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Size selection of large catches: using sorting grid in pelagic mackerel trawl

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Abstract

Two sorting grid systems with three different bar spacings for size selecting mackerel in pelagic trawls have been tested during four surveys. In the mackerel fishery, the value of the catch depends on fish size; the largest mackerel are priced substantially higher than the smaller fish. Using a grid-selection system to improve size selection in this fishery would therefore increase fishermen's income. Between 8 and 51% of each catch was sorted during 12 hauls, with catch weights ranging from less than 300 kg to more than 170 000 kg. There were significant differences in individual mean weight between mackerel that passed through the grid and mackerel retained in the codend in all hauls as a result of the reduction in the proportion of mackerel below 400 g, and an increase in the mackerel above 600 g. Using 1999 prices as the standard, grid selection increased the value of these hauls from 8 to 18%. Selectivity parameters are presented for all hauls and show that the sorting grid delivered a reasonably sharp size selection in all hauls. Four different models are presented to explore the selection data, and possible influence of catch size on selectivity parameters is tested. Data on grid angle and water flow through the grid are presented from four hauls.

Keywords: Mackerel; Size selection; Grid selection; Large catches; Pelagic trawl

1. Introduction

Atlantic mackerel (*Scomber scombrus* L.) are fished by modern and efficient fleets of pelagic trawlers and purse seiners. Since the end of the 1980s, the mackerel fishery has changed from an industrial to a human consumption fishery. Mackerel are nowadays priced at a very high level, and the mackerel fishery is one of today's most profitable fisheries in the northeast Atlantic.

Although most of the mackerel caught are larger than the legal minimum length, a considerable size-differentiated price is a compelling economic reason why size sorting of mackerel catches is of substantial interest. Mackerel below 400 g (G4−) are worth least, while mackerel above 600 g (G6+) achieve the highest price. Therefore, there is a monetary incentive for the fishermen to employ methods to increase the proportion of fish above 600 g in the catches.

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Table 1
Mean prices (NOK) paid for mackerel landings in Norway from Norwegian Fishermen's Sales Organisation for Pelagic Fish

Year	Norwegian fishing vessels				Foreign fishing vessels			
	G6+	G4–6	G4−	Mean[a]	G6+	G4–6	G4−	Mean[a]
1996	11.31	8.73	4.49	8.23	6.55	4.91	3.41	4.95
1997	14.33	9.04	3.81	9.06	10.13	7.17	3.46	6.95
1998	9.70	5.65	2.99	6.07	13.36	8.15	4.12	8.50
1999	8.79	5.27	2.74	5.57	8.11	3.73	2.04	4.54

[a] Average price assuming 30% G6+, 40% G4–6 and 30% G4−.

Prices paid for landings in Norwegian ports in the period 1996–1999 are presented in Table 1. The difference in price between Norwegian catches and foreign catches is due to different catching methods, seasons and markets for the fish. In Norway, mackerel are landed from August to February. The Norwegian fleet take their catches by purse seine from August to November. Vessels from Britain deliver catches of mackerel taken by pelagic trawl in the northern North Sea mostly in the period November–February. Mackerel caught by purse seine have usually been worth more than trawl-captured mackerel, but the difference has decreased, and in 1998 the trawl-captured mackerel delivered by foreign fishing vessels obtained a higher price than those caught by purse seine.

The price differentiation developed with the change to a human consumption fishery, and in the early 1990s, there were rumours that fishing vessels used mechanical sorting devices onboard and discarded the smallest fish with the lowest value. The regulation of the fishery has been improved, but there is still a demand for more size-selective fishing equipment.

During the period 1992–1996, selectivity experiments using a rigid sorting grid in purse seines were carried out (Misund and Beltestad, 1994). The selection results were good, but post-capture survival experiments showed that the size-selection process induced too high a mortality to justify the use of the selection method in commercial fishing (Beltestad and Misund, 1996; Misund and Beltestad, 2000).

Preliminary experiments using a sorting grid in mackerel trawls have been carried out (Beltestad and Misund, 1993). The sorting grid was constructed in the same manner as a grid tested in a bottom trawl for cod (Larsen and Isaksen, 1993), today known as the Sort-X system, but was designed as a single grid in three articulated parts. The results showed that 19% of the fish below 600 g were sorted out. The experiments were not followed up because most of the Norwegian mackerel quota was fished by purse seine. In the autumn of 1997, a Norwegian trawl manufacturer (Br. Selstad AS), requested the Institute of Marine Research to initiate experiments with a size-selective mackerel trawl for foreign customers. The experiments were started in December 1997 and continued until 1999; three surveys were conducted to test the prototype grids, which were based on the same system as the single grid made for demersal cod trawls in the Barents Sea (Isaksen et al., 1998). A total of approximately 800 t of mackerel was caught in the hauls used in this analysis.

2. Material and methods

2.1. Fishing trials

The preliminary experiments were carried out onboard the Norwegian combined purse seiner and pelagic trawler M/S "Selvåg Senior" (SS-1992) in the period 7–16 December 1992. The vessel was equipped with a Star Trawl from Egersund Trawl Factory. The circumference of the trawl was 800 m, and it was constructed as a 4-panel trawl with a mesh size of 4 m^2 in the top panel and the side panels and 2 m^2 in the bottom panel. The sorting grid was similar in design to a grid tested in bottom trawl for cod (Larsen and Isaksen, 1993), but it was made in three parts (1504×1000 mm^2) articulated together to allow the grid to be wound on a netdrum. It had a bar spacing of 40 mm and was made of stainless steel. The total weight of the grid was about 150 kg, and neutral buoyancy was achieved with plastic floats. The grid was mounted at a 30° angle inside an extension piece between the trawl and the codend and a coverbag was used to collect the mackerel that were sorted through the grid. Two hauls from these experiments are used in the analysis in this paper.

The second set of experiments were carried out onboard the Norwegian pelagic trawler "Gunnar Langva" (GL-1997) during the period 3–12 December 1997 (Kvalsvik et al., 1998). A pelagic trawl made by Br. Selstad AS was used. The trawl had an 848 m circumference and was constructed as a 4-panel trawl with a mesh size varying from 8 m^2 to 80 mm^2. Two types of trawl doors, Poly-Ice 8 m^2 and Nets 10 m^2, 80 m long sweeps, and 1500 kg weights, were used. A Scanmar grid sensor was used to measure the angle of attack and flow of water through the grid. The sorting grid was constructed and mounted according to the same principle as the single sorting grid (Sort-V) for bottom trawl (Isaksen et al., 1998), which is in use in the cod fishery. The grid had a bar spacing of 42 mm, chosen on the basis of results from the first trial, and covered an area of 6.0 m^2 (Fig. 1). The frame and crossbars were made of 75 mm aluminium, while the bars were made of 20 mm plastic composite. The grid weighed about 90 kg in air, and neutral buoyancy was achieved with plastic floats. The grid was mounted at a 30° angle inside a 15 m long extension piece (Fig. 2) between the trawl and the codend. A coverbag was used to collect escaping individuals. To ensure that the fish made contact with the grid, a guiding panel with 30 mm meshes was mounted in front of the grid (Fig. 2). Two hauls are included in the analysis of this paper.

The third series of experiments were carried out from 20 November to 7 December 1998 onboard the Norwegian combined purse seiner/pelagic trawler "Libas" (LI-1998). The rigging of the trawl and mounting of the grid were the same as in 1997, but a new grid of four parts articulated together, was used to make it possible to put the grid on the netdrum (Fig. 3). This grid had a bar spacing of 38 mm but was

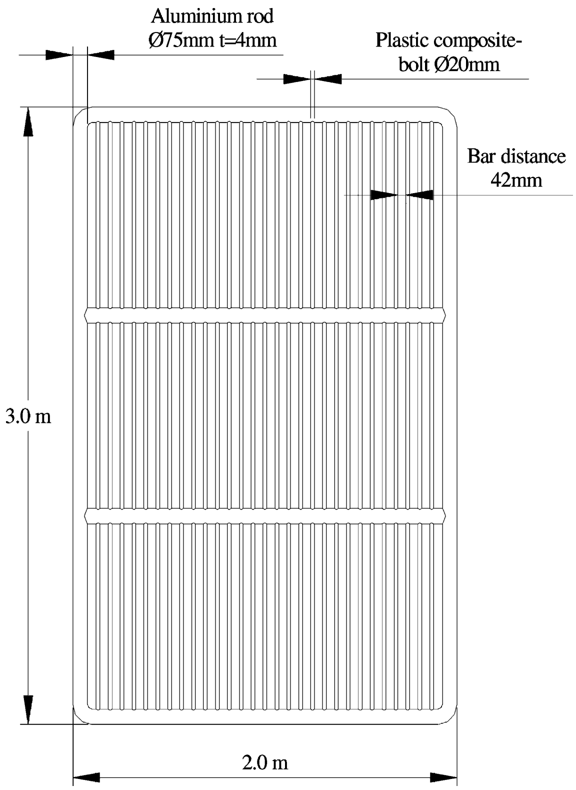

Fig. 1. Grid used during the 1997 experiments carried out onboard M/S "Gunnar Langva".

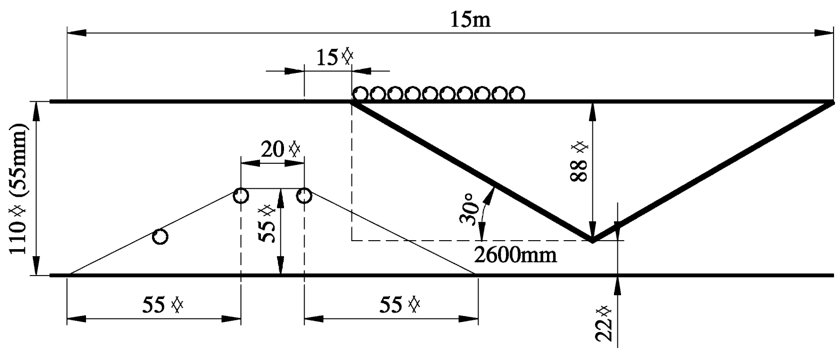

Fig. 2. Mounting of the grid and the guiding panel inside the 15 m extension piece.

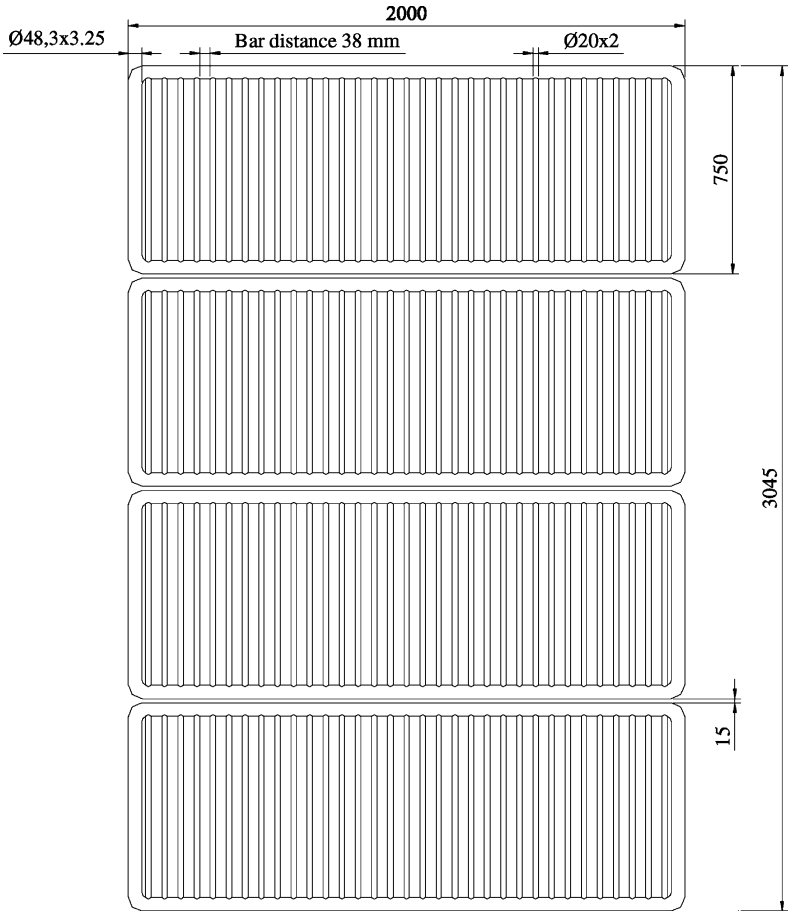

Fig. 3. Grid used during the 1998 and 1999 experiments carried out onboard M/S "Libas" and R/V "Scotia".

of the same size as the grid used in 1997. An articulated grid was preferred because it was easier to handle than the rigid one-piece grid that was used during the 1997 experiments. Four hauls from this survey are included in the analysis.

The last experiments were carried out onboard the Scottish research vessel R/V "Scotia" (SC-1999) during the period 18–25 October 1999. The rigging of the trawl and mounting of the grid were the same as in 1998 and the same grid was used. Four hauls from this survey are included in the analysis.

The mackerel were observed rather deep, at 100–150 m, during the experiments in November–December 1998. During trawling the fish went downwards and the trawl had to be towed on the bottom to catch the fish. A towing speed of 3–3.5 knots was too slow, and to catch the mackerel the speed had to exceed 4 knots. The catching procedure is presented in Fig. 4. The three main phases in the catch process are presented: (a) shooting the trawl and searching, (b) the catching phase, and (c) the selection phase before hauling. In the experiments in October 1999, the mackerel were at about 50 m depths, and did not dive substantially when passed over by the vessel or approached by the trawl. It was difficult to obtain sufficient spread of the trawl when operating so close to the surface, and the speed had to be about 5 knots to obtain sufficient opening of the trawl.

2.2. Data analysis

To estimate the size selectivity of the grid in these hauls, the codend was blinded by a 50 mm innernet, and fish escaping through the grid were collected in a

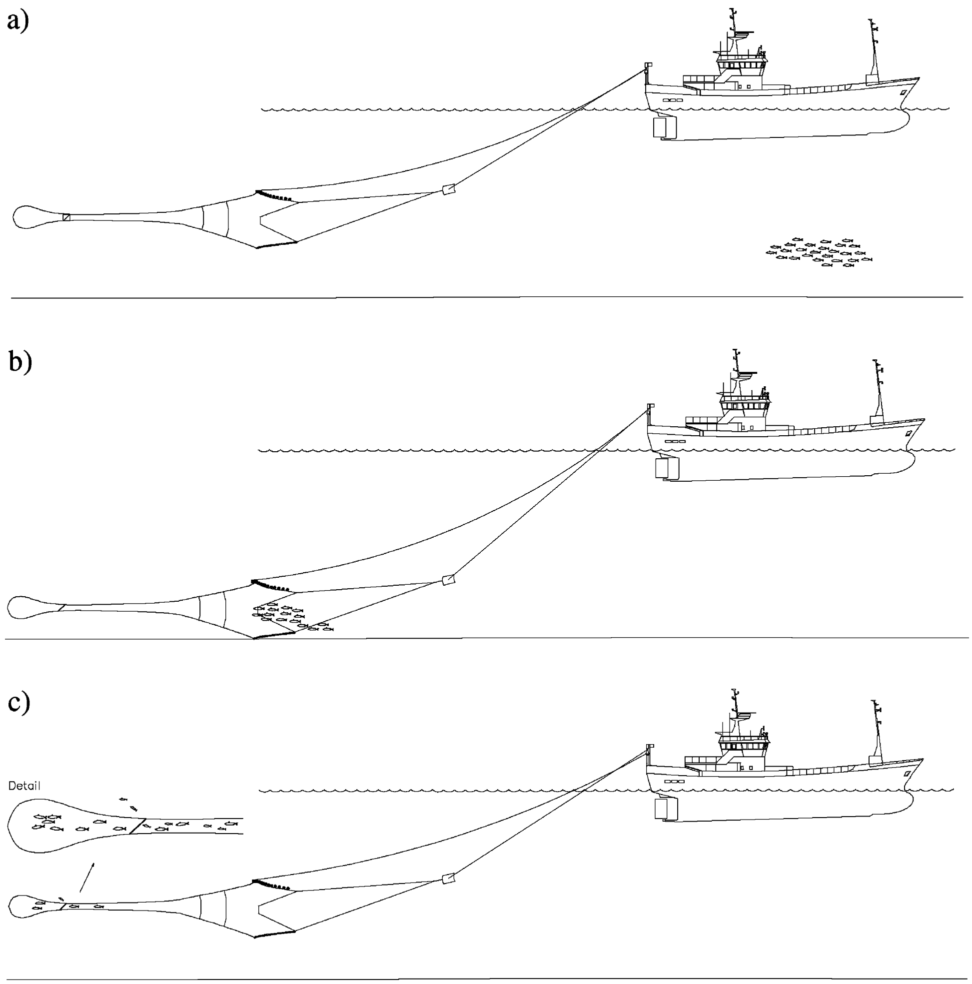

Fig. 4. Catching procedure when using sorting grid in pelagic mackerel trawl: (a) shooting the trawl and searching; (b) the catching phase; (c) the selection phase.

coverbag with 50 mm meshes (covered codend method). The length was measured as total length to the nearest centimetre and weight in gram. Selectivity parameters were estimated from the numbers of fish measured from the codend and the coverbag and taking the sampling ratios into account (Millar, 1994).

Due to very large catches, only a subsample of each catch was measured. About 200–400 fish were measured from both the codend and the coverbag. The total number of fish in the catch was estimated from the total catch and mean weights in the sample. The two-sample Kolmogorov–Smirnov goodness of fit test (KS test) (Zar, 1974) was used to test whether two sets of observations could reasonably have come from the same distribution. This test assumes that the samples are random, the two samples are mutually independent, and the data are measured on at least an ordinal scale. In addition, the test gives exact results only if the underlying distributions are continuous. The KS test is used to compare the weight distribution in each haul in the codend and the coverbag. Analysis of variance (ANOVA) (Zar, 1974) is generally used to explore the influence of one or more categorical variables upon a continuous response. ANOVA has been used to compare mean values of length and weight in the codend and the coverbag. ANOVA and KS test were carried out using S-Plus 2000 (MathSoft, 1999) and Statistica (StatSoft, 1995).

Linear regression (Zar, 1974) is used to describe the effect of continuous or categorical variables upon a continuous response. It is by far the most common regression procedure, and is in this paper used to evaluate changes in water flow and grid angle.

CC-Selectivity 2000, which implements the SELECT method (Millar, 1992) for indirect selectivity experiments with towed gears, is used to estimate logistic selectivity curves and selectivity parameters. For a more detailed description of the SELECT method and the statistics behind it, see Millar (1991, 1992), Anon. (1996), Millar and Fryer (1999).

2.3. Describing the selectivity using different models

Four different models are presented to explore the potential impact of bar distance in the grid upon selectivity. The data were collected during four experiments using a coverbag and a covered codend rigging. Three different bar spacings were tested during a total of 12 hauls. These are grouped into four experimental units; a year, a trip and a vessel compromise each experimental unit. Besides the catch at length data, there is auxiliary information on the catch sizes. The overall objective in this part of the paper is to assess the impact of bar spacing upon the selectivity of the grids.

The data provide an example of hierarchical (multi-level) data: two or more hauls are taken with the same gear. The gear is tested during four surveys. For use of the Laird–Ware model (Laird and Ware, 1982), which is commonly used for modelling of hierarchical normal data, it is implicitly assumed that dependencies are linear. With three different values of bar spacing, it might be worth considering treating bar spacing as a factor with three levels rather than a continuous, but it is considered continuous here.

In the following θ denotes the selectivity and $\hat{\theta}$ its estimated value. The notation is amended with indices representing bar distance of the grid used, haul and vessel, where appropriate.

2.4. Two-level hierarchical models

Two-level hierarchical models are commonly used in selectivity analyses, where several hauls are taken within one trip (Dempster et al., 1977; Fryer, 1991; Millar and Fryer, 1999). The first level in the hierarchical model represents the within-haul variance, which is related to the number of fish measured. The second level in the model represents the between-haul variance.

2.4.1. Model A1

As a starting point, the data are treated without paying attention to the different vessels and years from which they originate. The data are thus regarded corresponding to one trip with one vessel testing three different bar distances (BDs). By $\hat{\theta}_{h,g}$ we denote the estimated selectivity of haul h using grid g with bar distance BD. The model can be written as

$$\hat{\theta}_{h,g} = \theta + \mathrm{BD}_g\alpha + \varepsilon_h + \omega_h$$

where $\omega_h \sim N(0; R_h)$ and $\varepsilon_h \sim N(0; \Sigma)$ represent the within- and between-haul variation, respectively. The fixed part of the model describes the selectivity as an intercept and a BD effect expressed by the α parameter. Note that this model does not reflect the underlying error structure by which the data were generated. The model is therefore not suited for inference about the precision of the parameters.

2.4.2. Model A2

The next model focuses on using the vessel as an explanatory variable. This factor has four levels, corresponding to each of the four vessels represented in the data. Basically, there are two approaches that can be pursued: either to fit individual levels for each vessel or to use one vessel as a base and fit contrasts to the other vessels. The second approach, using "Libas" as the base is chosen here. This approach provides information about significant differences between the base vessel and all the other vessels. As some differences between "Libas" and other vessels are possibly insignificant, this model is likely to use fewer parameters than the first approach. The drawback of the second approach is that it does not tell anything about differences between other vessels. With the same notation as before, this model can be described by

$$\hat{\theta}_{h,v} = \theta_{\mathrm{Libas}} + \Delta_v + \varepsilon_h + \omega_h$$

Here Q_{Libas} is the selectivity of "Libas" and Δ_v gives the contrast to vessel v. The structure of the random variation is the same as in A1 and the same precaution does therefore also apply for model A2. Even though vessel and BD are highly confounded, the two models are conceptually different by A1 treating BD as a continuous variable and A2 treating vessel as a factor.

2.5. Three-level hierarchical models

Hierarchical models with more than two levels are generally very difficult to estimate in a classic Laird–Ware framework. We can however build a proxy by some tweaking and twisting:

1. Fit all individual curves and group them by vessel.
2. Fit a mean curve to each group.
3. Use the estimates from 2 and the corresponding estimated covariance matrices as input for estimating a mean curve across the groups.

A natural extension of the previous models is to utilise the overlap between "Libas" and *Scotia* which both used BD 38 mm. As mentioned earlier, this provides some information about the between-vessel variation. This variance component is, however, vaguely determined and does also include between-trip variance and between-year variance.

2.5.1. Model B1

The first three-level model is an analogue to model A1. BD is used as a continuous fixed effect and the random effect is given as an intercept, representing the between-vessel variation.

$$\hat{\theta}_{h,g,v} = \theta + \mathrm{BD}_{g,v}\alpha + \varepsilon_{h,v} + \varepsilon_v + \omega_{h,v}$$

where $\varepsilon_{h,v} \sim N(0; \Sigma_1)$, $\varepsilon_v \sim N(0; \Sigma_2)$ and $\omega_{h,v} \sim N(0; R_{h,v})$ represent the between-haul variation within-vessel v, the between-vessel variation and the within-haul variation, respectively. The dependency of BD upon the selectivity is given the α parameter.

2.5.2. Model B2

The second three-level model allows for different between-haul–within-vessel variation patterns by using the vessel category as a random effect. BD is still included as a fixed effect. This model has to be taken with high precaution due to high degree of confounding between vessel and BD size:

$$\hat{\theta}_{h,g,v} = \theta + \mathrm{BD}_{g,v}\alpha + \varepsilon_{h,v} + \varepsilon_v + \omega_{h,v}$$

where

$$\varepsilon_{h,v} \sim N(0; \Sigma_v), \qquad \varepsilon_v \sim N(0; \Sigma_2),$$
$$\omega_{h,v} \sim N(0; R_{h,v})$$

Note that model B2 differs from model B1 by allowing for different between-haul variances for the individual vessels. This is expressed by including a vessel-dependent index on the variance of the between-haul component.

All models were carried out by the use of EC model program. The EC model is directed at drawing inference from the effects of covariates upon the selectivity parameters. It implements a special version of the Laird–Ware model (Laird and Ware, 1982), which is used to analyse longitudinal data, and fixed and random effects models (see Laird and Ware (1982) and Jones (1993) for further details).

A comparison between the models was carried out by the use of AIC (Akaikes information criterion) statistics (Jones, 1993). The AIC statistics are used to compare "competing" models, and favour the model with the lowest AIC value.

3. Results

3.1. Catch data

Twelve hauls are included in the analysis in this paper. The catch sizes vary from less than 300 to 170 000 kg (Table 2). During the 1992 experiments, a bar spacing of 40 mm was used, during the 1997 experiments the bar spacing was 42 mm, and for the rest of the experiments the bar spacing was 38 mm. The proportion of fish retained in the coverbag and fish caught in the codend varied between hauls from less than 8% to nearly 50%. In total, 19.8% of the mackerel passed through the grid and were sorted out (Table 2).

The relative length distribution in the total catches for each survey differed markedly (Fig. 5). The mean length in the total catch for each survey varied from 34.92 to 37.46 cm (Table 3). The mean lengths between the four cruises were significantly different (ANOVA, Table 3). Significant differences in mean value of the length distribution between all cruises was found, except between the 1992 (SS-1992) and the 1998 (LI-1998) experiments (Tukey HSD test, Table 3).

Differences in mean weights of the mackerel caught in the codend and in the coverbag were tested, and significant differences between them were found in every haul (ANOVA, Table 4). The mackerel caught in the codend had mean weights from 52.3 to 107.6 g more than the mean weight in the coverbag. Absolute

Table 2
Position, operation and catch data for all trawl stations used in the analysis

Haul number	Date	Start trawling		Depth (fathoms)	Start time	Towing time	Bar spacing (mm)	Catch size (kg)		Sorted out (%)
		Position	Position					Codend	Coverbag	
SS1	15 December 1992	60°41′N	3°10′E	142	07:25	2 h 00 min	40	50000	4500	8.3
SS2	15 December 1992	60°43′N	3°6′E	132	12:00	2 h 20 min	40	100000	16000	13.8
GL1	4 December 1997	59°37′N	3°19′E	140 m	12:50	0 h 45 min	42	15000	14000	48.3
GL2	5 December 1997	59°40′N	3°20′E	[a]	[a]	0 h 45 min	42	45000	30000	40.0
LB1	23 November 1998	60°13′N	3°7′E	70	10:00	1 h 40 min	38	75000	14000	15.7
LB2	30 November 1998	60°20′N	2°47′E	49	11:45	2 h 15 min	38	157000	13000	7.6
LB3	5 December 1998	60°9′N	2°44′E	54	14:10	1 h 20 min	38	67000	18000	21.2
LB4	5 November 1998	60°11′N	2°55′E	60	22:58	1 h 15 min	38	106000	44000	29.3
SC1	20 October 1999	60°1′N	4°16′E	100 m	16:05	2 h 00 min	38	10000	1500	13.0
SC2	23 October 1999	60°28′N	1°58′E	44 m	19:30	1 h 00 min	38	128	134	51.1
SC3	25 October 1999	59°49′N	4°23′E	64 m	20.45	1 h 15 min	38	1000	1000	50.0
SC4	25 October 1999	59°8′N	4°9′E	40	11:30	1 h 30 min	38	26000	5000	16.1
Total								652128	161134	19.8

[a] Missing data.

weight frequency for each haul is presented in Fig. 6. The figures clearly show that the grids sorted out smaller individuals. Significant differences between the weight distributions were found in every haul (KS test, Table 4).

The proportion of mackerel less than 400 g (G4−) was reduced in all hauls (Table 5). The reduction varied from 3.5 to 14.3%. For the proportion of mackerel between 400 and 600 g there was a decrease in some hauls and an increase in other hauls. In all

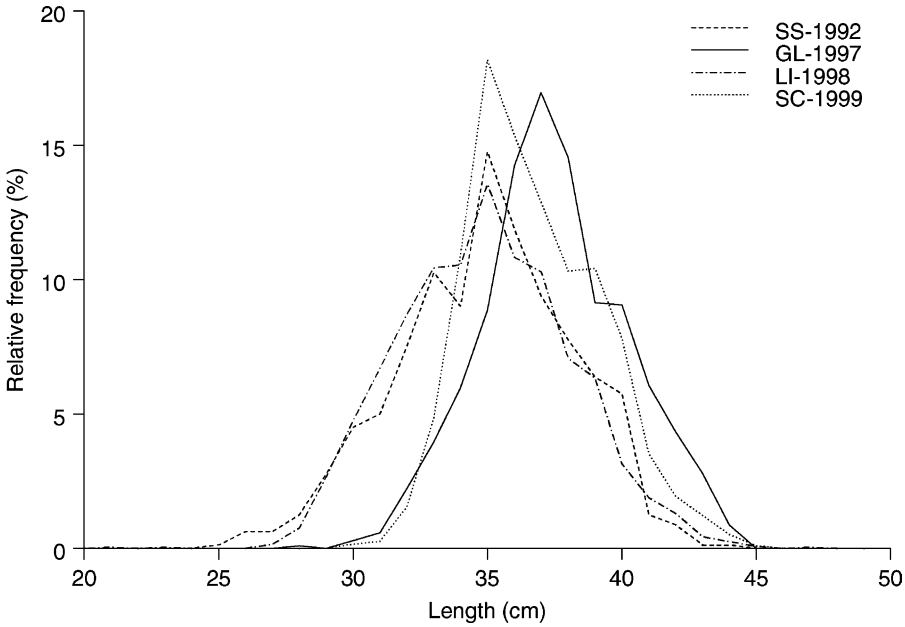

Fig. 5. Relative length frequency for the total catch for each survey.

Table 3
Mean lengths and testing between mean lengths for each survey

Data	Mean length	Standard deviation	Number measured	ANOVA	Tukey HSD test; probabilities for post hoc tests				
						SS-1992	GL-1997	LI-1998	SC-1999
SS-1992	34.92	3.23	799		SS-1992		$p < 0.05$	$p = 0.997$	$p < 0.05$
GL-1997	37.46	2.69	1038	$F(3, 6550) = 294.69$	GL-1997	$p < 0.05$		$p < 0.05$	$p < 0.05$
LB-1998	34.90	3.16	2759		LI-1998	$p = 0.997$	$p < 0.05$		$p < 0.05$
SC-1999	36.76	2.48	1958	$p < 0.05$	SC-1999	$p < 0.05$	$p < 0.05$	$p < 0.05$	
Total	35.86	3.10	6554						

Table 4
Testing for difference in mean weight between codend and coverbag (ANOVA) and two-sample KS test between weight distribution in coverbag and codend

Data	Codend			Coverbag			Difference	ANOVA		KS test	
	Weight	N	S.D.	Weight	N	S.D.		Analysis	p-Value	KS	p-Value
SS1-1992	392.18	197	109.63	335.30	200	96.16	56.9	$F(1, 395) = 30.23$	<0.05	0.227	<0.05
SS2-1992	462.71	199	113.58	391.50	200	90.97	71.2	$F(1, 397) = 47.81$	<0.05	0.298	<0.05
GL1-1997	464.98	317	107.46	412.67	251	95.26	52.3	$F(1, 566) = 36.67$	<0.05	0.212	<0.05
GL2-1997	567.98	223	114.84	497.41	247	107.16	70.6	$F(1, 468) = 47.49$	<0.05	0.280	<0.05
LB1-1998	385.12	367	119.41	342.92	363	81.57	42.2	$F(1, 728) = 31.02$	<0.05	0.213	<0.05
LB2-1998	474.40	368	106.17	378.91	331	90.69	95.5	$F(1, 697) = 161.66$	<0.05	0.384	<0.05
LB3-1998	386.41	362	115.92	316.89	444	95.91	69.5	$F(1, 804) = 86.80$	<0.05	0.253	<0.05
LB4-1998	478.11	244	115.43	384.64	280	117.04	93.5	$F(1, 522) = 84.23$	<0.05	0.371	<0.05
SC1-1999	453.47	233	110.57	388.77	317	66.26	64.7	$F(1, 548) = 72.95$	<0.05	0.306	<0.05
SC2-1999	553.85	231	91.68	446.25	301	88.82	107.6	$F(1, 530) = 186.54$	<0.05	0.487	<0.05
SC3-1999	537.38	252	109.48	439.03	269	93.17	98.4	$F(1, 519) = 122.43$	<0.05	0.413	<0.05
SC4-1999	534.83	178	100.26	431.61	174	104.96	103.2	$F(1, 350) = 89.04$	<0.05	0.437	<0.05

Table 5
Size distribution in total catches (equals fishing without grid), in the codend catches (equals using grid) and increases in income when using the grid system using 1999 prices as the standard (Table 1)

Data	Total catch			Codend catch			Difference			Increase in income (%)
	G4−	G4–6	G6+	G4−	G4–6	G6+	G4−	G4–6	G6+	
SS1-1992	53.4	40.7	6.0	41.9	48.4	9.6	−11.5	7.7	3.6	11.14
SS2-1992	27.0	62.8	10.2	17.1	64.7	18.2	−9.9	1.9	8.0	13.92
GL1-1997	23.8	63.0	13.2	18.2	63.1	18.6	−5.6	0.1	5.4	8.38
GL2-1997	6.3	53.8	39.9	2.8	44.4	52.8	−3.5	−9.4	12.9	11.62
LB1-1998	52.0	43.1	4.9	41.2	50.8	7.9	−10.8	7.7	3.0	10.12
LB2-1998	27.4	60.9	11.6	14.1	67.4	18.5	−13.3	6.5	6.9	14.07
LB3-1998	57.5	36.5	6.0	43.2	48.0	8.9	−14.3	11.5	2.9	12.33
LB4-1998	27.9	56.5	15.6	13.9	65.1	20.9	−14.0	8.6	5.3	11.80
SC1-1999	38.5	52.9	8.7	26.1	56.9	17.0	−12.4	4.0	8.3	16.44
SC2-1999	11.7	62.1	26.2	2.3	55.9	41.8	−9.4	−6.2	15.6	18.00
SC3-1999	15.5	60.2	24.3	7.2	56.2	36.6	−8.3	−4.0	12.3	14.98
SC4-1999	17.5	55.6	26.9	5.3	57.7	37.0	−12.2	2.1	10.1	14.06

hauls there were an increase of between 2.9 and 15.6% in the proportion of mackerel larger than 600 g (G6+).

Increase in income (%) was calculated as increase when using the size distribution caught in the codend compared to the size distribution in the total catch on the same amount of mackerel, and using the mean prices paid for landings by foreign vessels in Norway in 1999 as the standard (Table 1). The increase in income per haul when using the grid system varied between 8.38 and 18%.

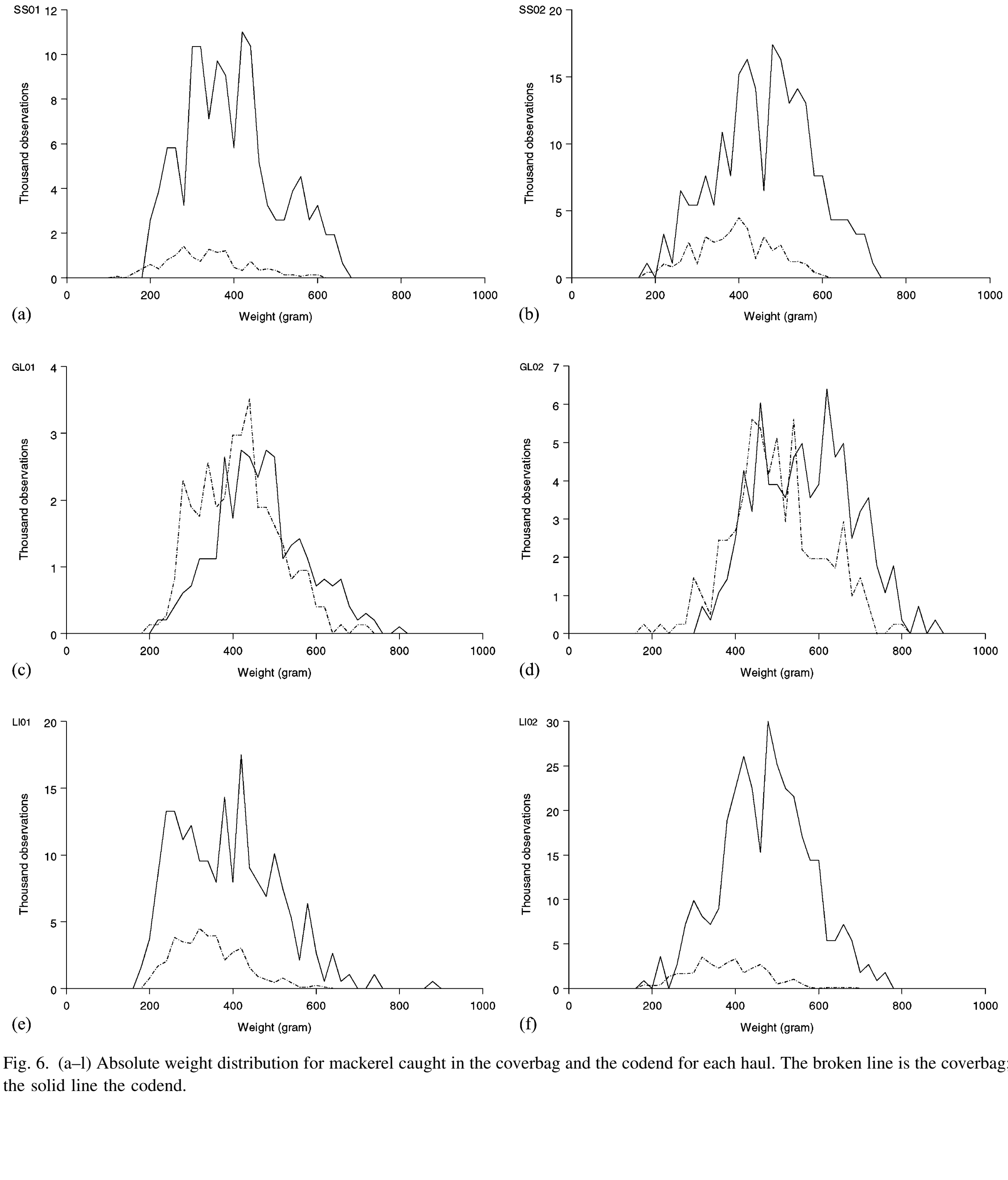

Fig. 6. (a–l) Absolute weight distribution for mackerel caught in the coverbag and the codend for each haul. The broken line is the coverbag; the solid line the codend.

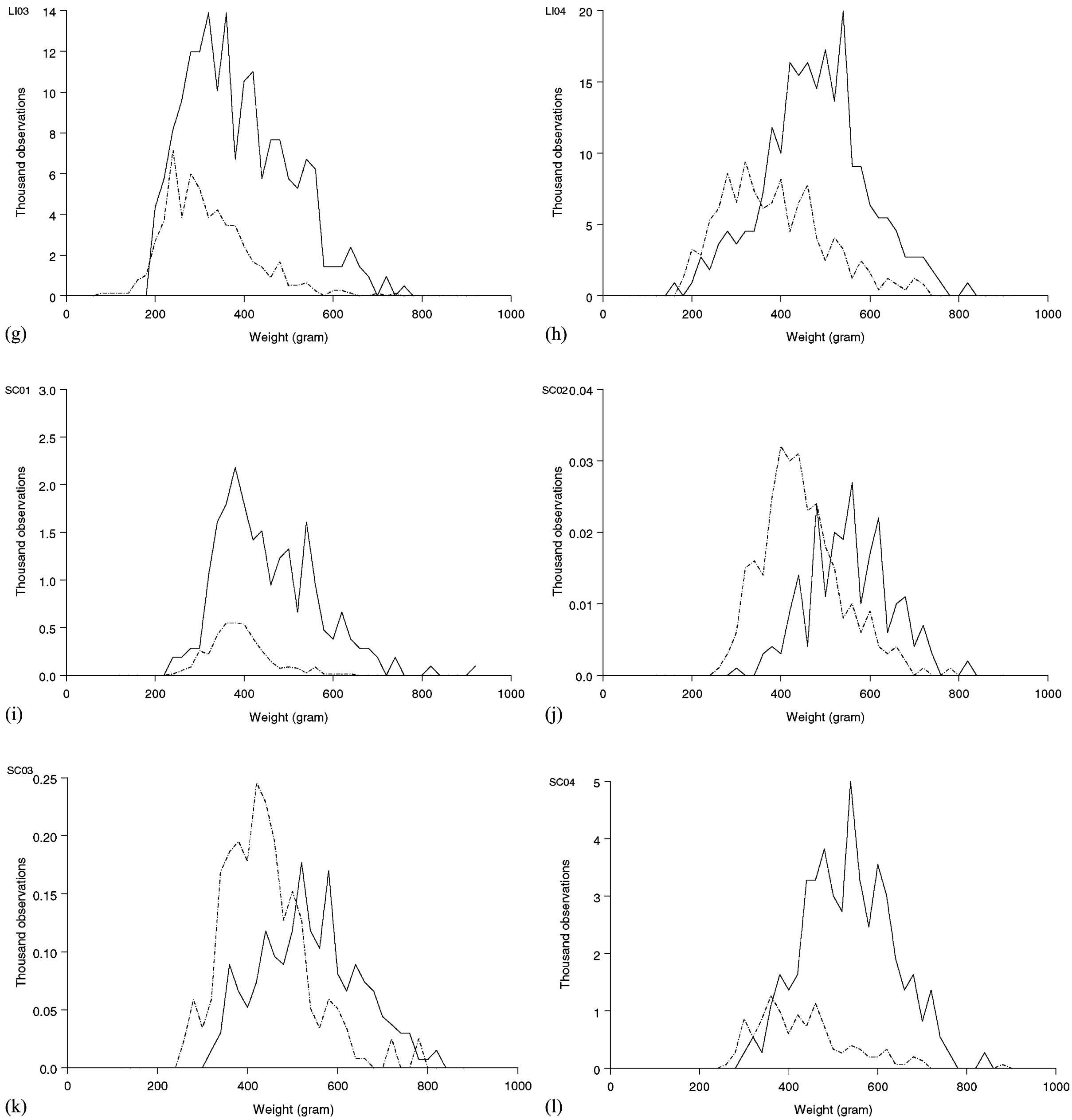

Fig. 6. (*Continued*).

3.2. Selectivity results and models

Logistic selectivity curves were fitted for all hauls using the SELECT method. Selectivity parameters were estimated for each haul, and mean parameters for each survey were estimated (Table 6). Selectivity curves including the estimated mean curves are presented in Fig. 7. One haul (LB1-1998) was deemed to be an outlier and was excluded from all subsequent analyses.

The reduction of the models showed the intercepts to be significant both for the 50% retention length

Table 6
Selectivity parameters estimated for all hauls

Vessel haul identification	L50%	SR
SS1-1992	29.324	4.666
SS2-1992	28.383	10.744
SS (estimated mean)	28.883	7.635
GL1-1997	37.393	10.725
GL2-1997	37.540	7.786
GL (estimated mean)	37.424	8.972
LB1-1998[a]	19.430	21.470
LB2-1998	29.128	6.317
LB3-1998	27.268	11.848
LB4-1998	33.480	11.175
LI (estimated mean)	30.116	9.420
SC1-1999	30.008	7.287
SC2-1999	37.782	4.435
SC3-1999	37.724	5.609
SC4-1999	33.770	5.653
SC (estimated mean)	34.861	5.569

[a] This haul is excluded from the analysis.

(L50) and the selection range (SR) in model A1 and B1. In model B2, only the intercept L50 was significant and $SR = 8.73$ (Table 7). All the estimated models are presented visually in Fig. 8.

In model A2, "LI" was used as the base when estimating contrasts (Table 8). No significant differences in SR where found between any of the experiments. In L50, no significant differences were found between the LI experiment and the "SS" experiment. For the SC experiment, an L50 of 34.31 $(30.23 + 4.18)$ was estimated, and for the "GL" experiments there was estimated an L50 of 37.83 $(30.23 + 7.60)$. Selection curves are presented in Fig. 8. The AIC for model A2 was estimated to be 95.16.

3.3. Catch-size-dependent selectivity

Linear regressions were used to test whether the selectivity parameters and the percentage sorted out of mackerel were influenced by the size of the catch (Table 9, Fig. 9). No significant effects were found, even though there are some indications. A negative correlation of −0.493 was estimated between catch size and L50. A positive correlation of 0.498 was estimated between catch size and SR. Between catch size and percentage of mackerel sorted out, a negative correlation of −0.464 was estimated. The selectivity parameters were also tested using the EC model, but catch size was not found to significantly influence the parameters.

3.4. Angle and flow measurements

Angle and flow measurements from three hauls carried out onboard M/S "Libas" in 1998 and one haul carried out onboard M/S "Gunnar Langva" in

Table 7
Estimated models for L50% and SR

Model number	Type	Estimated model L50%	Estimated model SR	AIC
A1	Two-level hierarchical	0.84784·BD	0.18238·BD	105.84
A2	Two-level hierarchical	See Table 8	See Table 8	95.16
B1	Three-level hierarchical	0.82511·BD	0.19672·BD	32.30
B2	Three-level hierarchical	0.78923·BD	SR = 8.73	29.08

Table 8
Estimated contrasts using "Libas" as the base

Contrasts	L50%	SR	Estimated L50%	Estimated SR
LI	Base	Base	30.23	7.18
SS	Insignificant	Insignificant	30.23	7.18
GL	7.60	Insignificant	37.83	7.18
SC	4.18	Insignificant	34.41	7.18

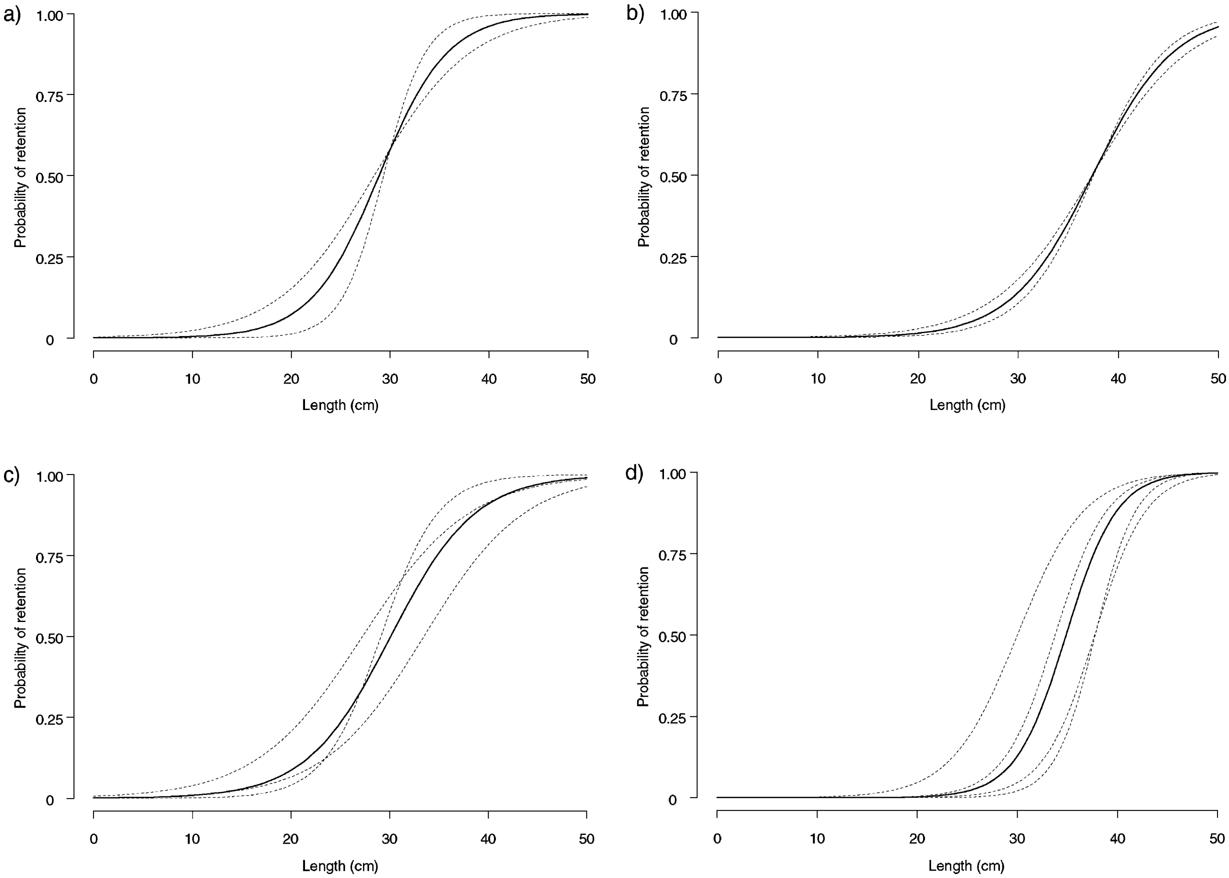

Fig. 7. Selectivity curves for all individual hauls (broken lines). Solid lines is estimated mean selectivity curve for each of the four surveys: (a) SS-1992; (b) GL-1997; (c) LI-1998; (d) SC-1999.

1997 were analysed. Both the grid angle and the water flow were unstable and varied a lot during the hauls (Fig. 10).

In two hauls, there were significant increases in grid angle in the "entrance zone". In the two others there were no significant change in grid angle, even though Fig. 11 and the estimated linear regression indicate a decrease. All figures indicate that the water flow decreases when the mackerel passes the grid (Fig. 11), and three of the regression lines had significant negative regression coefficients (Table 10). The water flow decreased from 3 to 5 knots when

Table 9
Linear regression between catch size, selectivity parameters and percentage of mackerel sorted out

Linear regression	Estimated value	Standard error	*t*-Value	Multiple R^2	p (>|t|)
Intercept	35.295	1.8330	19.255	0.2428	$p < 0.05$
L50%	0.000	0.000	−1.699		0.1236
Intercept	6.231	1.212	5.143	0.2475	$p < 0.05$
SR	0.000	0.000	1.721		0.1194
Intercept	36.438	7.657	4.759	0.2151	$p < 0.05$
Percent sorted out	0.000	0.000	−1.570		0.1508

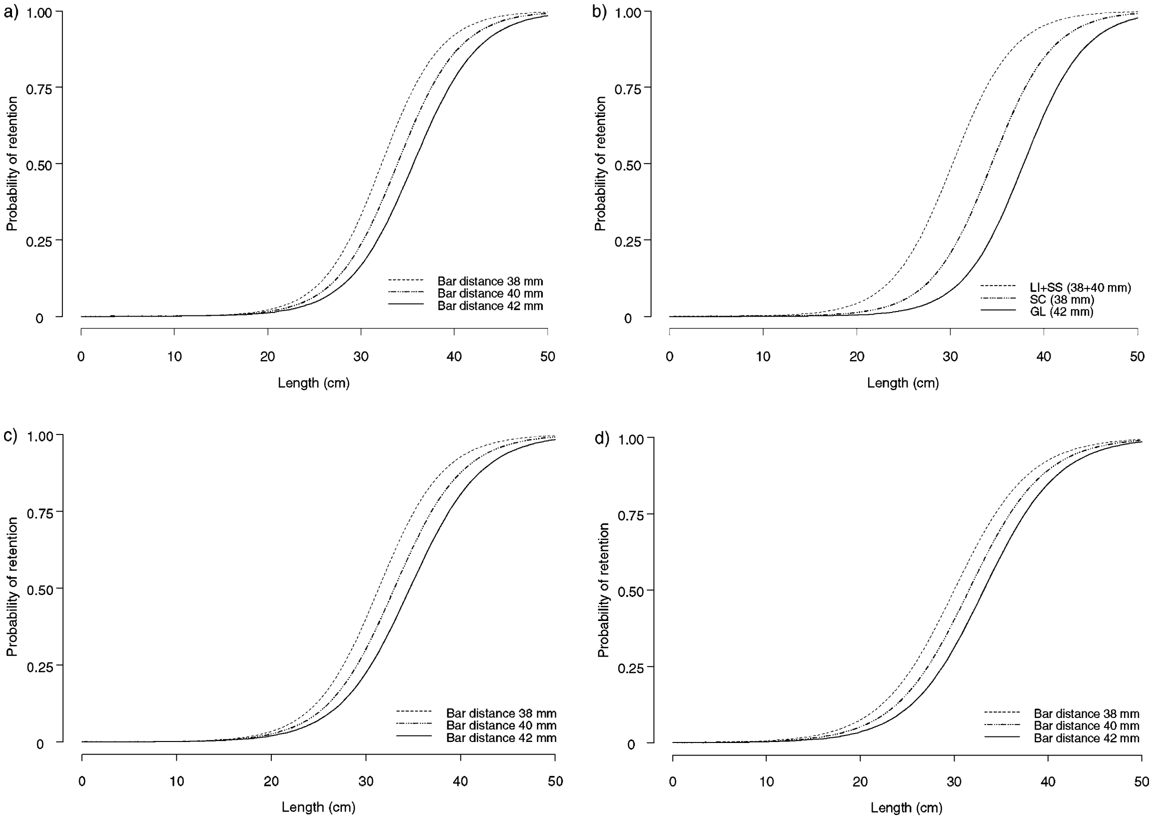

Fig. 8. Estimated mean selectivity curves from the four models: (a) A1 (two-level)—assuming no vessel effect; (b) A2 (two-level)—estimated mean curves for each survey; (c) B1(three-level)—assuming no vessel effect; (d) B2 (three-level)—using vessel as a random effect.

Table 10
Linear regression results of grid angle and water flow in the "entrance zone"

Data	Linear regression	Estimated value	Standard error	t-Value	Multiple R^2	p-Value
LI1-1998	Intercept	34.064	0.495	68.812	0.2854	<0.05
	Grid angle	0.053	0.009	5.860		<0.05
	Intercept	2.296	0.025	90.828	0.8497	<0.05
	Water flow	−0.010	0.001	−22.049		<0.05
LI2-1998	Intercept	18.813	0.343	54.852	0.2716	<0.05
	Grid angle	0.0267	0.003	8.170		<0.05
	Intercept	3.809	0.113	33.652	0.3935	<0.05
	Water flow	−0.012	0.001	−10.776		<0.05
LI3-1998	Intercept	24.861	2.290	10.858	0.0956	<0.05
	Grid angle	−0.350	0.407	−0.860		0.4182
	Intercept	5.172	0.434	11.910	0.7600	<0.05
	Water flow	−0.363	0.077	−4.708		<0.05
GL1-1997	Intercept	29.672	1.310	22.650	0.0908	<0.05
	Grid angle	−0.197	0.278	−0.707		0.5114
	Intercept	4.547	1.224	3.715	0.0108	<0.05
	Water flow	−0.066	0.314	−0.209		0.8446

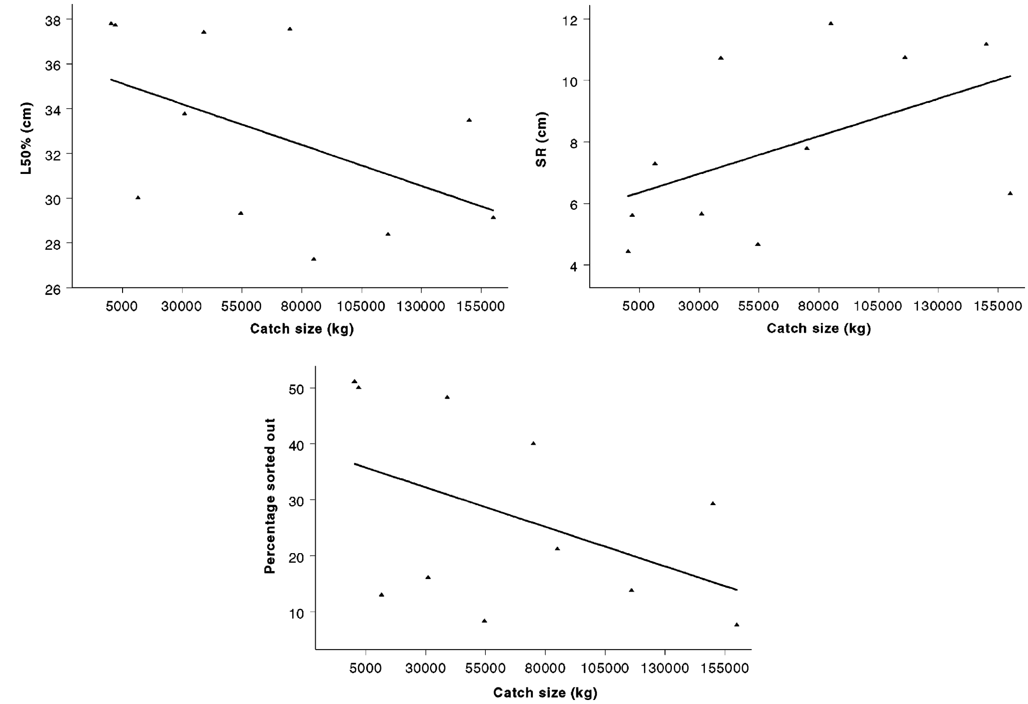

Fig. 9. Catch size plotted versus selectivity parameters and percentage sorted out.

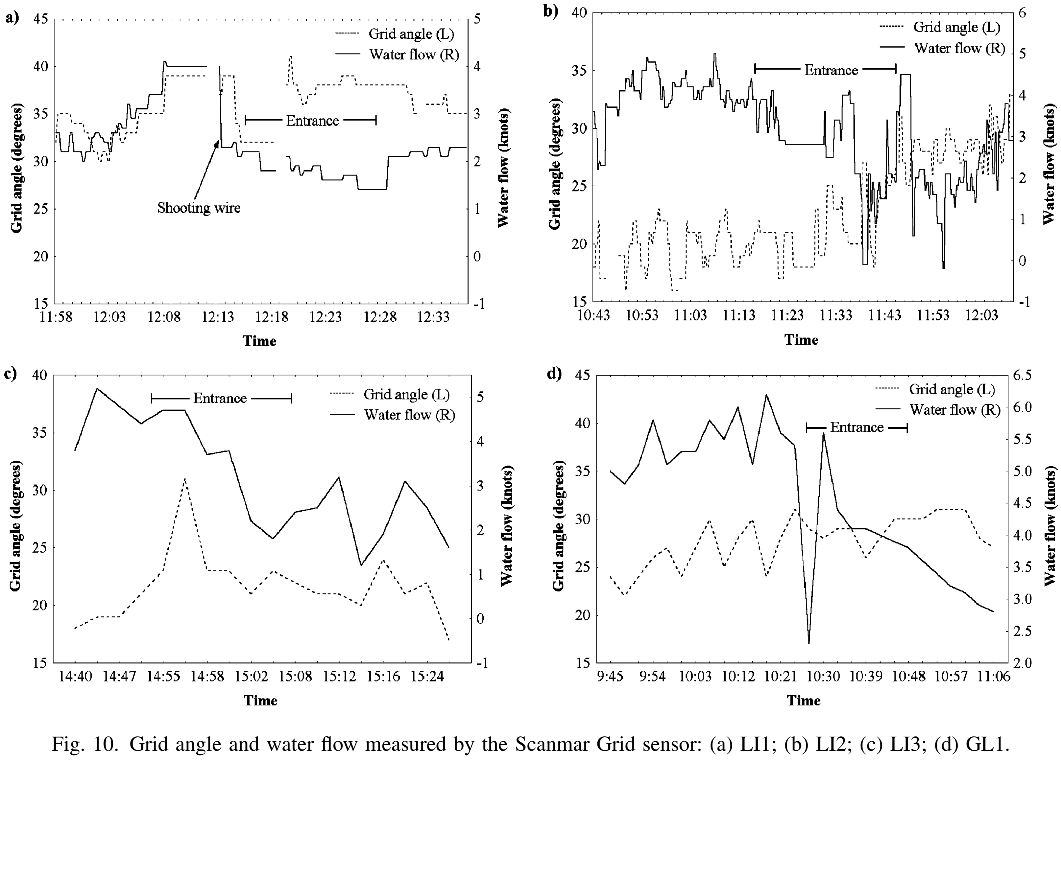

Fig. 10. Grid angle and water flow measured by the Scanmar Grid sensor: (a) LI1; (b) LI2; (c) LI3; (d) GL1.

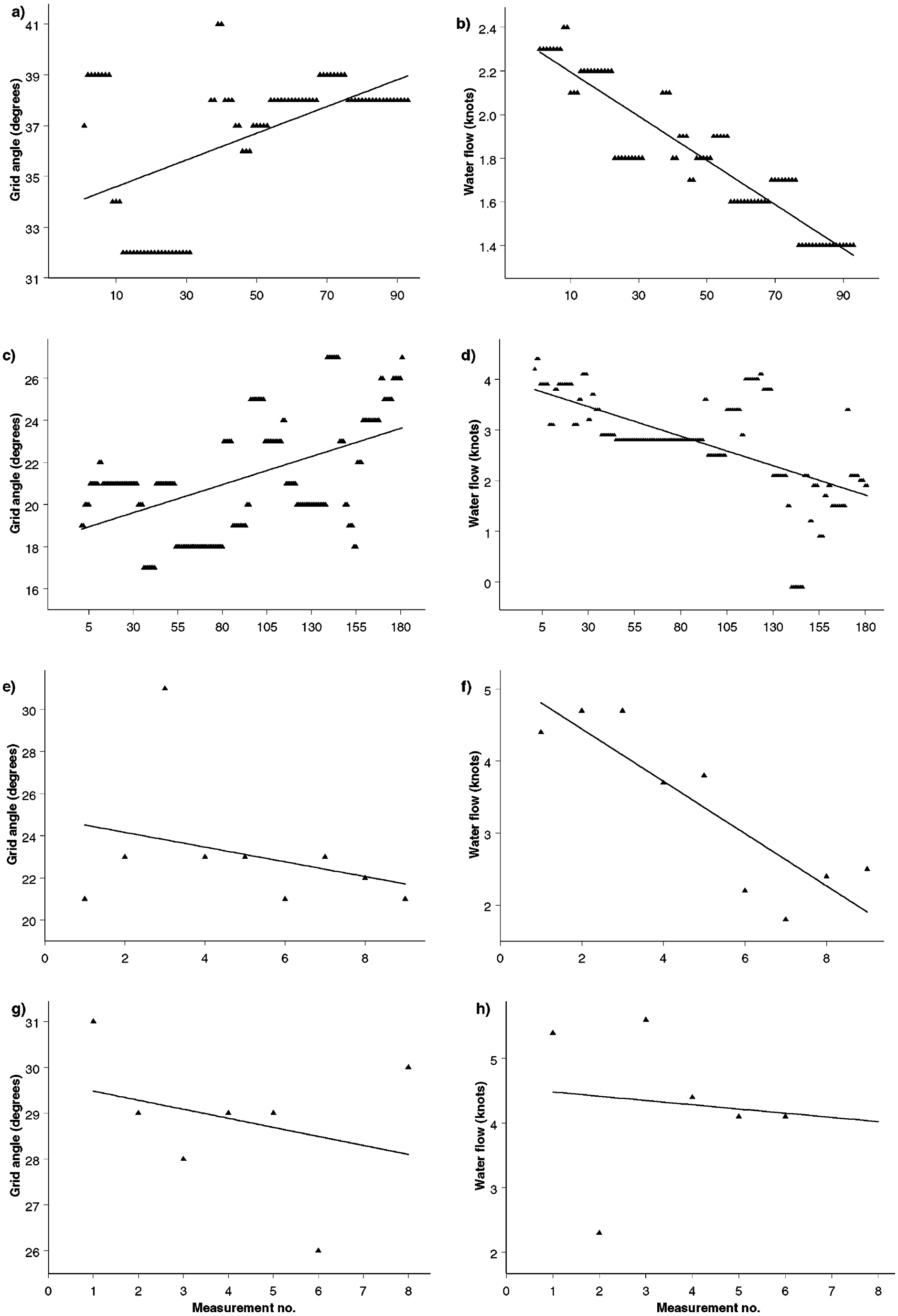

Fig. 11. Linear regression of grid angle and flow of water through the grid versus time in the entrance zone of the trawl haul: (a, b) LI1; (c, d) LI2; (e, f) LI3; (g, h) GL1.

trawling without fish to 1–2 knots when the fish pass through the grid. In the two hauls LI1 (Fig. 11a and b) and LI2 (Fig. 11c and d), the data were recorded automatically. In the other two hauls, the data are manually recorded, and there is a longer distance between the measurements (Fig. 11e–h).

4. Discussion

The selection properties of trawls with regard to both fish species and fish size have been greatly improved by the introduction of rigid sorting grids (Valdemarsen and Isaksen, 1994; Larsen and Isaksen, 1993). In comparison to size selection through meshes, the selection curves of selection grids are steeper with a narrower SR (Valdemarsen and Isaksen, 1994).

We have tested a single-grid size-selection system for pelagic mackerel trawls. The pelagic trawl fishery for mackerel differs from the bottom trawl fishery for gadoids in that there may be very large catches in a short time when schools of mackerel are caught. In some of the hauls there were catches between 100 and 200 t of mackerel. The time duration when the mackerel entered the trawl was usually short, from a few minutes up to 30 min. One of our fundamental questions was if it was possible to sort such large amounts of mackerel through a sorting grid system in a short period of time. In the SELMITRA (selective midwater trawling) project, they did find large catches to constitute a real problem (van Marlen, 1995; van Marlen et al., 1994). The results show that nearly 20% of the mackerel caught in our experiments were sorted out. The grid system therefore seemed to function well when sorting such large amounts of fish. The effectiveness of the grid system has also been tested on smaller fish. During the experiments carried out onboard ‘‘Libas’’ in 1998, 130 t of herring were caught in one haul. The data from this haul are not analysed in this paper, but nearly 45% of the herring was sorted through the grid system in only 25 min, indicating that the grid system effectively sorts out small individuals in large catches. But it is still likely that a too large amount of mackerel caught in a very short time may cause a concentration of mackerel in front of the grid that might ‘‘block’’ the selection. A grid sensor will therefore be a useful and necessary tool to indicate when the mackerel are passing through the grid, and whether there is too much fish in front of the grid. Likewise it is possible to tell when all the fish have passed the grid and the hauling can start.

Another effect of these large amounts of mackerel going into the trawl in a short time may be that all individual fish are not in contact with the grid and are thus not selected. If large amounts of mackerel are not in contact with the grid, this may reduce the effectiveness of the system, but the results indicate that the grid efficiently sorts out mackerel smaller than 400 g from the catch and thus increases the proportion of larger individuals in the catches. There are significant differences in size between the fish sorted out and the fish retained in the codend in all hauls, which also means that the grid system significantly increases the value of the catch. It is possible to get a higher rate of selection and a further increased value of the catch by using a wider bar spacing, but then the catch sizes will be reduced and the towing time must be extended to catch the same amount of mackerel.

There are relatively large variations between the estimated selectivity parameters, but the estimated values for SR indicate a reasonably sharp selection in most of the hauls. The SR varies between 11 and 43% in proportion of the L50, with a mean value of 24.5%. A rule of thumb from bottom trawling for gadoids is that a value of the SR of 25% of the L50 is regarded as a good selection. The variation in the estimated parameters may be a result of the rather narrow length distribution in the catches. The uniform catches during purse seining and trawling on schools is due to natural selection mechanisms with regard to species and size distribution in the formation of schools (Pitcher and Parrish, 1993). Estimating the selection curve from a narrow length distribution may cause problems when fitting the selection curves to the data, and thus a high variation in the estimated selection parameters.

Due to a total of only 12 hauls there are some limitations in the data when estimating the four different models that are presented to explore the potential impact of bar spacing in the grid upon selectivity. The experimental design is unbalanced and incomplete, and the same bar spacing is only repeated in two experimental units (combination of vessel, survey and year) and only for one bar spacing. No experimental units cover more than one bar spacing, and there is unequal number of repetitions (hauls) within the experimental units.

The experimental set-up is hierarchical, which results in multilevel data. Two or more hauls are taken with the same gear. The gear is tested during four surveys. An ideal design would test several gear types (e.g. bar distance) within each vessel. Each vessel would conduct several surveys within each year. Even though this would have been an unrealistic and expensive design, there are two points to make: there are multiple sources of variation (within-haul, between-haul, within-survey, between-survey within-year, between-year within-survey, between-vessel), and the sources of variation reside in a nested structure. But with the present design there is only one gear type tested at each survey. There are very few hauls within each trip (2–4), there is only one trip with each vessel, and there is only one vessel within each year.

The factors listed here are all possible candidates for sources of variation, and there is no evidence to support assumptions of negligible effects. Except for a single overlap between one level of the gear type (BD 38 mm) and two vessels, there is no information in the data to draw inference from this variation. Apart from this minimal overlap, the variation of interest (dependency of BD) is to a large extent confounded with the unknown random variation (between-trip, between-year, between-vessel). The overlap allows, however, for some minimal inference from the between-vessel variation, but this is subject to assumptions. The assumptions may be that there is no between-trip variation, no between-year variation and that the overlap is representative for the between-vessel variation for all vessels. These assumptions cannot be checked. The weak support of between-haul variance and the above-mentioned confounding could therefore leads to erroneous conclusions about the gear effect when it is in fact, for example, a vessel effect.

Almost all hauls had very large catches with a median of 65 t. Consequently, only subsamples were measured. The subsampling fractions ranged from 0.09 to 100%, with a median of 0.8%. The number of fish measured affects directly the within-haul variation. If this source of variation comprises a prominent part of the total variation, it may affect the ability to detect effects of interest. It is unclear whether the low sampling ratios used here are too small.

For model A1, there are two concerns. First, the model does not reflect the true nested sampling structure. It presents the data as collected from one trip with one vessel and with a considerably larger amount of hauls than were taken with any of the actual trips. The estimated between-haul variance does therefore not distinguish between the vessels and is underestimated. Second, the model assumes linear relations between L50 and BD, and between SR and BD. This might be a dubious assumption, and alternative relations might be worth considering. The low number of BDs provides, however, little support for any functional relations. The most appropriate choice might therefore be to treat BD as a factor with three levels. The first concern for model A1 also applies to model A2. It is of interest to estimate and compare the two models due to the large extent of confounding between vessel and actual level of BD. In other words: does the selectivity vary due to differences in BD or due to differences in vessels? A common approach for comparing competing models is by using the AIC statistics (Jones, 1993). The AIC favours the model with the lowest AIC value. Despite the results from model A1, the comparison indicates that there is more information about the selectivity in which vessel the data were collected with than what BD was used.

With regard to model B1 and B2 and with the precautions mentioned in mind, it appears that the use of vessel information primarily influences the way the SR is modelled. Furthermore, the slope of the regression of L50 upon BD is diminished in B2. The L50 is smaller in B2 than in B1, whereas the SR is larger. For a BD of 40 mm, L50 goes from 33.0 to 31.6 cm and SR goes from 7.87 to 8.73 cm. The AIC favours the second model. Similar to model A2, the inclusion of vessel information removes any effect of BD upon the SR. There is, however, a fundamental difference between the ways the two models include vessel information.

The two- and three-level models cannot be compared using the AIC statistics, because they are based on different data. But, both the two- and three-level models try to describe the general selection with regard to the variation in the parameters (vessel, hauls, trials, bar distance). In models A2 and B2, there is a focus on deciding the influence from the bar distance. The three-level model (B2) is theoretically the model, describing the experiments most correctly. But it is also the model that needs the largest amount of data. If the data are insufficient for this type of analysis, the results become uncertain.

To summarise the results from the models, it seems like the small change in bar distance (BD) has little influence on the selection parameters. There are, as expected, differences in L50 between the three BDs, but there is also a difference of only 4 mm in BD between the grid with the largest and the grid with the smallest BD. The SR is less influenced, even though small differences were estimated by models A1 and B1. For models A2 and B2, the BD did not influence the SR. All models give indications of a reasonably sharp selection.

The influence on the selectivity parameters of the catch size is tested. Selection in a diamond-meshed codend is sensitive to catch size (Isaksen et al., 1989; Pope, 1975), but size selection in grids in front of the codend is less sensitive (Valdemarsen and Isaksen, 1994). No significant effects of catch size were found on the selectivity parameters by the EC model or by linear regression between catch sizes and selectivity parameters. But there are indications of a reduced L50, reduced percentage of mackerel sorted out, and an increased SR with catch size, but it is unclear if the small amount of data may have effected the results.

Grid angle and water flow data measured by the Scanmar grid sensor during four hauls are presented, and the angle and flow of water in the entrance zone are analysed. This is the period of time where the mackerel are entering the trawl plus the time needed for the mackerel to pass through the grid (the selection phase). During the two first hauls presented (LI1 and LI2), there are qualitatively good data because the data were logged automatically. Significant changes in both grid angle (increased) and flow of water (decreased) were found when the mackerel were passing through the grid. In the two last hauls analysed (LI3 and GL1), the number of data points are small, and there were no significant changes in angle of the grid, and a significant decrease in water flow in only one of the hauls (LI3). This decrease in water flow indicates when mackerel are passing through the grid, whether there are too much fish in front of the grid, and tells when the selection phase is finished and hauling can start.

A critical constraint for application of this technology is the survival of the fish that escape through the grid. Experiments showed that gadoids, such as cod, haddock, and saithe, survive when they are sorted through meshes and through a grid system (Jakobsen et al., 1992; Soldal et al., 1993). The situation is different for pelagic schooling herring, where survival experiments showed that they are very sensitive to physical contact with the net in trawls, and a high mortality was observed for small herring escaping through trawl meshes or through sorting grids in trawls (Suuronen et al., 1996). Experiments with mackerel showed that this species might suffer high mortality when crowded into small net cages (Lockwood et al., 1983). Survival experiments carried out in experiments using a selection grid in a purse seine (Misund and Beltestad, 1994, 2000; Beltestad and Misund, 1996) attained a survival of 95% in the control group and maximally 60% survival in the experimental group. This indicates that the size-selection process in mackerel purse seining causes too high a mortality rate to allow it to be recommended for commercial fishing.

There are reasons to believe that the survival rates of sorted mackerel in trawls are better than the survival in the purse seine experiments. In the purse seine experiment (Misund and Beltestad, 2000), the mackerel suffered severe stress and skin injuries during the selection process. Mackerel caught in a pelagic trawl may not be confined together like in a purse seine, and if the mackerel are not in contact with the net panel they may not suffer from damage on the skin to the same extent. However, when catching large catches in a very short period of time, the mackerel may also be confined inside the trawl, resulting in contact with the surrounding net panels. Also the relative high towing speed may hurt the fish. During hauling one had to increase the speed to prevent the fish from going forward in the trawl. To make the fish move from the opening of the trawl to the bag, a towing speed of more than 4 knots is needed. This may lead to exhausting the fish and subsequently to a high mortality.

These experiments show that it is possible to use sorting grids in pelagic mackerel trawl to sort out small individuals and thus increase the economic value of the catches. Large catches have been sorted through the grid system in relatively a short period of time, and acceptable amounts of small fish are sorted out. But the most fundamental questions after showing that it is possible to use sorting grids in mackerel trawl, are the survival of the mackerel that is sorted out. In order to quantify the survival and mortality of mackerel sorted through a grid inside a mackerel trawl, it is necessary to carry out further experiments.

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