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Original research article

Smaller bar spacings in a Nordmøre grid reduces the bycatch of redfish (*Sebastes* spp.) in the offshore Northern shrimp (*Pandalus borealis*) fishery of eastern Canada

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ABSTRACT

The offshore Northern shrimp (*Pandalus borealis*) bottom trawl fishery in eastern Canada currently uses 22 and 28 mm bar spacing Nordmøre grids to limit bycatch from using small mesh codends. However, a recent rebound of juvenile redfish (*Sebastes* spp.), that can pass through the grids, has greatly increased bycatch. To address this concern, this study investigated the effectiveness of 17 and 15 mm bar spacing Nordmøre grids in a twin-trawl (paired) configuration against the traditional 22 mm bar spacing grid. Size selectivity analyses showed that the 17 and 15 mm grids resulted in no significant reduction in shrimp catch across all length classes. The 17 mm grid significantly reduced redfish bycatch for all length classes and the 15 mm grid significantly reduced redfish bycatch for individuals larger than 95 mm total length. Less redfish entered the codend with the experimental grids, however, the overlap in width between redfish and Northern shrimp limits the overall sorting efficiency of the grids, leaving some redfish still vulnerable to capture.

1. Introduction

Bottom trawls targeting shrimp usually use small mesh codends, which often result in considerable amounts of bycatch of juvenile fish from commercially important species (Bayse & He, 2017; Kelleher, 2005). Extensive efforts have been made around the world to reduce shrimp fisheries bycatch (Broadhurst, 2000; Eayrs, 2005), including the use of Nordmøre grids (Isaksen et al., 1992), which are employed to mechanically separate shrimp from larger animals. However, bycatch is an issue that persists in many shrimp fisheries because juvenile fish often have a similar size as the target species, can pass through the bar spacings, and are retained in the small mesh codend (Pérez Roda et al., 2019).

The offshore Northern shrimp (*Pandalus borealis*) bottom trawl fishery in eastern Canada is currently facing an increase in bycatch of juvenile redfish (*Sebastes* spp.) (DFO, 2020). Redfish biomass and recruitment (redfish <150 mm in total length) have increased considerably in recent years (DFO, 2020) and fishing vessels are encountering substantial quantities of juvenile redfish in their catches. Bottom trawls in this fishery are constructed with a small mesh size in order to retain shrimp; a minimum of 40 mm mesh size is authorized throughout the bottom trawl (DFO, 2018), therefore a reduction in the unwanted catch of groundfish species is achieved through the mandatory use of a bycatch reduction device (BRD) known as the Nordmøre grid (Isaksen et al., 1992). The Nordmøre grid was introduced in the Canadian shrimp fishery in 1993 and made mandatory in 1997, with maximum bar spacings of 22 and 28 mm depending on the fishing area (DFO, 2018), although the majority of the fishing effort uses 22 mm bar spacing (Carl Hillier, Newfound Resources Ltd. pers. comm.). Previous work has indicated that there was no difference in shrimp catch between 22 and 28 mm bar spacings in Shrimp Fishing Area (SFA) 6 (Hickey et al., 1993; CAFID, 1997). However, when larger shrimp are captured (which can be typical in SFA 4 and 5), the 22 mm bar spacing was shown to reduce shrimp catch (Orr, 2008). In the 1990's, the use of the Nordmøre grid greatly reduced bycatch in Canada's east coast shrimp fisheries, reducing finfish bycatch from 15% to 2% (>85% reduction by weight) of the total landings of shrimp (ICES, 1998). However, redfish exclusion was still problematic at the regulated bar spacings (ICES, 1996) as juvenile redfish are small and can transit to the codend instead of being excluded at the grid, thus fishing vessels can encounter large amounts of this species in their catch depending on the juvenile redfish abundance in the fishing area.

Abbreviations: BRD, Bycatch Reduction Device.

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There are three species of redfish off the northeast coast of Canada; beaked redfish (*Sebastes mentella*) and Acadian redfish (*S. fasciatus*) are commercially important species, while golden redfish (*S. norvegicus*) is found in smaller abundance (Government of Canada, 2021). They are long-lived and have slow growth rates (Campana et al., 1990), maturing at a size of 22–24 cm for *S. fasciatus* and *S. norvegicus* (Sévigny et al., 2007), and grow up to 38–39 cm (total length) for *S. mentella* (Magnússon & Magnússon, 1995). Both of the main commercial species of redfish were considered threatened under the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2010, and are currently being considered for Schedule 1 classification (Government of Canada, 2021). Therefore, the mortality of juvenile redfish is of concern and could have a negative impact on the stock's recruitment, biomass, recovery and the future of an emerging redfish fishery, as well as an impact on the trophic structures of communities, affecting other important commercial fisheries (Dayton et al., 1995; Devine & Haedrich, 2011).

Recently, conditions of licence have permitted up to 2.5% or 100 kg total weight of incidental catch of groundfish species per tow (DFO, 2018). When this is exceeded, a move-away protocol is triggered, and the vessel must change the fishing area by a minimum of 10 nautical miles from the last tow (DFO, 2018). Thus, vessels are potentially forced to leave shrimp-abundant fishing areas and move to potentially less lucrative areas where juvenile redfish could also be present. This can increase time-at-sea and fuel consumption, which in turn increases the operational costs for the fishing fleet and carbon dioxide emissions. Furthermore, increased amounts of juvenile fish bycatch can reduce shrimp quality and represent a sorting problem in the processing of the shrimp in the onboard factory.

Extensive research has previously been conducted on sorting grids in response to ecological and operational challenges, as well as to reduce the catch of small or undersized shrimp, including bar spacing experiments (CAFID, 1997; He & Balzano, 2012; Hickey et al., 1993; Orr, 2008; Silva et al., 2012; Araya-Schmidt et al., 2022), new grid designs (Grimaldo, 2006; Grimaldo & Larsen, 2005; He & Balzano, 2007, 2011, 2013; Veiga-Malta et al., 2020) and sorting grid configurations (Larsen, Herrmann, Sistiaga, Brinkhof, & Grimaldo, 2018; Riedel & DeAlteris, 1995). However, reducing bar spacing and its potential to reduce juvenile redfish bycatch has not yet been fully assessed. Northern shrimp carapace width (CW) is about 50% of its carapace length (CL) (He & Balzano, 2012), hence even large shrimp with 30 mm CL and 15.05 mm CW have a high probability of passing through the 22 and 28 mm bar spacing grids currently in use. This represents an opportunity to further reduce bar spacing without, in theory, significantly affecting shrimp catches across larger length classes. Yet, mechanical separation alone may not reduce the catch of all juvenile redfish sizes. The size range (body width) of juvenile redfish can overlap the size range (carapace width) of Northern shrimp, therefore the Nordmøre grid is not the ultimate solution, but it could reduce the capture of redfish sizes that do not overlap and still greatly reduce bycatch.

This study compared the size-selectivity of experimental 17 and 15 mm bar spacing Nordmøre grids against the traditional 22 mm bar spacing Nordmøre grid for Northern shrimp and redfish onboard an offshore factory freezer trawler during commercial fishing operations using the catch comparison method (Wileman et al., 1996). It builds upon previous bar spacing experiments in Canadian waters (CAFID, 1997; Hickey et al., 1993; Orr, 2008) and responds to a key research recommendation by Cadigan et al. (2022). Our objective was to investigate if smaller bar spacings could reduce the incidental bycatch of juvenile redfish while maintaining the catch of targeted Northern shrimp. A reduction in redfish bycatch could alleviate the operating pressures for the fishery when fishing in areas with an abundance of redfish, while also reducing the fishery's impact on redfish biomass. Furthermore, we assessed which Northern shrimp and redfish body-width-size classes overlapped and would mechanically fit between grid bar spacings and developed the morphometric relationships between commonly measured indices for shrimp (carapace length) and redfish (total length) to body width, which likely has more of a direct effect on sorting at the grid. Finally, the grid systems were separately video recorded during fishing with underwater cameras to assess their performance in terms of guiding panel shape, the general movement of species, flow to the grid, and obstruction of the grid.

2. Methods

2.1. At-sea trials

Comparative fishing was carried out in SFA 4 and 5 (Fig. 1) onboard the commercial factory freezer trawler *Newfoundland Victor* (length 79 m, width 16.6 m, gross tonnage 4,642 t) between May 9 and June 5th, 2021. The catch comparison method (Wileman et al., 1996) was used with a side-by-side twin-trawling setup to compare a traditional 22 mm bar spacing Nordmøre grid against 17 (trial 1) and 15 mm (trial 2) experimental Nordmøre grids. Comparison of the 17 and 22 mm grids took place in SFA 4 south (4S), while the comparison of the 15 and 22 mm grids took place in SFA 5 (Fig. 1). Position, depth and bottom water temperature were recorded for each of the paired tows at the beginning and end of the tow. Location (SFA), average temperature, tow duration and average depth was recorded for each tow (Table 1). Towing speed was 1.49 m/s (2.9 kt) for all tows. Headline height, door spread, and grid angles were monitored during twin trawling to ensure comparable trawl geometry in traditional and experimental trawls. Headline height ranged between 8 and 10 m, door spread between 120 and 140 m, and grid angles between 50° and 53°. Tows that had damage to the trawls, gear entanglement, or gear malfunction were not sampled and excluded from the experiment.

2.2. Fishing gear

Two Vónin 3440 mesh commercial Northern shrimp bottom trawls were used for the study. They had 71 m headlines, 75.2 m fishing lines, and 75 m roller footgears. The trawls had a four-panel design and were each equipped with a trouser codend with a 40 mm nominal mesh size. Following Fonteyne (2005) procedures, 41 codend meshes from the top panel were measured in both bottom trawls using an OMEGA gauge to ensure they were identical. The starboard trawl had a mean mesh size of 41.68 mm (standard error of the mean (SEM) 0.16 mm) and the port trawl had a mean mesh size of 41.43 mm (SEM 0.22 mm). The trawling system was towed using a pair of 14 m^2 trawl doors and a center clump (10,000 kg). See Montgomerie (2015) for a further description of twin trawling. Experimental Nordmøre grids with 17 and 15 mm bar spacings were manufactured by Selector Systems Inc. and assembled into full-scale grid systems by Vónin Canada Ltd. for comparison against the traditional 22 mm bar spacing grid currently used by industry and the fishing vessel. Experimental grids were designed and constructed according to the current configuration used by the fishing vessel to have identical traditional and experimental trawls, except for the Nordmøre grids bar spacing. The traditional bottom trawl was equipped with a nominal 22 mm (mean 21.14 mm, SEM 0.34 mm) bar spacing Nordmøre grid, while the experimental bottom trawls were equipped with a nominal 17 mm (mean 17.10 mm, SEM 0.07 mm) and a nominal 15 mm (mean 14.68 mm, SEM 0.08 mm) bar spacing Nordmøre grids (Fig. 2).

Grids were constructed of high-density polyethylene (HDPE) and had a total area of 5.1 m^2. Bar thickness was 9.81 mm for all grids. Area coefficients, also known as grid porosity (the ratio of the area of effective filtration/total area where 1.0 is solid) were 0.57, 0.53 and 0.50 for the 22, 17, and 15 mm bar spacing grids, respectively, which also can be considered as the solid area increased 9.3% for the 17 mm grid and 16.3% for the 15 mm grid, when compared to the 22 mm grid. The 22 mm bar spacing grid had 64 bars, while the 17 and 15 mm grids had 74 and 81 bars, respectively.

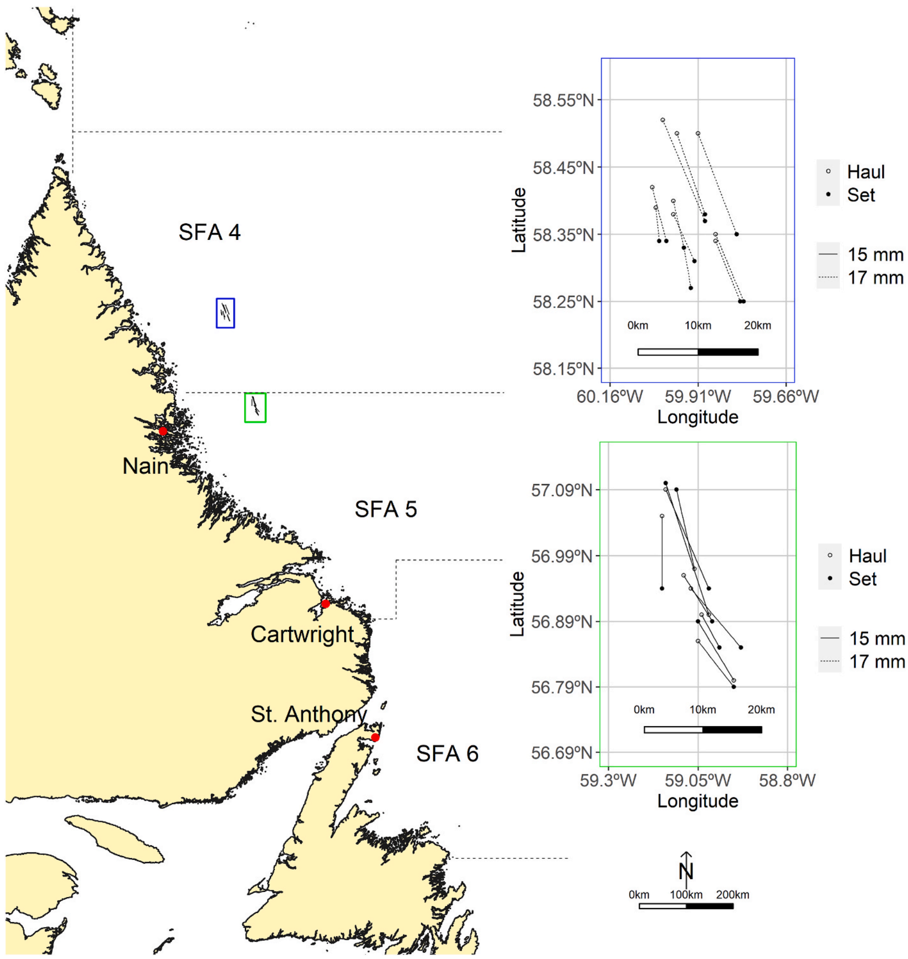

Fig. 1. Shrimp Fishing Areas (SFA; denoted by dashed lines) where the trials took place are shown, located in the Labrador Sea off the coast of Nain, Newfoundland and Labrador. Inset maps are shown for the two main study areas (blue (trial 1) and green (trial 2) rectangles). Map data from the GADM database of Global Administrative Areas (http://gadm.org/). Mercator projection WGS 84 was used.

Table 1
Operational conditions for trials 1 and 2, including paired tow number, the grid used, Shrimp Fishing Area (SFA), average bottom temperature, tow duration and average depth.

Tow	Grids (mm)	SFA	Temp (°C)	Tow Duration (hm)	Depth (m)
1	17 and 22	4S	4.4	3h15m	374
2	17 and 22	4S	4.2	4h	379
3	17 and 22	4S	4	2h35m	354
4	17 and 22	4S	4.5	4h	349
5	17 and 22	4S	2.8	1h10m	241
6	17 and 22	4S	3.5	1h40m	248
7	17 and 22	4S	4.4	2h30m	355
8	17 and 22	4S	3.5	1h30m	238
9	17 and 22	4S	2.6	1h30m	254
10	17 and 22	4S	4.4	1h45m	253
11	15 and 22	5	3.3	2h45m	276
12	15 and 22	5	3.2	1h55m	260
13	15 and 22	5	2.1	1h45m	267
14	15 and 22	5	2.2	2h	247
15	15 and 22	5	2.2	2h	241
16	15 and 22	5	2.2	3h	263
17	15 and 22	5	2.6	2h40m	320
18	15 and 22	5	4.4	3h30m	301
19	15 and 22	5	3.4	4h	295
20	15 and 22	5	3.4	3h	296

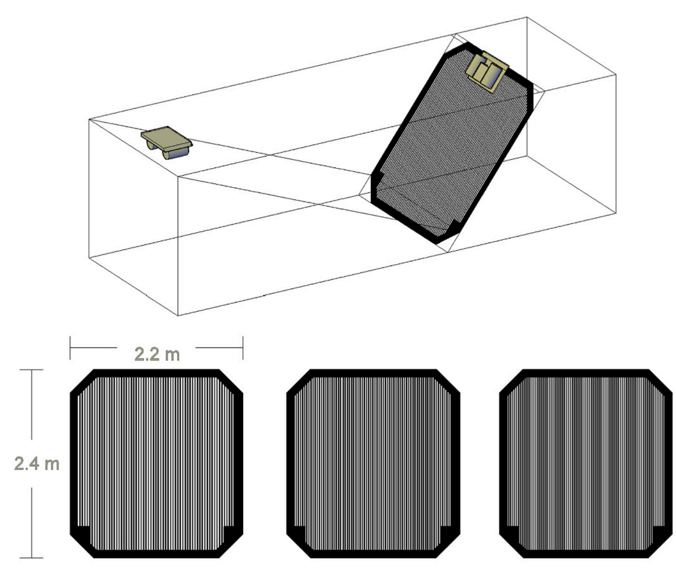

Fig. 2. Nordmøre grid section (top), 22, 17, and 15 mm bar spacing Nordmøre grids (bottom) used in the experiment. Camera system mounted on the upper panel and grid are shown on the Nordmøre grid section drawing (top).

2.3. Sampling procedure

The trawl nets were hauled back when the catch sensors mounted in the trawls codends indicated a catch of approximately 10,000 kg. Once the codends reached the vessel, the traditional and experimental trawl catches were transferred separately to the below deck compartments for onboard processing. In the factory, 500 shrimp were randomly sampled and measured to the nearest 0.5 mm CL and 300 redfish were randomly sampled and measured to the nearest 1 mm total length (TL) for the traditional and experimental trawls (1,000 shrimp and 600 redfish measured in total, per haul), using digital calipers (ABSOLUTE Coolant Proof Caliper Series 500, Aurora, Illinois, USA) connected to a laptop. Total weights were obtained for both shrimp and redfish samples. All redfish were collected in the factory in baskets at various locations (holding tank, bycatch separator, and picking belts), and then weighed to obtain the total redfish catch for each trawl. Total shrimp catch was calculated from the total shrimp production from each of the below-deck compartments (traditional or experimental) that were processed separately for this purpose. Sub-sampling ratios for shrimp and redfish were calculated per tow for each trawl as the number of individuals measured divided by the total number of individuals caught, where the total number of individuals caught was extrapolated from the total weight per trawl.

For the morphometric analysis, 246 shrimp were sampled; their CL and CW were measured to the nearest 0.01 mm, and their maturity stage (i.e., ovigerous or non-ovigerous) was recorded. For redfish, 350 individuals were sampled; their body width (BW) (measured at the endpoint of each operculum) and TL were measured to the nearest 0.01 mm (Fig. 3). Measurements were performed with digital calipers (ABSOLUTE Coolant Proof Caliper Series 500, Aurora, Illinois, USA) connected to a laptop.

The research performed in this study used fish that were already killed during commercial fishing, therefore no animal care protocol was required according to Canadian Regulations (Batt et al., 2005). Shrimp used in the experiment were processed at the onboard factory and redfish was returned dead to the ocean according to regulations set by Fisheries and Oceans Canada (DFO, 2018).

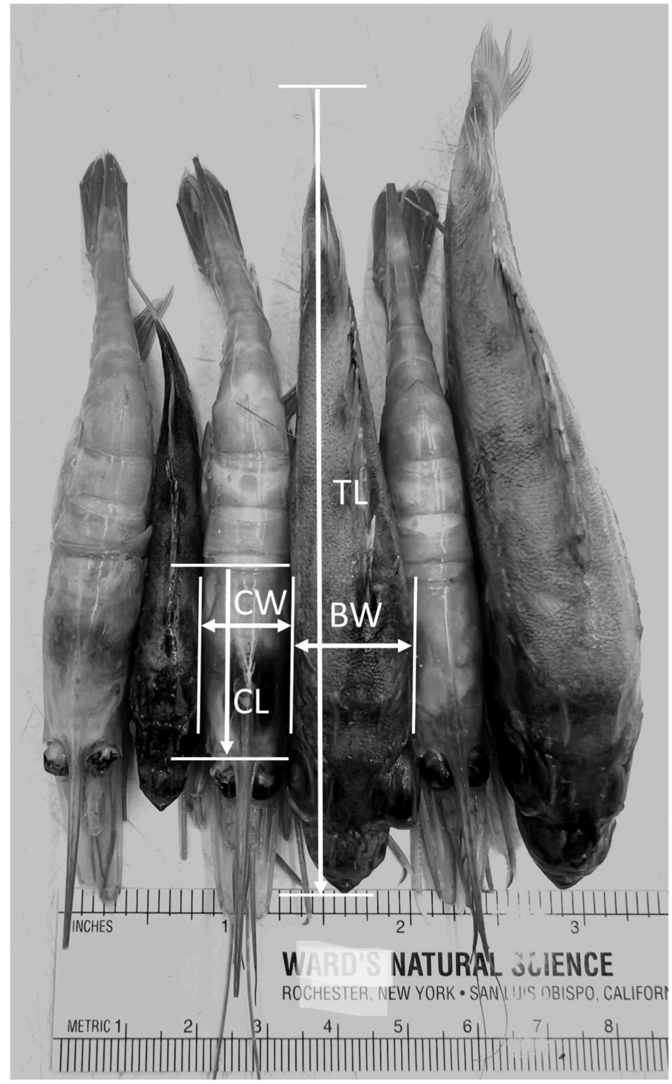

Fig. 3. Morphometric measurements of Northern shrimp (*Pandalus borealis*) and redfish (*Sebastes* spp.). Shrimp carapace length (CL), shrimp carapace width (CW), redfish body width (BW) and redfish total length (TL) measurements are shown for the two individuals in the center of the image.

2.4. Statistical analysis

All statistical analyses were performed using R statistical software (R Core Development Team, 2015). Size selectivity data was analyzed with the package selfisher (Brooks et al., 2022) using the catch comparison method (both gears are selective; Wileman et al., 1996). The relative retention probability was modeled using a generalized linear model of the proportion of individuals caught in the experimental and traditional gear as a function of length class (Holst & Revill, 2009). The logit [experimental/(experimental + traditional)] of the catches-at-length were estimated by low-order polynomials (degree 1–4) and splines (3–5 degrees of freedom), using ns function in the splines package. Due to large catch sizes, a subsampling ratio was used as an offset in the model (Holst & Revill, 2009). If the retention was 0.5, then there was no difference in catch between treatments at the particular length class. If 0.75, then 75% of the catch-at-length was captured by the experimental and 25% by the traditional trawl; if 0.25, then 25% of the catch-at-length was captured by the experimental and 75% by the traditional trawl. Model fit was investigated following Wileman et al. (1996) and Brooks et al. (2020) procedures.

The catch ratio analysis (Sistiaga et al., 2015) was used to give a direct relative value of catch efficiency between the traditional and experimental trawls using the formula, $cr = cc/(1 - cc)$, where cr is the catch ratio and cc is the catch comparison rate. A cr of 1.0 means that there is no difference in the catch between the traditional and experimental trawl at a particular length class, 0.75 means that the experimental trawl catches 75% of the number of individuals as the traditional at a particular length class, and 1.5 means that the experimental catches 50% more than the traditional at a particular length class.

Model selection was based on the model with the lowest AIC (Akaike, 1974), using the function AICtab in the bbmle package (Bolker & R Development Core Team, 2020). Confidence intervals for catch comparison and catch ratio curves were generated using the bootSel function of the selfisher package, where 95% Efron confidence intervals (CIs; Efron, 1982) were generated by 1,000 bootstrap simulations that account for within- and between-tow variation (Millar, 1993). For relative retention probability, if 0.5 was contained within the CIs then there was no difference between treatments. For catch ratio, if 1.0 was contained within the CIs then there was no difference between treatments.

Morphometric relationships between shrimp CL and CW, and between redfish TL and BW were estimated using linear regression analyses to predict the mechanical maximum size of individuals that would fit through the 15 and 17 mm bar spacings. Detrended normal Q-Q plots of the residuals, known as worm plots (Rigby & Stasinopoulos, 2010), were used in the gamlss package (Rigby & Stasinopoulos, 2005) to determine model distribution adequacy.

Correlation tests were performed in the ggpubr package (Kassambara, 2020) to understand the relationship between redfish and shrimp size and average fishing depth. Redfish lengths and shrimp CL were averaged for each of the tows using the traditional trawl ($n = 20$ total) at each depth. Data was not normally distributed; thus, Kendall's rank correlation tests was used (Kendall, 1938) for both, shrimp and redfish correlation tests.

2.5. Underwater video

Video of the grids was collected during non-experimental tows using a self-contained underwater camera system that consisted of a GoPro hero 4 black action camera, with a GoPro "Bacpac" battery, and an external battery (4,000 mAh, 3.7 V) similar to those described by Madsen et al. (2021). The external battery was plugged into a Powerboost (Adafruit industries) and then into the GoPro camera with a 90-degree USB cable. This allowed the camera to simultaneously charge while recording video with 1,000 mAh and 5.0 V until the external battery was drawn. Two DIV08W diving lights from Brinyte Technology Ltd. were used to illuminate the camera field of view. These 120° LED diving lights (luminous intensity of 629 cd) were capable of producing red light (350 lumens). An internal LC 26650, 5,000 mAh and 3.7V battery was used to power the lights. Underwater housings from Group B Distribution Inc. were used (certified to a depth of 1,500 m) for the camera and lights. The system was similar to the one used by Araya-Schmidt et al. (2021). A plate was designed to hold the camera and lights, which was mounted on the grid's upper edge looking down at the grid, and on the upper panel before the grid looking back at the grid (Fig. 2). The video was qualitatively observed to obtain information on guiding panel shape, the general movement of species and flow to the grid, and any obstruction of the grid. Tows containing the underwater camera system were not sampled for size-selectivity as red light could affect shrimp behaviour (Ingólfsson et al., 2021).

3. Results

3.1. Catch data

A total of 10 paired tows were carried out for each traditional versus experimental Nordmøre grid trial (a total of 20 tows for both experiments; Table 2). Total shrimp catch ranged between 2,964 and 5,827 kg for the 22 mm grid in trial 1, while the 17 mm grid total shrimp catch ranged between 3,260 and 7,073 kg. Redfish total catch ranged between 86.6 and 961.8 kg for the 22 mm grid, and between 69.5 and 583 kg for the 17 mm grid. Furthermore, redfish bycatch ranged between 1.93 and 24.03% for the 22 mm grid, and between 1.56 and 15.08% for the 17-mm grid in trial 1 (Table 2), with an overall 27.7% (±5.4% SEM) mean bycatch reduction.

In one tow during trial 1, the 22 and 17 mm Nordmøre grid bottom trawls caught in total ~7,000 kg of juvenile redfish (visually estimated), with visibly no shrimp in the catch and no noticeable difference in the amount of redfish between traditional and experimental codends. The catch was transferred to the below deck compartments separately but could not be sampled due to the large amount of redfish and was rapidly discarded to continue with the experimental twin-trawling.

For trial 2, shrimp total catch ranged between 2,582 and 9,630 kg for the 22 mm grid, while the 15 mm grid caught between 2,658 and

Table 2
Total Northern shrimp and redfish catch (kg), redfish bycatch (%) and sub-sampling ratios for the 22 and 17 mm, and the 22 and 15 mm Nordmøre grids trials (1 and 2, respectively). Total redfish (kg) and bycatch (%) that are higher than Fisheries and Oceans Canada condition of licence thresholds are shown in bold.

Trial	Tow	Grid (mm)	Total shrimp (kg)	Total redfish (kg)	Bycatch (%)	Shrimp sub-sampling ratio	Redfish sub-sampling ratio
1	1	22	5827	**112.2**	1.93%	0.000172	0.008913
		17	4910	87.6	1.78%	0.000204	0.011416
	2	22	3733	86.6	2.32%	0.000268	0.011547
		17	5590	**105.6**	1.89%	0.000179	0.009470
	3	22	4623	**183.3**	**3.96%**	0.000216	0.005456
		17	7073	**110.2**	1.56%	0.000141	0.009079
	4	22	2964	**417.0**	**14.07%**	0.000337	0.002398
		17	3573	**320.9**	**8.98%**	0.000280	0.003116
	5	22	5120	**259.8**	**5.07%**	0.000195	0.003849
		17	4669	**196.7**	**4.21%**	0.000214	0.005084
	6	22	5608	**331.3**	**5.91%**	0.000178	0.003018
		17	5965	**305.2**	**5.12%**	0.000168	0.003277
	7	22	4003	**961.8**	**24.03%**	0.000250	0.001040
		17	3865	**583.0**	**15.08%**	0.000259	0.001715
	8	22	5054	**326.7**	**6.46%**	0.000198	0.003061
		17	3957	**164.4**	**4.15%**	0.000253	0.006083
	9	22	5144	**145.4**	**2.83%**	0.000194	0.006878
		17	3978	69.5	1.75%	0.000251	0.014388
	10	22	3586	**448.8**	**12.52%**	0.000279	0.002228
		17	3260	**356.5**	**10.94%**	0.000307	0.002805
2	11	22	9630	82.3	0.85%	0.000104	0.012151
		15	10982	56.6	0.52%	0.000091	0.017668
	12	22	4303	53.9	1.25%	0.000232	0.018553
		15	4556	52.9	1.16%	0.000219	0.018904
	13	22	4091	**139.6**	**3.41%**	0.000244	0.007163
		15	4846	**134.3**	**2.77%**	0.000206	0.007446
	14	22	5612	**129.9**	**2.31%**	0.000178	0.007698
		15	6062	**112.6**	**1.86%**	0.000165	0.008881
	15	22	3092	60.2	1.95%	0.000323	0.016611
		15	3011	41.7	1.38%	0.000332	0.023981
	16	22	3557	43.7	1.23%	0.000281	0.022883
		15	4242	49.1	1.16%	0.000236	0.020367
	17	22	5664	62.8	1.11%	0.000177	0.015924
		15	5582	56.8	1.02%	0.000179	0.017606
	18	22	3349	**195.3**	**5.83%**	0.000299	0.005120
		15	3723	**142.0**	**3.81%**	0.000269	0.007042
	19	22	2582	**230.8**	**8.94%**	0.000387	0.004333
		15	2658	**161.0**	**6.06%**	0.000376	0.006211
	20	22	3300	**493.3**	**14.95%**	0.000303	0.002027
		15	3518	**310.0**	**8.81%**	0.000284	0.003226

10,982 kg of shrimp. Redfish total catch ranged between 43.7 and 493.3 kg for the 22 mm grid, and between 41.7 and 310 kg for the 15 mm grid. Additionally, redfish bycatch ranged between 0.85 and 14.95% for the 22 mm grid, and between 0.52 and 8.81% for the 15 mm grid in trial 2 (Table 2), with an overall 23.6% (±4.4% SEM) mean bycatch reduction.

A total of 10,000 shrimp and 6,000 redfish were measured in total for each trial. Shrimp sub-sampling ratios, for the trials, ranged between 0.000091 and 0.000387, and redfish sub-sampling ratios ranged between 0.001039 and 0.023980 (Table 2). Length classes that had <10 individuals were removed before modelling. Except for the 15 versus 22 mm redfish model, all models were overdispersed. However, the residuals showed no patterns, suggesting that the models adequately described the data.

3.2. *Trial 1: 17 versus 22 mm Nordmøre grids*

For Northern shrimp, most retained proportions were within close proximity (~0.05) of the 0.5 line indicating no catch difference (Fig. 4). Following the AIC criterion, the best size selectivity model was the logit-linear (Fig. 4, Table 3), which had a slight increasing slope for both the proportion retained and the catch ratio. Confidence intervals showed that there was no statistically significant difference in retention probability or catch ratio across all length classes. Most redfish retained proportions were below the 0.5 line, and the best model was the logit-constant, where redfish total length was not a factor in the curve fit and the model was entirely below the 0.5 line (Table 3). Confidence intervals showed that the 17 mm bar spacing grid caught significantly fewer redfish for all length classes (Fig. 4). Size classes of shrimp ($n = 6$) and redfish ($n = 19$) with less than ten individuals were removed from the statistical analysis.

Table 3
Differences of the Akaike information criterion (ΔAIC) and degrees of freedom (df) for the different models for shrimp and redfish in trials 1 and 2. Values in bold highlight the best fitting models.

Model	Trial 1: 22 vs 17 mm grid				Trial 2: 22 vs 15 mm grid			
	Shrimp		Redfish		Shrimp		Redfish	
	ΔAIC	df	ΔAIC	df	ΔAIC	df	ΔAIC	df
Logit-constant	7.0	1	**0.0**	**1**	**0.0**	**1**	41.7	1
Logit-linear	**0.0**	**2**	1.0	2	0.7	2	**0**	**2**
Logit-quadratic	0.8	3	2.3	3	2.5	3	1.3	3
Logit-cubic	2.7	4	3.9	4	4.5	4	0.7	4
Logit-quartic	2.5	5	5.7	5	6.3	5	2.7	5
Spline 2nd order	0.6	3	2.3	3	2.5	3	1.4	3
Spline 3rd order	2.4	4	3.7	4	4.2	4	0.5	4
Spline 4th order	3.9	5	5.8	5	6.1	5	2.5	5
Spline 5th order	4.9	6	7.4	6	6.3	6	4.5	6

3.3. *Trial 2: 15 versus 22 mm Nordmøre grids*

Most retained proportion values were close to or on the 0.5 line of no catch difference for Northern shrimp (Fig. 5). For the proportion retained and catch ratio, the best model was the logit-constant, where shrimp carapace length was not a factor in the model fit and the model was located slightly above the 0.5 line (Table 3). For both, CIs did not contain the 0.5 or 1.0 line indicating no catch difference, showing that the 15 mm grid caught slightly more shrimp across all length classes (Fig. 5). Redfish retained proportion values decreased with larger redfish lengths (Fig. 5). The best size selectivity model was the logit-linear (Table 3), and for proportion retained and catch ratio, CIs showed that the traditional gear captured more redfish for length classes >95 mm with no difference for lengths <95 mm (Fig. 5). Size classes of shrimp (n

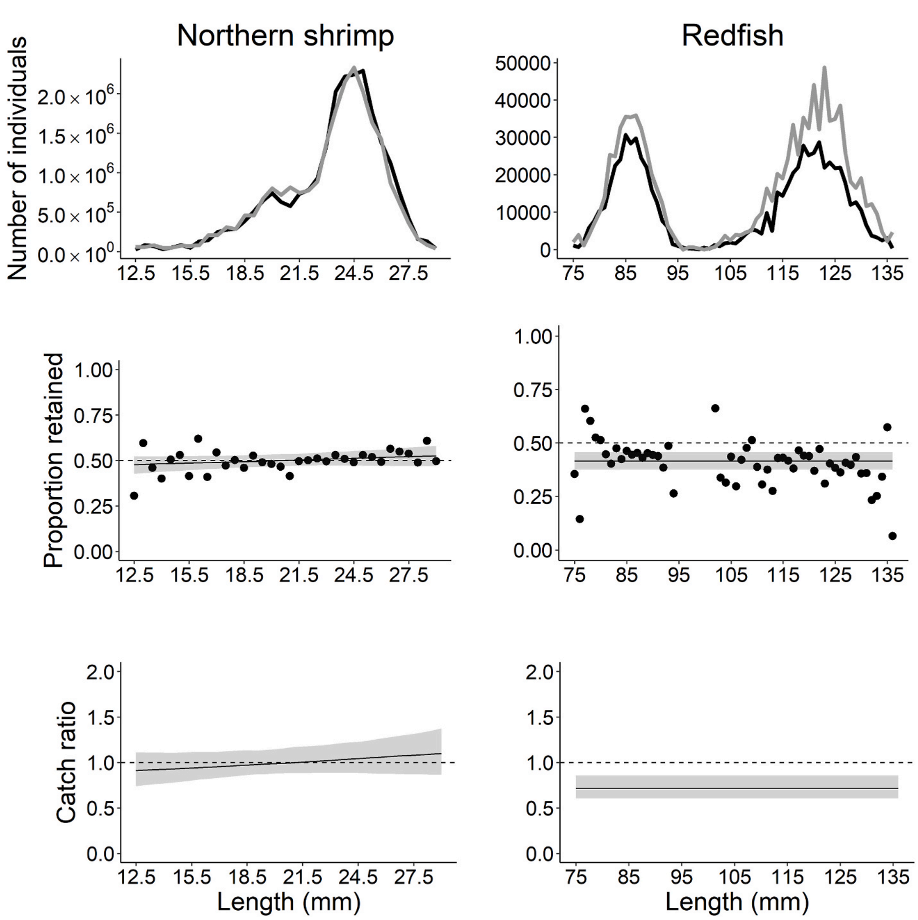

Fig. 4. Catch comparison and catch ratio plots for Northern shrimp (*Pandalus borealis*) and redfish (*Sebastes* spp.) for the 17- and 22-mm bar spacing Nordmøre grid trawls. Top: Length frequency distribution of Northern shrimp and redfish caught by the 17 mm grid trawl (black line) and 22 mm grid trawl (grey line). Middle: Mean curve from the generalized linear mixed model (GLMM) modeled proportions (black line) with 95% confidence regions (grey area). Black dots represent observed proportions retained. A value of 0.5 indicates an even split between the 17 and the 22 mm grids trawl, whereas a value of 0.75 indicates that 75% of the total individuals at that length were caught in the 17 mm grid trawl and 25% were caught in the 22 mm grid trawl. Bottom: Estimated catch ratio (black curve) with 95% confidence regions (grey area). Stripped line at 1.0 represents the point at which both gears have an equal catch rate.

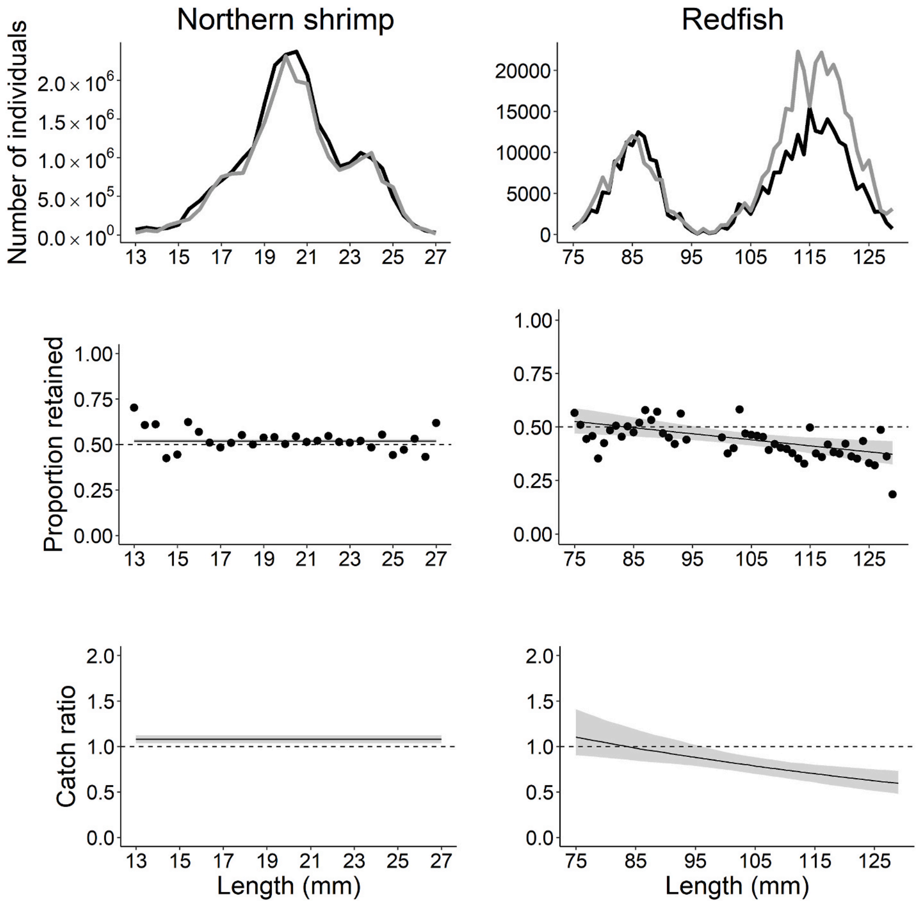

Fig. 5. Catch comparison and catch ratio analysis for Northern shrimp (*Pandalus borealis*) and redfish (*Sebastes* spp.) for the 15- and 22-mm bar spacing Nordmøre grid trawls. Top: Length frequency distribution of shrimp and redfish caught by the 15 mm grid trawl (black line) and 22 mm grid trawl (grey line). Middle: Mean curve from the generalized linear mixed model (GLMM) modeled proportions (black line) with 95% confidence regions (grey area). Black dots represent observed proportions retained. A value of 0.5 indicates an even split between the 15 and the 22 mm grids trawl, whereas a value of 0.75 indicates that 75% of the total individuals at that length were caught in the 15 mm grid trawl and 25% were caught in the 22 mm grid trawl. Bottom: Estimated catch ratio (black curve) with 95% confidence regions (grey area). Stripped line at 1.0 represents the point at which both gears have an equal catch rate.

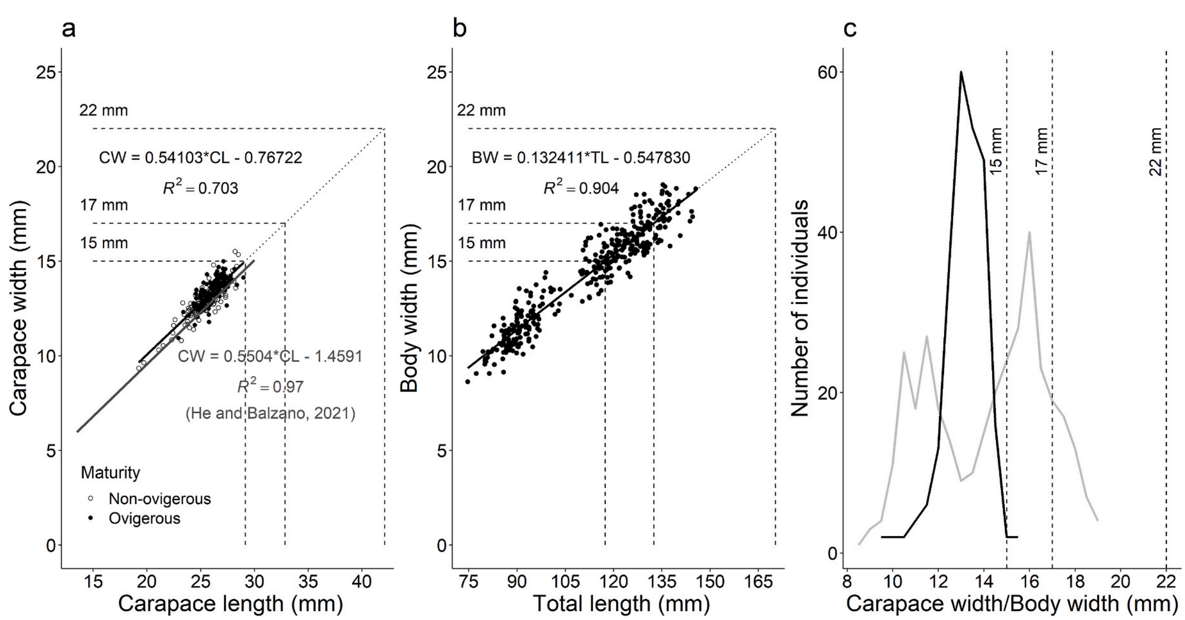

Fig. 6. Morphometric relationship between length and width of Northern shrimp and redfish. a: Northern shrimp carapace length (CL) and carapace width (CW) relationship, b: Redfish total length (TL) and body width (BW) relationship and c: Frequency distribution of shrimp (black line) and redfish (grey line) sampled. Dots show the observed data for northern shrimp and redfish. In the case of shrimp, dots also show the maturity stage (e.i. ovigerous or non-ovigerous). Black solid lines show the linear model regression and dotted lines represent the projection of the linear regressions. Grey solid line in plot a shows the linear regression obtained in the study performed by He and Balzano (2012). Dashed lines show the traditional and experimental Nordmøre grid bar spacings and their related CL or TL according to the linear regressions. Regression equations and coefficients of determination (R^2) are also presented in the figure next to their respective regression line.

= 7) and redfish (n = 9) with less than ten individuals were removed from the statistical analysis.

3.4. Morphometric relationship between length and width

Shrimp CL ranged between 19.25 and 28.99 mm, while CW ranged between 9.34 and 15.50 mm, for the 246 sampled individuals. Ovigerous females were observed and had a CL of 22.94 mm or larger, while non-ovigerous shrimp were observed across all size ranges. Linear regression results showed that the relationship between CW and CL is CW = 0.54103·CL-0.76722 and the estimated regression line reached just below the 15 mm CW intersection point (Fig. 6a). The large majority of the individuals sampled had a CW smaller than 15 mm (Fig. 6c).

Redfish TL ranged between 74.69 and 145.59 mm, while BW ranged between 8.62 and 19.03 mm, for the 350 sampled individuals. The linear regression relationship between redfish BW and TL is BW = 0.132411·TL-0.547830, thus the predicted mechanical maximum for redfish that would fit through the 15 mm grid spacing is 117.42 mm TL and 132.53 mm for the 17 mm grid spacing (Fig. 6b). All redfish sampled had a predicted mechanical maximum that would fit through the traditional 22 mm bar spacing Nordmøre grid (Fig. 6b and c).

3.5. Redfish total length and shrimp CL correlation with fishing depth

Results from Kendall's rank correlation test showed that mean depth and mean redfish length caught in the traditional trawl (n = 20) are significantly correlated with a positive relationship (T = 0.77; P <0.001). Similarly, mean depth and mean shrimp CL caught in the traditional trawl (n = 20) are significantly correlated with a positive relationship (T = 0.36; P = 0.034) (Fig. 7).

3.6. Underwater video of the Nordmøre grid system

In total, 12 tows were recorded during the sea trials; 6 tows for the 22 mm grid, 4 tows for the 17 mm grid and 2 tows for the 15 mm grid. Total duration was 16.1, 7.7, and 2.4 h of video for the 22, 17 and 15 mm Nordmøre grids, respectively. All grid systems experienced a gradual increase in the guiding panel exit opening as animals meshed and accumulated in the guiding panel meshes over the course of a tow (Fig. 8), especially in areas with a high abundance of shrimp, where the guiding panel exit was nearly the same size as the trawl section (i.e. four panels attached to the edges of the grid). During this phenomenon, animals were seen being randomly directed at different grid heights (e.g. higher), at lower speeds, and it seemed were more likely to exit through the grid opening, when compared to the initial guiding panel performance (e.g. directed animals to the base of the grid). Furthermore, there was evident turbulence going in different directions. Videos showed that larger-sized fish can get impinged to the grid, especially flatfish (Pleuronectiformes) and skates (Rajidae), however, except for one tow where the abundance of skates was high, there was no evidence of obstructed grids where shrimp could not transit to the codend through the grid bar spacings.

4. Discussion

Reducing the Nordmøre grid bar spacings from 22 to 17 and 15 mm significantly reduced juvenile redfish bycatch while maintaining, or slightly increasing, Northern shrimp catches. Even though the two species' size ranges overlap (Fig. 6c), the results showed that it is possible to improve the separation of some size-classes of redfish. For Northern shrimp, the main concern was the catch reduction of larger size classes and maintaining commercial capture levels with the smaller bar spacings. The tested grids either showed no difference in comparison to the traditional (17 mm), or showed an increase in the capture, though at very slight levels (15 mm). We expected that a reduction in bar spacing could decrease the catch of the largest shrimp, however, this was not the case. Observed shrimp CWs were mostly smaller than both experimental bar spacings, with all observed shrimp able to mechanically fit through the 17 mm grid and the vast majority through the 15 mm grid (Fig. 6a), and this is perhaps why no shrimp reductions were observed. Even though we found very few shrimps large enough to be potentially excluded by the 15 mm grid, we recommend caution when using this grid in areas or at depths were larger shrimp sizes may occur (>29.14 mm CL, which have a predicted CW of 15 mm).The 15 mm bar spacing grid could potentially exclude the larger and more valuable shrimp if they are present in the fishing area. Which was not the case for this experiment.

The underwater video showed that over the course of a tow there was a gradual increase in the guiding panel exit opening as shrimp and fish meshed and accumulated in the guiding panel meshes (Fig. 8). The gradually increasing amount of space between the guiding panel and the front of the grid seemed to reduce the efficiency of the panel to direct shrimp and other species to the bottom of the grid. Thus, considerable amounts of shrimp, and other species, were observed exiting the trawl when catch rates were high, likely due to a change in contact location between shrimp and the grid (i.e., contacting the grid at a higher point) as catch rates increased with increasing space between the guiding panel and the grid. For grids with no guiding panel, or in this case, with a guiding panel that is not properly directing the catch, individual shrimp would have a more random contact location on the grid, resulting in the escapement of shrimp that hit the grid closer to the opening (Riedel & DeAlteris, 1995). Animals accumulating in the guiding panel meshes increases the webbing solidity, which might reject catch at the guiding panel or panel entrance, create turbulence, and/or increase the time

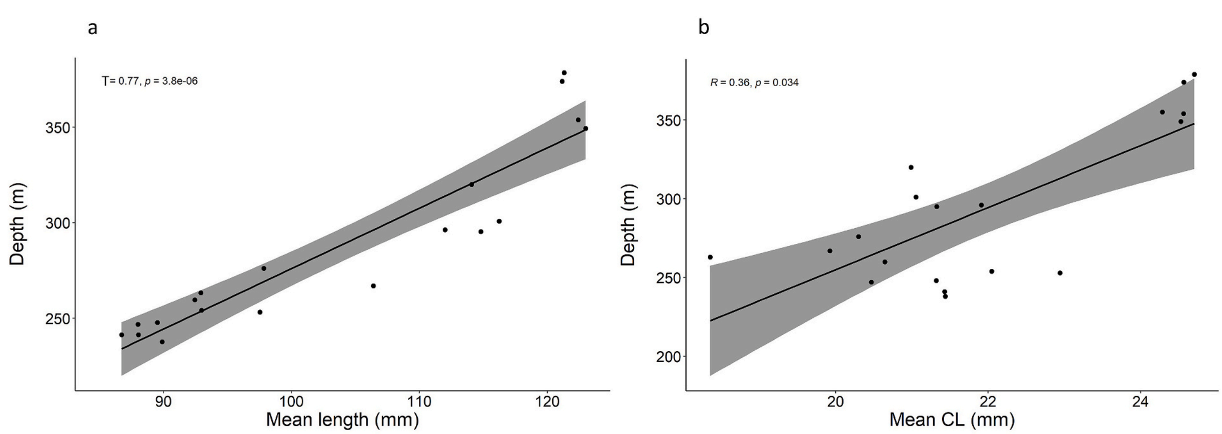

Fig. 7. The correlation of depth fished as a function of redfish mean length (a) and shrimp mean carapace length (CL) (b) for 20 tows using the 22 mm bar spacing grid. T coefficient and p-value from the correlation analyses are shown in the top left corner of each plot.

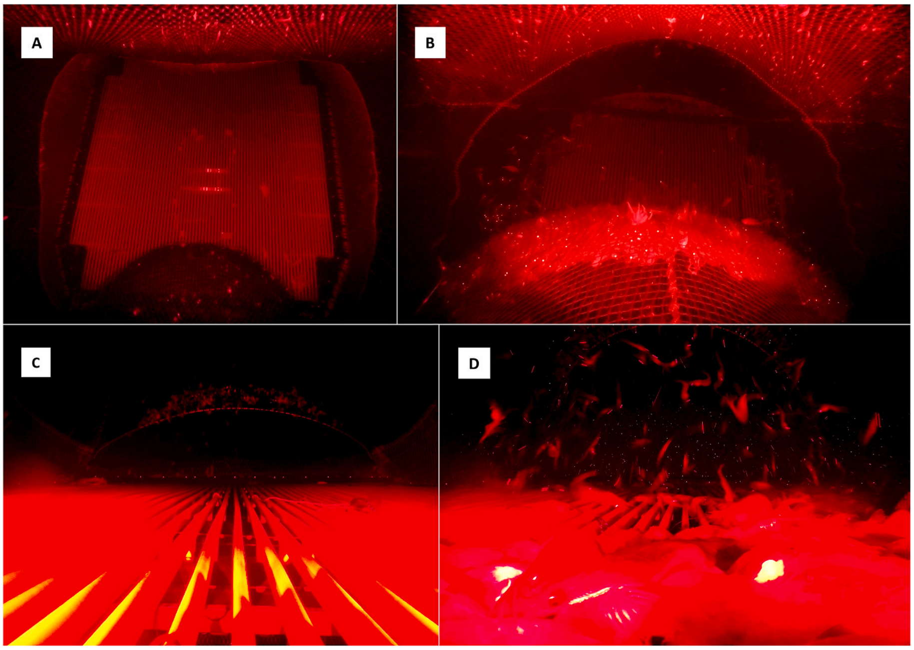

Fig. 8. Guiding panel deformation during tow. A: frontal view of a 17 mm bar spacing Nordmøre grid at the beginning of the tow showing a guiding panel that is directing flow at the base of the grid. B: frontal view of a 22 mm bar spacing grid towing for 2 h showing a deformed guiding panel that has meshed shrimp and fish. C: top view of a 15 mm bar spacing grid at the beginning of the tow showing a guiding panel similar to A. D: top view of a 17 mm bar spacing grid towing for 1.5 h showing a guiding panel similar to B.

until the shrimp makes contact with the grid (Riedel & DeAlteris, 1995). Each of these likely reduced the selective efficacy of the grid system and may be why there were unexpected observations, such as smaller bar spacings catching more shrimp and smaller redfish caught with the 15 mm grid and not the 17 mm grid.

The ideal BRD will function reliably in all fishing conditions. However, at-sea observations consistently show that a variety of hydrodynamic and behavioural factors affect BRD performance (Winger et al., 2010), often changing over the duration of a single tow. In this study, underwater observations showed evidence that at moderate to high catch rates, the grid systems are less than optimal. In these cases, the catch randomly hits the grid at different heights, shrimp accumulate on the grid face and exit through the opening, and there is evident turbulence going in different directions. All of these factors may have affected the size selection of Northern shrimp and redfish, leading to surprising results such as smaller bar spacings catching fewer, smaller redfish (17 mm) and slightly more Northern shrimp (15 mm). The guiding panel malfunction and turbulent water flow going in different directions might have increased the chances of smaller shrimp and redfish to contact the grid and subsequently transit to the codend.

Increasing the solid area of a grid will change water flow dynamics on the grid system, increasing rejected water flow and decreasing the water flowing through the grid (Grimaldo & Larsen, 2005; Veiga-Malta et al., 2020). However, recent flume tank observations demonstrated only a minor reduction in water velocity (approx. 4.1% and 5.1%) behind a Nordmøre grid when bars spacings were reduced from 22 mm to 17 mm and 15 mm, respectively (Araya-Schmidt, unpublished data, 2020). This is consistent with the camera observations in this study, which did not reveal any obvious difference in the amount of shrimp rejected for the different grids evaluated in this study. Similarly, Hickey et al. (1993) hypothesized that substantially lower grid angles than its initial value of 48° and dense shrimp concentrations were the main causes for significant shrimp losses, thus the reductions in bar spacing seemed to not increase shrimp losses.

Redfish length-frequency graphs showed that most of the redfish were between 80 and 90 mm (10.05–11.67 mm BW), and between 110 and 130 mm (14.02–16.67 mm BW) size classes, which likely indicates a strong presence of two cohorts of redfish overlapping in the fishing area. Saborido-Rey et al. (2004) estimated that previous redfish (*S. mentella*) cohorts (1986–1999) in the Flemish Cap had mean lengths of 90 and 127 mm, for ages 1 and 2, respectively. These results provide some level of confidence that the population we encountered was comprised of two redfish cohorts. Granted, the Flemish Cap is a different location (~1000 km to the Southeast of our sampling area) and we did not determine the species of our samples, though a recent survey (3 months prior; Jan.–Feb. 2021) did determine that some redfish captured (100% sampled for species identity) in the same fishery and fishing area were *S. mentella* (Bruce Chapman, Canadian Association of Prawn Producers, personal communication). The 17 mm Nordmøre grid reduced the catch of redfish for all size classes, even though the majority of redfish could mechanically pass through the 17 mm grid bar spacings (i.e. only redfish larger than 132.53 mm TL had BW larger than 17 mm). This is likely because not all of the redfish made contact with the grid (Larsen et al., 2017) and possibly exited the trawl following the strong water flows directed towards the grid opening (Grimaldo & Larsen, 2005). However, only size classes larger than 95 mm that had a predicted 12.03 mm BW were caught in significantly lower quantities when using the 15 mm grid, which shows that the effectiveness of this grid at reducing redfish bycatch is lower for the cohort of smaller redfish (between 80 and 90 mm). Perhaps, the flow was altered in front of the 15 mm grid in such a way that allowed increased capture efficiency of the smallest animals observed (for redfish and shrimp). Increased turbulence was observed in front of the grid on video, which cloud be affected by towing speed, where small shrimp and redfish would swirl around in the area just in front of the grid. Perhaps this added turbulence, when compared to the 17 mm grid, prevented the small animals from escaping out of the trawl, but only for the relatively larger redfish and not for the shrimp whose captures were higher for all sizes (Figs. 4 and 5). Thus, given the long-lived, slow-growing nature of redfish populations, using a grid that prevents the captures of both cohorts is a preferred option.

Both, the 17 and 15 mm bar spacing Nordmøre grids caught redfish that had BWs larger than the spacings between bars. Likely, these redfish experienced lateral compression when forced by water flows through bar spacings and were able to transit to the codend. When simulating redfish (*Sebastes marinus*) mesh penetration, Herrmann et al. (2012) found that a model that included a 25% lateral body compression best described redfish mesh penetration. Lateral body compression was considered at the cross-section located at the end of the opercula and the foremost point of the spiny dorsal fin, which is the same location as the body width measurements performed in this experiment. For Nordmøre grids, a redfish's chances of retention are maximized when oriented parallel to the bars, making body width the most relevant morphometric characteristic for redfish, which together with body compressibility and angle of attack (i.e., orientation of redfish with respect to the grid bars) influence its size selection (Herrmann et al., 2013). Therefore, redfish with a BW larger than what would mechanically fit through the bar spacing can be captured when considering lateral compression and optimal orientation to a certain degree. For the 17 mm bar spacing grid, few redfish larger than the predicted mechanical maximum (135.53 mm) passed through the grid, however that may be a reflection of the fished population. Contrarily, the 15 mm grid catches resulted in many redfish larger than the predicted mechanical maximum (117.42 mm) passing through the grid spacings, though at a lower rate than the 22 mm grid as expected. Regardless, the goal of the presented morphometric analysis was to provide evidence of the overlap of size between juvenile redfish and shrimp that can be unclear with analysis that relies on length measurements as is typical of the field (and for efficient at-sea sampling).

Recent conditions of licence permitted up to 2.5% or 100 kg total weight of incidental catch of groundfish species per tow (DFO, 2018), although recent amendments have been temporarily permitted for higher levels of bycatch (DFO, 2021). The 15 and 17 mm bar spacing grids were not effective at reducing redfish bycatch below these levels. In trial 1, from 20 opportunities (2 codends twin trawling over 10 tows), the 17 mm grid produced 2 tows with redfish bycatch below 2.5% or 100 kg, while the 22 mm grid produced 1. In trial 2, both the 15 and 22 mm grids produced 5 of 20 opportunities within the permitted amount of redfish bycatch from a total of 10 tows. It was observed that redfish can be caught in large quantities (~7,000 kg for one tow), which emphasizes the urge to address this bycatch issue. It is common to find small amounts of other groundfish species in the catch, which means that the redfish bycatch needs to be even further reduced to comply with conditions of licence. Juvenile redfish greatly overlap with Northern shrimp in the fishing area and is a slow-growing species, which means a higher probability of redfish passing through the Nordmøre grid and a higher bycatch relative to several other groundfish species over at least the near future (Orr et al., 2008). Even though the experimental grids did not prevent capturing redfish over permitted limits, we recommend its use, as any reduction in resource waste is beneficial from an ecological and operational point of view.

Different proportions of the two redfish cohorts observed during the experiment were mixed depending on fishing depths, which lead to a strong correlation between average redfish length and fishing depth. These results coincide with previous findings that relatively larger individuals appear to concentrate at greater depths (Senay et al., 2021). This is an important factor to consider since the bycatch reduction effectiveness of a 17 or 15 mm bar spacing Nordmøre grid could be greatly affected in shallower areas where larger proportions of smaller redfish are present. From the fisheries management perspective, this is especially interesting since it could lead to regulating Nordmøre grid bar spacing based on fishing depths. Alternately, fishing enterprises could avoid shallower fishing areas where the efficiency of the grids at reducing redfish is low. The scale of this size segregation is unknown, research investigating the regional extent is recommended.

5. Conclusions

Nordmøre grids with smaller bar spacing tested in this study significantly reduced juvenile redfish bycatch while maintaining Northern shrimp catches. Even though the size of shrimp and redfish overlap, the results showed that it is possible to improve the sorting of these two species. Since shrimp CW of large individuals can reach 15 mm, further reductions in the bar spacing will likely lead to a reduction in catch rates of the larger and more valuable shrimp. Therefore, purely mechanical separation using Nordmøre grids with reduced bar spacing is not the definitive solution and should be combined with other BRDs exploiting behavioural differences between species, such as escape panels (Cerbule et al., 2021; Larsen, Herrmann, Sistiaga, Brinkhof, & Santos, 2018), artificial lights (Larsen et al., 2017; 2018a) or other devices to aid in the bycatch reduction efforts. In the time being, until an effective combination of BRDs is found, fisheries management and fishers' decisions could play a key role in reducing redfish bycatch in areas with smaller individuals and a high abundance of redfish.

CRediT authorship contribution statement

Tomas Araya-Schmidt: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Shannon M. Bayse:** Conceptualization, Methodology, Validation, Formal analysis, Writing - review & editing, Visualization. **Paul D. Winger:** Validation, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition, Visualization. **Colin H. Frank:** Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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