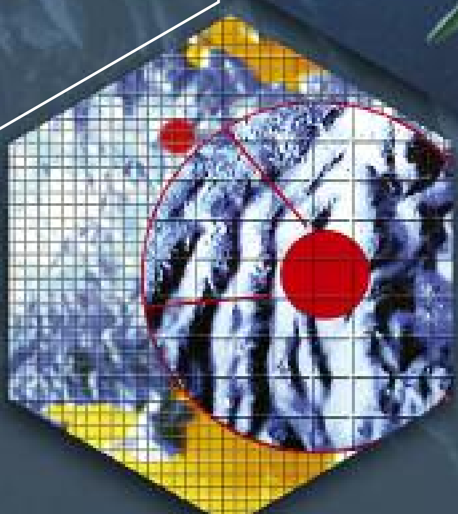
Reviews & Papers



From the Technical Editor

The theme for this edition of The Journal of Ocean Technology is counting, catching and sustaining fish stocks. The catching of wild fish is an area where there has been tremendous growth in the use of technology, to the point where it is possible to eliminate entire species. Living in Newfoundland, we are keenly aware of the decline of the cod stocks since Giovani Caboto arrived in 1497 and his vessel was slowed because of the number of fish. Modern industrial fishing boats are equipped with as much technology as a small warship for finding and harvesting fish. Government has a role to play in stock management, but this is difficult because fishing is typically carried out by small enterprises and existing regulations are hard to enforce. Some attempts have been made to limit the use of technology, but this may be too naïve when the economics of the industry are driving the need for lower costs and higher productivity.

Instead we should be using technology to make the industry more sustainable. Technology should be applied to fishing gear to make it smarter, so that only the target species and the required quantity are harvested. This will require a much better understanding of fish behaviour and how the fish interact with the harvesting equipment. We have technology now that can be used to track and observe individual fish. We have passed the time when it was acceptable to use gear that harvests every fish of every species, and even worse, destroys the habitat as well. Large bottom trawls and drift nets are not acceptable when practicing responsible fisheries management. In fact, there are two papers in this edition which consider changes in design of fishing gear to reduce the collateral damage to the stock and the environment.

Technology has also been used to improve the safety of fishing boats and their crew. In all parts of the world, fishing often ranks as the most dangerous working activity in terms of injuries and lives lost. Improved vessel design, affordable safety equipment, increased safety awareness, communication technology and reliable weather forecasting have all helped to reduce the risk in this economic sector.

Technology also has a huge role to play in aquaculture, which will likely be the future of an industrial fishery. Site selection for aquaculture is a trade-off between suitable locations for the fish, a market and other users of the waterways. Technology in aquaculture is used to build stronger cages for open ocean environments, provide methods for fattening the stock, prevent disease, and provide a means for disposing of waste.

In the end though, consumers must be willing to put more value on high-quality fish protein. Scientists can help to grow and manage healthier fish stocks. Engineers can make more advanced fishing gear, safer fishing vessels, and better aquaculture systems, but in the end the consumer must be willing to pay a fair price for high quality fish. In return, the industry must be prepared to function in an ethical and sustainable manner, with minimum government intervention. Of course, technology will continue to have a role to play in finding the balance between market price and affordable costs of production.

Dr. David Molyneux
Technical Editor

Going topless

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Chosid, Pol, Szymanski, Ribas and Moth-Poulsen show how scientists, technologists, fishers and regulators can work together to develop new approaches to sustainable fisheries.

Who should read this paper?

Harvesters and researchers with an interest in gear design and performance should read the paper to see if this design could be applied locally. Fisheries biologists should have an interest in the findings regarding the role that light and vision play in the capture process. Resource managers should take note of the difference in catch performance between day and night, and the implications this difference might have when developing regulatory policy.

Why is it important?

The changing ocean environment demands innovation from the ocean community. Current emphasis worldwide in trawl design is toward greater sustainability of marine resources by limiting the impact of fishing on non-target species. Improved selectivity of fishing gear reduces unwanted by-catch to the mutual benefit of the commercial enterprise and the overall health of the ocean ecosystem.

This project tests the species selectivity of a trawl net cut virtually in half. The design is a radical departure from traditional nets made possible by an understanding of fish reaction to trawls, as revealed by underwater imaging technology. Also, the impact of light and vision on fish behaviour has been theorized, but not often demonstrated. This paper emphasizes the need for future trawl research efforts to consider the ability of fish to perceive the innovation.

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Mark Szymanski is an Assistant Biologist whose interests include the use of electronic equipment for the at-sea acquisition of biological information.

Luis Ribas is an accomplished fisherman and vessel owner with 30 years experience in fishing and gear design.

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DIEL VARIATION WITHIN THE SPECIES SELECTIVE "TOPLESS" TRAWL NET

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ABSTRACT

An innovative species-selective flatfish trawl net, the Topless net, was designed to maintain catches of legal-sized yellowtail flounder *Limanda ferruginea* while reducing sub-legal yellowtail flounder, Atlantic cod *Gadus morhua*, and other non-target species. The Topless net is distinguished by the removed top section from the wings back to the belly. This design functions to exploit the behavioural properties of different species and exclude unwanted organisms during the herding process, a process which may show diel variability. The experimental net was compared against a standard flatfish trawl net on Georges Bank, USA, onboard a commercial fishing vessel fishing around the clock. Non-parametric paired randomization testing indicates that the Topless net significantly reduced catches of Atlantic cod, legal and sub-legal-sized yellowtail flounder, haddock *Melanogrammus aeglefinus*, American plaice *Hippoglossoides platessoides*, monkfish *Lophius americanus*, grey sole *Glyptocephalus cynoglossus*, and winter flounder *Pseudopleuronectes americanus*. Significant diel differences in the catching efficiency for legal and sub-legal-sized yellowtail, winter flounder, and grey sole were found. Our results imply that light levels affect the behaviour and reaction of these species to trawl nets, and that currently permitted use of this net or a similar design in a 24-hour/day flatfish fishery on Georges Bank should be reinvestigated to determine if Atlantic cod catch rates meet management needs.

INTRODUCTION

Current U.S. fishery management practices restrict the number of days or hours that can be fished and therefore reward improvements in efficiency and precision by harvesters. The development of fishing gear that is more selective (that is, that more accurately captures the size and species of marine organisms desired) not only can save valuable fishing time, but can also allow access to healthy species or stocks intermingled with fish stocks requiring protection.

Geospatially or temporally separate stocks can be selectively targeted with traditional fishing gear. Where healthy and less healthy stocks are intermingled, improved gear selectivity is necessary. The modification of trawl nets and all fishing gear to improve species selectivity in mixed stock fisheries begins with an understanding of the behaviour of fish near gear [Wardle, 1993; Kim and Wardle, 2005]. Wardle [1993] described the herding and exhaustion of fish in a trawl net through a series of involuntary optimotor responses by fish to trawl doors, wires, and the front end of the trawl net. As a result of this behavioural work, it has been possible to improve trawl gear by exploiting variation in behaviour or physical properties between fish species or within subsets of species. For example, the development of the semi-pelagic raised footrope trawl in Massachusetts reduced catch of flatfish and American lobsters *Homarus americanus* in a silver hake *Merluccius bilinearis* fishery by exploiting behavioural differences in bottom-affinitive fish [McKiernan et al., 1999; Pol, 2004].

An experimental "Topless" trawl was tested by Pol et al. [2003] to reduce Atlantic cod *Gadus morhua* catch while targeting yellowtail flounder *Limanda ferruginea*. This net, based on a Faroese design [Thomsen, 1993], differed from conventional fishing gear primarily in the lack of webbing in the top half of the net. These modifications were designed to exploit species-specific vertical distributions of fish and our understanding of the rising behaviour of Atlantic cod by easing escape over the top half of the net. Prior underwater observations revealed cod rising when herded until inhibited or restricted by the webbing along the top of the net, while flatfish have been observed to predominately pass just under, or just over, the footrope [Walsh and Hickey, 1993; Thomsen, 1993; DMF, unpublished data]. Main and Sangster [1981a; 1982] also found vertical separation during the herding process using a triple codend, dual separator panel net, with most haddock in the topmost codend, cod more likely to be found in a middle codend, and flatfish almost exclusively in the lowest codend.

Pol et al. [2003] found that the Topless net design reduced Atlantic cod catches while maintaining commercially viable catch rates of legal-sized yellowtail flounder (>33 cm (13.0 in)). This net also showed a marked decline in catch rates of sub-legal-sized yellowtail and winter flounder *Pseudopleuronectes americanus*. However, all tows were conducted during the daylight hours on inshore vessels 15.2-18.3 m (50-60 ft) in length. Since fish vision is important for reaction to fishing gear and in vertical distribution of fish, the possible effectiveness of a design that relied on vision, and therefore light levels, during nighttime fishing was questioned [Fridman, 1969]. In addition, the ability of this net to maintain its function on a larger size scale suitable to offshore vessels remained unknown.

Light level is a vital component of gear testing, but is difficult to evaluate [Olla et al., 2000]. Undersea light levels are influenced by water quality, temperature, depth, cloud cover, moon phase, bioluminescence, anthropogenic sources, and sun position in the sky [U.S. Navy, 1952]. Measurement of light is also complicated by multiple dimensions of intensity, wavelength, and polarization. Fish certainly employ senses other than vision to detect fishing gear; nevertheless, incorporation of gear modifications into a round-the-clock fishery should require determining whether the modification is effective at night or under low-light conditions.

Time-of-day is often used as a proxy for in-situ light measurements. Prior work attempting to compensate for a diel factor in groundfish catches indicated very specific situations based on time-of-year, location, light levels, depth, predator and prey densities, and overall stock structures [Lough and Potter, 1993; Casey and Myers, 1998; Adlerstein and Welleman, 2000; Petrakis et al., 2000; Hannah et al., 2005]. The protocol for defining the diel cycle or thresholds of light and dark conditions using time varies per author. Some test for day/night difference in catches using sunrise and sunset to define day and night [Bowering, 1979; Petrakis et al., 2000; 2001]. Other researchers have omitted any fish captured during a defined buffer time period [Beamish, 1966; Sissenwine and Bowman, 1978; Walsh, 1988; Lough and Potter, 1993; Aglen et al., 1997; Casey and Myers, 1998] while others incorporated events (such as twilight), or continuous light changes or the circadian cycle [Engås and Soldal, 1992; Michalsen et al., 1996; Sangster and Breen, 1998]. According to Helfman [1993], twilight periods signify times of behavioural transitions for diurnal species. Hjellvik et al. [1999] further suggests that different diel models may be appropriate for individual stock situations and age classes such as continuous daily light changes, circadian rhythms, or day/night threshold effects. Using this premise, they found that the most suitable models for Atlantic cod in the Barents Sea changed by fish size and season.

In addition to visual perception of fishing gear, fishes' movement patterns or height off the sea bed may alter their vulnerability to a trawl net based on day/night differences in catch rates. Adlerstein and Welleman [2000] present evidence of Atlantic cod in the North Sea performing diel movements based on prey availability. Walsh and Morgan [2004] showed through data tags that adult Grand Banks yellowtail flounder perform seasonal off-bottom behaviour during the night at various times of the year. From work with species such as haddock *Melanogrammus aeglefinus* and dab *Limanda limanda*, Adlerstein and Ehrich [2002] suggest that species with higher night catches are more closely associated with the sea bed while pelagic fish are more likely to be captured during the day.

Atlantic cod and yellowtail flounder are caught during day and night in a mixed species trawl fishery on Georges Bank, USA. While the current stock status does not allow for increased harvest of yellowtail flounder, a trawl net that catches yellowtail similar to standard designs and releases or avoids Atlantic cod could allow increased access to the yellowtail flounder stocks as cod stocks rebuild and provide a design that could be used worldwide to separate fish species in trawls.

We tested the Topless trawl design around the clock, on a larger vessel, and with a larger version of the net than used in the prior inshore research. Our objective was to maintain catches of legal-sized yellowtail flounder while reducing sub-legal yellowtail flounder, Atlantic cod, and other non-target species. Although this study focused on reducing Atlantic cod catch, this net was expected to also reduce interactions between Atlantic cod and other similar flatfish: winter flounder; grey sole *Glyptocephalus cynoglossus*, and American plaice *Hippoglossoides platessoides*; catches of these species were also analyzed.

METHODS

The research was conducted by the Massachusetts Division of Marine Fisheries (DMF) from a commercial fishing vessel, the F/V *Mary Elena*, a 27 m (90 ft) LOA, 653 kW (875 hp) Western-rig commercial trawler with Thyboron 4.2 m (96 in) type 4 doors. Testing took place in the Western and Eastern U.S./Canada areas, Georges Bank, USA, over three trips: November 6-10, 2003, March 17-22, 2004, and December 8-17, 2006.

The design of the control net was based on current industry practice. The body of both nets (Figures 1, 2) and the bottom wing of the Topless net were constructed with 160 mm (6 in) diamond mesh openings[1], 3 mm (0.1 in) diameter polyethylene (PE). The wings of the control net were constructed of 200 mm (8 in) mesh with 4 mm diameter twine. Codends were constructed of 165 mm (6.5 in) black knotless square mesh, 25 meshes wide on the top and bottom and 100 meshes long; both had chaffing gear on the bottom. The headrope and 7.6 cm (3.0 in) diameter cookie-wrapped footrope lengths in the standard net were 28.3 m (93 ft) and 33.8 m (111 ft) respectively. For the Topless trawl, the headrope followed a taper of the net's gore, or selvedge, into a modified top belly, reaching a length of 47 m (154.5 ft); the footrope was comprised of 7.6 cm (3.0 in) cookie-wrapped footrope length of approximately 33.5 m (110 ft). The fishing circle in the standard net was 360 meshes; the Topless net's fishing circle was 240 meshes. Forty-eight 203 mm (8.0 in) floats were used on the standard net; the Topless net had 25 203 mm (8.0 in) floats. Both the control and experimental nets used 73.2 m (240 ft) of 7.6 cm (3.0 in) cookie-wrapped ground cable and 36.6 m (120 ft) bridles.

[1] All mesh measurements are between the knots and nominal.

Twin trawling (one vessel towing two nets side-by-side), using two tow warps and a centre sled-design clump, was used on the first trip. On the second trip, a third wire winch was added to the vessel, and a three warp twin trawling method was used. Experimental and control nets were exchanged side-to-side after every other tow during twin trawling. Single trawling (one vessel towing one net) was used in the third trip due to equipment and logistic difficulties. During single trawling, the control and experimental nets were alternated in pairs (alternate tows) in close proximity to one another, although not directly overlapping, in order to reduce the inherent variability that may exist due to a change in location.

Each trip generally concentrated on different areas of the U.S. side of Georges Bank (Figure 3). Individual tow locations were based on captains' knowledge of the fishing grounds. However, for the third trip, greater restriction was placed on tow locations to achieve a wider geographic spread. For the first two trips, mixtures of Atlantic cod and yellowtail flounder were sought; the final trip concentrated on finding Atlantic cod with any other flatfish.

Nets and doors were equipped with net mensuration sensors and a Tidbit temperature logger (Onset Computer, Inc, USA) in order to estimate environmental conditions and net performances. In trips one and two, proper net configuration was monitored using Netmind (Northstar Technical Inc., Newfoundland and Labrador, Canada) door spread and wing spread sensors. Simrad ITI (Kongsberg Maritime AS, Norway) sensors with a hull-mounted

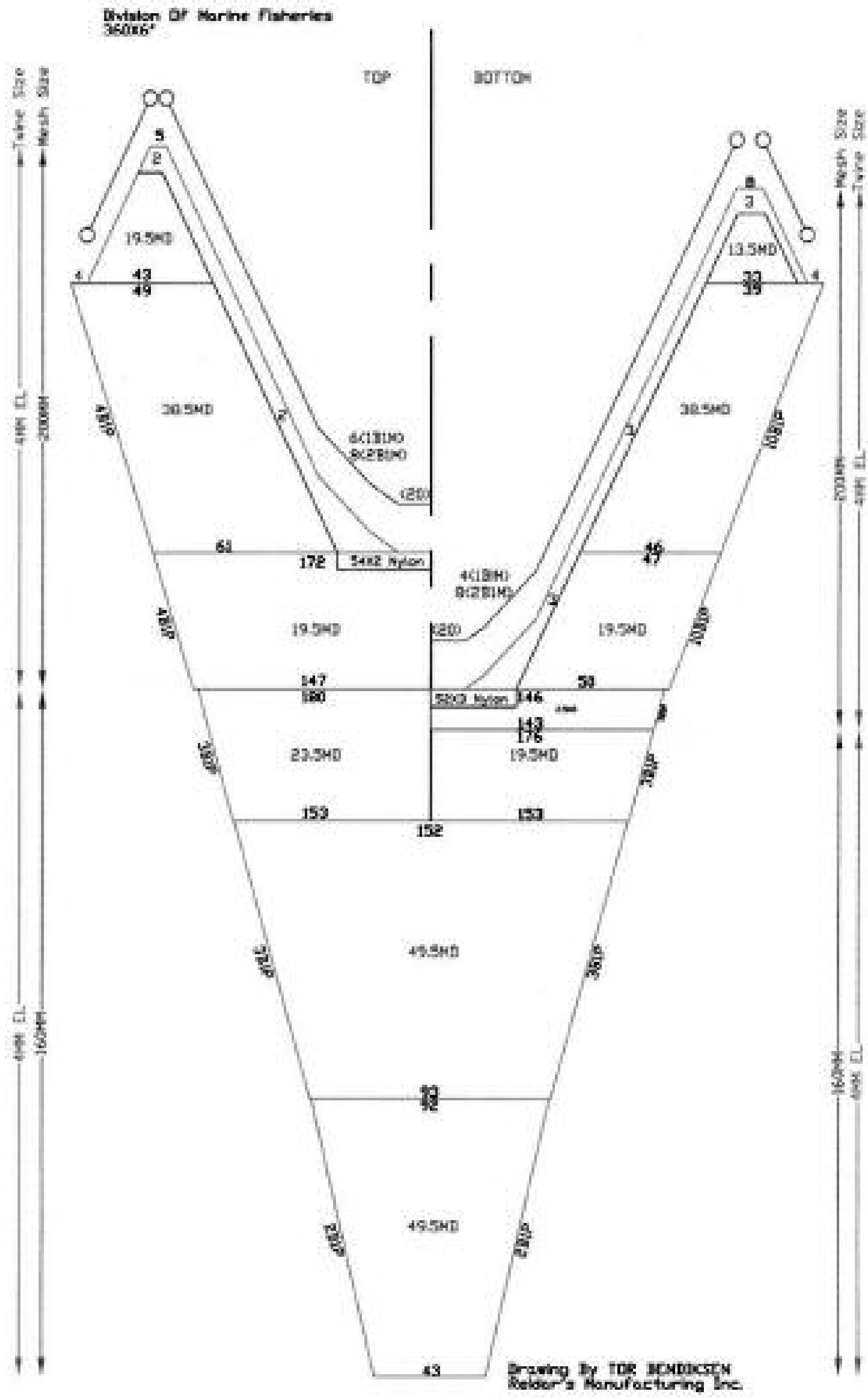

Figure 1: Diagram of the standard flatfish control net.

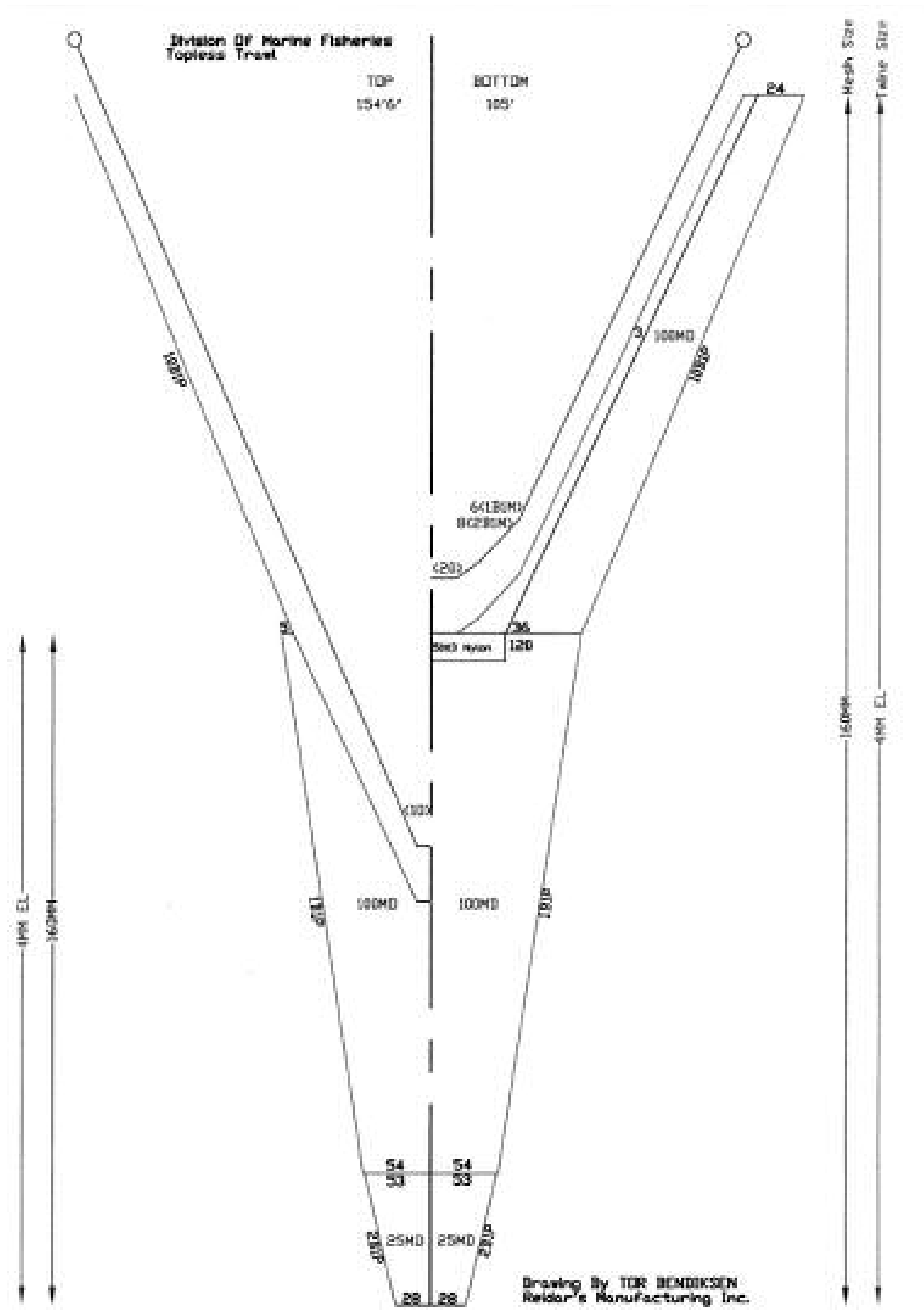

Figure 2: Diagram of the Topless net.

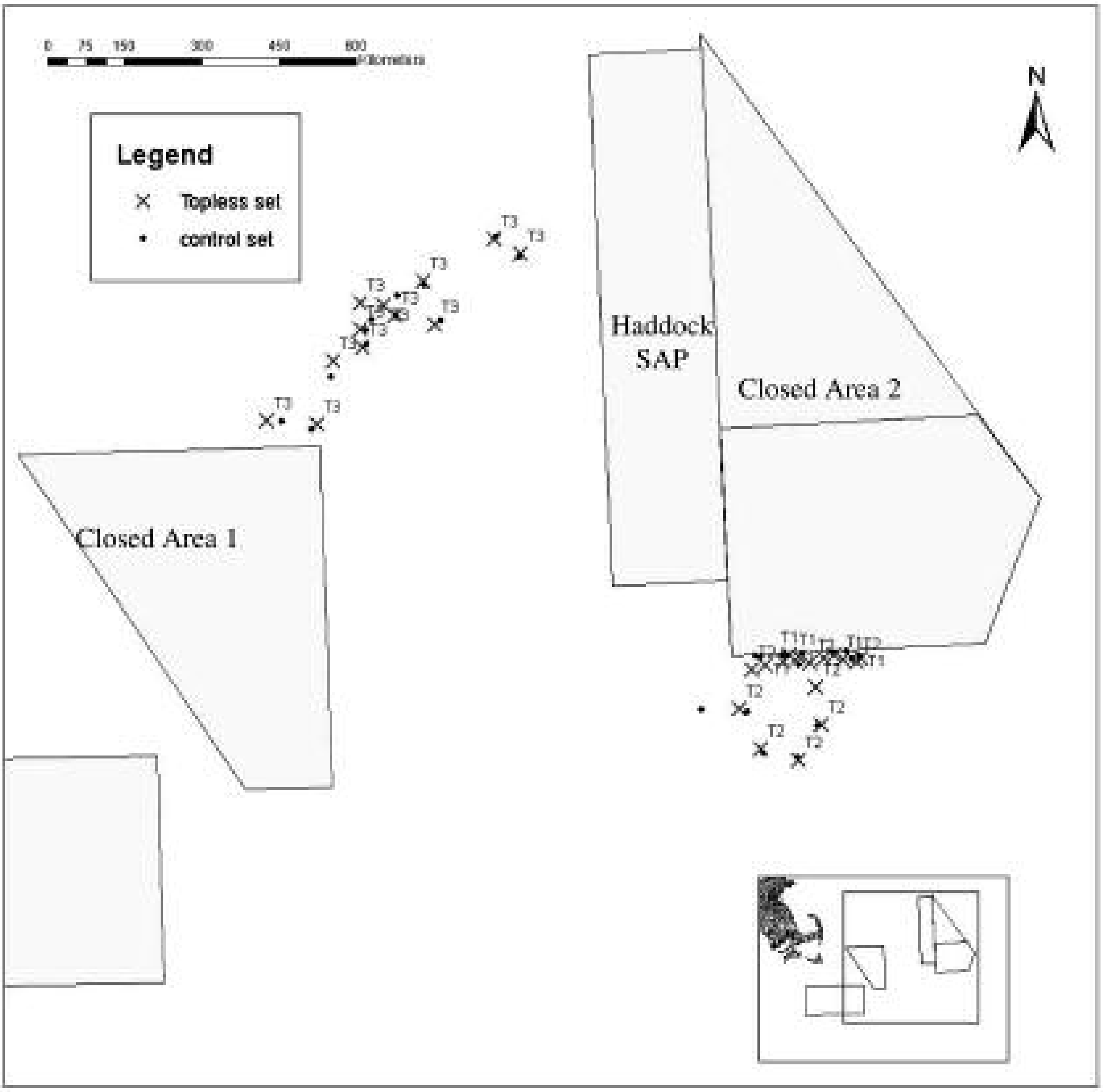

Figure 3: Location of start of tows on Georges Bank, USA. "T1" represents tows from trip 1. "T2" represents tows from trip 2. "T3" represents tows from trip 3. Marked areas are regulated Closed Areas or Special Access Program (SAP) areas. The window in the bottom right shows the greater area including coastal Massachusetts.

transducer were used to monitor door-to-sled and wing spreads; tow warp length was adjusted to maintain appropriate spreads. Due to hardware problems, no net or door geometry measurements were obtained during the third trip. The crew estimated correct bottom contact, in the latter case, by gear wear and the length of warp wire out.

We recorded time, tow duration, total codend catch weight, weather and sea conditions, starting depth, wire out, and the coordinates at the beginning and end of each trawl. The total tow durations varied within and between trips, although generally durations were approximately two hours. Variations in the durations were expected to minimally affect the mean length composition of trawl catches [Godø et al., 1990]. Tow speeds were kept at around 1.5 m/s (~3 kt).

Catch composition, species weights, and lengths of selected species were collected for each catch. Fish lengths were defined as the distance from the snout to the end of the fish's centreline. Sub-samples of lengths of the target fish species were collected from very large catches of those species. We measured no less than 100 individuals whenever possible in order to obtain adequate sample sizes without over-sampling.

ANALYSIS METHODS

The map showing tow locations was generated with ArcMap GIS (Figure 3). We carried out analyses using Microsoft EXCEL or R, an open source statistical analysis and data exploration program.

We adjusted catch weights and length-frequency counts for each tow by the tow duration. Both lengths and weights were raised to the total amount of catch when sub-sampling occurred. Counts of sub-legal (<33 cm (13.0 in)) and legal-sized yellowtail flounder, as defined by U.S. regulations, were derived from the total yellowtail flounder length frequency data and converted into catch weights using weight-at-length data provided by the National Marine Fisheries Service (NMFS).

For any given species, pairs of tows that had no catch (zero values) for both control and experimental nets were not included in these statistical tests; only paired tows with at least one fish present in either net were included in analyses for that species. Absence from both tows of a pair was considered evidence of the absence of that species from the fishing grounds. No adjustment was used to account for the different fishing techniques between twin and alternate towing, as comparisons centred on complementary pairs of tows.

Scatterplots were constructed in R for each selected species showing catch weights (lbs/hr) for the paired experimental nets with an equal catch line. Data points above the equal catch line show pairs of tows where the catch was higher in the experimental net; data points below the lines show tow pairs where the catch was greater in the control net.

Quantile-quantile normal distribution (Q-Q norm) plots were examined in R to determine deviations from normality for the difference in paired tows and $\log_2(x+1)$ transformed paired tows for each selected species. As non-normality was apparent in all cases, untransformed and transformed, non-parametric testing was necessary. We chose randomization testing over sign tests or similar tests to preserve the magnitude of the differences in the catch, and due to the rather straightforward methodology compared to more complex linear models.

Catch rates of Atlantic cod, yellowtail flounder (total, legal-sized, and sub-legal-sized), American plaice, grey sole, haddock, monkfish *Lophius americanus*, and winter flounder were tested for significance using non-parametric randomization testing in Microsoft EXCEL with 1000 iterations ($\alpha = 0.10$) [Rago, 2004; Pol, 2006]. For each analysis, adjusted catch rates of each pair were randomly assigned, without replacement, to one of the two net types, and mean differences were calculated. We compared the observed difference in paired treatments against a distribution of the randomly assigned paired values. The reported probability value is the proportion of the randomly determined differences that are greater than or equal to the actual observed value [Sprent, 1989].

Day was defined as sunup to sunset (when the sun first appears at the horizon until it disappears). Local sunup and sunset times were acquired from the U.S. Naval Observatory (http://aa.usno.navy.mil/) to the closest 30-minute latitude and longitude coordinates and are accurate to the nearest temporal minute. Transitional periods between day and night are referred to as dawn, which ends at sunup, and dusk, which begins at sunset. We considered multiple thresholds that define when dawn begins and when sunset ends [Helfman, 1993]. Civil and astronomical twilight represent the extreme sun declinations that define these categories and we ran analyses using both thresholds of twilight.

We placed tows into the sun cycle categories "dawn," "day," "dusk," or "night" based on the period where the majority of the tow occurred. Tows that occurred primarily during dawn and dusk were removed from the analyses along with the complementary paired tow. Randomization testing was repeated for each species group of interest, using multiple definitions of twilight. In the absence of clear known differences in fish behaviour based on different twilight definitions or knowledge of in situ light levels, results using the civil twilight definition, which defines the briefest twilight and allowed for the greatest number of tows, is reported.

Adjusted length frequency counts for species of interest and legal and sub-legal-sized yellowtail flounder were examined by net types, trips, and diel variations using both box and whisker plots [McGill et al., 1978] and length frequency histograms in R. Adjusted count data were multiplied by 10 to obtain even integers; therefore, relative data are depicted.

RESULTS

We completed twenty-eight valid pairs of tows: twelve pairs during the first trip and eight pairs each during the second and third trips. Estimated catch was over 41,000 kg (90,200 lbs) including 47 species or species groups. Species composition varied over the course of the experiment due in part to the lengthy time frame and large area (Figure 3). Skates were a large part of the catch but have low commercial importance and their catches are not analyzed.

Length frequency distributions appeared similar overall within species on a trip-by-trip basis (charts not reported).

Therefore, in order to maximize our sample sizes for later analyses, we combined the data for all trips. Further and more detailed box and whisker plots for trip variations are presented with respect to each selected species and net.

Catch weights by species varied widely between trips (Table 1). Atlantic cod were caught in relatively low weights and on trips two and three only. The majority of yellowtail flounder was caught during trip one. For other roundfish (all fish other than flatfish), haddock were caught in much larger weights on trip three; monkfish were caught in relatively large weights over all trips. For other flatfish, winter flounder were caught in much larger amounts on the first trip; grey sole were caught mainly during trips two and three; American plaice were caught in much larger weights on trip three.

In all cases, results of paired catch analyses produced identical conclusions using either the civil and astronomical twilight definitions.

Atlantic cod and other roundfish

Randomization tests for Atlantic cod catch weights showed very significant reductions in catch in the Topless net compared to the control net (Table 2). Haddock and monkfish catches were also significantly reduced. Scatterplots of the tow pairs for Atlantic cod and monkfish (Figure 4) show that for the majority of tow pairs, the control nets caught more for each of these species. The catch of haddock in the Topless net was always lower than in the control net. Significant differences between the Topless and control net for all three species were present for daytime and night time pairs (Table 2).

Length distributions of Atlantic cod were not different overall or trip-to-trip in the Topless and control nets (Figure 5); respective monkfish and haddock lengths were also not different. Box and whisker plots of haddock lengths on trip two appeared to be somewhat different between the nets; however, these differences are based on very small sample sizes.

Diel comparisons for lengths of Atlantic cod indicated no night and day differences within the nets (Figure 6); no differences were observed between nets as well. No haddock were caught during the day in the Topless net and night tows were comprised of extremely small counts. In the control net, haddock of similar lengths were caught during day and night although the interquartile ranges appear very different, which again may be due to small sample sizes in the daytime tows. No difference in length distributions during day and night was found for monkfish in the control net; the topless net shows different interquartile ranges in the diel cycles although this data is based on small counts.

Yellowtail flounder and other flatfish

Scatterplots for yellowtail flounder and other flatfish show a general trend of larger catches in the control net (Figure 4). Paired catches of total, legal, and sub-legal-sized yellowtail flounder and winter flounder were significantly lower in the Topless net compared to the control net overall (Table 2); during the day, no significant reductions were seen for these fish; at night, all showed a significant reduction in the Topless net. American plaice paired catches were significantly reduced in the Topless net overall and during the day and night. Paired catches of grey sole were also significantly different overall; a

Species	Trip 1 Control	Trip 1 Topless	Trip 2 Control	Trip 2 Topless	Trip 3 Control	Trip 3 Topless
Flounder, Yellowtail	5470.6	3452.4	359	222.2	354.5	158
Flounder, Yellowtail (Legal)	58.9	14.2	18.7	9	148	34.4
Flounder, Yellowtail (Sub-legal)	5415.9	3410.6	324.1	212.8	220	127.7
Monkfish (Angler, Goosefish)	1572.3	502.9	219.2	107	429.5	122.5
Haddock	0	0	115.1	35.8	2041	37
Flounder, American Plaice (Dab)	0	0	41.6	7	825	350
Flounder, Witch (Grey Sole)	8.8	1.1	155.8	115.8	314.5	239
Cod, Atlantic	0	0	269	121.8	326	138
Flounder, Winter (Blackback)	477.6	179.2	59.2	30.6	34.5	7.5
Lobster, American *Homarus americanus*	202.2	109.5	5	0	571.5	194.5
Skate, Winter (Big) *Raja ocellata*	0	0	12572	7888	9620.6	1947.6
Skate, Little *Raja erinacea*	0	0	3168	1772	12033.7	5992.5
Skate, Nk Rajidae	5782	3025	0	0	0	1280
Skate, Barndoor *Raja laevis*	0	0	187.6	44	720.1	158.9
Scallop, Sea *Placopecten magellanicus*	16.7	3.8	7	5.2	27	94
Flounder, Sand Dab *Scophthalmus aquosus*	0	1	939	502.6	88.5	59
Raven, Sea *Hemitripterus americanus*	1	0	259.4	85	199	44.5
Flounder, Fourspot *Paralichthys oblongus*	1.2	10.9	0	0.1	55	38.3
Sculpin, Longhorn *Myoxocephalus octodecemspinosus*	19.6	17	20.6	5.1	146.1	3.2
Flounder, Summer (Fluke) *Paralichthys dentatus*	0	0	73	69.2	0	9
Pollock *Pollachius virens*	0	0	8	0	131	7.5
Skate, Thorny *Raja radiata*	0	0	4	2.5	75	37
Hake, Silver (Whiting) *Merluccius bilinearis*	0	0	0	0	101.75	7.25

Table 1: Total control and Topless net catch by weights (lb) over all three trips for each major species. Species of primary interest are presented in the top section. Species other than those of primary interest whose total over all three trips was less than 100 lbs are not displayed. Additionally, weights of sea stars, snails, and sponges were removed.

Topless / control pairs

	All tows				day tows (civil twilight)				night tows (civil twilight)			
Species	n	sample mean	sample variance	probability	n	sample mean	sample variance	probability	n	sample mean	sample variance	probability
Atlantic cod	19	9.2	230.2	**<0.01**	9	6.1	139.2	**0.07**	7	8.0	41.6	**0.02**
yellowtail flounder	22	36.0	8517.2	**0.04**	13	18.9	8007.3	0.32	8	66.7	10115.2	**<0.01**
Legal yellowtail flounder	22	34.0	7966.7	**0.05**	12	21.6	8375.7	0.30	8	60.9	9413.3	**<0.01**
sub-legal yellowtail flounder	19	4.0	81.0	**0.01**	10	0.5	2.3	0.16	8	8.0	168.9	**0.02**
American plaice	20	13.0	271.0	**<0.01**	10	15.1	368.2	**<0.01**	7	3.0	5.8	**0.03**
grey sole	21	3.0	205.7	0.18	10	5.4	62.1	**0.04**	8	5.3	240.6	0.31
haddock	15	69.6	49175.4	**<0.01**	5	3.7	1.7	**0.02**	7	140.7	103582.7	**0.01**
monkfish	27	21.4	521.8	**<0.01**	15	18.0	383.0	**<0.01**	9	27.8	915.7	**<0.01**
Winter flounder	17	7.8	198.7	**0.01**	10	4.6	204.1	0.22	7	12.3	182.2	**0.01**

Table 2: Results from randomization tests for species and groups of primary interest for all paired tows and pairs, divided into day and night defined by civil twilight. "n" is the sample count. The sample mean and variance are derived from the actual differences in paired catch weight per hour (lbs/hr) samples (control – experimental). Probability values below $\alpha = 0.10$ are in bold.

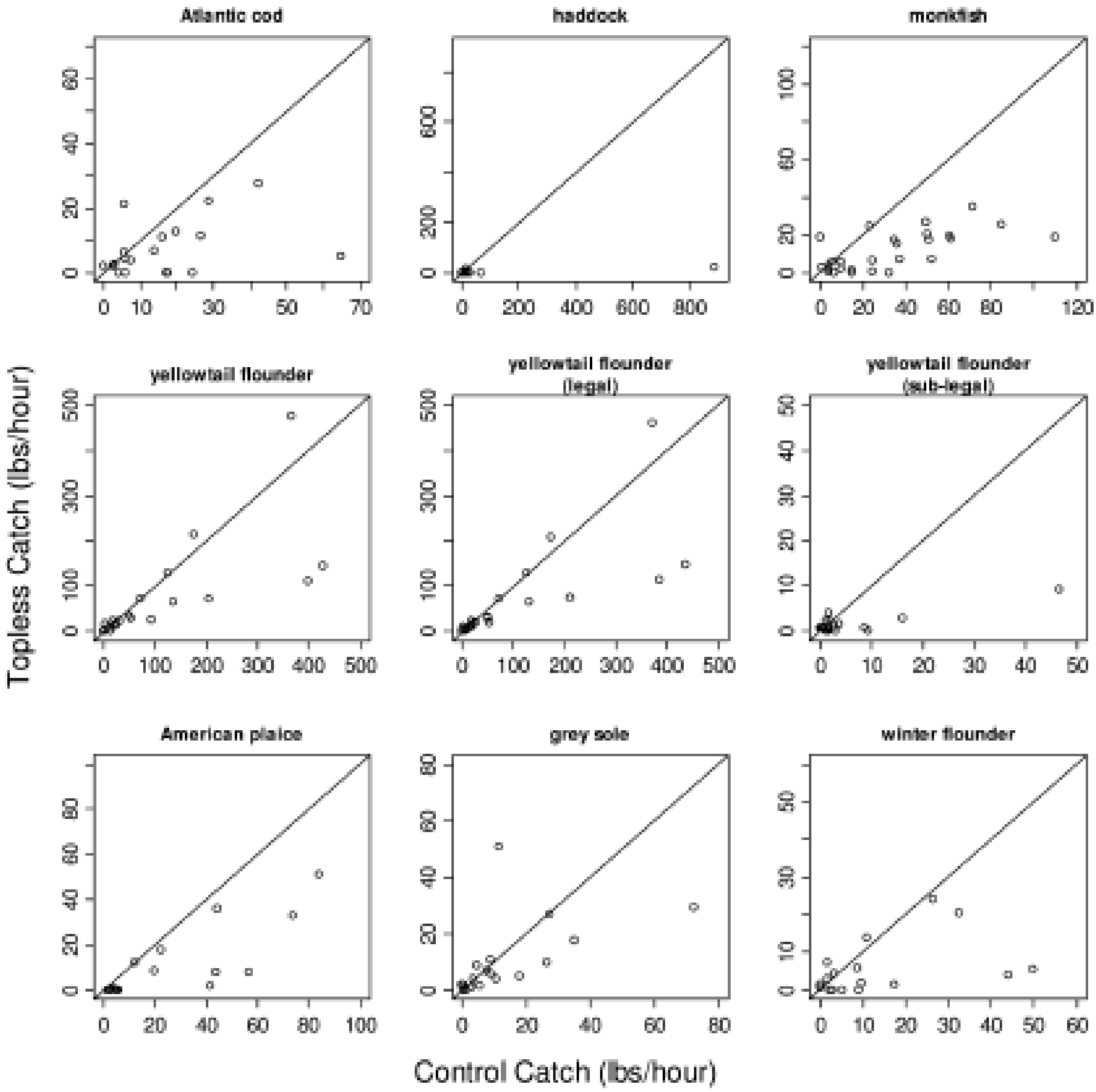

Figure 4: Paired catch data (lbs/hr) for all major species for the Topless and control tows with an equal catch line.

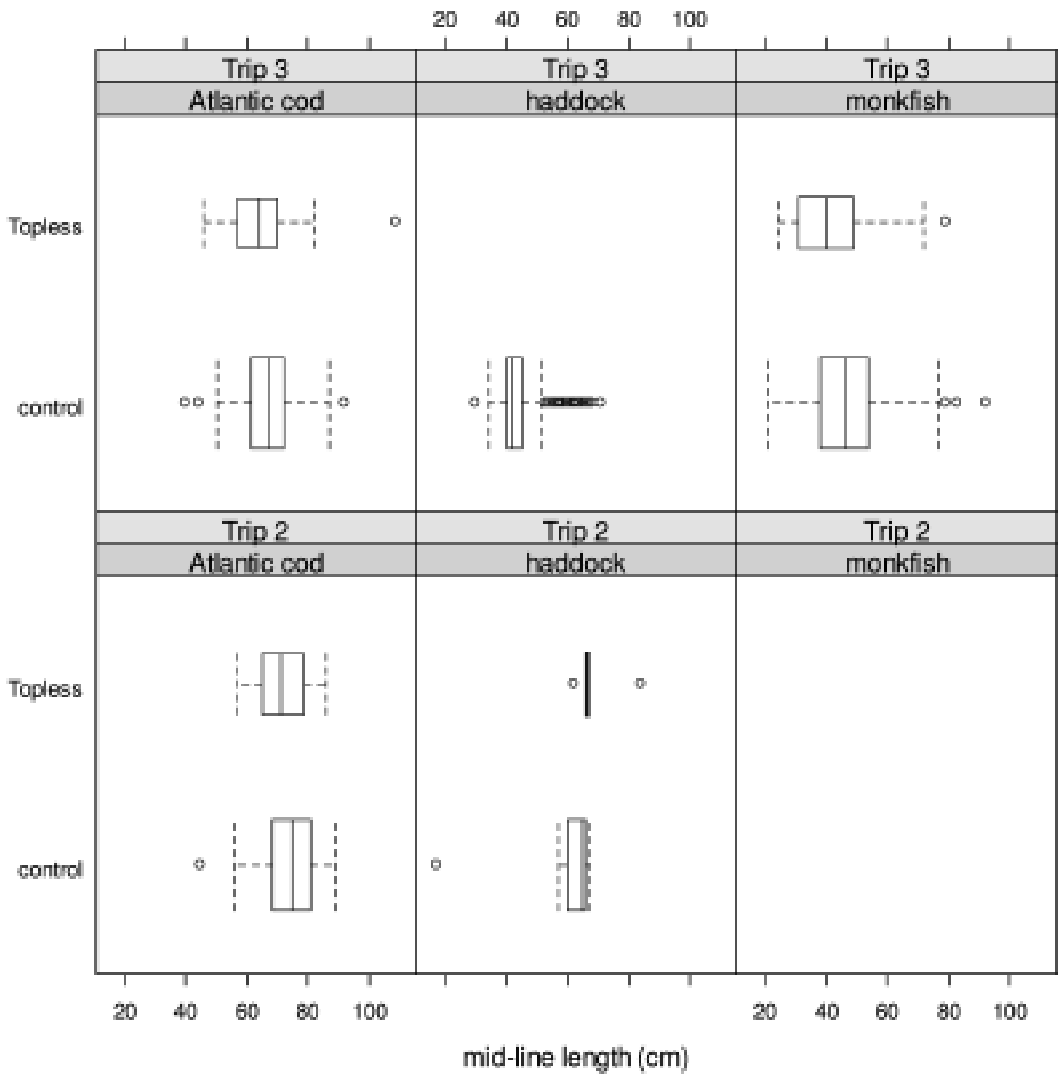

Figure 5: Box and whisker plots of lengths of major roundfish species (columns) comparing each trip (rows) and net (y-axis). Box widths are proportional to the square root of the sample sizes within each species and trip.

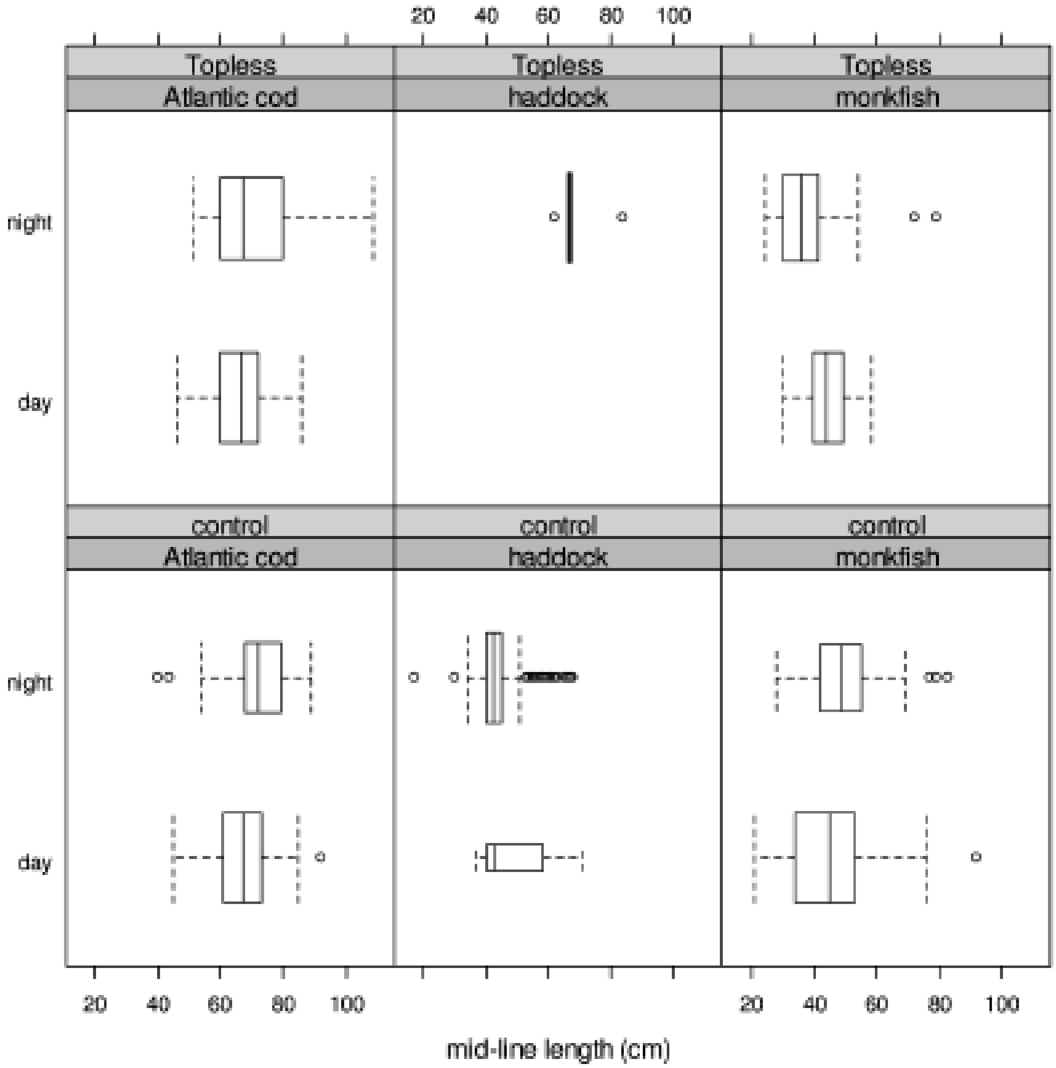

Figure 6: Box and whisker plots of lengths of major roundfish species (columns) comparing each net (rows) and diel period (y-axis). Box widths are proportional to the square root of the sample sizes within each species and net.

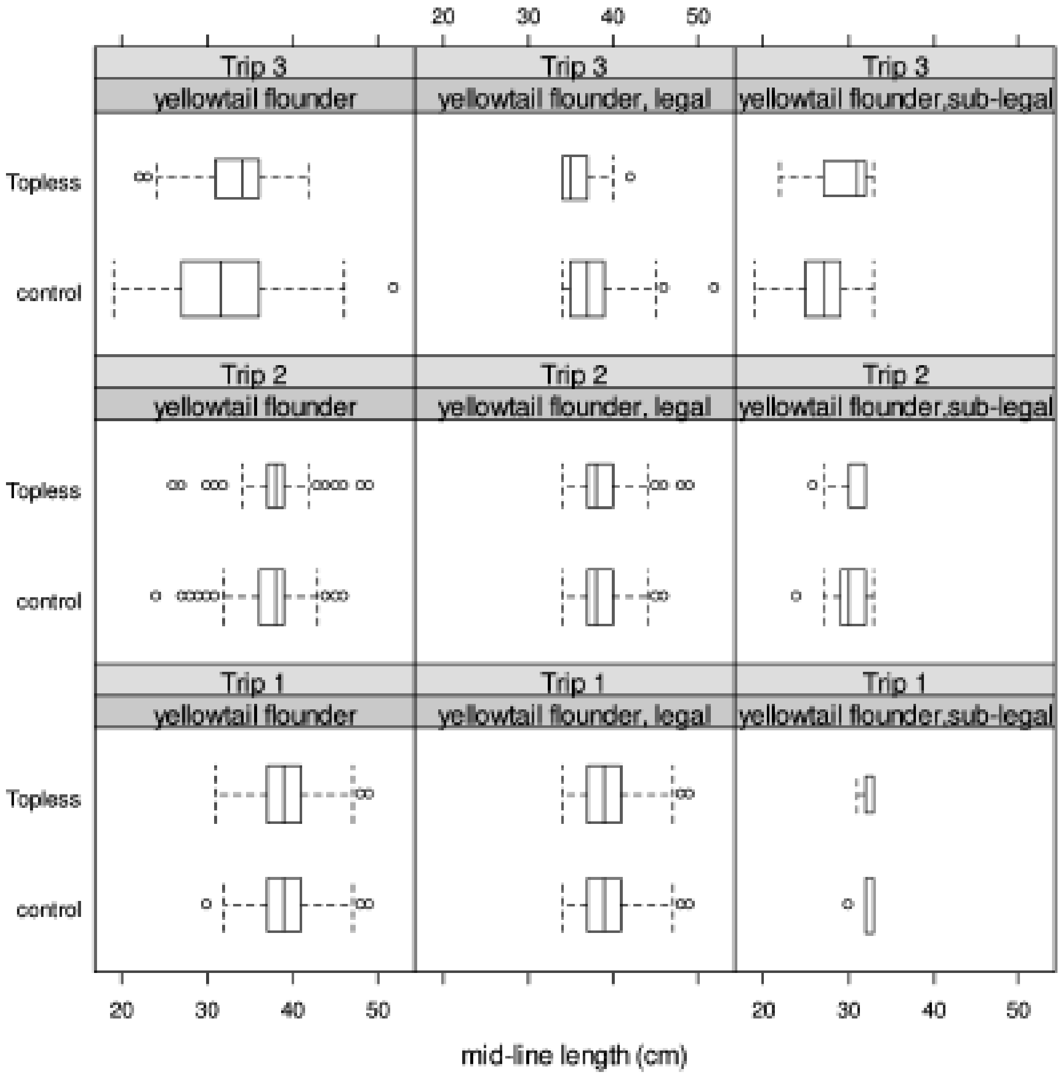

Figure 7: Box and whisker plots of lengths of yellowtail flounder categories (columns) comparing each trip (rows) and net (y-axis). Box widths are proportional to the square root of the sample sizes within each category and trip.

significant reduction was shown for grey sole during the day but not during the night.

Yellowtail flounder length frequency distributions combined from all tows and separated by nets indicate that the distributions are mostly similar (Figure 7). During trip three, histogram results of yellowtail show two modes (not shown). Length frequency distributions of yellowtail flounder are largely in agreement for diel periods (Figure 8).

Length frequency distributions of American plaice, grey sole, and winter flounder were similar for the Topless and control nets (Figure 9) and for diel periods (Figure 10), although the length ranges and medians were different for different species.

DISCUSSION

The primary goal of this project was to reduce Atlantic cod catches while retaining legal-sized yellowtail flounder catches using the Topless trawl net. The net was designed to exploit natural stratification and behaviour under pursuit and encourage escapement by or avoidance of Atlantic cod. The original study on inshore vessels using a smaller version of the net during the day showed success at decreasing Atlantic cod catches in the Topless net [Pol et al., 2003]. The current research, conducted over a large offshore area during all hours, showed that the Topless net met the goal of reducing catch rates of Atlantic cod which occurred during daytime and nighttime tows, and sub-legal-sized yellowtail, but only during nighttime tows (Table 2). Unfortunately, legal-sized yellowtail flounder were also significantly reduced during the night. Additional significant reductions were found in American plaice, grey sole, haddock, monkfish, and winter flounder as compared to the control net.

Escape of Atlantic cod upward is consistent with results of earlier work by Pol et al. [2003] and Madsen et al. [2006], whose experimental nets significantly reduced cod by allowing them to swim out of 203 mm (8.0 in) and 400 mm (15.7 in) meshes respectively for each study in the top of the nets. The reduction in the Topless net occurred during the day and night, suggesting that Atlantic cod could perceive the top exit and avoid capture under all light conditions. Also completed during this study [DMF, unpublished data], we tested a larger version of the Ribas net used by Pol et al. [2003], designed for the same purpose of reducing Atlantic cod catch while retaining yellowtail flounder. The Ribas net was close in dimensions to the Topless net; it replaced the standard 152 mm (6.0 in) diamond mesh on most of the top of the net with 203 mm (8.0 in) square mesh extending from the headrope to just before the codend. Unlike the prior research, cod were not significantly reduced within the Ribas net during the day or night. These results appear to contradict Pol et al. [2003] and Madsen et al. [2006] and may be due to differences in net sizes, unique behaviour of different cod stocks, or other unknown variables. Atlantic cod escape behaviour upward appeared to occur in our study despite other research describing a tendency to stay close to the sea bed, especially during the day [Main and Sangster, 1982; Ferro et al., 2007].

The Topless net also reduced catches of haddock. Haddock have been observed to swim upward when herded [Main and Sangster, 1981b, pers. comm., P. He,

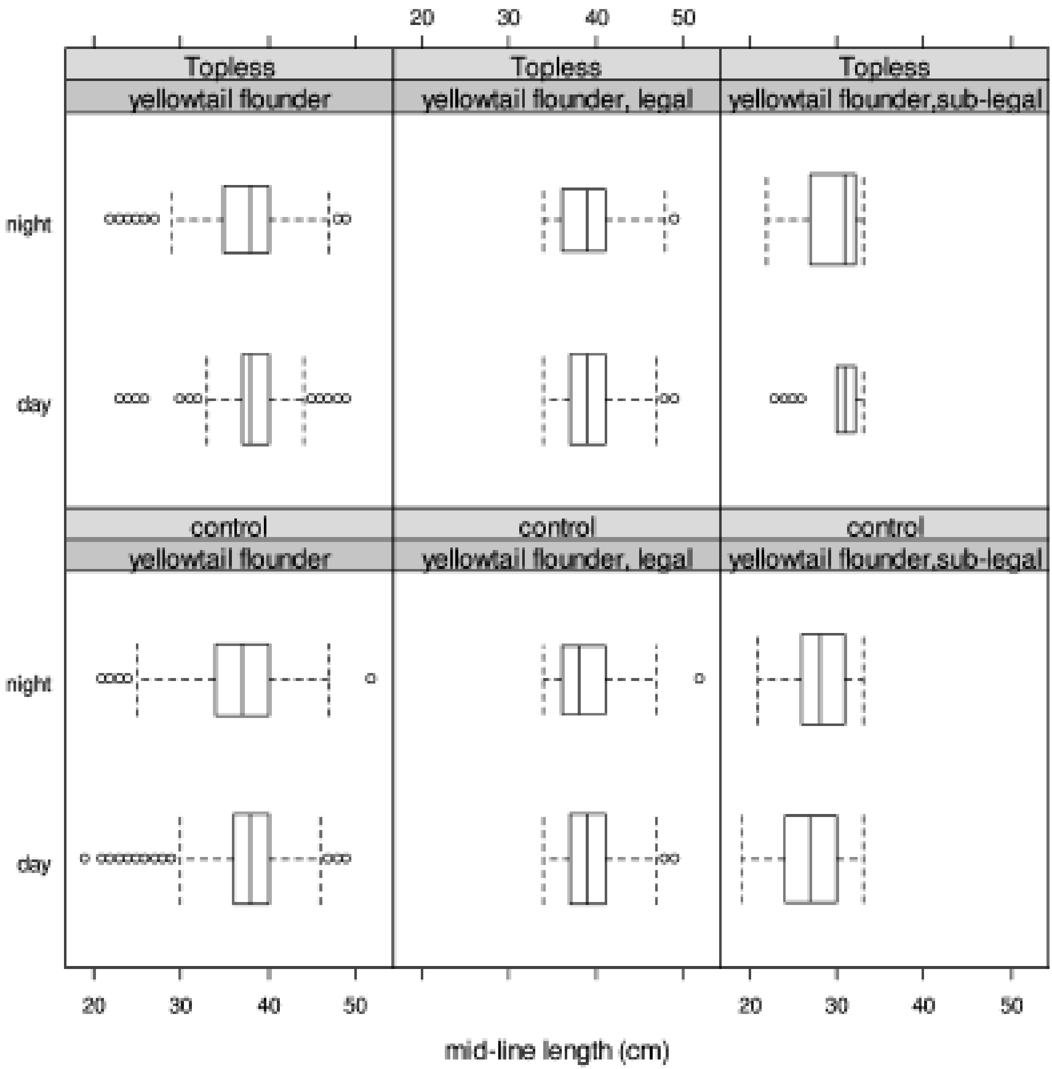

Figure 8: Box and whisker plots of lengths of yellowtail flounder categories (columns) comparing each net (rows) and diel period (y-axis). Box widths are proportional to the square root of the sample sizes within each category and net.

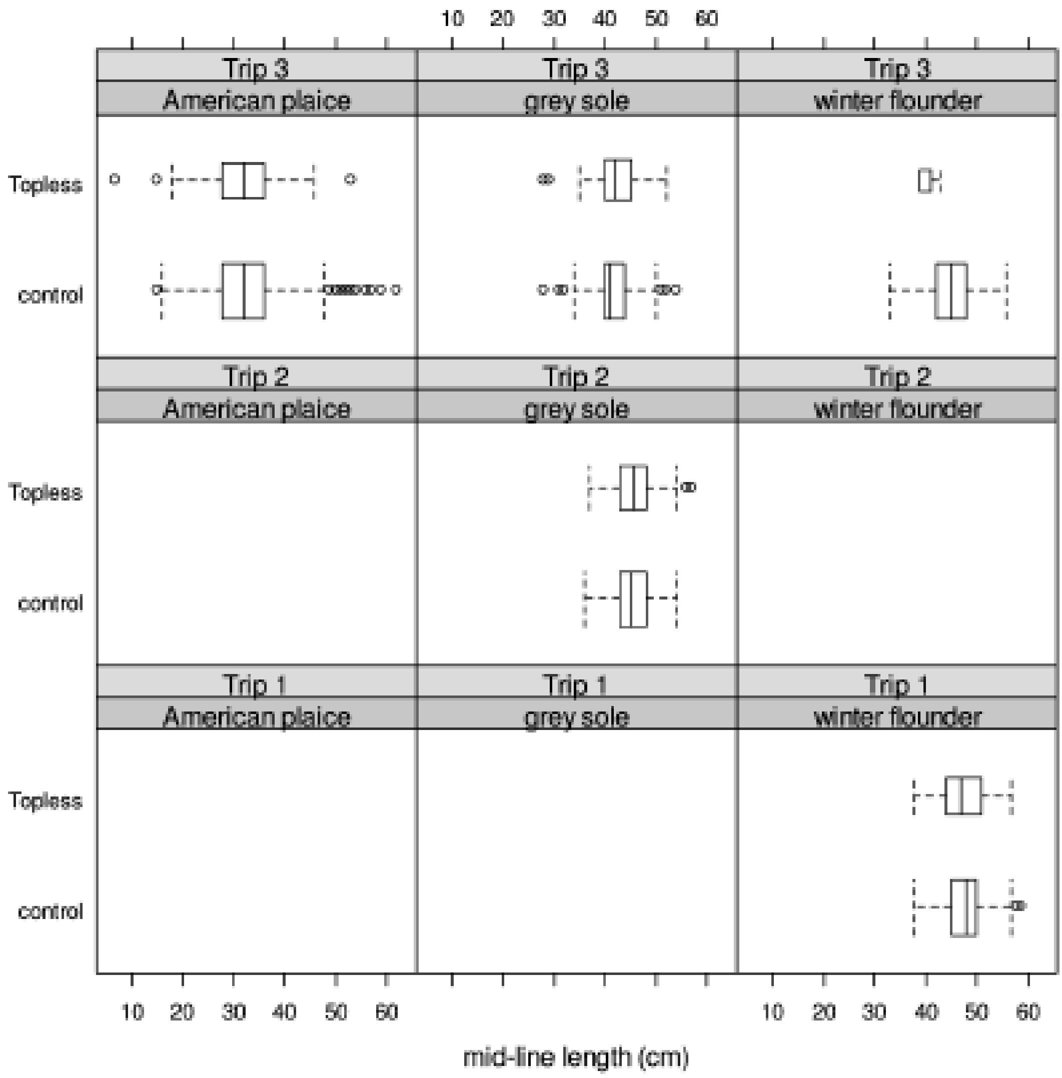

Figure 9: Box and whisker plots of lengths of major flatfish species (columns), excluding yellowtail flounder, comparing each trip (rows) and net (y-axis). Box widths are proportional to the square root of the sample sizes within each species and trip.

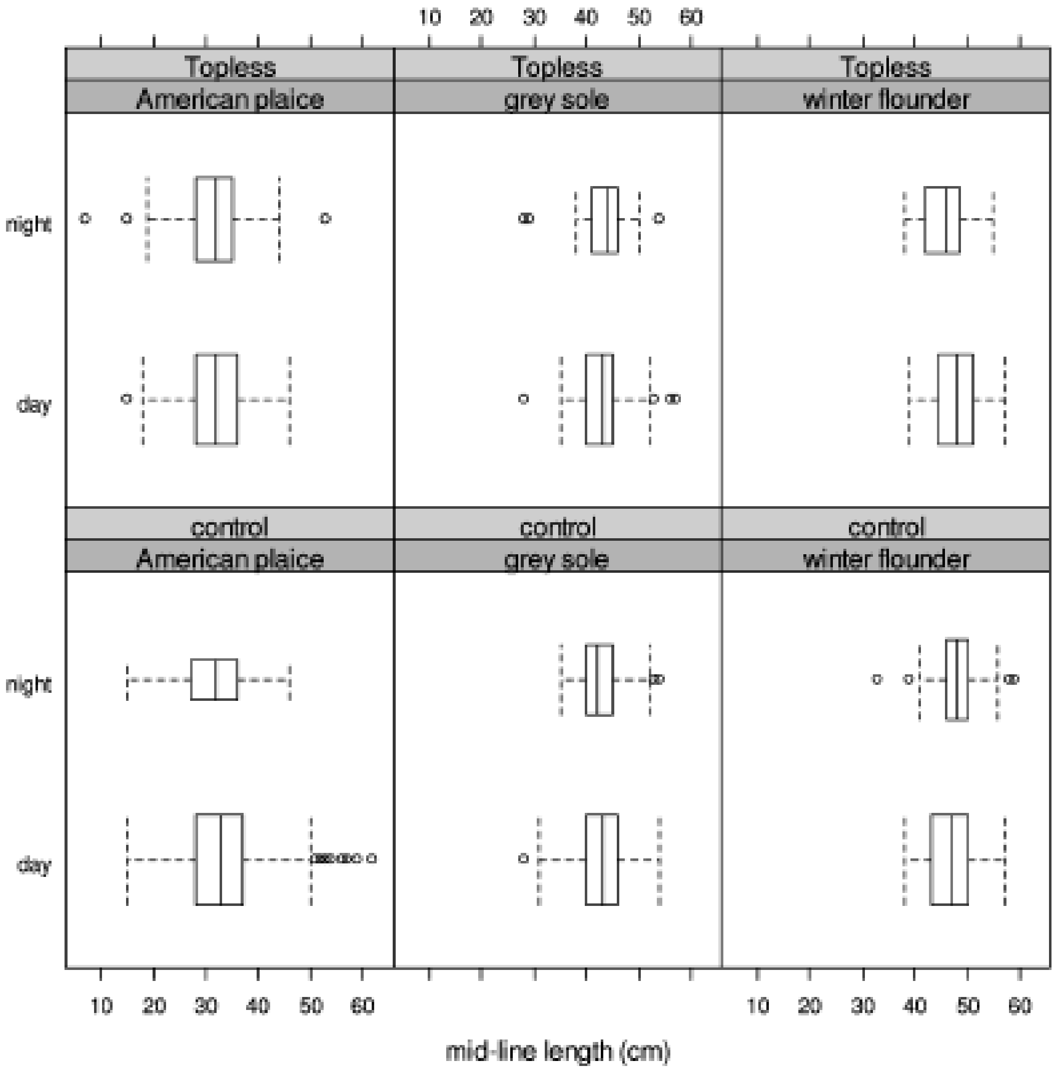

Figure 10: Box and whisker plots of lengths of major flatfish species (columns), excluding yellowtail flounder, comparing each net (rows) and diel period (y-axis). Box widths are proportional to the square root of the sample sizes within each species and net.

University of New Hampshire], and, in numerous studies, have been caught in the upper half of separator trawls [for example, Main and Sangster, 1982; La Valley, 2007]. The use of large meshes in the top portions of a net has been found to allow haddock escapement. Using the Ribas nets, a significant reduction in haddock was found as compared to the same control net during day and night in both sets of trials [Pol et al., 2003]. The escape of haddock through square mesh panels is also consistent with findings by Engås et al. [1998], who used a square mesh panel within a groundfish net round the clock. Based on the 2003 and contemporaneous research with the Ribas net and our Topless net results, we conclude haddock most likely escaped over the top of the net. This escape occurred both during the day and night tows, which suggest haddock could perceive and exit the opening under all light conditions.

Monkfish showed significantly decreased catches in the Topless net pairs and did not show diel differences (Table 2). These fish have been observed to show minimal swimming or response to trawl presence or contact [Reid et al. 2007]. Hannah et al. [2005], while testing a design similar to the Topless net, noted that lower wings and the absence of webbing facilitate fish escape and also allow more time for escape to happen. Testing of an unscaled Topless net model in a flume tank [Winger et al., 2006] suggested that the wings had low resistance to contact [DMF, unpublished data]. Thus, the escape of monkfish may have been due (or partially due) to passive tumbling over the top of the wings. This behaviour is probably not conditioned by light, and thus is consistent with our observations and with those of Reid et al. [2007]. Other possibilities, such as changes in selectivity of codends due to changes in catch volumes or the footrope not making bottom contact, are unlikely since similar length frequency distributions were generally seen within all nets at each diel period (Figures 6, 8, and 10).

The Topless net showed a significant reduction in catches compared to the control for legal and sub-legal-sized yellowtail flounder and winter flounder, but not during the day (Table 2). Grey sole displayed a general significant reduction in the Topless net but not during the night. Significant reductions were also found in American plaice during the day and night. Explanations of flatfish behaviour in trawl capture have typically treated all flatfish as if their reactions were similar [Walsh and Hickey, 1993; Bublitz, 1996; Winger et al., 2004]. Interspecies differences in flatfish behaviour during trawling are difficult to study due in part to low light levels, water clarity, and camera sensitivities. Our extensive filming of trawls has rarely allowed identification of any one of the more than ten species of flatfish present locally [DMF, unpublished data]. Catch results from this study suggest that significant differences in behaviour or orientation that affect trawl capture exist among flatfish species. The experience of the authors and of others [Bublitz, 1996; He, 2003] indicates that flatfish rarely venture off bottom when pursued by trawl nets, and thus changes to the tops of nets should not affect catchability. However, Bublitz [1996] observed two types of behavioural reactions by unspecified flatfish. The first is consistent with our experience; flatfish pass into the net just over the footrope. In the second, flatfish rose slowly to heights above 37 cm (14.6 in) and either swam in the tow direction or turned and swam into the net. Greenland halibut have been observed to express vertical swimming behaviour to escape from the sea floor to over the headrope [Albert et al., 2003]. Off-bottom behaviour of yellowtail flounder has been observed with increased height at night [Sissenwine et al., 1978; Cadrin and Westwood, 2004; Walsh and Morgan, 2004; Ferro et al., 2007]. Ryer and Barnett [2006] identified four categories of immature flatfish response to disturbance, two of which involved vertical movement that may have been adequate to avoid capture by a low-rise trawl. Vertical responses were more common during low light conditions. Any of the flatfish reductions we observed could be due to these types of reaction, which might allow sufficient height to escape over wings or a headrope.

We found no size-related differences in catch of yellowtail flounder, or by implication, yellowtail flounder behaviour. Beamish [1966] and Walsh [1988] found diel differences in catches of yellowtail flounder <22 cm (8.7 in), somewhat smaller than our sub-legal yellowtail (<33 cm (13.0 in)). Behavioural differences between yellowtail >22 cm (8.7 in) and <22 cm (8.7 in) might be ontological as yellowtail flounder typically mature only at 20 cm (7.9 in) [Collete and Klein-MacPhee, 2002]. While sub-legal (<33 cm (13.0 in)) yellowtail are fully mature [O'Brien et al., 1993], and thus ontological differences probably do not apply in this case, some species of flatfish show size differences in swimming strategies [Winger et al., 1999; 2004]. Georges Bank yellowtail flounder show sex-related length differences, with males maturing earlier at shorter length [O'Brien et al., 1993]. Males and females can segregate (DMF, unpublished data). We did not collect data on fish gender.

Day-night differences in fish avoidance observed in this study are partially consistent with previous work [Glass and Wardle, 1989] suggesting that some light is necessary for fish to react to trawl gear. The collection of information on light levels during tows has long been advocated by gear researchers to fully understand the fish capture process. Our experiences with this study reinforce this position on light importance by establishing that diel differences exist but is confounded by complex factors to record such as celestial and atmospheric conditions. Additionally, an analyst must choose among multiple definitions of twilight, and amongst models of fish reaction [as described in Hjellvik et al., 1999]. Even with knowledge of these factors, the light level on bottom is difficult to know. Jamieson et al [2006] suggests that bioluminescence generated by the trawl itself while fishing may provide adequate light to stimulate a fish escape response. Walsh and Hickey [1993] showed that the presence of artificial light using light sticks on a trawl net at night did not change escape responses (during darkness) for Atlantic cod, haddock, other roundfish, and unknown flatfish. However, this may have been due to the fishes' lack of acclimation time to the new light conditions.

The strength of our results is limited somewhat by low catches due to low stock sizes of both yellowtail flounder and Atlantic cod during most of the study. Actual pairs of tows where a species was caught in one of the paired tows were far fewer than 28. The amount of Atlantic cod was also low within each haul; the maximum catch in the control net was less than 31 kg/hr (70 lb/hour), despite our attempts to concentrate on catching Atlantic cod in our third trip. However, as Atlantic cod is a non-target species in the flatfish fishery, we consider conclusions based on this number of pairs and amounts to be valid and useful. Catches of other commercially important species approached or met commercial quantities on some tows.

Observed differences between trips or nets in length frequency distributions, such as with haddock, could be a result of small sample sizes. In trip three, yellowtail flounder were shown to have an overall smaller size distribution (Figure 7). While this may be an effect of proportionally smaller legal-sized yellowtail catches in the third trip, different fishing areas (even though it is considered the same stock), or a difference in performance of fishing technique (twin trawling vs. alternate trawling), it is likely an indication of a changed stock structure from the first two trips. Sangster and Breen [1998] found no significant difference for haddock, plaice *Pleuronectes platessa*, and anglerfish *Lophius piscatorius* between twin and alternate trawls; significant differences were detected, however, for Atlantic cod and *Nephrops norvegicus*.

The Topless design is currently permitted for use in the Eastern U.S./Canada Area (EUSCA) on Georges Bank for a 24-hour fishery based partly on the inshore research demonstrating its cod-reducing ability. These new results establish that the Topless net design is effective for avoiding Atlantic cod at all times while significantly retaining legal-sized yellowtail flounder during the day. The Topless net reduces sub-legal-sized yellowtail flounder during the day as well but significant reductions only occur at night. While results from our first trip and from Glass et al. [2004] suggest spatio-temporal separation of cod and yellowtail in the area, cod catch data from the 24-hour EUSCA fishery should be evaluated to determine if the commercial implementation of this design has been sufficiently effective.

Overall reductions for all commercially important species in the Topless design suggest it may not be economically sustainable on its own within a dedicated flatfish fishery. However, as a supplementary special access program which does not utilize regular allotted fishing days, the reduction in catch may be acceptable to the fishing community. Also, weak stock management may dictate the future of this fishery and necessitate available options such as the Topless net.

The Topless design can easily be replicated and applied to daytime flatfish fisheries around the globe where roundfish reductions are desired. Also, this gear is comparatively easy to define in legislation. This study emphasizes the importance of diel cycles and/or light levels on the reaction of fish to gear modifications. Future gear innovations must consider the impact of light levels during design, testing, and implementation on a regional basis. Twin trawling is a valuable method which removes some of the problems associated with comparing paired samples during a changing diel cycle. Our results also establish differences between flatfish species behaviours in a trawl net. The advancement of technology, including lower light, higher resolution cameras, and advanced sensors, should aid researchers attempting to define and describe differences in species behaviours.

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