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Avoidance of Atlantic cod (*Gadus morhua*) with a topless trawl in the New England groundfish fishery

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ABSTRACT

Low quotas of Atlantic cod in the New England groundfish fishery may restrict fishing with trawls for mixed stocks of groundfish. Previous studies using topless trawls (i.e. trawls with a headrope more than 20% longer than the footrope) in this region showed reductions of cod, but also reductions in species of flatfish. In May and June 2011, we tested a topless trawl on a commercial trawler with a much greater headrope to footrope ratio and greater flotation than previous studies in the region. Thirty haul-pairs were successfully conducted and demonstrated a 51% reduction in the catch of cod, with no significant loss of any flatfish species, except for a significant loss of sublegal American plaice. Our results suggest that a topless trawl can be an effective method of cod avoidance for fishermen in the region, without substantial loss of landable flatfish. We infer from the results that: cod rise in response to an approaching trawl footrope and sand cloud; headrope layback may not be a critical value in the effectiveness of topless trawl designs; and, headrope flotation, particularly in the center of the headrope, may be an important factor in retaining flatfish.

1. Introduction

The Atlantic cod (*Gadus morhua*) stock in the Gulf of Maine has been subject to persistent fishing pressure for over 400 years (Murawski et al., 1999). Cod landings reached a peak of approximately 68,000 mt in 1861 (Bolster, 2012), but have since declined significantly despite the introduction of bottom trawling and other technological advances. In 2013, the spawning stock biomass of cod in the Gulf of Maine declined to 4% of the target for maximum sustainable yield (NOAA, 2014), a record low in the fishery, and the commercial quota of cod was reduced to 207 mt (NOAA, 2015). The cod stock on Georges Bank has now suffered a similar fate. Deliberate fishing for cod in the region has now all but ceased, and the quota restrains ('chokes') the ability of fishermen to land relatively abundant species such as yellowtail flounder (*Limanda ferruginea*), American plaice (*Hippoglossoides platessoides*), and witch flounder (*Glyptocephalus cynoglossus*).

Commercial fishermen in the Gulf of Maine and nearby Georges Bank (collectively, "New England") now frequently need to avoid cod to the greatest extent practicable. However, achieving this outcome is a challenge because the imperative to avoid cod has never been strong in the fishery. Many New England fishermen have traditionally used the same trawl design to target a mix of groundfish, including cod, haddock (*Melanogrammus aeglefinus*), yellowtail flounder, and other species (Pol et al., 2003). Many of these species are also caught during the same tow (Rothschild et al., 2014). Consequently, a ready-made trawl design that can avoid cod and land other groundfish does not yet exist in the fishery.

One trawl design that has shown potential to avoid cod is the topless trawl. This revolutionary design, also dubbed the "coverless" (e.g. Eustace et al., 2007; Montgomerie and Briggs, 2012), or "cutaway" trawl (e.g. Catchpole and Revill, 2008), eliminates a significant portion of the upper panel of netting and permits cod an opportunity to rise upwards and escape prior to reaching the codend. Underwater observations of cod have confirmed rising behavior (Pol, personal observation), and several studies have exploited this behavior by fitting large- or square-mesh netting windows to the upper panel of a trawl (e.g. Thomsen, 1993; van Marlen, 1993; Walsh and Hickey, 1993; Pol et al., 2003). However, the circumstances that elicit rising behavior are not well understood, nor is if this behavior is consistent temporally and spatially.

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The topless trawl has been tested previously in the U.S. west coast groundfish fishery to avoid rockfish (*Sebastes* spp.) (King et al., 2004; Hannah et al., 2005), in the Gulf of Maine pink shrimp (*Pandalus borealis*) fishery to avoid herring (*Clupea harengus)* (e.g. He et al., 2007), and in the mid-Atlantic summer flounder (*Paralichthys dentatus*) fishery to avoid sea turtle bycatch (DeAlteris and Parkins, 2012; Gahm et al., 2014).

In the *Nephrops norvegicus* fishery in the northeast Atlantic, the topless design has been considered to avoid cod and other groundfish (Eustace et al., 2007; Catchpole and Revill, 2008). In the North Sea, at Farne Deeps, Revill et al. (2006) reported a reduction of small cod (<35 cm) by 42% with little reduction in large cod (although sample size was low).

Topless trawl designs have also been tested in groundfish-targeting fisheries to avoid cod, although the results have been inconsistent and sometimes inconclusive. Thomsen (1993) used a topless trawl in the coastal waters around the Faroe Islands to reduce cod by 38% with no loss of flatfish. Also at Farne Deeps, Dunlin and Reese (2003) reported reductions in whiting (*Merlangius merlangus*) and haddock using a topless design; reductions in cod were not significant, although fewer numbers of smaller cod were caught. Mieske (2012), using the same topless trawl off the coast of Denmark, reported a 63% reduction in cod and 92% increase in flounder on one boat followed by a 69% reduction in cod and a 23% reduction in flounder on another boat. In the Gulf of Maine, Pol et al. (2003) reduced cod by 87%, and in nearby Georges Bank, Chosid et al. (2008) reduced cod by 56%. Partly in response to Pol et al. (2003), a special gear provision was introduced in 2004 allowing fishermen to use a topless ("flatfish") trawl on Georges Bank, providing the headrope was at least 30% longer than the footrope and footrope length was not greater than 32 m (NOAA, 2004).

Here, we present a comparison of catching performance between a topless trawl and a traditional bottom trawl in the Gulf of Maine, USA. This experiment responded to a request from Captain Carl Bouchard, a local commercial fisherman who considered the topless trawl, if modified based on his ideas, a potential way to avoid cod while retaining catches of yellowtail flounder. This fisherman recognized the limitations of previous topless trawl designs, especially the escape of flounders, but was confident his modifications to the design would overcome these limitations.

2. Methods

We compared the catching performance of the topless trawl against a standard (traditional) bottom trawl over a 10-day period in May and June 2011 in the Gulf of Maine, USA (Fig. 1). Both trawls were newly constructed by Trawlworks Inc. (Narragansett, Rhode Island), and were identical in design and construction except for the longer headline in the topless trawl. Both were a two-seam design constructed from 152.4 mm polyethylene (PE) netting with a twine diameter of 3.5 mm (Fig. 2). The fishing circle of the standard trawl measured 43.59 m, and the lower panel of each trawl was identical. Both trawls were fitted with a cookie footrope (also called a sweep in New England) comprising a 27.0 m steel wire rope threaded through 76.2 mm Ø rubber disks. The headline length of the topless and standard trawls measured 46.27 m and 20.98 m respectively; their respective headline to footrope ratios were 1.71:1 and 0.78:1. Both trawls used identical nominal 165 mm square mesh codends.

A total of 32 plastic floats measuring 203 mm Ø was attached to the headrope of the topless trawl in 8 groups of four floats; 4 groups of floats were located either side of the center of the headrope, 1 group at each wingend, and 1 group at each wing between those at the wingends and those coming from the center of the headrope.

Catch data from each trawl was collected from three pairs of alternating hauls per day (6 hauls total): three 'standard' hauls and three 'topless' hauls in an A-B-A-B-A-B sequence. The trawl from the final haul was then used in the first haul the following day. Individual hauls in a haul-pair were conducted parallel to each other and in the same direction. The F/V Stormy Weather was used in this experiment, a 13.7 m stern trawler equipped with a double net reel so that each trawl could be quickly deployed or stowed clear of the deck when not in use. All hauls were limited to daylight hours, between 5:30 and 15:30; nominal haul duration and speed were 45 min and 1.35 m s^{-1} (2.6 kts) respectively.

For each haul the catch was sampled by species. All regulated groundfish were sorted by species into 'kept' and 'discarded' (undersized) categories before being enumerated or weighed in totes to the nearest kilogram. These fish were then measured (total length) to the nearest centimeter. Non-commercial species were similarly weighed and then discarded overboard. When the catch was excessive, a subsample was collected and the total catch of each species was extrapolated based on the proportion of the subsample to the total catch. All catch rates were standardized to a haul duration of 60 min.

Catch rates of regulated groundfish species and dominant species were compared between trawl types using equal catch plots. A paired two-sample *t*-test was applied to compare the catch weight of cod, American plaice, yellowtail flounder, witch flounder (*Glyptocephalus cynoglossus*), unclassified skates (Rajidae), and spiny dogfish (*Squalus acanthias)*; a Welch's *t*-test was used where F-tests for unequal variance indicated a significant difference ($p < 0.05$). For all species other than cod, two-sided hypotheses of equal mean catch rates (kg h^{-1}) were tested. Haul-pairs were excluded if a species was absent from both hauls.

Length-based differences were explored using generalized linear mixed models (GLMMs) to fit proportions of catch-at-length in the experimental net with biologically realistic low-order polynomials (Holst and Revill, 2009). Lengths were used as a fixed effect, and haul was a random effect. A binomial link function was used to fit the simplest model, followed by increasing complexity up to a cubic polynomial. Model terms were assessed with Wald tests at a level of $p < 0.05$. Only lengths from fully-sampled hauls were used in this analysis; also, haul-pairs were excluded if a species was absent from both hauls.

3. Results

A total of 60 hauls (30 haul-pairs) were completed using both trawls. Mean recorded towing speed was 1.4 m s^{-1} (min: 1.35; max: 1.45) and fishing depth was 62 m (IQR: 58.5–69.5 m). The median interval between hauls within a haul-pair was 35.5 min, and the median length of towing (warp) wire was 183 m (IQR: 100–229 m). The weather was calm throughout the experiment and wave height was no greater than 1 m.

Approximately 21,300 kg of fish, crabs, and lobsters from 26 taxa were captured over 48.4 h of trawling (Table 1). Six species/species groups (Atlantic cod, yellowtail flounder, American plaice, witch flounder, spiny dogfish, and unclassified skates) comprised 95% of the total catch by weight. Catches from the standard trawl were considered typical of the commercial fishery in composition and volume.

Catch rates of Atlantic cod were significantly reduced using the topless trawl by an average of 192.3 kg h^{-1}, or 51.4% (Welch's $t = 3.02$, df = 29, one-sided $p = 0.003$; Table 2). Catch rates ranged from 0 to 2000 kg h^{-1} and differences in catch rates in haul-pairs were consistently lower in the topless trawl, or nearly equal (Fig. 3). Length of cod (range 35–118 cm) between trawls was not significantly different in GLMM analysis (n = 25 pairs), although there was a decreasing proportion of cod in the topless trawl with size (Fig. 4).

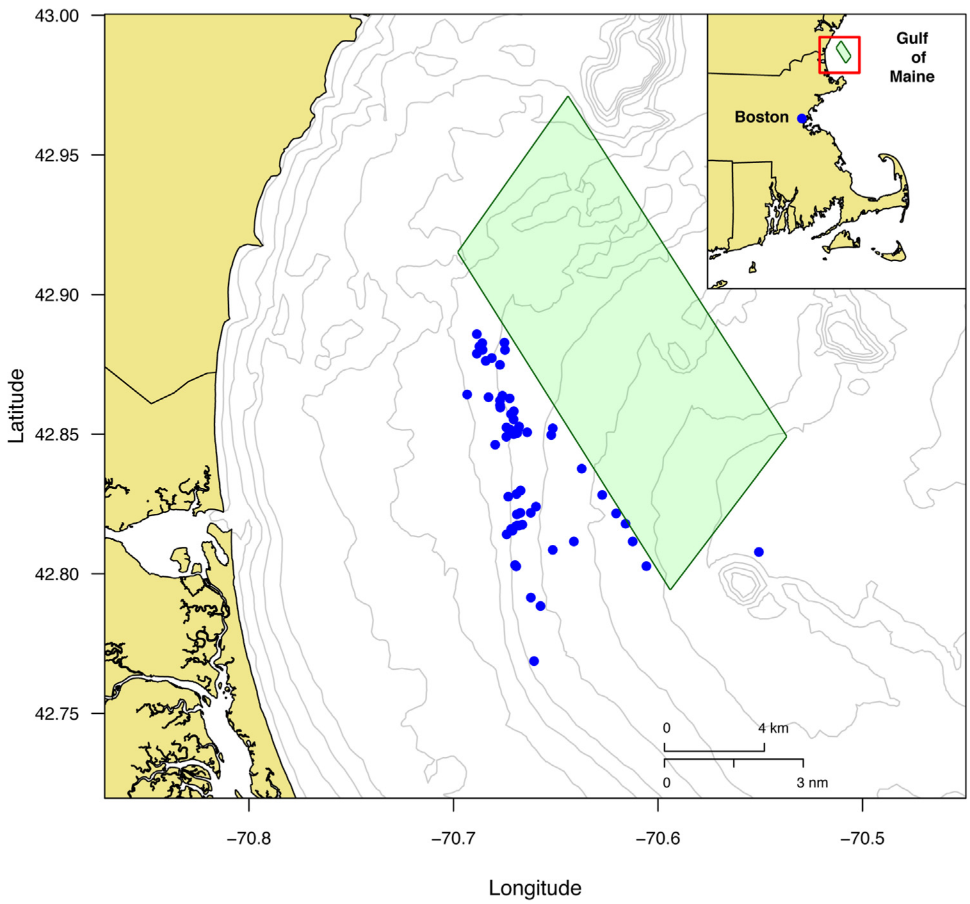

Fig. 1. Start location of trawl stations (dots) in the Gulf of Maine. The shaded box represents the boundary of the Whaleback cod spawning protection area. Bathymetry in 5 m intervals. Inset – Sampling location relative to Boston, Massachusetts.

Table 1
Catch weight (kg) by species and trawl type.

Common name	Scientific name	Trawl	
		Standard (kg)	Topless (kg)
Atlantic cod	*Gadus morhua*	8117.3	3857.8
Yellowtail flounder	*Limanda ferruginea*	1556.6	1618.0
American plaice	*Hippoglossoides platessoides*	1055.1	777.1
Skates	*Rajidae*	636.1	766.3
Witch flounder/Grey sole	*Glyptocephalus cynoglossus*	594.4	500.3
Spiny dogfish	*Squalus acanthias*	416.2	329.5
American lobster	*Homarus americanus*	194.5	165.9
Silver hake	*Merluccius bilinearis*	148.4	64.7
Atlantic wolffish	*Anarhichas lupus*	121.8	73.8
Monkfish	*Lophius americanus*	56.5	25.5
Haddock	*Melanogrammus aeglefinus*	48.5	23.1
Striped bass	*Morone saxatilis*	20.4	0.0
Sea raven	*Hemitripterus americanus*	19.0	43.1
Pollock	*Pollachius virens*	18.8	4.0
Winter flounder	*Pseudopleuronectes americanus*	15.3	15.1
American shad	*Alosa sapidissima*	1.6	0.0
Red hake	*Urophycis chuss*	1.2	0.4
Fourspot flounder	*Hippoglossina oblonga*	0.8	1.4
Jonah crab	*Cancer borealis*	0.6	0.9
Redfishes	*Sebastes* sp.	0.6	0.0
Atlantic herring	*Clupea harengus*	0.4	0.0
Lumpfish	*Cyclopterus lumpus*	0.2	0.8
Sand dab flounder	*Scophthalmus aquosus*	0.1	0.0
Longhorn sculpin	*Myoxocephalus octodecemspinosus*	0.1	0.1
Butterfish	*Peprilus triacanthus*	0.0	0.1
Atlantic halibut	*Hippoglossus hippoglossus*	0.0	3.8
Total		13024.5	8271.7

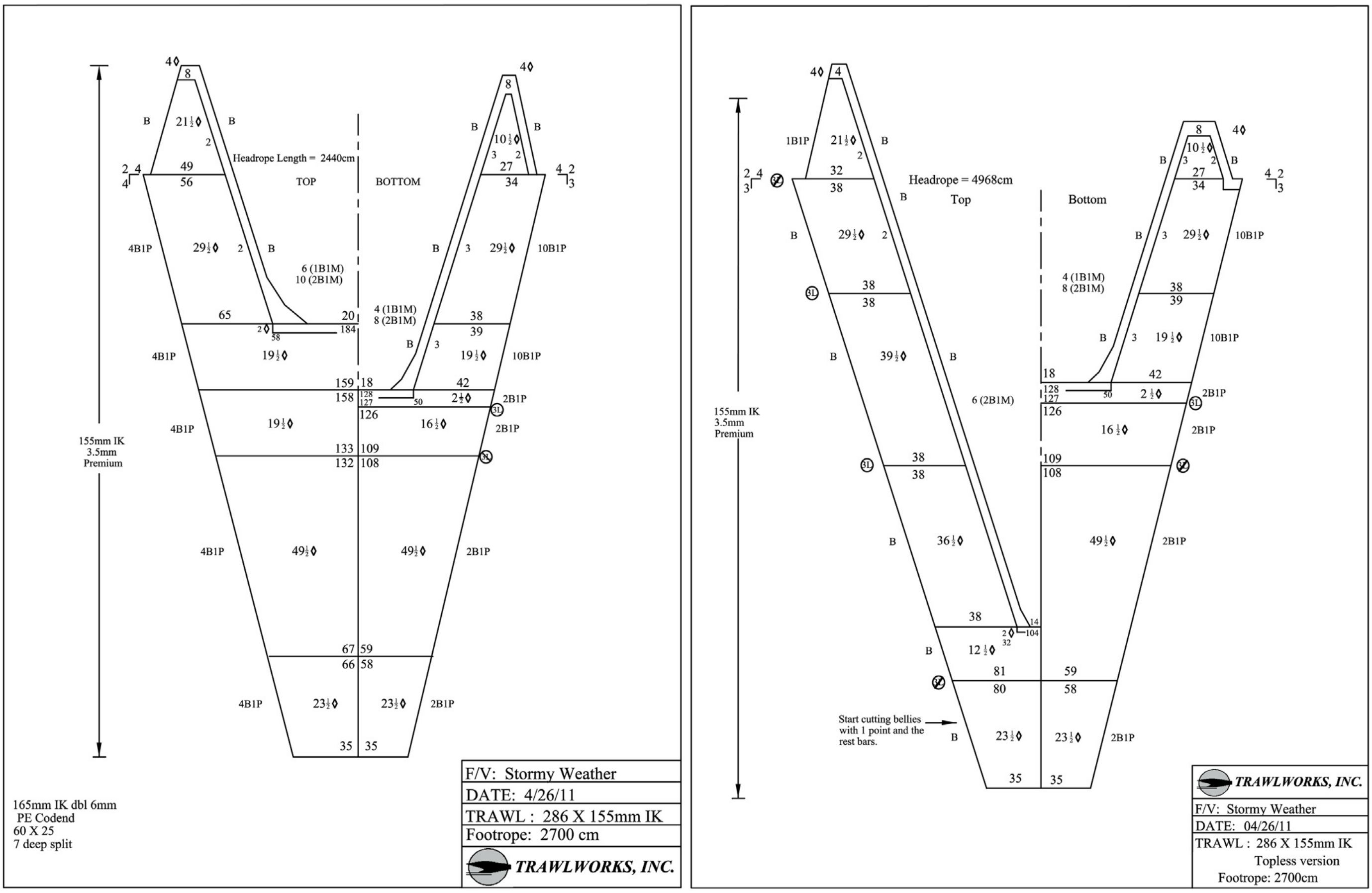

Fig. 2. Standard trawl (left) and topless trawl (right) construction plan.

Table 2
Descriptive statistics for each species by standard and topless trawl.

Species	Catch rate (kg hr^{-1})		Difference (Standard − Topless)					df	t-stat	p-value	variances	hypothesis
	Standard	Topless	%	95% C.I.		Min.	Max.					
Atlantic cod	374.4	182.1	51.4	84.00	Infinity	−67.7	1341.6	29	3.0166	0.0030	unequal	Std > Topless
Yellowtail flounder	81.5	83.4	−2.3	−18.17	14.35	−79.7	144.0	29	−0.2410	0.8120	equal	Std = Topless
American plaice	48.8	35.7	25.4	5.70	19.20	−19.4	55.2	29	3.7600	0.0010	equal	Std = Topless
Skates	31.5	36.3	−19.4	−16.60	6.90	−110.2	38.1	29	−0.8480	0.4034	equal	Std = Topless
Witch flounder/Grey sole	25.2	22.4	11.1	−2.20	7.80	−14.1	47.2	29	1.1337	0.2662	equal	Std = Topless
Spiny dogfish	26.7	22.3	19.9	−10.50	20.00	−22.4	74.6	11	0.6781	0.5110	equal	Std = Topless

Catch rates of American plaice were also significantly reduced by the topless trawl, by an average of 12.4 kg h^{-1}, or 25.4% (t = 3.76, df = 29, two-sided p = 0.001; Table 2). Rates ranged from 20 to >120 kg h^{-1} and differences in haul-pairs included seven tows where the topless trawl caught more American plaice (Fig. 3). Length of American plaice (range: 13–56 cm) was significantly different between the two trawls (n = 24 pairs; $p < 0.05$), with fewer small American plaice (20 cm and less) caught in the topless trawl (Fig. 4).

The mean difference in catch rates of yellowtail flounder between trawls was small (1.9 kg h^{-1}; −2.3%) and not significantly different (t = −0.241, df = 29, two-sided p = 0.81; Table 2). Lengths of yellowtail flounder ranged overall from 21 to 49 cm and no significant difference or trend between the topless and standard trawls was observed (Fig. 4). Similarly, catch rates of witch flounder were slightly lower in the topless trawl (2.8 kg h^{-1}; 11.1%), but were not significantly different (t = 1.134, df = 29, two-sided p = 0.27; Table 2). Lengths ranged from 22 to 48 cm without significant trend or difference between trawls (n = 23 pairs; Fig. 4).

Catch rates of unclassified skates also did not differ between trawls. A mean difference of 6.1 kg h^{-1} (-19.4%) was observed, but was not significantly different (t = −0.848, df = 29, two-sided p = 0.27). Length effects were not tested due to the mixing of skates from different species of different sizes. Catch rates of spiny dogfish were slightly decreased in the topless trawl (4.4 kg h^{-1}; 19.9%) but were also not significantly different (t = 0.678, df = 11, two-sided p = 0.40; Table 2). Lengths ranged from 74 to 99 cm between the two trawls (n = 12 pairs; Fig. 4).

4. Discussion

The performance of the topless trawl in our study represents a significant achievement towards avoidance of Atlantic cod compared to previous topless trawl studies in New England. Cod catches were reduced by 51% compared to the traditional bottom trawl and there was no reduction in the catch of yellowtail flounder, witch flounder, and skates. Moreover, a significant reduction in the catch of American plaice was almost exclusively comprised of sublegal

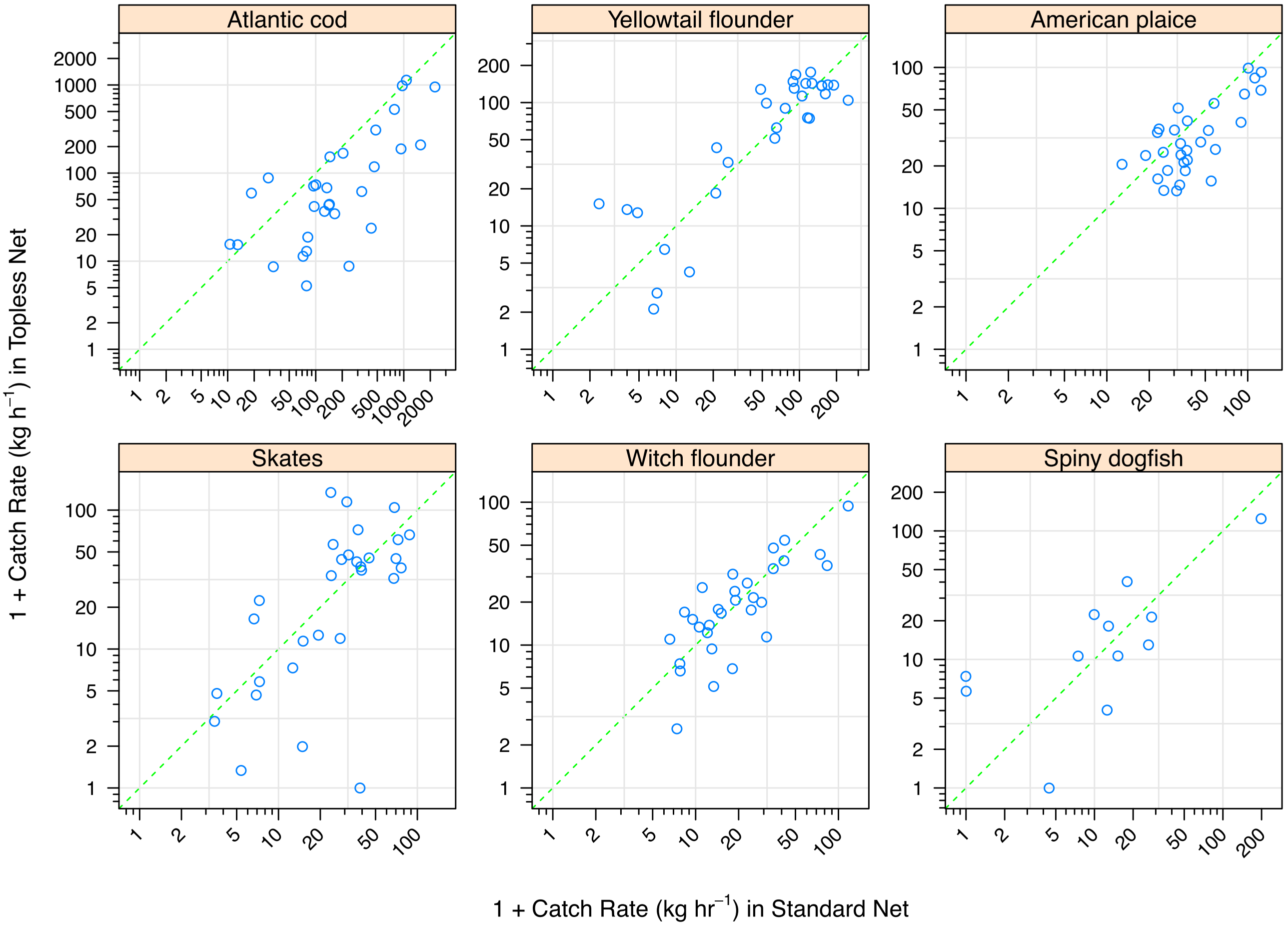

Fig. 3. Equal catch plots for Atlantic cod, yellowtail flounder, American plaice, skates, witch flounder, and spiny dogfish.

individuals. This performance represents the first time in a topless trawl study in New England that a significant reduction in cod was not accompanied by a significant reduction in legal sized flatfish.

The topless trawl was designed specifically to improve on previous studies in New England to avoid cod and retain flatfish. These improvements included increasing the headrope to footrope ratio and increasing headrope flotation (Table 3); the headrope to footrope ratio was 1.71:1 and thirty-two 200 mm diameter floats were attached to the headrope, an increase of at least 13% and 28% respectively compared to previous studies.

Neither net geometry measurements nor extensive behavioral observations were available for this or previous topless trawl studies in New England. Nevertheless, other studies and subsequent examinations provide some insight into possible mechanisms for cod avoidance and improved flatfish retention.

Scale-model testing of a topless trawl in a flume tank (Eayrs, unpublished observation) and flexible line theory allow estimation of the horizontal distance between the center of the headrope and footrope (layback distance) of the topless trawl in our study. We estimate this distance was approximately 9.2 m,[1] or 38% greater than the estimated layback distance of the trawl reported in Chosid et al. (2008) and 108% greater than reported in Pol et al. (2003). This difference means cod, flatfish, and other fish have a relatively longer period to rise from the trawl mouth and escape over the headrope. Based on a simple relative speed model, and assuming these fish swim upwards vertically from the trawl mouth over the approaching headrope (the shortest escape route), they appear to have sufficient swimming speed to rise and escape before the headrope passes overhead. In the flume tank, the headrope height of the topless trawl was equivalent to 2.6 m at 2.7 kts; while this height is considered higher than the trawl in our study, at this speed fish only need to swim vertically at 0.4 m s^{-1} to escape over the headrope providing layback distance is 9.2 m, and even slower at lower headrope heights.

It is likely that many flatfish species can generate escape speeds greater than 0.4 m s^{-1}, swim the necessary distance, and escape over the approaching headrope of our topless trawl. Kawabe et al. (2004) reported that Japanese flounder (*Paralichthys olivaceus*) ascend naturally into the water column at approximately 0.35 m s^{-1}, and small (15 cm) American plaice can swim a distance of 5 m at 0.30 m s^{-1}, even at a water temperature of 0 °C (Winger et al., 1999). The apparent ease with which these species could escape the approaching headrope is a signal that other flatfish species should similarly be capable of escape from our trawl. Nevertheless, based on video observations in a separate project of flatfish near the mouth of a topless trawl (Pol, unpublished observation), headrope layback may not affect their retention because flatfish typically turn and fall back into the trawl close to the lower panel or escape below the footrope (Walsh and Hickey, 1993; Bayse et al., 2016; Underwood et al., 2015). Furthermore, although some flatfish were observed swimming rapidly upward from the trawl mouth,

[1] This calculation was based on assumed headrope and footrope spread ratios of 31% and 43% respectively. Calculated spread to sag ratios were 0.68 and 0.96 respectively (Fridman and Carrothers, 1986). These assumptions are based on flume tank testing of a model topless trawl at 2.7 kts. The modeled headrope and footrope length were 47.4 m and 26.3 m respectively.

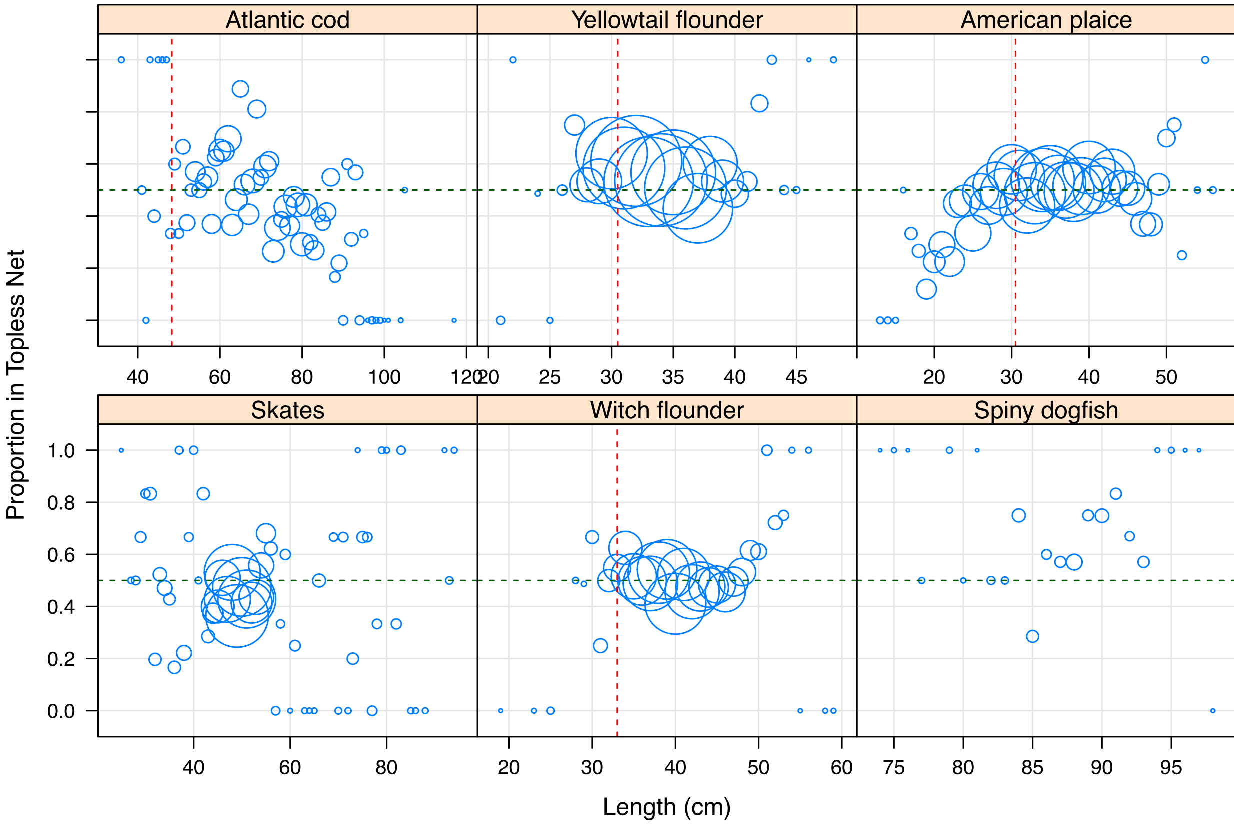

Fig. 4. Observed proportion of measured lengths retained in the topless net, by species. Bubble size is proportional to standardized total numbers in both nets for each length. Vertical dashed line (where existing) represents minimum legal landing size; horizontal line is the equal proportion line (0.5).

Table 3
Comparison between topless trawl studies in the Gulf of Maine. HR – headrope. FR – footrope. The first two columns indicate catch reduction of cod and yellowtail flounder in the topless trawl as a proportion of corresponding catch in the standard trawl.

Study	Cod	Yellowtail flounder	HR length (m)	FR length (m)	HR:FR	Towing speed (kts)	Floats – 200 mm Ø (#)
Pol et al. (2003)	0.87	0.40	27.41	18.30	1.50	2.6–3.1	9
Chosid et al. (2008)	0.56	0.38	47.12	33.55	1.40	3.0	25
This study	0.51	0.02	46.30	27.08	1.71	2.7	32

the headrope is far enough back in a topless trawl that there is opportunity to descend into the trawl and be captured.

Greater headline flotation likely prevented escape of flatfish over the wings of the topless trawl, as was theorized in Pol et al. (2003), by increasing wingend height and verticality of wingend meshes. Observations of a topless trawl in a flume tank have indicated rippling and oscillations in the headrope and adjacent netting in the absence of adequate headrope tension and flotation (Eayrs, unpublished observation). This contributes to low upper wingend height and greater upper wingend spread compared to the lower wingend (in the worst case the trawl effectively collapses), and likely eases the escape by flatfish and other species from this part of the trawl. The additional flotation in our study was a deliberate attempt to overcome this issue, and our results appear to confirm the utility of this modification. Furthermore, additional flotation may have aided escape of small American plaice by increasing mesh opening, both apparent and real.

The distribution of flotation on the headrope was also intentional, with half the flotation located close to the middle of the headrope. In this location the orientation of the floats produced maximal hydrodynamic drag, increasing tension in the headrope, and with the concentration of buoyancy was likely adequate to increase height both in the center of the headrope and along the wings. In contrast, Gahm et al. (2014) overcame the issue of low headrope height by using restrictor lines extending from wing to wing. They used a topless trawl similar to our design including headrope length and flotation, although their headrope to footrope ratio was 12% smaller and flotation was concentrated along the wings (where hydrodynamic drag acting on the floats would be minimized). The absence of towing speed data confounds deeper evaluation of their design, but our results with a deeper layback suggest flotation in the center of the headrope can be a simple solution, without the complexity of fitting lines of proper length or adding a potential barrier to rising behavior of fish.

The cod reduction in our study is less than Pol et al. (2003) and Chosid et al. (2008), although our results suggest an increasing proportion of larger cod were able to escape over the headrope. According to He (1993), sub-legal cod as small as 0.2 m should be able to generate sufficient burst swimming speed to escape vertically over the headrope of our topless trawl (even in water as cold as 2 °C). This suggests a layback distance of 9.2 m was more than enough for the smallest cod in our study to escape. Curiously, Revill et al. (2006) reported a significant reduction in the catch of small cod (<35 cm) using a topless trawl (headrope to footrope ratio not reported) but not for larger cod, and the possibility of length dependent behavioral responses to the trawl was a posited explanation for this result. In addition, Catchpole and Revill (2008) suggested large cod remain close to the seabed while small cod may rise upwards in a trawl and escape. While our results are contradictory, we too found evidence of length dependent responses to the trawl, although the layback distance was such that cod escape was feasible irrespective of their size. Therefore, variation in catch rates of cod between the differing studies in New England is unlikely due to swimming limitations but perhaps due to differences in neural processing time and decision-making during encounter with the trawl. These may have been influenced by variation in environmental conditions and intrinsic behavioral factors such as motivation, physiological condition, learning and experience (Winger et al., 2010) or density dependent responses to trawl gear (Engas, 1994).

It may also have been possible the layback distance in our study was too great, and, paradoxically facilitated cod capture; based on underwater video observations in a separate project (Pol, unpublished observation), cod were observed slowly rising over the footrope and associated sand cloud and then descending toward the lower panel while swimming in the towing direction. In contrast, some research has reported isolated individual cod staying low during their entry into a trawl (e.g. Main and Sangster, 1982; Walsh and Hickey, 1993), a result that is consistent with observations derived from separator trawl experiments (e.g. Valdermarsen et al., 1985; Boudreau and Tait, 1991) and other reports (e.g. Catchpole and Revill, 2008). While the fate of individuals observed in that separate project (Pol, unpublished observation) was not determined, it is likely they fell back into the trawl and were captured. This rising and falling behavior may also suggest that the trawl used in Pol et al. (2003), which almost eliminated the cod catch, achieved a close-to-optimum layback for cod escape under the conditions their research was carried out.

Previous efforts using a topless trawl to reduce cod have achieved greater success, but they have also suffered higher loss of flatfish. Such issues have also been reported elsewhere with topless trawl designs, including efforts to reduce finfish in *Nephrops* fisheries (Revill et al., 2006) and sea turtles in a summer flounder (*Paralichthys dentatus*) fishery (Gahm et al., 2014). Fishermen in New England are unlikely to adopt this trawl if they suffer lost income, even if avoidance of cod contributes to their recovery. However, the reported continued use of the topless trawl from our study by a New England fisherman is a strong signal of the efficacy of this improved trawl design.

Future work is now required to encourage other fishermen in New England to adopt this new topless trawl, which complies with current fishery regulations. With a 51% reduction in cod landings, fishermen have an increased ability to fish for flatfish species before low cod quota becomes a constraining influence. This trawl also reduces concerns by fishermen over exceeding and acquiring quota to lease. Further research would be required to validate cod reduction when fishing at night – Chosid et al. (2008) found diel variation in topless trawl performance for yellowtail flounder, winter flounder, and grey sole, but not cod – and in the adjoining Georges Bank fishery where cod bycatch is an issue. Efforts should also be made to understand the relationship between the layback distance and headrope height – measurement of upper and lower wingend spread and headrope height will be necessary – and its effect on fish escape, as well as evaluation of changes in fuel consumption compared to a traditional trawl. With the removal of a significant portion of the upper panel, trawl drag and associated fuel costs may be substantially reduced (Jacklin, 2005), assuming no change in trawl geometry. However, an anticipated reduction in fuel costs, coupled with reduced influence of cod on fishing activity, is an excellent starting point from which to encourage the uptake of the topless trawl in New England.

5. Conclusion

The results of this study are a substantial improvement over previous studies using a topless trawl in New England. For the first time in the region, we have demonstrated that a topless trawl can successfully avoid cod without loss of flatfish. Primarily, we believe this improvement is due to increased headrope flotation and concentration on center of the headrope. Coupled with anticipated gains such as reduced fuel consumption, the development of this trawl comes at an important time for fishermen and the recovery of the cod stock.

The lack of qualitative evidence or data on fish behavior or trawl geometry in our study, and that by others, limits our ability to describe causes for the effects observed. It also hampers comparison to other topless trawl studies and knowledge of the relationship between layback distance and headrope height and groundfish capture. We therefore acknowledge a high degree of speculation to interpret the results of our study, although our speculation is supported by video observation, flume tank tests, and history of experience in the fishery. Such speculation also highlights why greater knowledge of cod and flatfish response to trawl stimuli is necessary, including quantitative assessment of swimming performance and reaction under various light and other environmental conditions. Without this knowledge, interpretation of results from studies such as ours is significantly constrained.

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References

Bayse, S.M., Pol, M.V., He, P., 2016. Fish and squid behaviour at the mouth of a drop-chain trawl: factors contributing to capture or escape. ICES J. Mar. Sci., http://dx.doi.org/10.1093/icesjms/fsw007.

Bolster, J., 2012. The Mortal Sea: Fishing in the Atlantic in the Age of Sail. The Belknap Press of Harvard University Press, Cambridge, Massachusetts.

Boudreau, M., Tait, D., 1991. The performance of a horizontal split level trawl in the Gulf of St. Lawrence segregating cod from flatfish. In: ICES Fishing Technology and Fish Behaviour (FTFB) Working Group. 22–24 April, Ancona, Italy.

Catchpole, T.L., Revill, A.S., 2008. Gear technology in Nephrops trawl fisheries. Rev. Fish Biol. Fish. 18, 17–31.

Chosid, D., Pol, M., Ribas, L., Moth-Poulsen, T., 2008. Diel variation within the species selective "topless" net. J. Ocean Technol. 3 (2), 31–58.

DeAlteris, J., Parkins, C., 2012. Evaluation of a topless bottom trawl design with regard to excluding sea turtles. NOAA NMFS Contract No EA 133F-10-SE–2491.

Dunlin, G., Reese, R., 2003. Financial instrument for fisheries guidance (FIFG) project, an industry centered conservation project – commercial proving trials of a new prawn trawl design. Seafish.

Engas, A., 1994. The effects of trawl performance and fish behaviour on the cathching efficiency of demersal sampling trawls. In: Ferno, A., Olsen, S. (Eds.), Marine Fish Behaviour in Capture and Abundance Estimation. Fishing News Books, London, pp. 45–68.

Eustace B., Kelly C.J., Jackson E.H., Rihan D., 2007. Technical measures can be shown by experiment to reduce capture of unwanted fish, but can we see the effect on the stock in a stochastic world? ICES CM 2007/O:28, 13.

Fridman, A.L., Carrothers, P.J.G., 1986. Calculations for Fishing Gear Designs. Fishing News Books, England.

Gahm, M., DeAlteris, J., Parkins, C., 2014. Evaluation of a Topless Bottom Trawl Design with a 160 Foot Headrope and Two Restrictor Lines for Fish Capture in the Summer Flounder Fishery. Final Report. NMFS Contract Number: EA-133F-12-SE-2141, Retrieved from http://nefsc.noaa.gov/publications/reports/EA-133F-12-SE-2141.pdf.

Hannah, R.W., Parker, S.J., Buell, T.V., 2005. Evaluation of a selective flatfish trawl and diel variation in rockfish catchability as bycatch reduction tools in the deepwater complex fishery of the U.S. west coast. North Am. J. Fish. Manage. 25, 581–593, http://dx.doi.org/10.1577/M04-126.1.

He, P., Goethel, D., Smith, T., 2007. Design and test of a topless shrimp trawl to reduce pelagic fish bycatch in the Gulf of Maine pink shrimp fishery. J. Northwest Atlantic Fish. Sci. 38, 13–21.
He, P., 1993. Swimming speeds of marine fish in relation to fishing gears. In: Wardle, C.S., Hollingworth, C.E. (Eds.), Fish Behaviour in Relation to Fishing Operations, Vol. 196. ICES Marine Science Symposia, pp. 183–189.
Holst, R., Revill, A., 2009. A simple statistical method for catch comparison studies. Fish. Res. 95, 254–259.
Jacklin, M., 2005. Bycatch Reduction in the Nephrops Fishery of the Farne Deeps. Seafish, Technical Report.
Kawabe, R., Naito, Y., Sato, K., Kazushi, M., Yamashita, N., 2004. Direct measurement of the swimming speed, tailbeat, and body angle of Japanese flounder (*Paralichthys olivaceus*). ICES J. Mar. Sci. 61, 1080–1087, http://dx.doi.org/10.1016/j.icesjms.2004.07.014.
King, S.E., Hannah, R.W., Parker, S.J., Matteson, K.M., Berkeley, S.A., 2004. Protecting rockfish through gear design: development of a selective flatfish trawl for the U.S. west coast bottom trawl fishery. Can. J. Fish. Aquat. Sci. 61, 487–496, http://dx.doi.org/10.1139/F03-153.
Main, J., Sangster, G.I., 1982. A Study of Multi-Level Bottom Trawl for Species Separation Using Direct Observation Techniques, Scottish fisheries research report no. 26.
Mieske, B., 2012. Experiments to reduce cod bycatch in bottom otter trawls. Inf. Fischereiforsch. 59, 39–47.
Montgomerie, M., Briggs, R., 2012. SR 657 Irish Sea selectivity trials. Seafish.
Murawski, S.A., Brown, R.W., Cadrin, S.X., Mayo, R.K., O'Brien, L., Overholtz, W. J., Sosebee, K.A., 1999. New England Groundfish. N.M. Service, Our Living Oceans. Report on the status of U.S. living marine resources (NOAA Tech. Memo. NMFS-F/SPO-41 ed., pp. 71-80). U.S. Department of Commerce. Retrieved April 1, 2013, from http://spo.nwr.noaa.gov/fa2.pdf.
NOAA, 2004. Magnuson-Stevens Fishery Conservation and Management Act Provisions; Fisheries of the Northeastern United States; Northeast (NE) Multispecies Fishery; Amendment 13; Final Rule. Federal Register. 50 CFR Part 648, 69 (84), 23667. Department of Commerce.
NOAA, 2014. Gulf of Maine Atlantic Cod. 2014 Assessment Update Report. National Oceanic and Atmospheric Administration. National Marine Fisheries Service. Northeast Fisheries Science Center, U.S. Department of Commerce, Woods Hole, Massachusetts.
NOAA, 2015. Northeast Multispecies (Groundfish) Fishing Year 2015 Regulations. NOAA Fisheries, Greater Atlantic Regional Fisheries Office.
Pol, M.V., Carr, H.A., Ribas, L.R., 2003. Groundfish Trawl Nets Designed to Reduce the Catch of Atlantic Cod *Gadus morhua*. Northeast Consortium.
Revill, A., Dunlin, G., Holst, R., 2006. Selective properties of a cutaway trawl and several other commercial trawls used in the Farne Deeps North Sea Nephrops fishery. Fish. Res. 81, 268–275.
Rothschild, B.J., Kieley, E.F., Jiao, Y., 2014. Failure to eliminate overfishing and attain optimum yield in the New England groundfish fishery. ICES J. Marine Sci. 71, 226–233.
Thomsen, B., 1993. Selective flatfish trawling. In: Wardle, C., Hollingworth, C.E. (Eds.), Fish Behaviour in Relation to Fishing Operations, 196. ICES Marine Science Symposia, Bergen, Norway, pp. 161–164.
Underwood, M.J., Winger, P.D., Ferno, A., Engas, A., 2015. Behavior-dependent selectivity of yellowtail flounder (*Limanda ferruginea*) in the mouth of a commercial bottom trawl. Fish. Bull. 113, 430–441.
Valdermarsen, J.W., Engas, A., Isaksen, B., 1985. Vertical entrance into a trawl of Barents Sea gadoids as studied with a two-level fish trawl. ICES C.M. 1985/B,46.
van Marlen, B., 1993. Research on improving the species selectivity of bottom trawls in the Netherlands. In: Wardle, C.S., Hollingworth, C.E. (Eds.), Fish Behaviour in Relation to Fishing Operations, Vol. 196. ICES Marine Science Symposia, Bergen, Norway, pp. 165–169.
Walsh, S.J., Hickey, W.M., 1993. Behavioural reactions of demersal fish to bottom trawls at various light conditions. In: Wardle, C.S., Hollingworth, C.E. (Eds.), Fish Behaviour in Relation to Fishing Operations, Vol. 196. ICES Marine Science Symposia, pp. 183–189.
Winger, P.D., He, P., Walsh, S.J., 1999. Swimming endurance of American plaice (*Hippoglossoides platessoides*) and its role in fish capture. ICES J. Mar. Sci. 56, 252–265.
Winger, P.D., Eayrs, S., Glass, C.W., 2010. Behavior of marine fishes: capture processes and conservation challenges. In: He, P. (Ed.), Fish Behaviour near Bottom Trawls. Blackwell Publishing Ltd., pp. 68–104.