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The effects of hook and bait sizes on size selectivity and capture efficiency in Icelandic longline fisheries

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ABSTRACT

One of the major problems in marine fisheries is that species and sizes outside the range of those targeted may be captured, leading to discards. Although longline fishing is characterised by low energy consumption, low bycatch of non-target species and high catch quality, bycatch of undersized fish has been found to be a problem in some fisheries. We studied the effects of bait size and hook size on catching efficiency and size selectivity in the Icelandic longline fisheries targeting cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), tusk (*Brosme brosme*), ling (*Molva molva*) and wolffish (*Anarhichas lupus*). Five sizes of EZ-Baiter hooks (sizes 10 – 14) and two sizes (10 and 30 g) of Pacific saury (*Cololabis saira*) bait were tested in six fishing trials. There was a significant size selectivity effect for bait size in that larger bait caught more large fish and fewer small fish of all species, apart from ling. The large bait caught 45, 56, 35 and 76% more (by weight) cod, wolffish, tusk and ling, respectively. Haddock catches were reduced by 57% when the large bait was used. Increasing hook size lowered capture efficiency for all species, but had only a minor effect on size selectivity. Our results thus demonstrate that hook size and bait size affect the profitability of longline fisheries, in that smaller hooks improve capture efficiency, while larger baits increase catches of large fish and reduce those of undersized fish.

1. Introduction

There is a growing concern among fisheries managers and consumers about the impacts of fishing on marine ecosystems. Among the major problems in marine fisheries is the capture of species and sizes beyond those targeted, leading to huge quantities of discards, which often die immediately or are mortally injured (Kelleher, 2005; Suuronen et al., 2012). For this reason, the development and implementation of species- and size-selective fishing gear and methods have been a concern of fishery technologists for several decades (Pope et al., 1975; Burd, 1986; Main and Sangster, 1985; Løkkeberg and Bjordal, 1992).

Fishing practices and gears vary widely in their environmental impacts (Suuronen et al., 2012). Longline fishing has a number of appealing characteristics such as low energy consumption, minimal habitat impact, low bycatch of non-target species and high catch quality. However, bycatch of undersized fish is a problem in some longline fisheries (Løkkeberg and Bjordal, 1995; Huse and Soldal, 2000), and discarding fish caught by longlines often leads to high mortality (Milliken et al., 1999). Discarding dead or mortally injured fish is prohibited in Icelandic and Norwegian fisheries. A ban on discards will also come into force in EU fisheries under its recently reformed Common Fisheries Policy (European Commission, 2014), which requires that stocks should be exploited by more size-selective fishing gears. Improved size selection is also in the interest of fishermen, because area closure is a common management strategy when catches of undersized fish exceed a certain proportion. Furthermore, larger fish often obtain higher market prices, and thus offer an incentive for implementing new fishing technologies (Catchpole et al., 2005).

Research into size selection has tended to focus on trawl and gillnet fisheries. Few research efforts have focused on improving longline size selection, although bait size has been suggested as the most important gear parameter that affects the size selectivity of baited hooks (Løkkeberg and Bjordal, 1992). Small baits have been shown to catch more small cod (*Gadus morhua*) than large baits (Johannessen et al., 1993; Bjordal and Løkkeberg, 1996). For haddock (*Melanogrammus aeglefinus*), bait sizes were found to have negligible effects on size selection, but small baits (10 g) caught more than twice as many fish as large baits (30 g). Effects of hook size on size selectivity have been shown for porgies (*Pagellus* spp., Erzini et al., 1996; Czerwinski et al., 2010), while hook size had

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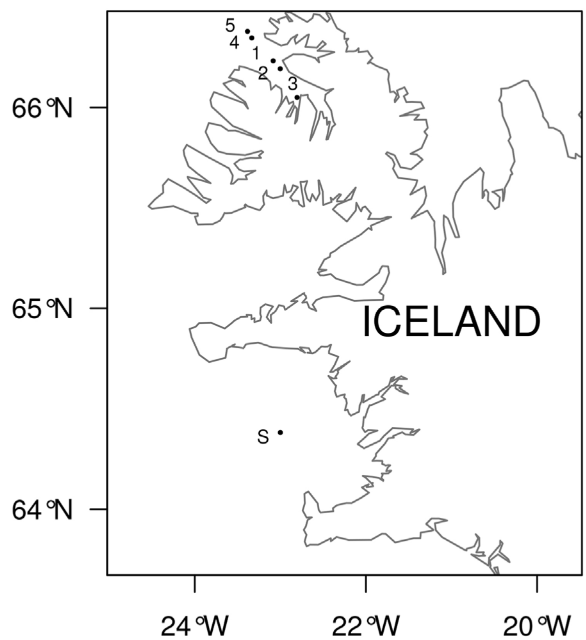

Fig. 1. Locations where the surveys were conducted.

Table 1
Hook dimensions, see Fig. 2 for reference.

	Hook size				
	10	11	12	13	14
Total length (mm)	44.0	55.0	57.5	66.5	76.5
Bite/throat (mm)	18.0	20.0	23.5	25.5	31.0
Front length (mm)	18.5	21.0	25.0	27.0	32.0
Gape (mm)	10.5	11.5	15.0	14.5	17.0
Wire thickness (mm)	1.9	2.1	2.3	2.7	2.9
Weight (g)	1.7	2.4	3.5	5.4	7.4

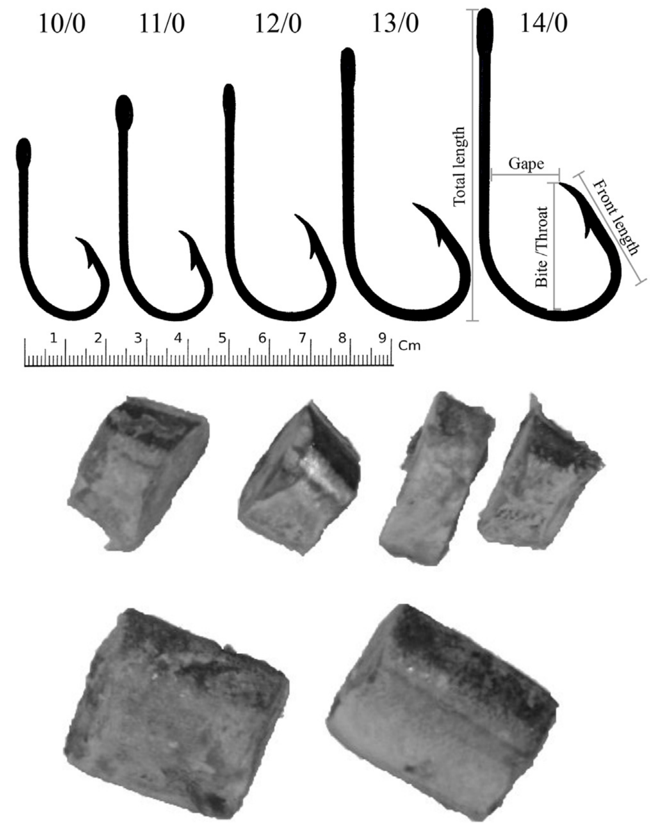

Fig. 2. Hooks and bait sizes tested in the experiments. The dimensions for the hook sizes are shown in Table 1.

Table 2
Actual bait weights (mean weight of >30 pieces along with s.d. and sample size).

Trip	Weight 10 g baitg ± s.d. (n)	Weight 30 g baitg ± s.d. (n)
North 1	9.0 ± 1.4 (37)	28.0 ± 4.8 (39)
North 2	8.9 ± 2.0 (66)	28.7 ± 4.8 (46)
North 3	10.3 ± 1.8 (41)	32.1 ± 3.6 (34)
North 4	11.1 ± 2.3 (30)	33.4 ± 4.5 (33)
North 5	9.5 ± 1.7 (42)	32.8 ± 4.5 (41)
South	12.2 ± 2.2 (65)	28.7 ± 5.4 (55)

no effect on size selectivity for gadoid fish (Bjordal and Løkkeborg, 1996).

The studies cited above indicate that the effects of bait size and hook size may differ between species. More research that includes a wider range of species is therefore needed to improve our knowledge of factors that affect longline size selectivity. Thus, we have studied how bait size and hook size affect catch efficiency and size selectivity in the Icelandic longline fisheries. Trials were performed in fisheries targeting cod, haddock, tusk (*Brosme brosme*), ling (*Molva molva*) and wolffish (*Anarhichas lupus*), which are the main species taken by longlines in the north Atlantic.

2. Materials and methods

2.1. Sea trials and gear description

Six fishing trials were carried out from November 2008 to December 2009 on board two chartered commercial longliners operating on the coastal banks off Iceland at depths of 50–140 m (Fig. 1). The vessels used 9 mm longlines with 50 cm-long ganglions spaced 1 m apart. Mustad EZ-Baiter hooks are assigned numbers, with higher numbers for larger sized hooks. Icelandic longliners use sizes 11–13 of the Mustad EZ-Baiter hook and bait sizes range from ~10 to 30 g. Five sizes of the EZ-Baiter hook (sizes 10–14, Fig. 2, Table 1) and two sizes of Pacific saury (*Cololabis saira*) bait (10 and 30 g, Table 2) were compared.

Frozen bait was cut with a cutting machine (series of rotating knives on an axle), and bait sizes were determined by adjusting the space between the knives. The head and tail of the saury were discarded in order to obtain uniform baits. The 10 g baits were 15–17 mm long and the 30 g baits were 42–47 mm. Samples of at least 30 baits were weighed to provide a measure of the range of weights (Table 2).

The experimental longlines were baited with the two bait sizes on alternating series of 100 hooks. A 10-m line without hooks was inserted between each 100-hook series and at each end of the longlines. Each 100-hook series of similar bait size was divided into five 20-hook blocks and each block was rigged with one of the five hook sizes (Fig. 3). Each series and block were marked to identify bait size and hook size. The longlines were hand baited and coiled into tubs (skates) with 300 hooks in each tub. Prior to setting, the lines from all tubs were joined to form one fleet of 16 tubs of longlines (4800 hooks), except for one trip on which 2400 hooks were set. The lines were set in the morning, 05:30–09:15 local time, at a speed of approximately 2.5 ms^{-1} (5 nm h^{-1}). Hauling started about 1 h after setting was completed. During hauling, all fish were recorded and their lengths measured.

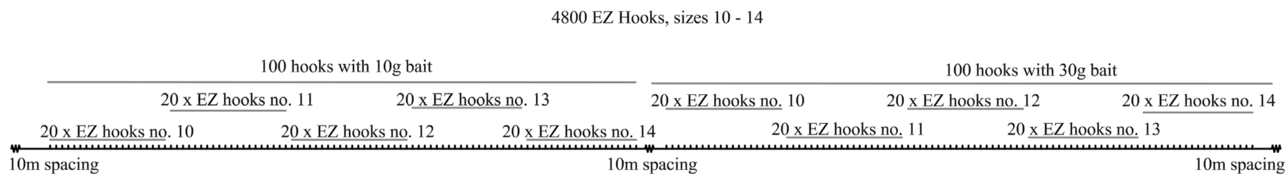

Fig. 3. Experimental setup, explaining how hook and bait sizes were arranged.

Table 3
Catches in number of fish for each bait size for all trips and catch increase/decrease with large bait. Total catches from all trips are given in both number of fish and catch weights. The total weights given are calculated from length-weight relationship for individual species.

	Bait size (g)	North 1	North 2	North 3	North 4	North 5	South	Total no. fish	Total weight
Cod	10	143	187	41	6	27	78	482	716
	30	111	229	42	5	6	93	486	1036
		−22%	22%	2%	−17%	−78%	19%	1%	45%
Haddock	10	180	162	98	3	6	333	782	900
	30	82	34	20	2	0	153	291	387
		−54%	−79%	−80%	−33%	−100%	−54%	−63%	−57%
Wolffish	10	1	10	0	196	80	0	287	455
	30	0	26	1	237	73	1	324	711
		−100%	160%		21%	−9%		13%	56%
Ling	10						41	41	66
	30						63	63	116
							54%	54%	76%
Tusk	10						166	166	124
	30						170	170	168
							2%	2%	35%

2.2. Statistical analyses

The total catch weight was calculated, applying a standard allometric equation to predict fish weight (W) at length L, $W = a \times L^b$. We calculated the parameters a and b for each species, from data collected by the Marine and Freshwater Research Institute (MFRI) stock assessment surveys (Anon., 2016).

Due to their natural order, hook sizes were treated as a continuous measurement in the statistical analysis. In order to determine whether hook size and bait size affected the sizes of the captured fish, as well as differences between northern and southern areas, we used a linear regression model for each species. Explanatory variables were elimintated backwards, based on AIC values (see e.g. Venables and Ripley, 2002) starting with:

$$FL = \beta_0 + \beta_1 \times Hooksize + \beta_2 \times Baitsize + \beta_3 \times Hooksize \times Baitsize + Area \quad (1)$$

where FL is fish length, β_0, β_1, β_2 and β_3 are the parameters to be estimated, *Hook* size refers to hook sizes 10–14, *Bait size* is zeros and ones, for 10 and 30 g baits respectively. *Area* is zeros and ones respectively for the North and South areas, and *Hook size* × *Bait size* was included to investigate the effect of hook size – bait size interaction. For replicate trips for cod and haddock catches, a mixed model was employed that took into account variations between trips (random effects) using the lme function in the nlme library in R (Pinheiro et al., 2016; R Development Core Team, 2015). In the case of random effects, the model becomes:

$$FL = \beta_0 + b + \beta_1 \times Hooksize + \beta_2 \times Baitsize + \beta_3 \times Hooksize \times Baitsize + Area \quad (2)$$

where b is the vector of random effects for trips, assumed to be normally distributed with mean 0 and variance $\sigma_b{}^2$.

A generalised least squares (gls) model was fitted to the same data using the gls function, also in the nlme library in R. The choice of model (mixed model vs. gls for cod in the northern area and haddock) was made by applying the likelihood ratio test (Zuur et al., 2009).

For visual presentation, inspection and to simplify comparisons, catches for each bait size = b and hook size = h from each trip were scaled by dividing the number of fish = n per trip and bait size by the mean number of fish = $\bar{n}$ caught on a given size on a given trip.

$$n'_{h,b} = n_{n,b}/\bar{n}_b, \qquad h = 10, \ldots, 14, \quad b = 10, 30 \quad (3)$$

A linear regression, $N = \beta_0 + \beta_1 \times$ *Hook size,* weighted by number of fish, was then run to evaluate the plausibility of hook size-related catch differences. On the plots of N as function of hook size, the regression lines are shown solid where slope parameter β_1 deviates significantly from zero ($p < 0.05$), but broken lines for $p > 0.05$. The slope parameters are shown on the plots along with p-values.

When two bait sizes, A (10 g) and B (30 g) are employed, the response probability $\pi = \pi(l)$ that a fish of length $l = (l_1, \ldots, l_j)$ is caught on bait B, given that it can be caught by either A or B, can be considered binary and modelled accordingly. A binomial generalised linear model (GLM) with a logit link was fitted to calculate the probability π. The following model was applied to the data, for separate species:

$$\text{logit}(\pi) = \beta_0 + \beta_1 \times fishlength \quad (4)$$

In the case of two or more replicate trials, the between-trial variation is taken into account by using a GLMM model (Zuur et al., 2009):

$$\text{logit}(\pi) = \beta_0 + \beta_1 \times fishlength + b \quad (5)$$

where b is the vector of random intercepts for trips, assumed to be normally distributed with mean 0 and variance $\sigma_b{}^2$. The estimated fish lengths where the two bait sizes catch equal numbers of fish can be calculated from the model results as $-\beta_0/\beta_1$ (Venables and Ripley, 2002).

We employed a GLMM using the glmer function in the lme4 library (Bates et al., 2015a,b) in R. Confidence bounds are plotted with the logistic regression curves as $\text{logit}(\pi) \pm 1.96 \times \text{SE}(\text{logit}(\pi))$

Table 4
Total number of fish caught in each of the areas, along with size ranges and mean fish lengths (cm) for both bait sizes.

		Northern area				Southern area			
			Fish length				Fish length		
Species	Bait size	n	min	mean	max	n	min	mean	max
Cod	10	404	20	45.7	83	78	40	70.3	116
	30	393	25	55.0	90	93	45	71.9	115
Haddock	10	449	20	44.8	70	333	39	51.9	66
	30	138	22	47.3	62	153	40	53.1	64
Wolffish	10	287	30	56.0	95	0			
	30	324	33	63.6	90	1	48	48	48
Ling	10	0				41	41	62.6	99
	30	0				63	32	64.8	118
Tusk	10	0				166	31	43.1	63
	30	0				170	31	46.9	78

Table 5
Effects of bait sizes and hook sizes on the size of fish caught with longlines. Linear mixed effect models for haddock and cod, generalised least squares model for wolffish and linear model for Tusk (models 1 and 2). Neither hook size nor bait size had significant effects on the sizes of ling or cod caught in the southern area.

Species	Parameter	Explanatory variable	Estimate	Std.error	p-value
Cod - North	β_0	Intercept	27.12	5.65	<0.001
	β_1	Hook	1.44	0.44	<0.01
	β_2	Factor (bait 30g)	26.9	7.15	<0.001
	β_3	Hook × factor (bait 30g)	−1.48	0.61	0.015
	σ_b		3.74		
Haddock	β_0	Intercept	45.98	2.35	<0.001
	β_2	Factor (bait 30g)	1.68	0.378	<0.001
	σ_b		4.69		
Wolffish	β_0	Intercept	41.45	4.48	<0.001
	β_1	Hook	1.27	0.38	<0.001
	β_2	Factor (bait 30g)	7.26	1.08	<0.001
Tusk	β_0	Intercept	43.1	0.5	<0.001
	β_2	Factor (bait 30g)	3.83	0.7	<0.001

(see eg. Hosmer and Lemeshow, 2000). SE(logit(π)) is the square root of the diagonal elements of the covariance matrix for the fitted values (see eg. Zuur, 2012 for practical examples using R). The procedures for calculations of confidence bounds are the same for GLM as GLMM, as the random component is treated as nuisance parameter.

Two-sample, two-tailed *t*-tests were used to test for differences in mean length of fish caught on each of the two bait sizes.

2.3. Model evaluation

For the linear regression models investigating the effect of bait and hook sizes on fish size, the likelihood ratio tests for cod and haddock indicate that the models that incorporate random intercepts are considerably better than the gls models. For cod North, $L = 16.88$ ($df = 1$, $p < 0.001$), for haddock $L = 412.6$ ($df = 1$, $p < 0.001$). For wolffish, the random intercept model was rejected in favour of the simpler gls model ($L = 5.87$, $df = 1$, $p = 0.99$). For tusk, with catches from one trip, a general linear model was employed. For cod South and ling, effects of hook and bait sizes were insignificant and no models are therefore presented. Model diagnostics for both linear and logistic regression were performed by visual residual inspection. In addition, the logistic models were checked for dispersion (Venables and Ripley, 2002). The residuals for all models were fairly well behaved, in that they did not violate assumptions of homogeneity or normality. The dispersion parameters were within reasonable limits, ranging from 0.86 to 1.43.

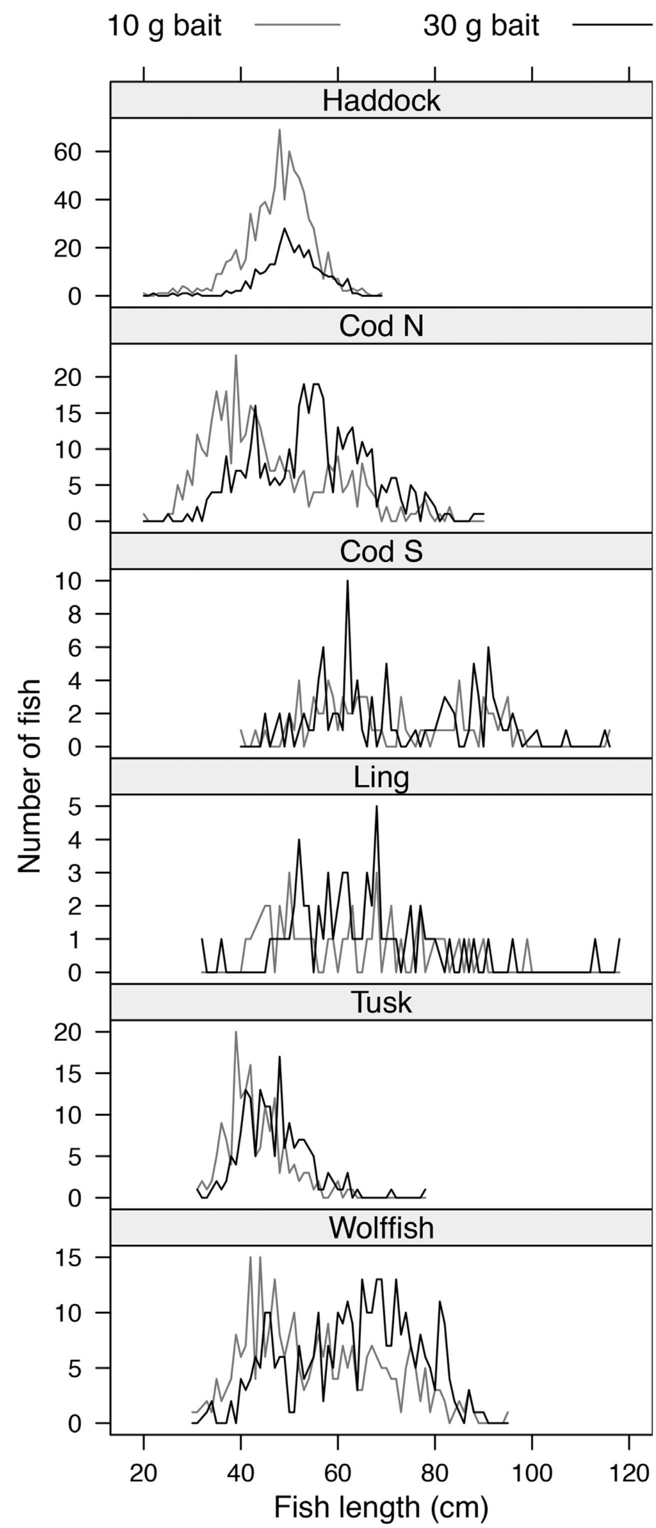

Fig. 4. Size distribution of all species for both bait sizes.

3. Results

3.1. Main catches

Cod and haddock dominated the catches in the four trials carried out during the winter months (North 1, 2, 3 and South; Table 3). Wolffish was the most prevalent species in the two trials in April (North 4 and 5), while tusk and ling were caught only in the southern area. Species such as redfish (*Sebastes* spp.), plaice (*Pleuronectes platessa*), whiting (*Merlangius merlangus*), spotted wolffish (*Anarhichas minor*), thorny skate (*Amblyraja radiata*), saithe (*Pollachius virens*), dab (*Limanda limanda*) and common dab (*Hippoglossoides platessoides*) were also caught, but in too limited numbers to be included in the statistical analyses.

3.2. Effects of bait size

The larger bait caught more large cod, wolffish and tusk and fewer small fish of these species than the smaller bait (Figs. 4 and 5). The mean lengths of cod (in the northern area), wolffish and tusk caught on the larger bait were therefore higher than those caught on the smaller bait (t-test, $p < 0.001$; Tables 4 and 5). The estimated fish lengths where the two bait sizes caught equal numbers of fish were 49.0 cm, 56.8 cm and 44.6 cm respectively, for the three species. Above these lengths the larger bait caught 133% more cod, 81% more wolffish and 63% more tusk by number.

The larger bait caught 54% more ling than the smaller bait. The catches of ling were relatively small, and although the mean length of ling was larger with the larger bait than the smaller bait (Table 4), the size-selective effect of bait size was not significant (Table 5).

The larger bait caught 57% fewer haddock than the smaller bait. The proportion of fish caught on the larger bait increased with fish size, and from the logistic curve, estimated equal catches for the two bait sizes would be at 65.2 cm fish length. The mean length was significantly higher with the larger than the smaller bait ($p < 0.001$; Tables 4 and 5).

3.3. Effects of hook size

The smallest hook produced higher catches (in number) of all species than the larger hooks, i.e. catch efficiency fell with increasing hook size. The hook size comparisons (Fig. 6) indicate that compared to estimated scaled catches of 1 made with hook size no. 12, the increase in catches would be expected to be 8–21% for every reduction in hook size ($\beta_1 = 0.8–0.21$).

There was no size-selective effect of hook size for haddock, tusk or ling. Hook size affected size selectivity only for wolffish, and for cod in the northern area. The mean length of wolffish caught increased by 1.3 cm for each increase in hook size, irrespective of bait size (Tables 4 and 5). For cod in the northern area, there were interactions between bait size and hook size, i.e. hook size affected size selectivity when the small baits were used but not with the larger baits (Table 5). With the smaller baits, the mean size of cod increased by 1.4 cm with every increase in hook size.

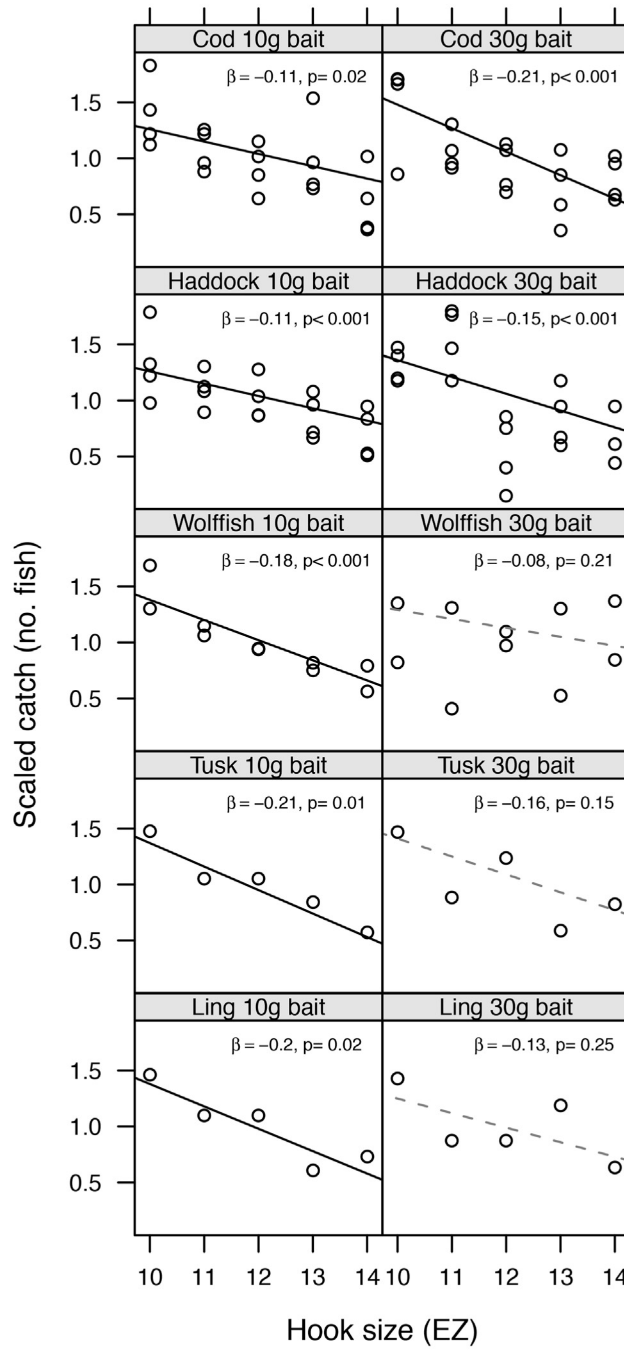

Fig. 5. Scaled catch rates for each of the hook sizes and both bait sizes for all species. Regression lines are drawn through the points and are shown solid where catch rates decrease significantly ($p < 0.05$) with hook size.

4. Discussion

4.1. Effects of bait size

The size of the bait affected size selectivity in demersal longlining. The larger bait caught more large fish and fewer small cod, wolffish, tusk and ling. The use of larger baits will increase the profitability of these fisheries due to both higher catch rates and higher market prices for larger fish, although this effect will be partly counteracted by higher bait costs. Using large bait is therefore an important incentive for fishermen to observe fishery regulations.

Studies have shown that bait size affects size selection in longline fishing for cod and haddock (McCracken, 1963; Løkkeborg, 1990; Johannessen et al., 1993; Løkkeborg and Bjordal, 1995; Huse and Soldal, 2000). These studies showed that larger baits caught fewer small fish than smaller baits, while bait size did not affect catch rates of larger fish, as large and small baits caught similar numbers of large fish. Behavioural studies of cod indicated that this is because small cod ingest large baits less frequently than small baits (Johannessen et al., 1993). Our findings showed that the large bait caught more large fish than the small bait, demonstrated for several groundfish species. This effect of bait size was not found by the studies cited above. Several studies of prey preference by fish show selection for certain sizes (Hart, 1986), and a linear relationship between predator size and optimal prey size have been observed (Werner, 1974). Furthermore, larger baits release more scent (i.e. have a higher release rate of attractants) and will therefore disperse bait odours over a larger area. Larger fish have a larger foraging area thanks to their greater swimming capacity (Hart, 1986), and constraints on feeding activity are less pronounced in larger fish due to their lower risk of predation (Milinski, 1986). Larger baits may therefore attract more large fish than small baits.

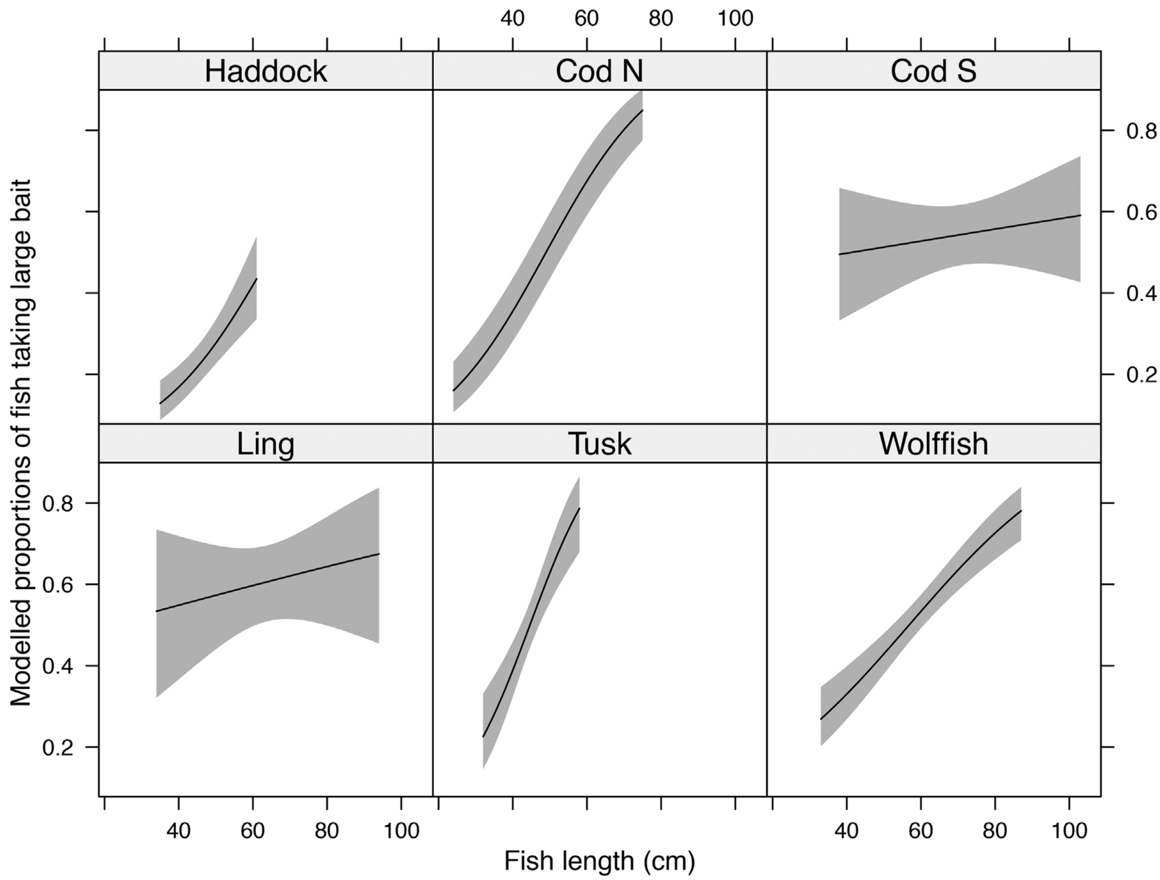

Fig. 6. Modelled proportions of fish taking large bait rather than small as a function of fish size. The preference plots for cod are shown for each of the two survey areas due to the observed differences in bait size preferences.

This effect, in combination with the limited ability of small fish to ingest large prey items, explains our findings.

4.2. Effect of hook size

Larger hooks significantly reduced catch rates. The decrease in efficiency with hook size is in line with results obtained for porgies (*Pagellus* spp., Erzini et al., 1996). Smaller hooks are constructed of thinner wire, which requires less force to penetrate the mouth cavity, and are therefore likely to result in higher hooking rates (Bjordal and Løkkeborg, 1996). Our findings demonstrated that this effect of hook size on catch efficiency applies to several species.

A small increase in fish size as hook size increased was only observable for cod in combination with small baits in the northern area, and for wolffish. Wolffish have been observed to swallow the bait quickly (Godø et al., 1997), compared to cod and haddock, which are generally more cautious, touching the bait with their lips or barbels before biting it (Johannessen et al., 1993; Løkkeborg et al., 1989). Larger hooks not only have a lower probability of hooking, but are also less likely to be swallowed by smaller fish, which could explain the size-selection property of hook size for wolffish.

4.3. Implications for fisheries managers and fishermen

When a surveillance programme reveals unacceptable proportions of undersized fish in catches, fisheries managers may close fishing areas or enforce gear restrictions. When we know that bait sizes affect fish size selection, an enlightened decision can be taken to require minimum bait sizes in areas where catches of undersized fish have exceeded acceptable limits.

For fishermen, knowledge of bait size affecting size composition of catches is a practical matter. By reducing catches of small fish, area closures due to a high proportion of undersized fish being taken are less likely to be necessary. There is also an incentive for fishermen to catch selective as higher market prices are obtained for larger fish. In line with the FAO code of conduct for responsible fisheries (FAO, 1995), fishermen's decision-making in terms of avoiding catches of undersized fish is also a matter of responsibility.

Information regarding catch efficiency are useful to fishermen for taking decisions to increase catches and thereby revenues. Our results on hook size affecting catch efficiency show that choices of hook sizes impact fishermen incomes. Also, with the knowledge that larger baits yield greater catches of larger fish, fishermen can assess the additional bait cost versus likelihood of catch increase. Furthermore, larger baits resulted in reduced haddock catches and increased catches of cod, wolffish, tusk and ling at various levels. These findings could be used to partially control the species composition of catches in a mixed fishery.

5. Conclusions

Our results demonstrate a significance effect of hook size and bait size on capture efficiency and size selectivity in longline fisheries. Larger baits increased catch rates and took larger fish. They also caught fewer undersized fish, which in turn reduces discard rates. Finally, smaller hooks increased capture efficiency. These effects give fishermen economic incentives to comply with regulations such as minimum landing sizes and discard bans.

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