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Release of unwanted flat-bodied fish from a horizontal-bar grid system as revealed through comparative fishing trials and underwater video observations

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ABSTRACT

Grid systems separate fish species primarily through physical means: fish size and body shape. On Georges Bank off the northeast USA, many species of flounders are overfished, and their catch needs to be reduced. Flat-bodied skates are also often discarded. We tested a European style horizontal-bar grid system to reduce these flat-bodied low quota species in a trawl targeting the haddock (*Melanogrammus aeglefinus*), whose population is robust. The grid system consisted of 4 grid sections, two on each side, with horizontal bars 70 mm apart. The alternating tow method was used to compare the catch characteristics between a trawl with a grid section and the same trawl without a grid section. A video camera was used to observe fish escape in the grid section. The results indicate that the grid system reduced the flounder catch rate (mainly winter flounder, *Pseudopleuronectes americanus*) by 51.3%, and skates (mainly winter skate, *Leucoraja ocellata* and little skate, *Leucoraja erinacea*) by 29.4%, while there were no differences in the catch of Atlantic cod (*Gadus morhua*). While haddock was reduced by 37% by weight, the reduction was primarily small undersized individuals. There was no reduction in large haddock greater than 50 cm. Video observations indicates that flounders and cod mainly escaped from the bottom half of the grid while haddock were from the top half. These finding suggest that this system reduced low quota flounders, as well as discarded skates and small haddock, while retaining Atlantic cod and large size haddock. Underwater observations indicate that differential spacing (narrower on the top and wider on the bottom) may improve the system performance by releasing more flat-bodied fish, that were observed to escape from the bottom part of the grid, while retaining more haddock, which typically escape from the top part of the grid.

1. Introduction

Grid systems are popular for trawls to release unwanted animals before they reach the codend (Graham, 2006). Most grid systems separate animals through mechanical means, either through differences in size or shape, or both. In a typical grid such as the turtle excluder device (TED), which was called the trawl efficiency device in early days, and the Nordmøre grid, large animals that cannot pass through the space between grid bars are diverted to an exit opening and released (Isaksen, Valdemarsen, Larsen, & Karlsen, 1992; Watson & Seidel, 1980). The use of TEDs has been shown to reduce bycatch of sea turtles by up to 95% in some tropical shrimp fisheries (Moore et al., 2009) and has been mandatory for many tropical shrimp fisheries that export shrimp products to the US. In the Gulf of Maine northern shrimp fishery, the required use of the Nordmøre grid in 1992 reduced the bycatch of groundfish from ~50% of the catch to less than 15% of the catch (Richards & Hendrickson, 2006).

The grid can also be designed in such a way that smaller animals passing through the space between the bars are led to an exit opening while large animal are led to the codend. These grids are usually called size-sorting grids (Jorgensen et al., 2006; Larsen & Isaksen, 1993; Sardà, Molí, & Palomera, 2004).

Most of these grid systems have bars vertically or longitudinally in contrast to bars that are horizontal and across the grid section, or in parallel to the towing direction. These horizontal bar grid systems intend to exploit the horizontal body shape of flounders and skates, as tested by Matsushita, Fujita, Ikegami, and Ohata (2004) to exclude juvenile Japanese flounder (*Paralichthys olivaceus*), Lomeli and Wakefield (2016) to exclude Pacific halibut (*Hippoglossus stenolepis*), and Santos et al. (2016) to exclude European plaice (*Pleuronectes platessa*) and

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European flounder (*Platichthys flesus*). These horizontal-bar grid systems seem effective in releasing flat-bodied flounders while retaining round-bodied fish.

It is commonly assumed that fish escaped or released from grids are likely to survive better than those escaped through meshes. A study by Ingólfsson, Soldal, and Huse (2002) showed haddock that escape from a grid system have significantly fewer injuries or skin damage compared to those that escape through the codend mesh. As such, a three-fold reduction in the post-escapement mortality rate of fish that escape from a grid system (8.5% mortality rate) compared to that escaped from the codend mesh (29.1% mortality rate) has been observed (Ingólfsson et al., 2002).

Over the past several years the fishing industry in the northeast US has been crippled by quota reductions to vulnerable flounder stocks. In 2019 the quotas of many key species have been increased, including haddock, Acadian redfish (*Sebastes fasciatus*) and pollock (*Pollachius virens*), all of which are at historic high abundances (NEFMC, 2019). Even the beleaguered Atlantic cod is showing signs of rebuilding with the annual quota increasing by 31%, a three-fold increase from 2017. Conversely, the overfished founder stocks such as yellowtail flounder (*Limanda ferruginea*), winter flounder (*Pseudopleuronectes americanus*), and windowpane flounder (*Scophthalmus aquosus*) are at, or near, historic low abundances. The most striking is the recent cut in Georges Bank yellowtail flounder quota to 85 mt, a 50% annual reduction and a 93% reduction from 2011 (NEFMC, 2019).

The disparities between populations have led to choke species limitations, leading to low commercial landing of healthier stocks. The fear of a large tow of low quota species has caused many industry members to restrict fishing operations to reduce the financial risk. This has resulted in only 20% of the groundfish quota landed annually from 2016 to 2018. The loss in foregone yield, mainly in haddock, pollock and redfish, exceeds 70,000–80,000 mt annually over the past three years. Reducing the catch of choke species would allow for a speedy recovery of these overfished "choke" stocks and lead to better utilization of the healthy stocks. At this point fishermen have few options. While recently developed selective trawls such as the Ruhle trawl, the separator trawl and the rope separator trawl allow fishermen to harvest haddock while minimizing bycatch, it requires substantial modifications to existing nets or the purchase of a new net (Beutel et al., 2008; He, Smith, & Bouchard, 2008; Main & Sangster, 1982, p. pp17). A species-selective device that can be added to the existing trawl would be an attractive option in terms of costs and flexibility.

Similar to the Georges Bank haddock fishery, the Baltic Sea cod fishery is being severely restricted due to low abundance of flounders. As a result, a Swedish fisherman designed a horizontal grid system that exploits the morphological difference between flatfish and roundfish. The grid system was further developed by the Thünen Institute in Germany and named the "FRESWIND" (Flatfish Rigid Escape WINDows) system (Santos et al., 2016). Comparative fishing trials demonstrated a 68% reduction in the catch of flounder. Larger reductions were associated with smaller individuals. Additionally, there was a 30% reduction in the catch of juvenile roundfish with only a small and insignificant reduction in the target catch (~7%, Santos et al., 2016).

In the US west coast Pacific cod trawl fishery, a flexible horizontal-bar grid system was tested to exclude Pacific halibut – a non-retention species in the fishery (Olafsson, 2016). Video footage from Olafsson (2016) showed successful release of halibut from a trawl equipped with the device. In another study that was to retain flatfish, such as Dover sole (*Microstomus pacificus*) and petrale sole (*Eopsetta jordani*), Lomeli and Wakefield (2016) successfully tested a version of horizontal-bar grid for a trawl to exclude rockfishes (Sebastes spp.), sablefish (*Anoplopoma fimbria*), and Pacific halibut (*Hippoglossus stenolepis*).

Results from the Baltic Sea and US west coast research indicate that a similar grid system might be adapted to the New England haddock fishery to release low-quota flounders. As skates also have flat bodies and swim with their bodies horizontal (in contrast to many round fish), the horizontal-bar grid system may also reduce skates. The goal of this study was to design and test a horizontal-bar grid system adapted from Santos et al. (2016) for the GB haddock fishery, and evaluate its performance in reducing unwanted flounders and skates through comparative fishing trials and underwater video observations.

2. Materials and methods

2.1. Grid design

The design of the grid system was adapted from the European FRESWIND system (Santos et al., 2016). The grid system consisted of four rectangular grid sections, two on each side of the trawl extension (Fig. 1). The front grid panels are 60 cm long by 100 cm high. The rear grid panels are 80 cm long by 100 cm high, both have horizontal bar openings to allow easy exit of flounders. The grid is constructed with a 20 mm steel rod for the outer frame and 13 mm steel rod for grid bars. Spacing between bars was 70 mm. The choice of grid spacing was a compromise between allowing flounder an easy escape while preventing the escape of legal-size haddock. The minimum landing size of haddock during the study was 40.6 cm fork length which had an average head height of 70 mm (Krag, Herrmann, Madsen, & Frandsen, 2011).

The grid system was housed in a 1 m × 1 m four-panel extension of 64 mm diamond mesh size netting of 3 mm braided twine (Fig. 1B and C). The leading grids were installed on each of the side panels at an angle of 25° into the net. The trailing grid was installed parallel to the extension forming an extended corridor, providing additional escape opportunities for the fish. Each grid was sewn into the net with 16 trawl floats (20 cm diameter) attached to the top of the grids to make the system neutrally buoyant. A small mesh panel (64 mm mesh size) was used behind the second set of the grids to prevent the escaped fish from re-entering the net. To promote contact with the grid, a deflector consisted of five 30 cm float with holes was placed 50 cm in front of the grids in the center of the extension (Fig. 1 A, not shown in B & C).

2.2. Comparative fishing trials

Comparative fishing trials were carried out on board F/V "Hera", a 25 m LOA commercial stern trawler in June of 2016. Two seven-day trips to Georges Bank (Northeast USA, Fig. 2) were completed to evaluate the performance of the grid using the alternating tow method. The area where the experiment was carried out is a traditional groundfish fishing area fished by fishers from the New England States. In this experiment a single trawl was used alternating between treatment configurations in a pattern of ECCE and CEEC, where E represents the experimental treatment (trawl with the grid) and C represents the control (trawl without the grid). Tow duration was targeted at 75 min at a towing speed of 3.0 knots.

The trawl used was two-seam balloon trawl with a fishing circle of 376 meshes of 165 mm mesh size. Mesh size throughout the trawl was 165 mm knot center using 4 mm PE twine. The headline length was 34.3 m. The groundgear of the trawl was 42.1 m, composed of alternating 12.7 cm diameter rubber disks between 40.6 cm diameter rubber "rockhoppers" spaced every 36 cm. The doors were 4.0 m^2 Hi-Lift trawl doors (Net Systems Inc., Bainbridge Island, WA, USA). Twenty-seven meters of 16 mm steel wire was used for the upper bridle, while the lower bridle consisted of 27 m of steel cable encased in 76 mm rubber "cookies". The two bridles connected to a steel delta plate. A ground cable (sweep) 74.2 m long (16 mm steel wire with 76 mm rubber cookies) connected the delta plate to the trawl doors.

The control tows used the standard groundfish trawl. The experimental treatment was the same trawl with the grid section installed in the extension just ahead of codend. The two treatments could be swapped in about 20 min by sewing the appropriate extension and codend to the net body. Two identical 152 mm mesh size diamond mesh codends were used for all tows. The extension of the control net was

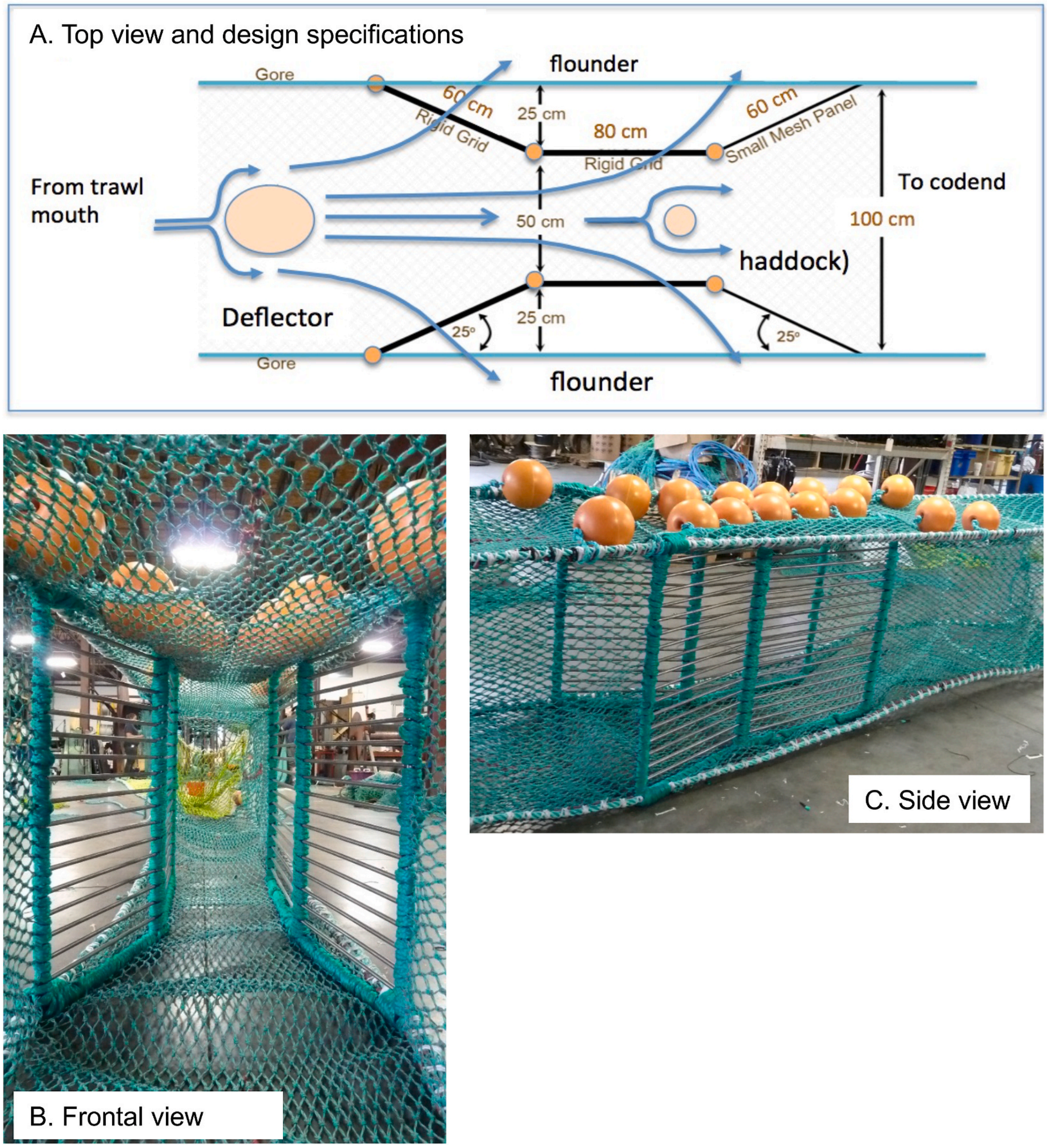

Fig. 1. A. top view of the grid system. The system consisted of 4 steel grids with horizontal bars (black lines). The first set of grids (60 cm × 100 cm) was angled into the extension at 25° leaving a 50 cm passage in the center. A second set of grids (80 cm × 100 cm) formed a corridor. A deflector was installed 50 cm in front the grids and small gillnet floats were placed inside the corridor as baffles. A small mesh panel was placed behind the grids to prevent the re-entrance of escaped flounders. Grid spacing was 70 mm. The grid system was built within the extension section using 64 mm diamond mesh netting of 3 mm braided twine. B. Frontal view of the grid system looking toward the codend. C. Side view of grid system.

elongated with 64 mm diamond mesh so both trawls had an identical length. No trawl geometry sensors were used in this study.

2.3. *Underwater video observations*

Underwater cameras were placed before and aft of the grid section to examine the grid rigging and behavior, the behavior and effectiveness of the deflectors, as well as fish behavior and escape events. GoPro cameras (GoPro Corp., San Mateo, CA) were used with custom deepwater housings and underwater lights (Sartek Industries, Port Jefferson). Video was collected on 15 tows, on the experimental trawl (with the grid) only.

2.4. *Data collection*

The catch from each tow was separated into species and weighed to the nearest 0.1 kg using a Marel marine scale (Marel Corp., Iceland). The length of all commercial species caught were measured from each tow to the nearest cm. During large hauls a sub-sampling of about 100 individuals were measured for length. Total fish lengths were measured for all fish except haddock and pollock (*Pollachius pollochius*) for which the fork length was measured. Less important bycatch species were counted, and their total weight measured. The catch from each tow was standardized to a catch rate (kg/hr).

Bottom temperature was measured every minute by a temperature sensor (TidbiT v2 Temperature Logger, Onset Computer Co., Bourne, MA) attached to a trawl door.

2.5. *Data analysis*

A non-parametric paired randomization test (Manly, 2006) was used to evaluate catch comparisons between the experimental and control gears for different species. The test first evaluated the mean difference in catch between the two treatments of all the tow pairs. Subsequently a random dataset was constructed by replicating the original catch data,

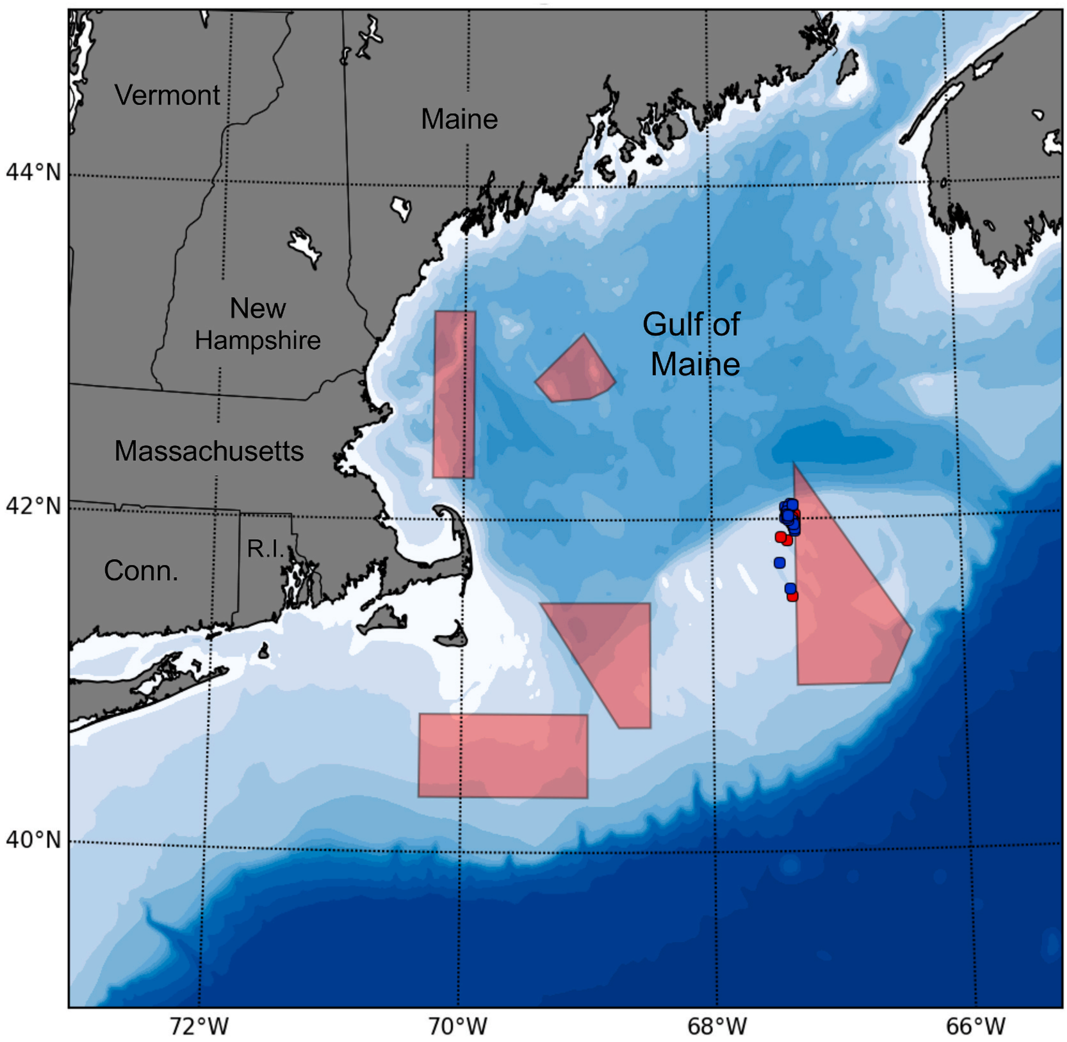

Fig. 2. Tow locations for trip 1 (red) and trip 2 (blue). Red polygons are areas closed to commercial bottom trawls as of 2016.

randomly reassigning the treatment while maintaining the pairing, and calculating the mean difference between the treatments. One thousand randomizing iterations were used to construct a robust, "random" data set. The field data was then compared to the randomized data set and given a rank. If the field data was in the top or bottom 2.5%, based on the rank, it was considered statistically significant. Statistically significant differences would indicate that the trends in the data were highly unlikely to be collected randomly thereby indicating an influence of the treatment on the results. The ρ-value was obtained as the rank divided by the number of iterations, significance was determined by $\rho < 0.025$ or $\rho > 0.975$.

To determine the potential differences in size selectivity between the two treatments, generalized linear mixed models (GLMMs) were used to evaluate the difference in catch for each length class. This approach followed the methods described by Holst and Revill (2009). In these models the response variable was the catch proportion at each length (ϕ; Experimental/(Control + Experimental)). A binomial GLMM with a logit link function was used to fit curves. The GLMM was implemented using the glmmPQL function in the MASS package (Venables & Ripley, 2002) of the R statistical software, which uses a penalized quasi-likelihood approach (Breslow & Clayton, 1993; R Core Team, 2014). Four different models were fit to the data including a constant (Eq. (1)), linear (Eq. (2)), quadratic (Eq. (3)) and cubic model (Eq. (4)).

$$(\Phi|b) = \log(qe/q_c) + \alpha \quad 1$$

$$(\Phi|b) = \log(qe/q_c) + b_1 \bullet L + \alpha \quad 2$$

$$(\Phi|b) = \log(qe/q_c) + b_1 \bullet L + b_2 \bullet L^2 + \alpha \quad 3$$

$$(\Phi|b) = \log(qe/q_c) + b_1 \bullet L + b_2 \bullet L^2 + b_3 \bullet L^3 + \alpha \quad 4$$

The sub-sample ratios for each tow was used as offsets with q_e and q_c representing the experimental and control trawl respectively. Due to the correlation between multiple hauls, a random intercept mixed effect parameter (α) was included where tow was the random effect. Length (L) was the only explanatory variable.

Significances of the model parameters were estimated using a Wald's test. Due to the use of a penalized quasi-likelihood to estimate parameters, Akaike's Information Criterion (AIC) was not used to compare models. The optimal model was defined as the most complex model in which all the terms were significant ($\rho < 0.05$) with no patterns in the residuals. GLMMs were applied to the most abundant species in the catch: Atlantic cod, haddock, and winter flounder.

2.6. *Video analysis*

Twenty hours of video from 15 tows were collected over the duration of the project. While the primary focus of the video work was to ensure adequate grid geometry and performance, behavioral and escape events of fish could be extracted from the video to assess species-specific escape behavior. Initially, videos were reviewed to determine adequate visibility and camera position for further analysis. Overall, water visibility was fair, however camera position was the primary factor determining overall usability. Video recordings in which the camera was placed in front of the grid system facing aft, yielded good images, however we are unable to obtain behavioral information from individual fish due to the large number of haddock in each tow (>1,000 individuals/hr). At this position, an individual's fate could not be determined because new fish were constantly entering the field of view obscuring fish as they move into the grid system. As a result, we could only use tows in which the camera was placed behind the grid system facing forward, as the example given in Fig. 3.

Frame by frame analysis of the collected video was analyzed using the BORIS software package (Friard & Gamba, 2016). Fish were tracked during their passage through the grid system. Each fish was speciated and their fate was recorded (escaped or transited to the codend). For escaped fish, the grid (front vs. rear, and right vs. left) was recorded as well as the vertical position in which the fish escaped. From the data, we estimated escape rates for each grid opening (from 1 in the bottom to 12 on the top of the grid). Five and a half hours of video (4 tows) were analyzed.

3. Results

3.1. Operational data

A total of 26 valid pairs (52 tows) were completed. The trawl with a grid system could be deployed and retrieved with the existing deck machinery and a usual compliment of crew. Adding or removing the grid section took about 20 min.

Tow duration ranged from 50 min to 91 min (mean: 76.2 ± 6.9 min). Towing speed averaged 2.9 ± 0.2 knots. Tow locations were in open areas primarily along the northwestern edge of Closed Area II on Georges Bank. Fishing depth averaged 49.7 ± 2.7 m. Bottom temperature during the tows were between 8.0 and 11.8 °C, and there were no statistical differences in bottom temperature between control and experimental tows (p = 0.858; Student's t-test).

3.2. Catch comparison

A total 26 species were caught during the experiment; their common and species names are listed in Table 1. The total catch by the control and the experimental trawl with grid for top five species or species group is provided in Table 2. These five main catch species/species group accounted for 95.6% of the catch weight, and included mixed skates (winter skate, *Leucoraja ocellata* and little skate, *Leucoraja erinacea*), Atlantic cod, winter flounder, haddock and spiny dogfish (*Squalus acanthias*) (Fig. 4).

Fig. 3. An example of video footage with the camera placed behind the grid system looking toward the mouth of the trawl.

3.3. Skates and spiny dogfish

"Mixed skates" were the primary bycatch species and accounted for 45.4% of the catch. The grid system significantly reduced the catch of mixed skates, 29.4% from 395.4 ± 62.9 kg/h (mean ± SE) to 279.1 ± 27.1 kg/h (p-value = 0.0120). Similarly, the catch of spiny dogfish was reduced 25.9% from 15.9 ± 3.8 kg/h in the control trawl to 11.8 ± 4.0 kg/h in the experimental trawl (p-value = 0.0646).

3.4. Flounder species

Winter flounder was the primary flatfish species caught and accounted for 12.2% of the total catch. The catch rate of winter flounder was reduced from 121.7 ± 9.8 kg/h to 59.6 ± 5.6 kg/h (51.0% reduction), and was statistically significant (p-value < 0.0001). In all tow pairs except two, the experimental trawl with the grid system reduced the catch of winter flounder compared with that of the control (Fig. 5).

A total of six other flounder species were caught, including Atlantic halibut, fourspot, windowpane, summer, witch and yellowtail flounder. The catch rate of these species was relatively low. Despite the overall low catch rates, three of the more abundant flounder species in the catch exhibited reduced catch rates in the experimental trawl compared to the control (Fig. 6). Yellowtail flounder was reduced by 36.8% from 1.9 ± 0.4 kg/h to 1.2 ± 0.2 kg/h ($p = 0.0275$). Summer flounder was reduced by 45.0% ($p = 0.0172$) and windowpane flounder was reduced by 54.7% ($p = 0.0291$). The reduction of witch flounder was 62.4%, but was not statistically significant ($p = 0.2443$). When aggregated, the catch of all flounders, including winter flounder, was reduced by 51.3% from 131.2 ± 9.6 kg/h to 63.9 ± 5.9 kg/h and was statistically significant ($p < 0.0001$).

Analysis of size selectivity was only conducted for winter flounder. For winter flounder, individuals of all sizes were reduced in the experimental trawl compared to the control (Fig. 7 A). This was confirmed in the GLMM analysis, indicating that a constant model provided the best

Table 1
Species, with common and scientific names, caught during sea trials.

American lobster *(Homarus americanus)*
Atlantic cod (*Gadus morhua*)
Atlantic Halibut (*Hippoglossus hippoglossus*)
Atlantic herring (*Clupea harengus*)
Atlantic longfin squid (Doryteuthis pealeii)
Black sea bass (*Centropristis striata*)
Cunner (*Tautogolabrus undulates*)
Four-spot flounder *(Paralichthys oblongus)*
Haddock (*Melanogrammus aeglefinus*)
Longhorn sculpin (*Myoxocephalus octodecemspinosus*)
Little skate (*Leucoraja erinacea*)
Monkfish (*Lophius americanus*)
Ocean pout *(Macrozoarces americanus)*
Pollock (*Pollachius virens*)
Red hake (*Urophycis chuss*)
Sea raven (*Hemitripterus americanus*)
Silver hake (*Merluccius bilinearis)*
Spiny dogfish (*Squalus acanthias*)
Summer flounder (*Paralichthys dentatus*)
White hake (*Urophycis tenuis*)
Windowpane flounder (*Scophthalmus aquosus*)
Winter flounder *(Pseudopleuronectes americanus)*
Winter skate (*Leucoraja ocellata*)
Witch flounder (*Glyptocephalus cynoglossus*)
Wolffish (*Anarhichas lupus)*
Yellowtail flounder (*Limanda ferruginea)*

Table 2

The total catch weight (kg) and number of individuals caught in the control and experimental trawl (with grid) for the top five species (or species groups). The subsample of fish measured for lengths are listed in brackets. Mixed skates were mainly little skate (*Leucoraja erinacea*) and winter skate (*Leucoraja ocellata*).

Species	Species name	Control		Experimental	
		Individuals	Total Weight	Total Weight	Individuals
Target species					
Haddock	*Melanogrammus aeglefinus*	1575.4	1966 (1276)	1397.5	1010 (1010)
Atlantic cod	*Gadus morhua*	8917.9	3559 (1998)	8410.8	3568 (2193)
Bycatch species					
Mixed skates	*L. erinacea and L. ocellata*	15594.4	N/A	11394.4	N/A
Winter flounder	*Pseudopleuronectes americanus*	4837.5	4010 (1677)	2491.7	1955 (1519)
Spiny dogfish	*Squalus acanthias*	1212.6	N/A	793.9	N/A

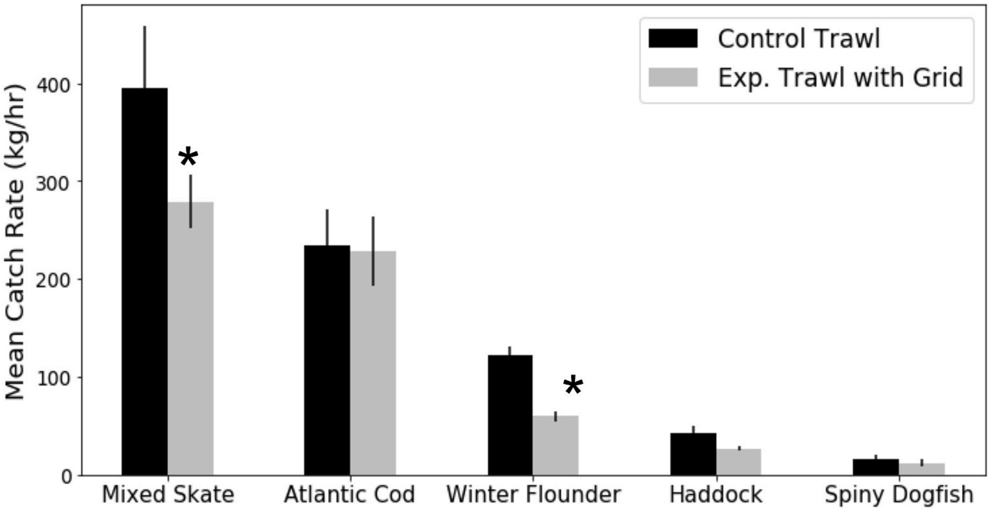

Fig. 4. Mean catch rates of the five major species (groups): mixed skates (mainly winter skate, *Leucoraja ocellata* and little skate, *Leucoraja erinacea*), Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), winter flounder (*Pseudopleuronectes americanus*) and spiny dogfish (*Squalus acanthias*), which accounted for 95.6% of the catch by weight. The asterisk (*) indicates a statistically significant difference between treatments.

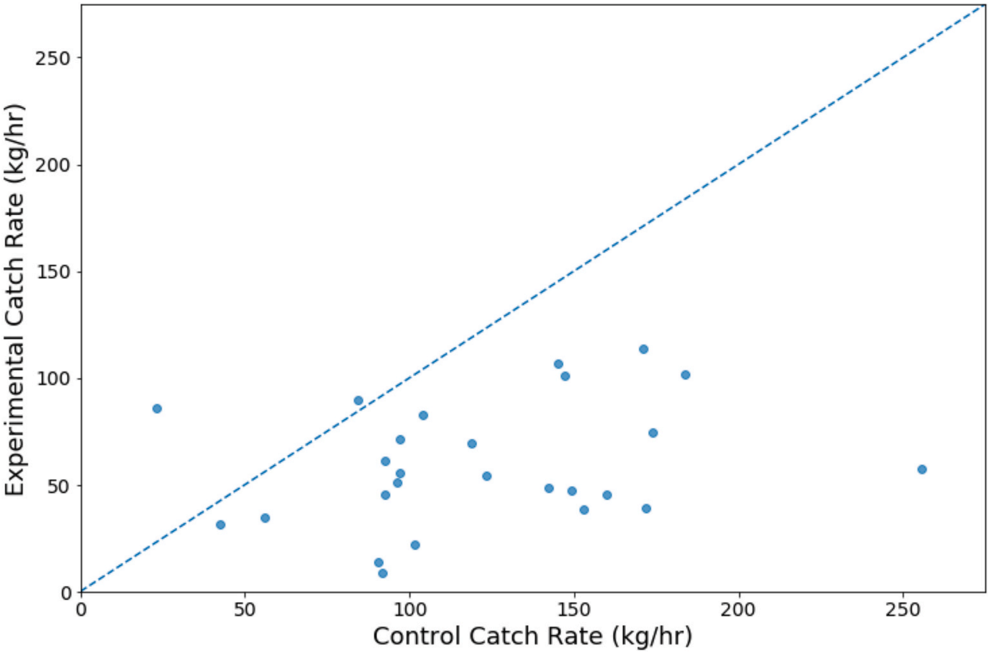

Fig. 5. Scatterplot comparing the catch of winter flounder (*Pseudopleuronectes americanus*) between treatments in each tow. Analysis of the tow data indicates that the control net caught more winter flounder in 24 of the 26 pairs. The dashed line in the figure indicates equal catch between the two treatments for that tow pair. Points below the line indicate pairs in which the control net caught more than the experimental net. Points above the line indicate tows where the experimental net caught more than the control net.

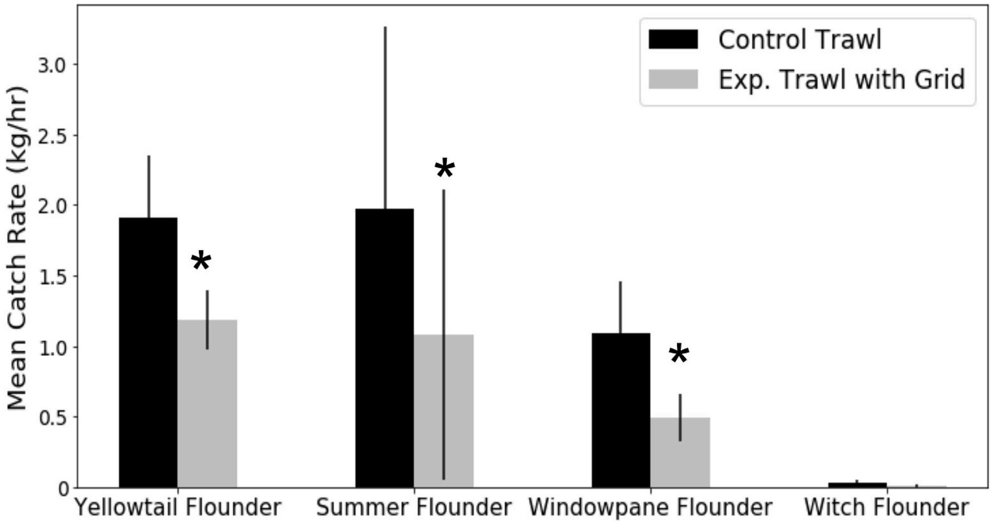

Fig. 6. Mean catch rates of the control and experimental trawls for four other flounder species: yellowtail flounder (*Limanda ferruginea*), summer flounder (*Paralichthys dentatus*), windowpane flounder (*Scophthalmus aquosus*), and witch flounder (*Glyptocephalus cynoglossus*). The asterisk (*) indicates a statistically significant difference between treatments.

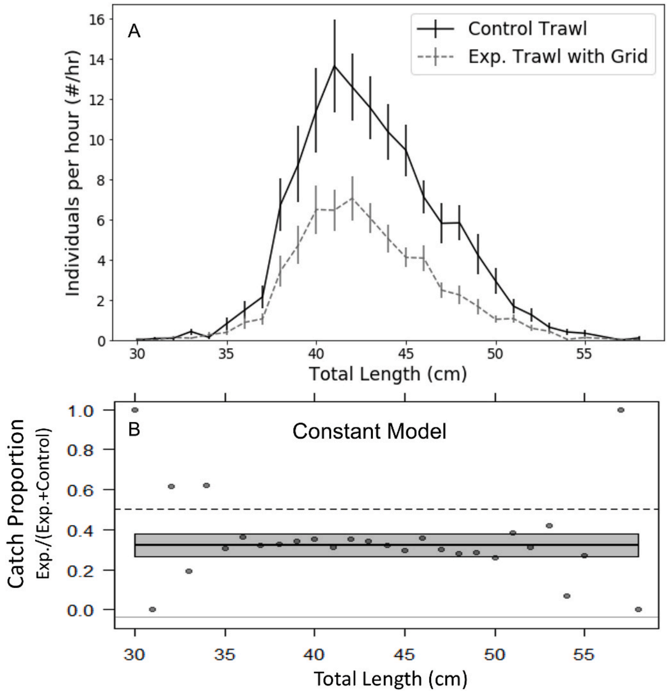

Fig. 7. The length frequencies of winter flounder (*Pseudopleuronectes americanus*) for each treatment (A). A constant model provided the best fit to the data in the GLMM analysis (B; $p < 0.0001$). This indicates no size related selectivity between the two treatments.

fit to the data ($p < 0.0001$, Fig. 7 B). This indicates that there was no observable size-based selectivity over the observed size range.

3.5. Atlantic cod and haddock

The two primary roundfish species included Atlantic cod (31.1% of the catch) and haddock (4.6% of the catch). There were no significant differences in the catch rate of Atlantic cod. The catch rate of the experimental trawl was 228.6 ± 35.3 kg/h compared to 233.7 ± 38.2 kg/h in the control (p-value: 0.4368, Fig. 4). In 50% of paired tows, the control caught more fish while in another 50% of tows, the experimental trawl caught more fish (Fig. 8).

The length composition between the two treatments appeared to be very similar (Fig. 9 A). A second order model provided the best fit to the cod length data (Fig. 9 B) and showed the confidence boundaries overlapped the equal proportion line (0.5, dashed line), except for very small fish <36 cm (Fig. 9 B, vertical line).

Overall, the catch rate of haddock was low with mean catch rate <50 kg/h. However, in terms of catch weight, the experimental trawl with grid reduced catch of haddock by 36.9%, from 41.8 ± 8.8 kg/h in the control to 26.4 ± 2.3 kg/h in the experimental trawl, and the reduction was not statistically significant (p-value: 0.0585) due to large tow-by-tow variations in the catch rate of haddock (Fig. 10). In four of the tow pairs, the control trawl caught much more haddock compared with the experimental trawl which resulted in large overall reduction in catch rates.

The reduction in catch of haddock was not uniform throughout the size distribution, however, with much greater reduction in the smaller fish (Fig. 11 A). The number of fish below the current U.S. minimum landing size (<40 cm FL) was reduced by 65.4% and small haddock (40–44 cm) was reduced 59.3%. In the meantime, scrod haddock (45–49 cm) was only reduced 21.7%, while large haddock (50+ cm) showed a 7.3% increase in catch. This trend was also observed in the GLMM analysis where a linear model provided the best fit to the data (Fig. 11 B). There was a significant reduction for haddock less than 41 cm, and significant increase for haddock greater than 56 cm, and no significant difference for haddock between 41 and 56 cm.

3.6. Fish escape from video observations

Video observations of winter flounder indicated that they primarily escaped out of the lower part of the grid. Escape out of the top, middle and bottom sections of the grid were 18.7%, 24.0% and 57.3%, respectively (N = 14, 18, 43; Fig. 12). Escape out of the codend appears to be low, as 356 individuals were observed transiting through the grid system and 401 were collected in the codend during the video tows (Table 3). Winter flounder were observed to enter the extension tail first, passively moving through the grid sections and then burst swimming in the towing direction to escape through the rear grids. Of the 75 individuals observed escaping from the grid system, 89.3% (67 individuals) escaped out of the rear grids.

Escape of Atlantic cod through the grid was very low, probably due to the large size of the fish. Of the 799 individuals observed by video

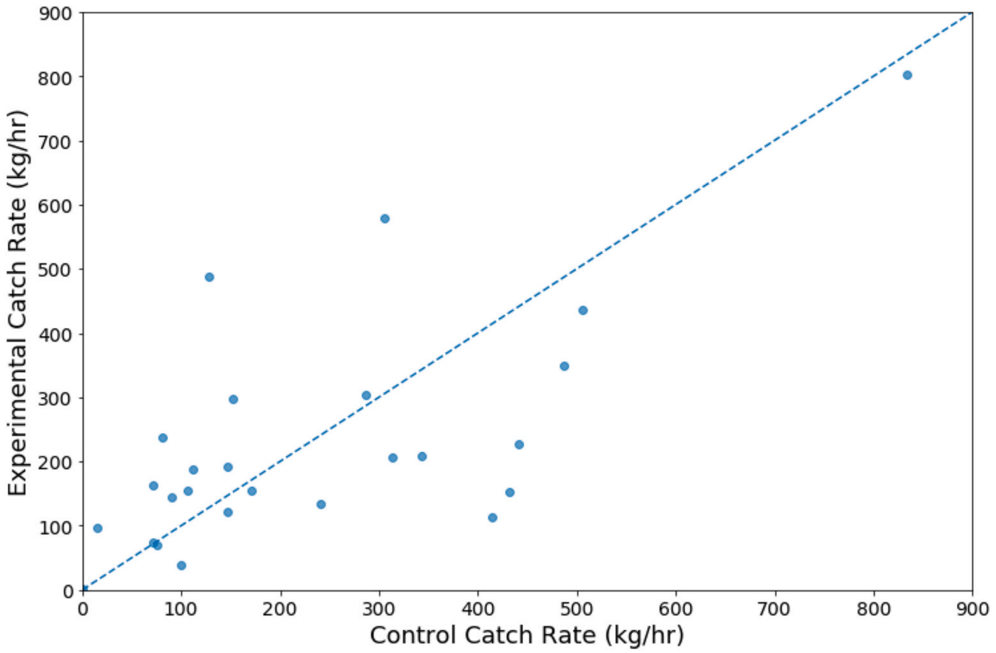

Fig. 8. Scatterplot comparing the catch of Atlantic cod (*Gadus morhua*) between treatments in each tow pair. Analysis of the tow data indicates that the control net caught more cod in 13 of the 26 pairs. The dashed line in the figure indicates equal catch between the two treatments for that tow pair. Points below the line indicate tows in which the control net caught more than the experimental net. Points above the line indicate tows where the experimental net caught more than the control net.

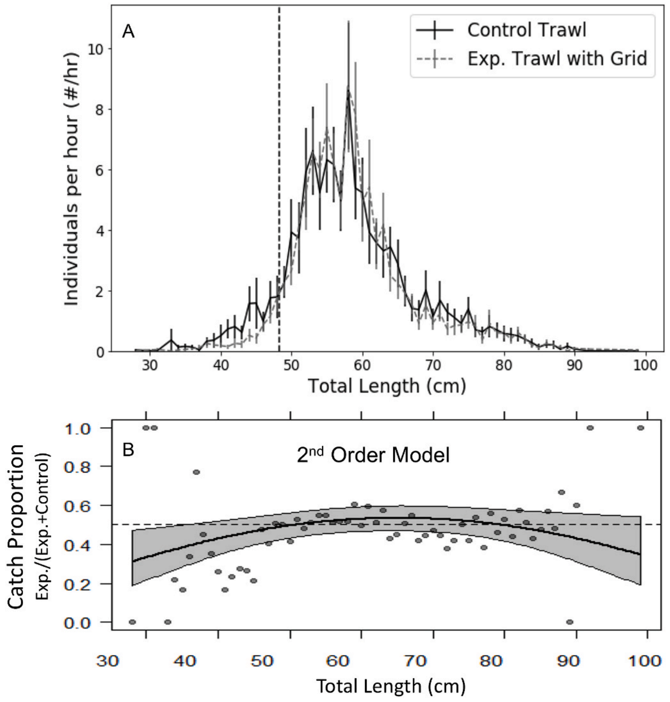

Fig. 9. The length frequencies of Atlantic cod *(Gadus morhua)* from both gear configurations (A). While the two length frequencies are similar between the treatments, the GLMM analysis indicated a small but significant reduction in small fish (<40 cm). A second order model provided the best fit to the data. The vertical dashed line is the current U.S. minimum landing size.

camera, only 76 individuals swam out of the grid. Of the 76 escapees, 26 reentered the trawl through the grid (Table 3). As a result, only 50 out of the 799 individuals were observed escaping. Cod were primarily observed to transit and escape the grid near the bottom of the grid system with 66.7% of observed escapes occurring out of the bottom third (Fig. 12). Cod predominately escaped out of the rear grids, 66 of the 76 escapes. A total of 544 individuals were caught in the codend compared with a total of 749 individuals observed transiting through the grid system, indicating a 27.3% codend escape rate.

Despite relatively low catches of haddock observed in the codend, numerous haddock were observed in the video observations (7512 individuals). Haddock were highly mobile in this section of the trawl. A total of 3,559 individuals were observed exiting the grid system, but many were subsequently observed to re-entering the trawl (952 individuals). As a result, 2607 haddock, or 34.7% of the observed fish, ultimately escaped out of the grid system. Escape was primarily associated with the top of the grid with 70.6% of individuals observed escaping out of the top half of the grid (Fig. 12). Two-thirds of the fish were observed escaping out of the rear grid while one-third were observed escaping out of the front grids. Only 206 individuals were retained in the codend in the four video tows, out of 4905 individuals observed transiting through the grid system to the codend. This indicates a 95.8% escape rate through the codend meshes.

4. Discussion

Increasing quota for healthy groundfish species such as haddock, pollock and Acadia redfish, and the continued reduction in quota of flounder species, especially yellowtail and windowpane flounder, in the US northeast multispecies fishery requires selective fishing gear and techniques to better utilize the available quota. Understanding behavioral and geometrical differences between species and species groups are the key to informed gear design (He et al., 2008).

Most flounder species tend to stay near or on the substrate, especially during the day (Walsh & Hickey, 1993); some are even buried into the substrate (Olla, Wicklund, & Wilk, 1969). They typically swim closed to the seabed and escape downward when approached by a towed fishing gear. He (2003) found that winter flounder never rose to 0.5 m off seabed in their natural environment as observed by a video camera. The majority of yellowtail flounder swim close to the seabed when they are approached by a bottom trawl, and seek to escape through gaps of the trawl's groundgear (Underwood, Winger, Fernø, & Engås, 2015). Heavy sweep and groundgear are often used to herd and catch flounders; and if a reduction of flounder bycatch is desired, a raised sweep or a floating sweep may be used to reduce herding of flounder (He, Rillahan, & Balzano, 2015; Ryer, Rose, & Iseri, 2010). Trawls with raised footrope or using drop chains that connect the groundgear and fishing line have been tested to reduce flounder bycatch (Bayse, Rillahan, Jones, Balzano,

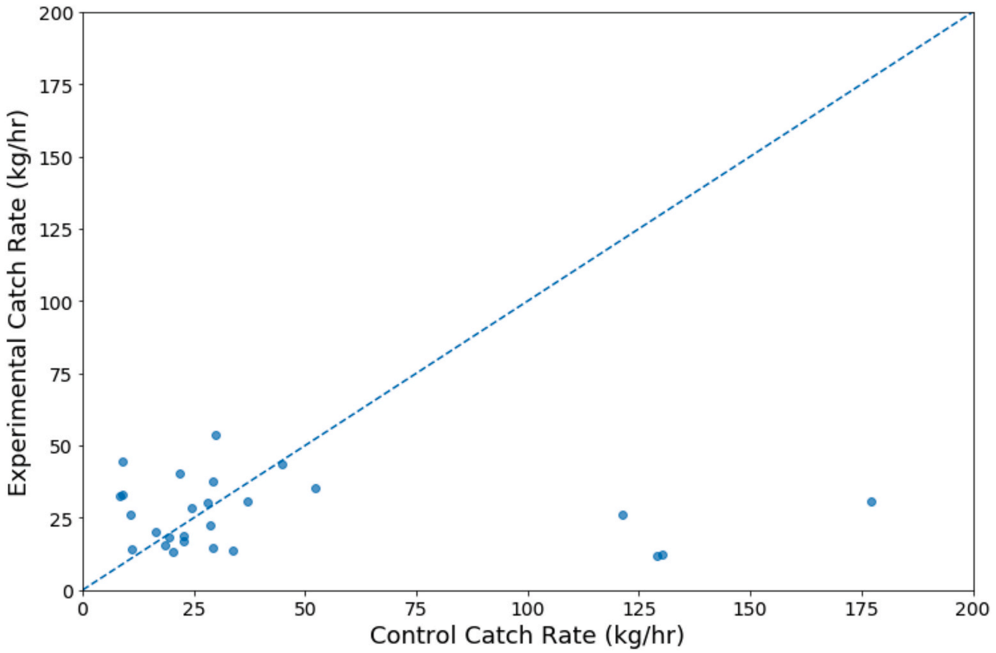

Fig. 10. Scatterplot comparing the catch of haddock *(Melanogrammus aeglefinus)* between treatments in each tow pair. Analysis of the tow data indicates that the control net caught more haddock in 15 of the 26 pairs. The dashed line in the figure indicates equal catch between the two treatments for that tow pair. Points below the line indicate tows in which the control net caught more than the experimental net. Points above the line indicate tows where the experimental net caught more than the control net.

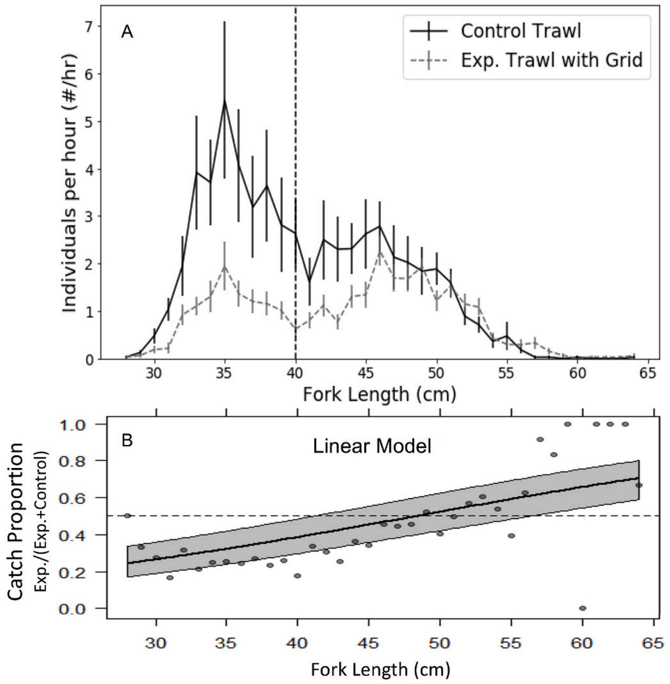

Fig. 11. The length frequencies of haddock *(Melanogrammus aeglefinus)* from both gear configurations (A). Significant reductions were observed for smaller fish (<50 cm, sub-legal, small and scrod), while no reduction for large fish (>50cm). A linear model provided the best fit to the data in the GLMM analysis (B), indicating a significant reduction for haddock <41 cm, no differences in media-sized haddock (41 - 56 cm), and an increase in large haddock > 56 cm. The vertical dashed line is the current U.S. minimum landing size.

& He, 2016; Scotti et al., 2014).

When flounders are inside the trawl, they often pass down the trawl toward the codend close to the belly netting of the trawl (Ryer, 2008). Large mesh belly windows have thus been tested to encourage the escape of flounder through the belly panel (Bayse, Pol, & He, 2016; Milliken & DeAlteris, 2004). Even down to the rear part of a trawl,

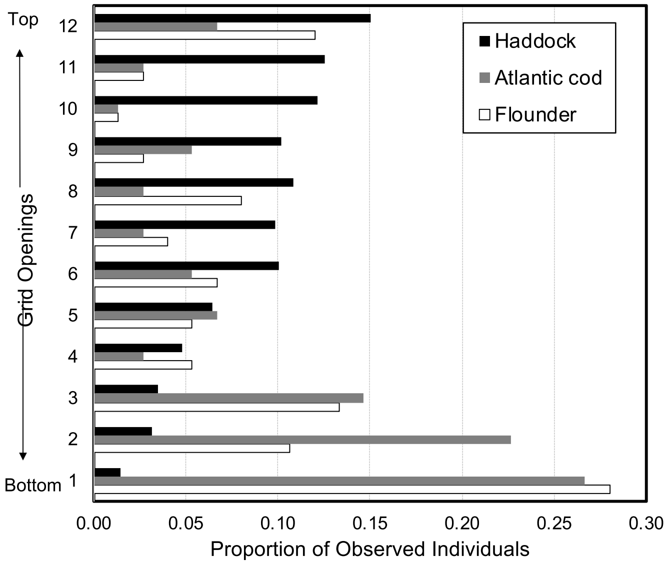

Fig. 12. The vertical escape location of haddock *(Melanogrammus aeglefinus)*, Atlantic cod *(Gadus morhua)* and flounder (mainly winter flounder, *Pseudopleuronectes americanus*) out of the grid system. The grid has 12 openings between the top and bottom of the grid.

flounders continue to stay in the lower part of the trawl extension (He et al., 2008).

In the realm of species separation and the release of unwanted animals, grids have been playing an important role since 1980s with the work by NOAA Fisheries on Turtle Excluder Device in tropical shrimp fisheries (Watson & Seidel, 1980), and with the work of the Norwegians on the Nordmøre Grid for coldwater shrimp trawls (Isaksen et al., 1992). Many versions of TEDs and Nordmøre-style grids are being used in many trawl fisheries worldwide, and many have become a part of fishery management tools. The advantage of the grid is that it can be inserted into an existing trawl, thus provide fishermen with flexibility and cost-effectiveness.

The results of this project showed that the modified European-style grid can reduce the catch of flounders without a loss of Atlantic cod or

Table 3
Underwater video observations of fish escaped and transited through the grid system for flounder (mainly winter flounder, *Pseudopleuronectes americanus*), Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). Codend escape rate is not provided as more flounders were retained than that observed transiting to the codend, presumably some of flounders entering the codend were not recorded in video.

	Flounders	Atlantic cod	Haddock
Total number observed	425	799	7512
Number exiting grid	75	76	3559
Number re-enter grid	6	26	952
Total number of grid escapes	69	50	2607
Number transited to codend	356	749	4905
Number observed in the catch	401	544	206
% escape through grid	16.2%	6.3%	34.7%
% escape through codend	–	27.3%	95.8%

large haddock. This indicates that fishermen can change the species selectivity of their trawls with minimal costs by adding a grid section to the trawl. This system was easy to deploy within an existing trawl system and can be retrieved with the existing deck machinery (net drum). Installation and/or removal only took 15–20 min, thus allowing impromptu decision by the vessel captain based on catch composition and the desire to retain or release certain fish species in relation to their conservation status or availability of quota of the vessel.

While the main flounder species encountered during the sea trials was winter flounder, our limited data indicates that other flounder species would have the same or even better results, especially for yellowtail and windowpane flounders which have smaller size and thinner body than winter flounder. The initial European grid showed a 68% reduction in flatfish catch (Santos et al., 2016). The sole species caught in that study was European plaice (*Pleuronectes platessa*), a close relative of yellowtail flounder. This is comparable with our data for winter flounder for which a 51% reduction was documented through comparative fishing trials. The European grid in Santo et al. (2016) had an alternative rigging which might have resulted in an increased grid angle, and therefore increased surface area to promote contact and hence escape. This study did not use the cross bars to maintain grid geometry as this was considered not feasible for the trawl fleet in New England, due to its inability to be wrapped on a net drum. We instead opted for an addition grid section behind the angled grids to provide fish with additional opportunity to escape.

Alternatively, a grid section could be made of T-90 netting instead of traditional diamond mesh (T-0); the former seemed to maintain geometry of grid section much better as revealed in another subsequent study (He, Rillahan, Pol, Walsh, & Bendikson, 2017, p. 27). Further work to improve grid geometry should therefore consider using T-90 netting instead of regular diamond mesh netting to ensure good geometry, thus functioning of the grid system.

Underwater cinematography and video technology have been playing an important role in understanding fish behavior in the wild and in aiding the design and modification of selective and/or efficient fishing gear (Graham, Jones, & Reid, 2004). Interestingly video observations from these two studies showed different escape behaviors between the two dominant species. The European study documented most fish entering the extension head first and escaping through the grid upon initial contact (Santos, Pers. Comm.). Winter flounder in this study were observed to enter the extension tail first, passively moving through the grid sections and then burst swimming forward in direction of tow to escape through the rear grids. Unfortunately, no yellowtail or windowpane were observed escaping during this study to inform their escape behavior. Species-specific escape behavior could provide further potential for additional selectivity.

The escape of juvenile fish, especially haddock, observed in this study is encouraging. Significant reductions in the catch of small cod (<38 cm) and haddock (<41 cm) were observed. Especially for haddock, small undersized fish constitute a large proportion in the catch (Fig. 10 A). Research has shown that fish which escape or were released from grids are more likely to survive than those that escaped through codend meshes (Ingólfsson et al., 2002). The use of a grid system will not only result in a relatively greater proportion of large haddock in the catch, but also less unobserved mortality of escapees, contributing to future stock biomass.

One interesting finding from current video observations shows that flounders were seen mostly escaping from the bottom half of the grid while haddock were mostly on the top half. This is consistent with findings of the flounder species where they stay in the lower half and haddock in the upper half of the extension of a trawl (He et al., 2008). This provides a rationale for designing a grid system with differential bar spacings. For the species and size compositions we encountered during the sea trials, a grid system with smaller spacing (about 60 mm) on the top half of the grid to improve retention of haddock, and larger spacing (about 80 mm) on the bottom half of the grid to further reduce the catch of flounders would likely improve the species separation – further reducing the catch of flounder while improve retention of haddock.

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