Development of selectivity systems for gadoid trawls

Tests with sorting shortened lastridge ropes, the influence of light on selectivity and application of FISHSELECT to saithe

Scientific status report June 2022

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Abstract

The present status report is part of the project “Development of selectivity systems for gadoid trawls”, which aims at improving exploitation patterns of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and saithe (*Pollachius virens*) in the Norwegian Sea and Barents Sea bottom trawl fisheries. It summarizes results for three cruises conducted on the commercial vessel M/Tr Hermes and the research vessel R/V Helmer Hanssen between November 2021 and March 2021. These were carried out in the fishing grounds around Bear Island and the grounds around Sørøya,, where in addition to cod and haddock, saithe can be abundant.

In the commercial cruise onboard M/Tr Hermes the size selectivity of a 55 mm sorting grid section (Sort-V type) was compared to that of an identical section with a bar spacing of 45 mm. The results showed that the size selectivity of the two sections is significantly different. The 45 mm grid retains in general significantly more fish over minimum legal size (*MLS*) but it may also retain more fish below *MLS*, which can become a challenging in areas with high juvenile densities. The data analysis evidenced the limitations of paired-gear analysis method.

In the first cruise onboard R/V Helmer Hanssen, a codend with 0, 15 and 30% shortened lastridge ropes was tested on cod, haddock, redfish and saithe. The results showed that while shortening the lastridge ropes by 15% can be beneficial for the size selectivity of these species, shortening them further to 30% can create issues regarding the fraction of fish that gets a chance to escape through the codend meshes. This issue is attributed to the potential folding in the codend netting panels created when lastridge ropes are excessively shortened.

During the second cruise onboard R/V Helmer Hanssen, the selectivity of saithe was evaluated using the FISHSELECT methodology, which determines if a fish can penetrate a certain mesh based on its morphology. In addition, trials conducted to determine the potential effect of red and white lights on size selectivity showed that lights, specially white lights, can have a significant negative effect on the size selectivity of haddock, redfish and saithe in sorting grids.

Sammendrag

Foreliggende statusrapport er en del av prosjektet «Utvikling av seleksjonssystemer i torsketrål» som tar sikte på å forbedre utnyttelsesmønsteret i bunntrålfiske etter torsk (*Gadus morhua*), hyse (*Melanogrammus aeglefinus*) og sei (*Pollachius virens*) i Norskehavet og Barentshavet. Den oppsummerer resultatene fra tre tokt utført ombord M/Tr «Hermes» og R/V «Helmer Hanssen» i tidsperioden november 2021 - mars 2021. Toktene ble gjennomført på fiskefeltene rundt Bjørnøya og utenfor Sørøya, hvor man i tillegg til torsk og hyse kan finne gode forekomster av sei.

Ombord M/Tr «Hermes» ble størrelseseleksjon til en 55 mm sorteringsrist (Sort-V type) sammenlignet med den en rist i en identisk seksjon med spilleavstand på 45 mm. Resultatene viste at størrelseseleksjonen til de to ristene er signifikant forskjellige. Risten med 45 mm spilleavstand tilbakeholder generelt betydelig mer fisk over minstemål, men den kan også tilbakeholde mer fisk under minstemål. Dette kan bli en utfordring i områder med høy yngeltetthet. Dataanalysen viser også begrensningene ved å benytte «paired-gear» metoden.

I det første toktet ombord på R/V «Helmer Hanssen» ble det testet en sekk med 0, 15 og 30 % innkortede leisetau på torsk, hyse, uer og sei. Resultatene viste at det kan være fordelaktig å korte inn leisetauene med 15 % for størrelseseleksjonen for disse artene. Å korte inn leisetauene 30 % viste seg derimot å skape redusere andelen fisk som får en sjanse til å rømme gjennom maskene i sekken. Dette problemet tilskrives potensiell «buktning» i panelene i sekken, som kan oppstå ved å korte leisetauene for mye.

Under det andre toktet ombord på R/V Helmer Hanssen ble seleksjon av sei evaluert ved hjelp av FISHSELECT-metodikken, som avgjør om en fisk kan trenge gjennom en bestemt nett-maske basert på dens morfologi. I tillegg ble det utført forsøk for å undersøke om kunstig lys (rødt og hvitt lys) hadde en effekt på størrelsesseleksjonen til torsk, hyse og uer. Det antas at spesielt hvitt lys, kan ha en betydelig negativ effekt på størrelsesselekjonen i sorteringsrister.

1. Background

The project “Development of selectivity systems for gadoid trawls” is a National initiative in Norway that aims at solving issues and challenges related to species and size selectivity in gadoid trawls. The main objective of the project is to:

- Contribute to improve exploitation patterns of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and saithe (*Pollachius virens*) in the Norwegian Sea and Barents Sea bottom trawl fisheries by developing existing selection systems and introducing alternative solutions.

And this main objective will be fulfilled through the following secondary objectives:

- Develop and test new user-friendly grid designs that can substitute the grids used in the fishery today (i.e. Flexigrid).
- Test and document the properties (incl. selectivity properties) for different codend designs that would potentially substitute the grid+codend gear used in the fishery today.
- Study the effect of using different bar-spacings and meshes for the exploitation pattern of cod, haddock and saithe.

The project is led by the Institute of Marine Research in Norway in close cooperation with the Arctic University of Norway and SINTEF Ocean AS, which are the three leading institutes in Norway regarding fishing gear technology research. In addition to these three institutes the Federal Research Institute of Fisheries and Oceanography (PINRO) and the Directorate of fisheries in Norway will participate as partners in the project. The directorate of fisheries and the Norwegian Research and Aquaculture Research fund are the main financing organisms in the project. See project description for further details (FHF, project number 901633, www.fhf.no).

The project started October 2021, and during the autumn 2021 and the first half of 2022, three cruises were conducted onboard the research vessel R/V Helmer Hanssen (University of tromsø, UiT) in connection with the project. During these three cruises, different sorting grid designs and vertical separation of cod and haddock were tested. In addition, initial tests were carried out to study the applicability and performance of codends with shortened lastridge ropes. The results from these tests were summarized in a report (Sistiaga et al., 2021), and were presented and discussed in a meeting project group meeting the 09.09.21. The discussions in the meeting led to the following priorities for the following cruises:

- Test of grids with bar spacings below 55 mm.
- Continue the tests with the codends with shortened lastridge ropes.

Based on these two priorities and the objectives of the project, the following activities were prioritized for the period 01.10.21 to 31.05.22:

- Test of the size sorting performance of a 45 mm bar spacing Sort-V grid and comparisons with the compulsory 55 mm sorting grid.
- Test of codends with different degrees of shortened lastridge ropes.
- Collection of size selectivity data for saithe and application of the FISHSELECT methodology.
- Effect of light on selectivity and use of video data to understand fish behavior towards sorting grids.

Three cruises were carried out during the autumn 2021 and spring 2022 to work with the priorities described in the points above. One cruise onboard the commercial vessel M/Tr. Hermes, and two cruises onboard the research vessel R/V Helmer Hanssen. The following chapters in this report describe the equipment tested in each cruise and include a summary of the results obtained. The results from the cruises will be finally published in scientific journals and at the moment this status report was completed they have been analyzed to a different extent. Thus, the data presented here can be expected to be further analyzed and completed through the project period.

2. Cruise November 2021 onboard M/Tr. Hermes

2.1. Tests with different bar spacing sorting grids

2.1.1. Summary

One of the main objectives in the project "Development of selectivity systems for gadoid trawls" is to "study the effect of using different bar-spacings and meshes for the exploitation pattern of cod, haddock and saithe". In 2020 a research cruise was carried out to compare two Sort-V grids with 45- and 55-mm bar spacing, respectively. The results from that cruise showed that the selectivity for cod and haddock larger than Minimum Legal Size (*MLS*) differed between the grids (i.e. the 45 mm grid retained more fish larger than *MLS*), whereas the selectivity for fish smaller than *MLS* did not. Encouraged by these results, an additional cruise to compare these two grids was carried out onboard the commercial trawler M/Tr Hermes in November 2021.

During the commercial cruise, data were collected in two different fishing grounds, around Bjørnøya and west of Sørøya, and for three different species, cod, haddock and saithe. The results of the cruise showed as in the research cruise of 2020, that the selectivity of the 45- and 55-mm grids differs substantially. For all three species, the 45 mm grid retains in general significantly more fish larger than *MLS* than the 55 mm grid, but in some cases it also retains significantly more fish smaller than *MLS*. In all cases, the difference in retention rate between the grids was larger for fish larger than *MLS* than for fish smaller than *MLS*. The exploitation pattern indicators calculated show that the sorting ability of grids can vary and that catch patterns depend largely on the area and population fished e.g. the discard ratio for haddock increased from <3% to >50% for both grids when the fishery moved from Bjørnøya to the areas west of Sørøya. The results obtained indicate that gear choice including sorting devices other than grids may be necessary in the near future to increase catch efficiency and consequently reduce effort.

Finally, the data analysis in this study was conducted using the paired-gear method and shows the limitations of an indirect data collection method. For future experiments where the size range of the species is expected to be at the edge of the selectivity range of the gear, a direct method like the covered codend method is recommended instead.

2.1.2. Introduction

A research cruise conducted onboard R/V "Helmer Hanssen" in December 2020 showed important selectivity differences between a 45 mm steel grid and 55 mm steel grid for cod, haddock and redfish (Sistiaga et al., 2021). For all three species, which have a Minimum Legal Size (*MLS*) of 44, 40 and 32 cm respectively, the retention of most length classes larger than *MLS* was significantly larger for the 45 mm grid, while the differences in retention for the fish smaller than *MLS* between the two grids tested were not significant in any case (Fig. 1).

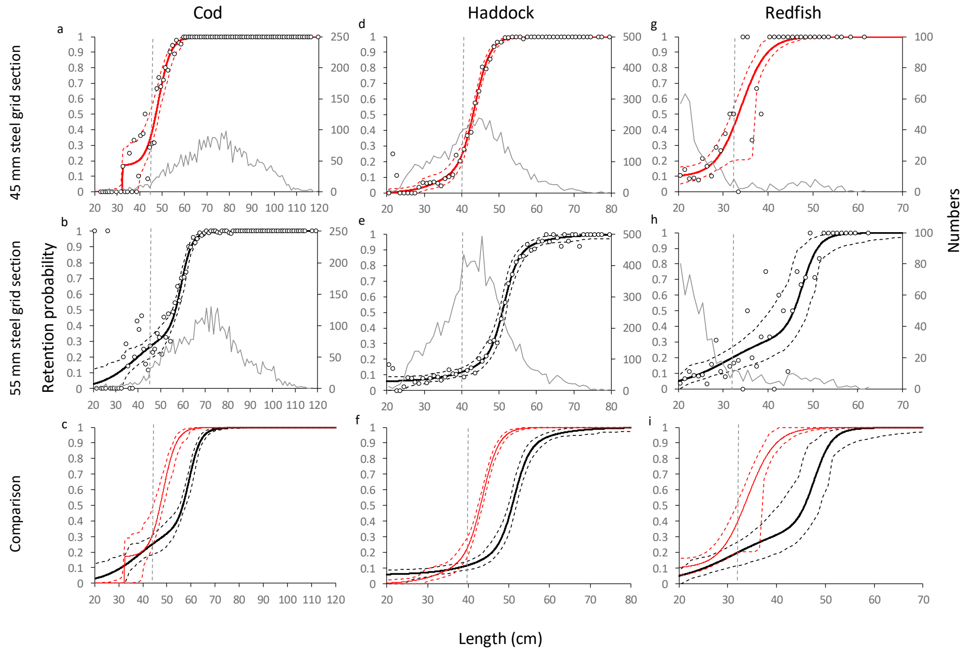


Fig. 1: Retention probability with the 45 mm steel grid and the 55 mm steel grid for cod (a-c), haddock (d-f) and redfish (g-i) in the research cruise carried out onboard R/V Helmer Hanssen in December 2020. In the comparison, the standard Sort-V section with a 45 mm steel grid in red and the standard Sort-V section with a 55 mm steel grid in black.

Encouraged by the results obtained in the research cruise in December 2020, the project group decided to compare the performance of the Sort-V steel grid with these two different bar spacings, 45- and 55-mm, in purely commercial fishing conditions.

2.1.3. Materials and methods

2.1.3.1. Fishing trials

Fishing trails were conducted in the Barents Sea, around Bear Island (73° 58’ 139” / 74° 31’ 071” N – 18° 11’ 733” / 25° 02’ 314” E), and off the coast of Norway, west of Sørøya (70° 53’ 291” / 71° 13’ 818” N – 21° 33’ 966” / 21° 57’ 379” E), between the 9th and 21st of November 2021. The commercial vessel “M/Tr Hermes” (55 m LOA, 1572 Gross Tonnage) was chartered for the trials. The vessel operates two Mørenot 634# trawls (headline height ca. 7m) in a twin setup with a pair of Scorpion injector doors (10.5 m, 4700 kg each), a central clump and 100 m sweeps. The door distance was typically 220-250 m.

One of the trawls was rigged with either a 55 mm or 45 mm steel grid sorting section (Sort-V type) in front of the extension piece and a blinded codend (test gear), whereas the other trawl was rigged without grid section and with a blinded codend (control gear). The codends used were built of 133 mm meshes (#100 meshes long and 80 free meshes around) and were blinded by means of liners built of 45 mm nominal size meshes, which ensured that no fish under 10 cm can escape from the codend (Sistiaga et al., 2011). The test and control gears were alternated between the starboard and port sides every 5 to 8 hauls (Table 1).

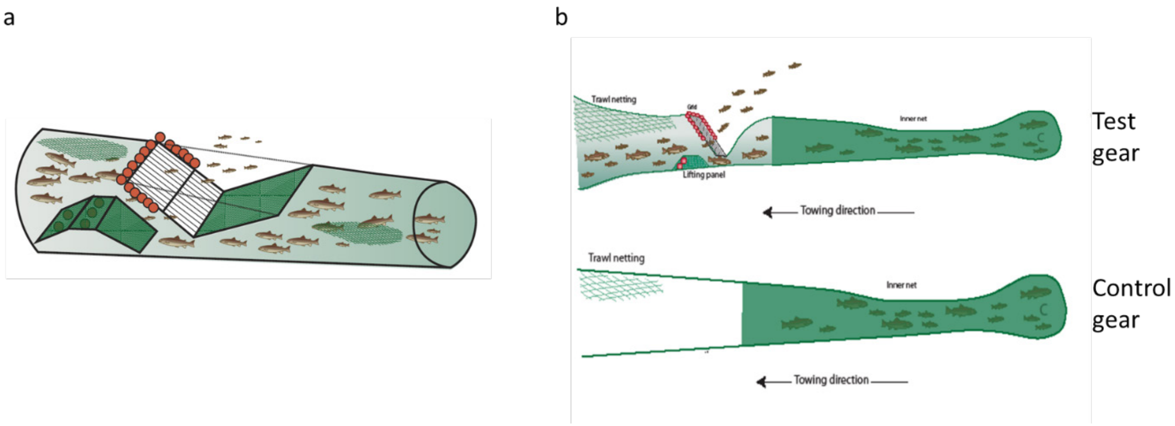


Fig. 2: Illustration of a Sort-V type grid section used during the fishing trials.

The catch in the test and control gear was kept separated. All cod, haddock and saithe (*MLS* = 45 cm) were measured to the nearest cm below except for those hauls where for practical issues the catch had to be subsampled. In the hauls where the catch had to be subsampled, all fish in the fraction that was not measured were counted and the subsampling factor calculated.

2.1.3.2. Data analysis

The length measurements were used as paired-gear data to estimate the selectivity of the two grid sections for cod, haddock and saithe. The selectivity analysis was carried out following the procedure described in Wileman et al., 1996 for paired gear data analysis. We used the software tool SELNET (Herrmann et al. 2012) for the analysis. Eight different models were considered: Logit, Probit, Gompertz, Richard, CLogit, CProbit, CGompertz and CRichard (Lomeli et al., 2019). The model with the lowest AIC value (Akaike, 1974) was chosen for further analysis. Once the specific size-selection model was identified for each species and codend configuration, the double bootstrap method implemented in SELNET was used to obtain the confidence limits for the size selection curve and the corresponding parameters. This bootstrapping approach is identical to the one described in Millar (1993) and takes into consideration both within-haul and between-haul variation. For each species analyzed, 1000 bootstrap repetitions were conducted. Each bootstrap run resulted in a set of data that was pooled and then analyzed using the identified selection model. Thus, each bootstrap run resulted in an average selection curve. The Efron percentile 95% confidence limits for the average selection curve were obtained based on the same 1000 bootstrap repetitions (Efron 1982; Herrmann et al. 2012).

To investigate how the different codend configurations affected the capture pattern for each species separately, we estimated the value of three exploitation pattern indicators, nP-, nP+, and nDiscard (discard ratio). nP- represents the probability for fish under *MLS* to be retained, nP+ is the probability for fish larger than *MLS* to be retained, and the discard ratio is the ratio between the number of fish smaller than *MLS* retained and the total number of fish retained in the test codend. These indicators, which are dependent on the entry population in the gear, are often used in fishing gear size selectivity studies to supplement assessment solely based on selectivity curves (Santos et al. 2016; Sala et al. 2017; Cheng et al. 2019; Kalogirou et al. 2019; Melli et al. 2020). The indicators were calculated using the procedure described in Wienbeck et al. 2014:

$$\begin{aligned} nP- &= 100 \times \frac{\sum_j \sum_{l<MLS}(nTestC_{jl})}{\sum_j \sum_{l<MLS}(nControlC_{jl})} \\ nP+ &= 100 \times \frac{\sum_j \sum_{l>MLS}(nTestC_{jl})}{\sum_j \sum_{l>MLS}(nControlC_{jl})} \qquad (1) \\ *\, DiscardRatio &= 100 \times \frac{\sum_j \sum_{l<MLS}(nTestC_{jl})}{\sum_j \sum_{l}(nTestC_{jl})} \end{aligned}$$

* Regarding discard ratio it is important to bear in mind that discards are not allowed in Norway, and that the name of the indicator was only chosen because it is the most commonly used term in literature.

2.1.4. Results

During the cruise we carried out a total of 46 hauls that were used for selectivity analysis, 24 in the area of Bjørnøya and 22 in the are west of Sørøya. The species captured in sufficient numbers to be included in the selectivity analysis were cod and haddock in Bjørnøya, and cod, haddock and saithe west of Sørøya (Table 1). During the cruise, a total of 28190 cod, 42987 haddock and 50325 saithe were measured.

Table 1: Overview of the hauls conducted during the experimental sea trials and the numbers of cod, haddock, and saithe retained in the test and control gears. BØ: Bjørnøya. SØ: Sørøya. SF: subsampling fraction applied to each compartment.

Area	Grid	Haul Nr	Test side	Towing time	Depth (m)	Cod				Haddock				Saithe			
						Test	SF	Control	SF	Test	SF	Control	SF	Test	SF	Control	SF
BØ	45 mm	2	BB	02:45	112	246	1.000	476	1.000	1739	0.863	2487	0.604	–	–	–	–
BØ	45 mm	3	BB	03:17	105	237	1.000	201	1.000	1066	1.000	823	1.000	–	–	–	–
BØ	45 mm	4	BB	03:39	127	190	0.926	287	0.833	840	1.000	729	1.000	–	–	–	–
BØ	45 mm	5	BB	03:04	116	200	1.000	275	1.000	1510	1.000	1633	0.980	–	–	–	–
BØ	45 mm	6	BB	03:12	130	160	1.000	196	1.000	1082	1.000	1210	1.000	–	–	–	–
BØ	45 mm	7	SB	04:58	130	97	1.000	195	1.000	407	1.000	482	1.000	–	–	–	–
BØ	45 mm	8	SB	04:58	125	293	1.000	260	1.000	3399	0.442	3644	0.412	–	–	–	–
BØ	45 mm	9	SB	02:53	135	207	1.000	173	1.000	1194	1.000	1323	1.000	–	–	–	–
BØ	45 mm	10	SB	02:56	111	96	1.000	112	1.000	290	1.000	340	1.000	–	–	–	–
BØ	45 mm	11	SB	03:00	111	136	1.000	350	1.000	73	1.000	333	1.000	–	–	–	–
BØ	55 mm	12	SB	03:59	135	99	1.000	203	1.000	80	1.000	204	1.000	–	–	–	–
BØ	55 mm	13	SB	03:57	68	187	1.000	153	1.000	133	1.000	142	1.000	–	–	–	–
BØ	55 mm	15	SB	03:54	132	402	1.000	592	1.000	4229	0.357	6107	0.247	–	–	–	–
BØ	55 mm	16	SB	03:41	130	436	1.000	686	1.000	2422	0.619	3920	0.383	–	–	–	–
BØ	55 mm	17	SB	06:10	130	599	1.000	885	1.000	5675	0.264	6795	0.221	–	–	–	–
BØ	55 mm	18	SB	07:42	132	440	1.000	947	1.000	2079	0.722	5053	0.297	–	–	–	–
BØ	55 mm	20	BB	02:05	125	32	1.000	178	1.000	75	1.000	381	1.000	–	–	–	–
BØ	55 mm	21	BB	02:54	135	19	1.000	228	1.000	36	1.000	129	1.000	–	–	–	–
BØ	55 mm	22	BB	03:14	120	73	1.000	338	1.000	13	1.000	370	1.000	–	–	–	–
BØ	55 mm	23	BB	03:41	280	1065	1.000	2013	0.745	–	–	–	–	–	–	–	–
BØ	55 mm	24	BB	03:36	300	1339	1.000	2659	0.572	1	1.000	14	1.000	–	–	–	–
BØ	55 mm	25	BB	02:48	295	1528	0.987	2690	0.565	4	1.000	14	1.000	–	–	–	–
BØ	55 mm	26	BB	04:11	290	1784	0.841	3764	0.399	1	1.000	10	1.000	–	–	–	–
BØ	55 mm	27	BB	03:46	300	850	1.000	1721	0.871	5	1.000	15	1.000	–	–	–	–
SØ	55 mm	28	BB	01:03	220	24	1.000	70	1.000	8	1.000	186	1.000	972	1.000	5093	0.295
SØ	55 mm	29	BB	02:40	190	15	1.000	95	1.000	14	1.000	987	0.412	325	1.000	4766	0.315
SØ	55 mm	30	BB	03:08	186	47	1.000	144	1.000	56	1.000	1107	1.000	1201	1.000	4747	0.319
SØ	55 mm	31	BB	04:30	200	14	1.000	150	1.000	8	1.000	1728	0.429	120	1.000	3479	0.431
SØ	55 mm	32	BB	03:34	185	23	1.000	122	1.000	12	1.000	1509	0.333	402	1.000	4858	0.313
SØ	55 mm	33	SB	03:07	180	25	1.000	116	1.000	32	1.000	861	0.333	938	1.000	7286	0.207
SØ	55 mm	34	SB	04:34	195	26	1.000	168	1.000	12	1.000	1206	0.222	167	1.000	2029	0.739
SØ	55 mm	35	SB	02:58	200	42	1.000	194	1.005	18	1.000	817	0.400	197	1.000	2776	0.540
SØ	55 mm	36	SB	03:29	220	30	1.000	167	1.000	16	1.000	662	0.285	580	1.000	3962	0.381
SØ	55 mm	37	SB	03:05	200	23	1.000	133	1.000	10	1.000	406	0.500	706	1.000	5703	0.264
SØ	45 mm	38	SB	03:14	200	88	1.000	121	1.000	107	1.000	1241	0.267	3184	0.474	4201	0.357
SØ	45 mm	39	SB	04:59	200	78	1.000	153	1.000	105	1.000	1345	0.200	3902	0.404	4581	0.322
SØ	45 mm	40	SB	03:21	205	85	1.000	143	1.000	59	1.000	1419	0.333	1213	1.000	2844	0.526
SØ	45 mm	41	SB	03:22	195	102	1.000	121	1.000	82	1.000	873	0.444	1859	0.807	2720	0.555
SØ	45 mm	42	BB	04:07	200	62	1.000	131	1.000	157	1.000	1205	0.182	2277	0.663	4215	0.358
SØ	45 mm	43	BB	03:55	220	39	1.000	137	1.000	26	1.000	1180	0.200	647	1.000	1114	1.000
SØ	45 mm	44	BB	01:37	210	53	1.000	78	1.000	185	1.000	532	0.250	2127	0.705	2940	0.510
SØ	45 mm	45	BB	02:09	195	9	1.000	17	1.000	14	1.000	547	1.000	315	1.000	695	1.000
SØ	45 mm	46	BB	01:19	200	30	1.000	60	1.000	33	1.000	473	1.000	281	1.000	323	1.000
SØ	45 mm	47	BB	01:50	225	70	1.000	114	1.000	43	1.000	491	1.000	1346	1.000	1402	1.000
SØ	45 mm	48	SB	02:02	210	108	1.000	65	1.000	853	1.000	55	1.000	1430	1.000	1352	1.000
SØ	45 mm	49	SB	01:29	200	38	1.000	32	1.000	313	1.000	34	1.000	1401	1.000	1557	1.000

2.1.4.1. Selectivity analysis

The size selectivity analysis results showed primarily that although the models chosen fitted the data well (Fig. 3-4), the p-values obtained for fit of the model were generally low and below 0.05 in 6 out of the 10 cases (Table 2). In the case of cod and saithe, these low p-values were most likely consequence of overdispesion of the data and the precission of the paird-gear sampling methodology used, which is substantially lower than for the covered codend method (Herrmann et al., 2016). For haddock, in addition to the lack of precission implicit in an indirect method, the lack of fish of sizes over the selective range of the gear contributed to the dificulty to fit a model to the data. For haddock captured in the area west of Sørøya with the 55 mm grid, the lack of fish that was large enough to define the whole selection curve led to that the split parameter (fishing power of the test gear with respect to the overall fishing power of both gears, i.e. a split of 0.5 means that both gears have equal fishing power) was manually fixed at 0.5, which seemed adequate considering that in most other cases the split was estimated to be close to 0.5.

In four out of the ten cases, the model with the lowest AIC value did not contain the parameter contact (*C*), which represents the fraction of fish that is subjected to a size selection process at the grid, e.g. a contact value of 0.8 would indicate that 80% of the fish entering the grid section was size selected by the grid. Considering that the contact parameter values estimated in the cases where the contact parameter was present in the chosen model was in all cases >0.95, it seems natural that in four cases the best fit was given by models with *C* = 1 (the parameter does not need to be considered in the model).

Table 2: Selection model, selectivity parameters, and fit statistics for the two grids tested during the sea trials.

			Model	*L50*	*SR*	Contact (*C*)	*CL50*	*CSR*	*D*	Split	Deviance	DOF	P-Value
BJØRNØYA	Cod	45 mm	CRichard	44.02 (40.64 - 47.70)	9.20 (5.18 - 13.62)	0.99 (0.85 - 1.01)	44.10 (40.69 - 48.00)	8.97 (3.88 - 13.51)	0.011 (-0.162 - 99.827)	0.502 (0.432 - 0.572)	90.9	93	0.542
		55 mm	Richard	57.39 (54.13 - 61.67)	20.78 (15.97 - 28.61)	–	–	–	0.084 (0.025 - 0.414)	0491 (0.448 - 0.550)	126.71	97	0.023*
	Haddock	45 mm	Richard	39.01 (35.95 - 41.33)	13.02 (8.83 - 17.74)	–	–	–	0.010 (-0.026 - 0.244)	0.502 (0.457 - 0.547)	102.04	63	0.001**
		55 mm	Probit	58.69 (48.45 - 76.94)	25.27 (19.54 - 33.67)	–	–	–	–	0.689 (0.528 - 0.849)	111.03	65	0.003**
SØRØYA	Cod	45 mm	Logit	43.44 (40.24 - 47.08)	12.16 (8.97 - 15.58)	–	–	–	–	0.510 (0.450 - 0.572)	92.79	87	0.316
		55 mm	CRichard	58.56 (55.91 - 61.09)	7.54 (4.59 - 11.84)	0.98 (0.94 - 0.99)	58.72 (56.02 - 61.23)	7.10 (4.32 - 11.26)	0.035 (0.016 - 100.002)	0.389 (0.317 - 0.465)	82.98	83	0.48
	Haddock	45 mm	CLogit	47.92 (43.29 - 52.59)	10.40 (7.00 - 13.92)	0.99 (0.95 - 0.99)	48.06 (43.54 - 52.75)	10.20 (6.68 - 13.69)	–	0.569 (0.393 - 0.698)	81.91	53	0.007**
		55 mm	CLogit	58.78 (54.27 - 65.15)	10.90 (4.74 - 17.35)	0.99 (0.99 - 0.99)	58.88 (54.30 - 65.28)	10.76 (4.69 - 17.14)	–	0.500 (0.500 - 0.500)	61.14	46	0.067
	Saithe	45 mm	CLogit	46.31 (44.17 - 47.80)	7.30 (0.70 - 12.55)	0.89 (0.60 - 0.99)	47.01 (44.59 - 49.30)	6.11 (4.16 - 8.74)	–	0.479 (0.422 - 0.537)	99.02	76	0.039*
		55 mm	CRichard	60.82 (58.76 - 64.82)	6.86 (5.28 - 11.23)	0.95 (0.88 - 0.99)	61.10 (59.23 - 65.16)	6.21 (4.53 - 10.85)	0.328 (0.117 - 2.160)	0.470 (0.378 - 0.616)	72.4	51	0.026*

Comparisons of the selectivity curves obtained with the 45- and 55-mm grids around Bjørnøya show clear differences between the grids for both cod and haddock. Compared to the 55 mm grid the curves show that the 45 mm grid will catch significantly more cod larger than *MLS* without significantly increasing the catch of fish smaller than *MLS* when fishing in the same fish population (Fig. 3c). For haddock on the other hand, the diffreence between the selection curves is larger for fish larger than *MLS*, but the 45 mm grid will also catch more fish under *MLS* than the 55 mm grid when fishing on the same population (Fig. 3f).

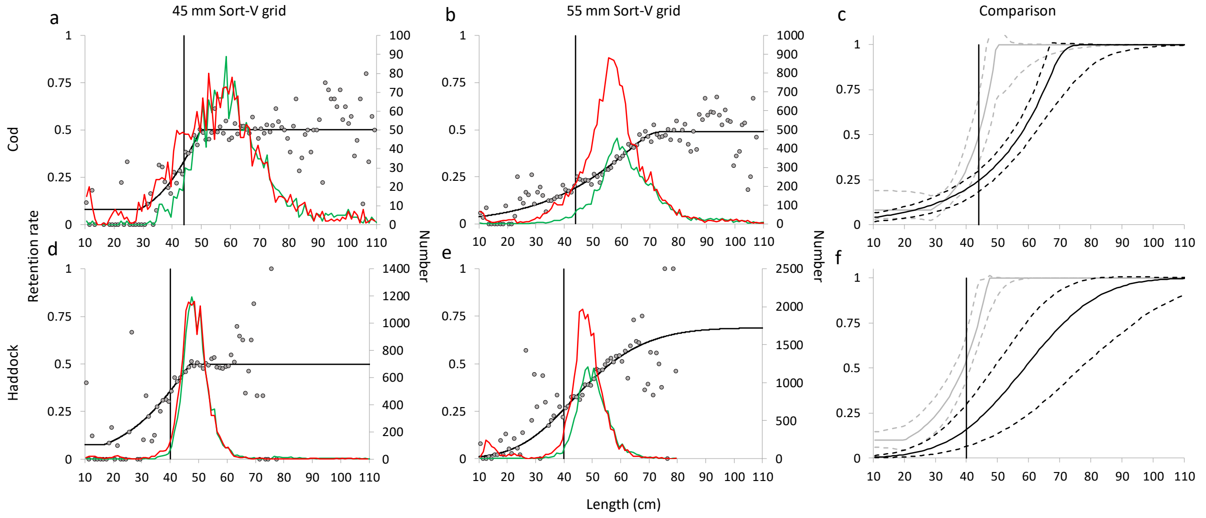


Fig. 3: Plots a-b and d-e show length-dependent retention probabilities for cod and haddock with the 45- and 55-mm grids in the Bjørnøya area. In each plot, the circles represent the experimental observations, the solid curve represents the model fitted to the data, and the dashed curves represent the 95% CIs. The red line represents the population caught by the control gear whereas the green line represents the population caught by the test gear. Plots c and f show comparisons between the selectivity curve obtained with the 45 mm grid (grey) and the 55 mm grid (black) for each species. Dashed curves represent the 95% CIs.

Comparisons of the selectivity curves obtained with the 45- and 55-mm grids in Sørøya show also clear differences between the selection properties of the grids, specially for cod and saithe. For cod, the results show that the 45 mm grid will catch significantly more fish larger than *MLS* than the 55 mm grid, however, unlike the results obtained in Bjørnøya, the 45 mm grid would also catch significantly more fish smaller than *MLS* (Fig. 4c). For haddock, the 45 mm grid would catch significantly more fish between ca. 40 and 53 cm catching little more fish smaller than 40 cm (Fig. 4g). Finally, the results for saithe show that the grid with 45 mm bar spacing would catch significantly more fish larger than *MLS* than the grid with a 55 mm bar spacing, and only significanty more fish of a few length classes smaller than its *MLS* of 45 cm (Fig. 4j).

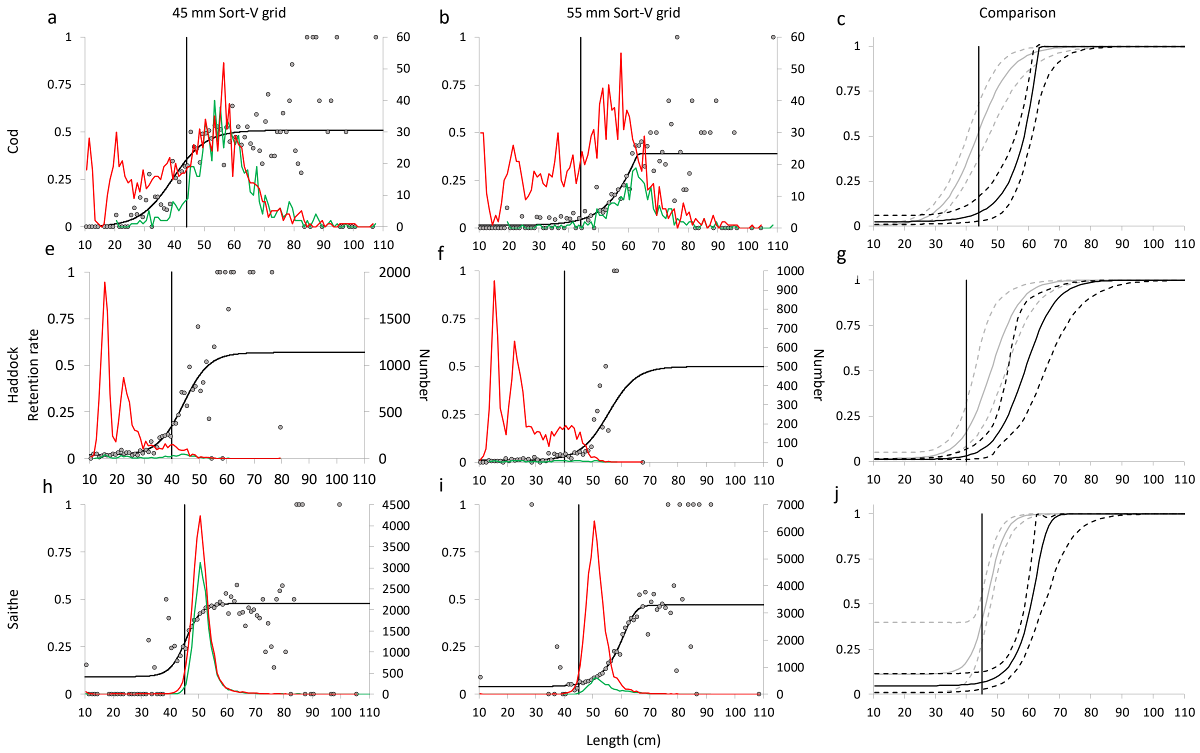


Fig. 4: Plots a-b, d-e and g-h show length-dependent retention probabilities for cod, haddock and saithe with the 45- and 55-mm grids in the Sørøya area. In each plot, the circles represent the experimental observations, the solid curve represents the models fitted to the data, and the dashed curves represent the 95% CIs. The red line represents the population caught by the control gear whereas the green line represents the population caught by the test gear. Plots c, f and i show comparisons between the selectivity curve obtained with the 45 mm grid (grey) and the 55 mm grid (black) for each species. Dashed curves represent the 95% CIs.

2.1.4.2. Exploitation pattern indicators

Regarding the exploitation pattern indicators, the results showed that in general, the probability to catch fish smaller than *MLS* was significantly higher for the 45 mm grid than for the 55 mm grid, whereas the probability to catch fish larger than *MLS* was significantly higher for the 45 mm grid than for the 55 mm grid. In all cases except for haddock in Sørøya, the discard ratio was significantly lower than the 15% in numbers allowed by the authorities today.

Table 2: Exploitation pattern indicator values for the two areas, two different grids tested, and three species sampled during the sea trials. Values are given in %.

			Probability below *MLS*	Probability above *MLS*	Discard ratio
BJØRNØYA	Cod	45 mm	24.24 (17.31 - 32.21)	96.68 (74.59 - 100.00)	6.32 (4.73 - 8.26)
		55 mm	17.07 (11.03 - 22.90)	55.38 (51.30 - 61.36)	3.54 (1.73 - 7.18)
	Haddock	45 mm	27.24 (16.43 - 40.37)	93.68 (82.17 - 100.00)	1.38 (1.06 - 1.74)
		55 mm	15.70 (7.29 - 22.59)	67.77 (47.77 - 82.69)	2.40 (1.36 - 4.30)
SØRØYA	Cod	45 mm	12.70 (8.00 - 18.52)	91.53 (73.87 - 100.00)	9.12 (5.70 - 13.54)
		55 mm	2.40 (0.98 - 4.57)	31.41 (24.23 - 39.25)	4.83 (2.02 - 8.39)
	Haddock	45 mm	3.12 (1.99 - 4.29)	45.21 (33.90 - 59.68)	50.45 (42.54 - 58.12)
		55 mm	1.25 (0.70 - 2.00)	6.29 (2.82 - 11.32)	54.84 (47.38 - 64.48)
	Saithe	45 mm	25.24 (12.88 - 40.63)	72.67 (61.08 - 84.96)	1.04 (0.61 - 1.47)
		55 mm	3.58 (1.56 - 6.81)	12.74 (9.12 - 16.72)	0.59 (0.25 - 1.04)

2.1.5. Discussion and conclusion

The results of this study show that in general, the use of a 45 mm grid significantly increases the proportion of fish larger than *MLS* caught by the gear with little increase of the proportion of fish smaller than *MLS*. This result is very similar to the result obtained for the research cruise carried out onboard R/V “Helmer Hanssen” in December 2020 (Fig. 1), where the comparison of both grids showed a significant increase of catches of cod, haddock and redfish larger than *MLS* with no significant increase in the catches of fish smaller than *MLS*. Thus, it can be concluded that in relation to the *MLS* of cod, haddock redfish and saithe in the Barents Sea today, 45 mm could be a more adequate bar spacing to use in the grid. However, it needs to be considered that Norwegian fishermen have in multiple occasions expressed their lack of interest for fish just larger than *MLS*, making in most cases would make a grid in 50- or 55-mm a more adequate choice. This conclusion is based on the selection curves i.e. proportion of fish expected to be retained at each length class, and the catches will of course depend on the size distribution of the population in the fishing area. If it is dominated by large quantities of fish smaller than *MLS* for example, it may be more adequate to use larger bar spacing, as a marginal difference in the selection curve at those sizes may have large implications. Contrary, if the numbers of fish smaller than and/or around *MLS* are low, it may be more beneficial to lower the bar spacing in the grid to increase the efficiency of the catches of commercial sizes of fish.

The implications of the population structure in the fishing area for the catch composition are well illustrated by haddock in this study. The retention curves obtained for haddock in Bjørnøya show higher retention rates than in Sørøya, however, the discard ratios calculated for the species with both grids are much higher for haddock in Sørøya than in Bjørnøya. The discard ratio was >50% in Sørøya vs <3% in Bjørnøya for both grids. This result is consequence of the high numbers of haddock under *MLS* present in the fishing ground outside Sørøya at the time the trials were carried out (Fig. 4e-f), and shows that flexibility in gear choice including sorting devices other than grids may be necessary in the near future to increase catch efficiency, reduce effort and make whitefish trawl fisheries more cost-efficient and rational. It must also be bear in mind that in mixed fisheries like the Barents Sea whitefish fishery, achieving satisfactory selectivity results with a universal gear for species with different morphology, behavior and *MLS*s implemented today is very difficult (only possible with very specific and seldom met population structures). In this context, adapting the *MLS*s of the species involved to realistic limits with the selectivity gear in force may also be necessary.

Another issue that the results of the present trials bring up, are the limitations of the paired-gear method for selectivity studies. The paired-gear method is a convenient method when the use of covers is challenging for practical issues, which is often the case on trials carried out on commercial vessels. It is indirect method, i.e. the fish retained by the gear is directly estimated from the fish retained by the test codend, whereas the population fished on is indirectly estimated from a small meshed control gear that is towed simultaneously, requiring a substantially larger amount of fish to be measured to provide the same precision (Herrmann et al., 2016). The numbers of fish measured in these trials were high (>120000 individuals), however, the lack of large numbers of length classes above the selective range, especially for haddock and saithe, created scatter in the data increasing the diversity of models suitable to describe the data and the uncertainty of the model finally fitted to explain the results. This is well illustrated by the haddock caught in Sørøya with the 55 mm grid (Fig. 4f), where the numbers of fish within the selective range of the grid (e.g., 50-60 cm) were so low that the upper part of the selection curve was difficult to define. For future experiments where the size range of the species is expected to be at the edge the selectivity range of the gear, it is recommended to use the covered codend method instead.

3. Cruise onboard R/V Helmer Hansen December 2021

3.1. Tests of codends with 0, 15 and 30% shortened lastridge ropes in Bear Island

3.1.1. Summary

Shortening codend lastridge ropes has proved to be an effective modification improve the size selection properties in diamond mesh codends. However, the extent to which lastridges should be shortened to maximize the potential of the measure is unclear. Shortening lastridge ropes opens codend meshes but it also can lead to a folding effect on the netting, which can potentially have negative effects for size selectivity. In the present study we tested the size selectivity properties of three configurations of a 129 cm diamond mesh codend in the Barents Sea gadoid fishery: 0%, 15% and 30% shortened lastridge ropes (SLR). Selectivity data were collected cod, haddock and redfish. Shortening the lastridge ropes had a significant effect on the size selectivity of cod and haddock, but the effect was limited for redfish. More specifically, reducing the length of the lastridge ropes increased the release efficiency for cod between 40 and 55 cm, and haddock between 35 and 50 cm. However, it also increased the retention of fish below 35 cm significantly for these two species, especially when the lastridge ropes were shortened from 15 to 30%. Moreover, the exploitation pattern indicators showed that while for discard ratio can be significantly reduced by shortening the lastridge ropes, there was no added

benefit from shortening them further from 15 to 30%. The study concludes that while shortening lastridge ropes by 15% can contribute to size selection, reducing them further to 30% is not recommended because it can substantially increase the retention of undersized fish probably due to net folding.

3.1.2. Introduction

The size selective properties of codends are one of the most studied issues within trawls and fishing gear technology in general because of its potential management implications in different fisheries. In a trawl, the codend accumulates the fish gathered by the gear, making it the most likely place in the gear for size selection processes to happen. Traditionally, trawl codends have been constructed of diamond meshes, and still today many fisheries are only regulated by a minimum diamond mesh size in the codend.

The size selection properties of diamond mesh codends can vary due to their flexible nature. Thus, the accumulation of catch can make the shape of the codend and the meshes in it vary greatly through a trawl tow. As catch builds, the longitudinal tension in the codend increases, which leads to that except for the meshes on a few rows just in front of the catch accumulation zone, the majority of the meshes in the codend close limiting the escape possibilities for fish (Robertson and Stewart, 1988; Herrmann, 2005a, 2005b; Herrmann and O'Neill, 2005; Herrmann et al., 2007; O'Neill and Herrmann, 2007).

Some of the modifications proposed to counteract the variability in the size selection properties of diamond mesh codends include the installation additional sorting devices. This is for example the case for the Barents Sea gadoid fishery, where fishermen are obliged to use a size sorting grid with a minimum bar spacing of 55 mm installed in the extension piece preceding the codend, in addition to a diamond mesh codend with a minimum mesh size of 130 mm (Brinkhof et al., 2020). However, the complexity added by the insertion of additional devices can lead to challenges (e.g. gear maneuverability challenges, extra costs, supplementary gear control, etc.) (Sistiaga et al., 2016). Therefore, simpler modifications that can improve the size selection properties of diamond mesh codends and eliminate the need for supplementary sorting devices are still sought. One such modification, which was proposed and tested in different fisheries during the nineties is the use of shortened codend lastridge ropes (Isaksen and Valdemarsen 1990; Lök et al. 1997). Lastridge ropes are in many fisheries attached to the selvedges (panel joints) in the codend with the purpose of withstanding the longitudinal forces created as catch builds up. The aim with shortening the ropes (i.e. attaching shorter ropes to the same length of netting panels), is to open the codend meshes and have them to maintain their shape better through the tow because as catch builds up, the load in the netting is transferred to the lastridge ropes sooner.

However, earlier observations of shortened lastridge rope (SLR) codends show that the netting in this type of codend can fold, resulting on wavy netting panels that in extreme cases can create "netting pockets" (Fig. 5). It can be speculated that the origin of these waves lies on that the more the lastridge ropes are shortened, the more the meshes open in the horizontal direction (Fig. 6a), which again increases the circumferential length of the meshes in the codend. If the lastridge ropes are shortened to a level where the circumferential length of the meshes exceeds the circumference length of the codend based on its diameter, then the netting needs to fold to absorb the additional mesh length (Fig. 6b). Alternatively, if the meshes cannot open further in the horizontal direction (due to stiffness in the codend construction material or other netting characteristics), and the lastridges are shortened further, then the netting in the codend becomes too long and the panel needs to fold to absorb the excessive length in the longitudinal direction (Fig. 6c). These folding effects, which could also happen simultaneously, will most likely have negative effects for the size selectivity of fish in the codend. For a fish to be able to escape the meshes in the codend, the fish need to first contact the meshes in the codend and second, it needs to be physically able to pass through the meshes. The contact with a size sorting device in the gear can be defined as the fraction of fish that condition it enters the gear, is subjected to a size-dependent selection process by the device (Sistiaga et al., 2010). It can be hypothesized that the potential folding created in the codend by SLRs would limit, at least partially, the access to the meshes in the codend, limiting contact, and consequently the escape probability for fish.

Fig. 5: Folding in a codend with SLR.

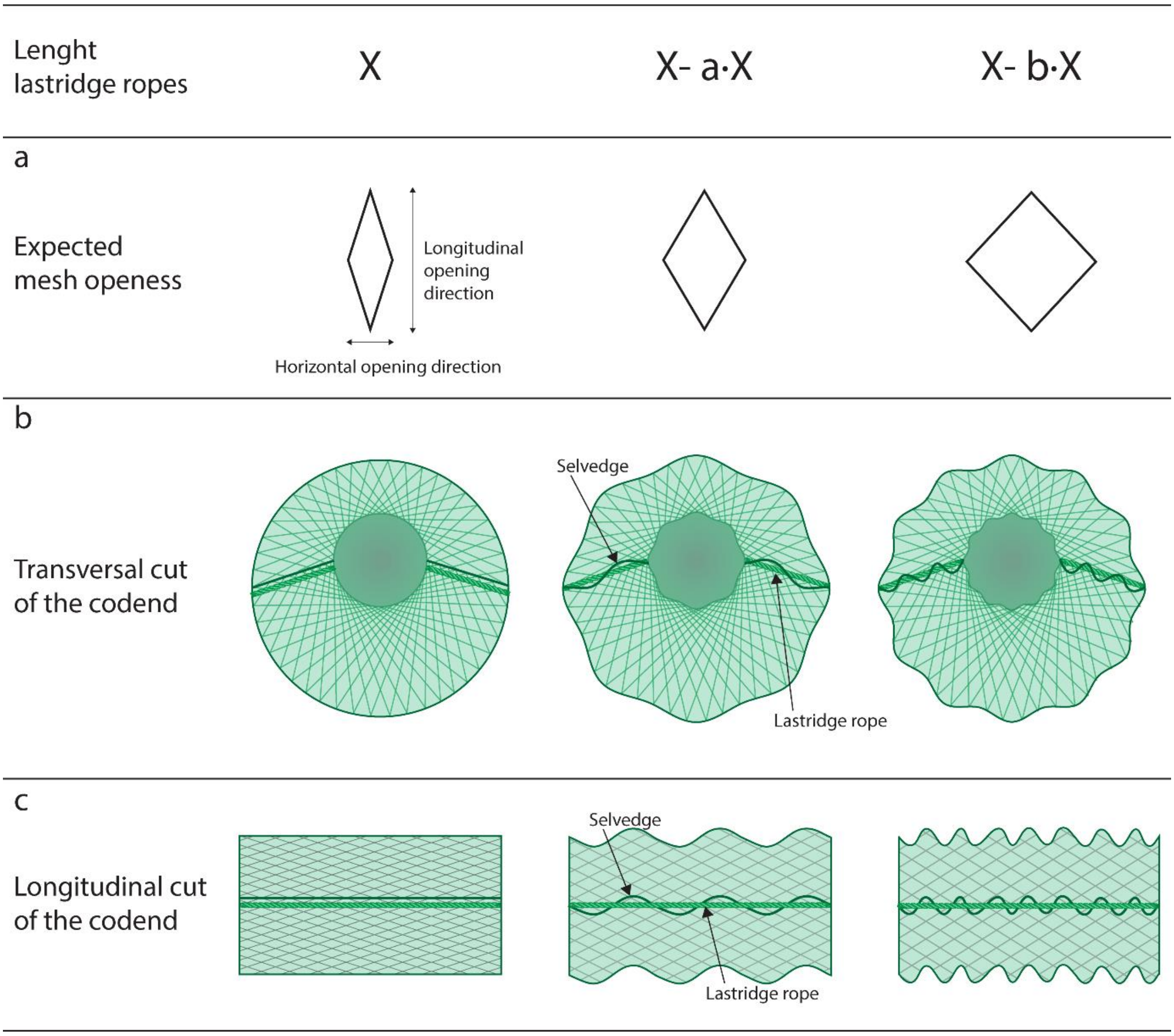


Fig. 6: Illustration of the effect of shortening lastridge ropes by two different percentages, a and b, on the codend geometry.

Various studies have reported that shortening codend lastridge ropes has positive effects for the release of fish through diamond mesh codends (Isaksen and Valdemarsen 1990; Lök et al. 1997; Ingolfsson and Brinkhof 2020) (Fig. 5). However, the degree to which the ropes are shortened in the different studies varies between 12 and 30% with only a single degree of shortening tested in each case. This makes it difficult determine whether in each of these studies there was a potential unexploited gain of shortening the ropes further or their results already reflected the negative effects of folding due to having "over-shortened" the ropes. Thus, a systematic study comparing the results obtained different degrees of SLR would help determining whether or where is the limit to the benefits of shortening diamond mesh codend lastridge ropes.

In the present study we investigated the size selection properties of three different SLR configurations for diamond mesh codends in the Barents Sea gadoid fishery, which is one of the most important demersal trawl fisheries in the world. In this fishery cod (*Gadus morhua*) and haddock (*Melanogramus aeglefinnus*) are the two main target species, whereas redfish (*Sebastes* spp.) is one of the main bycatch species in the fishery. These three species have different Minimum Legal Sizes (MLS) of 44, 40 and 32 cm respectively, and important morphological and behavioral differences that can lead to varying selectivity results and management implications depending on the properties of the codend configuration applied. Further, there is an established maximum discard ratio in numbers of 15% in the fishery and as fishermen aim at maximizing the revenue for their limited quotas, they are often only interested on catching fish cod and haddock well over the MLS.

The main objective of this study was to investigate the potential benefits of shortening diamond mesh codend lastridge ropes for size selectivity purposes. Specifically, we aimed at answering the following research questions:

- Do the size selectivity properties of diamond mesh codends vary when diamond mesh codend lastridge ropes are shortened to different degrees? And are the results the same for cod, haddock and redfish?
- Is there any potential sign for folding in the size selectivity results obtained with the different diamond mesh codend configurations tested?
- Is it possible to reproduces the selectivity results obtained for cod, haddock, and redfish and explain them by the potential use of diamond meshes with different openness?
- What is the best SLR configuration for the Barents Sea gadoid fishery considering the management objectives in the fishery?

3.1.3. Materials and methods

3.1.3.1. Sea trials and data collection

The sea trials were carried out onboard the research vessel Helmer Hanssen (63.9 m long and 4080 HP (3000 kW)) from the 8th to the 14th of December 2021. The fishing grounds were around Bear Island in central Barents Sea (7350.197483 – 7442.622028°N, 01723.793644 – 01602.228385°E). The fishing operations were conducted with an Alfredo 3 trawl, which has a 19.2 m long fishing line and a 36.5 m long headline, and a pair of Injector Scorpion trawl doors (3100 kg and 8 m^2). The trawl was the same and rigged identical to Brinkhof et al. (2022), with 60 m long sweeps, a 46 m long ground gear, and an 18.9 m long rock-hopper gear. During the whole trial period the performance of the trawl was monitored by means of a set of trawl door sensors and a trawl height sensor.

An extension piece followed by a 2- to 4-panel transition piece were mounted before the codend. The codend was constructed of 4 identical #80 × #15 knotless (braided Ø 6 mm PE twine) diamond mesh panels and the mesh size was measured to be 129.33 ± 2.07(mean ± SD). A 4-panel codend was chosen instead for a more traditional 2-panel construction because this construction allows the application of two additional lastridge ropes and consequently a potentially more profound effect of shortening them. Each selvedge contained 3 meshes meaning that the codend had 60 free meshes in circumference.

Three lastridge configurations were tested in the diamond mesh codend used during the trials:

- 0% SLR configuration: a configuration with the lastridge ropes with the same length as the codend selvedges.
- 15% SLR configuration: a configuration with the lastridge ropes in the last 6 m of the codend closest to the codline shortened by 15%.
- 30% SLR configuration: a configuration with the lastridge ropes in the last 6 m of the codend closest to the codline shortened by 30%.

In this study we applied the covered codend method (Wileman, 1996), with a cover of 51.13 ± 1.30 mm diamond meshes covering the entire length of the codend to catch potential escapees, which guarantees the retention of all cod, haddock and redfish below 10 cm. The cover was rigged with floats (Top), 6 kites (sides) and 12 kg chains (bottom) at the entrance, and 12 kites long the circumference of the cover ca. 2 m in front of the codline.

In all hauls the catch in the codend was kept separated from the catch in the cover, and the length of all cod, haddock and redfish above 10 cm was measured to the nearest cm below.

3.1.3.2. Estimation of size selection of the different codend configurations

In each haul, all fish over 10 cm was either retained in the codend or in the codend and therefore, the data could be analyzed as binominal catch data. The catch data for all hauls conducted with each of the three configurations separately were analyzed pooled, because we were only interested in the length-dependent retention probability for the different length classes of each species averaged over hauls. The analysis was carried out following the same procedure as in Sistiaga et al. (2022), where different parametric models of the form $\boldsymbol{r}_{codend}$ (l, $\boldsymbol{v}_{codend}$) were tested to model codend size selection. In Sistiaga et al. (2022) four basic models were considered, *Logit*, *Probit*, *Gompertz*, and *Richard* (further model information at Lomeli, 2019). The *Logit*, *Probit* and *Gompertz* models are fully described by the parameters *L50* and *SR*, which are defined as the length at which a fish has a 50% probability of being retained by the gear and the difference in length between fish with 75% and 25% probabilities of being retained, respectively. However, the *Richard* model requires the estimation of an additional parameter, the asymmetry parameter (D). In the present study, we also tested the same set of models but each considering an additional parameter that estimates the length-independent proportion of fish (C) that contacts the selection gear i.e. the proportion of fish that is subjected to a length-dependent probability to escape through the meshes in the codend (Sistiaga et al., 2010): *CLogit*, *CProbit*, *CGompertz*, and *CRichard*. These models were considered relevant because it was hypothesized that the potential folding in the codend netting created by shortening the lastridge ropes could be reflected on the lack of contact with the codend meshes for a specific fraction of fish. In these models, if 80% of the fish entering the codend contacts the codend meshes, *C* would acquire a value 0f 0.8, whereas if only half of the fish entering the codend contacted the gear, *C* would be equal to 0.5. It could be expected that the higher the extent of folding, the lower the escape chanced for fish though the codend meshes, which would be reflected on a lower value of *C*. Finally, a ninth model, which in the literature is referred to as *DLogit* (Herrmann et al., 2016) was also considered. The *DLogit* assumes that a fraction of the fish entering the codend (*C*) will be subjected to one logistic size selection process while the remaining fraction (1.0 – *C*) will be subjected to a different logistic size selection process. Thus, nine models were in total considered for $\boldsymbol{r}_{codend}(l, \boldsymbol{v}_{codend})$:

$$\boldsymbol{r}_{codend}(l, \boldsymbol{v}_{codend}) = \begin{cases} Logit\ (l, L50,\ SR) \\ Probit(l, L50,\ SR) \\ Gompertz(l, L50,\ SR) \\ Richard(l, L50,\ SR,\ D) \\ CLogit(l, C, L50,\ SR) \\ CProbit(l, C, L50,\ SR) \\ CGompertz(l, C, L50,\ SR) \\ CRichard(l, C, L50,\ SR,\ D) \\ DLogit(l, C, L50_1, SR_1,\ L50_2, SR_2) \end{cases} \quad (1)$$

The ability of the different models to describe the data was based on the p-value and residual inspection following Wileman et al. (1996), and final model selection for each of the codend configurations tested and species included was done based on AIC (Akaike, 1974). Thus, the model with the lowest AIC value was in each case chosen to represent the data.

The 95% confidence intervals (CIs) for the model selected for each configuration and each species were estimated by bootstrapping following the procedure described in Millar (1993), which takes both within-haul and between-haul variation into consideration. The bootstrap procedure applied was identical to that applied in Sistiaga et al. (2022) and based on 1000 bootstrap repetitions. The analyses described in this subsection and all following subsections were conducted using the software tool SELNET (Herrmann et al. 2012).

3.1.3.3. Effect of shortening lastridge ropes

To estimate the potential differences in $\boldsymbol{r}_{codend}$ (l, $\boldsymbol{v}_{codend}$) between the different codend configurations tested (codend configuration 1 vs codend configuration 2) and measure the potential effect of shortening the lastridge ropes, equation 2 was applied:

$$\Delta r(l,\boldsymbol{v}) = r_1(l,\boldsymbol{v}) - r_2(l,\boldsymbol{v}) \qquad (2)$$

The CIs for $\Delta r(l,\boldsymbol{v})$ were obtained creating a new bootstrap population with 1000 repetitions from the bootstrap population results obtained for $r_1(l,\boldsymbol{v})$ and $r_2(l,\boldsymbol{v})$. This procedure has been applied in many studies to compare the size selectivity performance of two different gears (e.g. Larsen et al., 2018; Cheng et al., 2019; Sistiaga et al., 2022).

3.1.3.4. Exploitation pattern indicators

Exploitation pattern indications provide a measure on how a particular gear configuration performs in a specific fishery situation. Unlike the size selectivity curves, indicators depend on the population encountered by the gear at the time the trials were carried out, but they enhance the understanding of the performance of the gear configuration investigated and therefore, are often used within fishing gear selectivity studies (Santos et al. 2016; Cheng et al. 2019; Kalogirou et al. 2019; Melli et al. 2020; Cuende et al., 2022).

In the present study we estimated three different exploitation pattern indicators, nP^-, nP^+ and *nDiscard* (Discard ratio) (equation 3), and their corresponding 95% CIs following the procedure described in Sistiaga et al. (2022). As in Sistiaga et al. (2022), the size selection curve estimated for each species and gear configuration was applied to the population $nPop_l$ for each species, which was obtained summing all fish in the cover and codend and in all hauls conducted during the trials independently for each species.

$$nP^{-} = 100 \times \frac{\sum_{l<MLS}\{r_{codend}(l, \boldsymbol{v_{codend}}) \times nPop_l\}}{\sum_{l<MLS}\{nPop_l\}},$$

$$nP^{+} = 100 \times \frac{\sum_{l>MLS}\{r_{codend}(l, \boldsymbol{v_{codend}}) \times nPop_l\}}{\sum_{l>MLS}\{nPop_l\}}, \tag{3}$$

$$nDiscard = 100 \times \frac{\sum_{l<MLS}\{r_{codend}(l, \boldsymbol{v_{codend}}) \times nPop_l\}}{\sum_{l}\{r_{codend}(l, \boldsymbol{v_{codend}}) \times nPop_l\}}$$

The indicators were estimated considering the current MLS of 44, 40 and 32 cm for cod, haddock and redfish, respectively. However, it was of interest to consider a more realistic fisheries scenario for the Barents Sea where fishermen are interested on cod and haddock well above their minimum size. Therefore, indicators were also estimated for an MLS of 50 cm for cod and 45 cm for haddock. All exploitation pattern indicator estimations were carried out on SELNET (Herrmann et al. 2012).

3.1.4. Results

During the experimental period we conducted a total of 29 hauls, nine with the codend with 0% shortened lastridges, ten with the codend with 15% shortened lastridges and ten with the codend with 30% shortened lastridges. In total, 7,044 cod, 18,582 haddock and 3,447 redfish were measured and included in the size selectivity analyses (Table 3).

Table 3: Hauls conducted during the experimental period. Date, time of the day, tow duration (min), Depth (m), and numbers (n) of cod, haddock, and redfish retained in the codend and codend cover are provided for each haul.

Series	Haul	Date	Time (UTC)	Tow duration (min)	Depth (m)	Cod		Haddock		Redfish	
						n codend	*n* cover	*n* codend	*n* cover	*n* codend	*n* cover
0% SL	1	8.12.2021	13:28:01	60	287.16	175	35	797	93	26	16
0% SL	2	8.12.2021	17:10:21	60	284.15	141	21	426	40	19	11
0% SL	3	8.12.2021	19:43:04	60	273.26	59	28	329	32	31	17
0% SL	4	8.12.2021	21:29:47	89	280.04	195	39	524	73	38	28
0% SL	5	9.12.2021	00:21:38	89	276.03	118	20	335	41	26	35
0% SL	6	9.12.2021	03:30:06	89	280.87	117	29	486	73	14	25
0% SL	7	9.12.2021	06:33:17	87	269.63	227	64	659	78	32	38

0% SL	8	9.12.2021	09:36:36	90	283.49	165	62	310	115	38	58
0% SL	9	9.12.2021	12:17:25	90	273.36	172	20	316	43	26	53
30% SL	10	9.12.2021	15:30:34	90	295.68	163	29	325	28	50	49
30% SL	11	9.12.2021	21:37:10	89	301.42	189	42	235	143	29	55
30% SL	12	9.12.2021	23:52:16	90	288.98	127	22	289	177	20	41
30% SL	13	10.12.2021	03:06:01	90	295.73	177	48	446	245	29	47
30% SL	14	10.12.2021	06:13:28	89	296.88	305	38	618	300	33	36
30% SL	15	10.12.2021	10:57:19	120	301.8	143	43	261	152	16	40
30% SL	16	10.12.2021	14:20:01	89	302.81	134	39	287	168	23	48
30% SL	17	10.12.2021	17:30:03	90	300.33	157	41	422	251	11	20
30% SL	18	10.12.2021	20:18:58	90	311.33	248	48	815	285	22	19
30% SL	19	11.12.2021	03:03:00	90	300.24	108	36	226	150	11	38
15% SL	20	13.12.2021	07:35:24	161	296.33	527	136	1019	191	65	336
15% SL	21	13.12.2021	11:26:37	90	260.61	142	35	215	309	6	124
15% SL	22	13.12.2021	14:36:05	90	255.21	180	49	248	259	11	149
15% SL	23	13.12.2021	17:33:01	89	308.91	169	70	253	486	16	44
15% SL	24	13.12.2021	20:06:07	79	246.15	94	53	144	407	6	38
15% SL	25	13.12.2021	22:02:31	180	272.48	272	61	568	345	28	112
15% SL	26	14.12.2021	02:53:06	120	282.46	417	34	972	403	39	86
15% SL	27	14.12.2021	07:02:49	120	298.68	212	53	412	428	20	128
15% SL	28	14.12.2021	10:45:35	104	323.38	370	95	454	260	52	851
15% SL	29	14.12.2021	14:33:00	90	297.96	211	40	260	356	23	145

3.1.4.1. Size selectivity analysis and model fit

For cod, and haddock and redfish, respectively, the probit and LogitS2 models were the most adequate models to fit the data when the codend lastridge ropes were not shortened. For the rest of the cases except for the redfish with the 30% SLR codend, models that considered a contact < 1.0 provided the best fit (Table 4). The fit statistics show that the models chosen represented the data well for all nine cases. The p-values were >0.05 in all cases meaning that the difference between the model and the data could be coincidental (Table 4). A visual inspection of the model fit to the data also show that the models follow the trend of the data well and that there are no patterns on the differences between the data and the curves (Fig. 7).

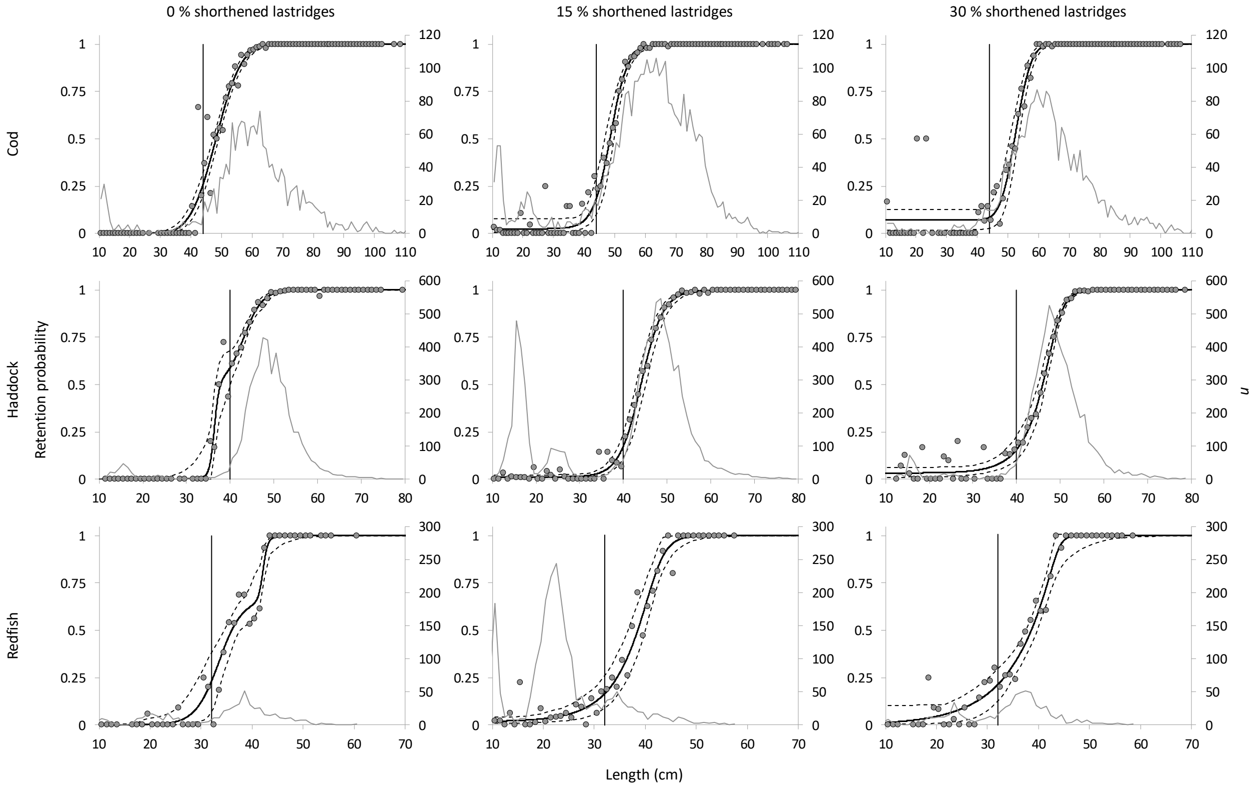
The estimated parameter values obtained showed that for cod, haddock and redfish L50 in general increased when lastridge ropes are shortened, which is similar to the effect one would expect of increasing mesh size. This increase was significant for all three species when the configurations with 0 and 30% SLR were compared, but not when the 0 and 15% SLR codends were compared. The pattern for SR was not as clear, and although SR was highest for the 0% SLR in every case, the only significant difference observed was for cod and between the cases with 0 and 30 % SLR codends (Table 4).

For five out of the six cases where the lastridge ropes were reduced in the codend, the estimates obtained for the contact parameter *C* were lower than 1, showing that in these cases a proportion of the fish in the codend was not able to find meshes to attempt escape. This result could be a consequence of folding in the codend. Further, for cod and haddock *C* is slightly reduced when the lastridge ropes are shortened from 15 to 30%, which could indicate that the extent of folding in the codend may increase when reducing the length of the lastridge ropes further form 15 to 30%.

Table 4: Parameter values for the models chosen to represent the selectivity data for cod, haddock and redfish and the three gear configurations tested.

			L50	SR	d	L501	SR1	L502	SR2	*C*	Deviance	DOF	P-Value
Cod	0% SL	Probit	48.17 (47.22 - 49.06)	8.83 (7.91 - 9.95)	–	–	–	–	–	–	31.23	95	1.000
	15% SL	CLogit	48.43 (48.80 - 49.81)	6.37 (5.00 - 7.77)	–	48.57 (46.86 - 50.11)	6.17 (4.66 - 7.63)	–	–	0.98 (0.92 - 0.99)	46.97	93	1.000
	30% SL	CProbit	52.21 (50.62 - 53.52)	5.92 (4.64 - 7.30)		52.60 (50.99 - 53.76)	5.38 (4.30 - 6.65)	– –	– –	0.93 (0.87 - 0.98)	49.72	94	1.000
Haddock	0% SL	Logit S2	37.77 (36.41 - 39.48)	6.83 (5.55 - 8.37)	–	43.05 (41.01 - 48.03)	4.69 (1.84 - 6.55)	36.34 (34.64 - 39.04)	1.19 (0.60 - 6.35)	0.51 (0.14 - 0.76)	28.36	58	1.000
	15% SL	CLogit	43.98 (42.83 - 45.07)	5.58 (4.99 - 6.11)	–	44.04 (42.96 - 45.12)	5.50 (4.93 - 6.02)	–	–	0.99 (0.98 - 0.99)	53.1	67	0.890
	30% SL	CRichard	45.96 (44.92 - 46.76)	6.07 (4.96 - 7.62)	0.37 (0.20 - 0.59)	46.13 (45.05 - 46.98)	5.69 (4.56 - 7.28)	–	–	0.97 (0.94 - 0.99)	36.21	60	0.990
Redfish	0% SL	Logit S2	36.02 (34.72 - 37.55)	9.46 (6.26 - 12.16)		42.13 (37.02 - 42.76)	1.00 (1.00 - 6.50)	33.48 (18.25 - 34.95)	5.08 (1.63 - 7.86)	0.33 (0.23 - 0.96)	26.12	41	0.966
	15% SL	CRichard	38.52 (36.52 - 40.09)	6.93 (5.12 - 9.24)	0.31 (-0.71 - 0.60)	38.62 (36.70 - 40.16)	6.69 (4.92 - 8.98)	–	–	0.98 (0.96 - 0.99)	47.26	47	0.462
	30% SL	Richard	38.60 (37.61 - 39.69)	8.53 (6.25 - 11.56)	0.10 (-0.01 - 1.65)	–	–	–	–	–	29.45	45	0.965

Fig. 7: Length-dependent retention probability for cod, haddock, and redfish with the 0, 15 and 30% SLR configurations tested during the trials. In each plot, the circles represent the experimental observations, the solid curves represent the models fitted to the data, and the dashed curves represent the 95% CIs. The grey line represents the population fished by the gear (codend + cover). The dashed vertical grey lines show the minimum legal size (MLS) for cod (44 cm), haddock (40 cm), and redfish (32 cm) in each case.

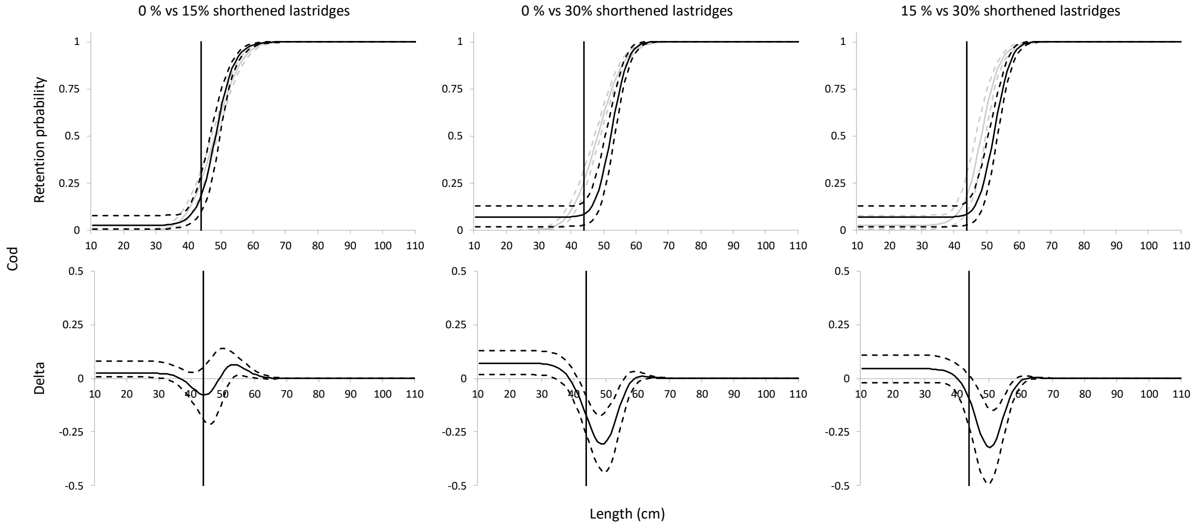


3.1.4.2. Effect of shortening lastridge ropes by 15 and 30%

Cod

The comparison of the selection curves obtained with the three codend configurations tested shows a significant effect of shortening the lastridge ropes for the size selectivity of cod. A similar pattern can be observed in the delta plots for the three comparisons carried out, but the differences between the configurations become more profound when the lastridges are shortened to 30 %. Thus, the retention of cod over 44 cm decreases significantly by shortening the lastridge ropes from 0 to 30% or from 15 to 30%, but not when they are shortened from 0 to 15% (Fig. 8). However, the increase in retention of small cod also increases significantly when the lastridge ropes are shortened, especially when the 0% and 30% configurations are compared. The clearest difference between the configurations tested for cod is the significant reduction in retention for sizes between ca. 45 – 55 cm observed when the lastridges are shortened from 15 to 30% (Fig. 8).

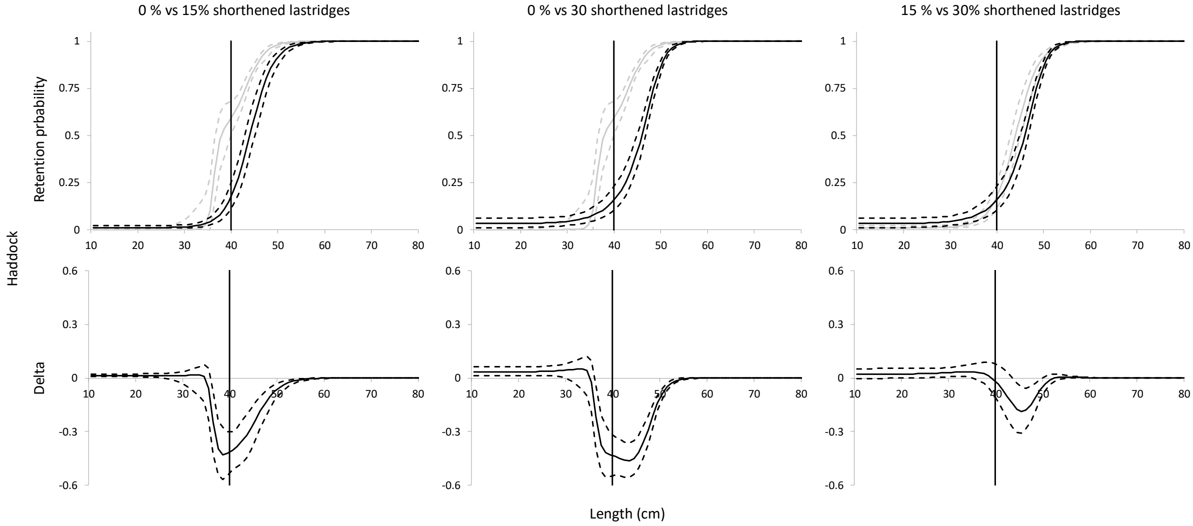
Fig. 8: Comparison of the 0 (grey) and 15% (black) SLR configurations, the 0 (grey) and 30% (black) SLR configurations, and 15 (grey) and 30% (black) SLR configurations for cod. Delta plots for each of the comparisons are shown below. Dashed curves correspond to the 95% CIs in each case and the vertical line to the MLS for cod (44 cm).



Haddock

As for cod, for haddock as well the effect of shortening the lastridge ropes had significant consequences for size selectivity. However, the consequences of reducing the lastridge ropes from 0 to 30% were different to those of reducing the lastridge ropes from 0 to 15%. While the retention of haddock between ca. 37–52 cm decreases significantly and to a similar level by reducing the lastridge ropes by either 15 or 30%, the retention of the length classes < 35cm shows a different pattern for the change from 0% SLR to these two configurations (Fig. 9). Reducing the lastridge ropes from 0 to 15% increases the retention of length classes <35 cm marginally whereas reducing them to 30% has a more pronounced and significant effect for these length classes. Considering that the MLS for haddock is 40 cm, reducing configuration with 15% SLR offers higher reduction of haddock below MLS, and lower loss of individuals over MLS (Fig. 9).

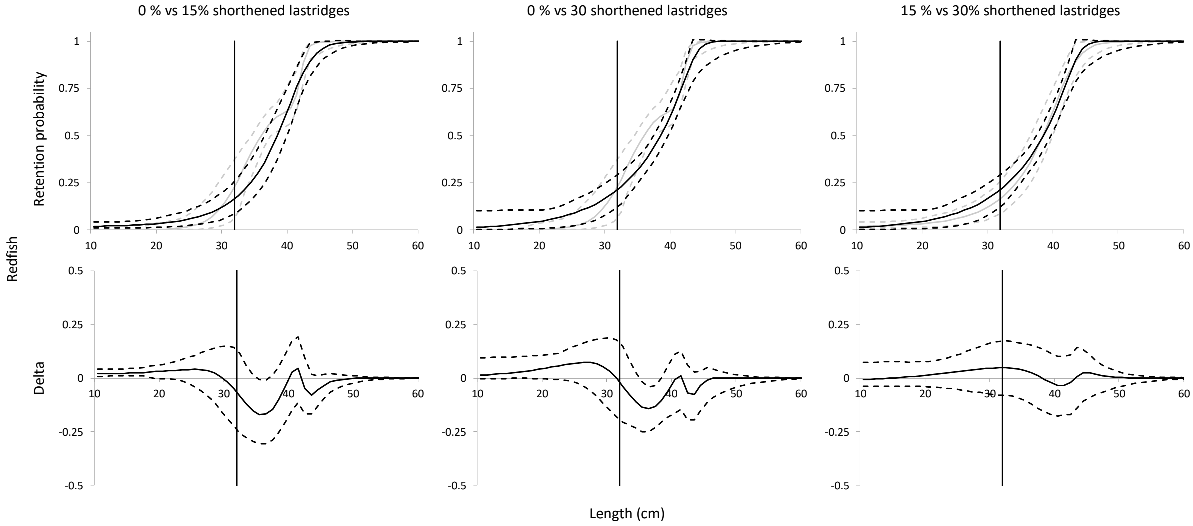
Fig. 9: Comparison of the 0 (grey) and 15% (black) SLR configurations, the 0 (grey) and 30% (black) SLR configurations, and 15 (grey) and 30% (black) SLR configurations for haddock. Delta plots for each of the comparisons are shown below. Dashed curves correspond to the 95% CIs in each case and the vertical line to the MLS for haddock (40 cm).



Redfish

For redfish, the effect of shortening the codend lastridge ropes was not analogous to that obtained for cod or haddock. The pattern observed in the delta plots was similar for the comparison between the 0 and 15% SLR configurations and the 0 and 30% SLR configurations, with generally slightly higher retention of redfish <MLS and lower retention of fish >MLS for the codend configurations with SLR. However, significant differences between the different configurations tested were only found for a few length classes between ca. 35–38 cm when the 0 and 30% SLR configurations were compared (Fig. 9).

Fig. 9: Comparison of the 0 (grey) and 15% (black) SLR configurations, the 0 (grey) and 30% (black) SLR configurations, and 15 (grey) and 30% (black) SLR configurations for redfish. Delta plots for each of the comparisons are shown below. Dashed curves correspond to the 95% CIs in each case and the vertical line to the MLS for redfish (32 cm).



3.1.4.3. Exploitation pattern indicators for codends with 0, 15 and 30% SLR

The exploitation pattern indicators for the three codend configurations tested were calculated based on the length frequencies of the total population that entered the gear during the whole trial period and for each species separately (Fig. 10). The indicator values depend on the population on the fishing area at the time the trials are carried out and therefore, to be able to fairly compare the results obtained with the 0, 15 and 30% SLR codends, all of them were calculated based on the same populations.

Most cod captured during the trials ranged between 40 and 90 cm and the fraction of fish under MLS that entered the gear was small compared to the fraction of gear over MLS. As for cod, for haddock as well the numbers of fish over MLS in the fishing area greatly exceeded the numbers of fish under MLS, although for this species there was a noticeable representation of fish between 10 and 20 cm. Else, most haddock in the fishing area ranged between 40 and 60 cm. Contrary to cod and haddock, the population encountered for redfish was dominated for fish under MLS and specially sizes between 15 and 25 cm (Fig. 10).

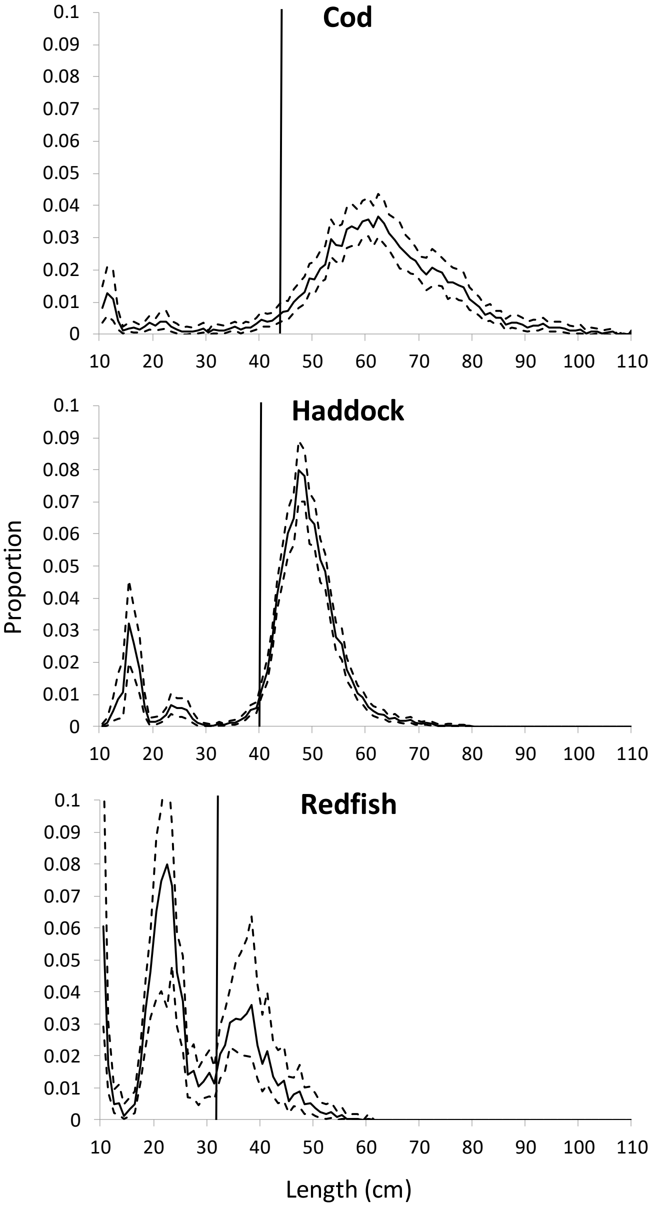


Fig 10: Normalized populations of cod, haddock, and redfish that entered the experimental trawl during the trials. The black dashed lines show the 95% confidence intervals for the variation in the populations encountered, and the vertical line in each plot represents the MLS for the species.

Cod

The exploitation pattern indicators for cod show that considering the MLS of 44 cm in the fishery today, the only noteworthy difference obtained between the codends tested was that the 30% SLR codend had significantly lower probability for retention of fish over MLS than the other two codend configurations tested. Else, the discard ratio for all three configurations was

< 1%, which is substantially lower than the 15% limit established in the fishery today. Considering an increase of the minimum size of cod to 50 cm increased the discard ratio for all three codend configurations, although this increase was not significant for the 30% SLR codend. Anyway, the discard ratio was well below the 15% limit in every case. It is also noteworthy that the probability to catch fish above 50 cm decreased significantly from the 15 to the 30% SLR configuration, whereas the probability to capture fish below 50 cm decreased, but the difference was not significant (Table 5).

Haddock

Reducing the length of the lastridge ropes resulted on a significant reduction of the probability to catch haddock above the MLS of 40 cm without significantly reducing the probability to catch fish below MLS. The discard ratio, which was lowest for the 15% SLR configuration, did not differ significantly between the configurations and was < 1.30% in all cases (Table 5). An increase of 5 cm in the minimum size for haddock resulted on a substantial increase of the discard ratio for all three configurations and especially for the 0% SLR configuration. The discard ratio for this configuration increased from 1.05 to 15.25% and was significantly higher than the value for the 15% SLR configuration (Table 5). The probability to capture haddock <45 cm decreased significantly when the lastridge ropes were shortened either by 15 or 30%, but so did the probability to catch haddock >45 cm, which was reduced from 96.56% with the 0% SLR configuration to 88.03 and 80.95% with the 15 and 30% SLR configurations, respectively (Table 5).

Redfish

The results for redfish are less clear than for cod and haddock. There is an increase in the probability to catch fish below MLS and a decrease in the probability to catch fish above MLS when the lastridge ropes are shortened from 0 to either 15 or 30%. This results in an increase of the discard ratio from 4.59% with the 0% SLR configuration to 13.10% for the 15% SLR configuration and further to 17.62 % for the 30 SLR configuration. However, none of the differences between the different configurations tested for any of the indicators calculated here were significant (Table 5).

Table 5: Exploitation pattern indicators for cod, haddock and redfish with the 0% SLR, 15% SLR and 30% SLR codends tested during the trials. In addition to values based on the MLS of 44 cm for cod, 40 cm for haddock and 32 cm for redfish, indicator values based on minimum sizes of 50 and 45 mm for respectively cod and haddock are also provided.

		0% shortened lastridges	15% shortened lastridges	30% shortened lastridges
Cod	nP- 44 cm	3.88 (2.29 - 6.38)	4.64 (1.94 - 9.53)	6.56 (2.17 - 12.48)
	nP+ 44 cm	91.04 (89.23 - 92.74)	92.35 (90.29 - 94.22)	85.86 (82.34 - 89.17)
	nDiscard	0.49 (0.28 - 0.70)	0.58 (0.24 - 1.18)	0.88 (0.30 - 1.64)
Cod	nP- 50 cm	20.42 (15.90 - 25.77)	19.37 (14.00 - 26.99)	11.12 (4.96 - 18.08)
	nP+ 50 cm	94.62 (93.34 - 95.85)	96.35 (95.03 97.24)	91.27 (88.59 - 93.87)
	nDiscard	4.24 (3.47 - 5.24)	3.96 (2.93 - 5.38)	2.44 (1.09 - 3.95)
Haddock	nP- 40 cm	5.04 (3.22 - 8.00)	2.25 (1.19 - 4.03)	4.10 (1.89 - 6.96)
	nP+ 40 cm	92.88 (91.63 - 94.11)	80.06 (74.18 - 84.63)	71.84 (67.50 - 76.56)
	nDiscard	1.05 (0.80 - 1.47)	0.55 (0.28 - 1.00)	1.11 (0.53 - 2.21)
Haddock	nP- 45 cm	38.47 (29.82 - 48.36)	21.41 (15.18 - 28.95)	16.43 (11.80 - 22.72)
	nP+ 45 cm	96.56 (95.20 - 97.67)	88.03 (83.30 - 91.43)	80.75 (76.88 - 84.68)
	nDiscard	15.25 (14.19 - 16.46)	9.89 (7.87 - 11.79)	8.41 (6.60 - 10.46)
Redfish	nP- 32 cm	2.08 (0.44 - 5.44)	4.47 (2.24 - 8.52)	6.33 (1.72 - 12.36)
	nP+ 32 cm	61.44 (55.29 - 67.35)	54.95 (46.63 - 65.49)	54.81 (49.07 - 60.84)
	nDiscard	5.89 (1.53 - 16.41)	13.10 (5.21 - 25.98)	17.62 (5.98 - 36.24)

3.1.5. Discussion

The results of the present study clearly reveal that the size selectivity properties of diamond mesh codends change when the lastridge ropes are shortened, which is well in agreement with the results reported by previous studies (Isaksen and Valdemarsen 1990; Lök et al. 1997; Ingolfsson and Brinkhof 2020; Sistiaga et al., 2022). However, they also show that the effect of shortening the lastridge ropes to different degrees does not influence the size selectivity for all species in the same manner. For cod, shortening the lastridge ropes by 15% was not enough to obtain any significant difference in size selectivity and it was first when the length of the lastridge ropes was reduced by 30% that the release of cod just above MLS was increased. This result is in agreement with Sistiaga et al. (2022), that reported no differences in the selectivity of a 128 mm codend with 0 and 15% SLR configurations. However, the same study also reported significant differences for this species for a codend in 137 mm diamond meshes with 0 and 15% SLR configurations, which disagrees with the result obtained here. Contrary to cod, the results for haddock show that shortening the lastridge ropes from 0 to 15% increases the release of fish above 35 cm significantly and that reducing the length of the lastridge ropes further to 30% has little additional effect for the release of fish above 35 mm. Unlike for cod and haddock, shortening the lastridge ropes by 15 or 30% had little effect on the size selectivity of redfish just below or above MLS, and only the release of a couple of length classes above 35 mm was increased significantly by shortening the lastridges. While the results presented for haddock here were in line with those presented in Sistiaga et al. (2022), the results for redfish different substantially. Sistiaga et al. (2022) reported significant differences in the size selection properties within two different codends that were tested in 0 and 15% SLR configurations.

An important result of the size selectivity analysis which can to at least a certain degree be observed for the three species studied here is that shortening the lastridge ropes in a codend can increase the retention of fish under *MLS*, especially the smallest sizes of undersized fish. This result is really clear for cod but also evident for haddock and redfish, and it is reflected on the models that provided the best fit to the data in the different cases. In all configurations with SLR except for the redfish with 30% SLR configuration, the models that fitted the data best were models where not all the fish entering the codend contact the meshes in the codend. We attribute this lack of contact to the potential folding in the codend, which can occur in the codend netting as a result of shortening the lastridge ropes in the codend. We believe that the more the lastridge ropes are shortened the larger the potential folding in the codend netting and consequently, the lower the escape possibilities for fish in the codend, which finally results in lower contact and higher retention of a certain percent of all sizes of fish that do not get an opportunity to escape through the meshes.

Unlike the size selection curves, the exploitation pattern indicators depend on the fish population size structure in the fishing area ate the time the sea trials were carried out. But, as the selection curves, the exploitation pattern indicators show that while the 15% SLR configuration provides results that may be beneficial for the management of the Barents Sea gadoid fishery and other fisheries involving the three species included in the present study, the use of the 30% SLR configuration has drawbacks like lower *nP+* combined in several cases with higher *nP-*.

The resent study suggests that although there are benefits of reducing lastridge ropes to 30% in the selectivity of for example cod, the reduction in contact and increase in the retention of undersized fish, presumably due to folding in the codend netting, suggest that reducing the length of the lastridge ropes more than 15% is not recommendable.

3.2. Tests of codends with 0 and 15% shortened lastridge ropes in Sørøya

3.2.1. Introduction

The tests carried out in Sørøya had the same goal as those presented in section 3.1. i.e. potential benefits of shortening diamond mesh codend lastridge ropes for size selectivity purposes. However, due to time constrains and administrative issues, it was not possible to conduct a series with a codend with 30% SLR in this area. The main interest for the area of Sørøya compared to Bear Island (Section 3.1.) was the presence of saithe, a species of interest in the northeast Atlantic with yearly landings of approximately 200,000 tones and whose selectivity has been only marginally studied compared to cod and haddock.

3.2.2. Materials and methods

The gear and experimental design used during the trials was identical to that used in Bear Island and is described in section 3.1.3.1. The only difference was that in this case only two series of hauls were carried out and a series with 30% SLR codend does not exist. The analysis conducted on the size selectivity data of cod, haddock, saithe and redfish was conducted following the procedure described in 3.1.3.2.

3.2.3. Results

During the experimental trials we conducted a total of 20 hauls between 7102.334-7106557N / 2231.151 – 2247.569E between the 4th and 7th of December 2022. In the trial period we captured and measured a total of 1156 cod, 7013 haddock, 8202 saithe and 5988 redfish. An overview of the hauls is provided in Table 6:

Table 6: Hauls conducted during the experimental period. Date, time of the day, tow duration (min), Depth (m), and numbers (n) of cod, haddock, and redfish retained in the codend and codend cover are provided for each haul.

						Cod		Haddock		Saithe		Redfish	
Series	Haul	Date	Time (UTC)	Tow duration (min)	Depth (m)	*n* Codend	*n* Cover	*n* Codend	*n* Cover	*n* Codend	*n* Cover	*n* Codend	*n* Cover
15% SLR	1	4.12.2021	23:02:15	89	216.63	22	34	24	307	337	190	8	158
15% SLR	2	5.12.2021	01:37:00	91	224.2	42	24	41	276	690	200	19	313
15% SLR	3	5.12.2021	06:02:00	91	214.74	23	13	26	470	325	156	15	383
15% SLR	4	5.12.2021	09:23:47	90	222.91	47	26	30	516	1066	353	21	463
15% SLR	5	5.12.2021	13:21:02	60	215.22	23	27	6	80	179	92	6	80
15% SLR	6	5.12.2021	16:19:05	60	218.42	14	12	26	271	219	34	28	164
15% SLR	7	5.12.2021	19:13:43	60	218.46	14	6	7	248	154	29	2	214
15% SLR	8	5.12.2021	21:25:44	89	*	26	16	17	358	155	30	11	208
15% SLR	9	5.12.2021	23:34:20	90	220.94	63	36	20	338	506	259	23	154
15% SLR	10	6.12.2021	08:53:17	90	215.17	44	8	23	373	328	63	15	336
0% SLR	11	6.12.2021	13:18:07	89	220.35	64	43	68	269	173	5	17	216
0% SLR	12	6.12.2021	16:05:00	90	216.54	40	45	36	417	332	12	6	218
0% SLR	13	6.12.2021	19:08:20	88	226.68	48	11	39	291	167	6	14	476
0% SLR	14	6.12.2021	23:45:43	90	225.03	65	39	50	269	604	60	14	334
0% SLR	15	7.12.2021	06:30:10	88	221.96	44	17	30	338	85	9	13	428
0% SLR	16	7.12.2021	08:48:13	89	223.14	37	2	35	513	176	10	21	617
0% SLR	17	7.12.2021	10:56:09	90	219.34	43	7	26	395	422	20	9	423
0% SLR	18	7.12.2021	13:54:00	60	221.49	31	19	24	185	502	23	7	145
0% SLR	19	7.12.2021	16:29:03	59	225.09	41	11	23	220	109	15	5	196
0% SLR	20	7.12.2021	18:29:05	57	221.01	18	11	13	315	102	5	19	189

The results from the size selectivity analysis show that the models used to represent the data were adequate. In all cases, the fitted model results in a p-value >0.05 meaning that the difference between the experimental observations and the model could be coincidental (Table

7). Visual inspection of the curves on the experimental data also show that the curves represent the experimental data well (Fig. 11).

Table 7: Fit statistics for models chosen to represent the selectivity data for cod, haddock, saithe and redfish and the two codend configurations tested.

			Deviance	DOF	P-Value
Cod	Series 1 15% shortened Sørøya	Logit S2	39.09	83	0.9744
	Series 2 0% shortened Sørøya	Logit S2	54.28	91	0.999
Haddock	Series 1 15% shortened Sørøya	Logit S2	33.02	49	0.961
	Series 2 0% shortened Sørøya	Logit S2	65.45	48	0.048
Redfish	Series 1 15% shortened Sørøya	Logit S2	40.08	40	0.467
	Series 2 0% shortened Sørøya	Richard	41.47	38	0.322
Saithe	Series 1 15% shortened Sørøya	Probit	25.04	56	1
	Series 2 0% shortened Sørøya	logit	28.34	50	0.994

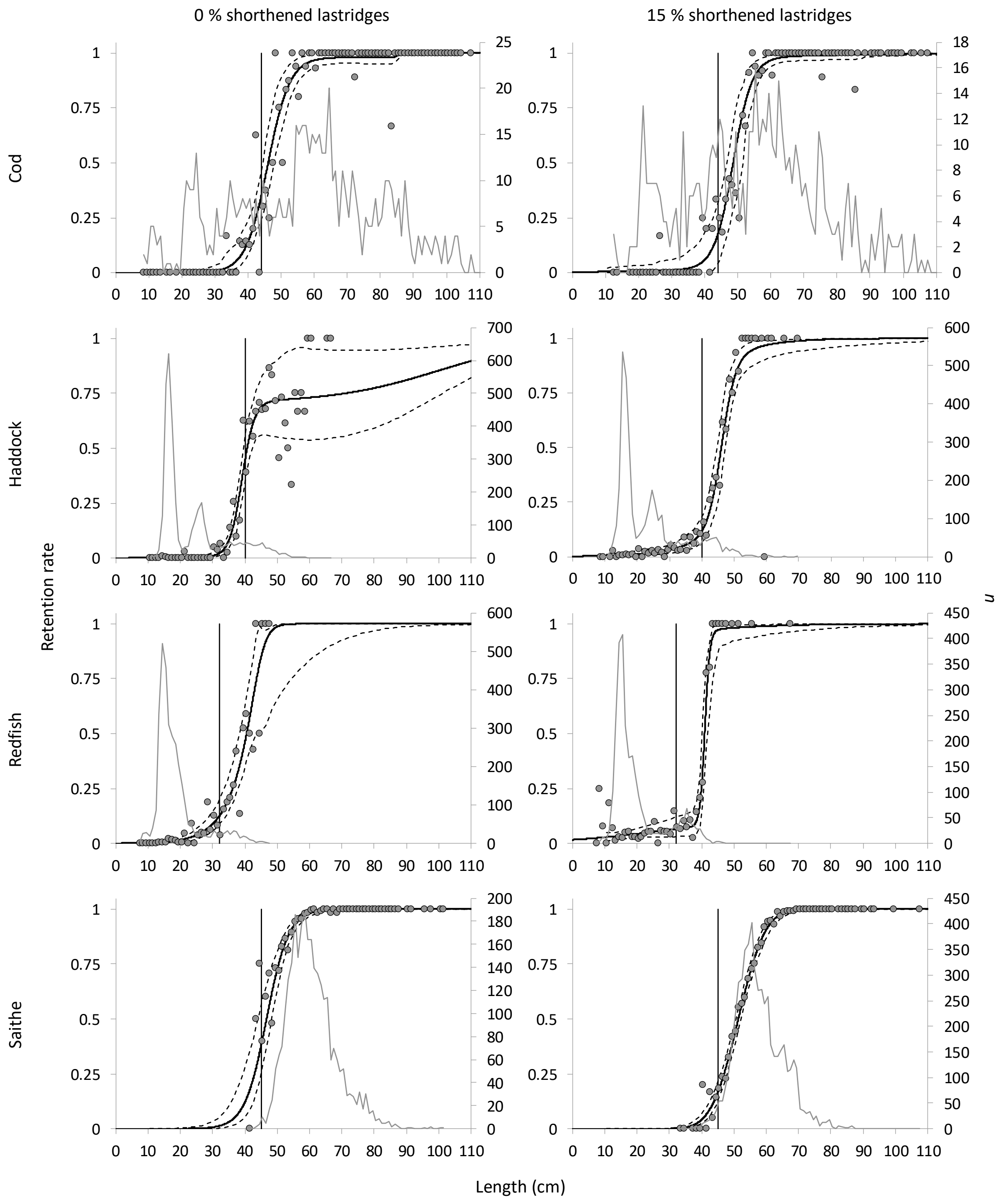


Figure 11: Length-dependent retention probability for cod, haddock, saithe and redfish with the 0 and 15% SLR configurations tested during the trials in Sørøya. In each plot, the circles represent the experimental observations, the solid curves represent the models fitted to the data, and the dashed curves represent the 95% CIs. The grey line represents the population fished by the gear (codend + cover). The dashed vertical grey lines show the minimum legal size (MLS) for cod (44 cm), haddock (40 cm), saithe (45 cm) and redfish (32 cm) in each case.

A comparison of the size selectivity curves shows that for all species except for cod, the selectivity curve for the 0% SLR and 15% SLR differ significantly for at least some length classes above *MLS* (Fig. 12). For haddock this difference was also significant for a few length classes below MLS indicating that the the 0% SLR codend retains more fish above *MLS* but also more fish below *MLS*. For saithe, which was the most interesting species in this trial, the curves show that the 0% SLR codend is in principle more suitable for this fishery than the 15% SLR considering that it retains more fish above MLS without retaining significantly more fish below *MLS*. However, as for redfish, the confidence intervals for the selectivity curve for saithe with the 15% SLR codend is substantially narrower, showing that selectivity for this codends in this case is more stable as it shows less variability. Further, the fact that the selectivity curves for the 15% SLR codend are placed more to the right shows that the availability for more open meshes that facilitate size sorting is likely larger in the 15% SLR codend than in the 0% SLR codend (Fig. 12).

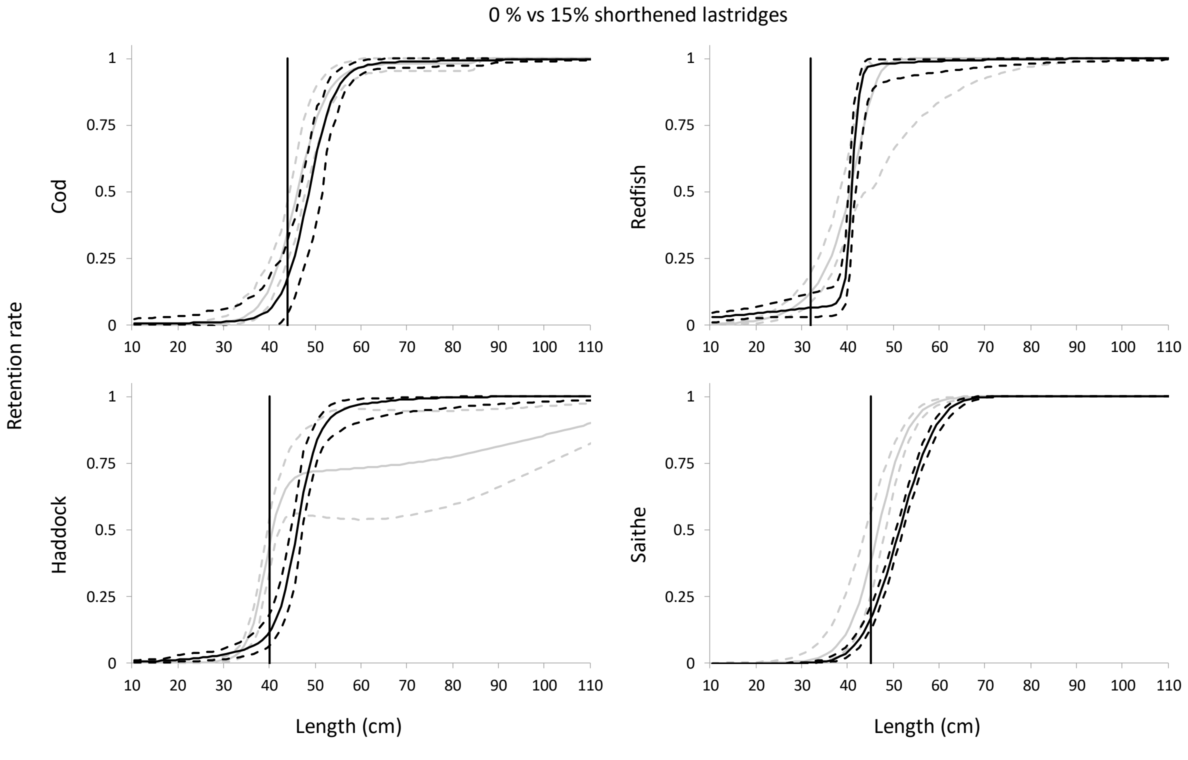


Figure 12: Comparison of the 0 (grey) and 15% (black) SLR configurations for cod, haddock redfish and saithe. Full lines are mean selection curves and dashed lines represent the 955 CIs.

3.2.4. Discussion

The results from the cruise show that shortening the lastridge ropes can have effect on the size selectivity of some species, corroborating earlier results reported with this type of codend (Isaksen and Valdemarsen 1990; Lök et al. 1997; Ingolfsson and Brinkhof 2020; Sistiaga et al., 2022; Section 3.1.4).

The differences between species were evident and while shortening the lastridge ropes by 15% had no effect for the size selectivity of cod and little effect for redfish, the effect was clear for haddock and specially for saithe. The results for cod were in agreement with the results obtained by Sistiaga et al. (2022) and the results obtained in Bear Island in the present project (Section 3.1.4.), although Sistiaga et al. (2022) obtained clear differences for this species with a codend with 137 mm meshes and 15% SLR. The results for redfish were as for cod similar to those obtained in Bear Island, although differed strongly from those reported by Sistiaga et al. (2022), who found significant differences for the selectivity of redfish between codends with 0% SLR and codends with 15% SLR. For haddock the results were in agreement with those obtained in Bear Island and those reported by Sistiaga et al. (2022), as in all cases the differences between codends with 0% and 15% SLR configurations differed significantly. Saithe was an important species in this study because despite its importance as commercial species in the Northeast Atlantic, very few studies have assessed the size selectivity of this species. The results here showed that the 129 mm codend with the 15% SLR configuration tested provided higher release efficiency than the same codend with the 0% SLR configuration. Further, the curve obtained with the 15% SLR configuration showed much narrower confidence intervals indicating less variation in the selective performance of this configuration than the 0% SLR configuration. This was also the case for the haddock and redfish curves, whereas for cod, the confidence intervals were similar for both configurations.

These trials in the area of Sørøya corroborate results earlier obtained for cod, haddock and partially for redfish and show that codends with a 15% SLR can be an alternative to increase the release efficiency for saithe and reduce variability in the selective performance of the codend.

4. Cruise onboard R/V Helmer Hansen February/March 2022

4.1. Application of FISHSELECT on saithe (*Pollachius virens*)

4.1.1. The FISHSELECT methodology (from Sistiaga et al., 2011)

FISHSELECT is a framework of methods, tools, and software developed to determine whether or not a fish is able to penetrate a certain mesh. Through computer simulation, FISHSELECT (Herrmann et al. 2009) enables the estimation of the selectivity parameters for a certain species and selection device by comparing the morphological characteristics of the former and the shape and size of the latter. To study the selectivity of a species using this method, both the FISHSELECT software and specific measuring equipment are needed. This methodology is thoroughly described in Herrmann et al. (2009) for a case study on cod. Here, we used FISHSELECT to investigate size selectivity of saithe in the Barents Sea and Norwegian Sea.

4.1.1.1. Data collection

The data collection process was conducted onboard the R/V Helmer Hassen (63.8 m length overall (LOA) and 4080 HP (1 HP = 735.5 W)) from the 22nd to the 25th of February 2022 off the coast of Finnmark (north of Norway). The fishing operation was continuous, meaning that we had constant access to fresh saithe. To obtain the correct morphometric measures for each fish using FISHSELECT, it is very important that the shape of the fish measured is not affected by dehydration, depressurization, rigor mortis, or any other factor that could alter the original shape of the fish. Therefore, the number of fish used for the measurements seldom exceeded ten individuals at a time. A water tank on deck helped keep fish alive for periods of time when necessary, so that they were as fresh as possible when measurements were taken. Because the final aim of FISHSELECT is to be able to predict the selective properties for a diversity of devices, the method requires that the morphometric characteristics of the largest possible size range be measured for each of the species being investigated. Therefore, apart from the condition of the fish, the only other selection criterion was the need to cover the widest possible size range for each species.

4.1.1.2. Measurement and estimation of fish shape

In FISHSELECT, the morphological characteristics of individual fish are defined by the shape of the cross-section of its body at different points. To determine the shape of the different cross-sections measured for each fish, we used a mechanical sensing tool called the Morphometer (see Herrmann et al. 2009). The shapes registered on the Morphometer for each cross-section were converted to a digital image – contour. To model the contour obtained for each crosssection, a variety of different geometrical shapes were tried. We compared the mean R^2 and mean Akaike information criterion (AIC; Akaike 1974) results obtained with the different geometrical shapes to determine which of them defined the contour for each cross-section best. R^2 represents the ratio of variance in the data explained by the model. Thus, while the R^2 value can never exceed 1.0, a value close to 1.0 implies that the model describes the shape data well. Everything else being equal, the model resulting in the highest R^2 is preferable. However, a more flexible model requiring a larger number of parameters to define the shape would in general be expected to produce a higher R^2 value. To be able to assess whether the improvement gained in the modeling of the shape is worth the cost of increasing the number of model parameters, the mean AIC value can be applied to choose between competing models. The model with the lowest AIC value should be preferred. We therefore apply mean R^2 values for the different shape models to evaluate their ability to describe the cross-section shapes, while we use the AIC values to rank models with different number of parameters. We measured two cross-sections for each individual saithe. The positions of these cross-sections were at the end of the opercula and at the point of maximum girth of the fish (Fig. 13). The cross-sections were chosen so that the points that could be critical for the fish to pass through the different selection devices were covered.

Figure 13: Pictures showing CS1 (left) and CS2 (right).

The total length (in mm) and mass (in g) of 100 saithe were measured. Comparisons of fish length vs. cross-section shape parameters allowed us to investigate the between individual variability of each cross-section. Furthermore, modeling the relationship between length and the parameters defining the shape for each cross-section allowed us to simulate virtual populations saithe with defined cross-sections. For the subsequent prediction analyses, we generated a virtual population of 2000 individuals for each species with a uniformly distributed length of between 5 and 90 cm.

4.1.1.3. Fall-through experiments

Fall-through experiments determine whether or not a fish can physically pass through a certain rigid shape (Fig. 14). Fish were inserted and allowed to fall through 5 mm thick solid nylon plates following the procedure described in Herrmann et al. (2009). We tested a total of 191 different shapes that included diamonds, hexagons, and rectangles (Fig. 15). The tests resulted in a total of 19100 fall-through results. The perimeter of the shapes tested during the experiments varied from 140 to 420 mm for the diamonds, from 120 to 400 mm for the hexagons, and from 120 to 1000 mm for the rectangles.

Figure 14: Fall-through trials.

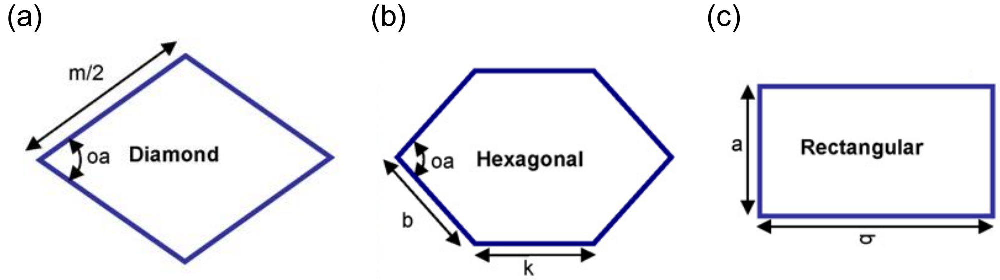


Figure 15: The three basic shapes represented in the solid nylon plates. OA represents the opening angle; m represents mesh size; and a, b, and k represent different sides in the geometry of the different shapes.

4.1.1.4. Simulation of mesh penetration and selection of a penetration model

Using a simulation tool in the FISHSELECT software and the morphometric data for each fish (represented by the measured cross-sections), we simulated the penetration of each fish through the 191 different shapes included in the fall-through trials. Thus, the shapes representing each cross section for each fish were geometrically compared with each of the 191 shapes to determine whether the fish could physically pass through them or not.

A fish can be both vertically and laterally compressed, but the compressibility changes along its body, as it (among other things) depends on the position and hardness of the bony structures. The penetrability of the cross-section of a fish depends on the shape and deformability of this cross section. For each cross-section, we simulated an asymmetrical penetration model with dorsal, lateral and ventral compressions. For CS1, the compression levels varied between 0% and 20% dorsally, and between 0% and 30% both laterally and ventrally in steps of 5% for a total of 245 (5 x 7 x 7) penetration models. For CS2, the compression levels varied between 0% and 30% dorsally and laterally and between 0% and 50% ventrally in steps of 5% for a total of 539 (7 x 7 x 11) penetration models. In addition, the different penetration models for each cross-section were individually combined with each other for a total of 132055 combined models (245 x 539). For each model, the simulations predict whether or not each fish would be able to pass through each of the 191 shapes. The analysis produced a total of 19100 fall-through results for each model simulated. The results of these models were compared with the actual fall-through results obtained during the data collection period. The penetration model that had the highest percentage of degree of agreement (DA) with the fall-through results was considered optimal for modeling fish escape and was used in further analyses.

With the optimal penetration model defined and with the ability to produce virtual populations with defined cross-sections, we estimated and predicted the selective properties of a range of geometrically defined selection devices. These selective properties are estimated as L50 and SR (i.e., the difference between L75 and L25, which represent the length at which a fish has a 75% and 25% chance of being retained, respectively). Because the calculation of these terms is based on whether or not the fish can physically pass through a shape, these estimates do not take the effect of fish behavior into consideration.

4.1.2. Results for diamond meshes and grids

In the Barents Sea and Norwegian Sea the size selectivity of Saithe is based on grids and diamond mesh codends. Therefore, the results simulated for saithe and provided in this report are for diamond meshes of 80-160 mm and OAs between 10-90 degrees (Fig. 16), and grids with bar spacings between 30-70 mm (Fig. 17).

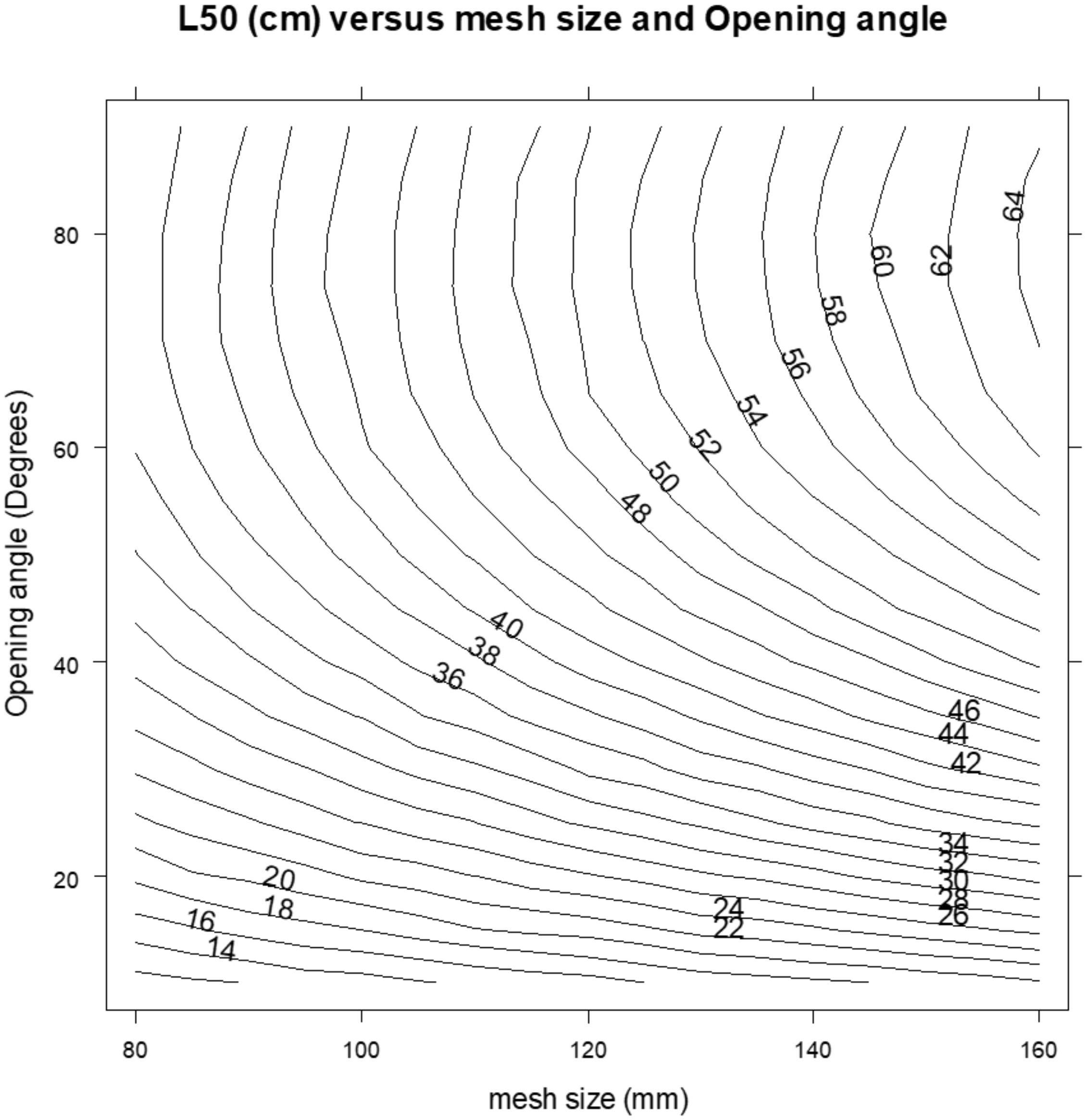


Figure 16: Isolines showing L50 for saithe with diamond meshes of 80-160 mm and OAs between 10-90 degrees.

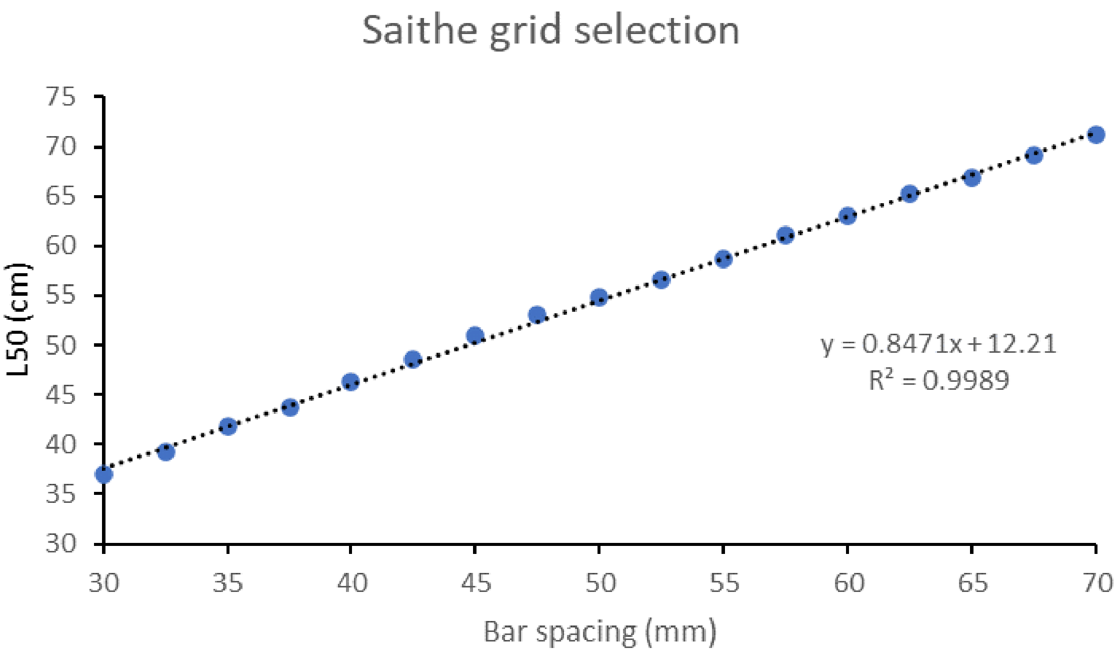


Figure 17: Selectivity results based on FISHSELECT simulations obtained with the different bar spacing grids for saithe (blue circles) and a trendline for the results (stippled black line). The equation for the trendline and the R^2 value are provided.

4.2 Effect of artificial light on behavior and selectivity of cod, haddock, saithe and redfish

Many selectivity studies, besides collecting length measurements also conduct underwater video-recordings of fish and their behaviour in relation to the selective gear. It is important to collect knowledge on fish behaviour in relation to selectivity as this in many cases explains given patterns and results seen in selectivity curves. Also, fish behaviour is important to consider when designing selective gear. However, towed fishing gear are often towed at large depths, or during night, thus under condition without ambient light. Under such circumstances video recordings require the use of artificial light to illuminate the field in front of the cameras. Using artificial light under dark circumstances may alter the behavior of the fish, which subsequently may affect the selectivity process (Glass and Wardle, 1989). In the scientific community a general accepted assumption is that white light affects fish behaviour, while red light due to shorter wave lengths does not. Therefore, many studies choose to apply red light when investigating fish behaviour assuming that the light does not alter fish behaviour. However, this assumption has not been investigated and is quite disputed. Therefore the aim of this study was to investigate if the use of white light, and red light has an affect on selectivity for cod, haddock, saithe and redfish in the Barents Sea demersal trawl fishery. More and more studies are showing that fish of different species have different responses towards different types of light. This has even been utilized to enhance selectivity (Hannah et al., 2015).

4.2.1 Data collection

The data collection process was conducted onboard the R/V Helmer Hassen (63.8 m length overall (LOA) and 4080 HP (1 HP = 735.5 W)) from the 25th of February to the 8th of March 2022 off the coast of Finnmark (north of Norway). We applied a Alfredo 3 trawl, a set of Injector Scorpion trawl doors, with 60 m long sweeps, and a Ø53 cm rock-hopper gear. The trawl was equipped with a steel Sort-V grid with 55 mm bar spacing followed by an extension piece and a blinded codend. To catch the escapees, we applied a cover over the escape outlet of the grid. All cod, haddock, saithe and redfish were length measured down to the nearest centimeter below. The data was analyzed using the software tool SELNET (Herrmann et al. 2012).

4.2.2 Results (preliminary)

During the cruise 14 hauls without artificial light, 14 hauls with white light and 11 hauls with red light were conducted. The results presented below are preliminary. The experimental data points, number of fish caught for each length group and size selectivity curves with 95% confidence limits for cod, haddock, saithe and redfish retained using no light, white light and red light is presented in Figure 18. The figure indicates that the retention probability for cod are relatively similar, but shows some difference for the three other species. Figure 1 also reveals that for most cases, especially when no light where used, only a small proportion of fish below MLS was retained while a relatively large proportion of fish above MLS escaped.

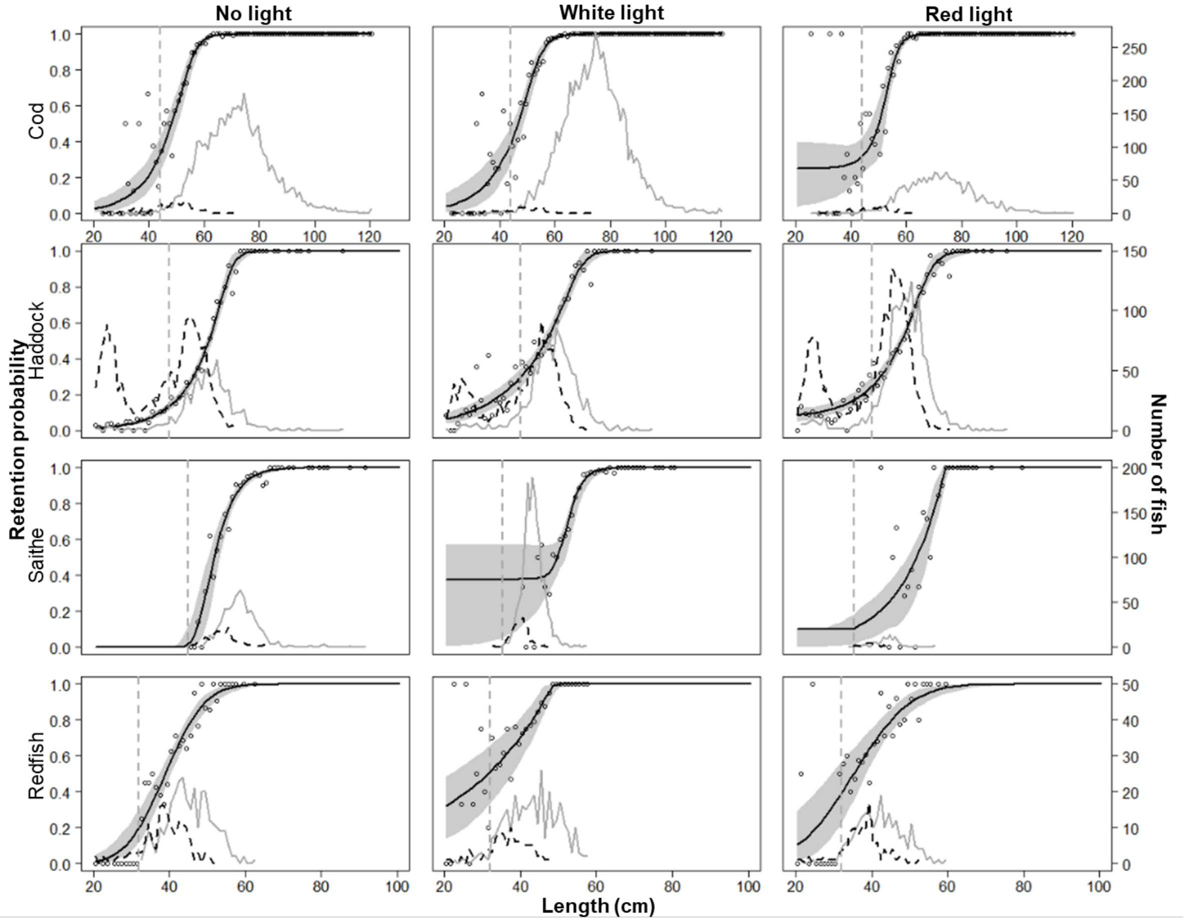


Figure 18. Size selectivity curves (black curves) with 95% confidence limits (grey polygons) for cod, haddock, saithe and redfish, retained without the use of artificial light, with white light, and with red lights. The black circles denote the experimental data points. The grey and black distribution curves represent the number of fish caught in the codend and cover respectively, and the grey vertical lines denote MLS.

Comparing the hauls conducted without light, with white light and with red light, shows that there is no significant difference in the retention probability for cod (Figure 19). However, for haddock, saithe and redfish significant differences were detected when applying artificial light (Figure 19).

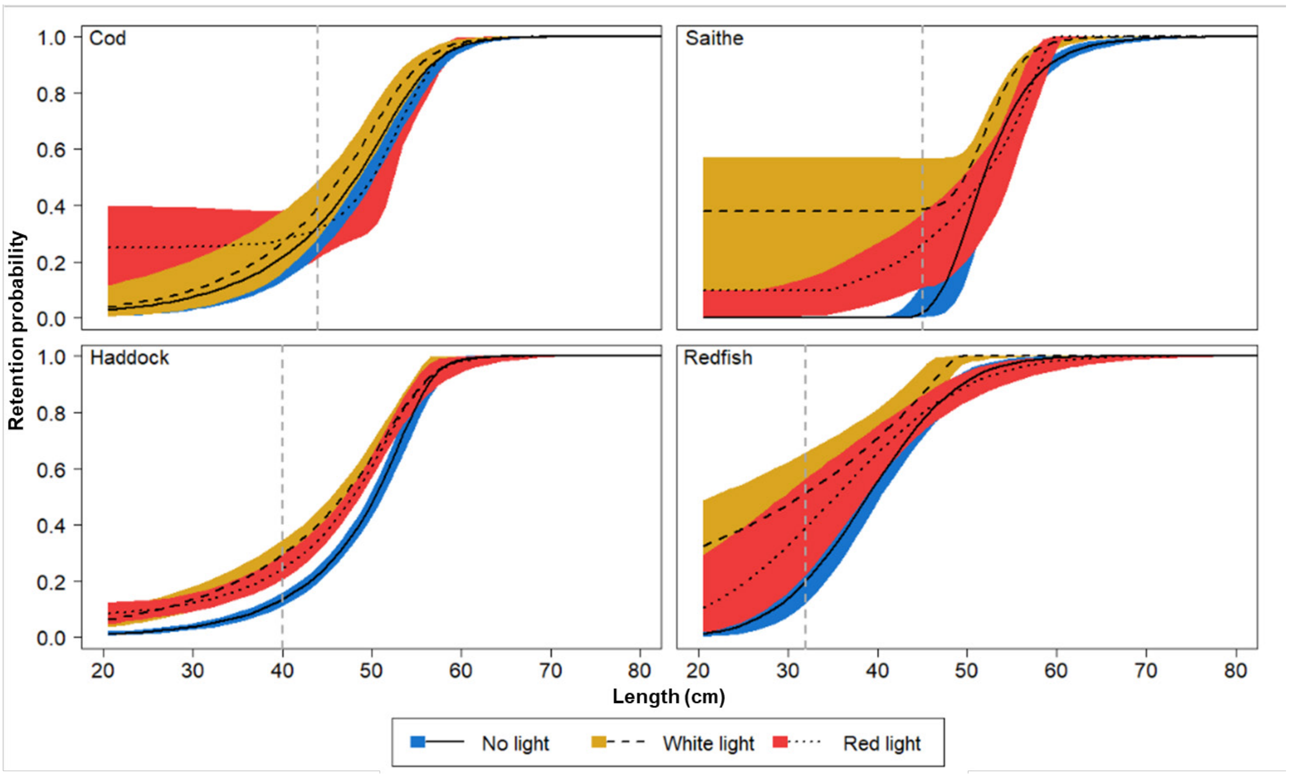


Figure 19. Size selectivity curves (black curves) with 95% confidence limits (polygons) for cod, haddock, saithe and redfish, retained without the use of artificial light (blue), with white light (yellow), and with red lights (red). The grey vertical lines denote MLS.

The delta plots in Figure 20 corroborates these results. The figure shows that there was no effect of white or red light in the retention probability. For haddock both white light and red light significantly reduced the catch efficiency, while there for was significant differences between red and white light (Figure 20). Similar results were found for saithe, with white and red light causing a significant lower retention probability compared to no light, however, there was also a difference between white and red light, the latter having a significant higher catch efficiency for a few length groups (Figure 20). For redfish, similar results as for saithe were found, however, the difference in retention probability between no light and red light was very small although significant (Figure 20).

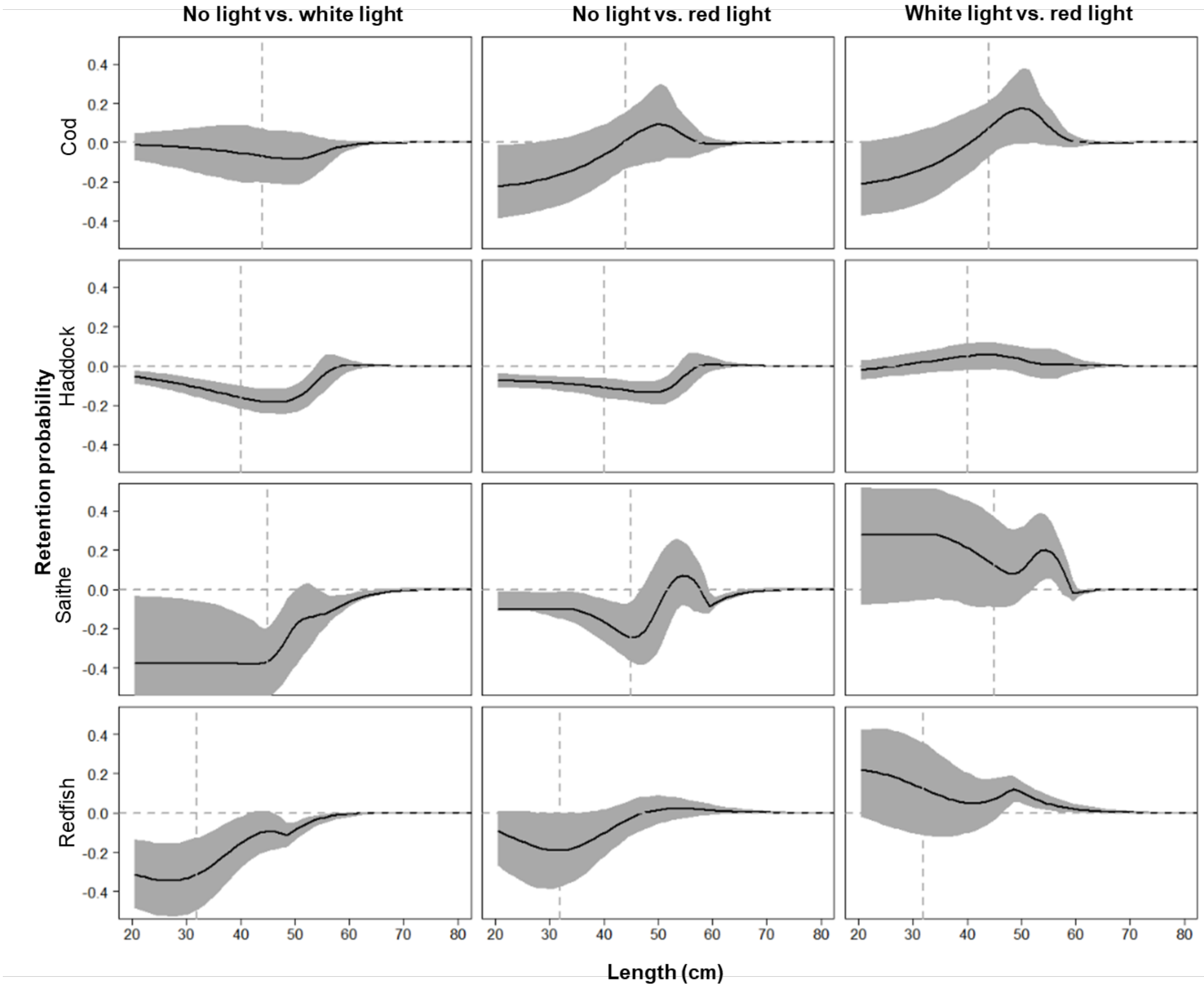


Figure 20. Delta plots (black curves) with 95% confidence limits (grey polygons) for cod, haddock, saithe and redfish, comparing the difference in retention between hauls carried out without artificial light and with white light, without artificial light and with red light and between white light and red lights. The grey vertical line denotes MLS, while the grey horizontal line denotes the point of equal retention probability.

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