Surface selection of haddock and cod in the Norwegian demersal seine fisheries

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Size selection in active fishing gears is a continuous process and undersized fish may escape during the whole fishing operation. Fish that escape during the surface hauling operation are likely to experience higher mortality due to barotrauma-related stress than fish escaping at the fishing depth during the towing process. A well-functioning selectivity device should therefore select mostly at depth for enhancing survival probabilities of escaping fish. The current gear regulation in the Norwegian demersal seine fishery is likely to cause large proportion of undersized fish to escape at the surface. In this study, we estimated surface selection of haddock and cod in demersal seine by using an automatic release system and a small meshed codend that collected fish escaping during surface hauling. The collecting bag contained 19% undersized haddock compared to 10% in the conventional square-mesh codend indicating that about 50% of undersized haddock brought to the surface were released. The proportions of undersized cod were 8% for the collecting bag and 1% for the conventional square-mesh codend. These results demonstrate that surface selection is significant for both haddock and cod. Based on this finding, we discuss methods to improve size selectivity at the fishing depth.

Keywords: cod, demersal seine, haddock, square mesh, surface selection

Introduction

Demersal seining is a fishing method used in commercial fisheries around the world. In Norway, demersal seine is mainly used to target cod (*Gadus morhua*), saithe (*Pollacius virens*), and haddock (*Melanogrammus aeglefinus*). On fishing grounds north of 64°N, it is mandatory to use square-mesh codends with minimum mesh sizes of 125 mm to enhance escape of undersized fish (Anon, 2005). Arguably, the prerequisite for a well-functioning selectivity device is that escaping fish are alive, vital, and with minimum and only reversible injuries and physiological stress that may affect long-term behaviour, survival, or fitness. Minimizing the cumulative stressors (Breen *et al.*, 2020) encountered during the capture and escape process is thus vital.

Demersal seining and trawling are continuous fishing operations where fish have been observed to escape during the entire process until the codend is taken onboard the fishing vessel (Isaksen and Løkkeborg, 1993; Grimaldo *et al.*, 2009; Herrmann et al., 2013b). Contrary to fish escaping during towing, those escaping at the surface are likely to experience more severe stressors due to barotrauma, physiological trauma, and physical injury (Davis, 2002).

The main improvement areas for optimized escape are to minimize the time that fish swim in the gear to reduce physiological impairment due to exhaustive swimming; enhance voluntary escape before reaching the codend to reduce crowding and injuries from physical contact; and to maximize escape at capture depth to eliminate barotrauma from reductions in ambient pressure, thermal shock, and risk of avian predation (Suuronen, 2005; Breen *et al.*, 2020).

The escape of cod and haddock from demersal seine during fishing and surface hauling operation was studied by Isaksen and Løkkeborg (1993). They found that about half of the total number of fish that escaped did so during surface hauling. Since 1993,

Norwegian technical regulations for codend specifications have changed, e.g. by introduction of a square-mesh codend. Still, more recent studies on the surface selectivity in demersal seine have not been carried out. Demersal seine conceptually shares many aspects with trawling as it is towing a net along the seabed. However, haul duration is much shorter in demersal seining (<1 h) as the fishing method is based on encircling concentration of fish inhabiting a small space. Thus, estimates of surface escapes in trawls (Madsen et al., 2008, 2012; Grimaldo et al., 2009; Herrmann et al., 2013b) cannot be directly transferred to demersal seine. Several fishing trials conducted during the last decade have demonstrated substantial surface escape (authors' observations). Surface selection tends to violate prerequisites for optimal and gentle escape and should thus be quantified.

The tow duration of a Norwegian demersal seine is short compared to trawling, usually 15–45 min. For promoting selection at depth, it is therefore important to assure rapid passage of fish to a well-functioning size-selective codend. Parameters known to have a negative relationship with selectivity include extension length and codend circumference (Reeves et al., 1992; Lök et al., 1997; Broadhurst and Millar, 2009), that can be explained by an associated reduction in lateral mesh openings due to increase in surface area with constant relative water flow. In addition, if circumferences of square-mesh codends and the anterior diamond-mesh extension are not matched, bunching of the square meshes can occur, reducing and/or masking lateral openings (Robertson, 1986). For vessels operating north of 64°N, a square-mesh codend is compulsory (Anon, 2005). There are no restrictions on lengths of diamond mesh extensions that often exceed 30 m. For vessels 15 m and longer, the square mesh section must be at least 12.5 m long with a circumference of 5–8 m. The square mesh bars have to be joined assuming about 50% opening of the anterior diamond meshes, in contrast to suggested 15–25% by Robertson (1986). The practice of the Norwegian demersal seine fisheries, with extreme codend dimensions and joining of the wide square mesh section to few diamond meshes of the extension seem thus suboptimal for size selection.

The objective of this study was to determine surface selection for cod and haddock in the Norwegian demersal seine fishery. A new method is described based on an automatic release system and a small meshed collecting bag, which allowed us to collect fish escaping during the surface hauling operation. Further, we discuss methods to improve size selectivity at the fishing depth.

Materials and methods
Experimental procedure
The fishing trials were conducted on fishing grounds off Finnmark in Northern Norway at depth ranging from 54 to 117 m. The trials were conducted on board the commercial seiner "Ballstadøy" (34.9 m length overall, 1350 kW main engine) from 2 to 16 May 2017. The vessel's conventional demersal seine was used which had a fishing circle (stretched seine opening) of 146.4 m (732 meshes of 200 mm netting) and 100 m fishing line. The length of the four-panel tapered seine belly was 53.8 m, ending with 100 mesh circumference of 130 mm nominal mesh size. The seine ropes were 2000 m long combination ropes with steel cores, 50 mm in diameter.

In line with fisheries regulations, a square-mesh codend was used. The codend had a total length of 13.5 m, the square mesh section was cylindrical (single panel without selvedges), 12.5 m long, 8 m circumference (116 bars), with 130 mm nominal mesh size of knotless 8 mm PE twine. The square meshes were joined in front to a diamond section of 130 mm mesh size, constructed of double 5 mm PE netting, 1 m in length, and 100 meshes in circumference. A codend extension of 130 mm nominal mesh size and 21.3 m long was used where the foremost 99.5 meshes where of 3 mm braided PE and the rearmost 49.5 meshes of double 4 mm braided PE. Hauls were also taken with an additional 99.5 mesh long (15 m) extension of double 4 mm braided PE. Hauls were thus taken with both 21.3 m (short) and 36.3 m (long) extensions (Figure 1).

The extensions had the same circumferences as the codend (100 meshes). Behind the codend, a 16 m codend of 75 mm mesh size was connected to the codend's codline. Midway through the experiment, two rows of 20 meshes were measured wet for opposite sides of the codend with an Omega mesh gauge (www.marelec.com), applying force of 125 N. The square-mesh codend measured on average 132.5 mm ($SD = 1.5$ mm) and the small-mesh codend 76.4 mm ($SD = 1.7$ mm).

The fishing operations were carried out as in commercial fishing. The seine was set on fish aggregations detected on the echo sounder and towed forward at a speed of $0.7–0.9$ m s^{-1} for 25–35 min, until the ropes were approximately parallel. Then the ropes were hauled until the wing ends were in the tow block (additional 24–25 min). The wing ends were then taken through a Triplex block on the vessels starboard side and the seine spooled until the codend was in the Triplex block (10–12 min). A vacuum pump was then connected to the codend and the fish pumped onboard.

The connection between the square mesh and small-mesh codends was closed during bottom hauling. Half of the hauls (control) were taken using an automatic codend releaser (https://jatronic.no/wp-content/uploads/2018/08/lav_POA.pdf) that opened the connection between the two codends at 30 m depth during ascend. When the gear was hauled and reached 30 m depth, a pressure sensor activated the releaser and the fish entered the small-mesh codend which prevented fish from escaping at the surface, i.e. no surface selection (Figure 2). The other half of the hauls (test) were taken without using the releaser and the square-mesh codend was tied as in conventional fisheries. When at the vessel's side, the codend was opened and the catch released into the small-mesh codend to avoid surface selection during onboard taking of fish.

Nine control (with releaser) and nine test hauls (without releaser) were taken. Three pairwise test and control hauls (i.e. with and without the codend releaser) were obtained using long extension and the remaining six sets were unpaired. We consider hauls being paired when time between deployments is less than 6 h, distanced within 1 nm. The intention was to compare codend lengths, but that plan had to be abandoned due to time constraints. Therefore, only two test hauls with the shorter extension were obtained.

The catch was pumped onboard from the codend in batches. The first ~100 haddock were taken from several batches from each haul and their total length measured to the nearest centimetre below. Most of the catch comprised haddock which was the main subject species. Measurements of haddock were prioritized, therefore fewer cod were measured. Haddock weight was obtained from a grader. The cod that was gutted onboard was also weighted on the grader. Number of haddock and cod
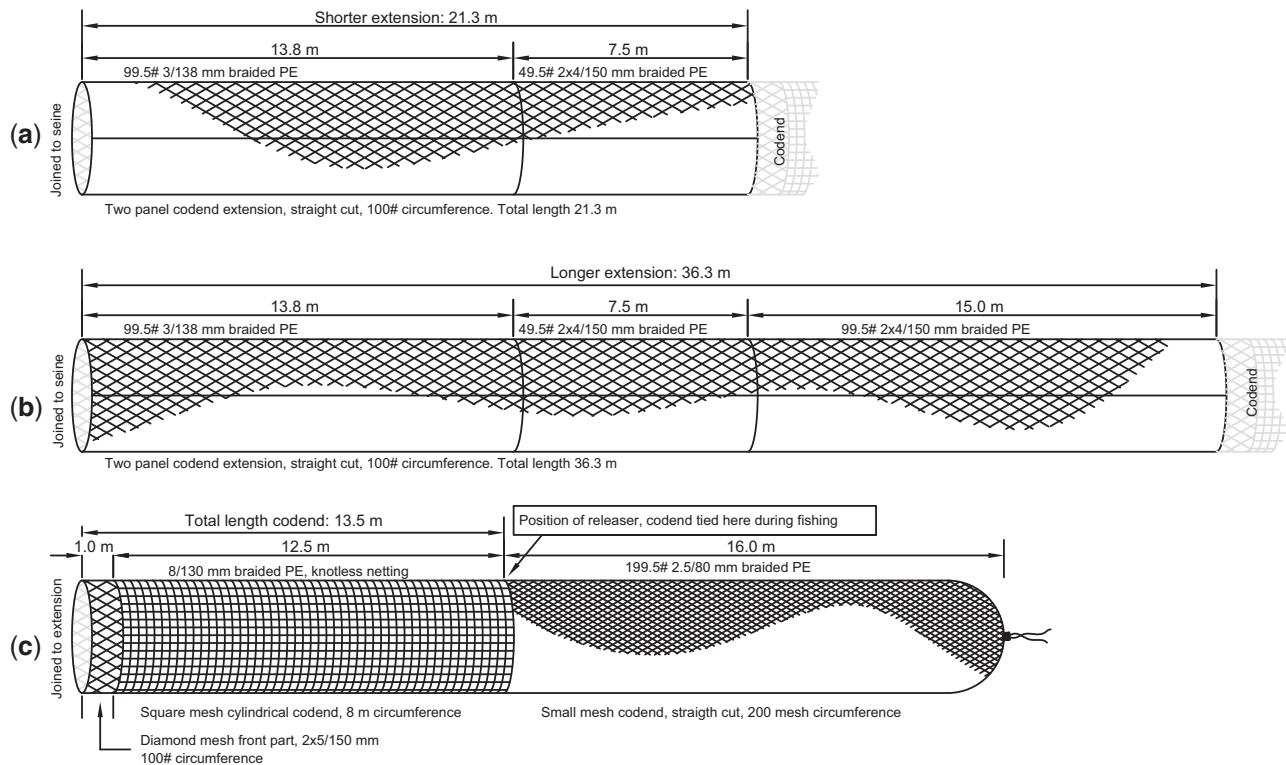
Figure 1. Schematic drawing of extensions and codend. (a) The shorter extension. (b) The longer extension. (c) The square-mesh codend with the small meshed codend attached.

were calculated based on length–weight relationships. Some of the cod were kept for live storage, counted, and weight estimated when delivered. While number of measured cod from each haul was in general low, a pooled analysis of surface selection was achievable.

Statistical analysis

The proportion of fish below minimum landing size (MLS; 40 cm for haddock, 44 cm for cod) was calculated for each haul. A binomial glm model was applied to compare differences in proportions between test and control hauls.

Due to the nature of the fisheries, i.e. targeting fish schools located by an echosounder, test, and control hauls were not always paired. An initial permutation test, fitting a generalized linear mixed effect model (glmm), was applied prior to fitting selection models to test if the selection was affected by catch size (catch per haul), extension length, and fishing depth. The test was done by repeatedly pairing test and control hauls randomly without replacement, keeping the three pairs.

A polynomial binomial logistic glmm model was applied for the permutation tests. This is an approach for catch comparison studies (Holst and Revill, 2009). The logit of the expected proportion of the total catch caught in the test codend is given by the "base model":

$$p_k(l; \boldsymbol{\beta}) = \beta_0 + b_0 + (\beta_1 + b_1)l + \beta_2 l^2 + \cdots + \beta_k l^k$$

Describing the probability that fish of length l is measured in the test codend, given that it is measured in either of the two gears. The β's are the fixed effect coefficients for $l, l^2, \ldots l^k$, and

b_0 and b_l random effects for intercept and fish length, respectively, at pair level. The analysis is conducted on measured fish, without raising. The glmm model was run for each of the 1000 permutations to test for order of polynomials and random effects for intercept and length at pair level, storing the AIC values (Akaike information criterion, Akaike, 1974).

Having selected a base model with the "best" set of polynomials, based on lowest average AIC, explanatory variables were added one at the time to investigate their effects on β_0 (intercept/curve shift) and β_1 (curve slope). The explanatory variables were; total catch (total catch of all species per haul for the test gear), fishing depth in metre, and extension length for the test gear (0 for short, 1 for long). For the permutations, the base model and a model with one explanatory variable were run on the same arrangement of data.

$$\text{base model}: \ \beta_0 + b_0 + (\beta_1 + b_1)l + \beta_2 l^2$$

compared to

$$\text{intercept effect}: \ \text{base model} + \text{fixed effect}$$

and

$$\text{slope effect}: \ \text{base model} + \text{fixed effect}: \ l$$

In addition, interactions between the fixed effects were added one at the time to the base model;

catch size: extension length, catch size: fishing depth and *fishing depth: extension length.*
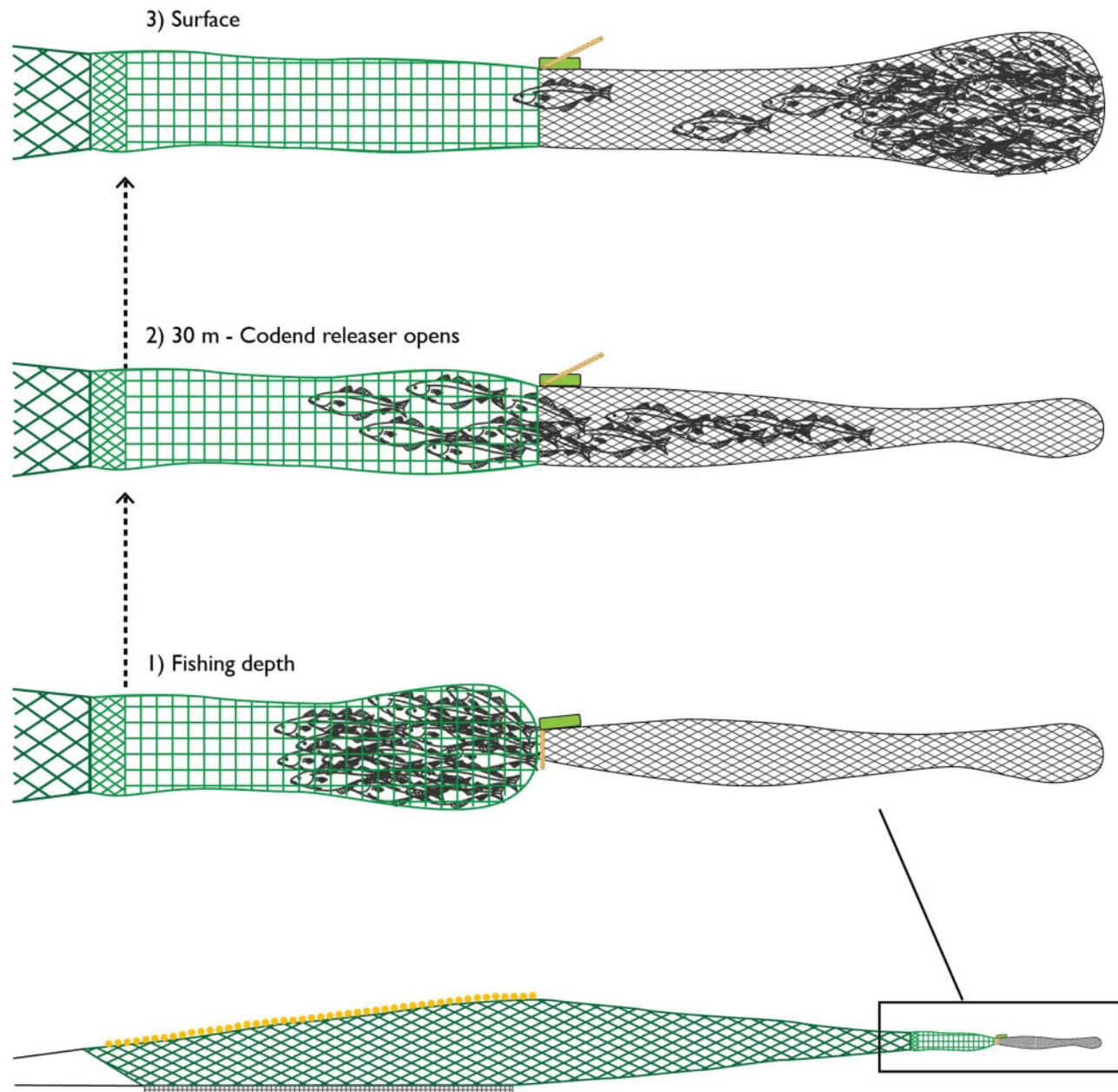
Figure 2. The procedure for preventing surface selection by use of the automatic codend releaser.

The permutation tests were performed for haddock such that paired hauls were kept to maintain the structure of the data, while unpaired hauls were randomly paired. This was repeated 1000 times without replacement.

The number of times that the explanatory variable yielded significant improvement, determined as at least 2 points lower AIC for each added parameter, is then counted and divided by number of permutations to get proportion P of significant improvements. The probability p of no effect due to the explanatory variable is then $1 - P$. For the permutation test, the function *gam* in the library *mgcv* in R (Wood, 2011) was applied. Few cod were measured, and it was therefore not considered feasible to conduct such an analysis on the cod data.

Only a few hauls were taken close in time and space and most hauls were unpaired. Therefore, a procedure similar to that of Sistiaga *et al.* (2016b) for analysing unpaired data was followed to obtain selection curves for surface selock and cod. A double bootstrapping was performed by sampling nine pairs (to incorporate between-haul variation) and fish measurements (to incorporate within-haul variation) with replacement.

For fitting the selection curves, several approaches were evaluated; random pairing of all hauls vs. keeping the three pairs, no raising of data, raising to correct number measured, and using an adjusted raising factor to equal number of large fish in all hauls. In addition, constraints on the slope parameter were set to fix it within realistic ranges. We tried setting ad hoc maximum SR

based on zero retention of fish at 6 cm (bar length of the codend meshes) and full retention of haddock at 60 cm. The maximum realistic SR, based on a straight retention line from 6 to 60 cm then becomes $(60 − 6)/2 = 27$ cm.

For the evaluation, a logistic model was fitted to the data as it was found to result in adequate fit and it is the simplest model. In addition, putting constraints on the Richards curve is not straight forward due to the asymmetry parameter. Most plausible results were obtained by keeping the paired data and use adjusted raising factor without any constraints (Supplementary material).

For the bootstrapping, the nine test hauls were paired randomly with control hauls, except for the three pairs which were kept to respect the structure of the data. A subset of the nine pairs was then sampled with replacement and size distributions within each haul resampled with replacement. After each resampling process, the data were raised with the adjusted raising factor for each haul, pooled, and a selection curve then fitted to the data. This procedure was repeated 1000 times and 95% confidence intervals for L50, SR, and length-dependent retention probabilities determined as 2.5th and 97.5th percentiles from all the selection curves. Four curves were fitted to the data, logistic, probit, Gompertz and Richards (ICES, 1996). The curve resulting in lowest AIC values was applied. The curve fit was evaluated by residual inspection and dispersion checking, calculating dispersion as the sum of Pearson residuals squared, divided by degrees of freedom (d.o.f.). In line with Millar *et al.* (2004), the summation is restricted to terms for which the expected catches for a length class in the test and control are greater than three, to prevent over-inflation of d.o.f.

When performing twin trawl analysis on subsampled data, using the SELECT method (Millar, 1992), a split parameter is estimated. If the population entering both gears is the same (fishing at approximately the same location) and efficiencies of both gears are equal [same number of fish enters the selection device (codend)], the expected value for the split parameter is 0.5. The method, however, only requires the size distributions of fish, and the split parameter can therefore be considered a nuisance parameter. When several hauls are taken, the population entering test and control gears can be expected to be about the same on average, given that the hauls are reasonably mixed. Performing a pooled analysis is thus a reasonable approach, and confidence intervals can be obtained by bootstrapping, preferably in two steps; bootstrap hauls to account for between haul variation and then size distribution for within haul variation (Fryer *et al.*, 2003). Fitting a selection curve to any two unpaired hauls is often unsuccessful. Therefore, owing to the variability in catch sizes, an erroneous conclusion may be reached if raised to the total number of fish in the catch prior to pooling. Some balanced weighting is needed in order to achieve sensible fits to the pool. To obtain about equal weight for each of the hauls in the pool, the data were raised to equal number of fish above presumed 100% retention. The subsampling factor for haddock was adjusted to raise all measurements so that the number of fish larger than 48 cm was equal in all measured samples (167 fish, equal to the number of fish above 48 cm in haul 18). From visual inspection, 49 cm and larger haddock have approximately 100% retention. For cod, the subsampling factor was adjusted to raise all measurements so that the number of fish larger than 62 cm was equal in all samples (132 fish, equal to the number of fish above 62 cm in haul 2). From visual inspection, the retention of cod 63 cm and larger is approximately 100%, consistent with Herrmann *et al.* (2016).

The selectivity curves were fitted using the function *optim* in R, maximizing a log-likelihood function (ICES, 1996; Appendix).

Results

A total of nine test hauls and nine control hauls were carried out (Table 1). Haddock was measured from all hauls and cod from eight control and eight test hauls. The haddock catches varied from 413 to 21 000 kg (median = 4220 kg) and number of fish measured ranged from 144 to 654 (median = 497). The cod catches ranged from 311 to 6351 kg (median = 1387 kg) from seven test and nine control hauls (Table 1). Fewer cod than haddock were measured (24–223 fish, median = 53).

Proportion of haddock below MLS in the control codend ranged from 10.1 to 35.9% ($\bar{x} = 18.6$), and exceeded the 15% criteria for area closure in six out of nine hauls (Table 2). For the test codend, one haul had more than 15% haddock below MLS (2.5–19.4%, $\bar{x} = 9.7$). Proportion of cod below MLS exceeded the 15% criteria in two out of seven hauls in the control codend (0–16.7%, $\bar{x} = 8.3$). None of the test hauls had proportion of undersized cod above this criterion (0–3.3%, $\bar{x} = 1.1$). These differences were statistically significant for both haddock and cod ($p < 0.001$).

The permutation test revealed a "best" model with a second order polynomial and random effects for intercept and length (Table 3). Neither the intercept β_0 nor slope parameter β_1 was significantly influenced by the 15 m additional extension ($p = 1$), catch size ($p = 1$), or fishing depth ($p = 0.33$ and 0.36, respectively). Interactions between the explanatory variables (extension: depth, extension: catch size, catch size: depth) did not affect the model parameters either ($p = 1$ in all cases).

A significant surface selection was detected for both haddock and cod. For haddock, the Richard's curve gave best fit (lowest AIC, Table 4). Mean L50 for haddock was 39.5 cm (median = 38.9, CI = 35.4–59.4 cm) and SR 10.6 cm (median = 13.2, CI = 7.9–24.0 cm). For haddock, the *p*-value for model fit was 0.02 and the dispersion parameter was 1.5, i.e. some overdispersion. From residual inspection (Figure 3), the fit seems adequate, and the overdispersion presumably due to between haul variation (ICES, 1996). For cod, the log–log resulted in lowest AIC (Table 4). Mean L50 for cod was 48.5 cm (median = 49.3, CI = 41.2–99.4 cm) and SR 12.7 cm (median = 12.3, CI = 2.0–57.7 cm). The *p*-value for model fit was <0.01 and dispersion parameter was 8.4, reflecting the low number of measured fish. In line with the haddock analysis, no heteroscedasticity was observed from the residual inspection (Figure 3).

Discussion

This study demonstrated high degree of surface selectivity for haddock and cod in the Norwegian demersal seine fishery. Most undersized fish that were still retained at 30 m depth, escaped close to the surface.

We use the term "surface selection" for selection at and close to surface, while Isaksen and Løkkeborg (1993) collected escapes from surface only. The ad hoc determined 30 m is a limit where selection should already have taken place for precautionary reasons. The swim bladder of cod and haddock bursts at pressure reduction of about 70% from the adapted level (Tytler and Blaxter, 1973). Cod rarely migrate vertically to depth corresponding to more than 50% reduction (Godø and Michalsen, 2000). Also, the relative pressure reduction happens more rapidly in the

Table 1. Haul details showing dates, setting time (local time, UTC—2 h), positions, setting depth, catch quantity, and number of measured fish

Haul	Pair	Date	Setting time (hh: mm)	Latitude	Longitude	Setup	Setting depth (m)	Cod (kg)	Cod measured (no)	Haddock (kg)	Haddock measured (no)	Other fish (kg)	Total catch (kg)
1	–	02 May	16:55	70°40.75	30°26.73	Test-long	72	2700	223	1025	272	0	3948
2	–	02 May	19:50	70°38.17	30°37.30	Test-long	81	2428	189	2145	407	0	4762
3	–	03 May	16:46	70°41.68	30°21.93	Control-long	88	6351	48	16805	644	156	23204
4	–	04 May	04:15	70°41.72	30°20.35	Control-long	94	722	–	16815	441	66	17552
5	–	07 May	10:25	70°39.70	30°28.60	Control-short	72	2224	94	5000	509	0	7318
6	–	07 May	18:15	70°40.35	30°25.40	Control-short	77	840	–	8253	480	40	9097
7	–	08 May	19:37	70°37.84	30°40.10	Test-short	97	3055	–	1564	484	0	4625
8	–	08 May	22:10	70°40.10	30°31.87	Test-short	99	1839	60	413	144	156	2312
10	–	10 May	10:17	70°41.60	30°20.74	Test-long	91	360	–	3462	466	27	3839
12	–	10 May	17:58	70°28.83	31°07.18	Test-long	93	768	64	5137	356	0	5969
14	1	12 May	20:45	70°26.94	31°06.94	Control-long	103	2000	55	21000	636	150	23055
15	1	13 May	01:33	70°26.93	31°07.63	Test-long	102	1500	51	18000	573	150	19551
16	–	14 May	11:44	70°41.84	30°21.21	Control-long	54	311	27	1884	587	0	2222
17	2	14 May	15:26	70°32.65	31°01.34	Test-long	97	570	65	1692	447	0	2327
18	2	14 May	17:50	70°32.48	31°01.96	Control-long	114	1130	24	8336	654	0	9490
19	–	14 May	20:20	70°32.35	31°02.62	Control-long	117	1274	51	3804	595	6	5129
20	3	15 May	10:00	70°26.45	31°08.45	Test-long	94	446	30	2894	592	100	3370
21	3	15 May	13:30	70°27.05	31°06.78	Control-long	98	702	37	4636	626	56	5375

uppermost layers [pressure reduction from 100 to 30 m (11–4 bars) is 63%, while from 30 m to surface (1 bar) it is 75%].

In the study area, the proportion of haddock below MLS in the control setup (no surface selection) mostly exceeded the 15% criteria for area closure. For the test setup with surface selection, however, the proportions were mostly within this limit. Isaksen and Løkkeborg (1993) observed that about half of the selectivity in a diamond-mesh codend took place at the surface. Madsen et al. (2008) investigated selection at different stages of the fishing process, and estimated L50 for haddock to be about the same at depth, during haulback and at surface. While our experiment did not include assessment of size selection at the fishing depth, the results showed that escapement of undersized fish at the fishing depth are insufficient to meet the 15% criteria for demersal seine fishing. The additional surface selection contributed significantly to reduce the proportion of undersized fish to levels well below the criteria.

Extension length, catch size, and fishing depth did not affect size selection at the surface. For the two extension lengths tested, the probability of no effect was high ($p = 1$). A small, yet significant effect of extension lengths on selectivity for demersal seines and trawls has been demonstrated by Reeves et al. (1992). They tested extension lengths up to 13.7 m, which is considerably shorter than what is commonly used in the Norwegian demersal seine fisheries. Cutting the extension length down to a bare minimum would have been worthwhile but was not achievable due to time constraints. It cannot be ruled out, however, that the overall selectivity, which is the product of the selectivity processes, including selection at the bottom, could be influenced by removing the codend extensions.

Surface selectivity was not affected by catch size either ($p = 1$). During a relatively short fishing process, the long extensions will delay the passage of the fish towards the codend where the selection takes place. The fish seem not to become densely packed in the codend, but a loosely moving mass. Therefore, the movement

of fish within the codend is to a little extent inhibited despite large catch quantities.

Size selection was also unaffected by fishing depth ($p = 0.33$ for the intercept and 0.36 for the slope parameter). With the same length of seine ropes and therefore similar hauling time, the fishing depth does not affect the time from start of hauling until the codend enters the surface. There is thus no obvious reason why moderate depth variations (54–117 m) should influence surface selection. It should be stated, however, that this finding is based on a relatively small dataset and between haul variation is to be expected due to the unpaired method. Therefore, the observed effect in two-thirds of the permutations warrants attention for future research.

The results for haddock clearly showed the significance of surface selection. For cod, the number of measured fish was low, which in turn resulted in wide confidence bounds. Due to the poor cod data, the scale of surface escape is unreasonable to predict. The overall conclusion, however, is that surface selection is significant for both haddock and cod.

The selection curve determines length-dependent retention probabilities of fish, given that it enters the gear. Taking hauls in pairs, close in time and space would be the best way to ensure that test and control hauls fish on similar populations. When pairs cannot be obtained, an alternative solution is to pair several hauls randomly and pool. By keeping the pairs that were obtained and pairing the rest randomly, we maintain the (little) structure in the data, which in turn results in better behaviour of the bootstrapped parameters (fewer unrealistic deviations). We have also chosen to raise the number of fish so that number of fish with retention probabilities of 1 is equal in all the hauls. For covered-codend analysis, the correct proportion between number of fish in the codend and the cover is essential. In a twin trawl analysis, however, for a single haul, the raising has no effect on the parameter point estimates, other than the split parameter which is generally not of interest. Spatial variations between the populations that are fished on are likely to occur throughout the experiment.

Table 2. Information on sampling of haddock and cod, percentage of fish below MLS (40 cm for haddock and 44 cm for cod), proportion measured, and the adjusted proportions for fixing equal split for both the permutation test and selectivity analysis

		Cod							Haddock						
Setup	Haul	No. measured fish.	Sample weight (kg)	Proportion measured	No. fish < 44 cm	Per cent <44 cm	No. fish >62 cm	Adjusted proportion measured	No. measured fish.	Sample weight (kg)	Proportion measured	No. fish <40 cm	Per cent <40 cm	No. fish >48 cm	Adjusted proportion measured
Control	3	48	112	0.0176	7	14.6	17	0.1288	644	682	0.0406	110	17.1	78	0.4671
Control	4						4	–	441	454	0.0270	84	19.0	57	0.3413
Control	5	94	184	0.0830	5	5.3	26	0.1970	509	556	0.1112	76	14.9	88	0.5269
Control	6						0	–	480	495	0.0600	88	18.3	64	0.3832
Control	14	55	129	0.0646	1	1.8	25	0.1894	636	682	0.0325	109	17.1	102	0.6108
Control	16	27	67	0.2155	1	3.7	12	0.0909	587	640	0.3397	130	22.1	135	0.8084
Control	18	24	51	0.0451	4	16.7	8	0.0606	654	786	0.0943	66	10.1	167	1
Control	19	51	139	0.1093	0	0.0	23	0.1742	595	717	0.1885	75	12.6	143	0.8563
Control	21	37	68	0.0963	6	16.2	9	0.0682	626	552	0.1191	225	35.9	48	0.2874
Test	1	223	601	0.2227	3	1.3	130	0.9848	272	381	0.3717	15	5.5	99	0.5928
Test	2	189	626	0.2579	0	0.0	132	1	407	481	0.2242	31	7.6	77	0.4611
Test	7							–	484	571	0.3651	45	9.3	114	0.6826
Test	8	60	140	0.0760	0	0.0	23	0.1742	144	167	0.4044	4	2.8	22	0.1317
Test	10							–	466	558	0.1612	55	11.8	124	0.7425
Test	12	64	281	0.3653	1	1.6	51	0.3864	356	408	0.0794	32	9.0	66	0.3952
Test	15	51	133	0.0890	0	0.0	31	0.2348	573	650	0.0361	86	15.0	118	0.7066
Test	17	65	165	0.2892	1	1.5	32	0.2424	447	531	0.3138	31	6.9	110	0.6587
Test	20	30	56	0.1249	1	3.3	9	0.0682	592	609	0.2104	115	19.4	91	0.5449

Table 3. The results from the permutation tests, showing *p*-values for the effects of the explanatory variables extension length, fishing depth, catch size, and their interactions on relative catch retention in the test gear compared to the control

Explanatory variable	Intercept, β_0	Slope (fish length), β_1
Extension	1	1
Fishing depth	0.33	0.36
Catch size	1	1
Extension: depth	1	1
Extension: catch size	1	1
Catch size: fishing depth	1	1

Table 4. AIC values for the tested models

Model	Haddock	Cod
Log-log	23 088.9	5909.5
Logit	23 076.7	5922.7
Richards	23 065.0	5913.2
Probit	23 080.3	5920.2

Achieving selectivity parameters from any two hauls will thus not always be successful. In the same way, if the hauls are pooled and raised, the size distribution from the largest haul can dominate, which in turn can result in non-achievable fit. This problem escalates in bootstrapping where the large, dominating haul can occur several times in some of the bootstraps. There is therefore no reason for raising to the total catch in an unpaired study with extreme variations in catch sizes. Fitting without any raising mitigates the problem, but our sample sizes varied and a number of unrealistic fits were observed. Setting constraints on the parameters to fix them within realistic levels is another option. We tried setting ad hoc maximum SR to 27 cm. This approach only resulted in fixing the upper limits of the confidence intervals. Raising the number to equal number of large fish resulted in pools with selection curves having split parameters distributed around 0.5, which in turn resulted in well-behaved distribution of the parameter estimates in the bootstraps. The resulting surface-selection curve is therefore based on unweighted average fish population entering the codend extension on the fishing grounds.

No other studies are known on surface selectivity using a square-mesh codend in the demersal seine fisheries, and limited studies on the overall selectivity. In a covered codend study, Ingólfsson *et al.* (2016) estimated overall selection for a 12.8 m long square-mesh codend of 125 mm mesh size, 6 m in circumference with 7 m extension. From four hauls, mean L50 for haddock was 42.0 cm (CI = 40.4–43.6 cm) and SR 9.9 cm (CI = 9.1–10.7 cm). In our study, with codend and extension of greater dimensions, similar or lower L50 would be expected. The overall selection of a gear is the product of the selection processes, which in this case can be simplified to depth and surface. Therefore, assuming similar overall selection in the present study, selection of haddock above 40 cm may take place mostly close to the surface. A narrower SR for the overall selection indicates significant selection of smaller fish at depth. One must be careful when comparing across studies, and the confidence bounds for the selection parameters in the current study are wide. This is, however, noteworthily in agreement with Isaksen and Løkkeborg (1993). They observed greater proportion of haddock below ∼36 cm escaping

at depth with a 125 mm diamond-mesh codend, while the opposite was true for larger haddock. An explanation to this could be that most of the haddock enter the selective codend late in the fishing process. During towing, some of the fish are then in the extension, where only the smallest haddock are able to penetrate due to narrow lateral mesh opening.

Fish escaping at the surface are likely to experience more severe stressors due to barotrauma, physiological trauma and physical injury than those escaping during the towing process (Davis, 2002). Haddock and cod are physoclistous (i.e. closed swim bladder) and thus unable to release excess gas during a rapid ascend to the surface. To some extent this results in fish floating at the surface, exposing fish to seabird predation. Mortality of cod escaping from demersal seine at the surface (Soldal and Isaksen, 1993) and after immediate discarding (Benoît *et al.*, 2012) has been estimated to be zero. In their study, Soldal and Isaksen (1993) estimated the overall mortality rates for haddock to range from 3.2% to 6.8%. It was, however, length related, and greatest mortality among the smaller individuals. Mortality of haddock escaping trawls at the fishing depth is inversely related to fish length (Breen, 2004; Ingólfsson *et al.*, 2007). The species-specific mortalities are likely to be associated with differences in abilities to cope with stress. Haddock are easily stressed (Martin-Robichaud, 2003), and believed to be more sensitive to pressure changes (Ingólfsson *et al.*, 2007) and post-exhaustion stress (Breen, 2004) than cod. Also, stressors that do not immediately kill fish may still cause delayed mortality, such as behavioural impairment making escaped fish more vulnerable to predation (Davis, 2005; Ryer *et al.*, 2004). The general consensus, therefore, is to release undersized fish as early as possible during the catching process.

With a large-mesh codend, there is no obvious method to avoid surface selection, as selection is a continuous process throughout the whole fishing operation. It could, however, be minimized by designing measures for maximizing escapement at the fishing depth. Therefore, passage from the seine body to a selective device/codend should be as open and short as possible. The application of rigid grids in demersal seine fisheries would be troublesome as they are cumbersome to handle. Furthermore, the selectivity performance of grids has not been proven to be superior to that of codends alone, neither overall (Jørgensen *et al.*, 2006), nor during haulback (Grimaldo *et al.*, 2009). Flexible grids have been tested and are in use in the Norwegian trawl fisheries, but have been proven to have low contact rate, i.e. large proportion of fish passes the grid and the selection is to a great extent dependent on codend selection (Sistiaga *et al.*, 2016a). Therefore, available knowledge suggests using a codend, which meshes should be open throughout its length to facilitate escape. Square-mesh configuration has been shown to give sharper selection (narrower SR) for demersal seines than diamond meshes (Isaksen and Larsen, 1988). Alternative approach could be to use T90 meshes (Herrmann et al., 2013a) or diamond meshes with short lastridge ropes (Isaksen and Valdemarsen, 1990; Lök *et al.*, 1997; Ingólfsson and Brinkhof, 2020). Codend circumference has significant influence on selectivity for both diamond (Reeves *et al.*, 1992) and square-mesh codends (Sala *et al.*, 2016). Twine stiffness/thickness also affects selection (Herrmann *et al.*, 2013a), yet undershooting thickness increases risk of fish being enmeshed (gilled) in the codend meshes (Bjørnar Isaksen, pers. comm.). In conclusion, the application of square-mesh codend in the seine fisheries is presumably a "good" practice, yet design refinements
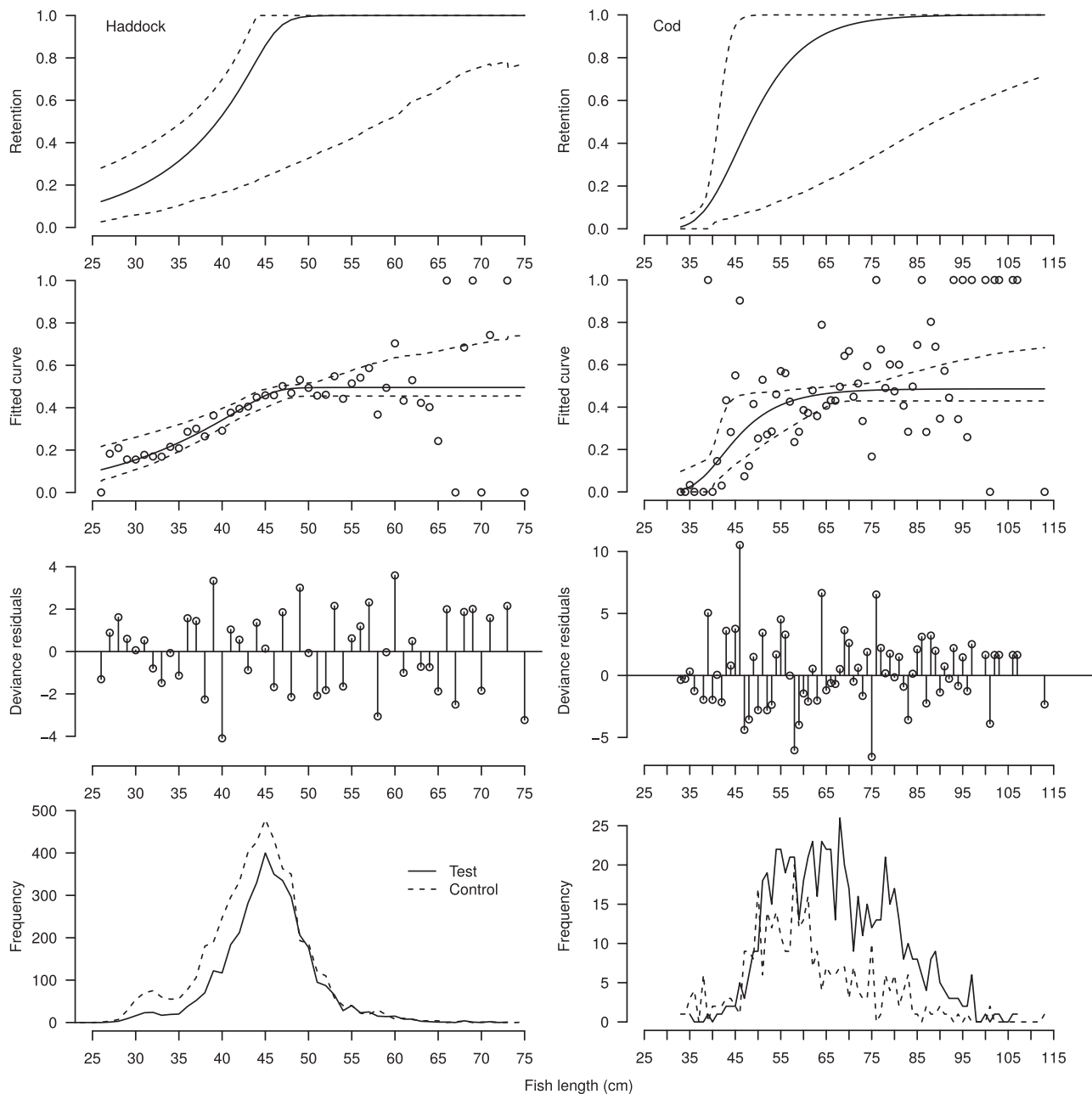
Figure 3. Results for haddock (left) and cod (right) surface selection. Surface selection curve (top), fitted curves (second from top), residual plots (second from bottom), and size distributions (bottom) for test (–) and control codends (- -).

should be tested, aiming for increasing the escape rate at the fishing depth.

Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Appendix

R-script for calculating selection curves [logistic, Richards, probit, and Gomperts (log-log)] for twin trawl analysis. From "Manual of methods for measuring the selectivity of towed fishing gears" (ICES, 1996).

```
### Function for estimating selection curves
trouser.fit <- function(Length, Test, Control,
                        q1=1, q2=1, b.=par,
                        curve= "logit")
  {
  m <<- Control
  o <<- Test
  n <<- Test + Control
  y <<- o/n
  l <<- Length
  # for fixed split = 0.5, set p <- 0.5 instead of
    b.[3]
  a <- b.[1]; b <- b.[2]; p <- b.[3]; d <- b.[4]
  if(curve == "probit") r.l <- pnorm(a+b*l)
  #
    probit
  if(curve == "log-log") r.l = exp(- exp
    (-(a+b*l))) # log-log
  if(curve == "logit") r.l <- exp(a+b*l)/
    (1+exp(a+b*l)) # logit
  if(curve == "richards") {
      r.l <- (exp(a+b*l)/(1+exp(a+b*l)))
        ^(1/d) # richards
  }
  p.i <<- q1*p*r.l/(q1*p*r.l+q2*(1-p))
  pe <- ifelse(n>0, y, 0.5)
  # pearson residuals
  pears <<- sqrt(n)*(y-p.i)/sqrt(p.i*(1-p.i))
  pears3 <<- subset(pears, n>3)
  dk <<- ifelse(pe > 0, pe * (log(pe)
    - log(p.i)), 0) +
      ifelse(pe < 1, (1-pe) * (log(1-pe)
        -log(1-p.i)), 0)
  # standardized deviance residuals
  d.k <<- sign(pe-p.i)*sqrt(2*n*(dk))
  d_l <<- subset(d.k, n>3)
  loglik <<- sum(o * log(p.i) + m * log(1 - p.i))
  -loglik
  }
### Fitting curve to data, needs initial start-
ing values
### see? optim for information on the function
result <- optim(par = c(-6.9, .157, 0.55, 1),
        control = list(reltol = 1e-22, maxit
        = 5000),
        fn = trouser.fit,
        Length = haddock$Length,
        Test = haddock$Test,
        Control = haddock$Control,
        curve = "richards",
        q1=1, # sampling ratio for test,
        q2=1) # sampling ratio for control
### parameters
a <- result$par[1] # parameter "a"
b <- result$par[2] # parameter "b"
p <- result$par[3] # split parameter
d <- result$par[4] # asymmetry parameter (for
Richards curve)
### L50
l50.logit <- -a/b
```

```
l50.loglog <- (0.3665-a)/b
l50.richards <- (log(0.5^d/(1-0.5^d))-a)/b
l50.probit <- -a/b

### SR
sr.logit <- log(9)/b
sr.loglog <- 1.573/b
sr.richards <- (log(0.75^d/(1-0.75^d))
  - log(0.25^d/(1-.25^d)))/b
sr.probit <- 1.349/b

### For plotting the selection curves
fish.length <- seq(25,80, by=0.1)
eta <- a+b * fish.length
curve.logit <- exp(eta)/(1+exp(eta))
curve.loglog <- exp(-exp(-(eta)))
curve.richards <- (exp(eta)/(1+exp(eta)))
  ^(1/d)
curve.probit <- pnorm(eta)
prop <- haddock$Test/(haddock$Test+
  haddock$Control)

### likelihood
result$value
### Degrees of freedom: no. length classes-no.
  parameters
dof.rich <- nrow(haddock)-4
### AIC: 2 * -log(likelihood) + 2 * no
  parameters)
aic.rich <- 2*result$value + 2*4
### Dispersion, using pearson
disp.rich <- sum(pears3^2)/dof.rich #
### Dispersion, using deviance
disp.rich <- sum(d_l^2)/dof.rich #
### p-value for fit
dev <- sum(d_l^2)
pchisq(dev, dof.rich, lower.tail = FALSE)

### Example for plotting Richards curve
PI. <- p*curve.richards/(p*curve.richards
  +(1-p))
plot(fish.length, curve.richards, type = "l",
  las = 1)
points(haddock$Length, prop)
lines(fish.length, PI., lty = 2)
```

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