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Selective flatfish seine: a knee-high demersal seine barely catches cod

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Norwegian coastal cod (*Gadus morhua*) protection restricts the use of active fishing gears. Demersal seines, acknowledged as being efficient for targeting flatfish, are therefore largely excluded from the fjords. To exploit plaice (*Pleuronectes platessa*), a species-selective gear that avoids catching cod is needed. We therefore designed a low-rise demersal seine with a 0.6 m vertical opening and tested it on fishing grounds in Lofoten (Northern Norway), comparing it with a conventional seine that had a vertical opening of $\sim$3.5 m, and fished both during the day and at night. Six to nine hauls were taken with each of the four gear/time-of-day categories (32 hauls in total). The low-rise seine caught no fewer plaice during day-time fishing, but less at night. Cod and haddock (*Melanogrammus aeglefinus*) catches were reduced by 94% and 98%, respectively, while catches of sole (*Solea solea*) increased with the low-rise seine. No catch differences were found for halibut (*Hippoglossus hippoglossus*), common dab (*Limanda limanda*), or monkfish (*Lophius piscatorius*). The low-rise seine therefore enables targeting flatfish while avoiding gadoid catches, although loss of plaice during night-time fishing is to be expected.

Keywords: cod, Danish seine, demersal seine, flatfish, haddock, plaice, species separation.

Introduction

A widespread and difficult challenge in many fisheries around the world is to protect vulnerable and protected species while maintaining profitable catches of the target species. In Northern Norway, fishing with trawls and demersal seine is banned in fjords in order to protect the declining stock of coastal cod (*Gadus morhua*). Vessels using towed fishing gears are forbidden to operate in fjords, and plaice (*Pleuronectes platessa*) and other flatfish are therefore unexploited species in Norwegian coastal waters.

Similar problems exist in other regions. Low quotas of cod in the North Sea and Baltic Sea trawl fisheries limit the ability of fishermen to catch flatfish (Madsen *et al.*, 2006), while the low cod quota in the New England groundfish fishery restricts trawling for relatively abundant flatfish species (Eayrs *et al.*, 2017). Similarly, for fishermen who target flatfish on the west coast of the United States, catches of rockfish (*Sebastes* spp.), sablefish (*Anoplopoma fimbria*) and Pacific halibut (*Hippoglossus stenolepis*) can be a problem, because quotas are limited relative to flatfish quotas (Lomeli and Wakefield, 2016).

Fishermen operating on many fishing grounds thus face the same classic mixed-species fishery problem that can probably only be solved by implementing more selective fishing operations. Fishing gear restrictions to improve selectivity is a management option that is more acceptable to fishermen than for example area or seasonal closures. Several trawl designs that can avoid roundfish while they harvest flatfish have been tested (e.g. Madsen *et al.*, 2006; Madsen and Valentinsson, 2010; Lomeli and Wakefield, 2016). The most promising methods are based on differences in behavioural patterns between target and non-target species when they encounter the approaching gear and interact with the trawl mouth. Observations have shown that most gadoid species tend to rise when they enter the trawl, while flatfish stay close to the sea bed (Thomsen, 1993). The low-rise trawl design (i.e. trawls with a low headline height) with either large meshes in the top panel or a reduced top panel (termed topless, coverless, or cutaway trawls) utilizes this behavioural difference to reduce gadoid bycatch (Eayrs *et al.*, 2017).

However, the results of studies that have tested trawl designs with lower headline heights are inconsistent and sometimes inconclusive (Eayrs *et al.*, 2017). Thomsen (1993) tested a topless trawl on the coast of the Faroe Islands and obtained 38% reduction in cod catches and more than 90% in haddock (*Melanogrammus aeglefinus*) and saithe (*Pollachius virens*), with no loss of flatfish. Madsen *et al.* (2006) used a low-rise trawl with large meshes (400 mm full mesh) in the top panel, and obtained a 15% reduction in bycatches of cod in the North Sea flatfish fisheries. Using a topless trawl at Georges Bank, Chosid *et al.* (2008) reported a 56% reduction in cod, but also a significant reduction in the target catch of yellowtail flounder (*Limanda ferruginea*). In the Gulf of Maine, Eayrs *et al.* (2017) obtained a similar reduction in catch of cod (51%), with no significant loss of flatfish species.

Cod is the gadoid bycatch that seems to be most difficult to avoid, as they enter the trawl close to the lower panel (Thomsen, 1993; Ingólfsson and Jørgensen, 2006; Krag *et al.*, 2010). Krag *et al.* (2015) showed that a topless trawl with a headline height of 2.4 m had no effect in reducing catches of cod, and a meta-analysis of vertical stratification in demersal trawls demonstrated that very few cod rise above separator panels that are more than 1.5 m high (Fryer *et al.*, 2017), which suggests that the separation effect for cod is very sensitive to the headline height of the gear.

We therefore tested a demersal seine with very low (0.6 m) vertical opening, as our aim was to obtain a near-zero catch of cod while maintaining viable catches of plaice. Several roundfish and flatfish species display diurnal variations in behavioural responses to towed fishing gear (Engås and Ona, 1990; Ferro *et al.*, 2007; Chosid *et al.*, 2008; Krag *et al.*, 2010; Fryer *et al.*, 2017), and ambient light levels have been shown to influence their avoidance behaviour (Glass and Wardle, 1989). Our behavioural-based gear design was therefore tested both at night and during the day.

Material and methods

Fishing vessel, gear, and area

The commercial seiner M/S Hornsund, with an l.o.a. of 14.1 m, was chartered for trials 10–19 October 2017 in ICES subarea IIa, on fishing grounds off Lofoten, Northern Norway (Figure 1). The performance of a low-rise two-panel seine was compared with that of a conventional seine. The low-rise seine had a fishing circle of 84 meshes in 140 mm mesh size, yielding 11.8 m stretched circumference (Figures 2 and 3). The seine had a 49.6-m long fishing line and a wing height of 0.6 m. The mouth height was approximately 0.6 m, estimated from underwater video recordings using the single 130 mm diameter float on the headline as a reference and using *ImageJ* image software for measurements (Schneider *et al.*, 2012).

Before the fishing trials, the seine was tested full size in a flume tank, without the 20 m wings. Floats on the 10 m mid-section were not found to be necessary, but one 130 mm diameter float (0.8 Kp) was left at the centre of the opening in order to ensure that the headline kept clear of the footrope during setting. The number of meshes in the fishing circle was adjusted to gain the desired height of 0.6 m. A previous version of the seine with a tapered belly resulted in an “hour-glass” form and narrow codend entrance. The N-cut seine belly in our design ensures an open passage to the codend.

The vessel’s own demersal seine, which had a fishing circle of 240 meshes in 200 mm mesh size (48 m stretched circumference) and a 71.5-m-long fishing line, was used as a control (Figure 3). The wings had 200 mm mesh sizes while the seine belly was constructed of 150 mm meshes. From underwater video recordings, the mouth height was estimated to be approximately 3.5 m. Both seines were horizontally symmetrical, i.e. no headline overhang (square), and had identical 125 mm (nominal) square meshed codends with 2.8 m circumference. They were fished with 32 mm seine ropes, setting rope lengths of 900–1000 m, and towing at speed of $\sim$0.6–0.7 ms^{-1}.

The hauls, which alternated between test and control seines, were made during the day and at night, defining day as the time between sunrise and sunset, and night as the time between sunset and sunrise (Table 1). Daytime at the beginning of the experiment was 07: 49 to 17: 49 and 08: 23 to 17: 11 on the last day (www.timeanddate.com, location: Henningsvær). Fishing depths and temperatures were monitored with depth and temperature loggers (RBR Duet, www.rbr-global.com) attached to the seines. Depths ranged from 17 to 52 m and temperatures from 10.5°C to 11.9°C. Tow duration varied from 23 to 50 min.

Sampling and data analyses

All fish were identified to species, counted, and total length (TL) measured to nearest cm below (Table 2). In 19 out of 32 valid hauls plaice were subsampled (28–75 fish, Table 1). Of 12 species caught, 7 species: cod, haddock, plaice, sole (*Solea solea*), monkfish (*Lophius piscatorius*), common dab (*Limanda limanda*), and halibut (*Hippoglossus hippoglossus*), were sufficiently abundant to permit statistical analyses. Thorny skate (*Amblyraja radiata*), wolffish (*Anarhichas lupus*), saithe, turbot (*Scophthalmus maximus*), and grey gurnard (*Eutrigla gurnardus*) were also observed in the catches, but were too few for analyses. The hauls with alternating gears were taken pairwise within the same day/night in the same area, however 8 out of 32 hauls were incomplete, i.e. paired hauls were not achieved within the same day/night.

To test differences in the total number of fish between the seines, generalized linear mixed (GLM) effect models with negative binomial distribution and log link were initially run for each species, with pairs as random effects and fixed effects for gear (control = 0 vs. test = 1), time (day = 0 vs. night = 1), setting depth (m), and tow duration (min). A full model was run, including gear–time interaction. To assess model improvement due to inclusion of the random effect (between-pair variation), a GLM model without random effects was then run and the significance of the random effects evaluated improvement in model fit due to the random effects were found to be negligible ($X^2 < 0.0001$, DOF = 1, $p \approx 1$ for all species). The insignificance of the random factors argues for omitting a mixed effect model, in favour of the simpler GLM. We applied the function “gam” in the R library mgcv (R Core Team, 2018; Wood, 2017), with the linear component $y = \log(\text{number of fish})$:

$$y \sim \beta_0 + \beta_1 \times \text{gear} + \beta_2 \times \text{time} + \beta_3 \times \text{depth} + \beta_4 \times \text{duration} + \beta_5 \times \text{time} \times \text{gear} \tag{1}$$

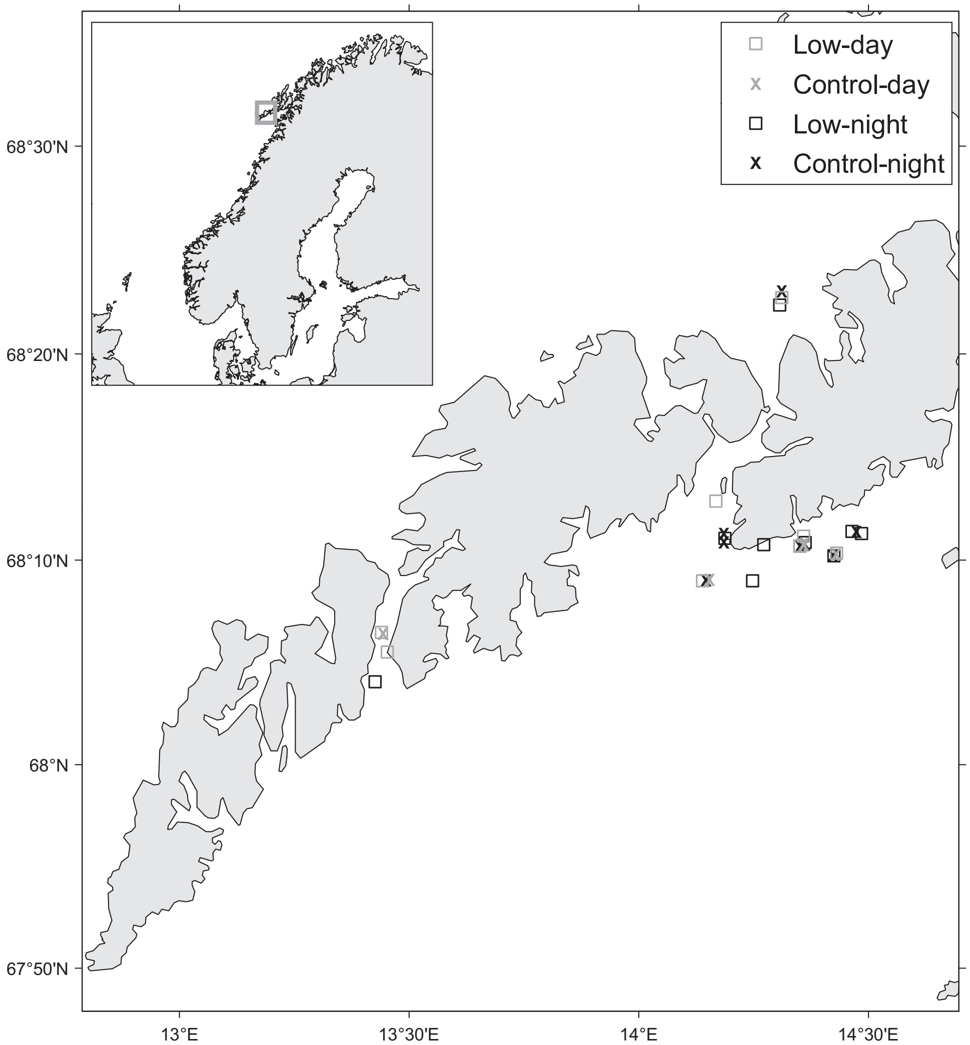

Figure 1. Map of the experimental area in Lofoten (Northern Norway).

Model selection were performed by backwards elimination of explanatory variables based on likelihood ratio tests.

For cod and plaice, a logistic regression analysis was performed to paired hauls to assess length-dependent catch loss. A binomial GLM model with a logit link was fitted, for assessing relative catch rates and length dependency in the test vs. control gear. The probability π, of fish of length L being caught in the test seine, given its retention in either seine, was calculated, starting with the model:

$$\text{logit}(\pi) = o + \alpha_0 + \gamma + \alpha_1 \times L + \alpha_2 \times \text{time} + \alpha_3 \times \text{time} \times L \quad (2)$$

The α's are the model parameters and γ the between-pair random effect vector for the intercept α_0, assumed to be normally distributed with mean 0 and variance σ^2. The α_2 term allows for testing significance in curve shifts, and α_3 reveals differences in slope parameters (different α_1's for day = 0 and night = 1). Due to subsampling of plaice for length measurement, the model was fitted to unraised data and $o = \ln(q_{1L}/q_{2L})$ set as an offset variable, where q_{1L} and q_{2L} denote the sampling proportions for fish of length L in the test and the control seines, respectively (Table 1). The "best" model was selected by backwards elimination of explanatory variables, based on likelihood-ratio tests. All p-values presented in the text are from the fitted models (Table 3).

We used the function *glmer* in the *lme4* library to fit the binomial GLM model in R (Bates *et al.*, 2015). Catch comparison curves with 95% confidence intervals are shown as well as size distributions from both seines, day and night (Figure 6). The confidence intervals are calculated as $\text{logit}(\pi) \pm 1.96 \times \text{s.e.}(\text{logit}(\pi))$ (Hosmer and Lemeshow, 2000; Zuur, 2012). There was no detectable overdispersion (Pearson squared residuals/residual degrees of freedom = 0.83 for cod and 0.97 for plaice).

Results

A total of 17 hauls were made with the low-rise seine, of which eight took place during the day and nine at night. The control gear was used for 15 hauls, 7 during the day and 8 at night. From image sequences taken from underwater recording at 1 min intervals throughout a 30-min tow, the average headline height was measured to be 0.58 m (SD = 0.18 m, Figure 4). One observation of 1.5 m is caused by a short stop, when the seine hit a boulder. The headline height reduces to 0.40–0.45 m the last 4 min of the tow as the speed increases when the ropes gradually became

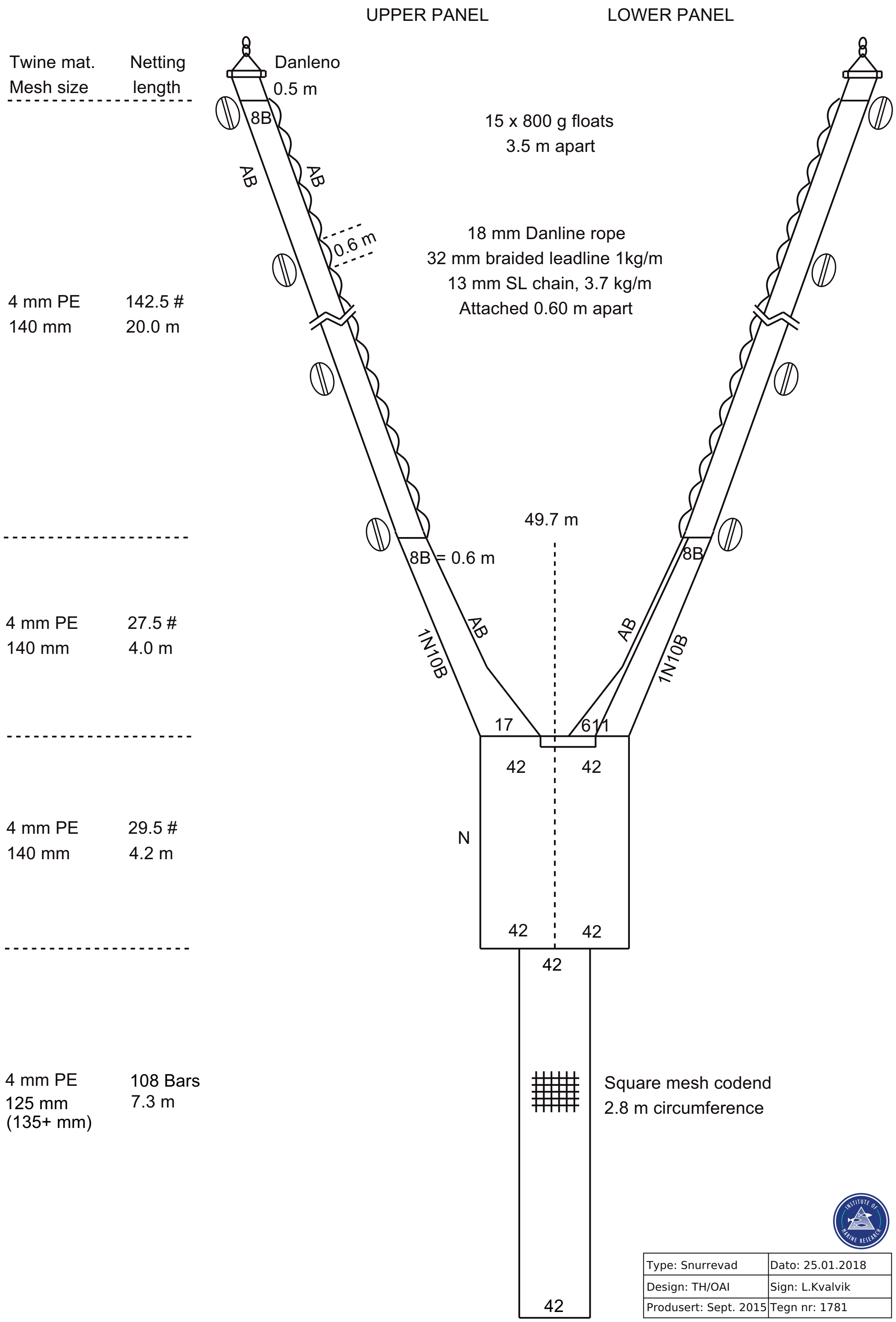

Figure 2. Plan view of the low-rise seine.

parallel to the towing direction. No effect of tow duration on catch was detected for any of the species. Final models from the negative binomial analysis, describing mean catches of each species as function of time, gear, and depth are shown in Table 3.

During the day, there was no significant difference in the mean catches of plaice between the low-rise and the control gear (323 and 171, respectively, Figure 5, $p = 0.22$). At night, the low-rise gear caught significantly fewer plaice than the control (62 and

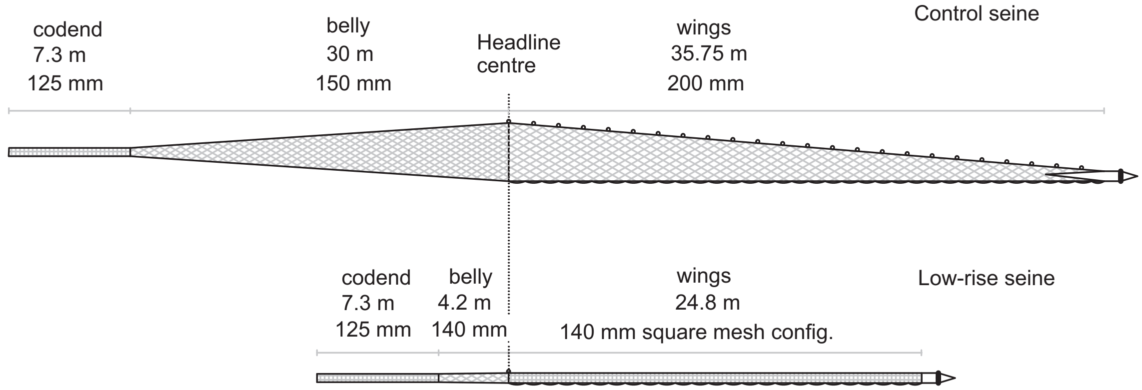

Figure 3. Both seines drawn in scale, showing lengths and mesh sizes of wings (half headline/fishing line lengths), belly (from bosom to forepart of codend), and codends.

Table 1. Haul sequence, pairs, date, time (local time, UTC + 1h), and catches by number of plaice, cod, and haddock for individual hauls of the control and low-rise seines.

Haul	Pair	Date (dd.mm.)	Seine	Time	Hour	Plaice	Species cod	Haddock	Sampling rate plaice
1	1	10.10.	Low rise	Day	10: 59–11: 33	128	0	0	0.547
2	1	10.10.	Control	Day	12: 34–13: 00	42	3	6	1
3	2	10.10.	Low rise	Day	14: 17–14: 40	41	1	0	1
4	2	10.10.	Control	Day	16: 40–17: 10	310	1	0	0.155
5	3	10.10.	Control	Night	18: 05–18: 46	250	25	0	0.112
6	3	10.10.	Low rise	Night	19: 45–20: 23	42	0	0	1
7	4	11.10.	Low rise	Day	15: 45–16: 09	380	4	0	0.134
8	4	11.10.	Control	Day	17: 35–17: 58	300	77	22	0.153
9	5	12.10.	Control	Night	02: 24–02: 50	530	1	0	0.0830
10	6	13.10.	Low rise	Day	14: 23–14: 58	310	0	0	0.223
11	6	13.10.	Control	Day	16: 45–17: 20	120	68	37	0.358
12	7	13.10.	Control	Night	18: 40–19: 17	220	51	7	0.195
13	7	13.10.	Low rise	Night	21: 30–22: 00	21	2	0	1
14	8	14.10.	Control	Night	00: 40–01: 20	54	7	10	1
15	9	16.10.	Low rise	Day	12: 30–12: 58	14	0	1	1
16	9	16.10.	Control	Day	13: 50–14: 31	18	2	9	1
17	10	16.10.	Low rise	Day	15: 18–15: 56	1291	0	0	0.0442
18	11	16.10.	Low rise	Night	20: 31–21: 06	71	2	4	1
19	12	17.10.	Low rise	Night	17: 45–18: 12	252	6	0	0.298
20	12	17.10.	Control	Night	19: 25–19: 58	388	13	13	0.165
21	13	17.10.	Low rise	Night	21: 35–22: 10	17	2	0	1
22	13	17.10.	Control	Night	23: 01–23: 26	165	23	11	0.133
23	14	18.10.	Low rise	Night	02: 34–02: 59	5	0	0	1
24	15	18.10.	Low rise	Day	16: 41–17: 11	121	1	0	0.554
25	16	18.10.	Control	Night	18: 20–19: 10	77	33	7	1
26	17	18.10.	Low rise	Night	20: 30–20: 55	38	0	0	1
27	17	18.10.	Control	Night	21: 39–22: 10	116	4	52	0.517
28	18	18.10.	Low rise	Night	23: 53–00: 28	8	0	0	1
29	19	19.10.	Low rise	Day	14: 50–15: 15	297	0	0	0.192
30	19	19.10.	Control	Day	16: 03–16: 37	234	6	69	0.291
31	20	19.10.	Low rise	Night	18: 25–18: 49	107	7	0	0.533
32	20	19.10.	Control	Night	19: 31–19: 54	125	50	10	0.480

The subsampling fractions for plaice are also given.

214, respectively, $p < 0.01$). The catches taken by the low-rise gear at night were also significantly lower than those taken during the day ($p < 0.01$). At night there was significant length-dependent reduction in catches for the low-rise seine ($\alpha_1 + \alpha_3 = -0.0994$, s.e. $= 0.0203$, $p < 0.001$, Figure 6). For fish of lengths below 37 cm, catch reduction was insignificant. For the low-rise gear, about half of the day- and night-time catches came from haul 17 and 19, respectively. Excluding these hauls from the analysis, however, did not alter the results.

Both day and night catches of cod taken by the low-rise gear were low (6 and 19 cod, respectively). These catches were significantly lower than those taken by the control gear (157 and 207, $p < 0.001$). The logistic regression [Equation (2)] revealed no length-related catch differences for cod ($\alpha_1 = -0.0190$,

Table 2. Total catches during day and at night of all species, mean lengths, standard deviations, and length ranges for the control and low-rise seines.

				Fish length			
Species	Time	Seine	No	Mean	Std. dev.	Min	Max
Plaice	Day	Control	1024	39.6	5.4	26	64
		Low rise	2582	39.9	5.7	28	62
	Night	Control	1925	40.5	4.9	28	58
		Low rise	561	39.1	4.4	27	54
Cod	Day	Control	157	68.5	12.5	43	127
		Low rise	6	60.0	8.4	50	73
	Night	Control	207	62.3	11.2	32	116
		Low rise	19	60.3	10.4	41	83
Haddock	Day	Control	143	54.6	3.8	44	64
		Low rise	1	57.0	NA	57	57
	Night	Control	116	52.8	4.0	43	65
		Low rise	4	52.5	2.9	49	56
Sole	Day	Control	3	39.7	2.5	37	42
		Low rise	17	39.1	4.0	32	47
	Night	Control	8	35.5	3.3	32	42
		Low rise	32	38.2	3.0	32	44
Monkfish	Day	Control	21	54.2	12.5	34	77
		Low rise	8	54.9	16.1	35	89
	Night	Control	9	48.2	13.2	34	67
		Low rise	5	48.0	21.9	29	85
Dab	Day	Control	93	31.9	4.6	24	43
		Low rise	267	34.2	3.3	24	43
	Night	Control	59	34.5	3.3	26	41
		Low rise	55	33.4	4.1	23	41
Halibut	Day	Control	23	48.3	7.1	40	66
		Low rise	17	47.9	9.0	37	68
	Night	Control	23	54.0	18.4	36	128
		Low rise	37	47.1	6.4	38	67

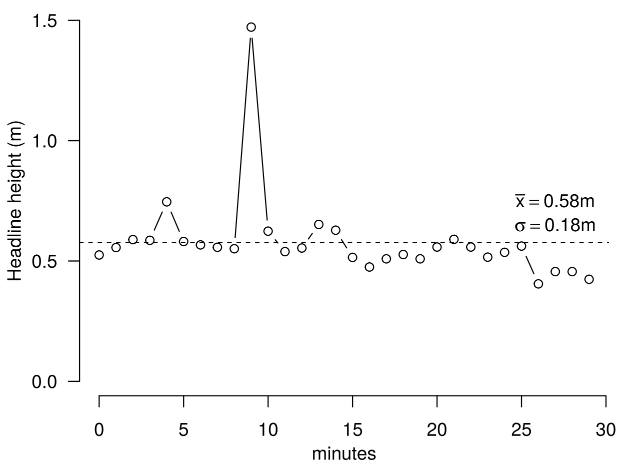

Figure 4. The headline height of the low-rise seine measured with 1-min intervals throughout a 30-min tow from image analysis.

s.e. = 0.0214, $p = 0.38$). Similar results were obtained for haddock, with negligible catches by the low-rise gear (1 and 4), which were significantly lower than the catches taken by the control seine (143 and 116, $p < 0.001$).

Catches of common dab, sole, halibut, and monkfish were low. The catch rate of sole was higher for the low-rise gear than for the control ($p < 0.001$). The catches of sole increased with fishing

Table 3. Parameters with standard errors in parentheses from the final models from the negative binomial regressions for all species.

Parameter	Plaice	Cod	Haddock	Sole	Monkfish	Dab	Halibut
β_0 (intercept)	5.14	3.19	2.85	−2.91	0.296	3.25	2.59
	(0.383)	(0.316)	(0.366)	(0.805)	(0.312)	(0.252)	(−0.0866)
β_1 (gear)	0.637	−2.80	−4.07	1.60			
	(0.506)	(0.474)	(0.670)	(0.456)			
β_2 (time)	0.226					−1.40	
	(0.494)					(0.346)	
β_3 (depth)				0.126			−0.0866
				(0.0334)			(0.0393)
β_4 (duration)							
β_5 (gear: time)	−1.87						
	(0.672)						

For the categorical variables gear and time, the value is 0 for control gear and daytime and 1 for test gear and night.

depth ($p < 0.001$). For common dab, halibut and monkfish, there were no significant differences between the two gear designs. The catches of halibut decreased with fishing depth ($p < 0.05$), and night-time catches of common dab were significantly lower than during the day ($p < 0.001$).

Discussion

This study demonstrates a solution for a classic mixed-species fishery problem that arose from the protection of the Norwegian coastal cod. The low-rise demersal seine produced negligible catches of cod and haddock compared with the conventional control gear.

Our findings could be explained by differences in behavioural responses between gadoid species and flatfish when they encounter towed fishing gear. Several studies have shown that haddock rise from the seabed in front of an approaching trawl (Thomsen, 1993; Ferro *et al.*, 2007; Krag *et al.*, 2010, 2015). A recent meta-analysis (Fryer *et al.*, 2017) demonstrated that most haddock swim above horizontal panels that are less than 1 m high. This behavioural pattern explains our observation that only 2% of the total catch of haddock (5 out of 264) were taken in the experimental seine with a vertical height of 0.6 m.

Previous studies have shown that cod enter a towed gear closer to the seabed than haddock. This difference in behaviour has been used to separate cod and haddock by inserting a horizontal separator panel in trawls (Engås *et al.*, 1998; Ferro *et al.*, 2007; Krag *et al.*, 2010). However, it also makes it difficult to avoid bycatch of cod when targeting flatfish. Various designs of the low-rise trawl concept have been tested to solve this particular mixed-species problem, although only a few have reported reductions of more than 50% in cod catches (Thomsen, 1993; Madsen *et al.*, 2006; Chosid *et al.*, 2008; Eayrs *et al.*, 2017). Most bycatch reductions for cod were in the range of 15–55%, and Fryer *et al.* (2017) concluded that very few cod swim above panels that are 1.5 m high. We obtained encouraging results with our 0.6-m-high seine, which caught only 6% of the total catch (25 out of 389) taken in the two gears. This is slightly higher than the catch of haddock (2%), which is not unexpected because cod swim closer to the seabed.

Catches of sole were significantly larger in the low-rise seine than in the control gear in spite of the seine's shorter wings and lower headline height. A plausible explanation is loss of fish through the larger mesh sizes in the forepart of the control gear.

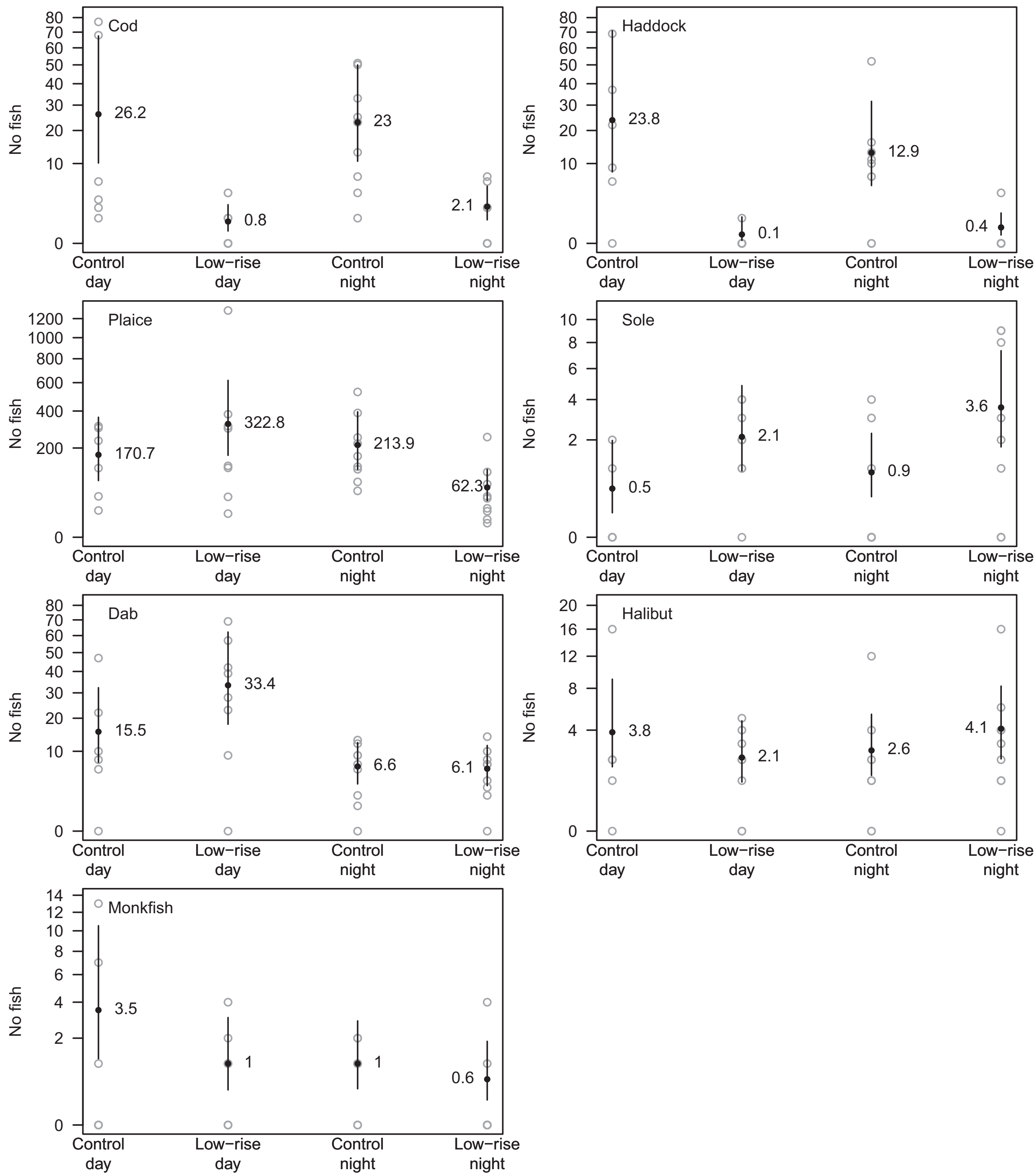

Figure 5. Catches of each species in the experimental categories (control vs. low-rise seine, day vs. night). Catches made by individual hauls are shown as open, grey circles. GLM negative binomial models with gear, and time and gear–time interaction, irrespective of parameter significance, were run to provide arithmetic means of number of fish per haul for each gear both day and night, and provide 95% intervals. The *x*-axes are on the square root scale to avoid loss of details.

The sole has a more elongated body form than the plaice, and mesh sizes in the front part of the gear may therefore have a greater influence on the retention of sole.

The low-rise seine was as least as effective as the conventional seine in catching plaice during the day. At night, however, the low-rise seine had lower catching efficiency than the control gear, with length-dependent catch loss. Similar day and night catches for the control gear indicate that the seine ropes herd fish efficiently also at low light levels. However, the vertical swimming response of plaice may be different during the day and at night.

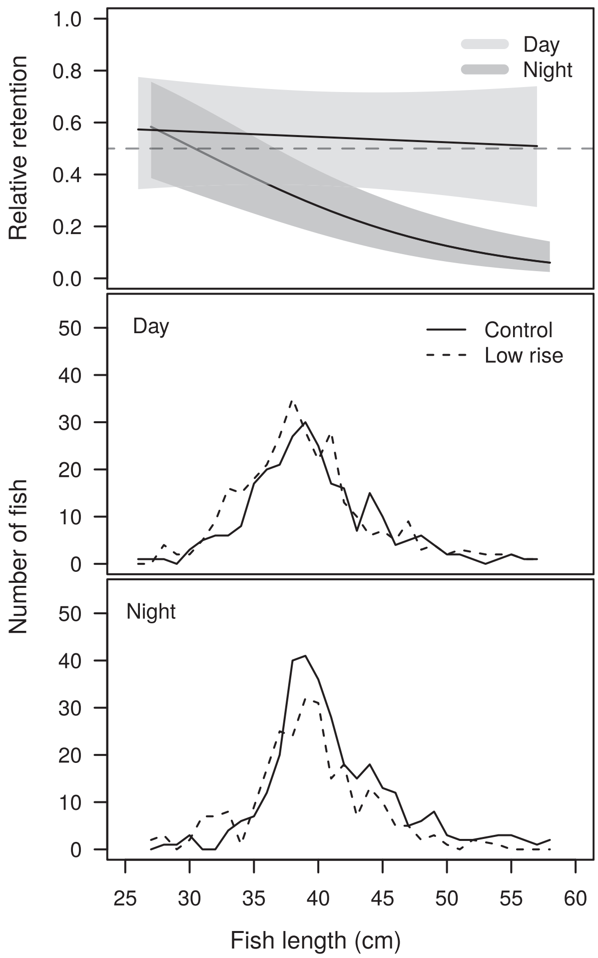

Figure 6. Relative day and night-time catches of plaice for the low-rise seine compared with the control seine (above) from the logistic regression [Equation (2), $\text{logit}(\pi) = 0.522 - 0.00853 \times L + 2.52 \times \text{time} - 0.0914 \times L \times \text{time}$]. The top figure shows mean (solid curves) relative retention in the low-rise seine vs. total catch in both seines, with 95% confidence regions (grey areas) for both day (light grey) and night (dark grey). Length frequency distributions for day (middle) and night-time (below) catches.

Fryer *et al.* (2017) found that a higher percentage of plaice rose above the separation panel at night than during the day. For a prey, the safe distance to a potential predator may be inversely related to visibility conditions. At low light levels, flatfish reacted to approaching gear at a greater distance and displayed a more intense startle response (Walsh and Hickey, 1993). An earlier and stronger startle response by plaice, leading to higher rise above the seabed, could explain the lower night-time catching efficiency of the low-rise gear. Diurnal changes in the vertical responses of cod and haddock have also been found. More small cod and haddock passed below the raised fishing line in a selective haddock trawl at night than during the day (Krag *et al.*, 2010). The length-dependent catch loss of plaice is likely due to size-dependent swimming speed. Distance travelled per tail beat will increase with fish length, and consequently the probability of larger fish to pass above the headline.

Poorer plaice catches at night would have only a marginal impact on coastal fishermen, who typically fish during the day and land their catches daily. While summer days are long at high latitudes, winter days are short. Further studies that aim to increase night-time catches are therefore of interest if fishing is to be conducted in the autumn and winter months. The diurnal changes in efficiency for catching plaice are unlikely to be overcome by extending the horizontal spread of the gear. A moderate increase in headline height could reduce the catch loss, but would probably increase catches of gadoids. An alternative might be to test artificial light during night fishing to mimic daytime fishing conditions.

Concluding remarks

As a management tool, the low-rise seine enables flatfish to be targeted, while avoiding catches of cod and haddock, although some loss of plaice during night-time fishing is to be expected. The critical factor for management control is the headline height, which is determined by design parameters such as circumference of the fishing circle, height of the wings, and limited float at the centre of the gear. These parameters can easily be controlled, and the low-rise design tested here could serve as a guide for selective flatfish fishing using towed gears.

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