Faculty of Biosciences, Fisheries and Economics | Norwegian College of Fishery Science

A study on the escape rate of Northeast Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) under the fishing line with two different ground ropes in the Barents Sea bottom trawl fishery

and the influence of some biotic and abiotic factors on the efficiency during bottom trawling

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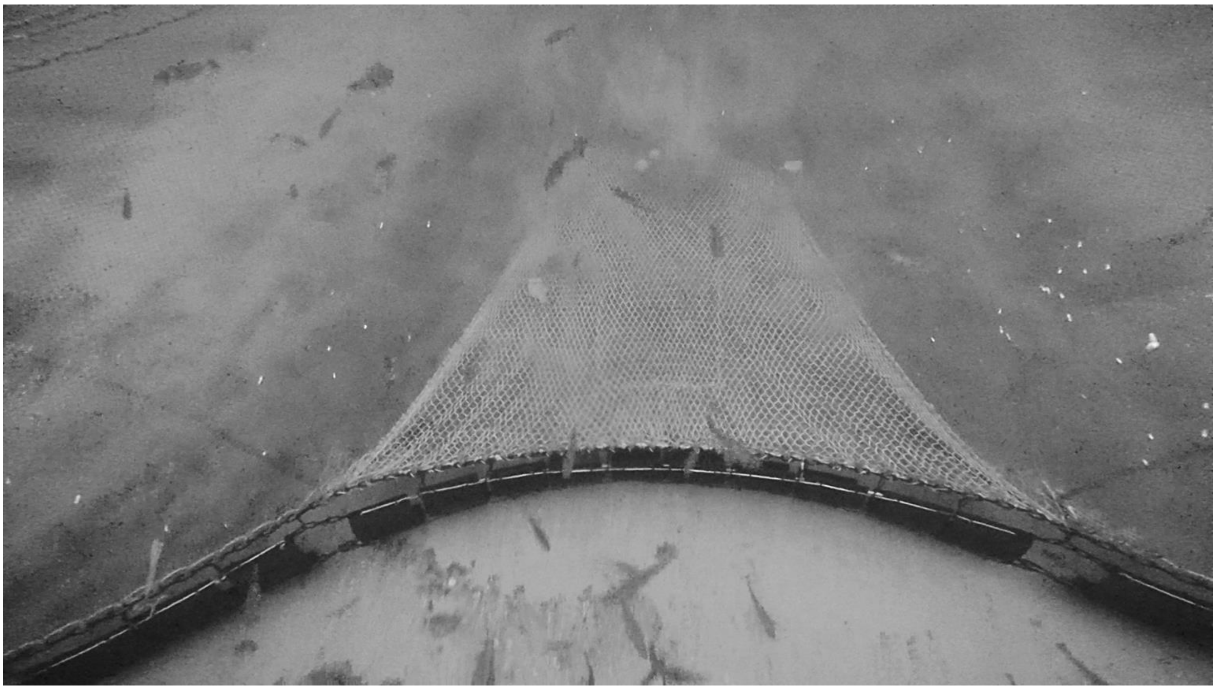

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Tromsø, 14th of May 2015

Jesse Brinkhof

Abstract

The aim of this study was to investigate the escapement under the fishing line for cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) with the conventional rock-hopper gear and a new type of gear termed semicircular spreading gear (SCSG). The trials were conducted during November 2014 and February 2015 in the Barents Sea under varying environmental conditions. In order to catch the escapees a retainer bag was attached to the fishing line of the trawl. Multi model averaging was applied for calculating the efficiency, i.e. escapement rate for all length groups. A highly significant difference in the rate of escapement between the two types of ground-gears was found. Summarized for all length groups above 65 cm, 14% of the cod escaped under the fishing line of the rock-hopper gear, and 5% under the SCSG during the trials in November 2014. This resulted in an efficiency improvement of 11%, and escapement reduction of 67%. In February 2015 the escapement was 5% for the rock-hopper, and 2% for the SCSG, resulting in an efficiency improvement of 3%, and an escapement reduction of 57%. The overall improvement of efficiency for cod is thus 8%, and a reduction in escapement of 63%. The escapement of haddock for all lengths above 62 cm was estimated to 7% for the rock-hopper gear, and 1% for the SCSG, implying an efficiency improvement of 6%, and an escapement reduction of 85%. Based on the present data no correlation was found between the rate of escapement and fish density, ambient light intensity, nor artificial light. However, a positive correlation was obtained between temperature and the escapement rate for some length groups.

Over the recent years the tendency in the bottom trawl fisheries has been increasing the trawl dimension in order to increase efficiency, with subsequent increase in fuel consumption and emission, as well as possibly increased negative bottom impact. The demonstrated improvement of the SCSG compared to the conventional rock-hopper gear entails multiple advantages such as increased efficiency due to reduced escapement, reduced fuel consumption and emission, and reduced negative bottom impact. By introducing a more efficient ground-gear this study provides an improvement from the current situation that is believed to be of importance both from fisheries and environmental point of view, as well as for the accuracy of the trawl surveys for stock assessment purpose.

Keywords**:** Escapement, efficiency, rock-hopper, semicircular spreading gear, fish behavior

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1. Introduction

1.1 Background

For the last 25-30 years the use of rock-hopper ground ropes, i.e. a dense and tight line of rubber discs along the fishing line, has been common in the Norwegian bottom trawl fisheries. The use of this type of ground rope is believed to increase bottom contact of the gear and subsequently increase its fishing power. The tendency over recent years has been to increase the length of the fishing line and hence the total weight of the ground rope. In order to match drag forces of the ground rope and net a similar increase of otter boards has been made. In total it means more fuel consumed per hour trawled and increased negative disturbance on the bottom fauna without any clear evidence of improved fishing power of the gears.

As with all other fishing gears one has been aware of the fact that fish behavior and trawl performance are important factors to take into consideration in order to fish in a targeted manner (Wardle, 1993; Walsh et al., 2002). An issue that one became aware of relatively early, is the amount of fish escaping underneath the trawl. To my knowledge relative few studies have investigated which factors influence the rate of escapement, nor have there been any large improvements in order to reduce the escapement rate since the transition from the steel bobbbins gear to the rock-hopper gear (Engås and Godø, 1989). Earlier investigations have pointed out that the rate of escapement underneath the trawls fishing line is remarkable high (Main and Sangster, 1981; Engås and Godø, 1989; Godø and Walsh, 1992; Ingólfsson, 2003; Ingólfsson and Jørgensen, 2006).

Most of the fish species targeted in the Barents Sea are caught with bottom trawl. With the recent years quotas being up to 1 million ton, the Northeast Arctic (NEA) cod (*Gadus morhua* L.) stock is the most important species targeted in the Barents Sea, both in terms of economic value and catch weight landed (IMR, 2015). The stock of NEA haddock (*Melonogrammus aeglefinus* L.) is slowly declining after a historical high peak, with this year's TAC (total allowable catch) being 178 500 ton, but has varied considerably over the years (IMR, 2015). The annual TAC is divided by the Joint Fisheries Commission between Norway and Russia, which are the two main nations targeting NEA cod and haddock (Shamray and Sunnanå, 2011). At present about 70% of the annual cod TAC is caught with bottom trawl (IMR, 2015). The landings from the Russian trawl fleet constitutes about 95% of the Russian cod quota (ICES, 2014). Due to the high diversity of fishing gears in the Norwegian fishing fleet only 35% of the Norwegian NEA cod quota is caught with bottom trawl (ICES, 2014). Most of the haddock is caught as bycatch in the fishery for cod, although a direct trawl fishery for haddock is conducted as well (ICES, 2014). On average 33% is caught with conventional gears (ICES, 2014), especially by Norway where nearly 50% of the annual Norwegian TAC is caught by the longline fishery (IMR, 2015).

Two major reasons for conducting this study are highlighted:

1. The NEA cod and haddock management system is provided with information about the stock status from three sources; fisheries statistics, programs monitoring biological status and trawl-acoustic surveys (Yaragina, 2011). The latter provides the management system with data for estimating the abundance indices (Yaragina, 2011), by integrating the survey data as a model calibrator with commercial CPUE (catch per unit effort) in the virtual population analysis (VPA) (Michalsen, 1996; Pennington et al., 2011). It is assumed that uncertainty in the stock assessment based on the VPA of cohorts is mainly caused by errors in the survey data (Pennington et al., 2011). The reliability of the data obtained from trawl surveys is highly dependent on the accuracy of the sampling trawls (Michalsen et al., 1996), i.e. errors in the survey data could possibly lead to major impacts on the stock assessment advice. Hence, in order to avoid errors with subsequent consequences, knowledge and understanding of fish behavior and trawl performance is crucial when conducting trawl surveys for application of stock assessment (e.g. Engås and Godø, 1989; Godø and Walsh, 1992; Michalsen et al., 1996; Aglen et al., 1997; Godø et al., 1999; Weinberg and Munro, 1999; Petrakis et al., 2001; Albert et al., 2003; Handegard et al., 2003).
2. Currently there is a growing focus on increasing fishing efficiency and reducing effort on one hand, and increasing sustainability and reducing environmental impacts on the other hand. Although this may seem a contradiction and incompatible to some people, these objectives are compatible. The increasing focus on the above mentioned objectives takes place in the entire fishing industry, but applies especially to trawling due to its claimed controversies. This means that in addition to being of importance for science and management, increased knowledge of fish behavior in relation to trawling and trawl performance can in this way contribute to improvements which are beneficial for both the

fisheries by reducing their costs, and the environment by reducing negative impact, and in this way increase overall sustainability.

1.2 Behavior of cod and haddock

The behavioral pattern of fish reacting to a trawl is complex due to the many influencing factors and combinations of influencing factors (Winger et al., 2010). Intrinsic factors such as fish species, length, life-stage, physiological conditions, and extrinsic factors such as water temperature, light intensity, trawl performance and fish density all affect the behavioral responds of fish towards an approaching trawl (Winger et al., 2010). The same factors affect the vulnerability of fish for capture (Aglen et al., 1997). It is thought to be of high importance to increase the knowledge on how these factors (both individually and in conjunction with each other) influence the rate of escapement under the fishing line.

When fish approach the trawl mouth they alter swimming direction and try to maintain a constant position to the trawl that requires a minimum of energy, resulting in prolonged endurance (Wardle, 1993). Exhaustion forces the fish to shift from aerobic metabolism to anaerobic metabolism, recognized by the transition from optomotor response to erratic response (Wardle, 1993: Kim and Wardle, 2003). The swimming speed and endurance depends on the length of the fish and towing speed (Winger et al., 2010), and water temperature (Wardle, 1993; Winger et al., 2010). Another important aspect that influences the behavioral pattern of fish in the vicinity of the trawl mouth is ambient light intensity. Both the distribution of fish in the trawl mouth (Engås and Ona, 1990), and the reactions due to the contrasts 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 optomotor response. At low light intensities the optomotor response ceases, resulting in fish swimming in different angels to the approaching gear, colliding with other fish and gear components (Glass and Wardle, 1989; Walsh and Hickey; 1993). *In situ* observations have shown that fish at night do not detect or respond to the approaching gear before being at a distance of 1-2 m (Warlde, 1993), often located close to the ground-gear (Engås and Ona, 1990). Due to the high reaction threshold and short reaction distances this often results in the fish colliding with the ground-gear and are subsequently overrun (Winger et al., 2010). In general cod tend to actively seek an escape route close to the bottom under the fishing line and between the rock-hopper discs, a process that is assumed to be both species and size selective (Engås and Godø, 1989; Ingólfsson, 2003; Ingólfsson and Jørgensen, 2006; Winger et al., 2010). Haddock on the other hand tends to seek an escapement route upwards, sometimes resulting in escapement over the headline (Wardle, 1993; Engås and Ona, 1990; Winger et al., 2010). It has been observed that fish escaping under the fishing line often have incurred injuries in the form of external scrape marks and internal ecchymosis (Ingólfsson and Jørgensen, 2006). Such injuries may contribute to an increase in unaccounted mortality. In addition to physical injuries it is assumed that also stress leads to increased mortality due to behavioral impairment, increased risk of predation and disease susceptibility (Chopin and Arimoto, 1995; Ryer, 2004).

For a more detailed but brief description of fish behavior and sensory organs in general in relation to trawling, see Appendix A.

1.3 The objectives

Studies have documented that the now widely used rock-hopper ground rope is more efficient than the formerly common bobbin-gear (e.g. Engås and Godø, 1989). Nevertheless, escape rates of 33% underneath the rock-hopper gear have been documented (Ingólfsson and Jørgensen, 2006). It is, as argued in section 1.1, of great importance to reduce the amount of escapement underneath the fishing line, both from an assessment and from a fisheries point of view. A new type of ground-gear, termed semicircular spreading gear (SCSG), has been developed by SINTEF Fisheries and Aquaculture. The SCSG is assumed to be equal or better in terms of catch and trawl performance compared with the standard rock-hopper gear (Gjøsund et al., 2012; Grimaldo et al., 2013). However, the rate of escapement has not yet been investigated.

The main objective of this study is to compare the two different ground-gears by quantifying the rate of escapement underneath the center part of the fishing line with the use of retainer bags to catch the escapees. Furthermore, I will also attempt to investigate whether or not the rate of escapement under both gears is dependent on fish length, species and/or fish density and how ambient light intensity and water temperature affect the escape rate. Finally, the effect of artificial light on the rate of escapement for the hauls conducted with video camera’s requiring artificial illumination is addressed.

2. Materials and Methods

2.1 Research vessel and study area

The data for this thesis were collected onboard the research vessel R/V “Helmer Hanssen” during two research cruises. Technical descriptions and user areas for R/V “Helmer Hanssen” can be downloaded at the web-pages of the University of Tromsø (UiT-Fartøyavdelingen, 2013[1]).

2.1.1 Cruise I, November 2014

The first dataset was collected from 17th to 24th November 2014 in the central Barents Sea. The research cruise lasted from 11th to 26th of November, and other data was collected both simultaneously and on the remaining dates. The data was collected in the central part of the Barents Sea, south-east of Hopen and around Sentralbanken (Figure 2.1). The commercial fleet was operating in the same area, targeting pre-spawning NEA cod. A total of 47 hauls were conducted during the research cruise (Table 2.1). Since the ice-conditions were unfavourable during these trials we (and the rest of the trawl fleet) were forced to move southwards during the trial period. However, the fishing depths, catch sizes and size distribution on cod were comparable between the areas.

Out of the 47 hauls 6 hauls are considered invalid due to technical malfunction, i.e. open codend, broken ground-rope, torn/split retainer-bag etc. Out of the remaining 41 valid hauls 9 were conducted with cameras and artificial light (Table 2.1). These hauls were important for confirming and visualizing the functioning of the trawl and behavior of fish. Furthermore, various light types and combinations were also studied to enhance the knowledge on fish reactions towards artificial lights. Artificial light is in some instances known to affect the behavior of fish (Glass and Wardle, 1989; Graham et al., 2004). These hauls are therefore excluded from the statistical analysis, besides when investigating the effect of artificial light on the escapement rate.

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[1] UiT – Fartøyavdelingen, 2013. http://uit.no/forskning/art?p_document_id=336568&dim=179012.

Table 2.1 Overview over conducted valid hauls with position at tow start as well as depth, date and time, duration, and ground-gear used for the data sampled in November 2014.

Haul #	Latitude (D°M.m)	Longitude (D°M.m)	Depth (m)	Date (UTC)	Start time (UTC)	Duration (h:mm)	Ground-gear
1	75˚49.51	27˚31.15	242.54	17.11.2014	12:10	0:30	Rock-hopper
2*	75˚49.25	27˚49.20	242.43	17.11.2014	13:56	1:04	Rock-hopper
3	75˚48.46	27˚59.65	241.30	17.11.2014	15:47	1:11	Rock-hopper
4	75˚47.34	27˚35.94	249.89	17.11.2014	17:38	1:02	Rock-hopper
5*	75˚44.05	27˚13.52	220.75	17.11.2014	20:08	1:29	Rock-hopper
6*	75˚48.48	27˚27.14	237.20	18.11.2014	00:04	1:01	Rock-hopper
7	75˚50.48	27˚42.26	247.80	18.11.2014	01:59	1:31	Rock-hopper
8	75˚47.59	27˚30.82	239.93	18.11.2014	04:24	1:30	Rock-hopper
10*	75˚48.23	31˚03.11	320.09	18.11.2014	14:53	1:03	Rock-hopper
12	75˚41.18	34˚14.03	211.37	18.11.2014	22:40	1:30	Rock-hopper
13	75˚40.78	35˚01.47	174.45	19.11.2014	01:29	0:47	Rock-hopper
14	75˚42.50	35˚18.79	163.47	19.11.2014	02:52	1:34	Rock-hopper
15	75˚45.92	35˚43.57	186.62	19.11.2014	04:59	1:42	Rock-hopper
17*	75˚56.17	37˚47.07	221.78	19.11.2014	13:31	0:40	Rock-hopper
18	75˚57.62	37˚36.40	226.57	19.11.2014	16:05	0:35	Rock-hopper
19	75˚58.53	37˚45.78	236.66	19.11.2014	22:13	0:18	Rock-hopper
20	75˚59.97	37˚41.04	231.09	20.11.2014	03:29	0:30	Rock-hopper
21	75˚56.45	37˚31.65	223.60	20.11.2014	07:52	0:58	Rock-hopper
22	75˚57.70	37˚09.74	231.40	20.11.2014	09:53	1:42	Rock-hopper
23	75˚55.02	37˚34.64	222.83	20.11.2014	12:59	1:01	Rock-hopper
24	75˚54.31	37˚12.03	206.83	20.11.2014	15:04	1:30	Rock-hopper
26	75˚35.44	33˚33.31	233.04	21.11.2014	02:13	1:32	SCSG
27	75˚21.91	32˚33.52	279.25	21.11.2014	06:29	1:04	SCSG
28	75˚17.10	32,˚19.41	288.20	21.11.2014	09:17	0:59	SCSG
29	75˚12.88	32˚15.54	283.87	21.11.2014	11:17	1:32	SCSG
30	75˚07.36	32˚08.66	281.38	21.11.2014	13:54	1:21	SCSG
31	75˚02.14	32˚06.44	242.91	21.11.2014	16:19	1:10	SCSG
32	74˚59.03	31˚49.34	275.82	21.11.2014	18:24	1:35	SCSG
33	74˚55.40	31˚32.06	304.22	21.11.2014	21:04	1:30	SCSG
34	74˚53.89	31˚23.07	323.87	22.11.2014	00:03	1:35	SCSG
35	74˚58.93	31˚45.49	281.34	22.11.2014	06:17	0:50	SCSG
36	74˚58.80	31˚49.95	272.92	22.11.2014	11:59	0:51	SCSG
37*	74,˚57.65	31˚43.08	284.11	22.11.2014	15:20	1:19	SCSG
38*	74˚55.35	31˚28.23	318.63	22.11.2014	18:44	1:24	SCSG
41	74˚58.62	31˚45.47	281.04	23.11.2014	04:30	0:40	SCSG
42	75˚00.82	31˚45.85	305.18	23.11.2014	15:20	0:19	SCSG
43*	74˚58.97	31˚37.38	309.85	23.11.2014	18:52	1:08	SCSG
44	75˚02.13	31˚43.88	313.82	23.11.2014	21:42	0:28	SCSG
45	75˚02.32	31˚44.69	312.60	24.11.2014	01:19	0:16	SCSG
46	74˚43.12	30˚58.12	321.11	24.11.2014	09:42	0:44	SCSG
47*	74˚41.19	31˚44.76	222.51	24.11.2014	12:42	0:52	SCSG

* Hauls conducted with camera for video recordings, demanding the use of artificial light.

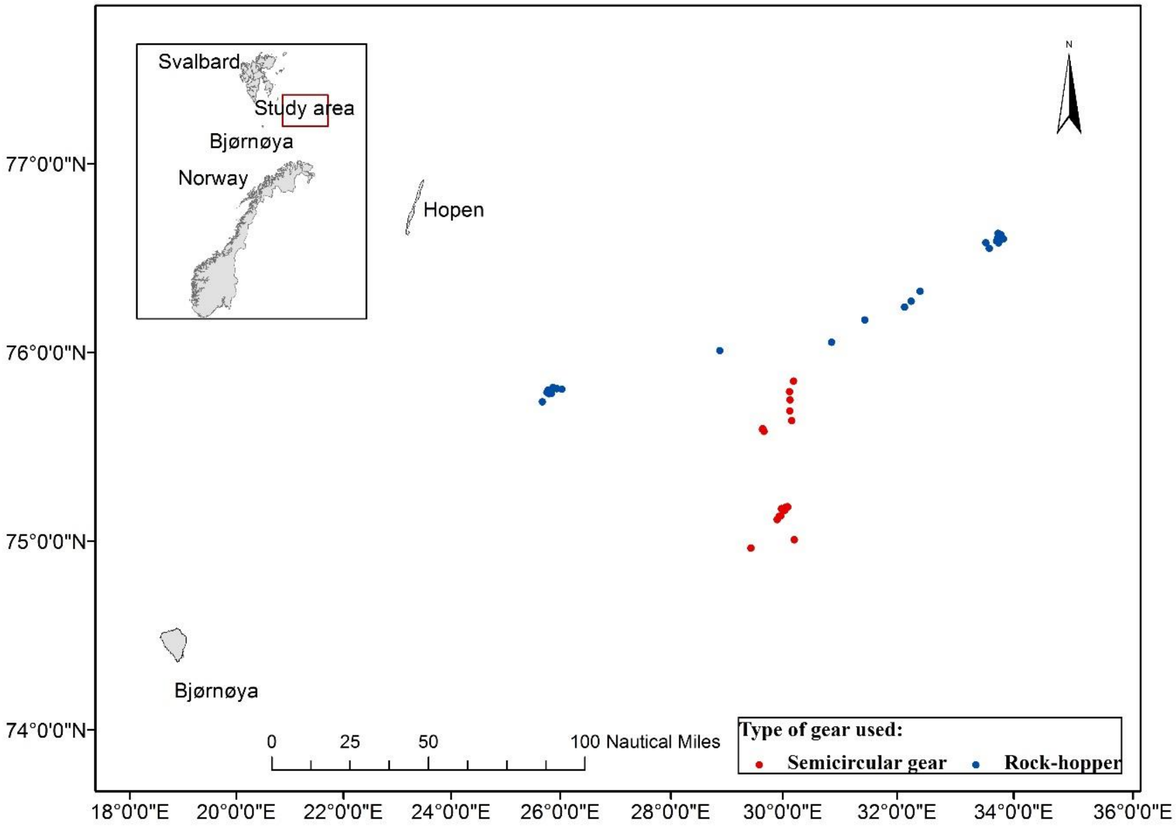

Figure 2.1 The study area in November 2014, showing all valid trawl stations in accordance to the type of gear used.

2.2.2 Cruise II, February 2015

The second dataset was collected from 17th and 27th of February in the southeastern part of the Barents Sea, on the southern part of Nordbanken. A total of 42 hauls were conducted whereof 16 hauls were invalid, mostly due to torn/split retainer bags. Of the remaining 26 valid hauls, 13 were conducted with the rock-hopper gear and 13 with the SCSG in an alternate haul setup (Table 2.2 and Figure 2.2). The first 14 hauls were conducted in a shallow area allowing to make video-recordings in natural light. Due to the environmental conditions, i.e. the sandy bottom with some large stones, resulting in torn retainer bags, none of these hauls were valid.

Table 2.2 Overview over conducted valid hauls with position at tow start, depth, date and time, duration and ground-gear used for the data sampled in February 2015.

Haul #	Latitude (D°M.m)	Longitude (D°M.m)	Depth (m)	Date (UTC)	Start time (UTC)	Duration (h:mm)	Ground-gear
1	70°48.5137	30°55.2974	290.33	21.02.2015	04:39	0:50	SCSG
2	70°45.5745	30°56.8307	315.62	21.02.2015	06:34	1:00	Rock-hopper
3	70°48.2212	30°52.2000	308.76	21.02.2015	08:18	1:30	Rock-hopper
4	70°45.4184	30°58.3752	308.73	21.02.2015	11:14	1:30	SCSG
5	70°49.3735	30°49.9218	301.66	21.02.2015	13:29	1:35	SCSG
6	70°45.9035	31°01.6382	304.88	21.02.2015	16:13	1:31	Rock-hopper
7	70°48.8073	30°47.4797	309.21	21.02.2015	19:04	1:30	Rock-hopper
8	70°45.5420	31°01.2122	302.89	21.02.2015	21:43	1:36	SCSG
9	70°50.2119	30°52.4791	289.18	22.02.2015	00:01	1:37	SCSG
10	70°46.5851	30°59.5947	302.43	22.02.2015	02:45	1:31	Rock-hopper
11	70°50.2238	30°52.1293	291.96	22.02.2015	04:56	1:35	Rock-hopper
12	70°46.1855	31°01.1614	303.57	22.02.2015	07:44	1:30	SCSG
13	70°49.3048	30°50.4465	299.56	22.02.2015	12:57	1:49	SCSG
14	70°48.5639	30°51.0168	308.39	22.02.2015	14:57	1:34	Rock-hopper
15	70°45.3186	31°05.3670	299.27	22.02.2015	17:50	1:30	Rock-hopper
17	70°45.6820	31°00.8563	303.59	22.02.2015	22:33	2:03	SCSG
18	70°50.3328	30°44.8169	300.66	22.02.2015	01:38	1:33	SCSG
19	70°47.0749	30°56.7736	306.63	23.02.2015	04:28	1:36	Rock-hopper
20	70°49.5166	30°47.2601	307.63	23.02.2015	06:45	1:35	Rock-hopper
21	70°46.3662	31°00.5173	302.66	23.02.2015	09:31	0:54	SCSG
22	70°48.8851	30°48.2338	307.38	23.02.2015	11:50	1:30	SCSG
23	70°46.0700	30°58.2006	306.09	23.02.2015	14:36	1:30	Rock-hopper
24	70°48.6642	30°51.6003	306.74	23.02.2015	16:50	1:31	Rock-hopper
25	70°45.4098	31°02.1341	301.89	23.02.2015	19:24	1:35	SCSG
26	70°48.4325	30°50.5101	309.77	23.02.2015	21:43	1:31	SCSG
28	70°50.3193	30°43.7999	301.59	24.02.2015	02:32	1:31	Rock-hopper

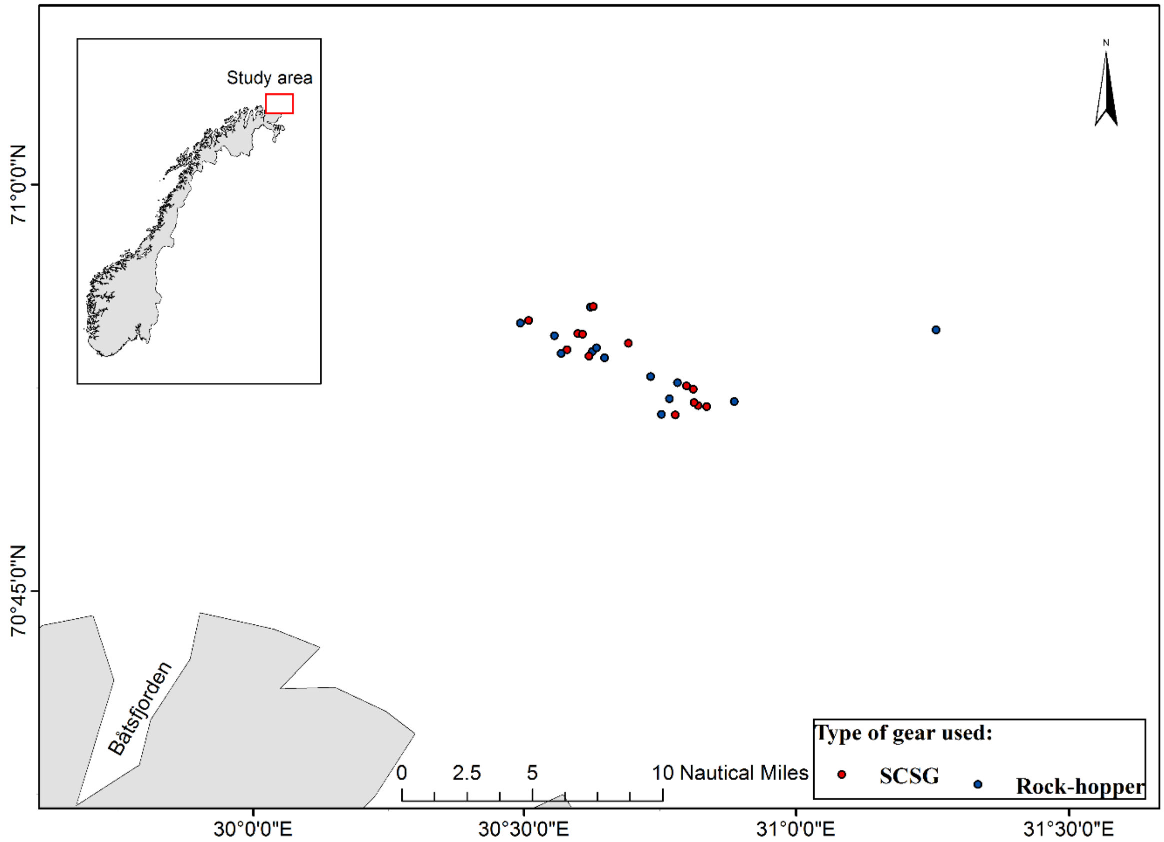

Figure 2.2 The study area in February 2015, showing all valid trawl stations in accordance to the type of gear used.

2.2 Trawl rigging

2.2.1 Overall trawl design

The trawl used was a modified two-panel Alfredo No. 3 fish trawl (Figure B.1 in Appendix B). The trawl wings, panels, belly and extension were entirely made of 80 mm Ø3.0 mm PE meshes, 810 meshes in circumference, originally designed for selectivity studies. The conventional codend was made of Ø8 mm PE (Euroline Premium) and had a nominal mesh size of 135 mm with an overall dimension of 60x60 meshes. The relative large mesh size in the codend is justified by the purpose of the experiments (i.e. retention of cod, haddock and snow crab of "legal" size), and the environmental conditions in the area (see section 2.2.4). The headline of the Alfredo no. 3 was

36.5 m long and was equipped with 170 8″ (200 mm) floats. The fishing line of the trawl was 18.9 m.

The trawl rigging used in the experiment in November 2014 was configured for semi-pelagic bottom trawling, i.e. the otter boards were held off the sea bed (Figure 2.3). This was necessary since other data collected during the same cruise required this setup.

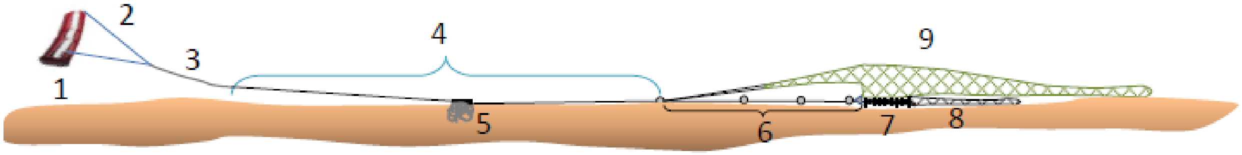

Figure 2.3 Trawl rigging of the trawl used in the experiment in November 2014 (From Larsen, 2014[2]).

The rigging details for the bottom trawl used in November 2014 are shown in Figure 2.3 above, and descriptions refers to numbers on the drawing: (1) The otter boards were Injector XF9 high aspect otter boards, each with an area of 7.0 m^2, weighing 2200 kg. (2) The backstraps were 15.9 m long and connected to the bridles by 12 m long Ø19 mm connector chains (3). (4) The sweeps were 60 m long (30 m + 30 m) divided by a 2 m long Ø19 mm chain in the middle. (5) A 450 kg chain clump was attached to the inserted chain part in order to ensure proper bottom contact of the ground-gear. The backstraps (15.9 m), the connector chains (12 m) and the foremost part of the sweeps (30 m) until the chain-clump are assumed to be off the sea bed during trawling. The foremost part of the ground-gear on each side consisted of a 46 m long Ø19 mm chain with four 21″ steel bobbins with ca. 11 m intervals (6). The length of the double bridles from the headline to the Danleno is 2x14.3 m long and the length of the upper wing is 17.2 m. (7) The central part of the ground-rope was either a rock-hopper gear or the SCSG and was attached to the 18.9 m long fishing line with Quick-links. The headline of the escape retainer bag was attached to the 6.3 m long center section of the fishing line of the main trawl (8). With this semi-pelagic trawl set-up we recorded an otter board spread of ca. 165 m, producing sweep angles close to 33°, and a calculated distance between the chain-clumps of 99 m.

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[2] Larsen, R., 2014. Trawl setup and details during fish trawl experiments November 2014. University of Tromsø – Norwegian College of Fisheries Science.

The trawl rigging used in February 2015 differed somewhat from the trawl setup used in November 2014 (Figure 2.4).

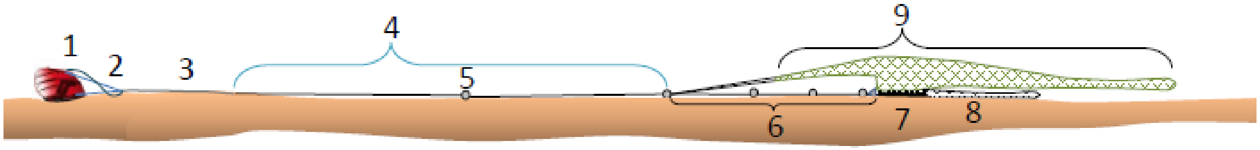

Figure 2.4 Trawl rigging of the trawl used in the experiment in February 2015 (From Larsen, 2015[3]).

Description refers to the numbers on the drawing (Figure 2.4): (1) The otter boards used were Injector bottom otter boards, each with an area of 7.5 m^2, weighing 2800 kg. (2) The backstraps were 3 m long and connected to the bridles by 7 m long Ø19 mm connector chains (3). Instead of a chain clump a 21″ steel bobbin was attached to the sweeps (5). The rest of the trawl setup was equal to the setup used in November 2014. With this setup we recorded an otter board spread of ca. 130 m, producing sweep angles of ca. 30°. The wing spread of the trawl was recorded to ca. 16.5 m, and the trawl height was ca. 4.5 m.

2.2.2 Ground-rope

Two different ground ropes were used during the experiment; a standard 21″ rock-hopper gear and a 20″ SCSG. The setup of the rock-hopper gear was similar to that of the commercial trawl fleet. The ground rope had an overall length of 18.9 m, consisting of three sections of equal length (6.1 m). The distance between the discs was 40.6 cm (16″) in both side-sections (Figure 2.5A), and 20.3 cm (8″) in the center-section (Figure 2.5B). In both side-sections the distance was kept by W8″ and L2x8″ disc spacers, and in the center-section by 8x8″ disc spacers. The sections were connected with 19 ML hammerlocks and the entire rock-hopper gear was built on an Ø19 mm center chain. The Ø10 mm chain through the upper part of the discs of the ground rope was equipped with steel rings for easy attachment to the fishing line with Quick-links (Figure B.2A in Appendix B).

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[3] Larsen, R., 2015. Trawl setup and details during fish trawl experiments February 2015. University of Tromsø – Norwegian College of Fisheries Science.

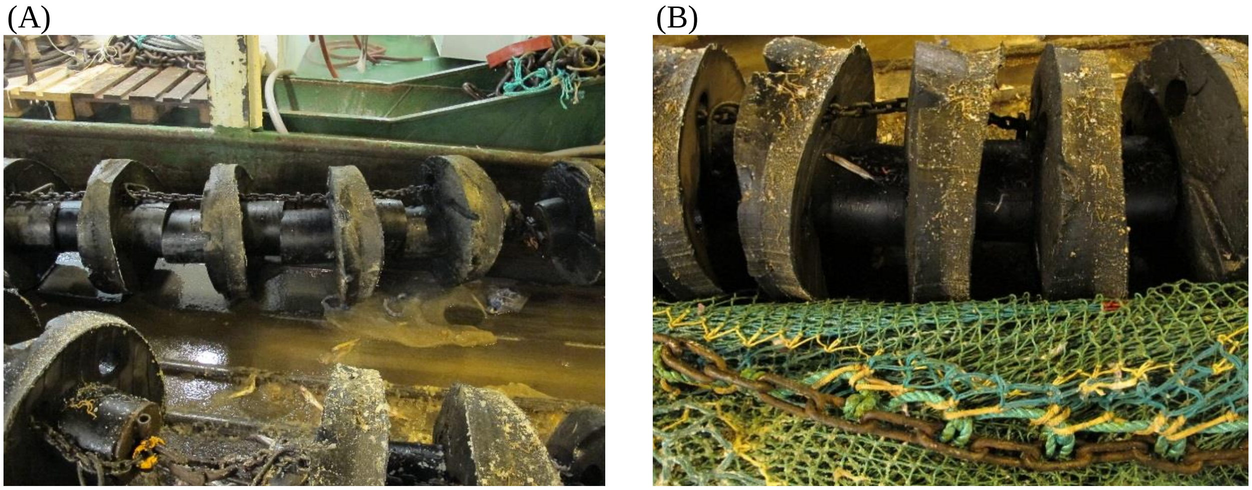

Figure 2.5 The rock-hopper gear showing the space between the discs on the side-section and between the sections (A), and between the discs in the center-section (B).

The other gear used was the SCSG (Figure 2.6). The SCSG had a total length of 18.9 m, consisting of three equal sections of 6.1 m. The semicircular elements made of PVC are 50 cm (19¾'') long and 3.4 cm (1⅓'') thick. The distance between the elements is 8 cm. The entire gear is built on a LL19-8 chain, and connected to the fishing line with rings attached to an Ø16 mm wire (Figure B.2B in Appendix B). For more information about the SCSG see Grimaldo et al., 2013.

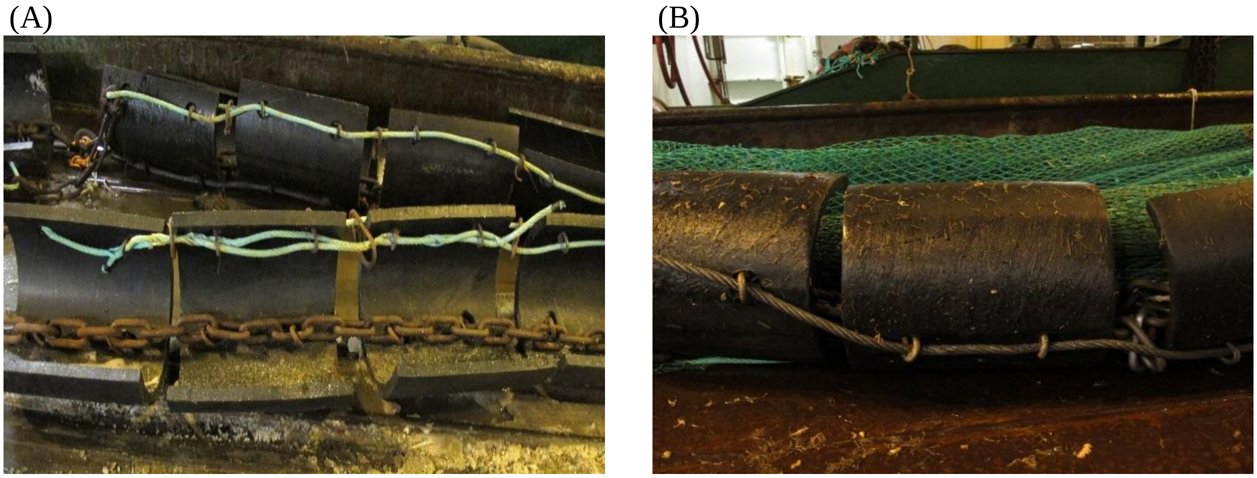

Figure 2.6 The semicircular spreading gear, from behind (A) and from the front (B).

2.2.3 Escape retainer bag

The purpose of the retainer bag was to sample any fish and snow crab (*Chionoecetes opilio*) that escaped beneath the fishing line of the trawl (Figure 2.7). The retainer bag was a modified version of the sample bag used by Ingólfsson and Jørgensen, 2006. Their sample bags were originally made of thin Ø2.5 mm PE and build of fine meshes (50 mm). The environmental conditions in the trail areas made a fine-meshed bag like they (Ingólfsson and Jørgensen, 2006) used inappropriate, due to the evident risk of filling the bag with clay and stones, resulting in torn bag and/or broken ground-gear. Hence, the bag used in the experiment was made of more durable materials. The upper panel was made of a double Ø5 mm PE, whilst the lower panel was made of double Ø6 mm PA and covered with a protection mat ("dollies") along the codend (Figure B.3, in Appendix B). Like the trawl codend, the retainer bag had an inner nominal mesh size of 135 mm (see section 2.2.4).

Another precaution for preventing destroying the retainer bags due to large rocks inside the codend was an opening made for stone emissions (Figure B.3 in Appendix B). In order to prevent fish escaping, the stone release opening was covered with a "dolly" having positive buoyancy, and therefore only opened due to the weight of sizeable stones falling out. After suspecting possible escapement of fish trough the stone emission opening, the opening was modified before the cruise in February 2015. The new opening was formed as a diamond by bar cut, 8 x 8 #, hold together by a 12 mm rope with 10% shrinkage. The opening was covered by a long "dolly" with increased positive buoyancy due to an additional 8″ float.

Due to the heavy construction and possible distortion of the trawl configuration as well as the evident risk of destroying the retainer bags, it was decided to use only one retainer bag, covering the track of the center-section of the ground rope. The headline of the retainer bag was attached to the fishing line of the trawl. The 6.6 m long fishing line of the retainer bag was made of Ø18 mm combi-rope and equipped with an approximately 75 kg heavy ground-gear. The ground-gear was made of 19 mm LL chain and inserted with steel fillers (Figure B.4 in Appendix B). To ensure proper bottom contact, 10 kg of chain clumps were attached on the wingtips of the retainer bag on each side. The chain clumps and a small chain bit attached to the ground-gear were visual inspected after each haul for polishing, i.e. meaning that the ground-gear had proper bottom contact during towing. After each haul the entire retainer bag was visual inspected for holes or other damages, i.e.

torn ground rope. If any holes were detected or the ground-rope was broken the haul was considered invalid.

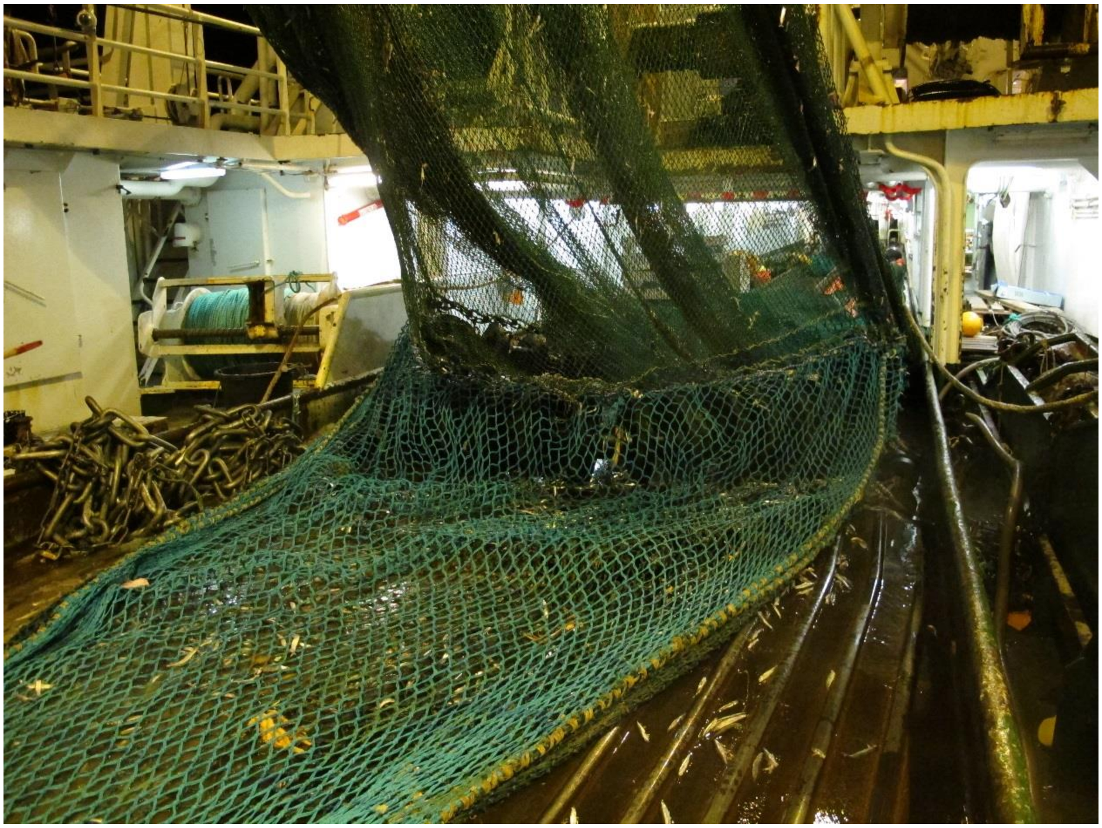

Figure 2.7 The escape retainer bag attached to the trawls fishing line covering the center-section of the ground-gear.

2.2.4 Codend mesh size

The purpose of the trials was to investigate the escapement of cod and haddock (and snow crab in November 2014) underneath the fishing line in the commercial trawl fishery, and compare the rate of escapement for the two different ground-gears. Hence, the mesh size of the trawl codend and the retainer bag were sat to the former minimum legal mesh size of 135 mm, in accordance with the Norwegian Law for Exploration of Sea Resources (Ot.prp. nr. 20 (2007-2008)). Since 2011 the minimum legal mesh size was reduced to 130 mm (Fiskeridirektoratet, 2014). Another important reason for choosing a relative large mesh size is due to the environmental conditions under which the trials were conducted. Typical for the fishing grounds around Hopen, Sentralbanken and Nordbanken is a sea bed consisting of soft clay and stones of any size. This is seldom causing problems for the trawl, although the otter boards get stuck in the clay relative frequently. But due to these conditions, the risk for damaging the retainer bag and its ground rope was considered evident. The relative large meshes were assumed to prevent clay aggregating inside the codend by filtering the clay through the meshes. For being able to detect any size dependent escapement the mesh size in the trawl codend and in the retainer bag had to be of equal size. Lastly, from own experience from other trials and as reflected by the results, the aggregations of pre-spawning NEA cod in these areas consists mainly of large fish, i.e. the majority of fish is larger than 60-70 cm. This is well above the minimum landing size and the predicted L_{50}-value (50% retention length) for cod with a codend mesh of 135 mm (Sistiaga et al., 2010).

2.3 Data collection

The main data for this thesis consists of length measurements from the catch in the codend and retainer bag. Towing time was restricted to maximum 90 minutes or shorter if the catch sensor revealed catch rates higher than 2-3 tons. The catch from the retainer bag and the main codend were kept in separate bins onboard. All fish were length measured, rounded to the lowest centimeter, and registered manually, i.e. no subsampling was performed. For both cruises ambient water temperature was recorded for all hauls. During the cruise in November 2014 the temperature was logged each 30 second throughout the entire haul using a Scanmar sensor. The temperature data from February 2015 was logged by a TDR – MK9 sensor from Wildlife Computers attached behind the headline of the trawl. This sensor was set to measure depth, temperature, and light intensity each 30 second. The initial intention was to measure the light intensity at depth for investigating the effect of light intensity on the escapement rate. Unfortunately the sensor logged relative light intensity and we were not able to calibrate the readings provided from the sensor adequately.

2.3.1 Trawl monitoring

For the cruise in November 2014 the trawl was monitored by a set of Marport sensors and a set of Scanmar sensors. All information from both systems was logged. The Marport system consisted of a pair of sensors measuring the spread of the otter boards and ambient temperature, and a pair of echo sounders measuring the clearance to the sea bed (Figure 2.8). This information was mainly used for controlling the trawl doors, i.e. keeping the doors stable at ca. 5 m of the sea bed. The Scanmar system consisted of a pair of sensors measuring the door spread, catch sensors, a trawl eye measuring the vertical trawl height and bottom contact, as well as temperature.

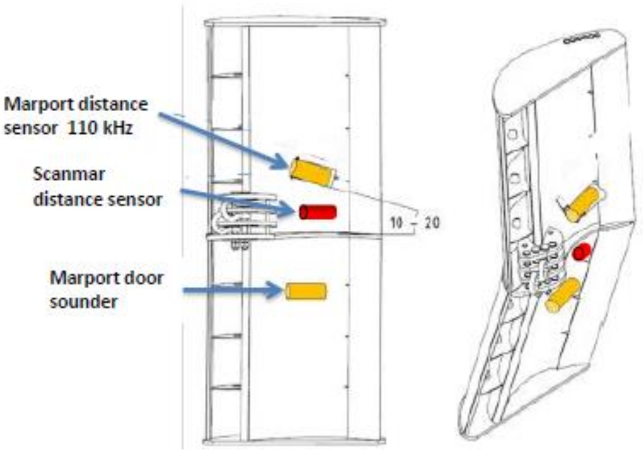

Figure 2.8 The positioning of the Marport sensor and door sounder (yellow) and the Scanmar sensor (orange) (Larsen, 2014[4]).

For the cruise in February 2015, when using bottom trawl otter boards, only the Scanmar sensors were used.

2.3.2 Underwater cameras

For the cruise in November 2014, five of the 22 valid hauls with the standard rock-hopper gear, and four of the 19 valid hauls with the semicircular gear, were conducted with cameras (Table 2.1, p. 6). All recordings were conducted with the use of artificial light. This was necessary due to the total absence of solar radiation in the study area during the time the experiments were preformed,

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[4] Larsen, R., 2014. Trawl setup and details during fish trawl experiments November 2014. University of Tromsø – Norwegian College of Fisheries Science.

as well due to the large depths. A downside of this method is that it possibly affects the behavior of fish, resulting in biased estimates of the escapement under the fishing line. As mentioned earlier the sea bed consisted mainly of soft clay and rocks. Due to the turbulence causing sediment disturbance and thus reduced or no visibility, this is often the biggest challenge when attempting to film trawls underwater. Artificial light causes even larger challenges since particles in the water are backscattered, resulting in even further reduced visibility. These problems have resulted in only one haul of each gear that are of adequate quality for analyzing. The area observed was the central part of the ground-gear covered by the retainer bag. The recordings were made with three different cameras with different light-systems (Table 2.3), positioned in different ways (Figure 2.9). The numbers in Figure 2.9 refer to the setup numbers in Table 2.3.

Table 2.3 The different cameras and light-system used for filming the center-section of the ground-gear.

Setup	**Camera**	**Light-system**	**Haul #**
1	Simrad OE 1324 low light camera with self-contained recorder	2x neon lights: - 9 W - 600 lumen - 4000 Kelvin	10 37 38 43
2	Gopro (Hero 2 and Hero 3), in special housings depth rated to 240m.	Metalsub halogen: - 50 W - 1500 Lumen - 3200 Kelvin	5 6 17*
3	Gopro (Hero 2 and Hero 3), in special housings depth rated to 240m.	2(4)x Metalsub led: - 27 W - 2000 lumen - 5000 Kelvin	2 47* 17*

* Haul 47 was conducted with 4x metalsub led lights. Haul 17 was conducted with 2x metalsub led lights and 1x metalsub halogen light.

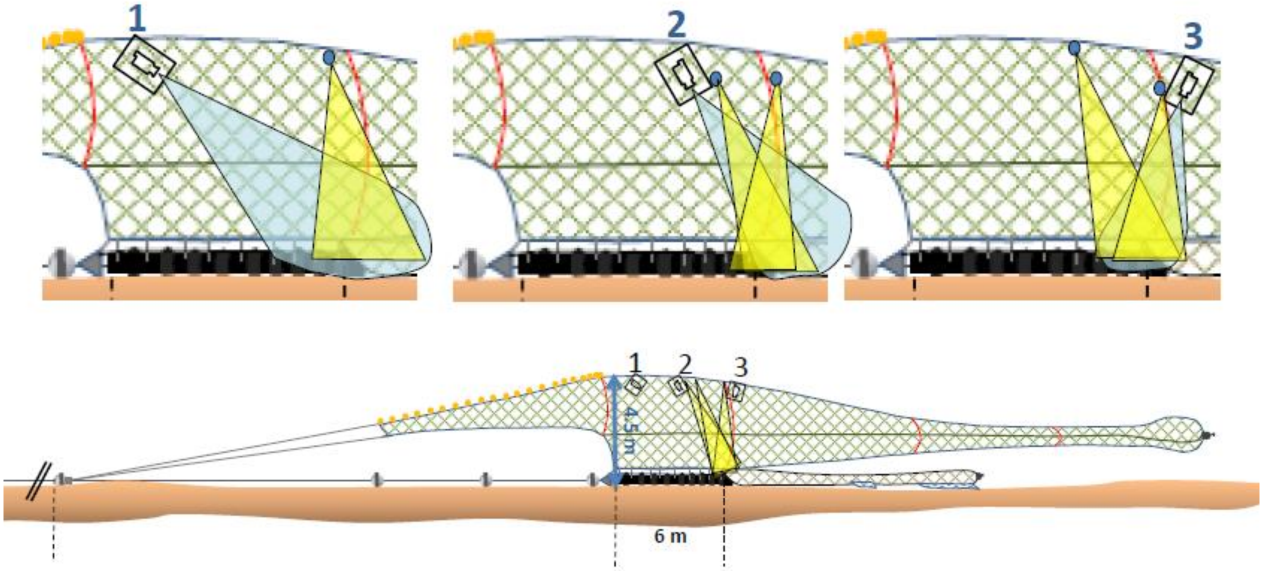

Figure 2.9 Positioning of the cameras and light sources during the trials in November 2014. The numbers refer to the setup numbers in Table 2.3) (Larsen, 2014[5]).

For the cruise in February 2015, both Gopro Hero 3 and 4 with special housings rated to 240 m were used for all recordings. Since the hauls for observations were conducted in a shallow area (60-80m), no artificial light was required. Unfortunately, due to the environmental conditions, i.e. large stones resulting in torn/split retainer bags, none of these hauls are valid for statistical analysis.

2.4 Statistical methods

Most of the statistical data analysis were conducted in the software SELNET (developed by Bent Herrmann). The results were exported to R, version 3.0.2, for graphical presentation (R Core Team, 2013). The escapement underneath the ground-gears can be regarded as a form of selection. Previous conducted studies have shown that the majority of escapement takes place in the center-part of the ground-gear and that the escapement on the sides is limited (Main and Sangster, 1981; Walsh 1992; Ingólfsson and Jørgensen, 2006; Krag et al., 2010). Since the retainer bag only

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[5] Larsen, R., 2014. Trawl setup and details during fish trawl experiments November 2014. University of Tromsø – Norwegian College of Fisheries Science.

covered the center-part of the ground-gear any inference will be limited to the area covered by the retainer bag. The experimental efficiency of the ground-gear can be quantified by:

$$EG_l = \frac{nc_l}{nc_l + \ nr_l} \tag{1}$$

Ideally EG_l should be close to 1.0 for all sizes *l*. It is reasonable to assume that several extrinsic factors affect different length groups before retention in one of the codends. EG_l can besides the efficiency of the ground-gear (GG_l) be affected by size selection in the trawl body (RB_l), and codend (RC_l), and size selection in the retainer bag (RR_l). Modelling EG_l leads to the following equation:

$$EG(l) \ = \ \frac{GG(l)\ x\ RB(l)\ x\ RC(l)}{GG(l)\ x\ RB(l)\ x\ RC(l) + (1 - GG(l))\ \ x\ RR(l)} \tag{2}$$

For equation (2) we see that in case RB_l, RC_l and *RR* all are close to 1.0, meaning close to their selective upper limit, the *EG* becomes a good approximation of the total *GG*. The trawl body (RB_l) with a nominal mesh size of 80 mm, and both codends (RC_l and RR_l) with a nominal mesh size of 135 mm, are believed to influence the efficiency curve. A conservative threshold limit for 100% retention was set at fish length of 65 cm for cod, and 62 cm for haddock. Several selectivity studies have shown that with a 135 mm codend it is reasonable to assume 100% retention of cod with a length well below 65 cm (Kvamme and Isaksen, 2004; Jørgensen et al., 2006; Sistiaga et al., 2010). The same was found for haddock at a length below 62 cm (Sistiaga et al., 2010). This means that it is reasonable to assume that the extrinsic selection processes (RB_l, RC_l and RR_l), may contribute to the curvature for fish with a length *l* below 65 cm for cod and 62 cm for haddock, and that the curvature for fish above this length solely can be explained by the ground-gear selection process (GG_l). Equation (2) models the selection for fish of all lengths, i.e. by taking all possible known selection processes into consideration.

The experimental data consist of binominal count-data for the different length groups (1 cm wide). It is binominal since fish are observed either in the codend or in the retainer bag. Based on these data we can estimate the curvature of a model for *EG* (*l*) by using maximum likelihood estimation by minimizing the following equation:

$$-\sum\nolimits_l \sum_{i=1}^{h} \{nc_{li}\ x\ \ln\big(EG(l,\boldsymbol{v})\big) + \ nr_{li}\ x\ \ln(1 - EG(l,\boldsymbol{v}))\} \tag{3}$$

Now we need to find an empirical model for *EG* (*l*, *v*) that is sufficiently flexible to account for the curvature, considering all the different processes potentially affecting *EG* (*l*), i.e. *GG* (*l*), *RB* (*l*), *RR* (*l*), *RC* (*l*).

Equation (1) is on a form which is often applied in catch comparison (*CC*) studies for the efficiency/selectivity of fishing gears (Krag et al., 2014). Therefore we adapt a model often applied for such also to model *EG* (*l*):

$$EG(l, v) = \frac{\exp(f(l, v))}{1.0 + \exp(f(l, v))} \tag{4}$$

Where f is a polynomial of order k with coefficients $v_0, \ldots, v_k$ so $\boldsymbol{v} = (v_0, \ldots, v_k)$. Thus *EG* (*l*,*v*) expresses the probability of finding a fish of length *l* in the codend given it is observed in the codend or retainer bag. A probability of 0.5 for *EG* (*l*,*v*) implies equal probability of finding a fish of length *l* in the codend or retainer bag.

We use $f(l,\boldsymbol{v})$ on the following formula:

$$f(l, \boldsymbol{v}) = \sum_{i=0}^{k} v_i \; x \left(\frac{l}{100}\right)^{i} = v_0 + \; v_1 \; \frac{l}{100} + v_2 \frac{l^2}{100^2} + \cdots + v_k \; \frac{l^k}{100^k} \tag{5}$$

We considered *k* up to four, leading to in total 32 different models which could be constructed based on equation (5) by leaving out one or more terms at the time. Since several factors affect the selection process for different length groups the nature of this ground-gear selection process is unknown, and gives therefore no criterion for model choosing. Therefore model averaging was applied based on the 32 competing models considered. Thus, multi-model inference was assumed to provide the most representative and robust results, and least possible amount of uncertainty (Katsanevakis, 2006). This multi-model inference is thus based on averaging the 32 different models, ranked in accordance to the AIC-values, i.e. the model with the lowest AIC-value is weighted most (Akaike, 1974). Another advantage of model averaging is that valuable information that is not necessarily obtained from the “best” model is taken into account by one or several of the other models (Burnham et al., 2011). In order to estimate Efrons percentile 95% confidence limits, double bootstrapping was applied. With this non-parametric double bootstrapping method both between-haul variation and within haul variation are taken into account (Sistiaga et al., 2015). The number of bootstrap iterations were set to 2000. The results obtained from the multi model inference for cod with a length above 65 cm, and haddock with a length above 62 cm, can solely be explained as ground-gear efficiency.

The average value for the EG_l, integrated for all lengths above the established limit for cod (65 cm) and haddock (62cm) was estimated in SELNET using the following equation:

$$EG = \sum_{l} \sum_{i=1}^{h} \frac{nc_l}{nc_l + nr_l} \tag{6}$$

For calculating 95% confidence limit the same procedure was applied as described earlier. In contrast to the length dependent evaluation of the efficiency calculated as described in the section above, the EG calculated using equation (6) is specific for the population encountered during the trail periods/areas, and should thus not be extrapolated to other scenarios.

For investigating the effect of diurnal variability the hauls conducted under nocturnal conditions, and the hauls conducted under diel conditions, were analyzed separately with multi model inference and 2000 double-bootstrap iterations. For investigating the effect of artificial light the same analysis was run for the hauls conducted with and without artificial light. A similar approach with multi model inference with 2000 double-bootstrapping iterations was used for investigating any correlation between fish density and the escapement rate, only this time the data was analyzed for each haul individually. The results were exported to R, were a simple linear model was applied in order to detect any correlation between fish density and escapement rate. The same approach was used for investigating any correlation between water temperature and the escapement rate.

3. Results

3.1 Environmental conditions and trawl performance

The data obtained from the first cruise in November 2014 is sampled from a large area (Figure 2.1, p. 7). The rock-hopper gear was applied in the first 25 hauls before changing to the SCSG for the last 22 hauls. The explanation to the separate periods and areas with the two types of ground-gears is that part of the experiments ongoing simultaneously were dedicated to investigations on how snow crab encounter the conventional rock-hopper gear. The area with snow crab was gradually packed by drift-ice and we and the rest of commercial fleet targeting cod were forced to change area. The gear and the study area were changed simultaneously, as Figure 2.1 (p. 7) shows. The use of semi-pelagic otter boars resulted in some unstable behavior of the otter boards especially during conditions with high waves, i.e. the otter boards lifting to high above the seabed. This problem was mitigated by increasing the trawl speed from ~3.4-3.5 knots to ~3.7-3.8 knots. The weather conditions, known to affect the trawl performance (O'Neill et al., 2003) varied between calm weather and full storm. The chain attached to the ground-gear of the retainer bag was polished after each tow, confirming proper bottom contact of the retainer bag. If any holes were detected the hauls were considered invalid. The holes were fixed prior to the next tow. Since the seabed in the study area consisted of large stones and clay, resulting in numerous invalid hauls, confirmed the importance of the stone emission opening in the retainer bag (Figure 3.1).

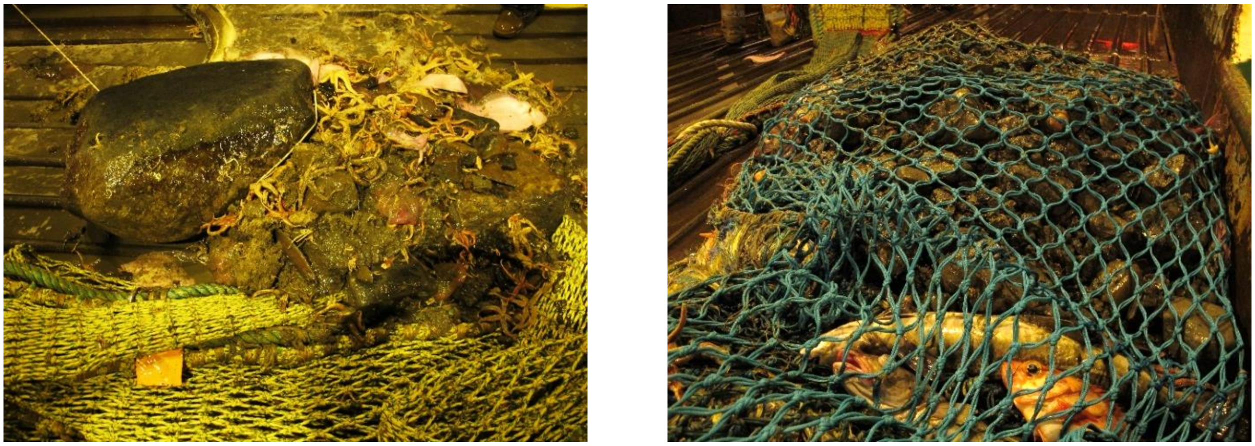

Figure 3.1 Catch in the retainer bag, often causing invalid hauls, as well as confirming proper bottom contact of the retainer bag.

The data obtained from the second cruise in February 2015 was sampled from a small area (Figure 2.2, p. 9). The data was sampled in an alternate haul setup, i.e. shifting between the two ground-gears (every second haul) so that the data was sampled pairwise (Table 2.2, p. 8). Since we used conventional otter boards for bottom trawling on this cruise, no problems with trawl performance were encountered, beside of the usual impact of high waves due to some bad weather. The bottom conditions in the shallow area where the video footages were taken consisted of gravel/sand with large stones, resulting in none valid hauls for gear comparison. Nevertheless, the hauls provided adequate video footage for observing the performance of the trawl, retainer bag and ground-gear, as well as fish behavior. The problem with torn/split retainer bags was mitigated by moving into deeper water where the seabed consisted of soft clay.

After suspecting possible escapement of fish through the stone emission opening during the first cruise, the opening was modified as described in section 2.2.3 (p. 13), prior the second cruise. Video recordings of the modified stone release opening showed little or no escape possibilities (Figure 3.2). Interestingly fish were observed calmly swimming back and forth inside the retainer bag during haul-back start (Figure 3.2B). Unfortunately we were not able to obtain adequate video footage of the former stone emission opening.

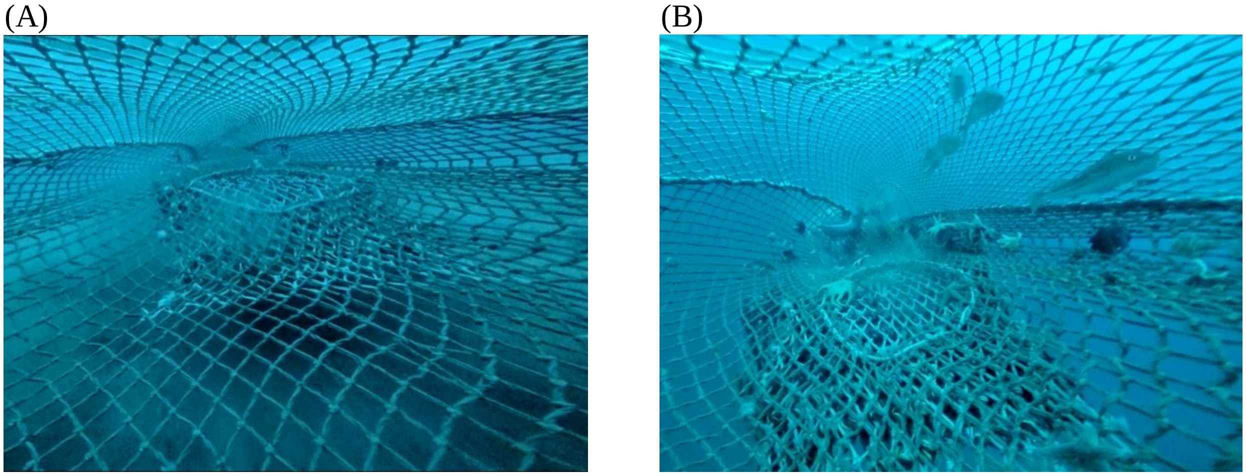

Figure 3.2 Still photos taken from video footage at hauling start showing the modified stone emission opening (A and B), and fish calmly swimming inside the retainer bag during haul-back (B). (Picture brightness is increased by 20%).

3.2 The data sampled

A total of 15 358 cod and 1682 haddock were caught and measured during both cruises (Table 3.1). Due to possible confounding, the length measurements of fish for the hauls conducted with artificial light are not included, besides when analyzing the effect of artificial light on the escapement rate. For number of fish caught for each haul individually see Table C.1 and C.2 in Appendix C. The numbers of fish caught per haul varied greatly, ranging from 28 to 1456 in the first cruise during November 2014 (Table C.1 in Appendix C). In the second cruise during February 2015 the numbers of cod varied between 72 and 417, while the numbers of haddock ranged from 13 to 174 (Table C.2 in Appendix C). As provided by Table 3.1 it appears to be a clear difference in the escapement rate between the two types of ground-gear for both species for all length-classes.

Table 3.1 Number of fish caught and measured.

	Rock-hopper				**SCSG**			
	# Hauls	**Codend**	**Retainer bag**	**Total**	**# Hauls**	**Codend**	**Retainer bag**	**Total**
Cod (Nov. 2014)	16	2887	872	3759	16	7127	485	7612
Cod (Feb. 2015)	13	1656	128	1784	13	2133	70	2203
SUM	**29**	**4543**	**1000**	**5543**	**29**	**9260**	**555**	**9815**
Haddock	13	836	64	**900**	13	766	16	**782**

Since we used a 135 mm codend in both the trawl and retainer bag, the escapement rate cannot solely be explained due the process of ground-gear selection. As argued a reasonable and conservative limit, were we can assume 100% retention in the codend, and where any kind of selection solely can be explained due to ground-gear selection, is at length 65 cm for cod and 62 cm for haddock. Figure 3.3A shows that the cod caught in both study areas at that time, had a main length distribution well above the established limit. On the basis of Figure 3.3A it is reasonable to assume that the amount of cod under the established limit for 100% retention was very limited in both study areas at that time. The average fish length calculated from all hauls for cod was 80.14 cm (SD ± 12.12) in November 2014 and 86.56 cm (SD ± 15.06) in February 2015. As for haddock a reasonable and conservative limit was set at 62 cm. This results into a very limited area that can be explained solely due to ground-gear selection (Figure 3.3B). The average length for the haddock caught was 55.89 cm (SD ± 5.63).

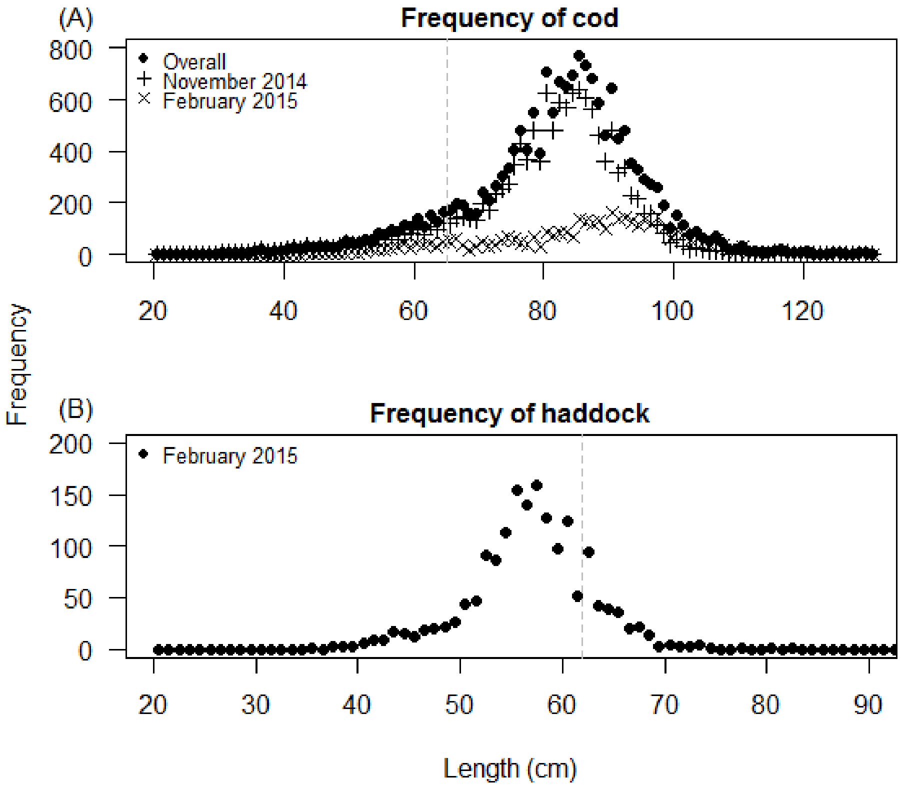

Figure 3.3 Length distribution of cod (A) and haddock (B) caught in the study areas, implying that the existing population of cod had a length distribution well above the established limit of 65 cm (grey dashed line), while the main haddock population had a main length distribution beneath the established limit of 62 cm.

The experimental efficiency, the modeled efficiency with confidence limits, and the catch frequency for each length class for both the codend and the retainer bag are shown in Figure 3.4-3.6. The length distribution in the data shows in addition to number of fish caught for each length group, also the distribution of power in the data. The width of the confidence limits for the modeled efficiency clearly coincides with the experimental efficiency and the distribution of power in the data.

It appears to be a clear difference in the rate of escapement between the rock-hopper gear (Figure 3.4A) and the SCSG (Figure 3.4B) for all length classes for the data from November 2014. The difference is not that large for the data from February 2015 (Figure 3.4C and 3.4D). The length distribution of fish in the codends between the data from November 2014 (Figure 3.4A and 3.4B), and the data from February 2015 (Figure 3.4C and 3.4D), indicate a shift in average fish length.

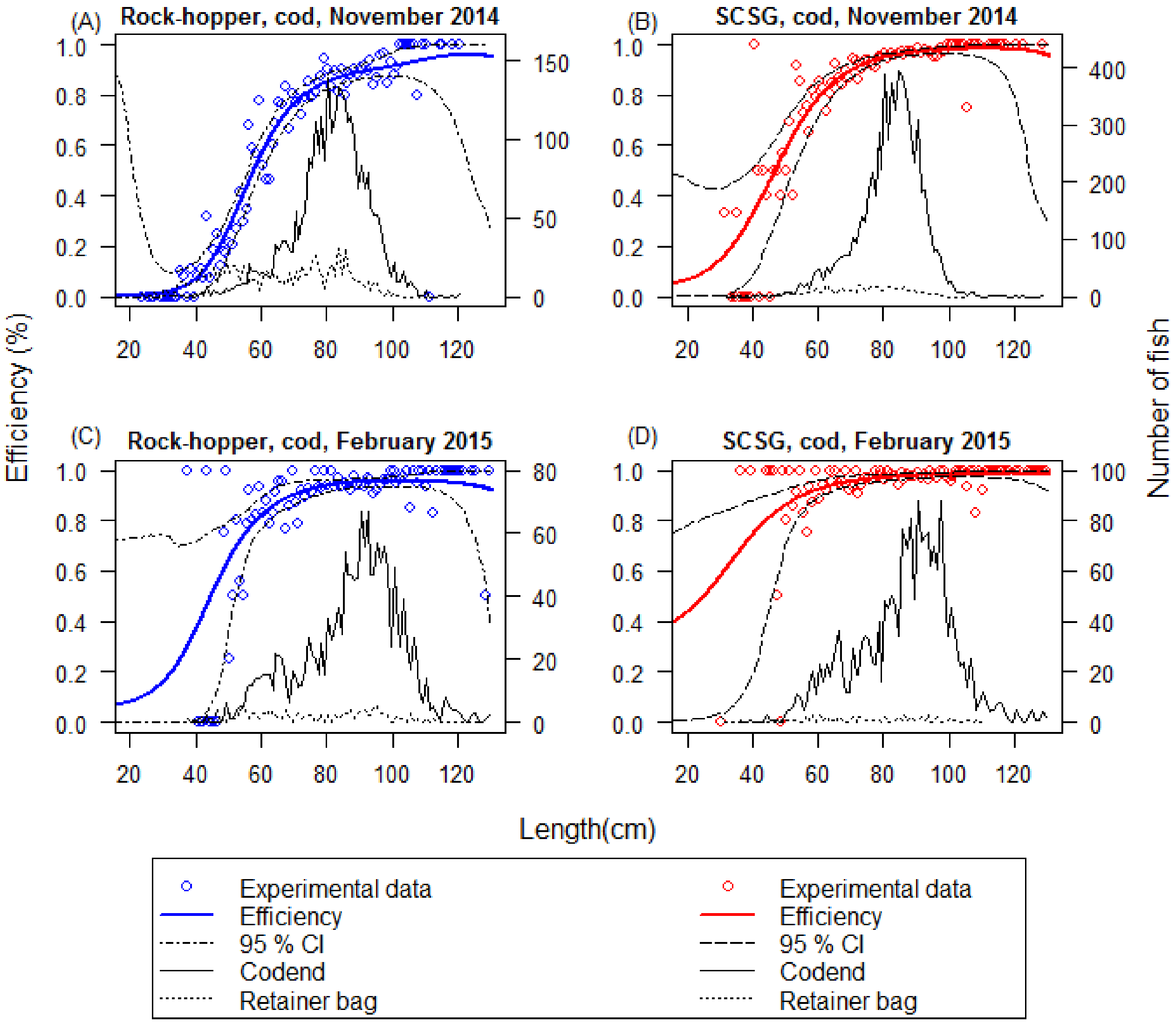

Figure 3.4 The catch efficiency for cod with confidence limits for the rock-hopper gear and SCSG for both cruises. The frequency of fish for codend and retainer bag show the length distribution of fish as well as the distribution of power in the data.

Due to few measurements of low efficiency the confidence limit in Figure 3.5B of the SCSG are wide in that specific area compared to the confidence limits for the rock-hopper gear in Figure 3.5A. The same is observed when comparing the data from November 2014 and February 2015 for the same ground-gear (Figure 3.4). Some of the hauls conducted with the SCSG resulted in large catches due to high fish density, resulting in much higher total number of fish caught with the SCSG, than the total number of fish caught with the rock-hopper gear (Figure 3.4 and 3.5).

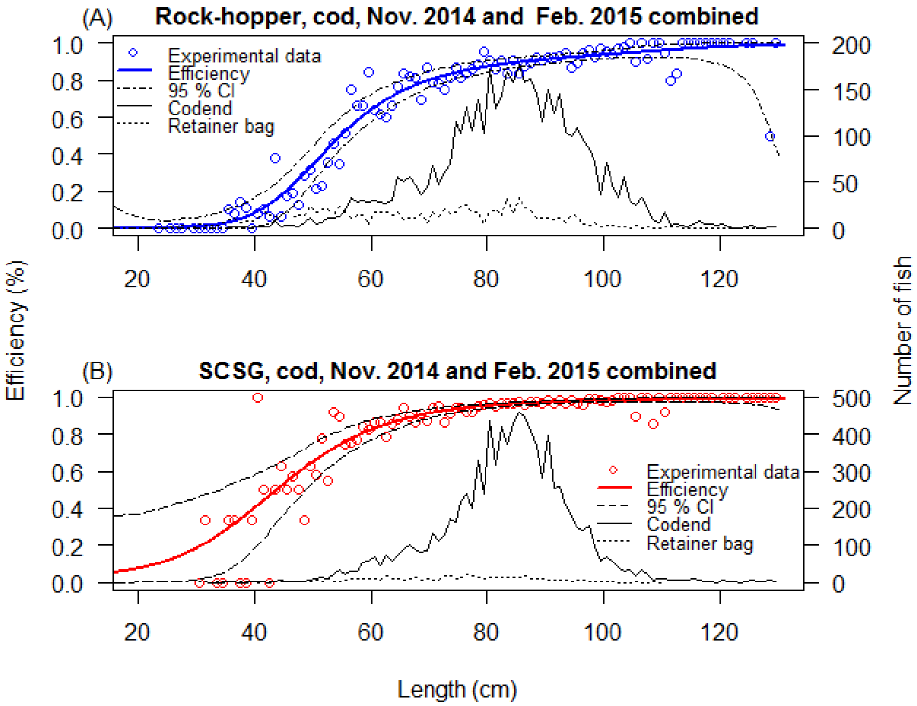

Figure 3.5 The catch efficiency for cod with confidence limits for the rock-hopper gear (A) and SCSG (B) for the data from both cruises summarized. The frequency of fish for codend and retainer bag show the length distribution of fish as well as the distribution of power in the data.

As for the catches of haddock they only constituted a small part of the total catches and the length distribution is considerably narrower compared to length distribution of cod (Figure 3.6).

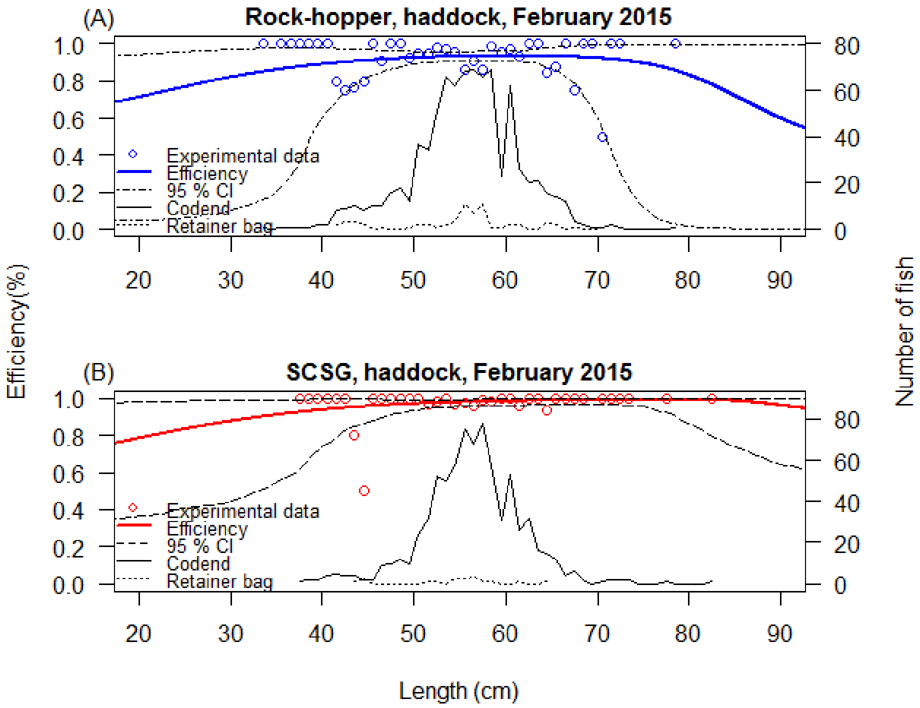

Figure 3.6 The catch efficiency for haddock with confidence limits for the rock-hopper gear and SCSG for both cruises. The frequency of fish for codend and retainer bag show the distribution of power in the data.

3.3 Comparing the rate of escapement between the two ground-gears

Any significant difference in catch efficiency for a given length group is verified under the condition that there is no overlapping between the confidence intervals for the hauls conducted with the rock-hopper gear and the SCSG. The escapement rate is inversely proportional to the catch efficiency. Figure 3.7A confirms a significant difference in the catch efficiency/escapement rate between the hauls conducted with the rock-hopper gear and the SCSG in November 2014. The difference is significant both below and above the established limit of 65 cm (grey dashed line), where all difference above the limit solely is caused due to ground-gear selection. The difference between the hauls conducted with both ground-gears for the data from February 2015 is as well significant, but for fewer length groups compared to the data from November 2014 (Figure 3.7B-I). Figure 3.7B-II is an enlarged version of Figure 3.7B-I, and shows that there is significant difference between the hauls conducted with the rock-hopper gear and the SCSG both above and below the established limit of 65 cm.

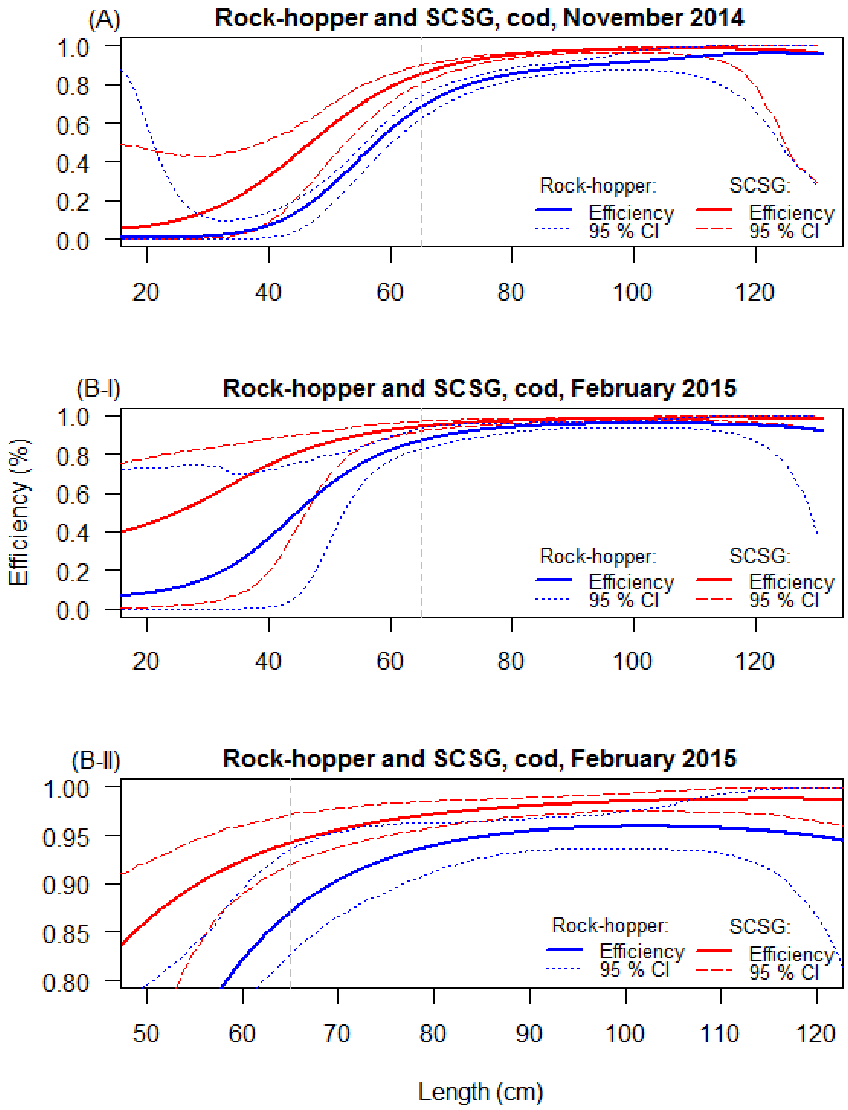

Figure 3.7 Comparison of the catch efficiency for cod between hauls conducted with the rock-hopper gear and SCSG in November 2014 (A) and February 2015(B-1). B-II is an expanded version of B-I, in the area of interest. The grey dashed line shows the established limit for cod at 65 cm length.

Comparing the efficiency for the rock-hopper gear from November 2014 and February 2015 shows clearly a significant difference in efficiency between the two time periods/areas (Figure 3.8A). The data from February 2015 showing higher efficiency than the data from November 2014, is significantly different both below and above the established limit of 65 cm for cod. Although the significant difference is less compared to the rock-hopper gear the same applies for the SCSG (Figure 3.8B-I). Figure 3.8B-II is an enlarged version of Figure 3.8B-I.

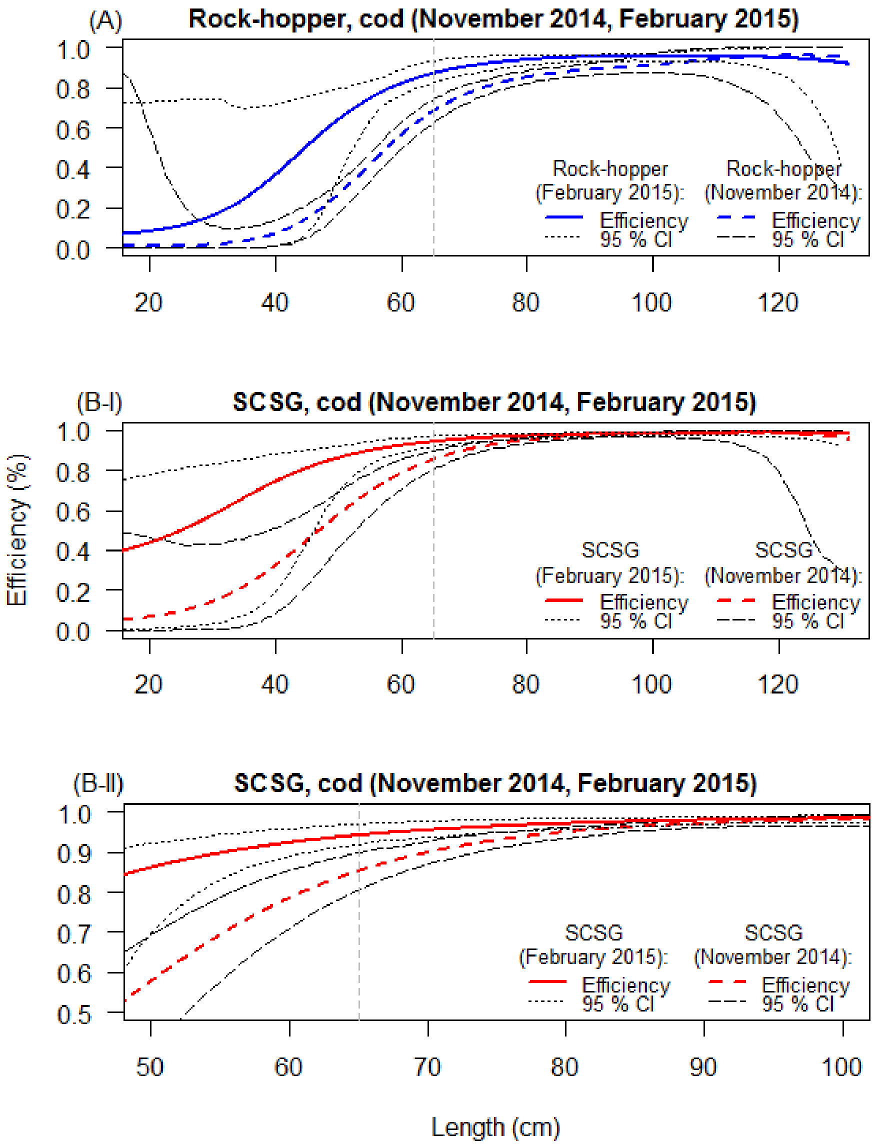

Figure 3.8 The difference in catch efficiency of cod for the data from November 2014 and February 2015 for the hauls conducted with rock-hopper gear (A) and SCSG (B-I). B-II is an expanded version of B-I, in the area of interest. The grey dashed line shows the established limit for cod at 65 cm length.

Based on the overall data from November 2014 and February 2015, Figure 3.9 confirms a significant difference between the hauls conducted with the rock-hopper gear and the SCSG. This significant difference applies for all length groups between 39 cm and 105 cm (Figure 3.9). Thus, both above and below the 65 cm limit, where the curvature above the limit solely is caused due to ground-gear selection.

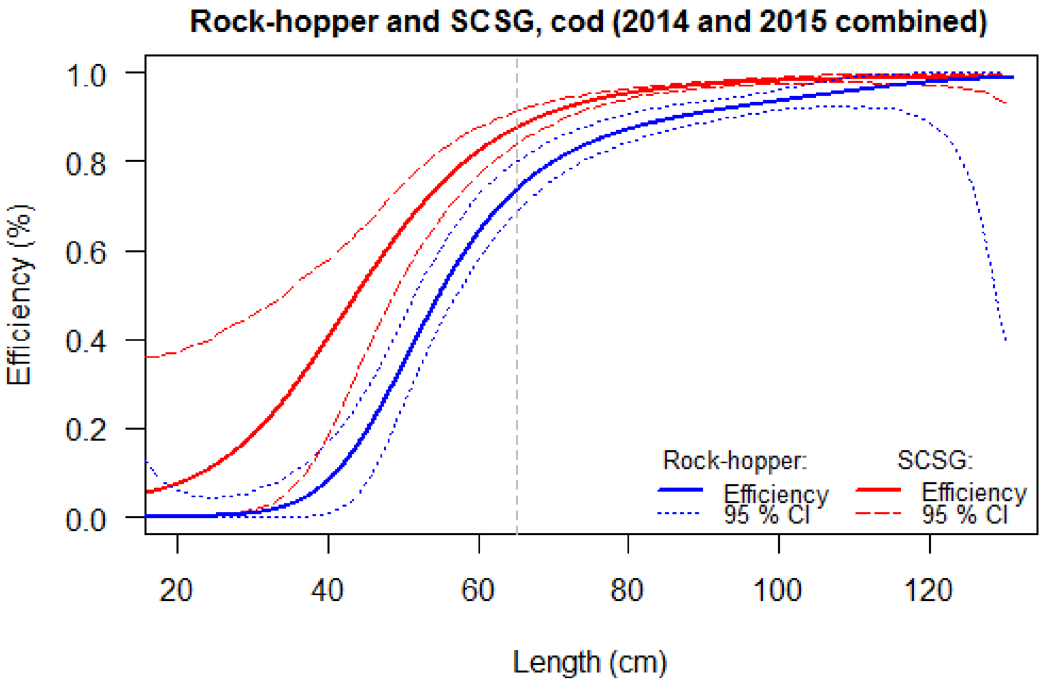

Figure 3.9 The overall difference in catch efficiency for cod between the hauls conducted with the rock-hopper gear and the SCSG for the data from both cruises. The grey dashed line shows the established limit for cod at 65 cm length.

The catch efficiency for haddock is not significantly different between the hauls conducted with the rock-hopper gear and the SCSG (Figure 3.10A-I). Figure 3.10A-II is an enlarged version of Figure 3.10A-I. The calculations that provide the confidence limits in Figure 3.10A show that the lower confidence limit for the hauls with the SCSG, and the upper confidence limit for the hauls with the rock-hopper gear are equal for haddock between 55 cm and 61cm.

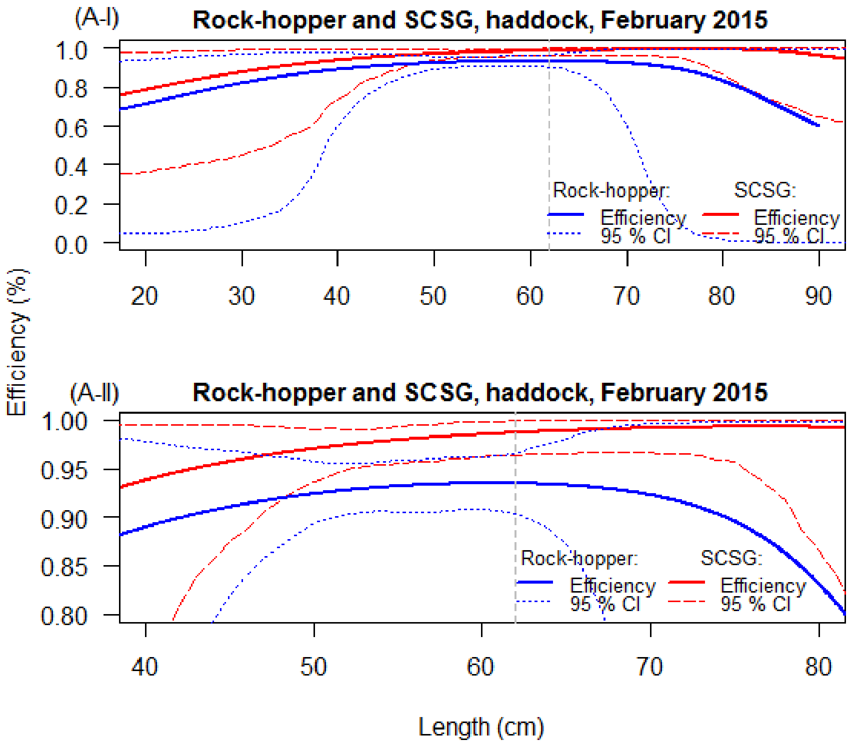

Figure 3.10 Catch efficiency for haddock for the hauls conducted with the rock-hopper gear and the SCSG in February 2015 (A-I). A-II is an expanded version of A-I, in the area of interest. The grey dashed line shows the established limit for haddock at 62 cm length.

The average ground-gear efficiency with 95% confidence limits, integrated for all cod with length above 65 cm and haddock above 62 cm, is computed in SELNET by applying equation (6), p. 21 (Table 3.2). The improved efficiency is then calculated by the percentage difference in the catch efficiency values provided from equation (6), between the rock-hopper gear and the SCSG. The results presented in Table 3.2 show a significant improvement in overall catch efficiency for all cod above 65 cm with the SCSG. In contrast to the length dependent evaluation of the efficiency described in Figure 3.7, Figure 3.9 and Figure 3.10, the average ground-gear efficiency calculated using equation (6) is specific for the population encountered during the trail periods/areas, and should thus not be extrapolated to other scenarios.

The rate of escapement for the rock-hopper gear and the SCSG for all cod above 65 cm, and haddock above 62 cm, is calculated by computing the inverse catch efficiency. The reduced escapement is calculated with the percentage difference in the escapement rate between the rock-hopper gear and the SCSG. The results presented in Table 3.2 show a considerable reduction in the overall rate of escapement for all cod above 65 cm for the SCSG. As presented in Table 3.2 there is a statistical significant increase in the efficiency, i.e. reduction in the escapement, for the SCSG for both periods for cod. The confidence limits also confirm a significant difference between the two periods, especially for the rock-hopper gear. For haddock the statistical difference in the efficiency, i.e. escapement rate is not significant. Although the difference is not significant, the upper confidence limit for the rock-hopper gear lies only slightly above the lower confidence limit of the SCSG. Nevertheless, the 99% efficiency of the SCSG for haddock is a considerable improvement compared to the efficiency for the rock-hopper gear.

Table 3.2 The summarized efficiency and escapement rate for all cod above 65 and haddock above 62 cm, with 95% confidence limits and the improvement catch efficiency as well as the reduction in escapement in percentages of the SCSG compared to the rock-hopper gear.

Cod > 65 cm	**Efficiency (%) (95% CI)**	**Escapement (%) (95% CI)**	**Improved efficiency (%)**	**Reduced escapement (%)**
Rock-hopper (Nov. 2014)	85.7 (83.9 - 87.9)	14.3 (12.1 - 16.1)	11.1	66.7
SCSG (Nov. 2014)	95.2 (94.2 - 96.4)	4.8 (3.6 - 5.8)		
Rock-hopper (Feb. 2015)	94.8 (93.9 - 95.7)	5.2 (4.3 - 6.1)	3.1	56.7
SCSG (Feb. 2015)	97.7 (96.9 - 98.6)	2.3 (1.4 - 3.1)		
Rock-hopper (Nov. 2014 & Feb. 2015)	88.7 (86.5 - 91.3)	11.3 (8.7 - 13.5)	8.0	63.0
SCSG (Nov. 2014 & Feb. 2015)	95.8 (94.9 - 96.8)	4.2 (3.2 - 5.1)		
Haddock > 62 cm				
Rock-hopper (Feb. 2015)	93.2 (88.4 - 97.7)	6.83 (2.3 - 11.6)	6.2	85.2
SCSG (Feb. 2015)	99.0 (96.8 - 100)	1.0 (0.0 - 3.16)		

3.4 The difference in escapement rate between cod and haddock

Any difference in the escapement rate between cod and haddock is investigated by plotting the catch efficiency for each length group for both species for the same ground-gear (Figure 3.11). Figure 3.11 shows that there is a significant difference in the catch efficiency, i.e. escapement rate, between cod and haddock caught with the rock-hopper gear (Figure 3.11A). The same applies for the cod and haddock caught with the SCSG (Figure 3.11B), although the significance is less compared to the rock-hopper gear.

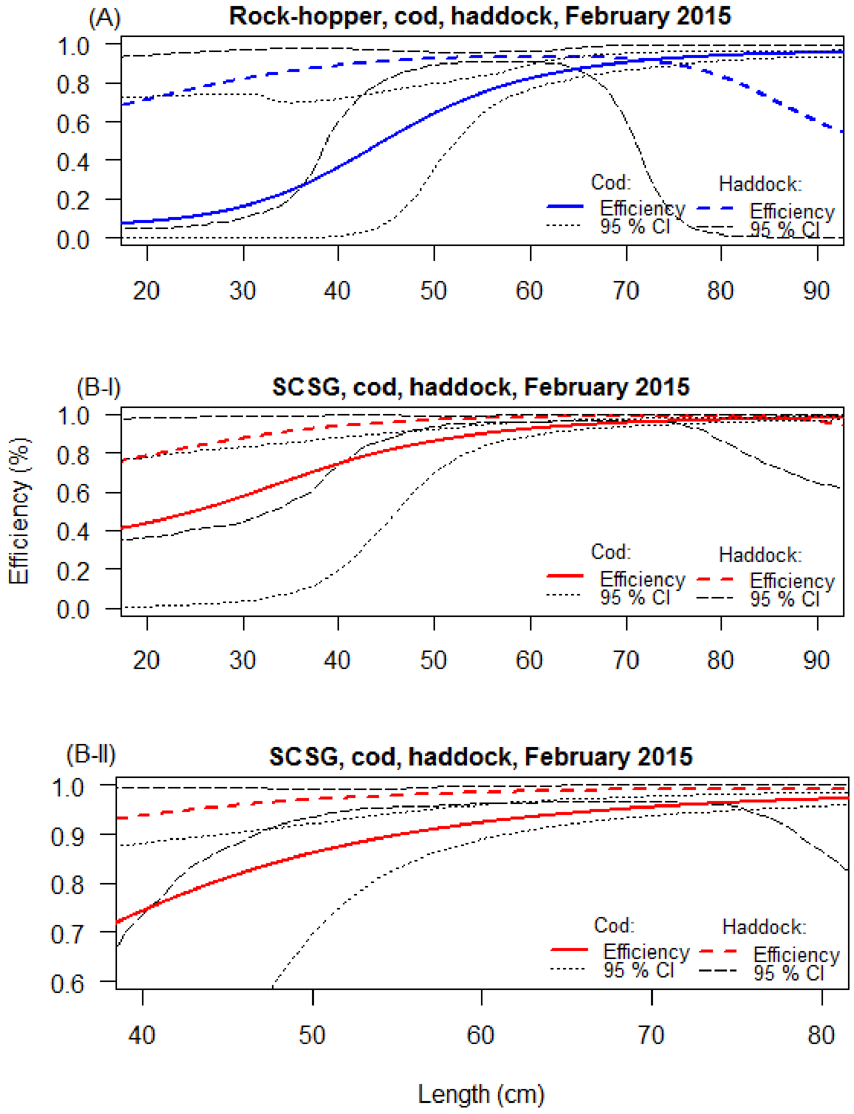

Figure 3.11 The difference in catch efficiency for cod and haddock for the hauls conducted with the rock-hopper gear (A), and the SCSG B-I. B-II is an expanded version of B-I in the area of interest.

3.5 The effect of fish density on the escapement rate

All length groups with 5 cm intervals from 60 cm to 100 cm for cod, and 55 cm to 80 cm for haddock, for both cruises and gear-types, were investigated for any correlation between fish density and the rate of escapement. The linear model showed no significant correlation between fish density and the rate of escapement for any of the cases investigated. This applies for all 66 cases investigated, whereof one of each case is presented in Figure 3.12. See Table C.3 in appendix C for the coefficients for all investigated cases. All p-values are not significant ($p > 0.05$), confirming no correlation (Table 3.3). The adjusted R^2-values are extremely low and reflect the large variance in the data. Based on the data, there is no evidence confirming any correlation between fish density and the rate of escapement. The analysis for the combined data from November 2014 and February 2015 for cod have a lower p-value than the analysis conducted for the periods individually, especially for the rock-hopper gear (Table 3.3 and Table C.3 in appendix C). This could indicate that the data is too weak and that an additional number of hauls should be included in the analysis in order to increase the power of the data and thus reduce uncertainty.

Although there was no correlation between fish density and the escapement rate, there was a clear trend in the difference in catch efficiency between the rock-hopper gear and the SCSG, in favor of the latter one. A clear increase in the catch efficiency with increasing fish length was also obtained.

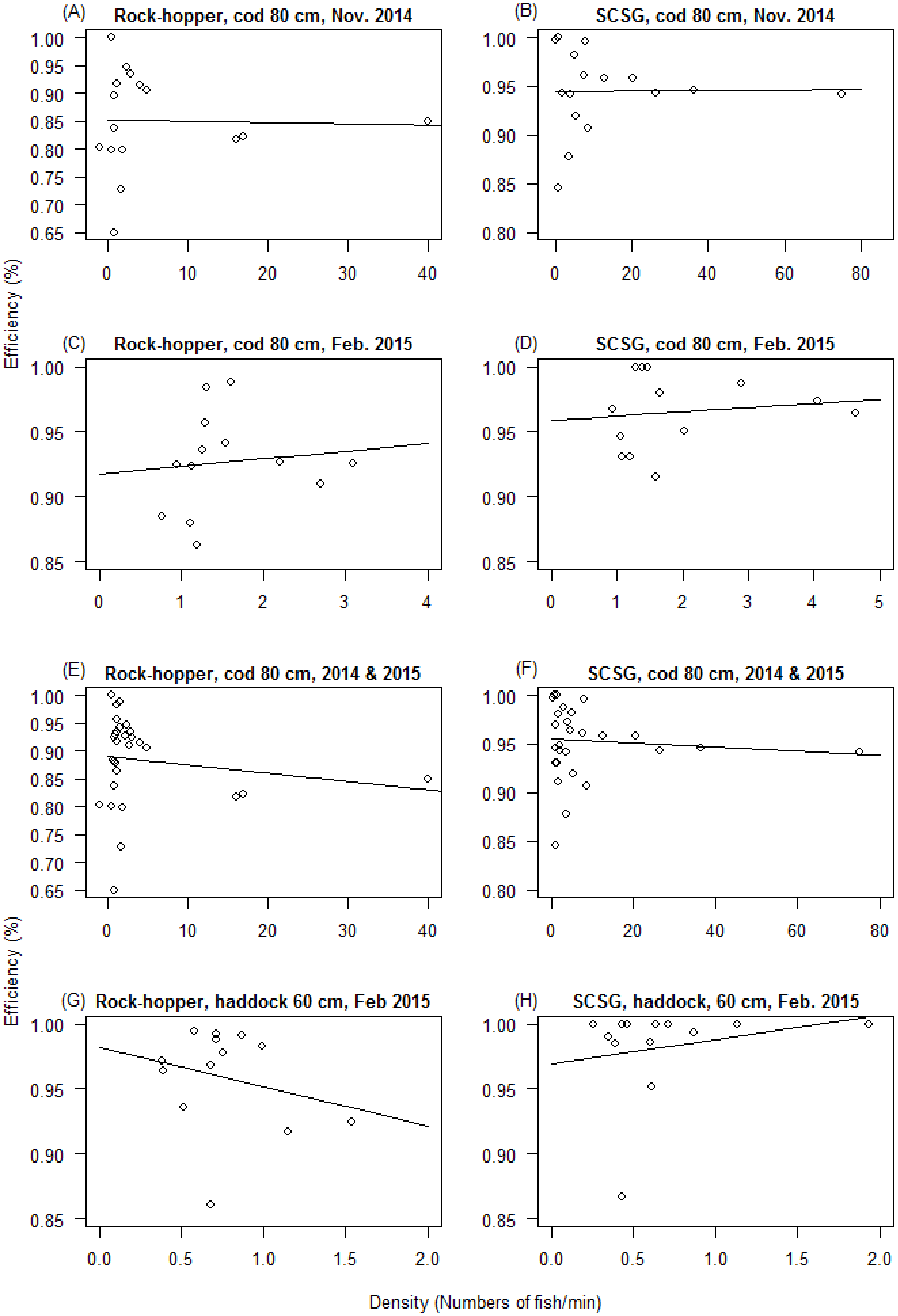

Figure 3.12 Examples from analyses on cod (80 cm) and haddock (60 cm) on the effect of fish density on the rate of escapement. No correlation between fish density and the rate of escapement was found.

Table 3.3 The coefficients provided from the linear models in R presented in Figure 3.12, showing no correlation between fish density and escapement rate as well as large variation in the data. (Call: lm (formula = Efficiency_L ~ catch rate)).

Cod, 80 cm	**Estimate**	**Std. Error**	**Pr(>|t|)**	**Adj. R^2**
Rock-hopper (Nov. 2014)				
Intercept	0.85207	0.02656	1.65E-14	-0.07057
Catch rate	-0.00024	0.00225	0.917	
SCSG (Nov. 2014)				
Intercept	0.94468	0.01355	<2e-16	-0.07127
Catch rate	0.00003	0.00059	0.964	
Rock-hopper (Feb. 2015)				
Intercept	0.91659	0.02701	1.74E-12	-0.07616
Catch rate	0.00622	0.01601	0.705	
SCSG (Feb. 2015)				
Intercept	0.95869	0.01623	4.04E-15	-0.07094
Catch rate	0.00327	0.00721	0.659	
Rock-hopper (2014 & 2015)				
Intercept	0.89019	0.01657	<2e-16	-0.0129
Catch rate	-0.00151	0.00188	0.429	
SCSG (2014 & 2015)				
Intercept	0.95561	0.00815	<2e-16	-0.02909
Catch rate	-0.00022	0.00047	0.652	
Haddock, 60 cm				
Rock-hopper (Feb. 2015)				
Intercept	0.98228	0.02976	2.35E-12	-0.02501
Catch rate	-0.03036	0.03610	0.418	
SCSG (Feb. 2015)				
Intercept	0.96972	0.01984	3.22E-14	-0.03811
Catch rate	0.01851	0.02475	0.47	

3.6 The effect of water temperature on the escapement rate

The water temperature differed substantially between the two areas/periods, with the average temperature being 0.6 °C for the hauls conducted in November 2014, and 5.1 °C for the hauls conducted in February 2015. Any correlation between the water temperature and the rate of escapement was investigated for the length groups from 60 cm to 100 cm for cod, and from 55 cm to 80 cm for haddock with 5 cm intervals and organized with respect to ground-gear. A total of 18 cases were investigated whereof each second case is presented in Figure 3.13. The coefficients are presented in Table 3.4. See Table C.4 in appendix C for the coefficients for all the investigated cases. The linear model showed a positive correlation between the water temperature and the escapement rate for some of the investigated length groups, i.e. increased catch efficiency with temperature (Figure 3.13). Of the 18 cases investigated, 2 cases for the rock-hopper gear showed no correlation (fish length 95 cm and 100 cm), and 4 cases for the SCSG (fish length 85-100 cm) (Table C.4 in Appendix C). In addition a p-value of 0.0504 was calculated for cod with length 60 cm caught with the SCSG, and is thus on the threshold limit for significance/not significant (Table. 3.4). The relative low values of the adjusted R^2 reflect the large variance in the present data. As it appears in Figure 3.13 the temperature from the data obtained during November 2014 ranged from below zero up to 1.2 °C and has a larger variance compared to the data obtained during February 2015 where the temperature ranged between 4.9-5.3 °C.

The efficiency, as presented in Figure 3.13, increases with increasing length, whilst the coefficient of the slope decreases (Table 3.4). No correlation was found between the water temperature and the catch efficiency, i.e. escapement rate, for cod of 85 cm and higher for the hauls conducted with the SCSG. For the hauls conducted with the rock-hopper gear no correlation was detected from 95 cm, indicating that the SCSG is more efficient compared to the rock-hopper gear. This is confirmed when comparing the efficiency for the same for the SCSG and the rock-hopper gear for fish of the same length in Figure 3.13 and the intercept, i.e. efficiency for a given length in Table 3.4.

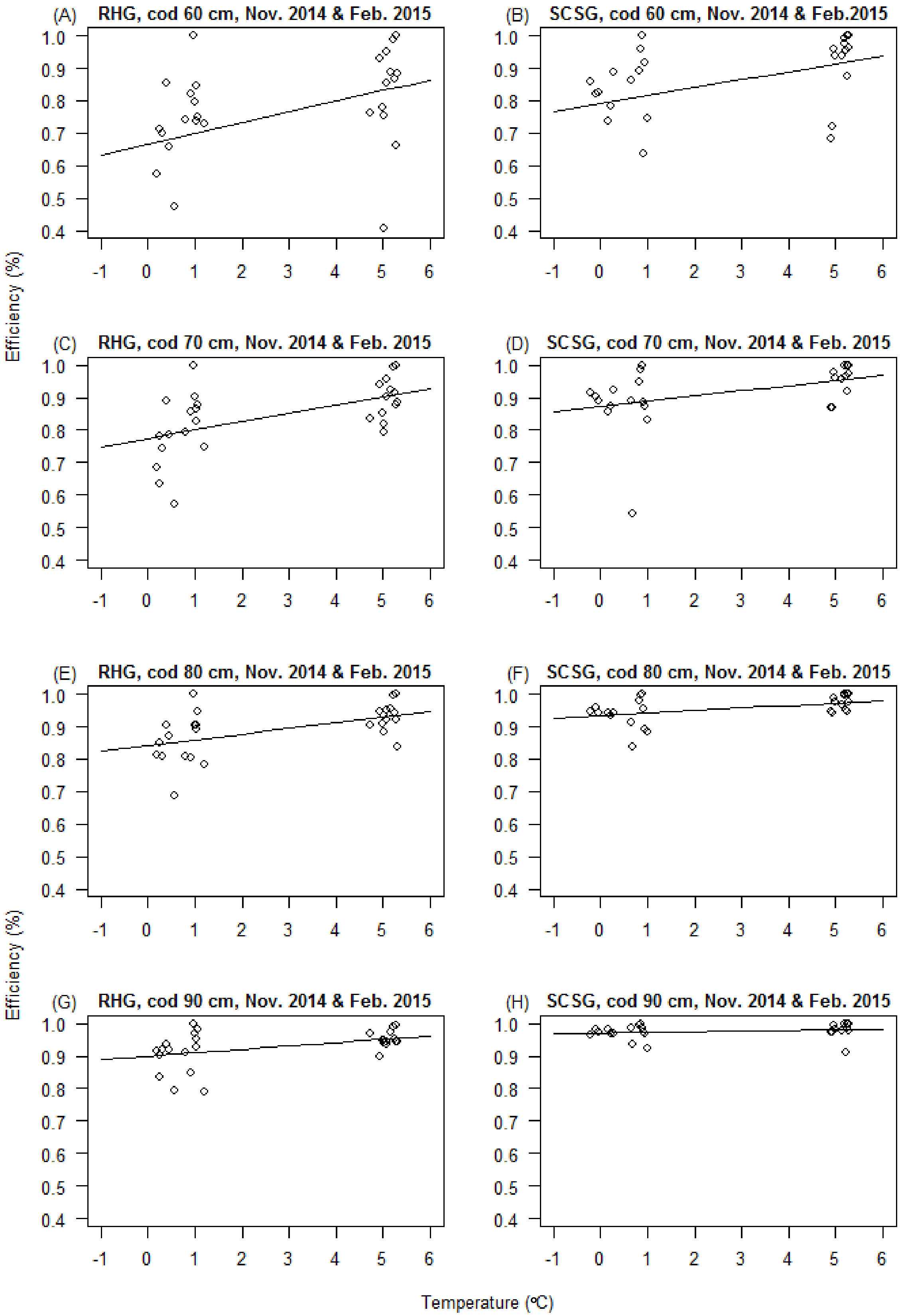

Figure 3.13 Examples from the analysis on the correlation between the water temperature and the escapement rate for cod. A positive correlation was found for all length groups, beside Figure 3.13H.

Table 3.4 The coefficients provided from the linear models in R presented in Figure 3.13, showing a correlation between the efficiency, i.e. rate of escapement and temperature for all cases investigated for the rock-hopper gear for fish of length 60cm, 70 cm and 80 cm, and for the SCSG for fish of length 70cm and 80 cm. The adjusted R^2 show large variation in the data. (Call: lm (formula = Efficiency_L ~ Temperature)).

Rock-hopper Nov. 2014 & Feb. 2015	**Estimate**	**Std. Error**	**Pr(>|t|)**	**Adj. R^2**
Cod, 60 cm				
Intercept	0.66466	0.0561	5.72E-12	0.11100
Temperature	0.0333	0.01593	0.0465	
Cod, 70 cm				
Intercept	0.77461	0.026616	< 2e-16	0.27890
Temperature	0.02553	0.00755	0.00228	
Cod, 80 cm				
Intercept	0.84122	0.01866	< 2e-16	0.27650
Temperature	0.01780	0.00529	0.00239	
Cod, 90 cm				
Intercept	0.89908	0.01483	<2e-16	0.16440
Temperature	0.01057	0.00421	0.0185	
SCSG, cod, Nov. 2014 & Feb. 2015				
Cod, 60 cm				
Intercept	0.79150	0.04186	6.37E-16	0.11490
Temperature	0.02447	0.01188	0.0504	
Cod, 70 cm				
Intercept	0.87159	0.02533	<2e-16	0.14600
Temperature	0.01651	0.00719	0.0307	
Cod, 80 cm				
Intercept	0.93409	0.01076	<2e-16	0.17580
Temperature	0.00768	0.00305	0.019	
Cod, 90 cm				
Intercept	0.97123	0.00680	<2e-16	-0.00188
Temperature	0.00188	0.00193	0.339	

3.7 The effect of diurnal variability on the escapement rate

The diurnal variability in rate of escapement was investigated by separately calculating the efficiency for the hauls conducted under nocturnal (night) conditions and under diel (day) conditions (Table C.5 in Appendix C). The hauls conducted during dusk and dawn are excluded from this analysis. The experimental and modeled efficiency with confidence limits, as well as the frequency showing the length distribution and the power in the data are presented in Figure 3.14 for cod and Figure 3.15 for haddock.

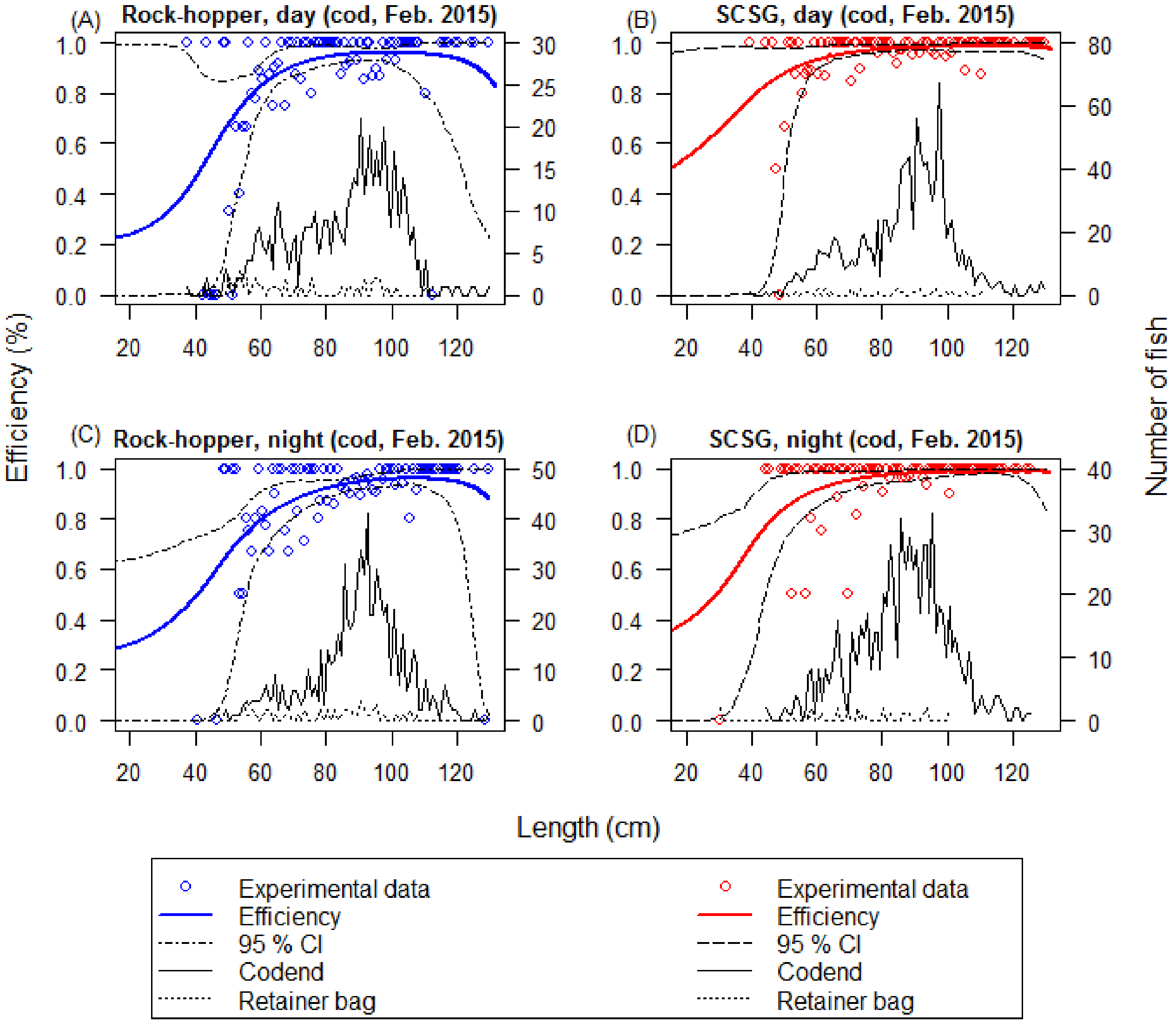

Figure 3.14 The catch efficiency for cod for the hauls conducted under diel (A, B) and nocturnal (C, D) conditions for the rock-hopper gear (A, C) and the SCSG (B, D). The number of fish show the length distribution of fish as well as the power in the data.

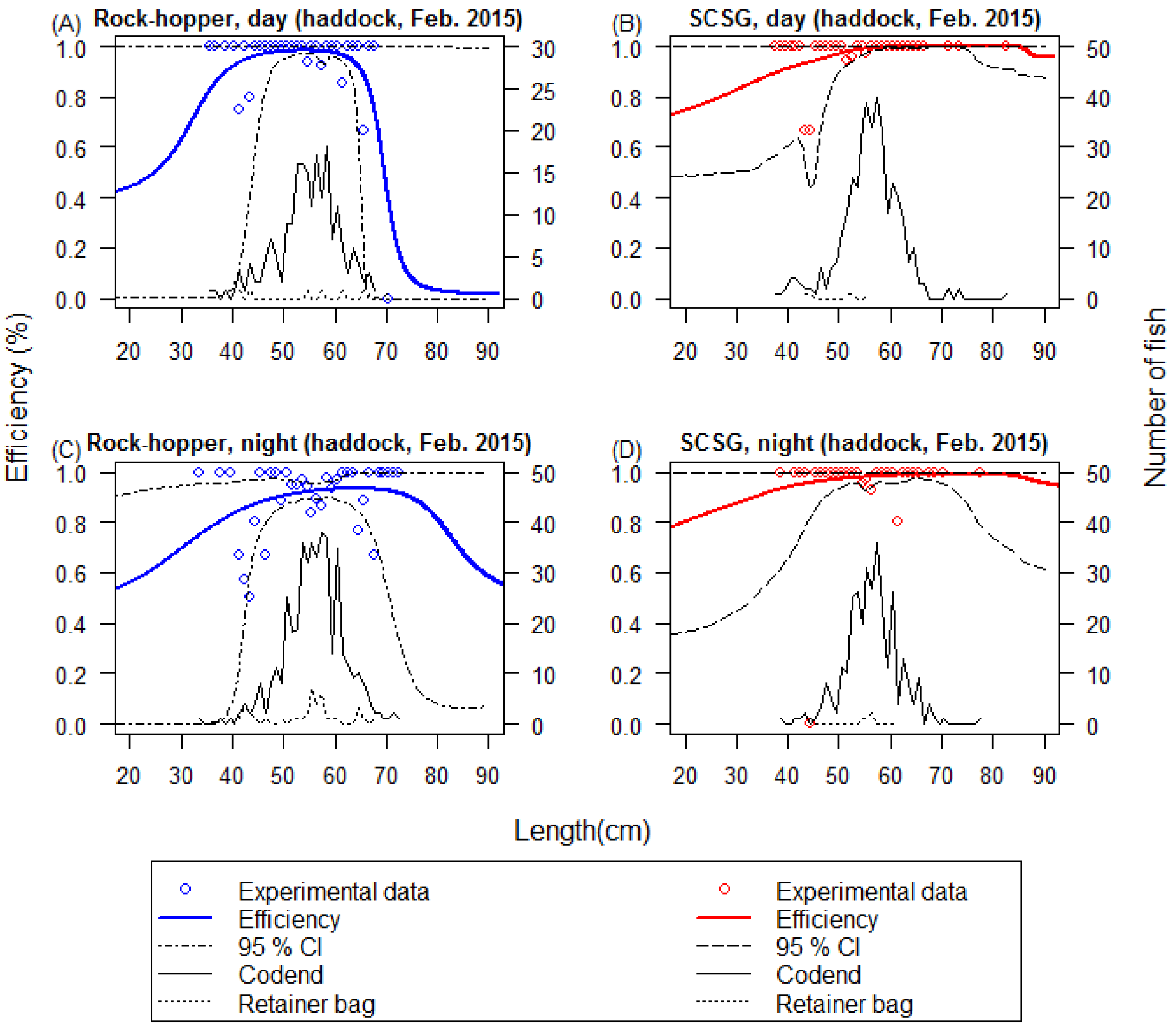

Figure 3.15 The catch efficiency for haddock for the hauls conducted under diel (A, B) and nocturnal (C, D) conditions for the rock-hopper gear (A, C) and the SCSG (B, D). The number of fish show the length distribution of fish as well as the power in the data.

By comparing the modeled efficiency with the confidence limits, no significant difference was found between the hauls conducted during the night and during the day for neither cod nor haddock (Figure 3.16). Although no correlation was detected the overall impression, as it appears from Figure 3.16, is that the hauls conducted under nocturnal conditions have a slightly lower efficiency compared to the hauls conducted under diel conditions. The reduced difference in the efficiency between the night-and day comparison for the SCSG (Figure 3.16B and 3.16D,) compared to the rock-hopper gear (Figure 3.16A and 3.16B), support the main results, i.e. the SCSG is more efficient, apparently due to reduced escape possibilities.

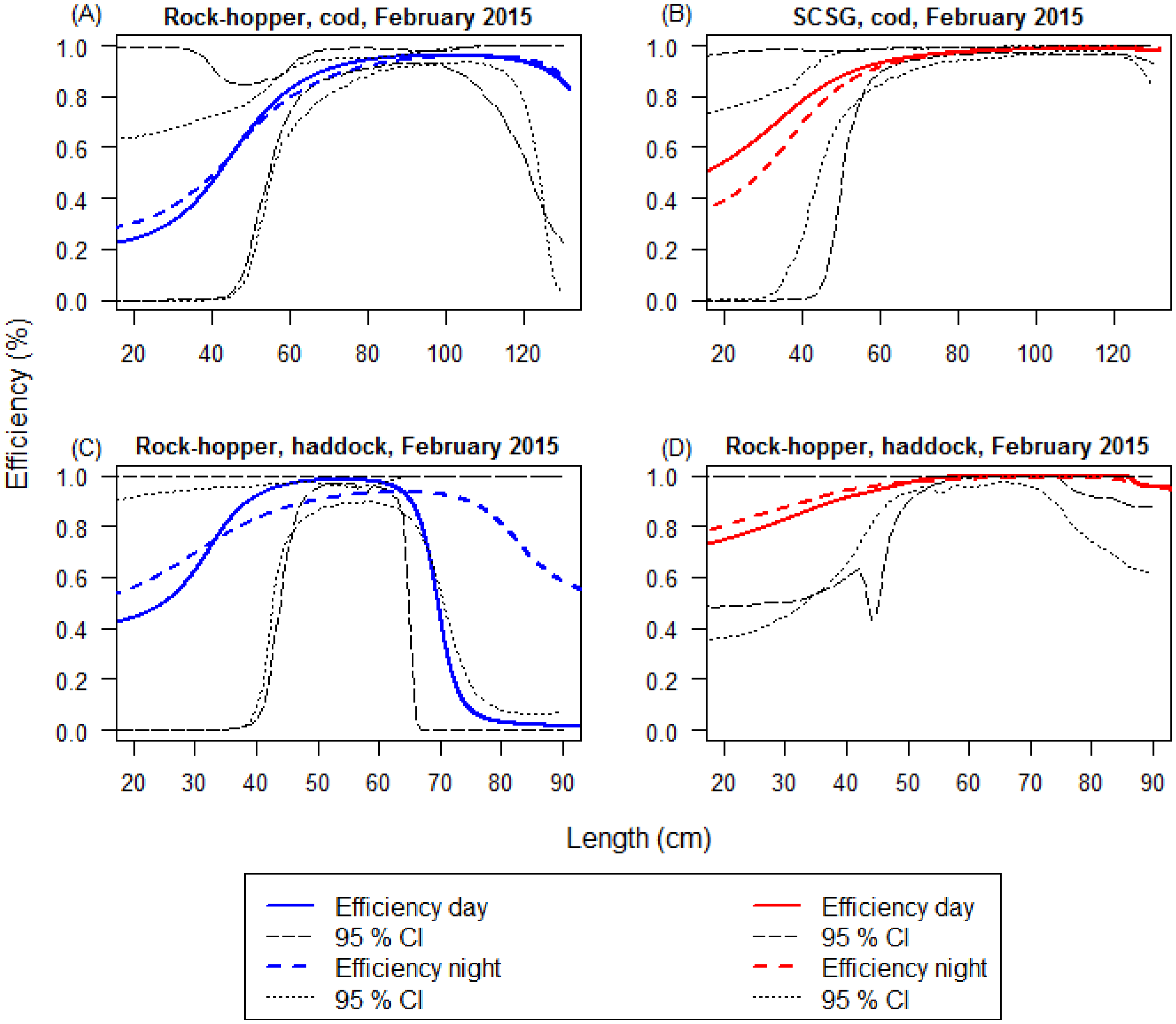

Figure 3.16 Catch efficiency with 95% confidence limits for the hauls conducted under nocturnal conditions and under diel conditions with respect to ground-gear and species, showing no significant difference.

For haddock there is a small significant difference for the hauls conducted with the rock-hopper gear for the length groups 52-56 cm (Figure 3.16C). The upper confidence limit for the hauls conducted under nocturnal conditions is 96%, whilst the lower confidence limit for the hauls conducted under diel conditions is 97%. This is caused by the distribution of the experimental data (Figure 3.15C) and is thus believed to be a coincidence due to scarce data.

3.8 The effect of artificial light on the escapement rate

In November 2014 five hauls with the rock-hopper gear were conducted with artificial light for video recordings. The same was done with four hauls with the SCSG. Figure 3.17 shows the experimental efficiency and the modeled efficiency with 95% confidence limits. In addition the frequency shows the number of fish caught in the codend and the retainer bag as well as the distribution of power in the data. Comparing Figure 3.17A and 3.17B indicate an increase in catch efficiency for the SCSG. This indication is emphasized by the number of fish caught in the retainer bag compared to the codend for both ground-gears.

Any influence of artificial light resulting in biased estimates of escapement, is investigated by comparing efficiency for the hauls conducted with and without artificial light. In Figure 3.18A, the hauls conducted with the rock-hopper gear in November 2014 with and without artificial light are compared. The same is done in Figure 3.18B for the hauls conducted with the SCSG. As presented in Figure 3.18 there was no significant difference between the hauls with and without artificial light for neither the hauls conducted with the rock-hopper (Figure 3.18A) gear nor the SCSG (Figure 3.18B). Although these result did not show any significant difference in the catch efficiency, i.e. rate of escapement, the between haul variance is considerable larger for the hauls conducted with artificial light compared to the between haul variance for the hauls that were conducted without artificial light (Table C.1 in Appendix C).

When comparing the catch efficiency for the hauls that demanded the use of artificial light, there is a significant increase in catch efficiency for the SCSG compared to the rock-hopper gear (Figure 3.19). This is consistent with the main results, i.e. the SCSG is more efficient compared to the conventional rock-hopper gear.

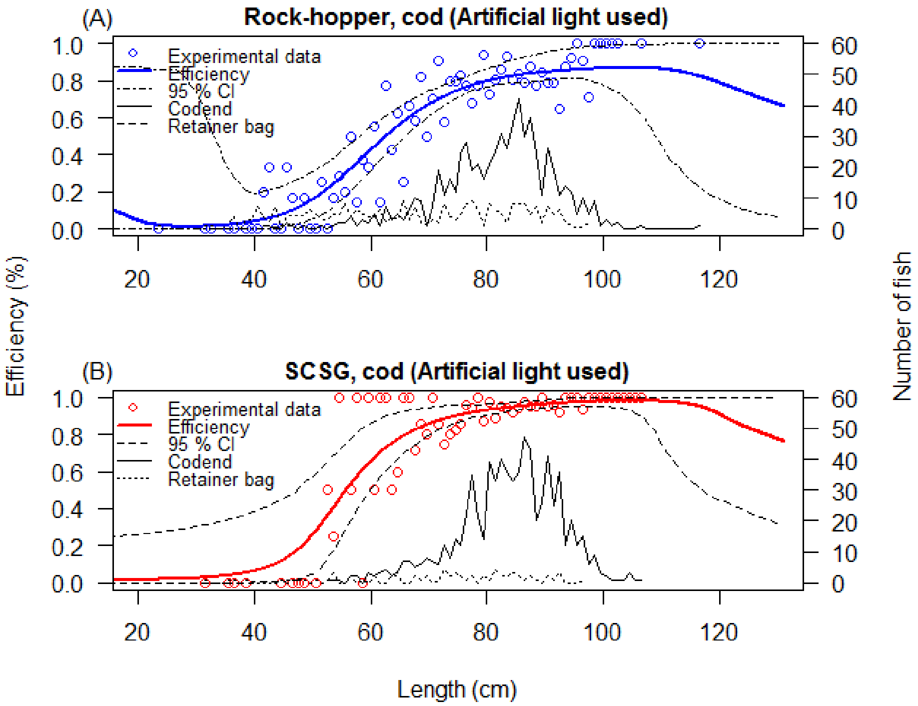

Figure 3.17 Catch efficiency with confidence limits for the hauls conducted with the rock-hopper gear (A) and the SCSG (B) and the utilization of artificial light for video-recording.

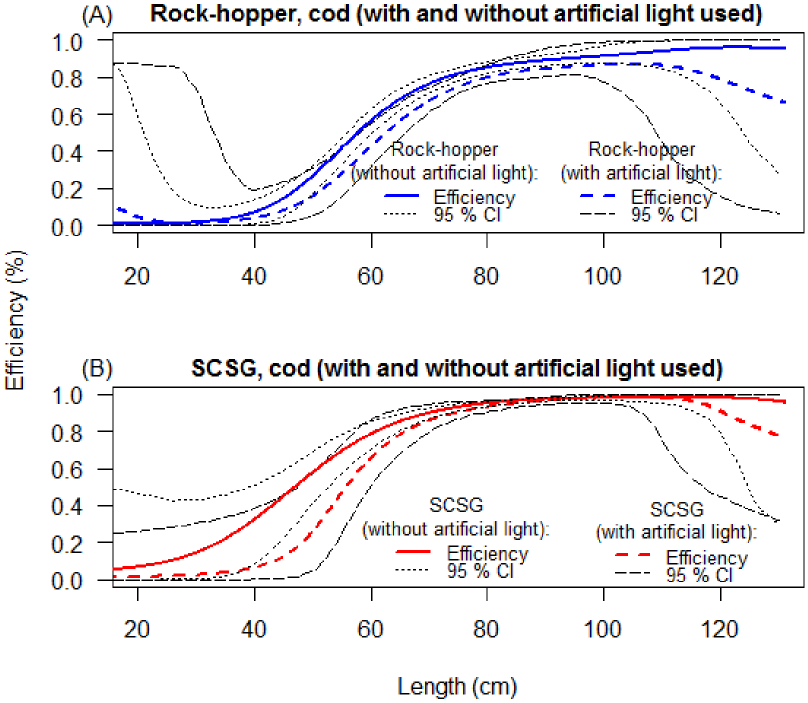

Figure 3.18 Comparison of catch efficiency for the hauls with and without the use of artificial light conducted with the rock-hopper gear (A), and the SCSG (B).

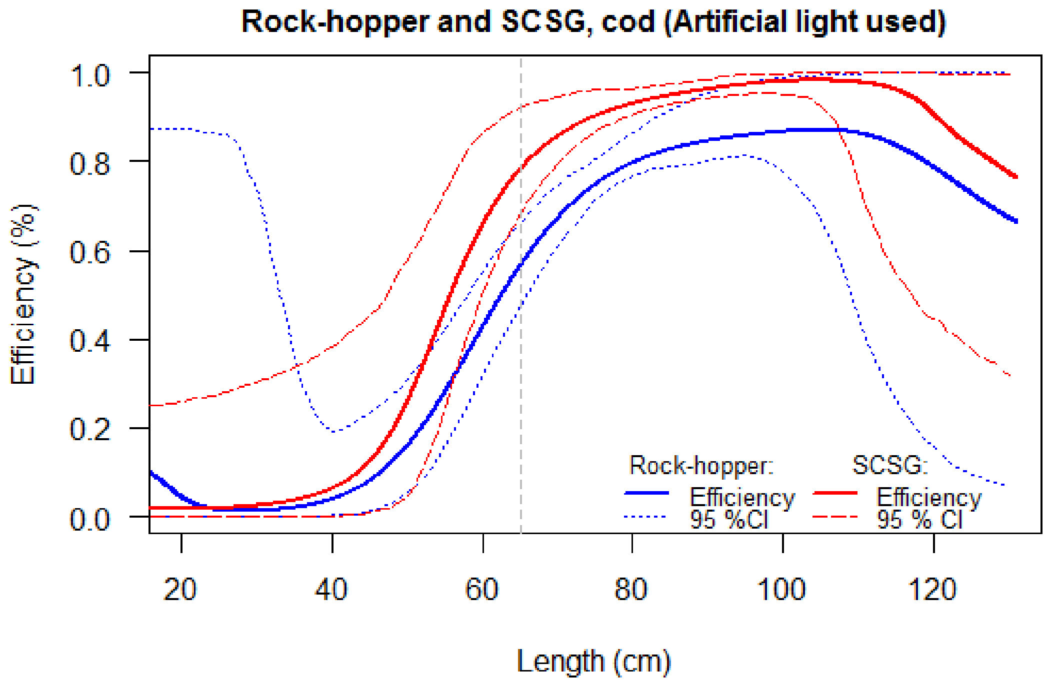

Figure 3.19 Comparison of the catch efficiency for the hauls using artificial light conducted with the rock-hopper gear and the SCSG. The grey dashed line shows the established limit for cod at 65 cm length.

3.9 Behavioral observations

The video recordings showed several behavioral aspects that are believed to affect the rate of escapement. Figure 3.20 shows some of these behavioral aspects under conditions with natural light. In general it was observed that cod herded in front of the trawl swam closer to the seabed than haddock. With increased densities, cod swam uniformly in front of the center section of the ground-gear (Figure 3.20A and 3.20B). Under such circumstances it was observed that cod swam in an apparently controlled manner in relation to its surroundings, i.e. trawl components and other fish. Under conditions with low densities, i.e., only a few individuals swimming in front of the trawl mouth, the behavior differed. Under such conditions cod was observed to swim independently in relation to the other individuals (Figure 3.20C and 3.20D). The swimming pattern was irregular, alternating between steady swimming and kick-and-glide swimming, as well as between swimming straight forward and “zig-zagging” between both ground-gear quarters. It appeared that some fish escaped actively between the discs of the rock-hopper gear. In some cases cod that had escaped under the fishing line were even observed re-appearing between the rock-hopper discs. Haddock was observed swimming steady before suddenly rising upwards while alternating swimming direction and falling back into the trawl mouth (Figure 3.20C and 3.20D).

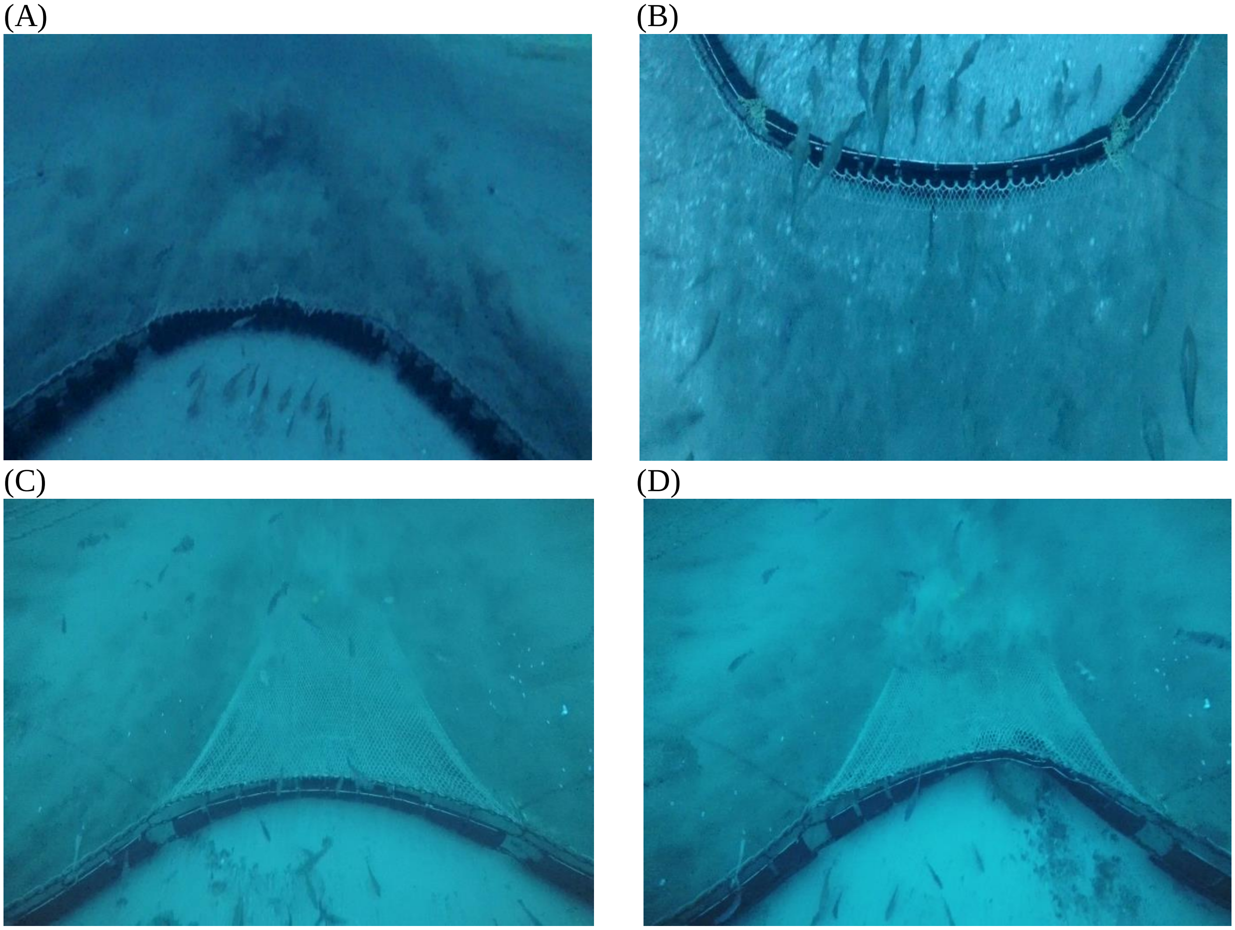

Figure 3.20 Still photos from video footage showing cod swimming in ordered manner, in aggregated densities in front of the center section of the ground-rope (A, B). C and D show a few cod swimming individually in chaotic patterns, as well as haddock rising up and alternating swimming direction. (Picture brightness increased by 20%).

The video footage recorded under conditions with total absence of solar light (demanding artificial light) revealed a completely different behavior (Figure 3.21). In general fish were observed swimming irregular with erratic responses with no uniform swimming direction. Compared to the conditions with natural light, the frequency of fish colliding with the ground-gear and the frequency of fish overrun was observed to increase substantial (Figure 3.21A, 3.21B and 3.21C). In addition to colliding with the ground-gear fish often collided with each other, especially under higher densities (Figure 3.21B). Compared to the conditions with natural light, fish were often overrun while swimming perpendicular to the towing direction. When the fish densities were low, fish swam erratically, covering the entire area in front on the center sections of the ground-gear, often resulting in escapement (Figure 3.21D). In many cases it was observed that fish reacted very late to the approaching trawl. Fish located a few meters in front of the ground-gear, just outside the light beam, were often observed motionless close to the bottom before reacting to the trawl by starting to swim resulting in a single mud-cloud produced by the first tail-beat. When inside the light beam, right in front of the ground-gear, the fish appeared to be panic-stricken. It is important to notice that the artificial light possibly affects the behavior observed. This complicates the observations since it is difficult to distinguish between the behavior caused by the artificial light (if any), and the behavior as a result of the natural environment and the approaching trawl.

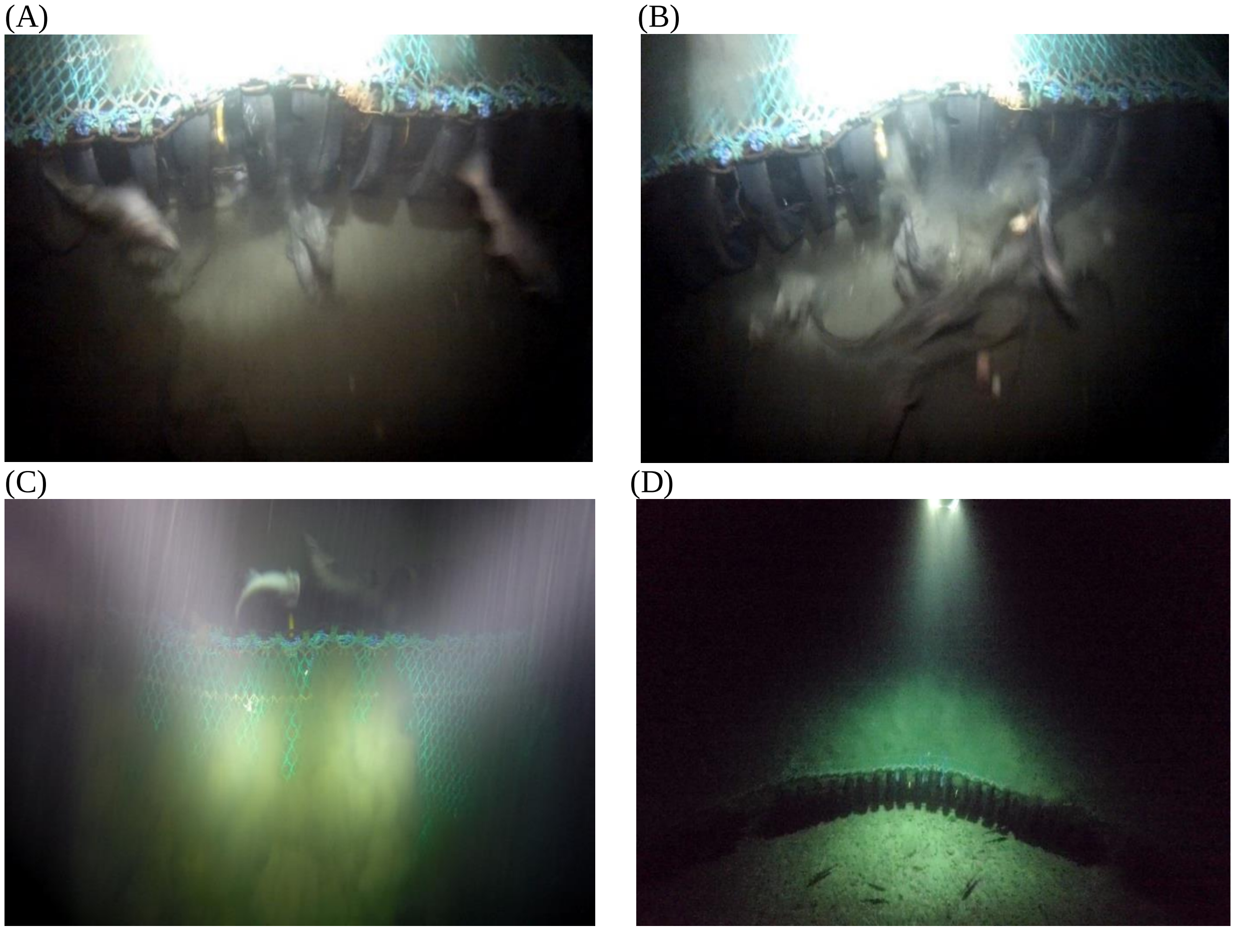

Figure 3.21 Still photos of video footage showing cod run over and colliding with the ground-gear (A, B, C), colliding with each other (B), and swimming frantic and disorientated in front of the ground-gear (D).

4. Discussion

The aim of this study was to investigate the rate of escapement under the fishing line for two different ground ropes for the two most commercially important species of fish in the Barents Sea. Additionally, it was studied how factors such as density, species, fish size, water temperature, diurnal variability and artificial light affects the rate of escapement. The overall results prove a significant improvement in the catch efficiency, i.e. reduction in the escapement rate for the SCSG compared to the conventional rock-hopper gear.

Several limitations are identified and taken into account in the present approach used for investigating the above mentioned objectives. Firstly, the mesh size in the codends, as justified in section 2.2.4 (p. 14) and Figure 3.1 (p. 22), limit the area of inference that exclusively is caused by the ground-gear selection process. Secondly, the retainer bag, only covering the center part of the fishing line, limits the area of inference to the area covered by the retainer bag. In general video observations showed that the fish herded into the trawl mouth aggregate in front of the center part of the fishing line (Figure 3.20A and 3.20B, p. 47). Also very little or no fish were observed escaping under both side sections of the fishing line. This could indicate that most of the escapement takes place in the center section of the fishing line. This observation is corroborated by other studies observing the same behavior (Main and Sangster, 1981; Walsh 1992; Ingólfsson and Jørgensen, 2006; Krag et al., 2010). Nevertheless, Ingólfsson and Jørgensen (2006) also measured a significant amount of fish escaping in the retainer bags attached on both side sections. Thirdly, a major assumption when investigating the rate of escapement is that one has to presume that the trawl and the retainer bag are 100% effective, and that no fish escape underneath the retainer bag. A lot of effort was put into investigate the performance of the retainer bag for assuring no secondary escapement. The monitored trawl performance and geometry as well as the video recordings showed no sign of the trawl being affected by the retainer bag. Thus, it is reasonable to presume that the trawl performed as it would under commercial conditions.

When comparing the study design between the two periods, the setup for the trials conducted in February 2015 contained fewer potential sources of error than the trials conducted in November 2014. The semi-pelagic trawl rigging used in November 2014 resulted in some unstable performance of the otter boards, but is not believed to have affected the results. The effect of simultaneously changing the study area and ground-gear in November 2014, although necessary, is more difficult to vindicate. Preferably, the setup should be equal to the setup used in February 2015, i.e. alternate haul setup. It is believed that sampling the data pairwise reduces the uncertainty arising due to the between haul variance and other influencing factors such as abiotic factors possibly affecting the rate of escapement.

Taking these limitations into account the results of this study are conservative estimations, and are likely underestimated. However, since it is reasonable to assume equal mesh-selection between the retainer bag and the trawl codend, as well as equal mesh-selection between the two ground-gears, the relative values in differences between them are evident.

4.1 The rate of escapement

The improved efficiency, i.e. reduced escapement for the SCSG can be explained due to two factors. Firstly, the design of the SCSG simply does not allow any escapement between the "elements", as often observed between the discs of the rock-hopper gear. The only space there fish possibly can escape is through the two openings between the section quarters of the ground-gear and underneath the ground-gear. Secondly, a possible explanation of the reduced escapement for the SCSG could be caused by the change in the water flow and hydrodynamic forces compared to the rock-hopper gear. According to Newton's third law all turbulence as a result of movement in a medium, is equal in magnitude but with an opposite reaction as the object causing the turbulence. Hence, it is thought that the rock-hopper gear with the large spaces between the discs causes a strong undertow between the discs. This again causes a hydrodynamic turbulence behind the ground-gear, which was visualized by the mud-clouds directly behind the ground-gear. These mud-clouds were observed to be much larger for the rock-hopper gear than for the SCSG. The SCSG on the other hand will due its design have no undertow between the "elements", but the water will flow over the upper side of the ground-gear, i.e. into the trawl mouth.

There is, as presented in Figure 3.7 (p. 29) and Figure 3.9 (p. 31), a significant difference in the catch efficiency for the hauls conducted with the rock-hopper gear and the SCSG for cod. For haddock the lower confidence limit for the SCSG and the upper confidence limit for the rock-hopper gear are equal at its best between 55 cm and 61 cm, implying no significant difference between the catch efficiency. The use of a codend with 135 mm mesh size was on one hand absolutely essential due to the environmental conditions (see section 3.1, p. 22). On the other hand, however, it limited the area of inference that solely can be explained due to ground-gear selection process. Since it is reasonable to assume that several selection processes affect different length groups, the nature of the ground-gear selection process is unknown. Therefore, since there was no criterion for model choosing, multi model inference was believed to provide the most representative result. Modeling all trawl-depended selectivity processes (Equation. 2, p. 19) enables a comprehensive interpretation of the entire curvature provided by the multi model inference. In case RB_l in both the nominator and denominator are marginal and RC_l and RR_l are equal, EG_l in equation (2) will actually solely represent ground-gear efficiency. Since the data does not provide any basis for inference on the mesh selection process, a reasonable and conservative limit, where 100% retention can be assumed, was established on the basis of other studies investigating selectivity in a 135 mm codend (Kvamme and Isaksen, 2004; Jørgensen et al., 2006; Sistiaga et al., 2010).

The average efficiency, i.e. rate of escapement integrated for all length groups above the established threshold length, showed a significant difference in the rate of escapement between both ground-gears, as well as between the two periods for cod (Table 3.2, p. 33). It is important to emphasize that in contrast to the length dependent evaluation of the efficiency, the ground-gear efficiency integrated for all length groups above the established limit is specific for the population encountered during the trail periods/areas, and should thus not be extrapolated to other scenarios. As presented in Table 3.2 (p. 33) and Figure 3.7 (p. 29) is the significance between the two ground-gear types of higher magnitude in November 2014 than in February 2015. When comparing the catch efficiency in Table 3.2 (p. 33) for the same ground-gear between the two periods, the data from February 2015 has a significant higher efficiency compared to the data from November 2014. When comparing these result with the length distribution and the mean length in both areas, this clearly corroborates the results of the escapement rate being highly length depended. At the same time, Figure 3.8 (p. 30) shows a significant difference between the two periods for the same ground-gear for each length group in a given interval. The data in November 2014 was obtained under conditions with complete darkness around the clock, while the data from February 2015 was obtained under conditions of ~10 hours of light and ~14 hours of darkness. Since it is assumed that ambient light affects the behavior of fish (Glass and Wardle, 1989; Walsh and Hickey, 1993), the difference in escapement could possibly be affected the different ambient light conditions in the two study areas (in addition to the length dependency). However, based on the present data no significant difference was detected between the hauls conducted under nocturnal or diel conditions (section 3.7, p. 41). However, a positive correlation was found between the rate of escapement and water temperature, with higher water temperatures resulting in increased catch efficiency (section 3.6, p. 38). With the average water temperature for the hauls conducted in November being 0.6 °C and in February 2015 being 5.1 °C, this could be a possible explanation for the significant difference in the rate of escapement between the two periods/areas.

Based on the present data no statistical significant difference in the efficiency, i.e. escapement rate for haddock was detected (Figure 3.10, p. 32 and Table 3.2, p. 33). Nevertheless the improved efficiency, i.e. reduced escapement is remarkable high for the SCSG, with 99% efficiency, compared to the 93% efficiency of rock-hopper gear resulting in an escapement reduction of 85.2% (efficiency improvement of 6.2%). Although there is no statistical significant difference, the lower confidence limit of the SCSG barley overlap the upper confidence limit of the rock-hopper gear (Table 3.2, p. 33). This is also indicated in Figure 3.10 (p. 32). Thus, since these calculations are based on relative few measurements, it is possible that an increased number of hauls or larger catches of haddock could possibly alternate these current results.

4.2 Length dependent escapement

The results clearly indicate that the escapement is highly length depended for both type of ground-gears as well as species (Figure 3.7, p. 29, and Figure 3.10, p. 32). This finding is corroborated by other studies investigating the rate of escapement under the fishing line, all confirming the escapement rate to be highly length depended (Engås and Godø, 1989; Walsh, 1989a; Godø and Walsh, 1992; Walsh, 1992; Dahm and Wienbeck, 1992; Ingólfsson and Jørgensen, 2006; Krag et al., 2010). For cod the length dependency appeared to be less for the data from February 2015 compared to the data from November 2014 (Figure 3.8, p. 30). This is likely to be caused due to the increase in the average length and size distribution for the data obtained in February 2015 (Figure 3.3, p. 25), and thus confirming the escapement to be length depended. However, a more likely reason for the dissimilar efficiency/escapement between the two periods/areas is to be caused by the results presented in section 3.6 (p. 38), implying the escapement to be temperature-depended.

A significant difference is observed when comparing the length dependent escapement rate between two types of ground-gears. The results indicated a significant increase in efficiency, i.e. reduction in escapement for the SCSG for most of the length classes (Figure 3.9, p. 31.). The increased efficiency (reduced escapement) for the SCSG is caused due to the ground-gears design resulting in minimal spaces between the "elements". Similar results were obtained in an earlier conducted study comparing the escapement rate under the fishing line between a Norwegian and a Canadian sampling trawl indicated that the higher escapement rate for the latter one could be caused due to larger spaces between the bobbins (Godø and Walsh, 1992). On the one side, the increased catch efficiency with the SCSG entails several advantages as mentioned earlier. But on the other side the increased catch efficiency also entails increased catches of undersized fish. Since several selection processes take place, further research should be conducted for quantifying the increase of undersized fish. Furthermore, it should be investigated whether ground-gear selection or mesh/grid selection expose fish to increased or reduced stress and injuries with eventual subsequent mortality.

The data also revealed a significant difference between cod and haddock in terms of length depended escapement. The escapement rate for cod was length depended in a much greater extent than the escapement rate for haddock for fish of equal length (Figure 3.11, p. 34). The difference was less for the SCSG compared to the rock-hopper gear. Again this indicates that there simply is no space for escapement between the "elements" of the SCSG.

4.3 Species dependent escapement

As mentioned above, there was a clear difference in the length dependency between cod and haddock, with less length depended escapement for the latter species (Figure 3.11, p. 34). These result are as expected on the basis of other studies investigating the behavioral differences between cod and haddock. According to several studies cod tend to swim close to the bottom, whilst haddock tends to swim higher from the bottom (e.g. Walsh and Hickey, 1993). Haddock tends to rise upwards in the water column when nearly exhausted, while alternating course and falling back into the trawl (or escape above the headline) (Main and Sangster, 1981; Wardle, 1993; Engås and Ona, 1990; Winger et al., 2010). This behavior was clearly observed on the video footage recorded at daylight (Figure 3.20C and 3.20D, p. 47). This behavioral characteristic for haddock has been utilized in order to improve species selectivity (Engås and West, 1995; Engås et al., 1998; Krag et al., 2010). The observed behavior of cod differed from that from haddock. Cod was observed swimming close to the bottom. When exhausted cod switched to kick-and-glide swimming mode, and started “zig-zagging” in front of the center section of the ground-gear between both quarters. Shortly after the overexertion cod was surpassed by the trawl, either falling back into the trawl or run over/escaped under the fishing line. These behavioral observations are supported by other similar observations, Main and Sangster (1981), amongst others.

Another factor that is known to affect the species depended escapement is diurnal variability (Engås and Ona, 1990; Krag et al., 2010). The study conducted by Engås and Ona (1990) elucidated that fish enter the trawl in the center section close to the bottom during nocturnal conditions, whilst during diel conditions fish entered the trawl over the entire opening. In conjunction with the behavioral characteristic for haddock, this leads to more escapement of haddock under the fishing line during the night, and more escapement above the headline during daylight. Observations from video footage conducted with natural light showed that cod in general swam close to the bottom, whilst haddock entered the trawl over the entire opening of the trawl.

4.4 Density depended escapement

Based on the present data no significant correlation was detected between the escapement rate/efficiency and fish density. Earlier conducted studies have demonstrated otherwise (Aglen et al., 1997; Godø et al., 1999). When combining the data from November 2014 and February 2015 it resulted in a slightly lower p-value, especially for the rock-hopper gear (Table 3.3, p. 37). This could indicate that an increased number of hauls would perhaps change the outcome of these results. This suspicion is enhanced by the behavioral analysis of fish in front of the fishing line from the video footage recorded under both nocturnal and diurnal conditions. In daylight, fish swimming in aggregated densities in front of the ground-gear were observed swimming in a controlled manner in relation to the surroundings. The fish both swam and responded uniformly, apparently trying to maintain a fixed position in the center of the trawl mouth, swimming head forwards, using optomotor response (figure 3.20A and 3.20B, p. 47) (Godø et al., 1999; Winger et al., 2010). At low densities, i.e. only a few fish swimming in front of the trawl mouth, the behavioral response changed. Cod were often seen swimming closer to the seabed, exhibiting more erratic responses, recognized by kick-and glide swimming, alternating and unstructured swimming directions, and colliding with trawl components (figure 3.20C and 3.20D, p. 47). Escapement under the fishing line at daylight often appeared to be an active attempt of escapement. This active escapement occurred often in the space between the ground-gear section quarters and between the discs of the rock-hopper gear. Due to the absence of open spaces between the “elements” of the SCSG, this active escapement applies more to the rock-hopper gear then the SCSG.

The observed behavioral responses are known to be highly affected by the available ambient light intensity, an interacting variable that is not taken into consideration in this analysis. All hauls in the data from November 2104 are conducted during the winter at high latitude, i.e. total darkness around the clock, whilst the data from February 2015 is conducted under conditions with ~10 hours of light and ~14 hours of darkness. Another factor that is difficult to account for in this analysis is the spatial distribution of fish throughout the towing, i.e. if fish appeared in aggregated “patches” or if they were evenly distributed.

Since the p-value reduction is greater for the rock-hopper gear than the SCSG (Table 3.3, p. 37), it can be speculated that in case any density depended escapement this would be more significant for the rock-hopper ground-gear. This coincides well with the observations from video footage, and the apparently active escapement between the discs of the rock-hopper gear.

4.5 Temperature depended escapement

The investigation of ambient water temperature affecting the catch efficiency, i.e. rate of escapement proved a positive correlation for 12 of the 18 investigated cases. All non-significant correlations concerned fish above 85 cm for the SCSG, and above 95 cm for the rock-hopper gear. Since this implies that the SCSG is more efficient than the rock-hopper gear, these results strengthen the main results. The correlation proved an increase in catch efficiency with increasing temperature, and is thus positive (Figure 3.13, p. 39). The results imply that more fish escape or are run over by the ground-gear under conditions with low temperatures. Earlier studies have proven that the water temperature has a profound impact on both swimming speed and endurance (He, 1993), with increasing temperature resulting in increased performance until a certain species-depended preferred limit is reached (Steinhausen et al., 2005). On the one hand, one could expect that increasing temperature resulting in increased swimming speed and endurance would entail increased “active/intentional” escapement. On the other hand, low temperatures resulting in reduced metabolic rate with subsequent reduced performance could result in more fish run over by the ground-gear, and thus entail increased escapement. Based on the present data the results confirm the latter theory.

Another factor that is believed to affect the rate of escapement is the visual capability of the fish affected by the water temperature. The flicker fusion frequency is the frequency of images that are compound into a continuous image, and affects the capability of fish to detect motion (Arimoto et al., 2010). In addition to decreasing light intensity this capacity of image perception is reduced with decreasing water temperature (Arimoto et al., 2010). In addition the velocity of the adaptation process of the relative positioning of the rods and cones in the retina is reduced with decreasing water temperature (Hodel et al., 2006). As mentioned earlier the data from November 2014 was obtained under conditions with total darkness around the clock, whilst the data from February 2015 is obtained under conditions with ~14 hours of darkness and ~10 hours of daylight. Since no diurnal variability in the rate of escapement was detected (section 3.7, p. 41) the present results on the effect of temperature are based on all hauls.

4.6 Diurnal variability in the escapement rate

Based on the present data no significant difference was detected between the hauls conducted under nocturnal (night) conditions and diel (daylight) conditions (Figure 3.16, p. 43). Although not significant, the hauls conducted under nocturnal conditions had a slightly lower efficiency compared to the hauls conducted under diel conditions. This is supported by the behavioral analysis from the video recordings. Several observations under diel conditions such as the ordered, uniform and controlled behavior relative to the surroundings, as well as the spatial distribution in the entire trawl mouth, is thought to entail less escapement. Contradictory, the frantic and uncontrolled behavior observed (with artificial light) under nocturnal conditions is thought to entail increased escapement. During night fish often appeared to be lying on the bottom, motionless until located in close proximity of the ground-gear before any response, detected by a single mud-cloud produced by the first tail-beat, was observed. These observations are corroborated by several studies observing escapement of haddock over the headline and irregular distribution of fish in the trawl mouth under diel conditions, whilst under nocturnal conditions the fish entered the trawl close to the ground-gear (Engås and Ona, 1990; Walsh and Hikcey, 1993; Winger et al., 2010). Krag et al. (2010) observed a significant increase in the escapement under nocturnal conditions for cod. The ceasing of the ordered behavioral pattern observed under nocturnal conditions (Wardle, 1993) is caused by the loss of visual stimulus, and entails prolonged respond time. But unlike what Wardle (1993) argues, the present observations as well as other studies (Sistiaga et al., 2015) indicate that other senses than visual stimulus take over. In general fish located in close proximity to the ground-gear (or other trawl components) often responded erratically, i.e. alternating velocity, swimming direction and swimming mode. Since fish under nocturnal conditions did often not react until located in close proximity of the ground-gear the response was mostly erratic. This erratic response under nocturnal conditions was often observed to result in fish getting overrun by the ground-gear. Whilst under diel conditions the escapement under the fishing line often appeared to be done intentional, i.e. the fish escaped headfirst between the discs or under the ground-gear. It is important to notice that in addition to the light intensity, other factors such as water temperature, currents, swimming speed, and stamina, affect the decision making of whether the behavior is erratic or optomotor (Kim and Wardle, 2003).

In addition to the diurnal variation in the behavior observed in front of the trawl mouth, the vertical distribution in the water column is as well known to vary between nocturnal and diel conditions, and hence affecting the catchability of the bottom trawl (Michalsen et al., 1996). Several studies have indicated diel variability in the mean length of the fish caught (Walsh 1989b; Michalsen et al., 1996; Petrakis et al., 2001). Like the present results, Walsh (1989b) observed a slightly higher escapement of cod under nocturnal conditions, although not significant. Several studies have reported higher catch efficiency under diel conditions (Petrakis et al., 2001; Jones et al., 2004), and lower efficiency under nocturnal conditions (Wardle, 1993; Aglen et al., 1999; Jones et al., 2004). Walsh (1989b) observed that under nocturnal conditions the efficiency for large cod was slightly higher, whilst the efficiency for small cod was slightly lower compared to the catches under diel conditions. As mentioned, several factors affect the diurnal variability of the catchability of the trawl. A factor hardly known which requires further investigations, is endogenous diurnal rhythms. Experience from bottom trawling is that the catches often are largest early in the morning. This is often visualized on the echo-sounder as well, with increased fish density close to the sea bed. Since fish often are located close to the bottom during that time of the day, and thus as well in the dead-zone of the echo-sounder, the catches are often disproportionate large compared to the readings from the echo-sounder (if the entrance in the trawl mouth is not monitored). This behavior is observed all year round and irrespective of the light conditions. It is possible that an increased numbers of hauls, and/or larger contrasts in the environmental conditions could alternate the present results.

4.7 The effect of artificial light on the rate of escapement

The present results show no significant difference between the hauls conducted with and without artificial light (Figure 3.18, p. 45). Based on these results the suspicion of alternated behavior with subsequent bias in the estimated escapement rate is thus groundless. (Nevertheless, the hauls conducted with artificial light are not included in the overall data used in this study). This finding is supported by Weinberg and Munro (1999), investigating the effect of artificial light on the escapement underneath a survey trawl. Walsh and Hickey (1993) did neither find any difference in the behavior of cod and haddock during night with and without light, except of the behavioral differences between diurnal and nocturnal conditions. Glass and Wardle (1989) detected an immediate change in behavior during night, i.e. ordered pattern when turning on strong floodlights. Two possible reasons can explain these contradictory results. Firstly, the spread of the light beam can be assumed to affect the reaction, i.e. a wide light beam will create strong contrasts of the surrounding trawl, whilst a narrow light beam (used in the video recordings at hand) will create a strong but narrow illuminated spot, with little spread. Secondly, in conjunction with the natural diurnal variability known to affect fish the diffuse light used on the recordings could simply not disturb the dark-adapted state (Walsh and Hickey, 1993).

On the other hand, observations from the video recordings showed that fish did not react notable before they were inside the center of the light beam and appeared to be in total panic. A possible explanation for this is that the eyes of the fish, adapted to total darkness for a long period, were blinded by the sudden light (Walsh and Hickey,1993), resulting in frantic behavior. A previous study concluded that the adaptation of a fish eye from dark to light takes in some cases only 30 seconds, and is much faster than the reverse adaptation (Walsh and Hickey, 1993). Although this adaptation takes relative short time, the observations from the video recordings showed that the fish were either retained or escaped under the fishing line only after a few seconds after appearing in front of the trawl. In addition the adaptation to the light conditions, a process called retinomotor response (Arimoto et al., 2010) is affected by various extrinsic factors. For instance, reduced water temperature will result in decreased velocity of the adaptation process (Hodel et al., 2006).

Although no significant difference was found, the between haul variance is considerable larger for the hauls conducted with artificial light compared to the hauls conducted without artificial light (Table C.1 in Appendix C). This might be a coincidence, but further investigation should be conducted, i.e. increase number of hauls, before any re-evaluation of the present results.

4.8 Recommendations for the future

Bottom trawling has been under critical view for decades and the method has especially been labelled as energy consuming, non-selective and destructive for various bottom habitats. While decades of research has led to improved size- (and species-) selective properties of bottom trawling (Walsh et al., 2002), less effort has been made in studies on the effects of changes by various trawl components. In the meantime the Norwegian trawl fleet has expanded the capacity by enlarging the trawl components (i.e. size and weights of otter boards, lengths and weights of ground rope and size of the nets), without any scientific evidence on the effect and consequences of such changes.

The current study has demonstrated that a lighter and less energy consuming ground rope (Grimaldo et al., 2013) is more efficient than the conventional rock-hopper gear. For the industry it would be a clear win-win situation to change to the SCSG type of ground rope, i.e. more fish per unit time for less fuel spent. Additionally the lighter plastic SCSG gear would give the fishery a more “sustainable” image as bottom impact is reduced compared to a rock-hopper ground rope, both due to less weight and shorter towing distances for achieving equivalent catches. In addition the reduced fuel consumption contributes to reduced emission of CO_2 and NO_x gasses.

It would be of interest for any type of bottom trawl fishery to do further investigations on alternative, more efficient and energy friendly footrope designs. It will be necessary to test these modifications in a commercial operation. Also, for being able to estimate the total escapement under the entire fishing line the study setup should include three retainer bags covering all three section of a ground-gear, as well as blinded codends (small mesh size) in order to preclude any other selectivity processes taking place. This demands however that the environmental circumstances allow such a setup.

Future investigations should also focus on the performance of the SCSG compared to the conventional rock-hopper gear under various conditions. Current studies have already indicated an improvement in terms of trawl performance for the SCSG compared to the rock-hopper gear, i.e. increased spread between the wings with equivalent door spreading (Grimaldo et al., 2013). Both present video observations and former (Grimaldo et al., 2013) observed good bottom contact for the SCSG. Any obstacles, i.e. stones and rocks, were easily passed and the gear regained bottom contact rapidly (Figure 3.20D, p. 47).

4.9 Summary and conclusion

Although there are obvious limitations in the data obtained, this study is believed to answer the main hypothesis in a plausible way. For cod there is a considerable difference in the efficiency between the two types of ground-ropes studied, with the SCSG being more efficient, i.e. less escapement under the fishing line. For haddock the difference in the catch efficiency between the two ground-gear was not significant, but further investigations should be conducted in order to enhance the present results. It is reasonable to assume that the overall rate of escapement underneath the entire fishing line in reality is larger than escapement rate estimated in this study. Thus, it is important to emphasize that the results in this study are conservative estimations. In addition no general applicable conclusion should be extrapolated without taking all the extrinsic factors into consideration. The results proved the escapement to be highly length depended as well as species depended. A positive correlation was also found between the effect of temperature and the escapement rate up to certain lengths. Despite the fact that no correlation was found between the rate of escapement and fish density, ambient light intensity, or artificial light, all the results implied an increase in the catch efficiency, i.e. reduction in the escapement for the SCSG. In this way these results underpin the main results of the SCSG being more efficient than conventional the rock-hopper gear.

5. References

Aglen, A., Engås, A., Godø, O. R., McCallum, B. R., Stansbury, D., Walsh, S. J., 1997. Density dependent catchability in bottom trawl surveys. ICES, CM /W: 16

Aglen, A., Engås, A., Huse, I., Michalsen, K., Stensholt, B. K., 1999. How vertical fish distribution may affect survey results. ICES J. Mar. Sci. 56 (3): 345-360 doi:10.1006/jmsc.1999.0449

Akaike, H., 1974. A new look at the statistical model identification. IEEE Transactions Automatic Control, 19(6), 716-723. doi: 10.1109/TAC.1974.1100705

Albert, O. T., Harbitz, A., Høines, Å. S., 2003. Greenland halibut observed by video in front of survey trawl: behaviour, escapement, and spatial pattern. Journal of Sea Research, 50(2–3), 117-127. doi: http://dx.doi.org/10.1016/S1385-1101(03)00063-7

Arimoto, T., Glass, C. W., Zhang, X., 2010. Fish vision and its role in fish capture, in: He, P., (Ed.). Behavior of marine fishes: capture processes and conservation challenges. Ames, Iowa: Wiley-Blackwell, pp. 25-44.

Burnham, K., Anderson, D., Huyvaert, K., 2011. AIC model selection and multimodel inference in behavioral ecology: some background, observations, and comparisons. Behavioral Ecology and Sociobiology, 65(1), 23-35. doi: 10.1007/s00265-010-1029-6

Chopin, F. S., Arimoto, T., 1995. The condition of fish escaping from fishing gears—a review. Fisheries Research, 21(3–4), 315-327. doi: http://dx.doi.org/10.1016/0165-7836(94)00301-C

Dahm, E., Wienbeck, H., 1992. Escapement of fish underneath the groundrope of a standard bottom trawl used for stock assessment purposes in the North Sea. ICES CM/B: 20

Engås, A., Godø, O. R., 1989. Escape of fish under the fishing line of a Norwegian sampling trawl and its influence on survey results. ICES Journal of Marine Science: Journal du Conseil, 45(3), 269-276. doi: 10.1093/icesjms/45.3.269

Engås, A., Jørgensen, T., West, C. W., 1998. A species-selective trawl for demersal gadoid fisheries. ICES Journal of Marine Science: Journal du Conseil, 55(5), 835-845. doi: 10.1006/jmsc.1998.0352

Engås, A., Ona, E., 1990. Day and night fish distribution pattern in the net mouth area of the Norwegian bottom-sampling trawl. ICES, 189: 123-127.

Engås, A., West, C. W., 1995. Development of a species-selective trawl for demersal gadoid fisheries. ICES, CM/B+G+H+J+K: l

Fiskeridirektoratet, 2014. J-208-2011: Forskrift om endring i forskrifter om maskevidde, bifangst og minstemål m.m. ved fiske i Svalbards territorialfarvann og indre farvann. http://www.fiskeridir.no/fiske-og-fangst/j-meldinger/gjeldende-j-meldinger/j-208-2011 Accessed: 07.01.15, 11:19 am.

Gjøsund, S.H., Hansen, K., Sistiaga, M., Grimaldo, E., 2012. MultiSEPT – Initial model scale tests of traditional and alternative trawl ground-gears. SINTEF Report A23318, 34 pp.

Glass, C. W., Wardle, C. S., 1989. Comparison of the reactions of fish to a trawl gear, at high and low light intensities. Fisheries Research, 7(3), 249-266. doi: http://dx.doi.org/10.1016/0165-7836(89)90059-3

Godø, O. R., Walsh, S. J., 1992. Escapement of fish during bottom trawl sampling — implications for resource assessment. Fisheries Research, 13(3), 281-292. doi: http://dx.doi.org/10.1016/0165-7836(92)90082-5

Godø, O. R., Walsh, S. J., Engås, A., 1999. Investigating density-dependent catchability in bottom-trawl surveys. ICES Journal of Marine Science: Journal du Conseil, 56(3), 292-298. doi: 10.1006/jmsc.1999.0444

Graham, N., Jones, E. G., Reid, D. G., 2004. Review of technological advances for the study of fish behaviour in relation to demersal fishing trawls. ICES Journal of Marine Science: Journal du Conseil, 61(7), 1036-1043. doi: 10.1016/j.icesjms.2004.06.006

Grimaldo, E., Sistiaga, M., Larsen, R. B., Tatone, I., Olsen, F., 2013. MultiSEPT - Full scale tests of the semicircular spreading gear (SCSG). SINTEF Report No. A24271, 23 pp.

Handegard, N. O., Michalsen, K., Tjøstheim, D., 2003. Avoidance behaviour in cod (*Gadus morhua*) to a bottom-trawling vessel. Aquatic Living Resources, 16(3), 265-270. doi: http://dx.doi.org/10.1016/S0990-7440(03)00020-2

He, P., 1993. Swimming speeds of marine fish in relation to fishing gears. ICES Marine Science Symposia 196, 183-189.

Hodel, C., Neuhauss, S. C. F., Biehlmaier, O., 2006. Time course and development of light adaptation processes in the outer zebrafish retina. The Anatomical Record Part A: Discoveries in Molecular, Cellular, and Evolutionary Biology, 288A (6), 653-662. doi: 10.1002/ar.a.20329

ICES, 2014. Report of the Arctic Fisheries Working Group (AFWG), 2014, Lisbon, Portugal. ICES CM 2014/ACOM:05. 656 pp.

IMR, 2015. Havforskninsrapporten, 2015 – Ressurser, miljø og akvakultur på kysten og i havet. Fisken og havet særnummer 1-2015.

Ingólfsson, Ó. A., 2003. Mye fisk unnslipper under en kommersiell torsketrål. Bergen: Havforskningsinstituttet, Hi-nytt nr. 14/2003.

Ingólfsson, Ó. A., Jørgensen, T., 2006. Escapement of gadoid fish beneath a commercial bottom trawl: Relevance to the overall trawl selectivity. Fisheries Research, 79(3), 303-312. doi: http://dx.doi.org/10.1016/j.fishres.2005.12.017

Jones, E. G., Glass, C. W., Milliken, H. O., 2004. The reaction and behaviour of fish to visual components of fishing gears and the effect on catchability in survey and commercial. ICES, WGFTFB, Poland, April 2004, 58 pp.

Jørgensen, T., Ingólfsson, Ó. A., Graham, N., Isaksen, B., 2006. Size selection of cod by rigid grids - Is anything gained compared to diamond mesh codends only? Fisheries Research, 79(3), 337-348. doi: http://dx.doi.org/10.1016/j.fishres.2006.01.017

Katsanevakis, S., 2006. Modelling fish growth: Model selection, multi-model inference and model selection uncertainty. Fisheries Research, 81(2–3), 229-235. doi: http://dx.doi.org/10.1016/j.fishres.2006.07.002

Kim, Y. H., Wardle, C. S., 1998. Measuring the brightness contrast of fishing gear, the visual stimulus for fish capture. Fisheries Research, 34(2), 151-164. doi: http://dx.doi.org/10.1016/S0165-7836(97)00087-8

Kim, Y. H., Wardle, C. S., 2003. Optomotor response and erratic response: quantitative analysis of fish reaction to towed fishing gears. Fisheries Research, 60(2–3), 455-470. doi: http://dx.doi.org/10.1016/S0165-7836(02)00114-5

Krag, L. A., Herrmann, B., Karlsen, J. D., 2014. Inferring fish escape behaviour in trawls based on catch comparison data: Model development and evaluation based on data from Skagerrak, Denmark. PLoS ONE, 9(2), e88819. doi: 10.1371/journal.pone.0088819

Krag, L. A., Holst, R., Madsen, N., Hansen, K., Frandsen, R. P., 2010. Selective haddock (*Melanogrammus aeglefinus*) trawling: Avoiding cod (*Gadus morhua*) bycatch. Fisheries Research, 101(1–2), 20-26. doi: http://dx.doi.org/10.1016/j.fishres.2009.09.001

Kvamme, C., Isaksen, B., 2004. Total selectivity of a commercial cod trawl with and without a grid mounted: grid and codend selectivity of north-east Artic cod. Fisheries Research, 68(1–3), 305-318. doi: http://dx.doi.org/10.1016/j.fishres.2003.11.011

Main, J., Sangster, G. I., 1981. A study of the fish capture process in a bottom trawl by direct observations from a towed underwater vehicle. Scott. Fish. Rep. 23:1–23.

Michalsen, K., Godø, O. R., Fernö, A., 1996. Diel variation in the catchability of gadoids and its influence on the reliability of abundance indices. ICES Journal of Marine Science: Journal du Conseil, 53(2), 389-395. doi: 10.1006/jmsc.1996.0054

O'Neill, F. G., McKay, S. J., Ward, J. N., Strickland, A., Kynoch, R. J., Zuur, A. F., 2003. An investigation of the relationship between sea state induced vessel motion and cod-end selection. Fisheries Research, 60(1), 107-130. doi: http://dx.doi.org/10.1016/S0165-7836(02)00056-5

Ot.prp. nr. 20 (2007-2008). Om lom om forvaltning av viltlevande marine ressursar (havressurslova). Oslo: Det kongelige fiskeri- og kystdepartement

Pennington, M., Shevelev, M S., Vølstad, J. H., Nakken, O., 2011. Bottom trawl surveys, in: Jakobsen, T., Ožigin, V. K., (Eds.). The Barents Sea: ecosystem, resources, management: half a century of Russian-Norwegian cooperation. Trondheim: Tapir Academic Press, pp. 570-583.

Petrakis, G., MacLennan, D. N., Newton, A. W., 2001. Day–night and depth effects on catch rates during trawl surveys in the North Sea. ICES Journal of Marine Science: Journal du Conseil, 58(1), 50-60. doi: 10.1006/jmsc.2000.0989

R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Ryer, C. H. 2004. Laboratory evidence for behavioural impairment of fish escaping trawls: a review. ICES Journal of Marine Science: Journal du Conseil, 61(7), 1157-1164. doi: 10.1016/j.icesjms.2004.06.004

Shamray, E. A., Sunnanå, K., 2011. Development of management strategies, in: Jakobsen, T., Ožigin, V. K., (Eds.). The Barents Sea: ecosystem, resources, management: half a century of Russian-Norwegian cooperation. Trondheim: Tapir Academic Press, pp. 534-540.

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R. B., 2010. Assessment of dual selection in grid based selectivity systems. Fisheries Research, *105*(3), 187-199. doi: http://dx.doi.org/10.1016/j.fishres.2010.05.006

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R. B., Tatone, I., 2015. Effect of lifting the sweeps on bottom trawling catch efficiency: A study based on the Northeast arctic cod (*Gadus morhua*) trawl fishery. Fisheris Research, 167, 164-173. doi:10.1016/j.fishres.2015.01.015

Steinhausen, M., Steffensen, J., Andersen, N., 2005. Tail beat frequency as a predictor of swimming speed and oxygen consumption of saithe (*Pollachius virens*) and whiting (*Merlangius merlangus*) during forced swimming. Marine Biology. 148:197-204.

Walsh, S. J., 1989a. Escapement of fish underneath the footgear of a groundfish survey trawl. ICES CM/B: 21.

Walsh, S. J., 1989b. Diel influences on fish escapement beneath a groundfish survey trawl. ICES CM/B: 23.

Walsh, S. J., 1992. Size-dependent selection at the footgear of a groundfish survey trawl. North American Journal of Fisheries Management, 12(3), 625-633. doi: 10.1577/1548-8675(1992)012<0625:SDSATF>2.3.CO;2

Walsh, S.J., Engås, A., Ferro, R., Fonteyne, R., van Marlen, B., 2002. To catch or conserve more fish: the evolution of fishing technology in fisheries science. ICES Marine Science Symposia, 215: pp. 493–503.

Walsh, S. J., Hickey, W. M., 1993. Behavioural reactions of demersal fish to bottom trawls at various light conditions. ICES Marine Science Symposia, 196: pp. 68-76.

Wardle, C., 1993. Fish behaviour and fishing gear, in: Pitcher, T.J., (Ed.). Behaviour of teleost fishes. London: Chapman and Hall, pp. 607-643.

Weinberg, K. L., Munro, P. T., 1999. The effect of artificial light on escapement beneath a survey trawl. ICES Journal of Marine Science: Journal du Conseil, 56(3), 266-274. doi: 10.1006/jmsc.1999.0442

Winger, P. D., Eayrs, S., Glass, C. W., 2010. Fish behaviour near bottom trawls, in: He, P., (Ed.). Behavior of marine fishes: capture processes and conservation challenges. Ames, Iowa: Wiley-Blackwell, pp. 67-103.

Yaragina, N. A., Aglen, A., Sokolov, K. M., 2011. Cod, in: Jakobsen, T., Ožigin, V. K., (Eds.), The Barents Sea: ecosystem, resources, management: half a century of Russian-Norwegian cooperation. Trondheim: Tapir Academic Press, pp. 225-271.

6. Appendices

Appendix A: Sensory organs and locomotion of marine fish

Locomotion

The locomotion ability of fish is highly related to their ecology and is thus species dependent (Videler and Wardle, 1991). Although the diversity in swimming styles is huge the basic principles are the same for all species. Locomotion includes various type of movement; swimming upwards and downwards, jumping, braking and accelerating, maneuvering and steady swimming at various speed (Videler and He, 2010). In addition that the swimming style reflects the life style of the species, the swimming style changes during the different life stages of a species (Videler and Wardle, 1991).

Morphology

Like all other animals locomotion is powered by muscle contractions that requires energy consumption (Altringham and Ellerby, 1999; Videler and He, 2010). Although the morphology related to locomotion is highly reflected by the lifestyle of the species, the basic principles are the same. All fish species consist of a lateral flexible vertebral column, dividing the body in to two lateral sides. The lateral longitudinal muscles on each side of the vertebral column are divided in vertical segmented blocks called myotomes (Wardle et al., 1995; Videler and He, 2010). These myotomes are separated by collagenous myosepts. Thrust is generated by alternately contracting the muscle on one side of the body and thus bending the body inwards, alternating between the left and the right side. The lateral displacement of the body increases from behind the head to the tail-tip, resulting in a similar increase of amplitude that is species specific (Vidler and Wardle, 1991). The lateral muscle activation appears undulant, running from anterior to posterior (Altringham and Ellerby, 1999; Videler and He, 2010). The lateral longitudinal muscle is divided in two main types; red muscle and white muscle (Videler and He, 2010). The red muscle, which is placed just beneath the lateral line, is used during aerobic metabolism and is therefore slow but nearly inexhaustible. The white muscle, accounting for about 80-100% of the total amount of muscle, is used during anaerobic metabolism and is therefore fast but rapidly exhausted (Altringham and Ellerby, 1999; Wardle et al., 1995). Some species have a pink intermediate transition layer between the red and the white muscle (Videler and He, 2010). The amount of red and white muscle is related to the ecology of the species. Pelagic species that are swimming continuously have a higher amount of red muscle compared to demersal/benthic species (Altringham and Ellerby, 1999). The transition from using red muscle to recruiting white muscle occurs progressively (Wardle et al., 1995). The usage of the white muscle can result in 100 times recovering rates, and is only used for a very short time at burst speed (Videler and He, 2010). The fact that different fish species have different amount of red and white muscle, affecting their swimming endurance, is important to take into consideration when determining optimal towing speed for trawls (Breen et al., 2004).

Also the exterior morphology reflects the ecology of the fish species and their swimming ability. In general one can categorize fish in to three groups with respect to their swimming ability. (1) long distance cruisers (e.g *Scombridae*), (2) ambush predators or sprinters (e.g. *Sphyraena*), and (3) all-round swimmers (e.g. *Gadiformes*). Cod, haddock and saithe belong to the latter group. Fish that are all-round swimmers are reasonable good at maneuvering, steering, breaking and accelerating, often with some kind of specialization. For instance gadoids, although having aspects from all the three groups mentioned above, are specialized in breaking, with saithe with the fastest deceleration rate measured (8.7 m/s^2) (Videler and He, 2010). Fish that are good all-round swimmers have a relative large caudal penducle and fin. Compared to the other two groups the pectoral fin is placed high on the body, and the pelvic fin is placed more anterior resulting in increased stability and maneuverability.

Swimming modes

According to Newton.s third law all movement in a medium results in turbulence, which is equal in magnitude but has an opposite reaction as the object that caused the turbulence. A fish swimming in water causes vortex rings around the body due to a local change in water velocities (Videler and He, 2010). The aim of an adapted swimming mode of a given species with a given body shape, is to reduce the hydrodynamic drag forces in order to reduce energy consumption. This is reflected by the number of wave curvatures on the body for a given time, varying between 0.7 and 1.7 depending on the species (Altringham and Ellerby, 1999; Wardle et al., 1995). An eel-like fish has a more than one wave curvature on the body at any time, while for instance a siathe will only have one wave curvature on the body at any time (Videler and He, 2010; Wardle et al., 1995). This means that a fish that has a wave body curvature close to 1.0 have a higher amplitude and thus a stride length resulting requiring less energy, compared to a fish that have more than one wave curvature on the body. The stride length varies between 0.5 BL and 1.0 BL depending on the fish species (Altringham and Ellerby, 1999). The stride length is also highly depended on the fish size (Wardle, 1975). For example a 10 cm long cod swimming 10 BL/s^{-1} will have a swimming speed of 1 m/s^{-1}, whilst a cod of 100 cm also swimming 10 BL/s^{-1} will have a swimming speed of 10 m/s^{-1} (at a temperature of 9.5 to 12.0 ˚C) (Videler and He, 2010). Swimming speed is often categorized in to "sustained" that represents a threshold limit for aerobic respiration, "prolonged" and "burst" (Breen et al., 2004; He, 1993). The different swimming modes and styles affect the amount of drag caused by thrust that is proportional to the square of swimming speed (Videler and He, 2010). This means that by doubling swimming speed a fish needs to overcome four times as much drag, requiring eight times more energy consumption (Videler and He, 2010). To cope with this negative impact of increasing drag and energy consumption several fish species, amongst them cod and haddock, have adopted the burst-and-coast (kick-and-glide) swimming style. This type of swimming is often seen for gadoids in front of the trawl mouth. It is often initiated when the swimming speed exceeds 2-2.5 BL/s^{-1}, and results in energy savings of 40-50% (Videler and He, 2010).

Endurance

Another important aspect in fish locomotion is swimming endurance. Swimming endurance decreases with an increasing speed and is limited by the ability to uptake oxygen (Breen et al. 2004; Videler and Wardle, 1991). In general demersal fish species fatigue faster than pelagic fish species as long as they swim within in their cruising speed, due the different amount of red and white muscle related to their life style, the latter having more red muscle (Videler and He, 2010). When looking at the endurance measured in BL/s^{-1} for one given species large fish fatigue much faster than small fish (Videler and He, 2010). Both *in vitro* and *in vivo* studies have shown that a small fish (10 cm) can reach a speed up to 25 BL/s^{-1}, whereas a fish large fish (100 cm) only can reach a speed up to 4 BL/s^{-1} (Wardle, 1975). It has been estimated that the burst swimming speed decreases with a factor of 0.89 measured in L/s^{-1} for each 10 cm increase in length (Videler and He, 2010). Even though small fish have a greater endurance in term of tail beat frequency, do larger fish cover a larger distance per tail beat, i.e. larger stride length (Breen et al., 2004). Another important factor related to the fish that affects the endurance is the condition factor (K). A starved fish in bad shape and condition has a low K and low endurance, compared to a fish in good condition (Breen et al., 2004). When the swimming velocity exceeds the cruising speed of the fish and the white muscle is gradually overtaking the red muscle, the endurance decreases rapidly (Videler and He, 2010).

The effect of water temperature

Water temperature has a profound impact on the swimming performance, both speed and endurance (He, 1993). In general it is assumed that the performance increases until a preferred temperature for a given species, and then decreasing under higher temperatures (Steinhausen et al., 2005). A 10˚C increase in water temperature results in halved muscle time contraction and a doubling in burst speed (He, 1993; Videler and He, 2010). The swimming speed that is determined by the tail beat frequency is affected by both temperature and the length of the fish (Videler and Wardle, 1991). Observations conducted in a flume tank have shown that the maximum sustained swimming speed for a cod of 49 cm is 0.9 BL/s^{-1} by 0.8 ˚C, and for a cod of 36 cm is 2.1 BL/s^{-1} by 5.0 ˚C (Videler and He, 2010). Another study, also conducted in a flume tank achieved the same results, showing that in water with a temperature of 5 ˚C a 35 cm long cod could have a sustained swimming speed of 2.1 BL/s^{-1} for 240 minutes, and prolonged swimming speed of 3.4 BL/s^{-1} for 4.2 minutes (Videler and Wardle, 1991). Observations conducted *in situ* using video camera have measured a swimming speed of 2.8 BL/s^{-1} for a 30 cm long cod, and 3.5 BL/s^{-1} for a 42 cm long cod, both by 12.0 ˚C (Videler and Wardle, 1991). All these observations show that both swimming speed and endurance are highly affected by the length of the fish and water temperature.

Vision

Vision is an important part of understanding the behavior of fish and their reactions towards fishing gear. Except for a few, all fish species have well-developed eyes (Guthrie and Muntz, 1993). Due to the position of the eyes, in most cases on both sides of the head, fish have a wide visual field. The visual field consists of a relative narrow binocular field in front of the head, a wide monocular field on both sides of the body and a narrow blind zone behind the body (Arimoto et al., 2010).

The structure of the eye

The basic structure of the eye is equal for all fish species, but the properties differ greatly among species according to their environmental adaptation (Arimoto et al., 2010; Guthrie and Muntz, 1993). For understanding the role of vision in relation to trawl fishing, especially two components are of significant importance; the lens and the retina. Fish have a spherical and focusable lens that serves as the main refracting component (Arimoto et al., 2010; Guthrie and Muntz, 1993). Unlike mammals accommodation is not achieved by changing the shape of the lens, but by changing the position of the lens controlled by one or several external muscles depending on the species (Arimoto et al., 2010; Guthrie and Muntz, 1993). The retina is composed of three layers of cells of which the retina is the most important when it comes to the visual traits of a given species. The retina consists of two types of photoreceptor cells; rod and cons. The amount and distribution of rods and cons varies between species and during different life stages, resulting in different photosensitivity reflecting their adaptation in the environment (Arimoto et al., 2010). The rods consist of only one pigment and are used for dark-adapted vision (scotopic vision), while cons consist of single to quadruple cones containing different types and number of pigments and are used for light-adapted and color vision (photopic vision) (Arimoto et al., 2010). Cones are either blue-, red-, green or in some cases ultraviolet-sensitive. In order to discriminate between colors fish must have minimum two types of cones (Arimoto et al., 2010; Guthrie and Muntz, 1993). Fish that have retinas composed of only rods without cons are color-blind. The retina of cod consists of both cod and rods, indicating that the vision of cod is well adapted to a wide range of light intensities (Anthony, 1981). A change in ambient light intensity will result in a relative change in the positions of the cons and rods on order to adapt to the changing light intensity. This process is called retinomotor response (Arimoto et al., 2010). This is important due to the properties of water and absorption of solar radiation. Several studies have shown that for cod transition from photopic to scotopic vision occurs at light levels between 10^{-2} lux and 10^{-3} lux (Anthony, 1981).

Light transmission in water

The solar radiation diminishes gradually trough the water column due to backscattering from the water molecules and other particles. Low frequency colors (short wavelength) such as red will therefore be absorbed first, while high frequency colors (long wavelength) such as green and blue will transmit deeper in to the water column (Arimoto et al., 2010; Guthrie and Muntz, 1993). This results in monochromatic light at a certain depth. The intensity of ambient light through the water column is highly variable. It changes both temporal and spatial throughout the day and year, water turbidity and temperature, stratifications in the water column, weather and latitude (Anthony, 1981; Guthrie and Muntz, 1993).

Fish vision

Vision underwater can be divided in to four main categories; color vision, light vision, form vision and motion vision. Color vision is determined by the amount and distribution of cons and rods in the retina (Arimoto et al., 2010). The same applies for light vision, where in addition the available amount of ambient light also plays a vital role. The determining factor for fish to detect objects underwater is the contrast and brightness of the object against the background, especially under scotopic conditions (Anthony, 1981; Glass et al., 1986). However, the former appears to be of more importance than the latter (Arimoto et al., 2010). Form vision is the ability of fish to perceive details of a visual object or pattern, i.e. visual acuity and is depending on the accommodation ability and composition of the retina (Arimoto et al., 2010). Motion vision is the ability of the fish to detect movements and is affected by the amount of illumination (Arimoto et al., 2010). The frequency of images that are compound into a continuous image of an object is called flicker fusion frequency (FFF), and is affected by flash duration, light intensity and water temperature and is species depended (Arimoto et al., 2010). Decreasing light intensity or water temperature results in a lower capacity of image perception and thus perception of motion (Arimoto et al., 2010). This means that under conditions with low light intensities fast moving objects are not necessarily detected. Studies have shown that fish are able to perceive motion under conditions with very low light intensity, down to 10^{-7} lux (Arimoto et al., 2010). The ability of a fish to maintain a visual image of an object fixed on the retina is called optomotor response, and is of great importance when studying fish behavior in front of trawls (Arimoto et al., 2010).

References

Altringham, J.D., Ellerby, D.J., 1999. Fish swimming: patterns in muscle function. Journal of Experimental Biology. 202:3397-3403.

Anthony, P.D., 1981. Visual contrast thresholds in the cod *Gadus morhua* L. Journal of Fish Biology. 19:87-103.

Arimoto, T., Glass, C. W., Zhang, X., 2010. Fish Vision and Its Role in Fish Capture, in: He, P., (Ed.), Behavior of marine fishes: capture processes and conservation challenges. Ames, Iowa: Wiley-Blackwell, pp. 25-44.

Breen, M., Dyson, J., O.Neill, F.G., Jones, E., Haigh, M., 2004. Swimming endurance of haddock (*Melanogrammus aeglefinus* L.) at prolonged and sustained swimming speeds, and its role in their capture by towed fishing gears. ICES Journal of Marine Science: Journal du Conseil. 61:1071-1079.

Glass, C.W., Wardle, C.S., Mojsiewicz, W.R., 1986. A light intensity threshold for schooling in the Atlantic mackerel, *Scomber scombrus*. Journal of Fish Biology. 29:71-81.

Guthrie, D. M., Muntz, W. R. A., 1993. Role of vision in fish behaviour, in: Pitcher, T.J. (Ed.), Behaviour of teleost fishes. London: Chapman and Hall, pp.89-128.

He, P., 1993. Swimming speeds of marine fish in relation to fishing gears. ICES marine science symposia Copenhagen, ICES Mar Sci Symp.

Steinhausen, M., Steffensen, J., Andersen, N., 2005. Tail beat frequency as a predictor of swimming speed and oxygen consumption of saithe (*Pollachius virens*) and whiting (*Merlangius merlangus*) during forced swimming. Marine Biology. 148:197-204.

Videler, J. J., He, P., 2010. Swimming in Marine Fish, in: He, P., (Ed.), Behavior of marine fishes: capture processes and conservation challenges. Ames, Iowa: Wiley-Blackwell, pp. 5-23.

Videler, J.J., Wardle, C.S., 1991. Fish swimming stride by stride: speed limits and endurance. Reviews in Fish Biology and Fisheries. 1:23-40.

Wardle, C., Videler, J., Altringham, J., 1995. Tuning in to fish swimming waves: body form, swimming mode and muscle function. Journal of Experimental Biology. 198:1629-1636.

Wardle, C.S., 1975. Limit of fish swimming speed. Nature. 255:725-727.

Appendix B: Trawl construction

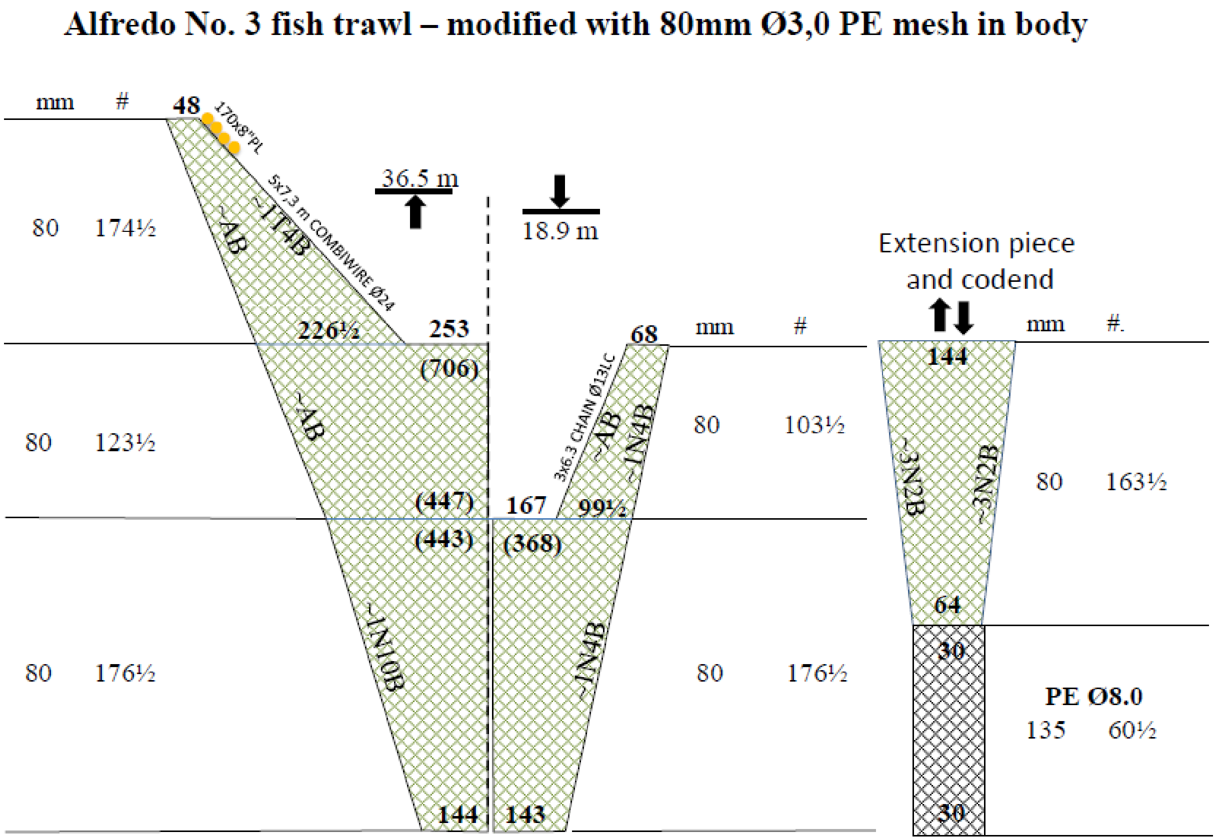

Figure B.1 The construction of the Alfredo 3 trawl used in the experiment (From Larsen, 2014[1]).

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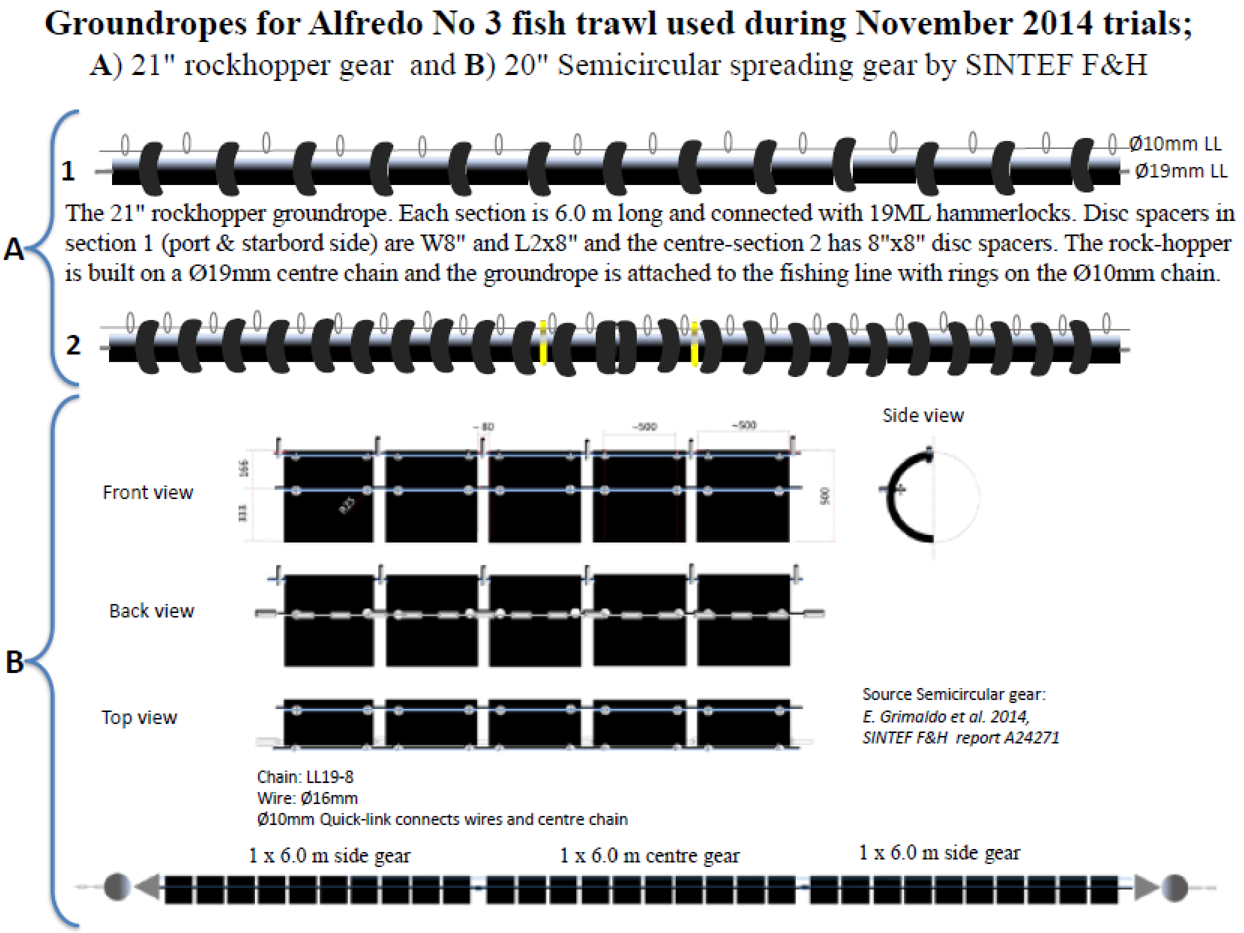
[1] Larsen, R., 2014. Trawl setup and details during fish trawl experiments November 2014. University of Tromsø – Norwegian College of Fisheries Science.



Groundropes for Alfredo No 3 fish trawl used during November 2014 trials;
A) 21" rockhopper gear and **B**) 20" Semicircular spreading gear by SINTEF F&H

The 21" rockhopper groundrope. Each section is 6.0 m long and connected with 19ML hammerlocks. Disc spacers in section 1 (port & starbord side) are W8" and L2x8" and the centre-section 2 has 8"x8" disc spacers. The rock-hopper is built on a Ø19mm centre chain and the groundrope is attached to the fishing line with rings on the Ø10mm chain.

Source Semicircular gear:
E. Grimaldo et al. 2014,
SINTEF F&H report A24271

Chain: LL19-8
Wire: Ø16mm
Ø10mm Quick-link connects wires and centre chain

Figure B.2 The construction of the ground-gears used in the experiment; (A) standard rockhopper gear, (B) semicircular spreading gear. (From Larsen, 2014[2]).

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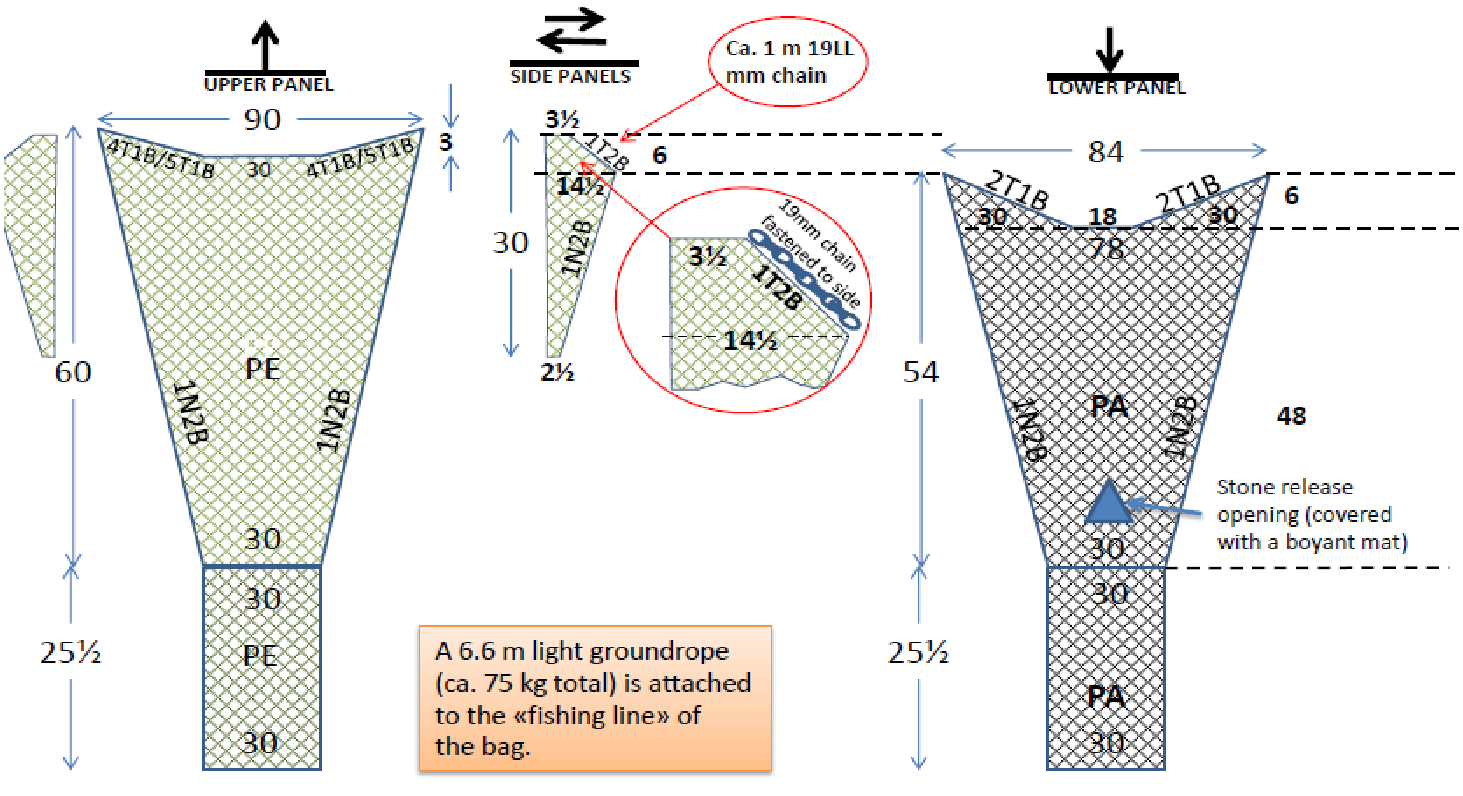
[2] Larsen, R., 2014. Trawl setup and details during fish trawl experiments November 2014. University of Tromsø – Norwegian College of Fisheries Science.



Upper panel and sidepanels made from dbl. 155 mm (135 mm inside) PE. Lower panel made from dbl. 155 mm (135 mm inside) PA

A 6.6 m light groundrope (ca. 75 kg total) is attached to the «fishing line» of the bag.

Modified version of sketch in Ingolfsson & Jørgensen 2006; Fish. Res. 79. (RB Larsen UIT 10.09. 2014)

Figure B.3 The construction of the escape retainer bag. (From Larsen, 2014[3]).

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[3] Larsen, R., 2014. Trawl setup and details during fish trawl experiments November 2014. University of Tromsø – Norwegian College of Fisheries Science.

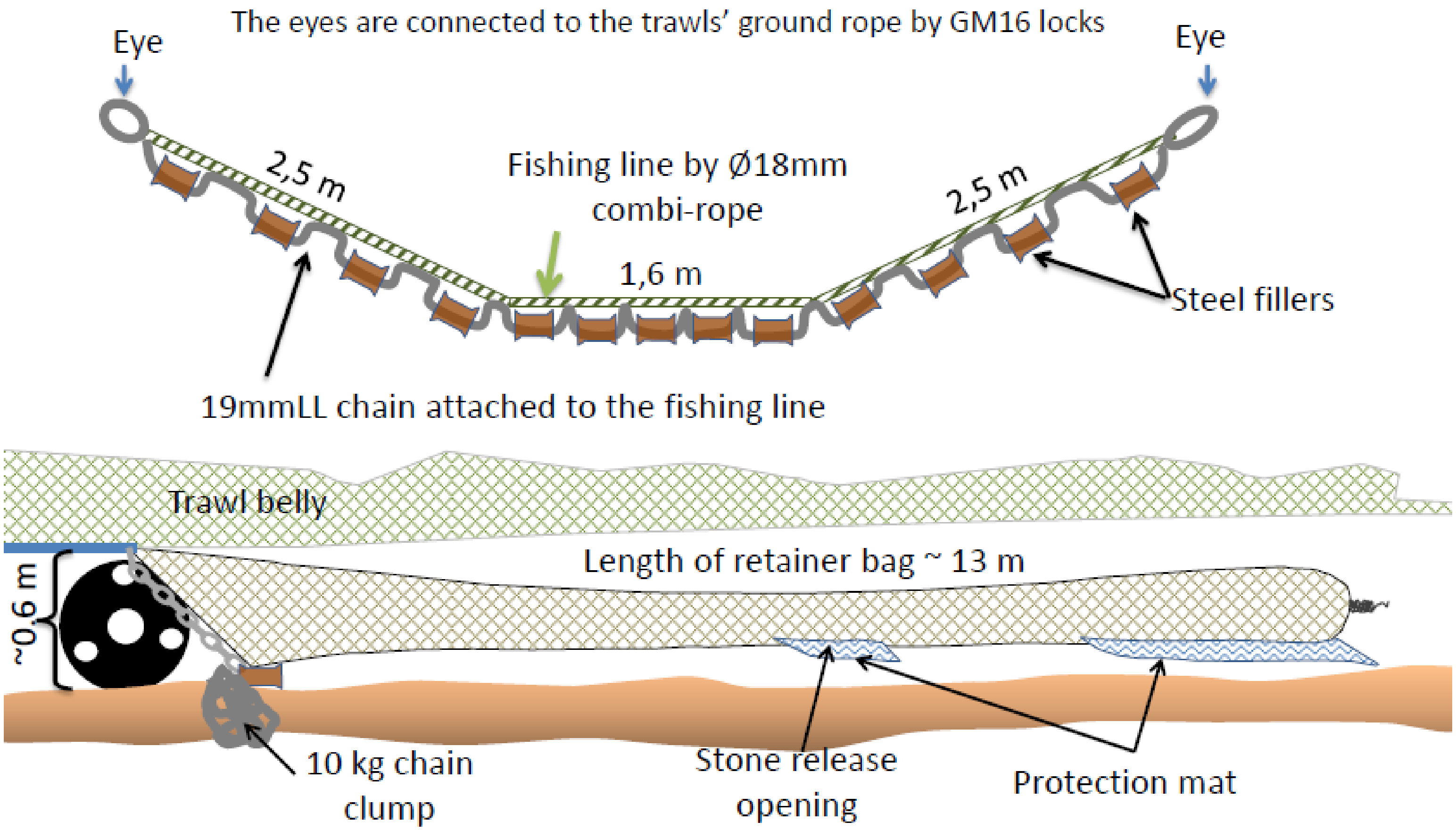

Figure B.4 The ground-gear and the mounting of the escape retainer bag underneath the trawl. (From Larsen, 2014[4]).

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[4] Larsen, R., 2014. Trawl setup and details during fish trawl experiments November 2014. University of Tromsø – Norwegian College of Fisheries Science.

Appendix C: Results

Table C.1 Numbers of fish caught in each individual haul for the data obtained in November 2014.

		Numbers of fish catched/measured		
Haul #	**Gear**	**Codend**	**Retainer bag**	**Total**
1	RH	66	35	101
2*	RH	62	68	130
3	RH	137	67	204
4	RH	84	62	146
5*	RH	31	46	77
6*	RH	92	47	139
7	RH	276	100	376
8	RH	334	109	443
10*	RH	62	17	79
12	RH	62	10	72
13	RH	21	7	28
14	RH	30	19	49
15	RH	63	35	98
17*	RH	398	103	501
18	RH	471	126	597
19	RH	607	114	721
20	RH	385	100	485
21	RH	86	19	105
22	RH	136	38	174
23	RH	42	16	58
24	RH	87	15	102
26	SCSG	24	0	24
27	SCSG	328	18	346
28	SCSG	41	14	55
29	SCSG	59	5	64
30	SCSG	153	11	164
31	SCSG	246	22	268
32	SCSG	310	44	354
33	SCSG	427	19	446
34	SCSG	741	7	748
35	SCSG	600	36	636
36	SCSG	408	34	442
37*	SCSG	350	34	384
38*	SCSG	133	23	156
41	SCSG	1379	77	1456
42	SCSG	463	40	503
43*	SCSG	83	5	88
44	SCSG	523	51	574
45	SCSG	1117	86	1203
46	SCSG	308	21	329
47*	SCSG	184	7	191

*Hauls recorded on video, demanding the use of artificial light

Table C.2 Numbers of fish caught in each individual haul for the data obtained in February 2015 for both cod and haddock.

		# cod catched/measured			# haddock catched/measured		
Haul #	**Gear**	**Codend**	**Retainer bag**	**Total**	**Codend**	**Retainer bag**	**Total**
1	SCSG	75	5	80	13	0	13
2	Rock-hopper	118	14	132	33	2	35
3	Rock-hopper	261	18	279	77	1	78
4	SCSG	146	3	149	41	1	42
5	SCSG	85	3	88	36	5	41
6	Rock-hopper	92	9	101	59	6	65
7	Rock-hopper	78	7	85	65	3	68
8	SCSG	97	7	104	61	0	61
9	SCSG	109	7	116	83	1	84
10	Rock-hopper	109	6	115	92	13	105
11	Rock-hopper	238	18	256	136	10	146
12	SCSG	401	16	417	174	0	174
13	SCSG	150	0	150	64	2	66
14	Rock-hopper	65	7	72	43	5	48
15	Rock-hopper	92	9	101	33	2	35
17	SCSG	158	1	159	42	1	43
18	SCSG	134	2	136	40	0	40
19	Rock-hopper	140	8	148	62	3	65
20	Rock-hopper	139	13	152	90	4	94
21	SCSG	150	6	156	61	0	61
22	SCSG	355	9	364	62	2	64
23	Rock-hopper	114	3	117	30	4	34
24	Rock-hopper	112	5	117	63	2	65
25	SCSG	95	5	100	35	2	37
26	SCSG	178	6	184	54	2	56
28	Rock-hopper	98	11	109	53	9	62

Table C.3 The coefficients provided from the linear models in R, showing no correlation between fish density and escapement rate as well as large variation in the data. (Call: lm (formula = Efficiency_L ~ catch rate)).

Rock-hopper, Nov. 2014	**Estimate**	**St. Error**	**Pr(>|t|)**	**Adj. R^2**
Cod, 60 cm				
Intercept	0.48083	0.06010	0.00000	-0.06169
Catch rate	0.00183	0.00510	0.72500	
Cod, 65 cm				
Intercept	0.61487	0.05909	0.00000	-0.06989
Catch rate	0.00071	0.00501	0.88900	
Cod, 70 cm				
Intercept	0.72820	0.04239	0.00000	-0.07138
Catch rate	-0.00009	0.00360	0.98100	
Cod, 75 cm				
Intercept	0.80249	0.03325	0.00000	-0.07079
Catch rate	-0.00026	0.00282	0.92800	
Cod, 80 cm				
Intercept	0.85207	0.02656	0.00000	-0.07057
Catch rate	-0.00024	0.00225	0.91700	
Cod, 85 cm				
Intercept	0.88823	0.02090	0.00000	-0.06963
Catch rate	-0.00027	0.00177	0.88000	
Cod, 90 cm				
Intercept	0.91469	0.01645	<2e-16	-0.06633
Catch rate	-0.00036	0.00140	0.80000	
Cod, 95 cm				
Intercept	0.93640	0.01433	<2e-16	-0.05538
Catch rate	-0.00056	0.00122	0.65200	
Cod, 100 cm				
Intercept	0.94689	0.01451	<2e-16	-0.06054
Catch rate	-0.00047	0.00123	0.71000	
SCSG, Nov. 2014				
Cod, 60 cm				
Intercept	0.70835	0.06782	0.00000	-0.04096
Catch rate	0.00188	0.00294	0.53200	
Cod, 65 cm				
Intercept	0.79401	0.05939	0.00000	-0.05502
Catch rate	0.00120	0.00257	0.64800	
Cod, 70 cm				
Intercept	0.85795	0.04349	0.00000	-0.06022
Catch rate	0.00072	0.00188	0.70600	

Table C.3 continued

	Estimate	St. Error	Pr(>|t|)	Adj. R^2
Cod, 75 cm				
Intercept	0.91094	0.02451	0.00000	-0.06721
Catch rate	0.00025	0.00106	0.81700	
Cod, 80 cm				
Intercept	0.94468	0.01355	<2e-16	-0.07127
Catch rate	0.00003	0.00059	0.96400	
Cod, 85 cm				
Intercept	0.96520	0.00862	<2e-16	-0.07044
Catch rate	-0.00004	0.00037	0.91100	
Cod, 90 cm				
Intercept	0.97820	0.00614	<2e-16	-0.06715
Catch rate	-0.00006	0.00027	0.81600	
Cod, 95 cm				
Intercept	0.94485	0.03193	0.00000	-0.03754
Catch rate	0.00093	0.00138	0.51000	
Cod, 100 cm				
Intercept	0.98240	0.00708	<2e-16	-0.06498
Catch rate	0.00009	0.00031	0.77500	
Rock-hopper, Feb. 2015				
Cod, 60 cm				
Intercept	0.74534	0.07797	0.00000	-0.02606
Catch rate	0.03854	0.04622	0.42200	
Cod, 65 cm				
Intercept	0.80637	0.06116	0.00000	-0.03669
Catch rate	0.02750	0.03626	0.46400	
Cod, 70 cm				
Intercept	0.85276	0.04680	0.00000	-0.04837
Catch rate	0.01854	0.02774	0.51800	
Cod, 75 cm				
Intercept	0.88934	0.03573	0.00000	-0.06347
Catch rate	0.01128	0.02118	0.60500	
Cod, 80 cm				
Intercept	0.91659	0.02701	0.00000	-0.07616
Catch rate	0.00622	0.01601	0.70500	
Cod, 85 cm				
Intercept	0.93542	0.02071	0.00000	-0.08384
Catch rate	0.00329	0.01228	0.79400	
Cod, 90 cm				
Intercept	0.94655	0.01802	0.00000	-0.08608
Catch rate	0.00236	0.01068	0.82900	

Table 3.C continued

	Estimate	St. Error	Pr(>|t|)	Adj. R^2
Cod, 95 cm				
Intercept	0.95304	0.01785	0.00000	-0.08639
Catch rate	0.00227	0.01058	0.83400	
Cod, 100 cm				
Intercept	0.96013	0.01652	0.00000	-0.09013
Catch rate	0.00087	0.00980	0.93100	
SCSG, Feb. 2015				
Cod, 60 cm				
Intercept	0.92439	0.03333	0.00000	-0.09078
Catch rate	0.00054	0.01481	0.97100	
Cod, 65 cm				
Intercept	0.93409	0.02741	0.00000	-0.08589
Catch rate	0.00275	0.01218	0.82600	
Cod, 70 cm				
Intercept	0.94287	0.02325	0.00000	-0.08026
Catch rate	0.00340	0.01033	0.74800	
Cod, 75 cm				
Intercept	0.95101	0.01970	0.00000	-0.07574
Catch rate	0.00345	0.00875	0.70100	
Cod, 80 cm				
Intercept	0.95869	0.01623	0.00000	-0.07094
Catch rate	0.00327	0.00721	0.65900	
Cod, 85 cm				
Intercept	0.96556	0.01327	0.00000	-0.06530
Catch rate	0.00303	0.00590	0.61700	
Cod, 90 cm				
Intercept	0.97225	0.01090	<2e-16	-0.06652
Catch rate	0.00243	0.00484	0.62600	
Cod, 95 cm				
Intercept	0.97931	0.00823	<2e-16	-0.07920
Catch rate	0.00126	0.00366	0.73600	
Cod, 100 cm				
Intercept	0.98341	0.00666	<2e-16	-0.08566
Catch rate	0.00068	0.00296	0.82200	
Rock-hopper, Nov. 2014 & Feb. 2015				
Cod, 60 cm				
Intercept	0.64587	0.04772	0.00000	-0.01999
Catch rate	-0.00363	0.00541	0.50700	
Cod, 65 cm				
Intercept	0.73787	0.04032	<2e-16	-0.01632
Catch rate	-0.00339	0.00457	0.46500	

Table C.3 continued

	Estimate	St. Error	Pr(>|t|)	Adj. R^2
Cod, 70 cm				
Intercept	0.80653	0.02877	<2e−16	−0.01178
Catch rate	−0.00268	0.00326	0.41900	
Cod, 75 cm				
Intercept	0.85561	0.02154	<2e−16	−0.01155
Catch rate	−0.00201	0.00244	0.41700	
Cod, 80 cm				
Intercept	0.89019	0.01657	<2e-16	-0.01290
Catch rate	-0.00151	0.00188	0.42900	
Cod, 85 cm				
Intercept	0.91552	0.01271	<2e−16	−0.01169
Catch rate	−0.00118	0.00144	0.41800	
Cod, 90 cm				
Intercept	0.93382	0.00987	<2e−16	−0.00700
Catch rate	−0.00100	0.00112	0.37700	
Cod, 95 cm				
Intercept	0.94724	0.00849	<2e−16	−0.00314
Catch rate	−0.00092	0.00096	0.34800	
Cod, 100 cm				
Intercept	0.95448	0.00838	<2e−16	−0.01568
Catch rate	−0.00072	0.00095	0.45800	
SCSG, Nov. 2014 & Feb. 2015				
Cod, 60 cm				
Intercept	0.82340	0.04035	<2e−16	−0.03322
Catch rate	−0.00074	0.00234	0.75500	
Cod, 65 cm				
Intercept	0.87023	0.03315	<2e−16	−0.03416
Catch rate	−0.00053	0.00192	0.78600	
Cod, 70 cm				
Intercept	0.90615	0.02391	<2e−16	−0.03437
Catch rate	−0.00037	0.00139	0.79400	
Cod, 75 cm				
Intercept	0.93476	0.01374	<2e−16	−0.03227
Catch rate	−0.00028	0.00080	0.72700	
Cod, 80 cm				
Intercept	0.95561	0.00815	<2e-16	-0.02909
Catch rate	-0.00022	0.00047	0.65200	
Cod, 85 cm				
Intercept	0.96847	0.00551	<2e−16	−0.03252
Catch rate	−0.00011	0.00032	0.73400	

Table C.3 continued

	Estimate	St. Error	Pr(>|t|)	Adj. R²
Cod, 90 cm				
Intercept	0.97750	0.00413	<2e-16	-0.03582
Catch rate	-0.00004	0.00024	0.86000	
Cod, 95 cm				
Intercept	0.96384	0.01694	<2e-16	-0.02708
Catch rate	0.00050	0.00098	0.61300	
Cod, 100 cm				
Intercept	0.98400	0.00384	<2e-16	-0.03476
Catch rate	0.00005	0.00022	0.80900	
Rock-hopper, Feb. 2015				
Haddock, 55 cm				
Intercept	0.92679	0.03525	0.00000	-0.08428
Catch rate	0.01109	0.04277	0.80000	
Haddock, 60 cm				
Intercept	0.98228	0.02976	0.00000	-0.02501
Catch rate	-0.03036	0.03610	0.41800	
Haddock, 65 cm				
Intercept	0.91010	0.09982	0.00000	-0.08966
Catch rate	0.01358	0.12111	0.91300	
Haddock, 70 cm				
Intercept	0.89060	0.24780	0.00421	-0.07640
Catch rate	-0.11580	0.30060	0.70750	
Haddock, 75 cm				
Intercept	0.99070	0.27660	0.00431	-0.00401
Catch rate	-0.32740	0.33560	0.35017	
Haddock, 80 cm				
Intercept	1.00760	0.27120	0.00341	0.03102
Catch rate	-0.38710	0.32900	0.26423	
SCSG, Feb. 2015				
Haddock, 55 cm				
Intercept	0.95593	0.02058	0.00000	0.01609
Catch rate	0.02808	0.02567	0.29700	
Haddock, 60 cm				
Intercept	0.96972	0.01984	0.00000	-0.03811
Catch rate	0.01851	0.02475	0.47000	
Haddock, 65 cm				
Intercept	0.98041	0.01320	0.00000	-0.04205
Catch rate	0.01183	0.01648	0.48800	
Haddock, 70 cm				
Intercept	0.98201	0.00867	<2e-16	0.00137
Catch rate	0.01091	0.01082	0.33500	

Table C.3 continued

	Estimate	St. Error	Pr(>|t|)	Adj. R²
Haddock, 75 cm				
Intercept	0.98032	0.01095	<2e-16	-0.07850
Catch rate	0.00486	0.01366	0.72900	
Haddock, 80 cm				
Intercept	0.98649	0.01947	0.00000	-0.00941
Catch rate	-0.02289	0.02429	0.36600	

Table C.4 The coefficients provided from the linear models in R, showing a correlation between the efficiency, i.e. rate of escapement and temperature for all cases investigated for the rock-hopper gear up to fish length 95 cm and the SCSG for fish of length up to 95 cm cm. The adjusted R^2 show large variation in the data. (Call: lm (formula = Efficiency_L ~ Temperature)).

Rock-hopper Nov. 2014 & Feb. 2015	**Estimate**	**Sd. Error**	**Pr(>|t|)**	**Adj. R^2**
Cod, 60 cm				
Intercept	0.66466	0.0561	5.72E-12	0.11100
Temperature	0.0333	0.01593	0.0465	
Cod, 65 cm				
Intercept	0.71418	0.04565	9.57E-15	0.1369
Temperature	0.02975	0.01295	0.0298	
Cod, 70 cm				
Intercept	0.77461	0.026616	< 2e-16	0.27890
Temperature	0.02553	0.00755	0.00228	
Cod, 75 cm				
Intercept	0.815531	0.021181	<2e-16	0.2831
Temperature	0.020515	0.006007	0.0021	
Cod, 80 cm				
Intercept	0.84122	0.01866	< 2e-16	0.27650
Temperature	0.01780	0.00529	0.00239	
Cod, 85 cm				
Intercept	0.869785	0.016702	< 2e-16	0.2338
Temperature	0.014399	0.004737	0.00534	
Cod, 90 cm				
Intercept	0.89908	0.01483	<2e-16	0.16440
Temperature	0.01057	0.00421	0.0185	
Cod, 95 cm				
Intercept	0.921331	0.015099	<2e-16	0.03217
Temperature	0.005899	0.004282	0.18	
Cod, 100 cm				
Intercept	0.921942	0.024968	<2e-16	-0.03065
Temperature	0.003143	0.007081	0.661	
SCSG, cod, Nov. 2014 & Feb. 2015				
Cod, 60 cm				
Intercept	0.79150	0.04186	6.37E-16	0.11490
Temperature	0.02447	0.01188	0.0504	
Cod, 65 cm				
Intercept	0.835267	0.03456	<2e-16	0.1189
Temperature	0.020507	0.009806	0.0473	
Cod, 70 cm				
Intercept	0.87159	0.02533	<2e-16	0.14600
Temperature	0.01651	0.00719	0.0307	

Table C.4 continued

	Estimate	St. Error	Pr(>|t|)	Adj. R^2
Cod, 75 cm				
Intercept	0.903795	0.016689	<2e-16	0.1852
Temperature	0.012241	0.004735	0.0162	
Cod, 80 cm				
Intercept	0.93409	0.01076	<2e-16	0.17580
Temperature	0.00768	0.00305	0.019	
Cod, 85 cm				
Intercept	0.957984	0.008509	<2e-16	0.007264
Temperature	0.002626	0.002414	0.288	
Cod, 90 cm				
Intercept	0.97123	0.00680	<2e-16	-0.00188
Temperature	0.00188	0.00193	0.339	
Cod, 95 cm				
Intercept	0.956372	0.017393	<2e-16	0.008268
Temperature	0.005425	0.004935	0.283	
Cod, 100 cm				
Intercept	0.942425	0.022241	<2e-16	0.015
Temperature	0.007415	0.00631	0.252	

Table C.5 Hauls conducted in February 2015 categorized according to the light conditions in the area, used when investigating the effect of diurnal variability in the rate of escapement. Nocturnal conditions lasted from ~15:00 pm to ~05:30 am, and diel conditions lasted from ~06:30 am until ~14:00 pm. The conditions with twilight lasted in about one hour and are excluded from the analysis.

Haul #	Gear	Start time (UTC)	Duration (h:mm)	Light condition
1	SCSG	04:39	00:50	Twilight
2	Rock-hopper	06:34	01:00	Diel
3	Rock-hopper	08:18	01:30	Diel
4	SCSG	11:14	01:30	Diel
5	SCSG	13:29	01:35	Twilight
6	Rock-hopper	16:13	01:31	Twilight
7	Rock-hopper	19:04	01:30	Nocturnal
8	SCSG	21:43	01:36	Nocturnal
9	SCSG	00:01	01:37	Nocturnal
10	Rock-hopper	02:45	01:31	Nocturnal
11	Rock-hopper	04:56	01:35	Nocturnal
12	SCSG	07:44	01:30	Diel
13	SCSG	12:57	01:49	Diel
14	Rock-hopper	14:57	01:34	Twilight
15	Rock-hopper	17:50	01:30	Nocturnal
17	SCSG	22:33	02:03	Nocturnal
18	SCSG	01:38	01:33	Nocturnal
19	Rock-hopper	04:28	01:36	Twilight
20	Rock-hopper	06:45	01:35	Diel
21	SCSG	09:31	00:54	Diel
22	SCSG	11:50	01:30	Diel
23	Rock-hopper	14:36	01:30	Twilight
24	Rock-hopper	16:50	01:31	Nocturnal
25	SCSG	19:24	01:35	Nocturnal
26	SCSG	21:43	01:31	Nocturnal
28	Rock-hopper	02:32	01:31	Nocturnal