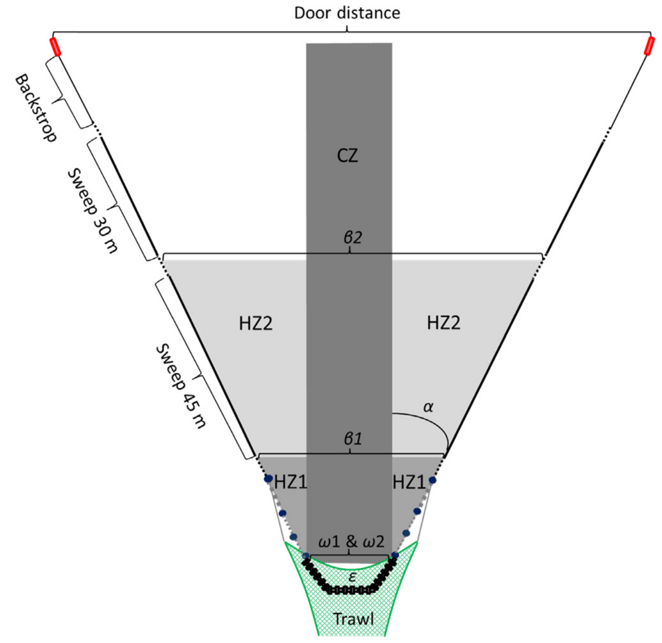

Fig. 2. Illustration of the different geometrical parameters used to evaluate the herding efficiency of the trawl. The darkest gray zone represents the catch zone (CZ), whereas the two lighter gray zones represent the herding zone for setup 1 (HZ1) and for setup 2 (HZ2) (Note that HZ2 is included in HZ1). $\beta1$ is the distance between the clumps when fishing with setup 1; $\beta2$ is the distance between the clumps when fishing with setup 2; ω is the distance between the lower wings of the trawl, which determines the CZ of the trawl and was identical for both setups (therefore the subscript is omitted); ε represents the probability for a fish to escape below the rockhopper gears; and α is the sweep angle of the trawl.

Using Eq. (8) and incorporating the calculation of $CR(l, \boldsymbol{v})$ based on $CC(l, \boldsymbol{v})$ for each relevant length class into the double bootstrap procedure described for the catch comparison rate, we estimated the confidence limits for the catch ratio. This procedure directly quantifies the relative effect of using setup 1 versus setup 2 on the length-dependent gear catch efficiency. A value of 1.0 for $CR(l, \boldsymbol{v})$ would indicate that there is no difference in catch efficiency between setups 1 and 2. On the other hand, a value of 0.75 would indicate that setup 1 catches only 75% of the number of fish caught with setup 2. Thus, $CR(l, \boldsymbol{v})$ gives a direct relative quantification of the catch efficiency of using setup 1 compared to setup 2.

2.2.3. Herding efficiency

While we can assume that the fish in the path of the ground gear are available to the trawl net (meaning that they will interact with the trawl net), the fish outside this area need to be herded into the trawl net path, or catch zone, so that that they become available to the trawl net. In an area characterized by small variations in fishing conditions and where fish can move freely (i.e., uninfluenced by the gear), the number of fish available for the gear is assumed to be uniform when summing over time. Herding efficiency is defined as the ratio between the fish available in the herding zone and the fish that actually become available to the trawl net. Thus, depending on the herding efficiency of the gear, more or fewer fish would move from the herding zone into the catch zone. We assume that the components of a trawl gear between the doors and the trawl net that have seabed contact have a herding effect on cod, and we define this area as the cod herding zone (Fig. 2). Because the doors and the sweeps (up to the clumps) were maintained in the water column and we were fishing cod at the seabed, we assumed that the herding effect of the portion of the gear in the water column to the clumps was negligible. Thus, the cod herding zones for the two setups were assumed to be the area from the clump at the seabed to the lower wings of the trawl net (edges of the rockhopper) (see Fig. 2). The extent to which the fish in the herding zone move into the catch zone basically depends on the herding efficiency of the sweeps. If the herding efficiency was 0, no fish would move from the herding zone into the catch zone, whereas if the herding efficiency was 1, all of the fish in the herding zone would move from the herding zone into the catch zone.

To estimate the herding efficiency of the gear tested in this study, we used the differences in catch (catch ratio $CR(l, \boldsymbol{v})$) between setups 1 and 2 (Fig. 1). Because the towing speed, sweep angle (α), and gear were identical in both setups, the herding efficiency in both situations should be the same when fishing a similar population of fish. However, because the clumps were placed at different points along the sweeps, the cod herding zone differed between setups 1 and 2. Thus, we were able to estimate the herding efficiency by comparing the catches between the two tested setups.

We define herding efficiency ($hf(l)$) as the proportion of fish in the herding zone that ends up in the catch zone. We developed a model that can estimate $hf(l)$ based on the geometrical characteristics of the gear and the differences in the catches between two different setups of the gear ($CR(l, \boldsymbol{v})$). The model considers the differences in the horizontal distance swept with the sweeps between setups 1 and 2 ($\beta1$ and $\beta2$), the potential differences in the lower wing distance ($\omega1$ and $\omega2$), the densities of fish ($\rho(l)$) for the two setups, and the probability that a fish in front of the gear will be able to escape below the gear ($\varepsilon(l)$) in both cases (Fig. 2). The expected average catches ($n1(l)$ and $n2(l)$) with the two different setups can be modeled using the following equations:

$$\begin{aligned} n1(l) &= (1-\varepsilon(l)) \times \rho(l) \times (\omega1 + (\beta1 - \omega1) \times hf(l)) \\ n2(l) &= (1-\varepsilon(l)) \times \rho(l) \times (\omega2 + (\beta2 - \omega2) \times hf(l)) \end{aligned} \tag{9}$$

By using the definition of the catch ratio (Eq. (6)), we can express this as:

$$CR(l) = \frac{(1-\varepsilon(l)) \times \rho(l) \times (\omega1 + (\beta1 - \omega1) \times hf(l))}{(1-\varepsilon(l)) \times \rho(l) \times (\omega2 + (\beta2 - \omega2) \times hf(l))} \tag{10}$$

If we then isolate the term $hf(l)$, we obtain the following equation for the herding efficiency:

$$hf(l) = \frac{CR(l) \times \omega2 - \omega1}{\beta1 - \omega1 - CR(l) \times \beta2 + CR(l) \times \omega2} \tag{11}$$

The terms $\varepsilon(l)$ and $\rho(l)$ disappear because the probability that a fish can escape under the trawl gear and the density of fish are considered to be the same for setups 1 and 2.

The confidence limits for the herding efficiency were estimated using the same bootstrap procedure as for the catch comparison and catch ratio procedures.

2.2.4. *Predictions of catch loss due to sweep lifting*

Using the average geometrical values of the trawl and the catch size distributions obtained with setups 1 and 2, we were able to estimate the herding efficiency of the sweeps (Eq. (11)). As all of the parameters (e.g., sweep angle, trawling speed, etc.) in setups 1 and 2 were constant except for the sweep length, we can assume that $CR(l)$ varies depending on the difference in the length of the sweep that is in contact with the seabed between the two setups. The length of sweeps with seabed contact in each setup is determined by the position of the clumps. We define clump factor (CF) as the ratio between β and ω, which gives an indication of the position of the clumps or sweep length with seabed contact. Thus, if the clumps are located at the lower wing ends of the trawl, β and ω would be equal and CF would be equal to 1.

$$CF1 = \frac{\beta1}{\omega1} \quad \text{and} \quad CF2 = \frac{\beta2}{\omega2} \tag{12}$$

Based on Eqs. (11) and (12), catch ratio can be expressed as follows:

$$CR(l) = \frac{\omega1}{\omega2} \times \frac{1 + (CF1 - 1) \times hf(l)}{1 + (CF2 - 1) \times hf(l)} \tag{13}$$

In this experiment, $\omega1$ and $\omega2$ were equal and $hf(l)$ was assumed to be the same for both setups. Thus, $CR(l)$ will only vary depending on $CF1$ and $CF2$. Because $\omega1$ and $\omega2$ were equal, $CR(l)$ depends only on the positions of the clumps in the setups. As we estimated $hf(l)$ for both setups using Eq. (11) and we had the geometrical parameter values from the trawl ($\beta1$, $\beta2$, $\omega1$, and $\omega2$), we were able to predict fish loss based on the position of the clumps using (13).

3. Results

During the sea trial we collected data to evaluate the catch comparison rate, catch ratio, and herding efficiency for cod. A total of 32 successful hauls (16 pairs) were completed and 12,777 cod were measured. Hauls 1–5 we used to do some initial adjustments in the gear and to make sure all the equipment was working as expected before we started collecting the actual data. Thus, they were not included in the data analysis. An additional four hauls were not evaluated due to operational problems. Half of the hauls were collected with setup 1 and half of the hauls were collected with setup 2. The average trawling time (mean ± standard deviation) was 71.7 ± 18.7 min. The difference in the duration of the tows was a consequence of the availability of fish in the area and the processing capacity of the vessel. A constant towing speed of 3.5 kn was maintained. Small speed variations within each tow (±0.2 kn) are expected due to wind and waves. However, these small variations are normal oscillations around the average speed (3.5 kn) that would not be expected to have any effect on the overall results of the hauls.

The Marport distance sensors and the Scanmar distance sensors showed consistent results. The numbers of readings obtained with the different sensors during the cruises (Table 2) were high enough to obtain good average estimates for the average door distance, average wing distance, average distance of the door over the seabed, average headline height, and average temperature at depth. The differences in the numbers of readings represent ordinary punctual communication gaps between the sensors and the transducer of the vessel. All parameters except for average door distance to the seabed had very similar values when the clumps were in place in setup 1 or setup 2. The average door distance to the seabed differed because the skipper kept the doors higher in the water column when fishing with setup 1. The reason for this was that it was important that the sweeps were maintained up in the water column while fishing with this setup and that the clumps were the first component in the gear that had bottom contact at all. The clumps were examined after each tow to visually confirm that they had been polished by contact with the seabed.

Based on the mean geometrical dimensions recorded for the trawl during the trials (see Table 2 "All"), we calculated $\beta1$, $\beta2$, ω, and α (see Fig. 2) and to be respectively 82.59(1.34) m, 49.17(0.69) m, 16.15(0.30) m, and 19.94(0.41)° (standard error values are given in brackets). These estimates were used in the herding model to calculate the differences in herding efficiency between setups 1 and 2 for cod.

The cod length span included in the analysis ranged between 30 and 106 cm, as these length classes contained at least 20 fish. Each length interval from 75 to 90 cm contained over 500 fish, so the results for this length range should have high precision (Fig. 3b). The catch comparison, catch ratio, and herding efficiency results documented significantly differences in catches collected with setup 1 and setup 2 (Fig. 3a and b). The catch comparison curve fitted the observations well and showed a constant average value of 0.40.

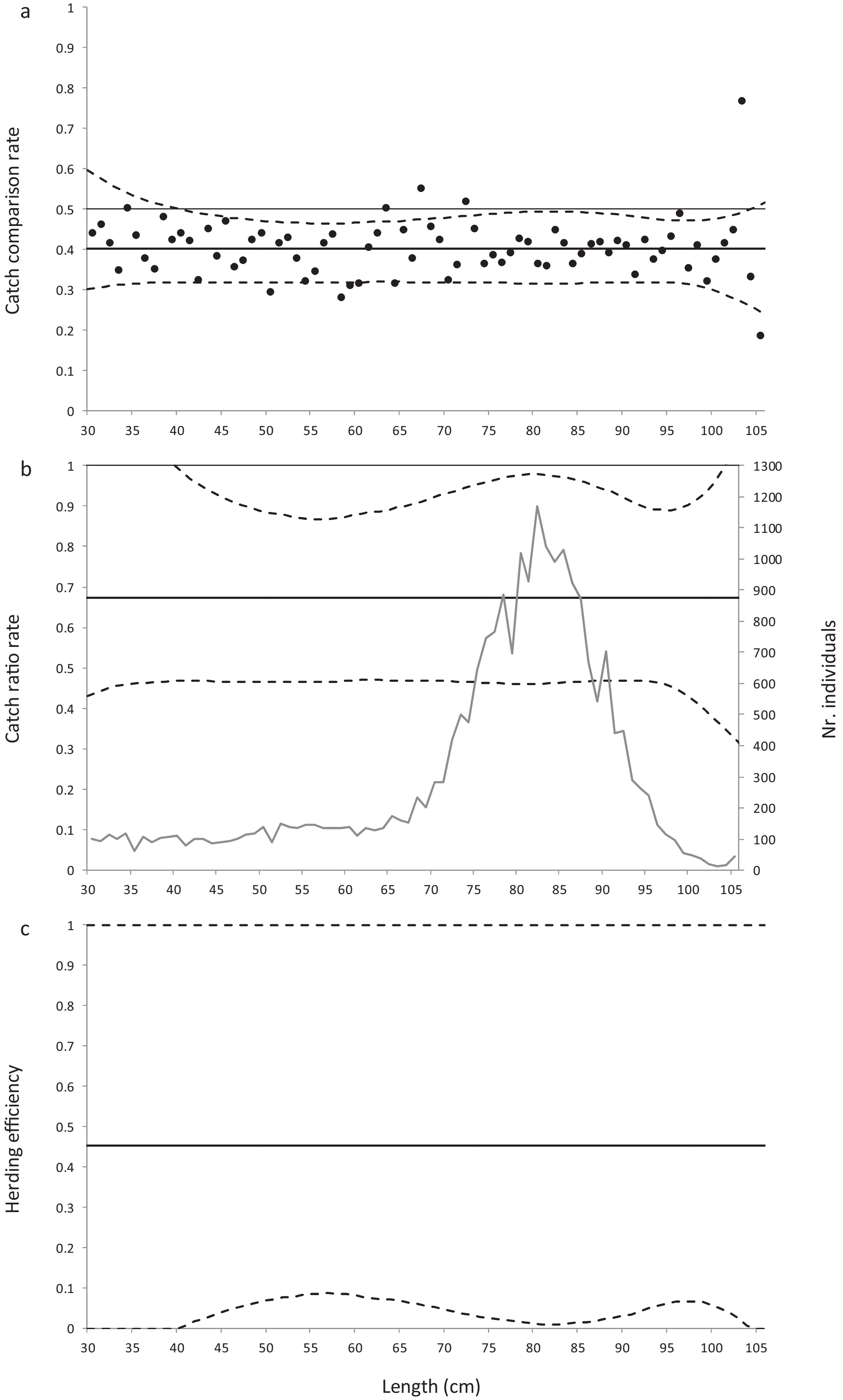

Fig. 3. Setup 1 as compared to setup 2. (a) Average catch rate (full thick black line) and confidence intervals (stippled black lines) estimated for cod between 30 and 106 cm in length. The full line at 0.5 represents the line where both gears would have the same catch efficiency; (b) average catch ratio (full thick black line) and confidence intervals (stippled black lines) estimated for cod between 30 and 106 cm in length and the size distribution (gray line) for cod in the same length range. The full line at 1 represents the line where both gears would have the same catch efficiency; and (c) average herding efficiency (full black line) and confidence intervals (stippled black lines) estimated for cod between 30 and 106 cm in length.

Table 2
Mean value and standard deviation for the registered door distance, wing distance, distance of the doors over the seabed, headline height, and temperature (°C) at depth registered with the sensors in the trawl for setup 1, setup 2, and all hauls (setup 1 + setup 2).

		Door dist. (m)		Wing dist. (m)		Door dist. over seabed (m)		Headline height (m)		*T* (°C)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Cod	Setup 1	117.67	29.65	16.07	1.24	11.05	3.25	5.38	0.58	0.97	0.17
	Setup 2	116.92	32.29	16.22	1.66	5.84	1.44	5.17	0.59	0.82	0.07
	All	117.30	30.97	16.15	1.45	8.44	2.34	5.28	0.58	0.89	0.12

The analysis resulted in a *p*-value of 0.02, a deviance of 168.98, and 69 degrees of freedom. The *p*-value was low, but we considered this to be a result of overdispersion in the data that likely was due to the data collection method employed during the trials, as there was no pattern in the deviation between the catch comparison data and catch comparison curve (Fig. 3a). The fact that the observations were well represented by a constant value shows that the differences in catches between the setups were length independent. The upper confidence interval (CI) for the curve (Fig. 3a) was below 0.5 between the 41 and 104 cm length classes, thus the differences between the catches in this size interval are significant. The catch ratio curve, which is the result of the direct comparison between the setups, shows a constant average value of 0.67; this result means that setup 1 captured 33% fewer fish than setup 2 independent of the length of the fish. As the catch comparison rate and catch ratio are directly related (Eq. (8)), the CIs for the catch ratio curve show significant differences (upper CI curve <1) between the setups for the same length class range as the catch rate curve. The lower CI curve shows a value below 0.5 throughout the whole cod length span, which means that the differences in catch may be as great as 50% between the setups. The loss of catch (illustrated by the catch ratio curve in Fig. 3b) can be explained by the herding efficiency curve (Fig. 3c). The herding efficiency results show that when the sweeps were at the seabed (i.e., setup 2), they were able to herd 45% of the cod independent of their length into the catch zone of the gear. When the sweeps were lifted from the seabed, however, these fish would be lost. The CIs show that the herding efficiency was significantly different from 0 for the 41 to 104 cm length classes (i.e., lower CIs).

The predictions of catch loss due to lifting of the sweeps from the seabed, which was determined by the position of the clumps in each setup, showed that catch loss increased substantially with increasing difference between *CF*1 and *CF*2, especially at low *CF* values. *CF*1 in this experiment had a value of 3.04, whereas *CF*2 was based on the geometry of the trawl and was calculated to be 5.11. Applying these values to our catch loss prediction plot resulted in a catch loss estimation of 33%. To illustrate the use of the prediction plot shown in Fig. 4, we estimated *CF* for a case in which β was the average door distance estimated from the trials (117.30 m), meaning that the clumps would be placed at the doors. This case represents a situation in which the doors and the trawl are joined by a sweep with seabed contact from the doors to the ground gear. We estimated *CF* for this case to be 7.26. A comparison between setup 1 and this case in the prediction chart shows that fish loss would be 50%. This means that considering only the effect of the sweeps (and neglecting the potential herding effect of the doors at the seabed), the fish loss due to lifting the whole sweep length would be 50%.

4. Discussion

The results of this investigation show that cod catch rates decrease when the sweeps are lifted from the seabed during the bottom trawling process. These results highlight both the potential herding effect of the sweeps and the importance of keeping them in contact with the seabed when fishing for benthic species such as cod. Engås and Godø (1989) found the herding process to be size selective, as sweep elongation had an effect only on large cod, and small cod did not follow the same pattern. However, the results of our study show clear length independency, as the mean catch comparison rate and catch ratio curves had a constant value throughout the length classes.

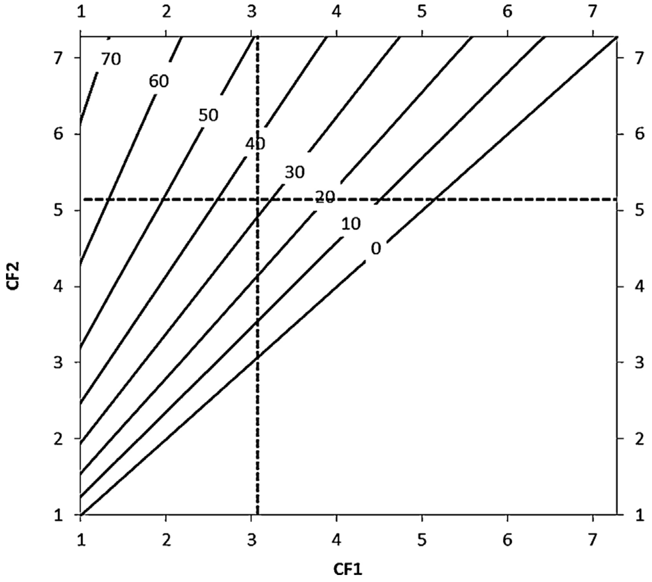

Fig. 4. Isolines (full lines) showing predicted fish loss percentage relative to the position of the clumps (sweep length at the seabed) in each of the trawl setups (*CF*1 and *CF*2). The stippled lines show the values estimated for *CF*1 and *CF*2.

For other fish species, such as flatfish, sweeps play a major herding role (Ryer, 2008). The development of Danish seining as a fishing technique is a further illustration for the effect of an approaching rope/cable on flatfish (Wardle, 1993). This technique is effectively used today for several other benthic species, including cod, which again fits well with the result of this study that indicates that an approaching cable on the seabed has a discernible herding effect in certain benthic fish species such as cod. Rose et al. (2010) measured the height at which the sweep cables begin to lose herding efficiency; they concluded that for flatfish herding efficiency started to decrease at a sweep height of 10 cm, whereas slightly lifted sweeps proved to be more effective than traditional bottom sweeps for walleye pollock (*Gadus chalcogrammus*) in Alaska. Apart from the sweep length and height, sweep angle and towing speed are also important factors for fish herding. A sweep approaches a fish at a speed of *towing speed* × Sin(α), with α being the sweep angle. If the speed is higher than the swimming capability of the fish, which varies among species, sizes, and behaviors related to abiotic factors (Wardle, 1993), the fish will be overrun by the sweeps and the gear will not fish effectively. If the speed is too low, the fishing area covered will decrease and the fish can swim away from the gear. For setup 1 and 2 in these trials we estimated an average sweep angle of 19.94°. At the average 3.5 kn speed maintained during the trawling period, a sweep with a 20° angle would approach the fish in the herding zone at a speed of 1.2 kn until the fish reached the rear part of the ground gear (the rockhopper in this case), where it would need to maintain the towing speed in order not to be overtaken. According to Strange (1984), at sweep angles greater than 20°, the catch efficiency of cod is reduced. The angle registered with the setups tested in this study was lower than 20°.

The length of the sweeps in this study was 83 m (including the two 4 m chain pieces inserted to attach the clumps) (see Fig. 2), and the difference in the length sweeps in contact with the seabed between setup 1 and 2 was designed to be 45 m. However, we cannot rule out the possibility that at certain stages this difference might have been greater, which could result in a partial overestimation of fish loss. When using setup 2, the doors were maintained low in the water column to facilitate the correct functioning of the gear, as lifting the doors too high would increase the risk of lifting the clumps. Because the position of the doors in the water column was controlled manually by the skipper, natural oscillations of the door distance to the seabed occurred, and part of the sweeps in front of the clumps might have come into contact with the seabed at times. Because of the door distance to the seabed maintained when using setup 1, it is unlikely that this phenomenon occurred while fishing with this setup. Contact between the ground gear and the sea floor was important in this experiment, as fish loss due to excessive jumping of the ground gear would bias the results. Video observations from an earlier cruise in which the same doors, sweep length, and trawl were used showed that the trawl had a slight tendency to lose bottom contact. However, the 210 extra kg added to each side of the ground gear solved this issue, and the trawl maintained steady bottom contact during the whole trial period in the current study.

The environmental conditions of the fishing ground, particularly light and water temperature, are also known to affect fish herding (Ryer and Barnett, 2006). In this study, data collection was conducted in November in the northern Barents Sea, which means that it took place during the polar night (sun below horizon and almost 24 h darkness). Despite the darkness, cod seemed to react to the approaching sweeps. This does not indicate that the fish necessarily saw the approaching sweeps, but it does show that fish were able to sense them, perhaps via the sound of the sweeps and the 450 kg chain clumps against the seabed or vibrations created in the water. He (1991) studied the swimming endurance of Atlantic cod at different temperatures and swimming speeds and concluded that endurance is reduced at faster towing speeds and at lower temperatures. Other fish species are also known to exhibit reduced endurance at lower water temperatures (e.g., Winger et al., 1999; Özbilgin, 2002; Yanase et al., 2007). The average water temperature at the seabed during the trials in our study was 0.89 °C, which is low considering the water temperature preferences of Atlantic cod (He, 1991). Our results show that even at these temperatures the sweeps had a discernible herding effect; however, this result does not contradict earlier results, as we did not document differences in potential herding efficiency at higher water temperatures. The length independency in herding efficiency documented in the present investigation was unexpected, as results from earlier studies indicated that swimming endurance generally increases with increasing body size. However, considering that the sweeps approached the fish at a speed of 1.2 kn (0.62 m/s) and the swimming endurance times recorded for cod (He (1991) found the swimming endurance for cod of 36–43 cm at −0.3–1.4 °C and a towing speed of ca. 0.6 m/s to be approximately 50 min), the towing speed might not have been high enough or the mean towing time of the cruise long enough (the average towing time for the cruise was estimated to be 72 min (Table 1)) to create differences between different sized fish. In addition to these environmental factors, parameters such as fish density may have influence in the herding efficiency of a towed gear. The results presented in this study are specific for the fish densities present in the fishing grounds during the trials (see catch rate in Table 1) and could change in areas with higher or lower availability of fish.

Because bottom trawling has the highest fuel consumption rate in terms of l/kg fish produced (Schau et al., 2009), efforts to make this fishing technique more environmentally friendly have become increasingly important. The substitution from traditional bottom trawl doors to semi-pelagic doors is a clear example of an attempt to reduce fuel consumption while trawling for demersal species. However, using these types of doors without proper control of the location of the doors in the water column can result in the sweeps being partially lifted from the seabed. For example, the results obtained in this study show that at a constant towing speed of 3.5 kn and with the trawl geometry parameters of the trawl used in this study, lifting 47 m of sweeps from the seabed leads to an average cod catch loss of 33%. Furthermore, this loss could be explained by the loss of fish herding by the sweeps (i.e., when at the seabed, the sweeps were able to herd 45% of the cod into the catch zone of the gear). Previous studies documented herding of different fish species based on the geometry of the trawl and the catches obtained (e.g., Ramm and Xiao, 1995), but we were not able to find any quantitative measure for the herding ability of trawl sweeps for cod. The aim of the study was to evaluate the potential loss in fishing efficiency that may occur when parts of the sweeps are lifted from the seabed, which simulates a semi-pelagic trawling scenario with lack of control over the position of the doors in the water column. The results of this study show that substantial quantities of the catch could be lost if a long portion of the sweeps does not touch the seabed because the doors are lifted above the seabed. The loss of catch and consequent loss in fishing efficiency suggest that effort would need to be proportionally increased to achieve the same catch level. However, having to increase the effort above a certain level would make the change in door type less valuable from the energy saving point of view, and it also would increase the fishing ground area swept by the ground gear, resulting in increased seabed damage.

Acknowledgements

We would like to thank the crew of the R/V Helmer Hanssen for their valuable help during the cruises. We also want to express our sincere gratitude to the Norwegian Research Council and the Norwegian Fisheries and Aquaculture Research Fund for partially financing the study. Thanks are also due to Kjell Gamst and Jesse Brinkhof for their assistance during the data collection period. Finally, we would like to show our most sincere gratitude to the reviewers of the manuscript, which have helped improving it substantially.

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