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Grid selection in the North Sea industrial trawl fishery for Norway pout: Efficient size selection reduces bycatch

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Abstract

Experiments were carried out during three cruises in the period 1997–1999, to develop and test a sorting grid system in the North Sea industrial trawl fishery for Norway pout. The system should separate bycatch species like haddock, whiting and other human consumption species from the main target species Norway pout, and other target species like blue whiting, etc. During the first cruise a prototype of the grid system was developed and tested with different mountings of guiding panel in front of the grid and with different spacing (25, 22 and 19 mm) between bars. The last two surveys tested if the mesh size in the grid section and the thickness of the bars influenced the selectivity of the grid system. Two different mesh sizes and three different thicknesses of bars were tested. Based on the results from the 1997 experiments, only a bar space of 22 mm were used in the later experiments. The 1998 and 1999 experiments were carried out in different seasons (May and September/October) to test the system on different size distributions of target and bycatch species. Hydrodynamic studies of the grid system using the two different mesh sizes and the three different thickness of bars were conducted in a flume tank, and a 25% difference was found in water flow speed behind grids with 22 mm bar spacing but with different thickness of bars (15, 10 and 5 mm). During the 1998 experiment a total of 94.6% (weight) of the bycatch species was sorted out with a 32.8% loss of target species. In the 1999 experiment 62.4% of the bycatch species were sorted out and the loss of target species was 22%. When testing selectivity parameters for haddock, the main bycatch species, the parameters indicated a sharp size selection in the grid system. Size selection differences between different configurations of the grid system are discussed.

Keywords: Industrial trawl fishery; Sorting grid; Grid selection; Size and species selection

1. Introduction

In the Norwegian industrial trawl fishery for Norway pout in the North Sea there is a well-recognized bycatch problem (Table 1). The main bycatch species are haddock and whiting. The bycatch arises because the small codend mesh size entraps large quantities of juvenile non-target species. Frequently large quantities of adult saithe are also caught. With the increasing recognition on the dramatic effects of fishing on the biomass of gadoids and other predatory fishes in the Northern Atlantic (Christensen et al., 2003; Myers and Worm, 2003; Pauly et al., 2002), efforts are needed to reduce the bycatch of the larger gadoid fishes in the Norway pout fishery in the North Sea. We have developed and tested a grid sorting device to be used in a bottom trawl for this purpose.

The trawl fishery for Norway pout occurs mainly at depths of less than 250 m along the western slope of the Norwegian Deep (Bergstad, 1990); this has been the main fishing area over the last 30 years (Lahn-Johannesen et al., 1978). Inevitably large quantities of bycatch species below minimum legal landing size are caught. In the Norwegian zone, a fishing vessel is allowed to have a maximum of 20% of bycatch species, and is not allowed to catch fish below minimum legal landing size of cod, haddock, whiting, hake and saithe. Nevertheless, a large bycatch of adult saithe often occurs and there is also often a considerable amount of small cod and whiting in the catches. On other fishing

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Table 1
Common target and bycatch species in the North Sea industrial fishery

Target species	Bycatch species
Norway pout (*Trisopterus esmarkii*, Nilsson)	Haddock (*Melanogrammus aeglefinus* L.)
Blue whiting (*Micromesistius poutassou*, Risso)	Saithe (*Pollachius virens* L.)
Greater Argentine (*Trachurus trachurus* L.)	Whiting (*Merlangius merlangus* L.)
Silvery pout (*Gadiculus argenteus thori*, J. Schmidt)	Cod (*Gadus morhua* L.)
Horse mackerel (*Trachurus trachurus* L.)	Ling (*Molva molva* L.)
	Tusk (*Brosme brosme*, Ascanius)
	North sea herring (*Clupea harengus* L.)
	Mackerel (*Scomber scombrus* L.)
	Monkfish(*Lophius piscatorius* L.)
	Wolf-fish (*Anarhichas* spp.)
	Hake (*Merluccius merluccius* L.)
	Pollack (*Pollachius pollachius* L.)
	Redfish (*Sebastes* spp.)

fields, such as Fladen ground and the area around Shetland, there can be similar problems with bycatch of saithe and cod, and the bycatch of whiting and haddock may be even greater.

Few experiments have been conducted on the separation of Norway pout from other species in the fishery (Main and Galbraith, 1990). Some trials have attempted to develop technologies that minimize the bycatch of human consumption species. These attempts have mainly concentrated on applying interspecific differences in behaviour towards the trawl gear.

Dickson (1960) used two trawls mounted one above the other, each having a 2 m vertical opening. Roughly half of the total catch of Norway pout was caught in the upper level by day, but only one sixth by night, whereas other gadoids were caught mainly in the lower trawl, both by day and by night.

Bailey et al. (1983) used a horizontally divided, three-level bottom trawl during two cruises to ascertain the bycatch levels at selected depth strata. The proportion of Norway pout in the catch was significantly correlated with bottom depth, but not with time of day. Norway pout were caught predominantly in the middle and bottom compartments and distribution between vertical levels did not vary significantly with time of day or depth. Haddock of all sizes were caught predominantly in the bottom compartment. There was a significant variation in distribution between four haul categories (deep, shallow, light and dark) in the second cruise but not in the first one. Significant differences in distribution between species in the hauls carried out in daylight were found in both cruises, but not in those during darkness. In daylight, haddock were more concentrated in the bottom compartment than both Norway pout and whiting, but there was no difference between pout and whiting in this respect. During darkness there was no difference between species. Bailey et al. (1983) concluded that the results did not in any way suggest how their type of net could be used to achieve a more complete separation.

Wileman and Main (1994) sought to separate herring, whiting and haddock from Norway pout in industrial trawls. They tested three different devices, a horizontal separator panel, square mesh escape panels and a grid. The first was based on fish entering the trawl mouth in different heights and the other two on fish having different escape reactions in front of the codend. The horizontal separator panel failed to achieve a proper species separation. The height at which pout entered the trawl was variable and differences between pout and haddock/whiting were too small. Escape rates for bycatch species through the square mesh panel were lower than for pout, and again no satisfactory species separation was achieved. The grid caused handling problems, few fish passed through it and there was only evidence of size, not species separation. Wileman and Main (1994) concluded that it is not possible to reduce bycatch levels of food species in Norway pout trawls by separating species within the trawl.

Today, sorting grids are in common use in different trawl fisheries, and a grid sorting system that has been tested in the mixed industrial fishery at the Faroes reduced the bycatch of haddock from on average 5% in weight to 1.3% (K. Zachariassen, personal communication). In this study, we have developed and tested a new sorting grid system for the industrial trawl fishery for Norway pout in the North Sea. The idea was that the sharp size selection attained by grids (Larsen and Isaksen, 1993) might also be used to increase the species selection by separating small target species from larger bycatch species. The grid is based on the same principle as the Nordmøre grid used in the shrimp fishery (Isaksen et al., 1992). We have carried out three different surveys, the first experiment as a preliminary investigation to test a prototype of the grid system using different bar spacing and different mounting of the grid and the guiding panel. In the two next experiments the final grid system were tested with three different grids having different bar-thickness (15, 10 and 5 mm) on different size distributions of target and bycatch species. Based on the results of the first experiments, only the grid with 22 mm bar space was used. A flume tank test was carried out to test for differences in water flow inside the grid system when using different thickness of bars and different mesh sizes in the system. An understanding of the water flow inside the selection devices allows for the determination of the optimum designs for the device so as to efficiently reduce bycatch without reducing the catch of target species (Riedel and DeAlteris, 1995).

2. Material and methods

2.1. Fishing gear, operational procedures and surveys

The first survey was carried out in June 1997 in the western part of the Norwegian trench, close to Oseberg at depths between 150 and 300 m, using the R/V “Michael Sars”

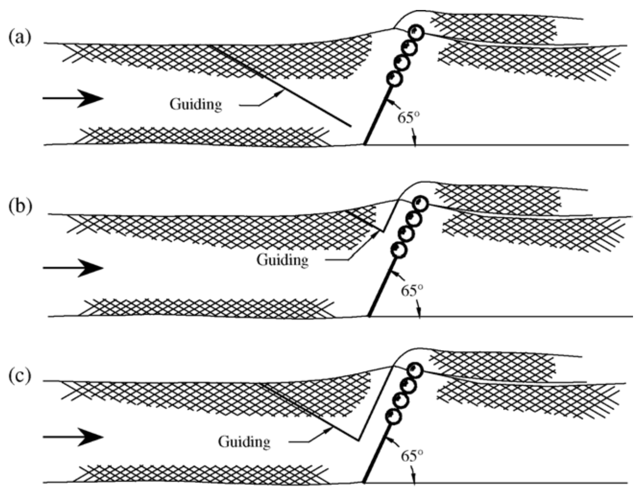

Fig. 1. (a–c) Alternative mounting of guiding panel tested in the 1997 experiments. The arrows indicate direction of flow. Side views.

equipped with a commercial EXPO (1200 meshes) industrial trawl rigged with Waco trawl-doors (1400 kg) and 160 m long sweeps. Scanmar instrumentation measured the vertical opening and door-spread of the trawl during all hauls; a grid sensor measured the angle of the grid and water-flow through it. The grid was mounted in a 65° angle. The grid should sort out individuals wider than the bar distance into the cover-bag mounted on top of the grid (Fig. 1a–c). In the first haul a guiding panel was mounted from the top panel, sloping backwards (Fig. 1a) to guide the fish against the grid. In the next haul this guiding panel was moved closer to the grid to force the fish against it. In hauls without the guiding panel, the selection results were poor.

A new guiding panel, sloping backwards down to the upper 1/3 of the grid and then following the grid to the top was then mounted (Fig. 1b). After three hauls this guiding panel was extended down to the lower 1/3 of the grid, following the grid to the top (Fig. 1c). This rigging was used during the rest of the first survey.

The grid (1308 mm × 1999 mm) was mounted in an extension piece with 24 mm meshes, the same mesh size as in the codend and the cover-bag. The grid was mounted inside a frame, which made it easy to change grids with different bar configuration. Two hauls with 25 mm bar distance, 17 hauls with 22 mm and 4 hauls with 19 mm were carried out at depths between 150 and 250 m. In 18 of these 23 hauls, an RS video-system was used to make observations in front of the grid. Three hauls were carried out at depths around 95 m at the Old Viking bank, to make video-observations both inside the trawl using the RS system and outside using a Focus 400 towed vehicle. All hauls were carried out during daytime because the fishery for Norway pout is typically a daytime fishery. The towing time varied between 20 and 60 min and the towing speed around 2.5–3 knots (≈1.3–1.5 m s^{-1}).

The second survey was carried out during 12 days in May 1998 with R/V "Johan Hjort". All hauls were carried out in almost the same area as the first cruise, but in more shallow waters at depths between 175 and 220 m.

The same trawl and trawl-doors were used and all hauls were carried out during daytime, with the same haul duration and towing speed as in the first cruise. An RS video system was operated during each haul to make observations of the grid and the extension piece. The grid was mounted in a 60° angle (Fig. 2). A frame was mounted on the grid to hold the guiding panel in position from the grid and to make a proper "tunnel" between the guiding panel and the grid.

Based on the results from the first experiments, only the 22 mm bar space was used. To test if a difference in the effective opening (light opening) of the grid and thus the water-flow through the grid could influence the selection, three different diameters of bars were tested (15, 10 and 5 mm). In the grid with 15 mm bars, the ratio between the effective opening and the "closed area" of the grid, is about 6:4; in the grid with 10 mm bars the ratio is about 7:3; and for the grid with 5 mm bar thickness the ratio was about 8:2.

To test if a smaller mesh size in the extension piece would change the water flow through the grid and possibly change the selection, an alternative extension piece with only 10 mm meshes was also tested. This gave six combinations of grid (5, 10 and 15 mm bars) and extension piece (10 or 24 mm mesh size). Five hauls of each combination were carried out, a total of 30 hauls.

To conduct the same experiment on different size distributions of target and bycatch species, a third survey was conducted during 13 days in September/October 1999 with R/V "Michael Sars". The survey was carried out in the same area as in 1998. The rigging of the trawl and mounting of grids were the same as in 1998, and again 30 hauls were carried out.

Flow measurements of the grid system were made during 1 week in August 1999 in IFREMER's flume tank in Boulogne

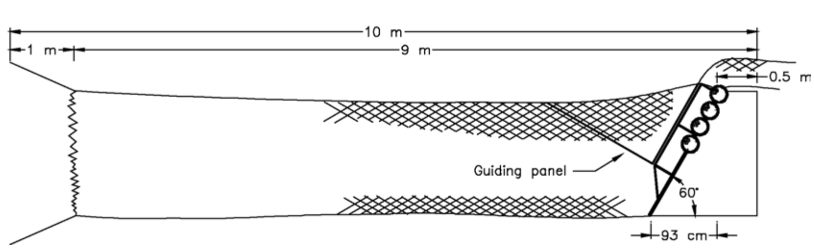

Fig. 2. Mounting of the grid in the extension piece during the 1998 and 1999 experiments. The frame where the guiding panel was attached is shown.

sur Mer, testing for differences in water flow among our six bar thickness/mesh size combinations. Because the grid system was too big for the flume tank, a 1:2 model of the system was made, but for simplicity full scale of the bar distance, bar thickness and the mesh size in the extension piece was used. Water flow was measured at different distances both in front of and behind the grid.

2.2. Data analysis and statistics

A sample of about 120 kg from both the codend and the cover-bag was taken from the catches and then sorted by species. The weight (g) and length (cm) of each species in the sample was measured. The total weights of the catch in the codend and in the cover-bag were measured and the ratio of the codend and the cover-bag catch was used to scale up the length class frequencies of each species in the sample. This gave estimated length class frequencies for the entire codend and the cover-bag. Selection curves and parameters such as 50% retention length (L50%) and selection range (SR = L75% − L25%) were calculated using CC2000 (Constat, 1999), which implements the Share Each Length class's Catch Total (SELECT) method (Millar, 1992) for indirect selectivity experiments with towed gears. Selection curves were calculated with probability of exclusion instead of probability of retention on the *y*-axis. Other statistics were calculated using S-Plus 2000 (MathSoft, 1999) and Statistica (StatSoft, 1995). The basic idea of the SELECT method is to maximize a conditional likelihood function that corresponds to estimation of an associated curve, rather than the selection curve itself. For a detailed and thorough description of the SELECT method and the statistics behind it, see McCullagh and Nelder (1989), Fryer (1991), Millar (1991, 1992), Gagnon (1992) and Anon. (1996). Analysis of variance (ANOVA) was used to test for a difference in mean lengths for each of the mesh/grid combinations.

The EC MODEL (Constat, 1999) was used to estimate common selection curves for all hauls, for each survey and for groups of hauls. It was also used to test for differences in selection parameters between the tested combinations of bar thickness and mesh size in the second and third surveys. The EC MODEL is a program specifically designed for fishing gear selectivity research. The program is directed at making inference on the effects of covariates on the selectivity parameters. It implements a special version of the Laird–Ware model (Laird and Ware, 1982), which is used for analysing longitudinal data and fixed and random effects. This version of the Laird–Ware model, assumes that the within-subject covariance matrices R_i are known, whereas the general model allows different structural forms of these to be estimated. The use of the Laird–Ware model in the analysis of fishing gear selectivity data was introduced by Fryer (1991), who demonstrated how between-haul variation could be modelled rigorously as a random effect. In terms of the Laird–Ware model, the selectivity parameters from individual hauls are considered independent response variables from a number of different "subjects". See Laird and Ware (1982) or Jones (1993) for further details.

3. Results

3.1. Grid-rigging experiment

A total of 35 hauls were carried out during the grid-rigging experiments in 1997. In the first 12 hauls, different guiding panels were tested and the 23 other hauls formed a selection experiment testing the three different bar distances (19, 22 and 25 mm). The catches of the guiding panel testing were not sorted by species and measured and are therefore not presented here.

The catch sizes in the selection experiments varied from 283 to 2284 kg in the codend and from 77 to 1066 kg in the cover-bag (Table 2). The catch in the codend is the fish caught, while the catch in the cover-bag is the fish sorted out by the grid. For target species, such sorting entails a loss of catch. The total percentage of fish sorted out varied between 12.9 and 57.6%.

The distribution of the catch for the four main species is presented in Table 3. There was a total loss of 13.9% of the target species Norway pout, but for the two hauls with

Table 2
Total catch in codend and cover-bag and percentage of loss (target)/sorted out (bycatch) for the three bar distances used during the grid-rigging experiment

Haul no.	Bar distance (mm)	Catch 1997 (kg)		% Sorted out
		Codend	Cover-bag	
1	22	365	376	50.7
2	22	775	454	36.9
3	22	576	349	37.7
4	22	2238	460	17.0
5	22	536	728	57.6
6	22	1650	652	28.3
7	22	394	205	34.2
8	22	283	167	37.1
9	22	729	610	45.6
10	22	446	197	30.6
11	22	1509	418	21.7
12	22	2255	1066	32.1
13	22	1008	314	23.8
14	25	381	77	16.8
15	25	531	113	17.5
16	19	1060	594	35.9
17	19	588	376	39.0
18	19	1880	302	13.8
19	19	1184	387	24.6
20	22	2284	553	19.5
21	22	1037	368	26.2
22	22	879	181	17.1
23	22	2109	311	12.9
Total	19	4712	1659	26.0
Total	22	19073	7409	28.0
Total	25	912	190	17.2

Table 3
Distribution of catch between codend and the cover-bag for the four main species, and % loss of three main target species and % sorted out of the non target species haddock

Species	Catch (kg)		Loss of target species/sorted out of bycatch species (%)			
	Codend	Cover-bag	All hauls	19 mm bar space	22 mm bar space	25 mm bar space
Norway pout	6896.9	1112.2	13.9	13.8	14.0	2.7
Blue whiting	13595.1	5355.4	28.3	30.5	28.6	8.9
Greater argentine	1517.3	829.6	35.3	49.2	33.8	32.3
Haddock	1591.7	1226.6	43.5	76.5	41.2	34.1

Table 4
Result from two-sample Kolmogorov–Smirnov Test between length distribution in cover-bag and codend

Data	p-Value	KS	n (codend)	n (cover-bag)
Haddock 1997	<0.05	0.3220	1613	2571
Norway pout 1997	<0.05	0.1896	1961	1810
Argentine 1997	<0.05	0.3015	1438	1408
Blue whiting 1997	<0.05	0.1437	2981	2640

n is number of individuals measured for length in each bag.

the 25 mm grid the loss was only 2.7%. The 19 mm and the 22 mm grid had a loss of about 14% each. The catches consisted mostly of blue whiting and Norway pout, with smaller amounts of the target species argentine and the non-target species haddock. For blue whiting and argentine there was also a smaller loss in the two hauls using the 25 mm grid compared to the 19 mm grid. For haddock there was a total percentage sorted out of 43.5% and the percentage sorted out decreased with increasing bar space.

The length distributions for the four main species are presented in Fig. 3. For each species, there was a significant difference between the length distribution in the codend and in the cover-bag (Table 4).

Haddock was the most important bycatch species, and it was the only one to occur in large numbers below the size where all individuals are sorted out by the grid. Nearly all the other bycatch species are sorted out (Table 7). In the further analysis of the size selection of the different grids, haddock is therefore the only species considered.

The estimated mean L50% increased from 18.51 cm for the grid with 19 mm bar space to 22.43 cm for the 25 mm grid (Table 5). The SR also increased with increasing space between bars. The estimated parameters for the 19 mm and the 25 mm grid should be treated carefully owing to the small number of hauls. The selectivity curves and the estimated mean curve is presented in Fig. 4.

3.2. Mesh size and bar thickness combination experiments

A total of 60 hauls were used in the analysis of the mesh size and bar thickness combination experiments, 30 from 1998 and 30 in 1999 (Table 6). The catches in each bag varied from 46 to 2100 kg between hauls, and the mean catch sizes were about 400 kg for both the codend and the cover-bag in 1998 and about 900 kg in the codend and 400 kg in the cover-bag for 1999.

The catches in the 1998 experiments consisted mostly of blue whiting, Norway pout, saithe, mackerel and haddock, while the catches in the 1999 experiments consisted mostly of Norway pout, blue whiting, haddock, saithe and herring (Table 7). About 100% of the bycatch species saithe, cod, ling, hake, mackerel, whiting and tusk, and the target species horse mackerel were sorted out during the 1998 experiments. The same species were sorted out almost 100% during the 1999 experiments, except whiting that mainly consisted of smaller individuals that season. The catch of the species sorted out consisted almost exclusively of fish larger than 25 cm. These species, except whiting, were not included in the further analysis.

During the 1998 experiments a total of 94.6% (weight) of the bycatch species were sorted out and there was a loss of target species of 32.8%. In the 1999 trials, 62.4% of the bycatch species were sorted out and there was a loss of target species of 22%. For both surveys combined, a total of 78.5% of the bycatch species were sorted out and there was a loss of 26.4% of the target species.

The pout caught during the 1999 experiments were considerably smaller compared to the pout caught in 1998 (Fig. 5a

Table 5
Estimated mean selectivity parameters for haddock for each grid with different space between bars

Estimated parameter	Bar space	Estimate	S.D.	No. of hauls	d.f.	p-Value
Intercept (L50%)	19	18.51	0.473	4	3	<0.05
	22	20.96	0.555	17	32	<0.05
	25	22.43	3.612	2	1	0.1017
Intercept (SR)	19	2.66	0.382	4	3	<0.05
	22	4.56	0.467	17	32	<0.05
	25	9.22	2.781	2	1	0.1865

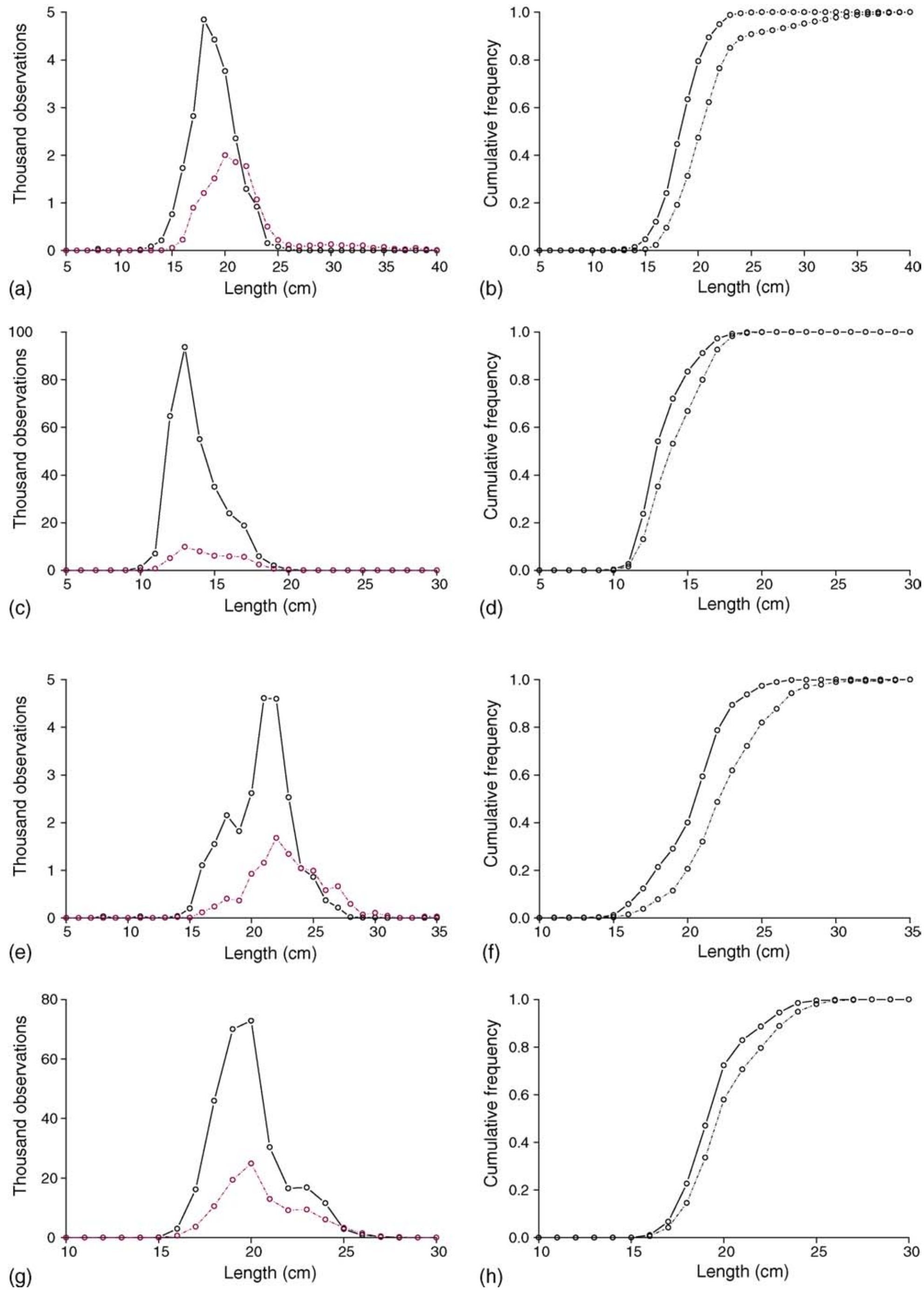

Fig. 3. Length distribution and cumulative frequency distribution for the four main species in the 1997 experiment: (a and b) haddock; (c and d) Norway pout; (e and f) argentine; (g and h) blue whiting. Continuous curves, codend; broken curves, cover-bag. All data combined.

and c). There was a significant difference between the length distributions in the codend and cover-bag for both of these trials (Table 8; Fig. 5b and d). The Argentine caught in 1998 was between 11 and 23 cm long, with maximums at 13 and 19 cm (Fig. 5e). There was a significant difference between the length distribution in the codend and the cover-bag (Table 8; Fig. 5f). During the survey in 1999 most of the Argentine were individuals between 14 and 20 cm and almost all individuals were caught in the codend (Fig. 5g). In our samples there were just found a total of 25 individuals from the cover-bag, and the KS-test shows no difference between the length distributions (Table 8; Fig. 5h). The blue whiting caught during the 1999 cruise were considerably smaller than the blue whiting caught during the 1998 experiments (Fig. 5i–l). There was a significant difference between the length distributions in the codend and the cover-bag for both surveys (Table 8). In the 1998 sur-

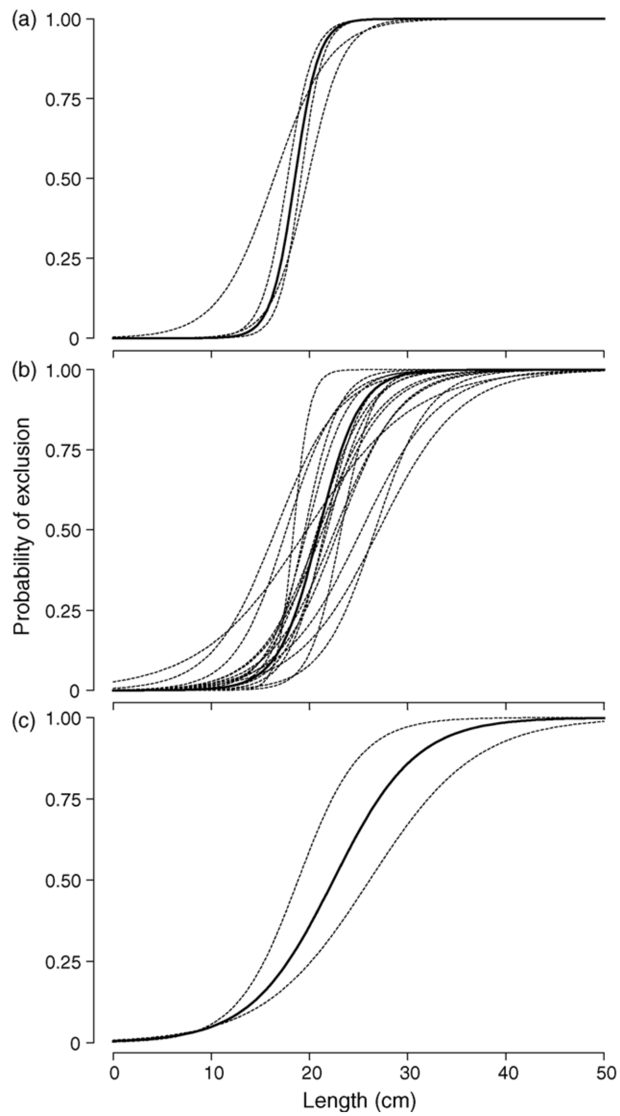

Fig. 4. Selectivity curves for each haul and estimated mean selectivity curve (solid line) for each grid: (a) 19 mm bar space, (b) 22 mm bar space and (c) 25 mm bar space.

vey most of the haddock had a length distribution from 14 to 35 cm (Fig. 5m). No haddock above 24 cm were caught in the codend. During the 1999 survey the haddock caught were considerably smaller (Fig. 5o). There was a significant difference between the length distributions in the codend and the cover-bag for both surveys (Table 8; Fig. 5n and p). The whiting caught in the 1998 survey consisted exclusively of relatively large individuals of lengths above 25 cm (Fig. 5q). Approximately 100% of these large individuals were sorted out and into the cover-bag and there was only caught a total of 12 individuals in the codend. The KS-test shows no significant difference between the length distributions in the codend and the cover-bag (Table 8). During the 1999 experiments the whiting caught were considerably smaller (Fig. 5s) and the KS-test shows a significant difference between the length distributions (Table 8).

3.3. Selection results from mesh size and bar thickness combination experiments

For the two last experiments, haddock was the only species analysed for selectivity parameters. Both experiments indicated a relatively sharp selection of haddock in the grid system (Table 9; Fig. 6). There was a larger variation in the selectivity parameters during the 1999 trials than during the 1998 experiments (Table 9). Standard deviation in the estimated mean selection curves (Fig. 6) indicates the same, with larger standard deviation both for the L50% and the SR for the haddock 1999 data compared with 1998.

3.4. Differences between the configurations

Significant differences in SR between the 10 mm and the 24 mm mesh were found during the 1998 cruise. The 15 mm grid and the 24 mm mesh size were used as "ground level", which means that a *p*-value of 0.007 in "10 mm mesh (SR)" signifies a significant difference between the 10 mm and the 24 mm mesh size in SR, and that the estimated SR is 1.168 cm larger for the 10 mm mesh size (SR = 5.10 cm) than for the 24 mm mesh (SR = 3.94, Table 10). Selectivity curves are presented in Fig. 9. There was no difference in the L50% between the two mesh sizes, but a significant difference between the 5 mm bar and the two others (10 and 15 mm) in L50%. For the 1998 survey there is estimated one SR for the 10 mm and the 24 mm mesh size, independent on the thickness of the bars, one L50% (=17.98 cm) for the 5 mm bar independent on the mesh size in the grid section, and one common L50% for the 15 mm and the 10 mm bar (=19.44 cm) also independent of the mesh size. No significant differences were found between the six combinations during the 1999 trials, and thus only one common SR and L50% for all combinations is estimated (Table 10; Fig. 7).

Informal plot's to reveal any two-way interactions between configurations indicated a very small or almost no such interactions (Fig. 8).

The differences between the mean lengths of the distributions obtained for each of the mesh/grid combinations were significant (Table 11), but small (Fig. 9). This implies that all experiments were carried out sampling from rather similar size compositions.

3.5. Flow measurements

Fig. 10 gives differences in speed of water behind the grid, with nearly a 20% difference in maximum speed of the water flow behind the grid with 15 mm bar thickness and the 5 mm grid, and the 10 mm grid in between. The difference between the mesh sizes is also shown, with speed highest in the middle and decreasing rapidly to the top and the bottom for the 24 mm mesh-size codend, while the 10 mm mesh codend had a more uniform water flow from the top to the bottom, decreasing when close to the net panel. The explanation for this difference is that the 24 mm mesh-size extension piece was more

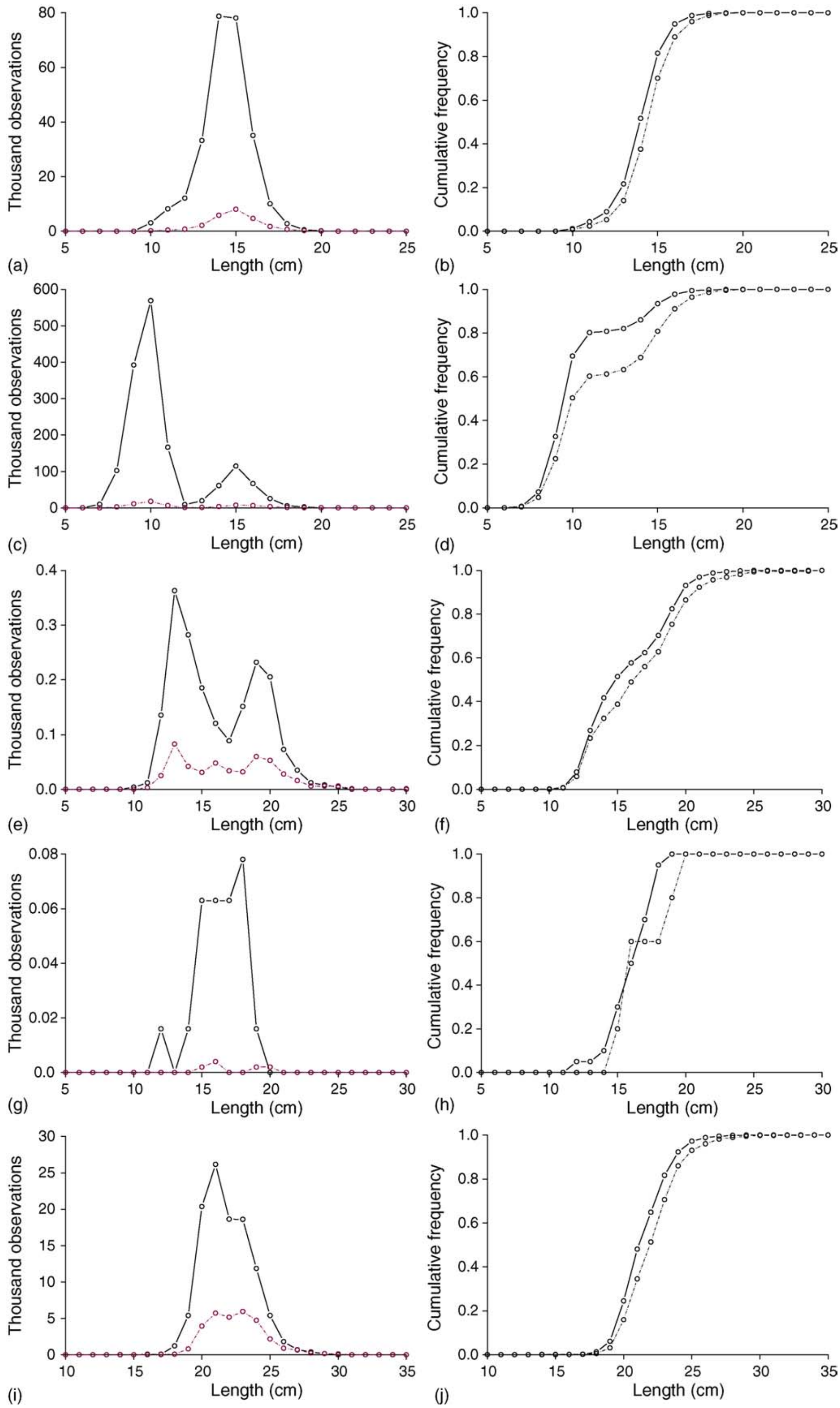

Fig. 5. Length distribution and cumulative frequency of the distribution in the cover-bag and the codend. (a and b) Norway pout 1998; (c and d) Norway pout 1999; (e and f) argentine 1998; (g and h) argentine 1999; (i and j) blue whiting 1998; (k and l) blue whiting 1999; (m and n) haddock 1998; (o and p) haddock 1999; (q and r) whiting 1998; (s and t) whiting 1999.

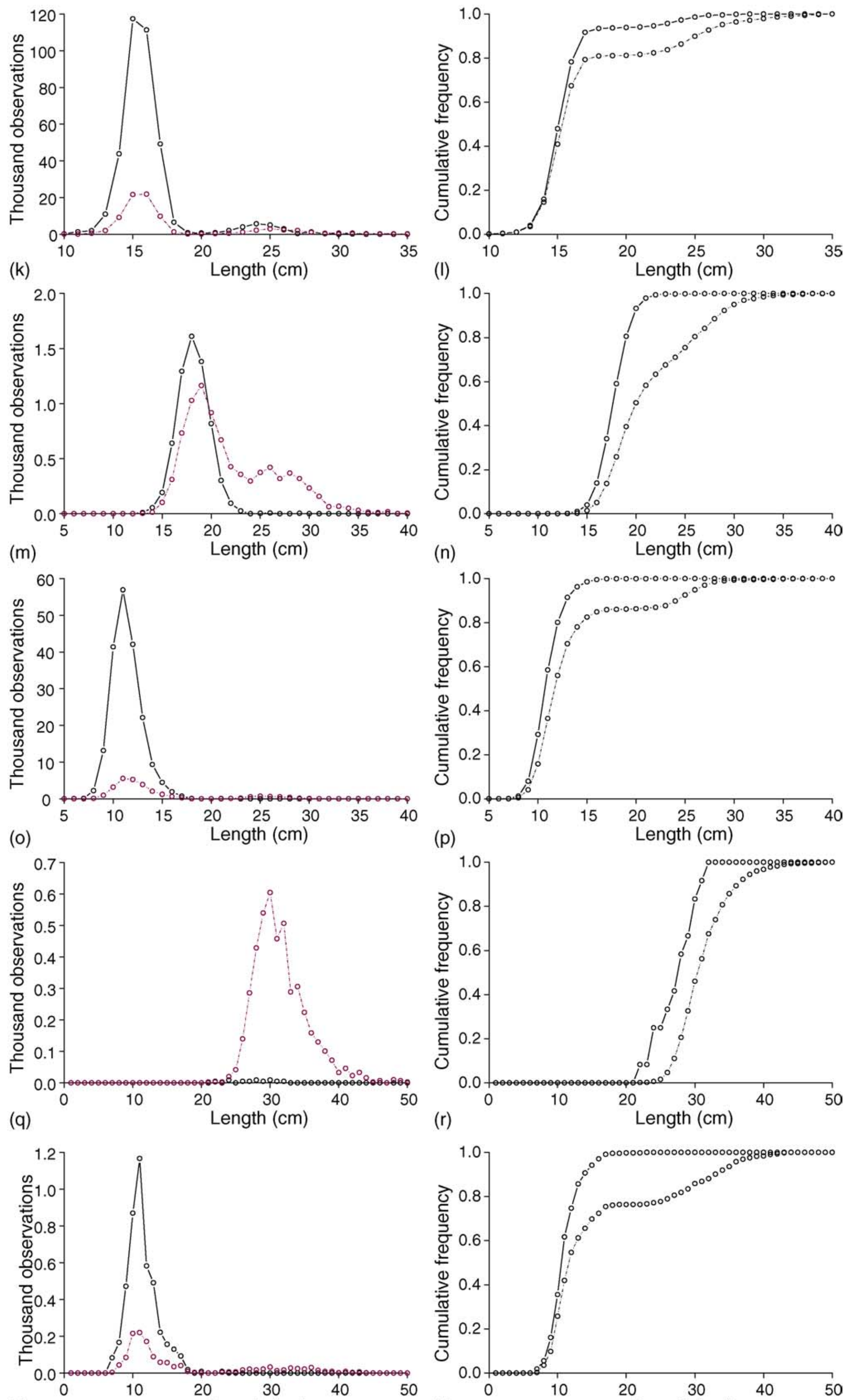

Fig. 5. (*Continued*).

Table 6
Combination of thickness of bars in the grid and mesh size in the extension piece, and total catch in the codend and the cover-bag for all hauls during the 1998 and 1999 trials

Haul no.	Thickness of bar (mm)	Mesh size (mm)	Catch 1998 (kg)			Catch 1999 (kg)		
			Codend	Cover-bag	% Sorted out	Codend	Cover-bag	% Sorted out
1	5	10	106	129	54.9	541	281	34.2
2	5	10	203	112	35.6	385	230	37.4
3	5	10	183	150	45.0	1663	967	36.8
4	5	10	195	197	50.3	350	350	50.0
5	5	10	71	91	56.2	385	115	23.0
6	10	10	342	224	39.6	1645	140	7.8
7	10	10	211	160	43.1	1995	1317	39.8
8	10	10	212	294	58.1	595	697	53.9
9	10	10	272	183	40.2	1015	686	40.3
10	10	10	342	169	33.1	875	507	36.7
11	15	10	170	161	48.6	980	297	23.3
12	15	10	285	310	52.1	630	171	21.3
13	15	10	108	388	78.2	805	132	14.1
14	15	10	105	162	60.7	490	510	51.0
15	15	10	203	145	41.7	980	456	31.8
16	5	24	205	162	44.1	945	475	33.5
17	5	24	349	228	39.5	1505	295	16.4
18	5	24	389	1446	78.8	210	163	43.7
19	5	24	423	407	49.0	700	297	29.8
20	5	24	616	469	43.2	700	414	37.2
21	10	24	340	474	58.2	1295	904	41.1
22	10	24	49	147	75.0	525	135	20.5
23	10	24	211	628	74.9	770	248	24.4
24	10	24	46	246	84.2	945	253	21.1
25	10	24	114	148	56.5	910	227	20.0
26	15	24	1795	460	20.4	1645	410	20.0
27	15	24	1300	649	33.3	455	154	25.3
28	15	24	1193	1992	62.5	2100	334	13.7
29	15	24	240	1106	82.2	1610	512	24.1
30	15	24	1994	509	20.3	1190	586	33.0
Total			12272	11946	49.3	28839	12263	29.8
Mean			409	398	49.3	961	409	29.9

Bar distance 22 mm.

stretched than the 10 mm mesh, resulting in a much smaller effective diameter of the extension piece in front of the grid (Fig. 11).

4. Discussion

Dickson (1960) and Bailey et al. (1983) found no difference in behaviour that could be used to separate Norway pout from food species in industrial trawling in the North Sea. Wileman and Main (1994) concluded that there was evidence only of size selection, not of species selection, when using different devices to try to separate herring, whiting and haddock from Norway pout. Wileman and Main (1994) experienced handling problems with their grid and few fish passed through it, but grids are today used in many other fisheries (Isaksen and Valdemarsen, 1994). Grids are used to expel sea turtles and jellyfish (Kendall, 1990) and to reduce the by-catch of fish in shrimp trawl fisheries (Isaksen et al., 1992). Inclined netting panels at the codend mouth have been tested to divert fish to escape through outlet openings (Karlsen, 1981), but rigid grids, notably the Nordmøre grid, are more effective and robust (Isaksen et al., 1992).

Although the initial aim in applying grids was to separate species of widely differing sizes, it was found that grids could also separate a single species by size. A second generation of grids was made to increase size selection in bottom trawl fisheries for gadoids (Larsen and Isaksen, 1993). Grids are today mandatory to increase the size selectivity in the bottom trawl fishery for cod and haddock in the Barents Sea. An efficient selection is attained by the use of different grid systems in this fishery.

The idea behind the present study was that the efficient and sharp size selection attained by selection grids may also be used to increase the species selection by separating small target species from larger bycatch species. The basic principle of our grid system, which fills the net in front of the codend, is that all individual fish caught must encounter the grid and

Table 7
Species distribution in the total catch and distribution in catch between codend and cover-bag from 1998 and 1999 trials (loss of target species (%) and percentage sorted out of bycatch species is shown)

Species	1998			1999		
	Codend (kg)	Cover-bag (kg)	Sorted out/loss (%)	Codend (kg)	Cover-bag (kg)	Sorted out/loss (%)
Target species						
Norway pout	6017.5	615.2	9.28	14807.3	925.7	5.9
Blue whiting	8620.4	2950.2	25.5	10272.2	2792.9	21.4
Argentine	139.5	100.2	41.8	99.9	27.9	21.8
Silvery pout	104.9	3.1	2.9	106.0	3.3	3.1
Horse mackerel	0.5	340.9	99.9	0	88.2	100
Bycatch species						
Haddock	429.7	1159.5	73.0	3023.1	1006.4	25
Saithe	0	5672.4	100	0	3906.1	100
Whiting	10	1098.5	99.1	64.0	116.0	64.5
Cod	2.9	577.5	99.5	3.5	57.8	94.3
Ling	1.3	188.7	99.3	0	21.5	100
Hake	0.5	34.5	98.7	0	21.4	100
Mackerel	67.4	2092.3	96.9	0	531.0	100
Herring	61.4	139.6	69.5	361.7	2759.0	88.4
Tusk	0.5	13.3	96.7	[a]	[a]	[a]

[a] No individuals caught.

Table 8
Result from two-sample Kolmogorov–Smirnov test between length distribution in cover-bag and codend in 1998 and 1999

Data	*p*-Value	KS	*n* (codend)	*n* (cover-bag)
Norway pout 1998	<0.05	0.1409	5400	4641
Norway pout 1999	<0.05	0.1995	5088	4262
Argentine 1998	<0.05	0.1265	494	325
Argentine 1999	0.6638	0.3500	20	5
Blue whiting 1998	<0.05	0.1360	2814	2556
Blue whiting 1999	<0.05	0.1298	2709	3680
Haddock 1998	<0.05	0.4313	1771	3076
Haddock 1999	<0.05	0.2421	4497	5883
Whiting 1998	0.0658	0.3776	12	1385
Whiting 1999	<0.05	0.2509	483	622

n is number of individuals measured for length in codend and cover-bag.

be selected (Anon., 1999). The grid is mounted with the bars running fore and aft rather than across the net. This makes it easier for small fish to pass through and helps fish that do not approach the grid to slide to the outlet on top of the grid. The efficiency of the selection depends on the angle of the grid to the water flow and the water speed through the grid. The angle must be tuned to the application in order to optimise selection. Too steep an angle traps fish against the bars and hinders passage to the fish outlet, while too shallow an angle makes it difficult to pass through the bars, reduces selection and increases losses of target species.

The final mounting of our grid system was based on the preliminary experiments during the 1997 survey. The angle of the grid was chosen based on the experience with the Nordmøre grid, which is used in the shrimp trawl fishery (Isaksen et al., 1992), but the angle is steeper due to the large amount of relatively passive target, which must hit the grid to be selected. The guiding panel was chosen so that to force the fish a relatively long way down the grid, to increase the possibility that individuals come into contact with the grid. An individual too big to pass between bars has to follow the grid to the top to go out the outlet, and before it reaches the top it will probably come in contact with the grid because of the water flow through the grid. The bar spacing was chosen partly by considering the numbers of bycatch species sorted out, and the loss of target species, with the aim to sort out as much as possible of the main bycatch species haddock, while minimising loss of target species. Consequently, the selectivity parameters for haddock are also important for the choice of bar spacing.

The video-observations were checked for indications of differences in behaviour that could be used for species

Table 9
Estimated L50% and SR for haddock (all data combined for each survey)

Data	Estimated parameter	Estimate	S.D.	No. of hauls	d.f.	*p*-Value
Haddock 1998	Intercept (L50%)	18.97	0.299	30	56	<0.05
	Intercept (SR)	4.33	0.210	30	56	<0.05
Haddock 1999	Intercept (L50%)	18.34	0.657	30	58	<0.05
	Intercept (SR)	6.49	0.391	30	58	<0.05
Both surveys combined	Intercept (L50%)	18.21	0.304	60	118	<0.05
	Intercept (SR)	5.48	0.227	60	118	<0.05

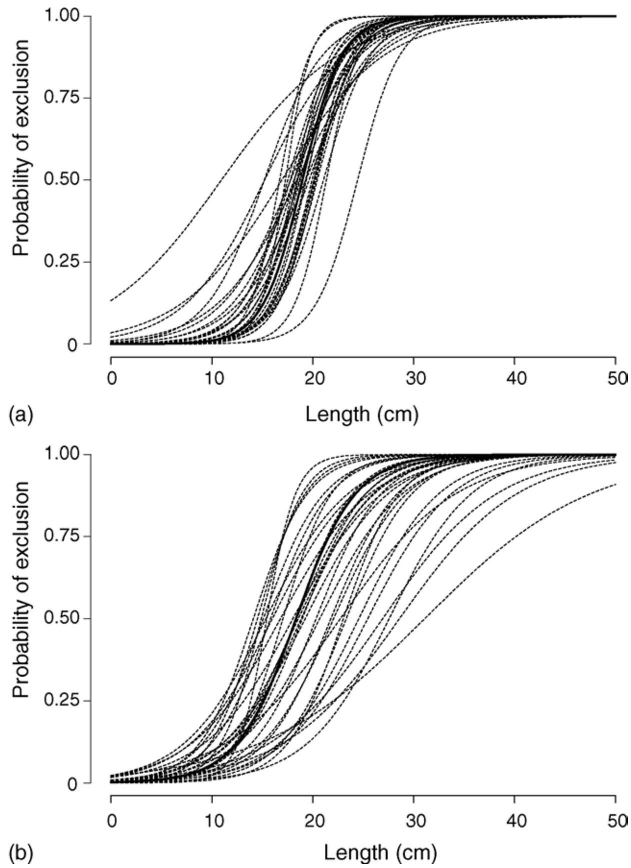

Fig. 6. Selection curves for haddock from 1998 and 1999 trials. The solid line is the estimated mean selection curve for the cruise.

separation, but no such indications were found. However, the size selection induces a high degree of species selection. About 100% of the large bycatch species saithe, cod, ling, hake and tusk were sorted out during the 1998 and 1999 surveys. These were mostly individuals longer than about 30 cm, and were too large to pass through the bars in the grid. The grid sorted out almost all the whiting larger than 24 cm in the 1998 survey, but few of the smaller whiting in 1999. About 100% of the haddock above 24 cm (and most of those just below 24 cm) were sorted out during the 1998 survey. During the 1999 survey, only a marginal proportion of the small haddock were sorted out. These findings indicate that the grid sorts out almost all individuals of the most common species longer than about 24 cm.

The main disadvantage using a grid in this fishery is the loss of target species. For Norway pout this amounted to about 9% in 1998 and about 6% in 1999. Seen in the light of the recent decline in the biomass of the gadoid stocks in the North Sea (Anon., 2004), such a loss of the target species is acceptable when the purpose of the grid system is to reduce the bycatch of overexploited gadoids as cod, haddock and saithe. Nevertheless, a loss of up to 26% of blue whiting which was the case in the 1998 survey, will be more difficult to get acceptance for. But if the purpose of the fishery is to catch Norway pout, then such a reduction of bycatch should be acceptable if necessary for being allowed to conduct the fishery. In some areas at some times of year, blue whiting is the main target species, and during the 1998 survey more blue whiting was caught than Norway pout. But then the fishery should possibly shift to aim for blue whiting as the target species. This is very relevant with the present stock situation in the North Sea with the Norway pout population at a historically low level. For 2005 ICES recommended a zero catch of Norway pout (Anon., 2004), and EU and Norwegian fishery regulating authorities agreed to a small bycatch quantity of Norway pout only, and on no direct fishery for this species. A directed fishery for blue whiting in the North Sea should be carried out with trawls with larger mesh size in the bag than allowed for the Norway pout fishery, and possibly with a dedicated grid system to sort out bycatch of other, larger fishes.

The length distribution for blue whiting indicated that the losses were roughly the same both for the small individuals caught in 1999 and for the larger individuals caught in 1998. Blue whiting has a thin body so that long individuals (around 24–25 cm) are not sorted out as efficiently as for example whiting of the same length. Herring, mackerel and horse mackerel were almost completely sorted out by the grid; nearly all of them were longer than 26 cm. This indicates that when using a grid with 22 mm bar space one does not catch these species. Neither is it possible to catch these species without catching larger individuals of other human consumption species. Experiments with sorting grids with 38–44 mm bar space have been carried out to try to increase the size selectivity in mackerel trawl and purse seine (Beltestad and Misund, 1993; Misund and Beltestad, 1994; Kvalsvik et al., 2002). There was also a relatively big loss of argentine, and a very small loss of silvery pout, but the catches of these target species were small.

Table 10
Significant results from EC-Model (Constat, 1999), testing for differences between the six combinations of bar thickness in the grid and mesh size in the grid section

Data	Estimated parameter	Estimate	S.D.	d.f.	*p*-Value
Haddock 1998	Intercept (L50%)	19.44	0.344	56	<0.05
	Intercept (SR)	3.936	0.218	56	<0.05
	5 mm bar (L50%)	−1.46	0.595	56	<0.05
	10 mm mesh (SR)	1.168	0.417	56	<0.05
Haddock 1999	Intercept (L50%)	18.38	0.670	58	<0.05
	Intercept (SR)	6.531	0.398	58	<0.05

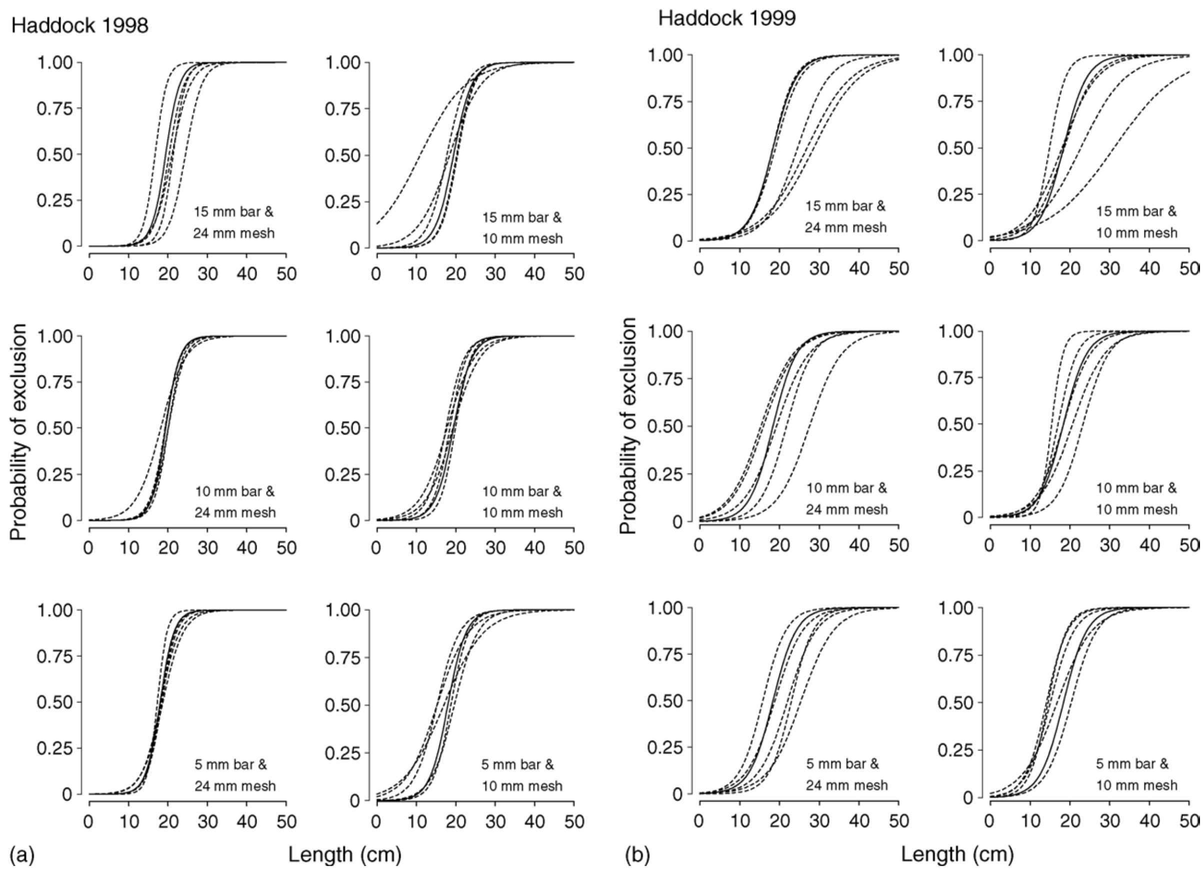

Fig. 7. Selectivity curves and estimated selectivity curve (solid line) for all combinations from both surveys.

Haddock is the main bycatch species in this fishery, and it was the only species caught in large enough numbers to calculate selectivity parameters for all hauls. Therefore, haddock was the only species analysed for selectivity parameters in this study. The size selection of haddock during the 1998 survey was sharp. The somewhat wider selection range during the 1999 survey seems to be due to smaller haddock being available this year.

An understanding of the water flow inside the selection devices allows for the determination of the optimum designs for the device so as to efficiently reduce bycatch without reducing the catch of target species (Riedel and DeAlteris, 1995). The ideal configuration of a grid system will therefore be a construction that minimally distorts the water flow through it. This would increase the probability that small target species, having a poor swimming ability compared

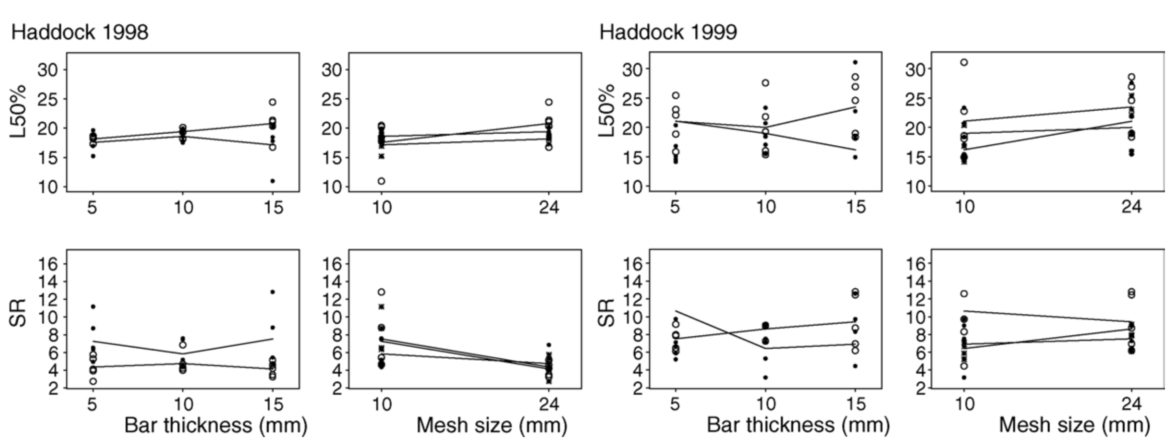

Fig. 8. Two-way interaction plots for L50% and SR for bar thickness in the grid and mesh size in the grid-section/extension piece. For the bar thickness plot: ● = 10 mm mesh size; ○ = 24 mm mesh size. For the mesh size plots: ✱ = 5 mm bar thickness; ● = 10 mm bar thickness; ○ = 15 mm bar thickness. The lines are plotted between mean values for each bar thickness/mesh size.

Table 11
Testing for differences in mean lengths of the distributions for each combination (ANOVA)

Combination		Haddock 1998			Haddock 1999		
Mesh size (mm)	Bar (mm)	Mean length (cm)	*n*	ANOVA	Mean length (cm)	*n*	ANOVA
10	5	20.330	993		12.885	1546	
10	10	21.406	648	$F(5, 4841) = 31.56$	14.329	2682	$F(5, 10374) = 38.04$
10	15	21.187	721		12.979	1484	
24	5	21.251	840		12.835	1316	
24	10	20.695	1071	$p < 0.05$	13.074	1717	$p < 0.05$
24	15	23.073	574		13.403	1635	

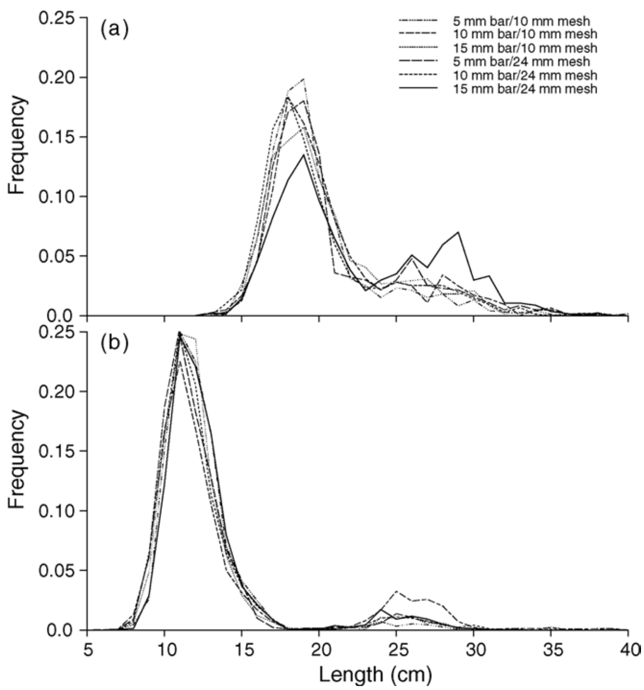

Fig. 9. Length distribution of haddock caught during the testing of each grid/mesh combination during both surveys—(a) 1998 and (b) 1999.

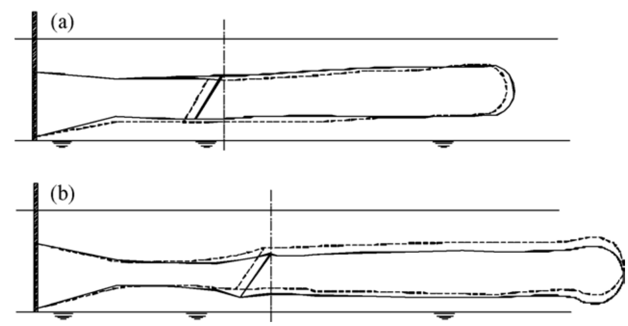

Fig. 11. Shape of the grid section for (a) the extension piece with 10 mm meshes and (b) the extension piece with 24 mm mesh size.

to larger fish (Wardle, 1977), should follow the water flow through the grid. The experiments carried out in the flume tank revealed a 20% difference in maximum water speed behind the grid with 15 and 5 mm bar thickness. Tests were carried out to check if this difference in water flow might influence the selectivity parameters of haddock. When testing for differences in selectivity parameters between the six grid/mesh combinations a significant difference in L50% was found between the 5 mm bar and the two thicker bar sizes independent of the mesh sizes used.

An L50% of 18 cm was estimated for the 5 mm bar compared to 19.4 cm for the 10 and the 15 mm grids, indicating that larger individuals are more effectively sorted through the grid when using the grid with the highest flow of water. This finding does not support our hypothesis that smaller fish, having a poorer swimming ability (Wardle, 1977), should be more effectively sorted through the grid with the highest value of water flow. The change in L50% may be a result of difference in behaviour between different sizes of fish when trying to avoid the grid when sensing different values of water flow.

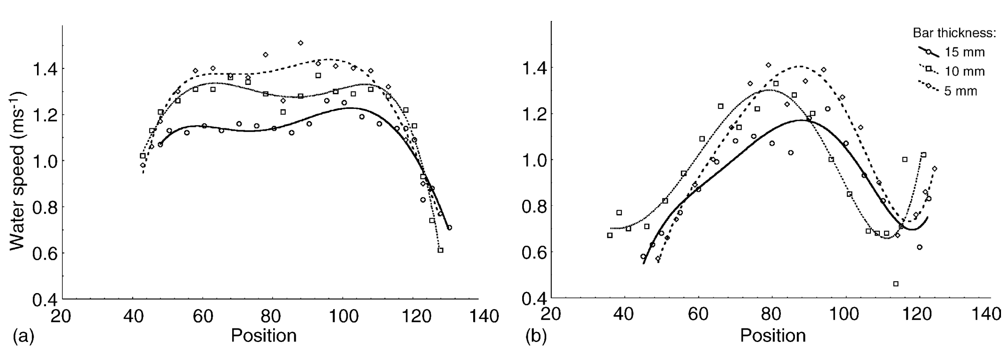

Fig. 10. Speed of water (m s^{-1}) in a vertical line from top (position 140) to the bottom (position 20) measured behind the grid. (a) 10 mm meshed extension piece and (b) 24 mm meshed extension piece. Water speed into the grid section is 1.53 m s^{-1} $\approx$ 3 knots.

A distinct difference in SR was found between the two mesh sizes in the 1998 experiment, independent of the bar thickness in the grid being used, with an SR of 5.1 cm for the extension piece with 10 mm meshes and a smaller SR of 3.9 cm for the 24 mm extension piece. No differences in selectivity parameters were found between the combinations during the 1999 survey. This might be due to the relatively high variance in the selectivity parameters estimated for each haul because of a large amount of small haddock caught during this survey. The estimated curve for the 1999 catches of haddock does not have a good fit to the selection curves for each haul for all combinations of grid/mesh.

There were no clear two-way interactions between the configurations of mesh size and bar thickness, indicating that a change in mesh size in the grid section has no significant effect on the selectivity. However, the ANOVA results presented in Table 11 show that there were significant differences between the mean values of the length distribution for each of the grid/mesh combinations. This implies that the testing of the six combinations was not carried out sampling from the same size composition. But as shown in Fig. 9 the differences were small, and the size compositions rather similar.

In practical terms these differences in selection characteristics between the mesh size and bar thickness combinations are small and almost of no significance when constructing grid systems for size and species separation in Norway pout trawls. The change in mesh size in the extension piece where the grid is mounted has no or a very small effect on the selectivity. There are indications of an effect when using thinner bars that have an increased water flow through the grid, and this may have an effect when separating species or fish sizes with different swimming capability. But the change may also be a result of this grid having a larger effective area where individual fish can go through the grid.

The results from these experiments supports Dickson (1960) and Bailey et al. (1983) who found no difference in behaviour that could be used to separate these species. The results also support Wileman and Main (1994) who concluded that there was evidence only of size selection, not of species selection. However, by the use of known grid selection technology, a grid system that employs efficient size selection has been used to separate small target species from larger bycatch species. The grid system effectively sorted out large human consumption species, but it did not always manage to sort out small individuals of these species.

The loss of target species was probably acceptable for Norway pout but probably to high for blue whiting. It is possible to reduce the loss of target species by making a grid with larger bar spacing. A negative effect of using a larger bar space would be that the separation of target and bycatch species will be reduced and larger bycatch species will be caught. If a grid system is to be used in this fishery, the challenge will be to find the bar spacing with the best balance between sorting out bycatch species and loss of target species. It is also likely that different bar spacing should be used at different times of year and in different areas.

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References

Anon., 1996. Manual of Methods of Measuring the Selectivity of Towed Fishing Gears. ICES Coop. Res. Rep. 215, 126 pp.

Anon., 1999. Selection Grids. Information Leaflet 4 – Capture and Conservation – Fisheries Research Services. Aberdeen, 2 pp.

Anon., 2004. Extract of the Report of the Advisory Committee for Fishery Management, Book 2. ICES, Copenhagen, 472 pp.

Bailey, R.S., Galbraith, D., Hutcheon J.R., Walsh, M., 1983. Experimental Fishing for Norway Pout using a Horizontally-Divided Trawl. ICES CM 1983/G:60.

Beltestad, A., Misund, O.A., 1993. Sorting of mackerel by grids in purse seines and trawls. FiskenHav (8).

Bergstad, O.A., 1990. Ecology of the fishes of the Norwegian Deep: distribution and species assemblages. Neth. J. Sea Res. 25, 237–266.

Christensen, V., Guénette, S., Heymans, J.J., Walters, C.J., Watson, R., Zeller, D., Pauly, D., 2003. Hundred-year decline of North Atlantic predatory fishes. Fish Fisheries 4, 1–24.

Constat, 1999. EC Model Help Module. http://www.constat.dk.

Dickson, W., 1960. The problem of headline height. World Fishing 9 (9), 38–48.

Fryer, R.J., 1991. A model of between-haul variation in selectivity. ICES J. Mar. Sci. 48, 281–290.

Gagnon, P., 1992. The Analysis of Comparative Trawl Selectivity Experiments. CAFSAC Research Document 92/120, 13 pp.

Isaksen, B., Valdemarsen, J.W., Larsen, R., Karlsen, L., 1992. Reduction of fish bycatch in shrimp trawl using a rigid separator grid in the aft belly. Fish. Res. 13, 335–352.

Isaksen, B., Valdemarsen, J.W., 1994. Bycatch reduction in trawls by utilizing behaviour differences. In: Fernø, A., Olsen, S. (Eds.), Marine Fish Behaviour. Fishing News Books. Blackwell Science Ltd., Oxford, pp. 69–83.

Jones, R.H., 1993. Longitudinal Data with Serial Correlation: A State-Space Approach. Chapman and Hall, London, 225 pp.

Karlsen, L., 1981. Forsøk med sorteringsnett i reketrål i tidsrommet 1975–1978. FTFI Report, April (in Norwegian).

Kendall, D., 1990. Shrimp retention characteristics of the Morrison soft TED: a selective webbing exclusion panel inserted in a shrimp trawl net. Fish. Res. 9, 13–21.

Kvalsvik, K., Misund, O.A., Engås, A., Gamst, K., Holst, R., Galbraith, D., Vederhus, H., 2002. Size selection of large catches: using sorting grid in pelagic mackerel trawl. Fish. Res. 59, 129–148.

Lahn-Johannesen, J., Jakupstovu, S.H., Thomassen, T., 1978. Changes in the Norwegian mixed fisheries in the North Sea. Rapp. Proc.-V. Réun Cons. Int. l'Explor. Mer 172, 31–38.

Laird, N.M., Ware, J.H., 1982. Random effects models for longitudinal data. Biometrics 38, 963–974.

Larsen, R.B., Isaksen, B., 1993. Size selectivity of rigid sorting grid in bottom trawls for Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). ICES Mar. Sci. Symp. 196, 178–182.

McCullagh, P., Nelder, J.A., 1989. Generalized Linear Models, second ed. Chapman and Hall, London, 511 pp.

Main, J., Galbraith, R.D., 1990. A review of research into species separation with particular reference to Norway pout (*Trispoterus esmarkii*). Scott. Fish. Work. Pap. 14/90. Department of Agriculture and Fisheries for Scotland.

MathSoft, 1999. S-PLUS 2000 User's Guide. Data Analysis Products Division. Mathsoft, Seattle, WA.

Millar, R.B., 1991. Estimation of Asymmetric Selection Curves for Trawls, ICES CM 1991/B:56.

Millar, R.B., 1992. Estimating the size-selectivity of fishing gear by conditioning on the total catch. J. Am. Stat. Assoc. 87 (420), 962–968.

Misund, O.A., Beltestad, A., 1994. Size-Selection of Mackerel and Saithe in Purse Seine. ICES C.M. 1994/B:28.

Myers, R., Worm, B., 2003. Rapid worldwide depletion of predatory fish communities. Nature 423, 280–283.

Pauly, D., Christensen, V., Guénette, S., Pitcher, T.J., Sumaila, U.R., Walters, C.J., Watson, R., Zeller, D., 2002. Towards sustainability in world fisheries. Nature 418, 689–695.

Riedel, R., DeAlteris, J., 1995. Factors affecting hydrodynamic performance of the Nordmøre Grate System: a bycatch reduction device used in the Gulf of Maine shrimp fishery. Fish. Res. 24, 181–198.

StatSoft, 1995. STATISTICA for Windows (Computer Program Manual). StatSoft, Inc., 2325 East 13th Street, Tulsa, OK 74104. Tel.: +1 918 583 4149; fax: +1 918 583 4376.

Wardle, C.S., 1977. Effects of size on the swimming speeds of fish. In: Pedley, T.J. (Ed.), Scale Effects in Animal Locomotion. Academic press, New York, pp. 299–313.

Wileman, D.A., Main, J., 1994. Attempts to Develop a Species Selective Trawl for Fishing Pout. ICES CM 1994/B:94.