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Comparative fishing to evaluate the viability of an aligned footgear designed to reduce seabed contact in Northern shrimp bottom trawl fisheries

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Draft

Abstract

We developed and evaluated an innovative trawl technology that reduces seabed contact while targeting Northern shrimp (*Pandalus borealis*) off the east coast of Canada. The innovative footgear, referred to as the “aligned footgear”, was evaluated in a flume tank to estimate contact area with the seabed and then tested at-sea for engineering performance and catchability. Results demonstrated that the aligned footgear trawl produced a substantial reduction (i.e., 61%) in the predicted contact area with the seabed compared to the identical trawl equipped with traditional rockhopper footgear. A total of 20 paired tows (n=40 tows) were subsequently conducted at-sea to evaluate fishing performance. The aligned footgear trawl caught significantly more Northern shrimp (+23%), capelin (+71%), Greenland halibut (+99%) compared to the traditional rockhopper bottom trawl. This study was part of Project 2.2 in the Canadian Fisheries Research Network (CFRN).

Keywords:

bottom trawl, seabed impact, footgear, shrimp, bycatch

1. Introduction

Industrial scale fishing of shrimp and prawns is predominantly conducted worldwide using mobile bottom trawls (see review by Gillett 2008). These modern fishing systems are more advanced and sophisticated than previous decades as a result of increasing fuel costs, the need for species- and size-selectivity, stringent bycatch restrictions, and the necessity to minimize impact on the environment (Graham 2006; Winger et al. 2006). However despite their ubiquitous use in almost all coastal nations, bottom trawls are not without their ecological impacts. These are commonly categorized into one of three categories: bycatch of non-targeted species, fuel consumption and its associated carbon footprint, and seabed impacts.

The topic of seabed impacts of bottom trawls has increased significantly in the past two decades. Dozens of research initiatives have now documented a wide collection of potential impacts, including: physical perturbation of the seabed, habitat damage, decreased benthic biomass, community shifts, sediment suspension, and changes in seafloor chemistry (see reviews by Jones 1992; Jennings et al. 2005; Løkkeborg 2005; Gilkinson et al. 2006). Looking forward, the challenge is not so much what are the impacts, but how do we achieve sustainable levels of fish production while at the same time minimizing the wider ecological impacts of trawling? In truth, there is a trade-off to be balanced. Identifying knowledge-needs and transitioning toward ‘best practices’ has been suggested as a pathway toward balancing the trade-off between the effects of mobile fishing on the seabed and the benefits of fish production for food security (Kaiser et al. 2015). In that study, the authors developed and prioritized 108 knowledge-gaps associated with bottom trawling. In the top ten, was the need to determine “what gear configurations exist to mitigate habitat impacts and how can these benefits be quantified?” (Kaiser et al. 2015). Indeed,

the development of gear modifications to reduce the seabed impact of bottom trawls is not a new field of investigation. Gear technologists have developed and tested novel concepts over the last couple decades. Most of these innovations have focused on reducing the total contact area of a trawl on the seabed or reducing the pressure of a trawl that is exerted on the seabed (see reviews by He 2007; Valdemarsen et al. 2007; He and Winger 2010).

In Canada, mobile bottom trawling occurs in all three coastal oceans. Since the mid 1990's, the majority of this trawling activity has targeted Northern shrimp (*Pandalus borealis*) off the northeast coast of Newfoundland and Labrador. This fishery is a major contributor to the local economy of the province, with landings in 2015 exceeding 73,306 metric tonnes with a landed value of approximately CAD \$282 million (DFA 2015). Some of this trawling activity overlaps with lucrative snow crab (*Chionoecetes opilio*) fisheries, particularly in NAFO Divisions 3K and 3L (Dawe et al. 2007). Survey and fishery catch rates of snow crab have decreased in each of these divisions in recent years (Mullowney et al. 2012; DFO 2016). Industry stakeholders are concerned about the situation and suspect multiple contributing factors, including poor recruitment, changing environmental conditions, increased predation, and interaction with the mobile trawling sector which targets Northern shrimp. Recent underwater video camera observations of snow crab encountering the traditional footgear (i.e., rockhopper) of a shrimp trawl demonstrated that snow crab are quickly overtaken by the trawl, with approximately 54% of individuals observed experiencing an encounter with the footgear (Nguyen et al. 2014). Rose et al. (2013) demonstrated that the mortality of decapod crabs in response to such encounters with trawl footgear can range from 10-31% depending on the species and region of the footgear they encounter. Subsequent work by Hammond et al. (2013) showed that simple modifications to

trawl footgear (i.e., rubber disk footgear with off-bottom sweeps/bridles) achieved a 36% and 50% reduction in mortality levels for Tanner crab (*Chionoecetes bairdi*) and snow crab (*C. opilio*), respectively. These findings suggest that minimizing potentially negative encounters through the use of footgear modifications is a valuable research pathway as it can promote the reduction of unaccounted fishing mortality.

Bycatch most commonly observed while bottom trawling for Northern shrimp are capelin (*Mallotus villosus*) and Greenland halibut (*Reinhardtius hippoglossoides*). Depending on the region and time of year, these can contribute 1-7% of the total catch weight in a tow, removing less than 1% of the population abundance estimates for these species annually (e.g., Kulka 1995; DFO 2010; Savard et al. 2012). Both species are vulnerable to capture as bycatch due to their overlapping spatial distribution with Northern shrimp in some areas. Capelin typically enter the trawl in large dense schools and while most escape through the mesh, many will end up passing directly through the Nordmøre grid and are retained in the codend. Greenland halibut by comparison are herded by the bridles toward the trawl mouth similar to most flatfish species. Here they swim until exhaustion, at which point most will pass between the toggle chains and escape under the trawl, however many will rise and fall back into the trawl. Large individuals tend to escape using the Nordmøre grid, however smaller individuals can pass through the bar spacing and be retained in the codend (see review by Winger et al. 2010).

In this study, we developed and tested a novel trawl footgear that reduces the total contact area of a bottom trawl with the seabed. Building on the previous work of He and Balzano (2009), we changed the alignment of the rubber discs in a traditional footgear in order to make them parallel

to the towing direction. The trawl is ‘aligned’ as the rubber discs in the footgear are aligned with the direction of tow. This was achieved by boring the centre holes of the discs diagonally (rather than concentrically) with custom angles depending on their position within the trawl footgear. This allowed the footprint of the trawl to be reduced as the narrow facing side of the disc is facing the direction of tow, rather than the blunt side as is currently the case in the wing sections of traditional rockhopper footgear. Through comparative at-sea fishing trials, we investigated the engineering and catch performance of the experimental aligned footgear trawl in comparison to an identical trawl equipped with a traditional rockhopper footgear. We documented the geometry of the trawls as well as the catch results for target species (Northern shrimp) and non-targeted bycatch.

This study was part of Project 2.2 in the Canadian Fisheries Research Network (CFRN). The goal of the project was to reduce seabed impacts of mobile fishing gears used in Canada, including the development of innovative harvesting technology. This project uniquely benefited from the network because it required the scientific expertise of researchers from engineering, applied mathematics, marine ecology, and fisheries science. The network offered a unique opportunity to expand Canada's research capacity in applied fisheries science while addressing relevant issues to the mobile trawler fleet.

2. Materials and methods

2.1 Gear design

The control and experimental trawls used in this study were 4-seam Vónin 2007-1570 inshore shrimp trawls with 33.8m headline and 32.9m fishing line (Fig. 1a). The control and

experimental trawls were identical in every way, except for modifications to the footgear. Flotation was provided using 203mm diameter trawl floats, with 100 floats mounted on the headline, 18 floats mounted on the fishing line, and five floats mounted on each of the upper selvages. The trawls were constructed with 45-100mm diamond mesh and were equipped with identical high-density polyethylene Nordmøre grids. The control trawl was rigged with a 32.9m rockhopper footgear commonly used throughout the fishing fleet. The rockhopper footgear, with a weight of 354 kg, was constructed from different components including wires, travel chains, spacers, bobbins, and rubber discs/wheels. This consisted of 28 rockhopper disks with a diameter of 356mm, 38 disks with a diameter of 305mm, and two 356mm diameter steel bobbins linked together by a 13mm long-link footgear chain, a 10mm long-link travel chain, and a 10mm long-link weight chain (Fig. 1b). Due to its inherent design, most of the rubber discs in the wing sections scuff the seabed with as much as 70 degrees out of alignment with the direction of tow, dramatically increasing the surface area of the trawl with the seabed. The experimental aligned footgear, by comparison, had all rubber discs facing parallel to the towing direction of the trawl (Fig. 1b). The discs located in the quarter and wing sections (n=32) had diagonally positioned centre holes, custom cut at individual angles depending upon their relative position within the footgear. The discs were attached directly to the fishing line by a series of toggles instead of a typical travel chain in order to ensure the proper alignment of the discs with the direction of tow.

2.2 Flume tank tests

Engineering models (1:4 and 1:8) of the control and experimental trawls were scaled, constructed, and evaluated in a flume tank at the Fisheries and Marine Institute of Memorial University in St. John's, Newfoundland (Winger et al. 2006). The smaller models (1:8) were

used to visualize the entire trawling system (including bridles and doors) while the larger models (1:4) without doors and bridles were built so as to better evaluate footgear performance. Underwater cameras were used to examine the degree of seabed contact by both footgears. This was accomplished by positioning cameras above to models with a downward field of view to estimate contact area of individual footgear components. The traditional (control) footgear made contact with 69% of the seabed between the wings of the trawl mouth (Fig. 2a). The experimental (aligned) footgear by comparison made contact with only 27% of the seabed between the wings of the trawl mouth (Fig. 2b), representing a 61% reduction in contact area with the seabed. Both trawls were otherwise identical in engineering performance.

2.3 Trawl quality control

Two full-scale inshore shrimp trawls were constructed of new materials and thoroughly evaluated for quality control prior to sea-trials to ensure the trawls were identical with the exception of the footgear. Following the DFO (1998) protocol, we measured 100 meshes per panel, counted the number of meshes in the transverse and longitudinal direction for each panel, measured twine thickness, and documented all associated components such as ropes, floats and weights. Mesh sizes were measured as inside stretched mesh (mm), using the ICES mesh gauge (see description by Fonteyne et al. 2007).

2.4 Sea trials

Sea trials were carried out from 29 August and 7 September 2012 off the west coast of Newfoundland near Port au Choix, at depths ranging from 129-149 m (Fig. 3). The study area represents current and historically productive fishing grounds for shrimp trawlers. The area is

also inhabited by various commercially important groundfish species such as capelin and Greenland halibut as well as snow crab. In total, 20 paired tow (n=40 tows) were completed in 6 fishing days. The *F/V Newfie Pride*, a 19.8m (65') inshore shrimp trawler, was used for all comparative fishing trials. The tow duration was 15 minutes and the towing speed was 2.3 knots. A technical team (n=5) of employees and graduate students from Memorial University were onboard for all tows to carry-out experimental procedures and data collection.

Comparative fishing with the experimental and control trawl was conducted in order to test the null hypothesis H_0 : there is no difference in catch volume and composition between trawl types. The alternate-haul method was employed to compare catches among trawls. This method alternatively tows an experimental and control gear in paired sequences. The fishing gears were identical except for the component being evaluated. The tows were made as close as possible to each other in both time and space (DFO 1998). In our study, time between paired tows ranged from 20 to 42 min. A maximum distance of 400m between paired tows was chosen to ensure similar habitat and water depth. Paired tows were conducted in the same direction, either with or against the tide. Towing order followed the ABBA BAAB protocol, where A was the control trawl and B was the experimental trawl (DeAlteris and Castro 1991). All fishing was conducted during daylight hours.

Trawl geometry data was recorded, including; door spread (m), wingspread (m) and headline height (m) using a combination of E-Sonar™ and Netmind™ acoustic sensors. Door spread was recorded in order to ensure proper upright alignment of the doors. Wingspread and headline height were recorded in an effort to compare trawl net geometry between treatments. Differences

in engineering trawl performance between the control and experimental trawls were compared using paired *t*-tests.

2.5 Catch sampling and analysis

All catch was sorted to the species level and measured after each tow. The shrimp catch was sorted into 20 L baskets which were then weighed to estimate catch rate (kg min^{-1}). A 750 ml subsample of shrimp was removed from five of the 20 L baskets. These shrimp were separated and taken back to the laboratory and weighed ($\pm 0.01 \text{ g}$) to obtain count data (count kg^{-1}). All major fish species captured as bycatch were counted and measured for body length ($\pm 1 \text{ cm}$). Subsamples of 55 individuals were taken when a large number of bycatch for a given species was caught. Length-weight relationships for capelin (Hurtubise 1993) and Greenland halibut (Bowering and Stansbury 1984) were used to estimate the weight per tow. Miscellaneous bycatch species captured infrequently and in low abundance were only counted and weighed.

Similar to He et al. (2014), non-parametric paired randomization tests (Manly 2007) were used in the current study to statistically compare catch rates of Northern shrimp and bycatch between the control and experimental trawls. The proportion of catch at each length class for shrimp and major bycatch species from the control and experimental trawls was analyzed using the Generalized Linear Mixed Models (GLMM) with carapace length (shrimp) or fish length (bycatch) as the explanatory variable (fixed effect), the catch proportion as the response variable, the individual tow as the random effect, and subsample ratio as an offset, following the technique described in Holst and Revill (2009). The GLMM was implemented using the *glmmPQL* function in the MASS package (Venables and Ripley 2002) of R statistical software (R

Development Core Team 2014), which used a penalized quasi-likelihood approach (Breslow and Clayton 1993).

3. Results

3.1 Trawl geometry

Acoustic data received from the trawl's geometry sensors was frequently interrupted due to vessel noise and sea conditions, yielding useable estimates of door spread (m) for 16 of 40 tows, wingspread (m) for 13 of 40 tows, and headline height (m) for 21 of 40 tows. Results revealed that the experimental (aligned) trawl was slightly more spread than the control trawl. Mean door spread recorded for the experimental trawl ($\bar{X}=57.5\text{m}$, s.d.=1.8) was significantly larger than the mean door spread recorded for the control trawl ($\bar{X}=55.5\text{m}$, s.d.=1.3)($t=-2.49$, $p=0.026$). The corresponding wing spread was also significantly larger in the experimental trawl ($\bar{X}=21.0\text{m}$, s.d.=0.5) compared to the control trawl ($\bar{X}=20.0\text{m}$, s.d.=0.6)($t=-3.31$, $p=0.007$). This increase in the spread of the trawl produced a significantly lower headline height in the experimental trawl ($\bar{X}=4.9\text{m}$, s.d.=0.1) compared the control trawl ($\bar{X}=5.2\text{m}$, s.d.=0.2)($t=2.75$, $p=0.013$).

3.1 Northern shrimp

The experimental trawl caught significantly more shrimp than the control trawl ($10.19 \pm 2.18 \text{ kg min}^{-1}$ vs. $8.28 \pm 2.18 \text{ kg min}^{-1}$; Table 1). The 23% increase in shrimp catch by the experimental trawl was statistically different ($p = 0.001$). Figure 4 illustrates catch rates of Northern shrimp for each pair of tows ($n=20$), with the control trawl plotted on the x-axis and the experimental trawl plotted on the y-axis. The points above the 1:1 line (dashed) indicate that the experimental trawl caught more shrimp than the control trawl (i.e., the experimental trawl outperformed the control

trawl in 17 out of 20 pairs). The size of shrimp caught by the control and experimental trawls was not statistically different (257.14 ± 15.02 vs. 256.92 ± 10.93 count kg^{-1} count kg^{-1} ; Table 1). GLMM length analysis indicated that there was no size-based selectivity for Northern shrimp between the control and experimental trawls (Fig. 5).

3.2 Bycatch

Total bycatch of non-targeted species was very low, accounting for 1.59% and 1.54% of the total catch weight on average for both the control and experimental trawls, respectively. The dominant bycatch species were capelin and Greenland halibut. Together these two species comprised of 93.2% and 92.9% of the total number of individuals captured incidentally by the control and experimental trawls, respectively (see Table 2). Rather unexpectedly, the experimental trawl caught significantly more capelin (0.05 kg min^{-1}) than the control trawl (0.03 kg min^{-1}) ($p=0.025$) as well as significantly more Greenland halibut (0.05 kg min^{-1}) than the control trawl (0.03 kg min^{-1}) ($p=0.008$) (Table 1). Figures 6 and 7 illustrate the length frequency distributions observed for capelin the Greenland halibut using both trawls. Also shown is the modelled proportion for each body length. The lack of slope or curvature (lower figures) indicates there was no size-dependent selectivity for the fish lengths captured.

Minor bycatch species captured, which accounted less than 7% of the total bycatch, listed from most to least abundant include; Atlantic herring, American plaice, redfish, sandlance, lanternfish, witch flounder, eelpout, alligator fish, snakeblenny, mud star, and sea pen (see Table 2 for scientific names and percent occurrence). The overall amount of minor bycatch (miscellaneous species) was not statistically different between trawl types ($p = 0.378$) (Table 1).

4. Discussion

Results from the sea trials demonstrated that the experimental trawl captured significantly more shrimp than the control trawl (+23%). It also captured significantly more capelin and Greenland halibut than the control trawl, without affecting the fish sizes captured. We speculate that the increased vulnerability to capture by these species may have been attributed to the slightly larger wingspread observed in the experimental trawl. This increase in wingspread was unexpected as it was not observed in during flume tank trials. Although not empirically measured *in situ*, the authors speculate that reduced friction of the aligned footgear with the seabed may have reduced the total overall drag of the trawling system, allowing the doors and wings of the experimental trawl to open slightly more than the control trawl. An alternate explanation for the increased catch rates may be that the height of fishingline of the trawls was different. To minimize bycatch of benthic species, vessels in Shrimp Fishing Areas (SFA) 6 and 7 must configure their trawls with toggle chains set to a minimum length of 71.12 cm (H. DeLouche, personal communication). Although the toggle chain lengths of the experimental and control trawls were the same in this study, their design was slightly different. The control trawl was equipped with a typical travel chain whereas the experimental trawl used a series of toggles bored directly into the footgear discs (see Fig. 2ab). Although not observed in the flume tank, the toggle chain design of the aligned trawl combined with the orientation of the rubber disc in the wings (sled-like contoured face with the direction of tow) may have increased the tendency of the footgear discs to roll forward, causing the toggle chains to shorten and thereby bringing the fishingline closer to the seabed. If this had occurred, the vulnerability of shrimp would have increased as their densities are generally higher closer to the seabed (DeLouche et al. 2006) and the

vulnerability of capelin and Greenland halibut would have increased as a result of reduced escape opportunities beneath the fishingline (Winger et al. 2010). To investigate this hypothesis, we recommend that commercial tows should be conducted with the aligned footgear using underwater cameras to document the behaviour of the toggle chains as well as the use of geometry sensors attached to the fishingline to accurately document height off the seabed.

Notwithstanding above, the observed bycatch of fish in this study was very low. The size of Greenland halibut caught in both trawls (6-32 cm) were below the legal limit of 44 cm (DFO 2010). These fish are considered 1-2 year old recruits. We estimate that Greenland halibut comprised 0.49% of the total catch for the experimental trawl and 0.36% for the control trawl. These values are well below the 1-7% reported by Fishery Observers for the Gulf of St. Lawrence region (DFO 2010). The cause of the low catches demonstrated in this study is unknown, however it may be a product of local juvenile abundance which may have been low in the study area.

Results from our flume tank testing revealed that the experimental trawl had a substantial reduction (61%) in the predicted contact area with the seabed. While the predictive reliability of scaled engineering models in flume tanks can be quite good (Nguyen et al. 2015a), the authors recognize that no actual field monitoring was conducted *in situ* to document the contact area of the control or experimental trawls with the seabed. It is conceivable for example, that the increase in observed door spread (+4%) and wing spread (+5%) in the experimental trawl may have affected the alignment of the discs in the wing sections of the trawl, although in the authors opinion, this would have had negligible effect on the degree of seabed contact. Nevertheless, we

recommend caution in interpreting these results and encourage future research to verify the performance of the experimental trawl and its interaction with the seabed.

This project joins recent and similar innovations intended to reduce the seabed contact of bottom trawls targeting Northern shrimp in eastern Canada. A study by Nguyen et al. (2015b) developed and evaluated a novel ‘dropchain’ footgear that completely replaced the rubber discs in traditional rockhopper footgear. The authors developed and tested two prototypes: a 9 drop chain and 5-drop chain footgear, reducing predicted contact area with the seabed by 84% and 91%, respectively. Using underwater video, they also demonstrated reduced encounters with snow crab compared to traditional rockhopper footgear. Although the aligned footgear developed in our study did not achieve the same level of reduction in seabed contact (i.e., only 61% reduction), we predict that it is more user-friendly and less likely to experience tear-ups than the drop chain footgear, thus providing a compromise between the need to minimize seabed contact and subsequent encounters with snow crab, and operational functionality.

Rolling discs and bobbins can provide similar conservation objectives as the aligned footgear described in this manuscript. A previous study by Ball et al. (2002) evaluated a *Nephrops* (*Nephrops norvegicus*) trawl equipped with a footgear constructed of 34 swivelled rollers. Flume tank tests revealed a 12% reduction in towing resistance compared to a traditional trawl and subsequent sea trials on the west coast of Ireland demonstrated comparable catch rates for the target species, while at the same time producing a 32 and 66% reduction in benthic invertebrates and debris material, respectively. Zachariassen (2004) developed and tested a footgear constructed of rolling rubber discs (0.22 m wide). Each disc had a steel axle and was

mounted to the trawl with a swivel, allowing independent movement. In a later study, Norwegian and Danish researchers developed rolling bobbins fitted inside special frames so as to align their direction of movement with the towing direction of a trawl (see van Marlen et al. 2010). Underwater camera observations revealed the bobbins functioned properly, although smaller steel bobbins seemed to perform better than larger plastic bobbins. Rolling or not, these studies demonstrate the value of aligning footgear components with the direction of tow. This can be done using swivels or by mounting the footgear components in pre-defined angled orientations. Potential benefits include reduced towing resistance (drag) and reduced seabed contact.

In conclusion, this study developed and evaluated an innovative trawl technology that reduces seabed contact while targeting Northern shrimp. Unlike a traditional bottom trawl, the experimental trawl was equipped with footgear components “aligned” with the direction of tow. Results from the flume tank tests demonstrated that the experimental trawl produced a substantial reduction (i.e., 61%) in the predicted contact area with the seabed compared to the identical trawl equipped with traditional rockhopper footgear. Sea trials revealed that the experimental trawl caught significantly more Northern shrimp (+23%) as well as certain bycatch species, including capelin (+71%) and Greenland halibut (+99%).

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Table Captions

Table 1. Catch comparison of Northern shrimp, major bycatch species and miscellaneous species between the control and experimental trawls. Mean catch rate (kg min^{-1}) and mean shrimp size (count kg^{-1}) for Northern shrimp, mean catch rate (kg min^{-1}) for capelin, Greenland halibut, and miscellaneous species, standard deviation (SD), percent change (% change), and p-value denoted in bold are statistically significant based on paired-sample randomization tests.

Table 2. Bycatch species caught during the shrimp trawl experiment.

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Figure Captions

Figure 1. Schematic netplan of the Vónin 2007-1570 shrimp trawl (panel a), rigged with the experimental aligned footgear (panel b top) and traditional rockhopper footgear (panel b bottom).

Figure 2. Schematic of the estimated percentage of seabed contact of a traditional rockhopper footgear which made 69% of seabed contact (a) and experimental aligned footgear which made only 27% of seabed contact (b). The colour coding of seabed contact is described for different footgear components/sections: Bobbin (Green), Wingtip sections (Black), Wing sections (Blue), Bunt wing sections (Red), and Bosom section (Purple).

Figure 3. The experimental study area in the Northern Gulf of St. Lawrence.

Figure 4. Catch rates of Northern shrimp (*Pandalus borealis*) between the control and experimental trawls. Each black dot demonstrates one pair of tows. The dashed line demonstrates the control and experimental trawls had the same catch rate. Dots above the line demonstrate that the experimental trawl caught more shrimp and *vice versa*.

Figure 5. (a) Pooled length frequency curves and observed proportions (experimental / (experimental + control)) for Northern shrimp (*Pandalus borealis*) in the control and experimental trawls. (b) Generalized linear mixed model (GLMM) modelled proportion of Northern shrimp at carapace length caught in the experimental trawl. The dashed lines at 0.5 indicate equal shrimp catch between the two trawls, whereas a value of 0.75 indicates that 75% of the total shrimp at that carapace length were caught in the experimental trawl and 25% were caught in the control trawl. The shaded areas around the mean curves (bold lines) are the 95% confidence regions. GLMM analysis (b) indicated that there was no difference in catch for shrimp of any size (i.e., no size-based selectivity) between the control and experimental trawls.

Figure 6. (a) Pooled length frequency curves and observed proportions (experimental / (experimental + control)) for capelin (*Mallotus villosus*) in the control and experimental trawls. (b) Generalized linear mixed model (GLMM) modelled proportion of capelin at body length caught in the experimental trawl. The dashed lines at 0.5 indicate equal catch between the two trawls, whereas a value of 0.75 indicates that 75% of the total catch at that body length were caught in the experimental trawl and 25% were caught in the control trawl. The shaded areas around the mean curves (bold lines) are the 95% confidence regions. GLMM analysis (b) indicated that there was no difference in catch for capelin of any size (i.e., no size-based selectivity) between the control and experimental trawls.

Figure 7. (a) Pooled length frequency curves and observed proportions (experimental / (experimental + control)) for Greenland halibut (*Reinhardtius hippoglossoides*) in the control and experimental trawls. (b) Generalized linear mixed model (GLMM) modelled proportion of capelin at body length caught in the experimental trawl. The dashed lines at 0.5 indicate equal catch between the two trawls, whereas a value of 0.75 indicates that 75% of the total catch at that body length were caught in the experimental trawl and 25% were caught in the control trawl. The shaded areas around the mean curves (bold lines) are the 95% confidence regions. GLMM

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Tables

Table 1. Catch comparison of northern shrimp, major bycatch species and miscellaneous species between the control and experimental trawls. Mean catch rate (kg min^{-1}) and mean shrimp size (count kg^{-1}) for Northern shrimp, mean catch rate (kg min^{-1}) for capelin, Greenland halibut, and miscellaneous species, standard deviation (SD), percent change (% change), and p-value denoted in bold are statistically significant based on paired-sample randomization tests.

Pair no.	<u>Northern shrimp</u>				<u>Capelin</u>		<u>Turbot</u>		<u>Miscellaneous</u>	
	Catch rate		shrimp size		Control	Exp.	Control	Exp.	Control	Exp.
	Control	Exp.	Control	Exp.						
1	9.57	7.60	234.30	232.90	0.012	0.033	0.017	0.139	0.083	0.08
2	7.00	7.87	286.70	259.30	0.009	0.019	0.005	0.030	0.083	0.08
3	6.67	7.00	227.80	243.70	0.009	0.024	0.011	0.085	0.000	0.08
4	6.87	9.17	249.80	249.50	0.041	0.076	0.011	0.052	0.083	0.08
5	7.13	10.85	263.40	257.80	0.071	0.031	0.009	0.011	0.083	0.13
6	3.53	10.41	247.60	264.90	0.049	0.039	0.032	0.024	0.083	0.00
7	7.47	10.64	254.30	256.30	0.067	0.071	0.020	0.037	0.083	0.08
8	5.80	8.80	257.00	258.40	0.105	0.358	0.005	0.029	0.100	0.08
9	10.88	9.60	279.00	259.90	0.018	0.130	0.067	0.001	0.067	0.08
10	7.73	10.64	271.80	271.90	0.035	0.035	0.025	0.043	0.083	0.08
11	9.90	11.57	279.80	268.90	0.020	0.013	0.028	0.059	0.083	0.10
12	9.43	12.60	262.10	259.20	0.024	0.041	0.073	0.064	0.100	0.10
13	5.07	7.27	254.00	242.40	0.030	0.031	0.001	0.013	0.000	0.08
14	10.32	12.88	251.20	265.70	0.016	0.017	0.001	0.034	0.083	0.08
15	9.66	9.84	253.40	250.40	0.004	0.003	0.019	0.059	0.083	0.00
16	8.60	10.72	237.50	255.70	0.024	0.025	0.002	0.100	0.000	0.00
17	10.28	8.80	265.40	268.80	0.016	0.008	0.062	0.062	0.073	0.10
18	7.20	10.24	259.40	253.90	0.007	0.015	0.040	0.110	0.073	0.12
19	10.20	14.19	260.00	275.40	0.013	0.026	0.081	0.043	0.083	0.00
20	12.23	13.02	248.30	243.40	0.021	0.017	0.000	0.019	0.073	0.07
Total	165.54	203.71	5142.80	5138.40	0.591	1.012	0.509	1.014	1.399	1.420
Mean	8.28	10.19	257.14	256.92	0.030	0.051	0.025	0.051	0.070	0.071
SD	2.18	2.00	15.02	10.93	0.026	0.078	0.026	0.036	0.031	0.039
% diff	23.1		-0.1		71.4		99.2		1.5	
p-value	0.001		0.459		0.025		0.008		0.378	

Table 2. Bycatch species caught during the shrimp trawl experiment.

Group	Species	Scientific name	% of bycatch by counts	
			Control	Experimental
Major	capelin	<i>Mallotus villosus</i>	78.0	76.4
	Greenland halibut	<i>Reinhardtius hippoglossoides</i>	15.1	16.3
Minor	Atlantic herring	<i>Clupea harengus</i>	2.6	1.7
	American plaice	<i>Hippoglossoides platessoides</i>	1.2	2.1
	redfish	<i>Sebastes spp.</i>	1.3	1.6
	sandlance	<i>Ammodytes spp.</i>	0.8	0.6
	lanternfish	<i>Ceratoscopelus maderensis</i>	0.3	0.3
	witch flounder	<i>Glyptocephalus cynglossus</i>	0.1	0.4
	eelpout	<i>Zoarces spp.</i>	0.3	0.2
	alligator fish	<i>Aspidophoroides monopterygius</i>	0.0	0.1
	snakeblenny	<i>Lumpenus lamprætaeformis</i>	0.1	0.0
	mud star	<i>Ctenodiscus crispatus</i>	0.0	0.1
	sea pen	<i>Pennatulacea spp.</i>	0.1	0.1

Figure 1a. Schematic netplan of the Vónin 2007-1570 shrimp trawl (panel a), rigged with the experimental aligned footgear (panel b top) and traditional rockhopper footgear (panel b bottom).

190x128mm (96 x 96 DPI)

Figure 1. Schematic netplan of the Vónin 2007-1570 shrimp trawl (panel a), rigged with the experimental aligned footgear (panel b top) and traditional rockhopper footgear (panel b bottom).

397x242mm (123 x 109 DPI)

Figure 2. Schematic of the estimated percentage of seabed contact of a traditional rockhopper footgear which made 69% of seabed contact (a) and experimental aligned footgear which made only 27% of seabed contact (b). The colour coding of seabed contact is described for different footgear components/sections: Bobbin (Green), Wingtip sections (Black), Wing sections (Blue), Bunt wing sections (Red), and Bosom section (Purple).

246x182mm (150 x 150 DPI)

Figure 3. The experimental study area in the Northern Gulf of St. Lawrence.

215x279mm (300 x 300 DPI)

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219x158mm (96 x 96 DPI)

Figure 5. (a) Pooled length frequency curves and observed proportions (experimental / (experimental + control)) for Northern shrimp (*Pandalus borealis*) in the control and experimental trawls. (b) Generalized linear mixed model (GLMM) modelled proportion of Northern shrimp at carapace length caught in the experimental trawl. The dashed lines at 0.5 indicate equal shrimp catch between the two trawls, whereas a value of 0.75 indicates that 75% of the total shrimp at that carapace length were caught in the experimental trawl and 25% were caught in the control trawl. The shaded areas around the mean curves (bold lines) are the 95% confidence regions. GLMM analysis (b) indicated that there was no difference in catch for shrimp of any size (i.e., no size-based selectivity) between the control and experimental trawls.

203x189mm (96 x 96 DPI)

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203x188mm (96 x 96 DPI)

Figure 7. (a) Pooled length frequency curves and observed proportions (experimental / (experimental + control)) for Greenland halibut (*Reinhardtius hippoglossoides*) in the control and experimental trawls. (b) Generalized linear mixed model (GLMM) modelled proportion of capelin at body length caught in the experimental trawl. The dashed lines at 0.5 indicate equal catch between the two trawls, whereas a value of 0.75 indicates that 75% of the total catch at that body length were caught in the experimental trawl and 25% were caught in the control trawl. The shaded areas around the mean curves (bold lines) are the 95% confidence regions. GLMM analysis (b) indicated that there was no difference in catch for Greenland halibut of any size (i.e., no size-based selectivity) between the control and experimental trawls.

205x198mm (96 x 96 DPI)