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Design and test of a grid to reduce bycatch in the longfin inshore squid (*Doryteuthis pealeii*) trawl fishery

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Summary

A species separation grid was tested for a squid trawl to reduce finfish bycatch in the Nantucket Sound longfin inshore squid (*Doryteuthis pealeii*) fishery in southern New England, USA. The experimental trawl with a grid significantly reduces bycatch of summer flounder (*Paralichthys dentatus*) (76.4%, $p < .001$), black sea bass (*Centropristis striata*) (71.7%, $p = .001$), smooth dogfish (*Mustelus canis*) (86.0%, $p < .001$), and total bycatch (69.2%, $p < .001$) when compared to a conventional trawl. The catch rate of scup (*Stenotomus chrysops*) is 40.2% less than in the experimental trawl, but this difference is not statistically significant ($p = .258$). However, the experimental trawl also reduces targeted squid capture by 47.5% ($p < .001$), which is commercially unacceptable. Length analysis indicates no size effect on the retention for squid between the trawl with a grid (experimental) and the one without a grid (control), but the experimental trawl significantly reduces larger scup (>27 cm FL) and larger black sea bass (>37 cm TL), and all summer flounder size-classes. Therefore, this grid design may not be a suitable bycatch reduction device for the Nantucket Sound squid trawl fishery, and further work is needed to understand squid behavior within a trawl to develop a successful bycatch reduction strategy for the New England longfin inshore squid fishery.

1 | INTRODUCTION

The longfin inshore squid (*Doryteuthis pealeii*, hereafter "squid") is widely distributed in the western Atlantic Ocean from Venezuela to Newfoundland (Cohen, 1976; Dawe, Shears, Balch, & O'Dor, 1990). In the northwest Atlantic, squid are concentrated between Cape Hatteras and Georges Bank, where they are harvested commercially (Hatfield & Cadrin, 2002; Lange & Sissenwine, 1983). During autumn and winter months, they are found offshore in deeper waters (>30 m) and are pursued by larger otter trawl vessels (>22 m). During spring and summer, squid migrate inshore to spawn in warm shallow waters, and are fished by smaller vessels with otter trawls and weirs in Nantucket Sound and southern New England (Hatfield & Cadrin, 2002; Serchuk & Rathjen, 1974).

Squid co-occur with many finfish species in the eastern USA that are often captured as bycatch by the small mesh trawl codends (76 mm or less) used in the fishery, including butterfish (*Peprilus triacanthus*), scup (*Stenotomus chrysops*), summer flounder (*Paralichthys dentatus*), black sea bass (*Centropristis striata*), and smooth dogfish (*Mustelus canis*) (Bayse & He, 2017). Butterfish had no directed fishery prior to 2014 and had a limited market (Hendrickson, 2011). Consequently, any butterfish catch was simply discarded. Scup has had small (e.g., 363 kg) per-trip landing quotas (NEFSC, 2010). Because scup are commonly found in large schools, the scup trip quota can potentially be exceeded with a single tow, again resulting in wasteful discards (Bayse, He, Pol, & Chosid, 2014; Pol & Carr, 2000). Bycatch of butterfish, scup, and other fish species has led to a variety of trawl gear modification tests, each having partial success, but all losing too many squid for commercial applications (Glass, Sarno, Milliken, Morris, & Carr, 1999; Glass et al., 2001; Hendrickson, 2005; Pol & Carr, 2000; Pol, Carr, & Glass, 2002).

One particular bycatch reduction device (BRD), the Nordmøre grid, has been introduced successfully into many small-mesh shrimp fisheries worldwide (Fonseca, Campos, Larsen, Borges, & Erzini, 2005;

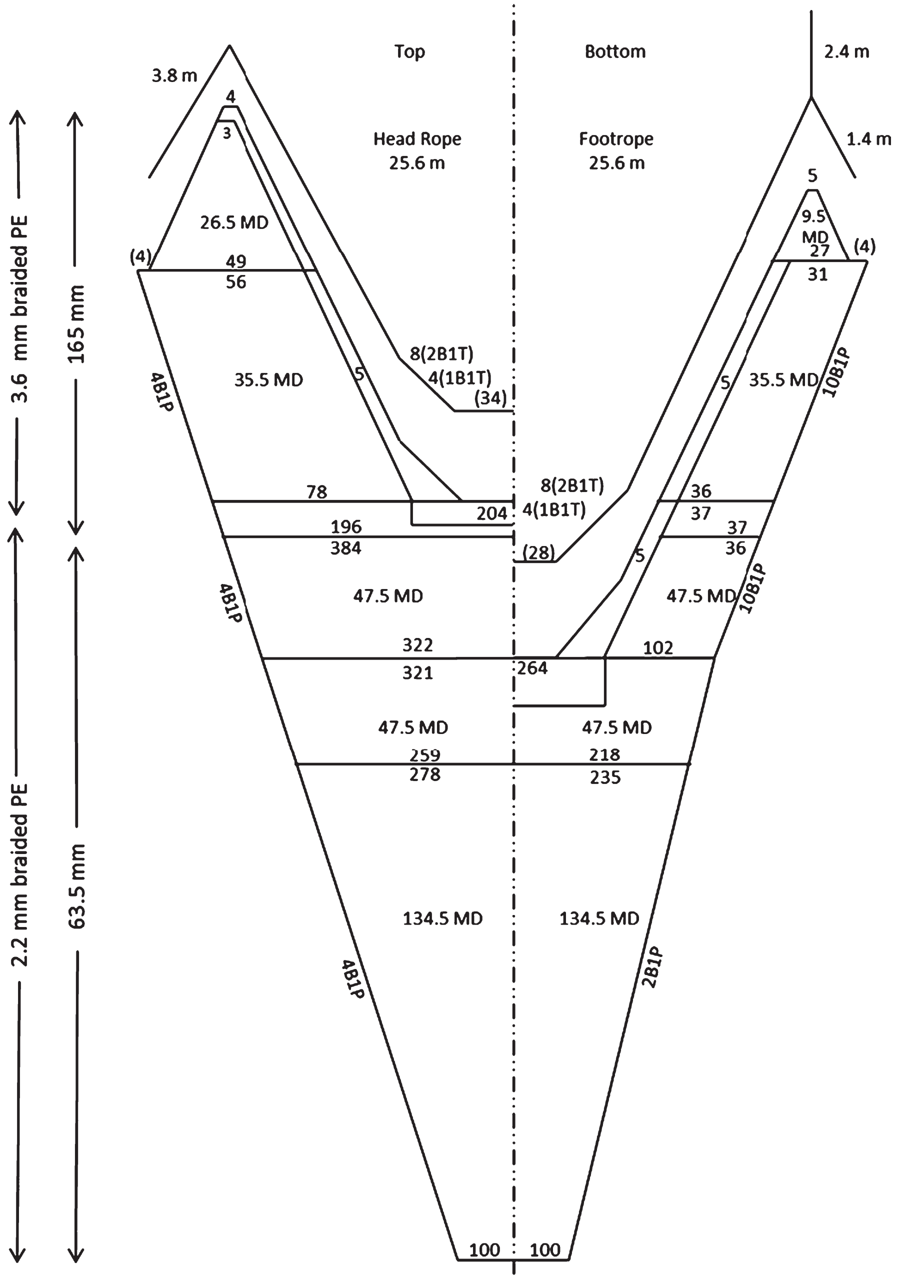

FIGURE 1 Net plan of trawl used. Measurements are in number of meshes unless otherwise noted (modified from Bayse, Pol, & He, 2016)

Isaksen, Valdemarsen, Larsen, & Karlsen, 1992; Silva et al., 2011), and has been mandated in the nearby Gulf of Maine Northern shrimp (*Pandalus borealis*) fishery where it has successfully separated finfish from Northern shrimp (He & Balzano, 2007, 2011, 2012a,b, 2013; Richards & Hendrickson, 2006). The Nordmøre grid separates species both mechanically (by size) and via behavioral differences (e.g., length and species related swimming capacity) (Fonseca et al., 2005; He, 1993; He & Balzano, 2011).

In the New England squid fishery, several grid-like BRDs within the trawl extension were also tested (Pol et al., 2002). The “vee excluder” (a 63.5 mm mesh panel with two lateral fisheye separators) and a ring excluder (grid-like separator made up of 59.9 mm rings with two lateral fish eye separators) successfully reduced larger-sized scup, but were inconclusive or suffered unacceptable levels of squid loss. A large 360° opening (connected by ropes) in a squid trawl between the extension and codend significantly reduced large-sized scup but did not significantly reduce squid or butterfish catch (L. Skrobe, personal communication).

We theorize that a modified Nordmøre grid within a squid trawl extension can allow commercially acceptable squid catch quantities while reducing bycatch. Based on previous success of the Nordmøre grid reducing fish capture while maintaining the catch of smaller, slower swimming target species, and due to prior experiences in bycatch reduction for the squid fishery, we hypothesize that a squid trawl with a modified Nordmøre grid would reduce the capture of unwanted fishes, such as scup, while retaining enough squid to maintain a viable commercial fishery.

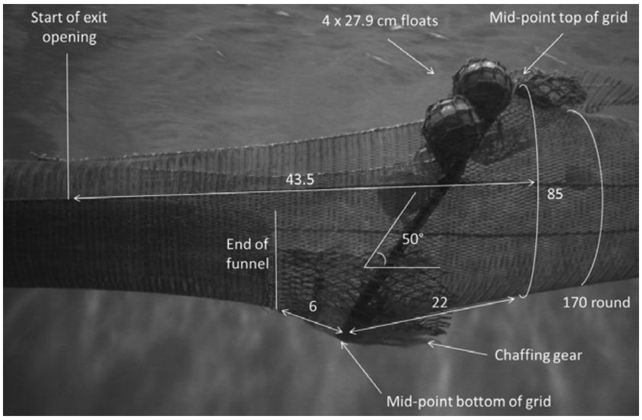

FIGURE 2 Structure and dimensions of the experimental trawl extension, including grid and escape window, during flume tank testing. Measurements are in number of meshes, unless otherwise specified (modified from Bayse, He, Pol, & Chosid, 2014)

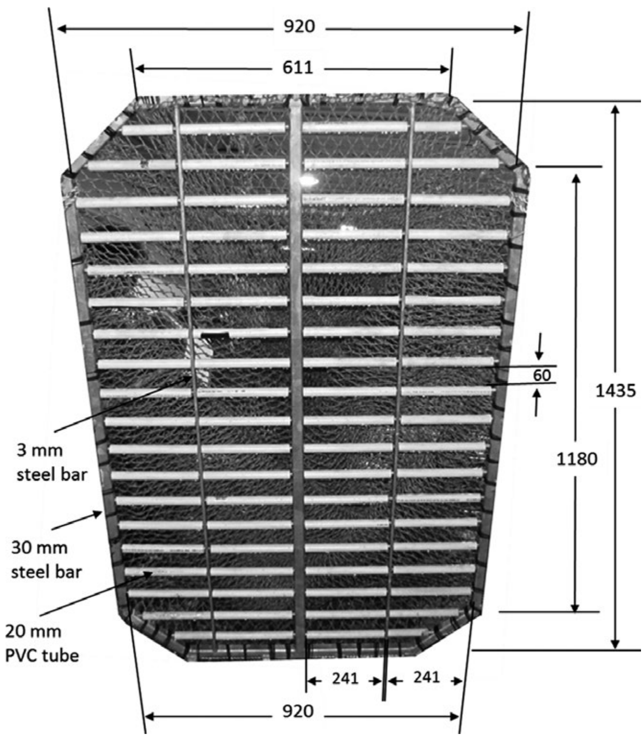

FIGURE 3 Structure and dimension of grid. Measurements are in mm (modified from Bayse, He, Pol, & Chosid, 2014)

2 | MATERIALS AND METHODS

2.1 | Trawl design

A balloon-style trawl net was modified to incorporate the experimental changes (Figure 1). The headline length is 21.5 m, and both the groundgear and fishing line measure 25.6 m. The groundgear is a modified "drop-chain" design (Bayse, Pol, & He, 2016; Nguyen et al., 2015), where chains connecting the fishing line and groundgear allow the fishing line to "rise" off the seabed and away from the groundgear. Drop-chains are 30.5 cm long at the center section of the groundgear, and 20.3 cm at the wingends to allow for the appropriate tapering of the trawl mouth. The groundgear consists of 30.5 cm rollers and 7.6 cm rubber discs, and has a 60 cm distance between adjacent rollers. One drop-chain is installed at the middle of two adjacent rollers along the entire length of the groundgear; thus the distance between two nearest drop chains is also 60 cm. At the center of the groundgear, the fishing line is 49.6 cm above the seabed, and 39.4 cm at the wingends. Both control and experimental hauls use the same trawl from the extension forward. The extension rigging was alternated between the experimental design and the standard extension (see below). Both codends are identical in design, and constructed of 63.5 mm polyethylene single twine diamond mesh (inside knot), with a 127 mm polyethylene double twine diamond mesh codend strengthener.

2.2 | Trawl extension and grid design

The experimental trawl extension and separator grid design were described in Bayse et al. (2014) (Figure 2). External dimensions of the grid are 1465 mm × 935 mm with inner spacings of 60 × 241 mm (Figure 3). The grid is set within the trawl extension at 50° upward from horizontal with the top of the grid leaning toward the codend, and four 27.9 cm floats are used to compensate for the weight of the grid. A grid with horizontal bars was chosen to prevent passage of scup and butterfish, both of which have laterally compressed body types. PVC tubes (20 mm external-diameter) cover the grid bars to provide a rolling effect during fishing to facilitate squid capture. The extension includes a guiding funnel (forward end 192 meshes round, 82 meshes from center-forward to center-aft, and 24 meshes semicircle aft end), which terminates six meshes from the base of the grid, and the escape window is triangularly shaped with an aft base of 0.9 m and an apex forward 2.4 m. A small section of chaffing gear is used at the bottom of the grid. For control tows, a conventional extension (no grid, funnel, or escape window) of equal length and mesh size is used.

2.3 | Sea trials

Sea trials were carried out in Nantucket Sound, Massachusetts, USA aboard the F/V *Atlantic Prince*, a 21 m, 272.2 kW (365 hp) commercial trawl vessel, between 25 May and 4 June 2011. Mean door and wing spread were measured with the TrawlMaster system (Notus Electronics Ltd., St. John's, NL, Canada). The experimental and control extension and codend were detached and attached using a rope laced through plastic rings at the forward section of the extension for easy switchover. Tows were alternated between the experimental and control configurations in an ABBA and BAAB format (A = control; B = experimental), alternating which tow was used first daily. All tows were during daylight hours, and tow durations were standardized to one hour. A video was taken at the trawl extension, grid, and escape window for fish and squid behavior for tows prior to comparative fishing. Details

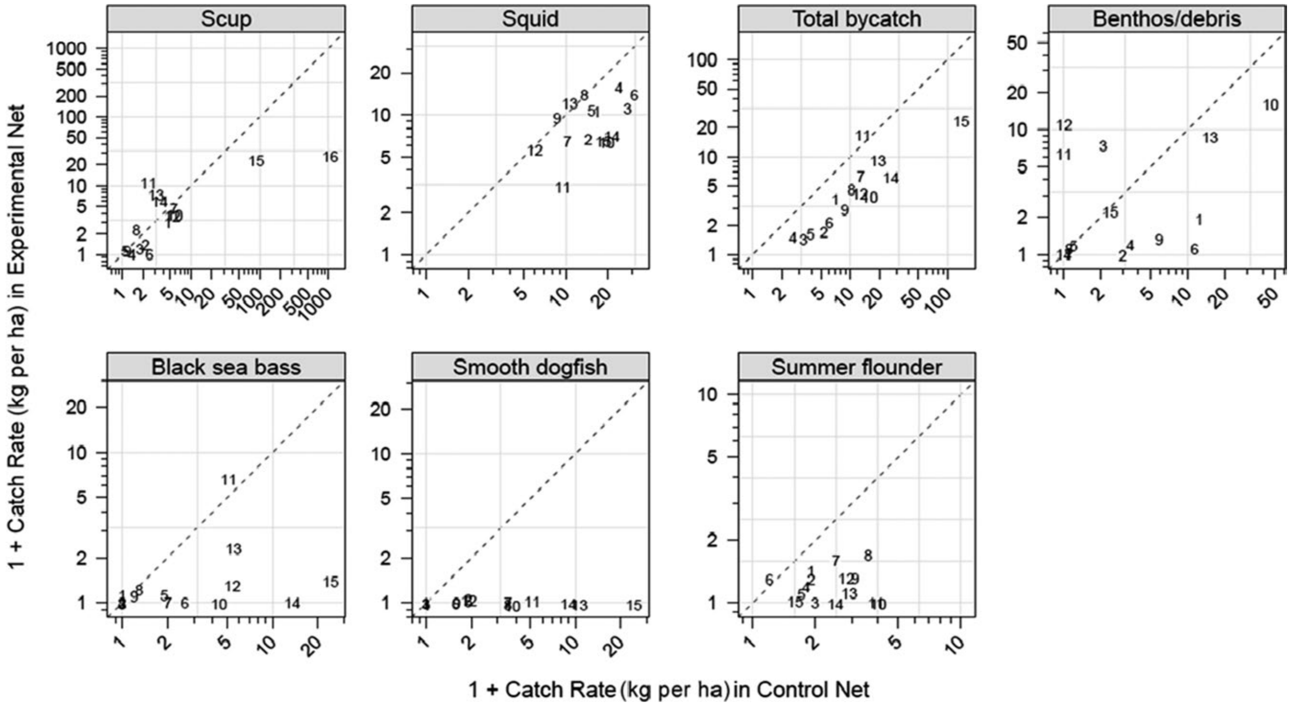

FIGURE 4 Pair-by-pair comparison of the catch rate (kg ha^{-1}) for each of the main species between the experimental (y-axis) and control (x-axis) gear. Each number represents a pair (number indicates which pair). The dashed line indicates equal catch rate between the two gears. Numbers below the dashed line indicate a greater catch rate by the control trawl, and above a greater catch rate for the experimental trawl

of camera placement and squid behavior were described in Bayse et al. (2014).

2.4 | Data collection and analysis

Catches in the codends were sorted by species and weighed to the nearest 0.1 kg using a Marel 1100 motion compensated scale; catches in front of the grid were noted but not quantified. Squid were measured by mantle length and fish were measured by total length or fork length (cm), where appropriate. When large numbers of a species were caught, a subsample of 50–70 individuals was taken for length analysis. Sea grass, other marine macrophytes, marine litter, rocks, and some other catch components were grouped together as "benthos/debris".

Catches between trawls for major species were analyzed with linear mixed models (Bayse, Rillahan, Jones, Balzano, & He, 2016). Catch weights (kg) were standardized to per ha trawled by the area swept of the footrope (average wing spread x the distance trawled). Catch data were log transformed so that differences between trawls would be modeled as multiplicative. Predicted mean weights per ha were obtained by back-transforming. The fixed effect was "trawl" (grid or no grid), and the random effects were "days" and "tow sequence" within a day for each model. Models were fitted using the lme4 package of the R statistical software (Bates, Maechler, Bolker, & Walker, 2013; R Development Core Team, 2009). The significance of each trawl type was determined using likelihood ratio tests where the test statistic (χ^2) is the difference in deviance $d_o - d_a$, where d_a is the deviance of the full model and d_o is the deviance of the constrained model (Bates et al., 2013). Catches between trawls (kg/ha) for major species and groups were examined using equal catch plots, where each point represents one control-experimental pair, with the catch in the control net on the *x*-axis (Figure 4).

Fish catch-at-length was analyzed for tows using a grid by comparing the proportion of catch at each length class using the methods of Holst and Revill (2009). This approach uses polynomial generalized linear mixed models (GLMMs) to fit curves of the expected proportions of catch length using the MASS package (Venables & Ripley, 2002) in R. This method uses low-order polynomial approximations (cubic, quadratic, linear, or constant) to fit the proportions at length retained in the grid trawl codend to those retained by the control and grid codends producing realistic curves and confidence intervals. A proportion of 0.5 indicates no difference in catch between the two trawls at the specific length. A proportion of 0.75 indicates that 75% of fish at a length were caught by the experimental trawl and 25% by the control trawl. The fixed effect was "length", random effects were "tow" and "day", and the subsample ratio was used as an offset. Using a binomial link function, the analysis began by fitting the cubic polynomial followed by subsequent reductions of terms until all showed statistical significance ($p < .05$) based on Wald *t* tests, with removal of one term at a time to determine the best model fit (either constant, linear, quadratic, or cubic) (for additional details see Holst & Revill, 2009).

3 | RESULTS

Thirty-two tows were completed. Towing speeds were between 2.8 and 3.4 knots, and fishing depths between 10.1 and 19.8 m. Mean door

TABLE 1 Mean predicted weight (kg) per ha trawled from linear mixed models, percent predicted catch rate change between experimental trawl with grid and control trawl designs, and likelihood ratio statistics (χ^2), and *p*-value for squid and major bycatch species

Species	Mean (kg/ha)	% Change	χ^2	*p*-value
Longfin inshore squid				
Control	14.1	−47.5	22.877	<.001*
Experimental	7.4			
Scup				
Control	2.8	−40.2	1.282	.258
Experimental	1.7			
Summer flounder				
Control	1.4	−76.3	30.866	<.001*
Experimental	0.3			
Black sea bass				
Control	1.2	−71.6	11.649	.001*
Experimental	0.3			
Smooth dogfish				
Control	1.4	−86.0	27.331	<.001*
Experimental	0.2			
Total bycatch				
Control	8.9	−69.2	21.769	<.001*
Experimental	2.7			
Benthos/debris				
Control	1.4	−33.3	0.431	.512
Experimental	0.9			

*Statistical significance at α of 0.05.

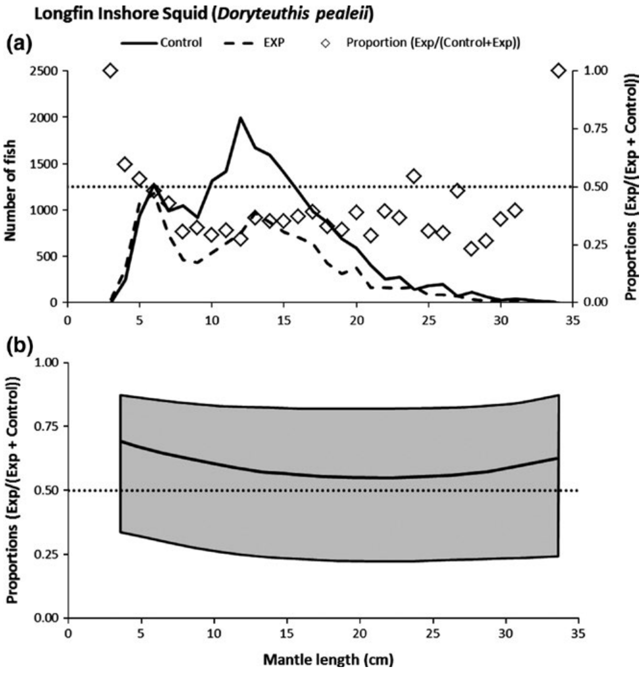

FIGURE 5 (a) Pooled length frequencies of squid from the control (solid line) and experimental (dashed line) nets and observed proportions (exp/(exp + control)). (b) Generalized linear mixed model (GLMM) of proportions of squid at length caught in the trawl with a grid (exp) compared with the total of experimental and the control (exp + control) in a tow pair. A value of 0.5 indicates an even split between the experimental and the control. The shaded areas around the mean curves (bold lines) are the 95% confidence regions

spread was 40.1 m (*SEM* ± 0.7) and wing spread 11.0 m (*SEM* ± 0.3). Mean tow distance was 5,489 m, and mean area swept was 6.0 ha. For one tow, a large amount of scup was caught in the control codend (~6,000 kg), and was only partially retrieved. A visual estimate was made for scup; estimates of other species were not possible.

Mean predicted catch rates of squid were reduced 47.5% by the experimental trawl, which was significantly different ($p < .001$, Table 1). According to an equal catch plot (Figure 4), squid catch was greater in the control trawl for nearly all hauls, with four pairs being approximately even. Squid mantle lengths ranged between 3 and 34 cm for the experimental tows and 4–33 cm for the control tows (Figure 5). According to the GLMM analysis, length was not a factor in catch differences between the two trawls for squid that were retained in the codend (Figuer 5; Table 2). No squid were observed to escape under the fishing line; for further details for behavior and rates of escape under the fishing line for finfish see Bayse, Pol, and He (2016).

Scup was the most abundant bycatch species, with the predicted mean catch rate trend 40.2% less for the experimental trawl, but was not statistically significant ($p > .258$, Table 1). The predicted mean difference was likely a result of two large catches by the control trawl (Figure 4); most pairs had similar catches. Based on the GLMM, only scup greater than 27 cm were significantly reduced by the experimental design; a quadratic curve provided the best fit (Figure 6; Table 2). Catches above 27 cm were, however, very few compared to catches of smaller fish. Scup were observed by video to typically enter the trawl extensions in large groups, but large amounts of time passed with no scup in the trawl extension. Scup swam with the trawl at the experimental extension for times ranging from only a few seconds (reaching the grid and immediately exiting out the escape window), to greater than 30 min at the grid, until haul back.

Black sea bass (*Centropristis striata*) predicted mean catch rate was reduced by 71.6% in the experimental trawl, which was significantly different ($p = .001$, Table 1). When black sea bass were present in the catch a majority was captured by the control trawl for all but one pair (Figure 4). Black sea bass greater than 37 cm were significantly reduced by the experimental trawl; based on the GLMM, the linear curve fit best (Figure 7; Table 2). Black sea bass displayed similar behavior as scup in the trawl extension, swimming for a large range of time in the trawl from a few seconds to more than 20 min.

Summer flounder (*Paralichthys dentatus*) predicted mean catch rate was reduced (76.4%) significantly in the experimental trawl ($p < .001$, Table 1), and for all but one pair (Figure 4). All summer flounder length classes were caught less by the experimental trawl; a quadratic curve was the best fit (Figure 8; Table 2). Summer flounder typically entered the trawl extension individually, and exited the trawl by swimming directly up the grid and out of the escape window.

TABLE 2 Generalized linear mixed model parameters for squid, scup, summer flounder, and black sea bass, where model and parameter is the chosen model [either constant (β_0), linear (β_1), quadratic (β_2), or cubic (β_3)], estimate is the value of the slope or intercept, *SE* = standard error of the estimate; *df* = degrees of freedom

Treatment	Model	Parameter	Estimate	*SE*	*df*	*t*-value	*p*-value
Longfin inshore squid	Quadratic	β_2	0.002	0.001	341	1.985	.048
		β_1	−0.099	0.037	341	−2.670	.008
		β_0	1.241	0.888	341	1.398	.163
Scup	Quadratic	β_2	−4.474	2.271	150	−1.970	.050
		β_1	0.464	0.219	150	2.117	.036
		β_0	−0.012	0.005	150	−2.330	.021
Summer flounder	Quadratic	β_2	−14.117	6.131	105	−2.303	.023
		β_1	0.670	0.307	105	2.179	.032
		β_0	−0.009	0.004	105	−2.253	.026
Black sea bass	Linear	β_1	6.104	1.709	94	3.571	<.001
		β_0	−0.216	0.041	94	−5.260	<.001

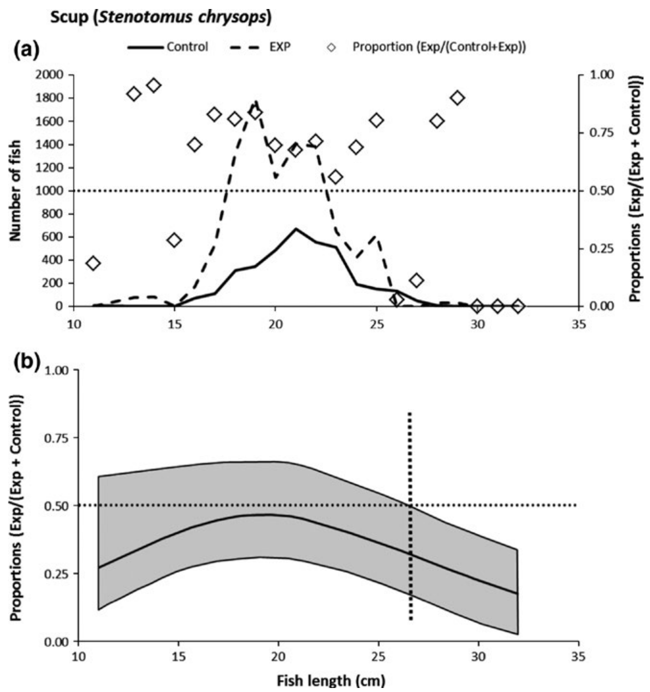

FIGURE 6 (a) Pooled length frequencies of scup and observed proportions (exp/(exp + control)). Points are pooled experimental proportions and read on the right Y-axis. (b) Generalized linear mixed model (GLMM) of proportions of scup at length caught in the trawl with a grid (exp) compared with the total of experimental and the control (exp + control) in a tow pair. A value of 0.5 indicates an even split between the experimental and the control. The shaded areas around the mean curves (bold lines) are the 95% confidence regions. The vertical dotted line indicates the length where a significant difference occurs

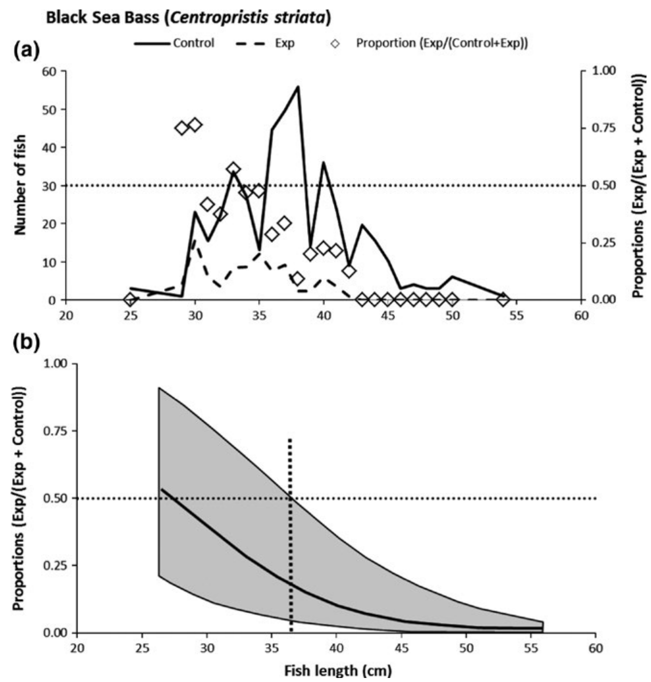

FIGURE 7 (a) Pooled length frequencies of black sea bass and observed proportions exp/(exp + control)). (b) Generalized linear mixed model (GLMM) of modeled proportions of black sea bass catch at length caught in the trawl with a species-separator grid (experimental). The vertical dotted line displays the length where a significant difference occurs

Smooth dogfish (*Mustelus canis*) predicted catch rate was reduced 86.0% by the experimental net, and was significantly different ($p < .001$, Table 1). For each pair, the control trawl captured more smooth dogfish. Smooth dogfish were not observed on video.

Other species were captured infrequently and not analyzed individually, but were included in the total bycatch category. Mean predicted catch rate for total bycatch was significantly reduced (69.2%, $p < .001$, Table 1), and all but one pair had a greater catch rate by the control trawl (Figure 4). Mean predicted catch rate of benthos/debris trended less for the experimental trawl (33.3%), but was not significant ($p = .512$, Table 1); haul-to-haul benthos/debris catch rate was inconsistent between trawls (Figure 4).

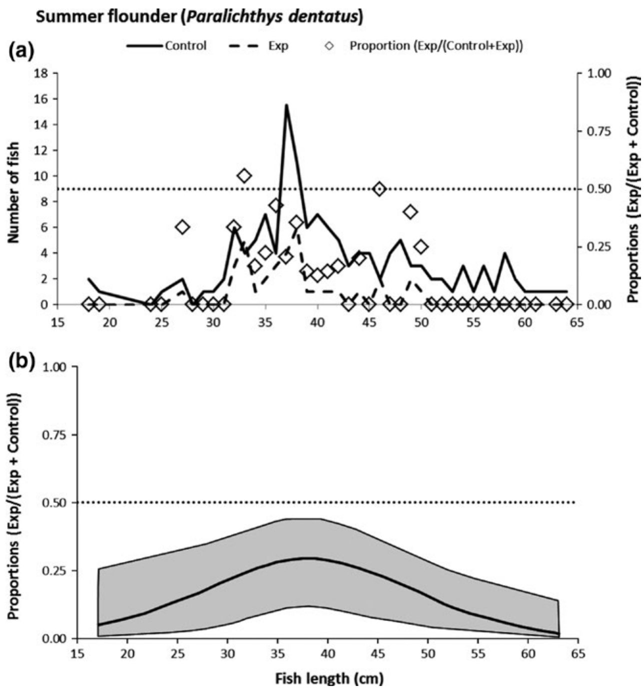

FIGURE 8 (a) Pooled length frequencies of summer flounder and observed proportions (exp/(exp + control)) (b) Generalized linear mixed model (GLMM) of modeled proportions of summer flounder at length caught in the trawl with a species-separator grid (experimental)

4 | DISCUSSION

The results of this study demonstrate that a separator grid can reduce catches of many commonly encountered bycatch species, as well as total bycatch and benthos/debris. Significant catch rate reductions are found for black sea bass, summer flounder, smooth dogfish, and total bycatch. However, results for scup and benthos/debris were equivocal – large mean reductions were observed, but no statistical significance was found; haul-to-haul variation is the likely reason why. The patchy distribution and vulnerability of scup has confounded previous attempts to reduce their bycatch (Pol et al., 2002). Both scup and benthos/debris catches were not consistent over the 32 tows. Additionally, mean reduction of scup was primarily due to two tows with large scup retention in the control trawl. These two tows can be considered outliers, but is also consistent with how scup are caught within the fishery, typically by sporadic large catches.

The large loss of squid (47.5%) indicates that the grid may not be suitable for commercial application in this fishery. Video observations (Bayse et al., 2014) showed that squid easily escaped upward through the escape window before reaching the grid. No length differences were observed between control and experimental trawls for squid, implying that escape ability is not length-dependent within the length range of squid caught.

Squid have been observed escape-jetting, a rapid inflation of the mantle that powerfully forces water out of the funnel one to several times in a row (Anderson & DeMont, 2005; Bayse et al., 2014). Escape jetting provides squid with a mechanism to easily escape from trawl openings, such as that used in this study. Small and juvenile squids, which could pass through the grid, have the ability to jet escape (Hanlon & Messenger, 1996). Combined with escape through net meshes, this escape jet ability of small sized squid may be the reason that no length effect was found between the experimental and control trawls.

A grid with horizontal bars should logically reduce catches of laterally flattened scup. Our results indicate it did not do so consistently. Some of our observations from collected video suggest that scup passage can occur at haul back when scup were observed to turn laterally and pass through grid openings. Additionally, our video suggests that scup were disinclined to move upward toward the escape opening when faced with an obstacle. In prior research (Pol et al., 2002), lateral escape openings were very effective (up to 100%) at eliminating scup larger than 10 cm from a squid trawl, but not smaller-sized scup; optimal grid design and escape opening placement remains to be determined for scup.

Large scup and black sea bass (27 cm and 37 cm and greater, respectively) catches were significantly reduced by the experimental trawl. Larger finfishes are likely excluded due to the small grid spacings (which they could not fit through). Additionally, larger fish can swim for longer periods of time (He & Wardle, 1988). Larger scup and black sea bass could likely swim in front of the grid longer than smaller fish, providing more opportunities to use the escape window.

In contrast to scup, the exclusion of summer flounder was unexpected based on their dorso-ventrally flattened body type. The horizontal spacings of the grid are designed to inhibit laterally-compressed finfish entrance, but not dorso-ventrally flatter fish body shapes. Nevertheless, all summer flounder size classes were significantly reduced in the experimental gear. Summer flounder were observed on video to swim directly up the grid and out of the escape window. This finding contributes to other studies that have found flatfish using the water column, and not remaining on the bottom (e.g., Bublitz, 1996; Cadrin & Westwood, 2004). Further research on this topic is needed.

Smooth dogfish catch was significantly reduced in the experimental trawl. Although smooth dogfish are not currently a major bycatch issue, this result could ultimately be a positive outcome for this fishery, as this species has the potential to become a nuisance in trawl fisheries (Lawson, DeAlteris, & Parkins, 2007). This exclusion by a grid with horizontal bars in the small mesh squid trawl fishery echoed observed reductions of the morphologically similar spiny dogfish (*Squalus acanthias*), a nuisance bycatch species in the small mesh silver hake fishery in the same region (Chosid, Pol, Szymanski, Mirarchi, & Mirarchi, 2012).

The large reductions in squid catch (reported in this paper) subsequently prompted modifications to the nettings surrounding the grid (modifications tested after tests reported in this paper, and not reported within this paper). These latter tests included: reducing the escape window size, modifying the funnel into an escape ramp, and increasing the distance between the terminal end of the ramp and the grid. None of these modifications effectively separated fish from squid. Video depicted large fish congregations able to exit through the escape window, holding station just forward of the grid, where they remained until haul back, ultimately being captured.

Separating squid from fish in the extension of a trawl remains challenging for the New England squid fishery. Bayse et al. (2014) documented squid reactions to the grid and found that squid could perceive and react quickly to both a grid and an escape window, which explains the large squid escape rates, whereby this study determined that this squid loss was too great for a commercial fishery. The lack of motivation by scup to escape from smaller escape windows suggests a behavioral difference that could be exploited to reduce bycatch. Further investigation of the behavior of scup may yield useful results. Decreasing the size of the escape window and altering the funnel (as compared to prior research) improved squid retention, but little separation was observed for bycatch or debris. Future work aiming to separate squid and fishes in the extension needs to concentrate on limiting the squid escape jet mechanism, yet still provide fish with proper motivation to exit the trawl.

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