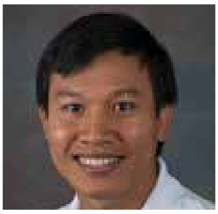
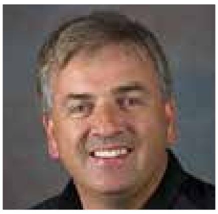
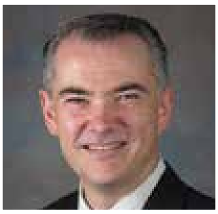


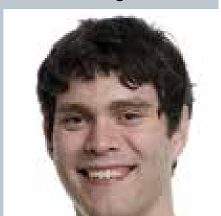
Truong X. Nguyen



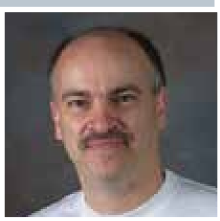
Philip Walsh



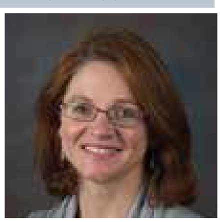
Paul D. Winger



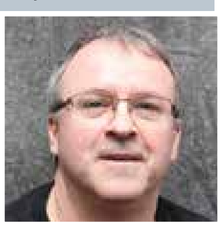
Brett Favaro



George Legge



Kelly Moret



Scott Grant

What a drag

Nguyen, Walsh, Winger, Favaro, Legge, Moret and Grant get ticklish about footgear.

Who should read this paper?

Anyone with an interest in learning how improvements in fishing technology can help reduce environmental impacts and ensure more sustainable fisheries.

Why is it important?

Bottom trawling ("dragging") entails towing a trawl (net) along the sea floor. Variations on this method are widely used to catch demersal or semi-pelagic species. The growing demand for certification of fisheries by eco-labels such as the Marine Stewardship Council are a strong indication that consumers are increasingly concerned with the sustainability of fisheries, particularly those that involve trawling. The challenge for the fishing industry in this regard is two-fold: limiting the amount of by-catch (incidental capture and mortality of non-target species) and reducing the impact of the trawl on the seabed. Improvements in one or both will not only lessen impacts on marine resources and the environment, but will also mitigate the potential for economic losses as a result of consumer boycotts and sanctions by regulatory bodies.

The work outlined here addresses the pros and cons of a modified trawl system for use in the northern shrimp fishery in waters off Newfoundland and Labrador. The study team investigated an alternative design that would reduce bottom contact by the trawl. The modified trawl was tested first in a flume tank, where substantial reductions in contact with the bottom were observed. The study team then conducted experimental fishing trials and demonstrated that the modified trawl system showed good potential for reduced impact on the marine ecosystem, including reduced disturbance of the bottom, and fewer encounters with snow crab – a fishery that overlaps spatially with shrimp in many areas.

Results of this work demonstrate that the modified trawl system yielded comparable amounts of shrimp and by-catch, while at the same time minimizing the likelihood of snow crab mortality when compared to a traditional shrimp trawl. At the present time, the modified trawl system cannot be readily adopted by the fishing industry due to unresolved issues around durability and operational safety. Further work will be required to determine methods to reduce snagging of the modified trawl during deployment and retrieval, as well as potential damage of the trawl while fishing.

About the authors

All of the authors are affiliated with the Centre for Sustainable Aquatic Resources (CSAR), part of the School of Fisheries, located at the Fisheries and Marine Institute, Memorial University. The Centre promotes the sustainable development of aquatic resources through collaborative industrial research and development, technology transfer, and education services to the global fishing industry. Key research themes include 1) fishing gear design and testing, 2) biological resource assessments, 3) fisheries development, 4) fish behaviour, and 5) hydrodynamic testing of marine structures. To learn more, please visit www.mi.mun.ca/csar.

ASSESSING THE EFFECTIVENESS OF DROP CHAIN FOOTGEAR AT REDUCING BOTTOM CONTACT IN THE NEWFOUNDLAND AND LABRADOR SHRIMP TRAWL FISHERY

Truong X. Nguyen[1], Philip Walsh[1], Paul D. Winger[1], Brett Favaro[1, 2], George Legge[1], Kelly Moret[1], and Scott Grant[1]

[1]*Centre for Sustainable Aquatic Resources, Fisheries and Marine Institute, Memorial University of Newfoundland, St. John's, NL, Canada*

[2]*Department of Ocean Sciences, Memorial University of Newfoundland, St. John's, NL, Canada*

ABSTRACT

This study compared the effectiveness of a reduced seabed impact footgear versus a traditional rockhopper footgear on identical bottom trawls targeting northern shrimp (*Pandalus borealis*) in Newfoundland and Labrador, Canada. The experimental trawl used in this study was designed to be low seabed impact through the reduction of contact area of the footgear by replacing traditional heavy rockhopper footgear with only a few drop chains lightly in contact with the seabed (i.e., drop chain footgear). Two variants of the experimental drop chain footgear (9-drop chain and 5-drop chain) were designed, evaluated in a flume tank to estimate contact area with the seabed, and then briefly tested at sea for engineering performance and catchability. Results from the flume tank tests were encouraging, demonstrating that the traditional and experimental trawls were similar in performance, but with the experimental drop chain footgears producing substantial reductions in the predicted contact area with the seabed. Comparative commercial fishing trials were then subsequently made with a total of five pairs of tows (10 tows) for the 9-drop chain and six pairs of tows (12 tows) for the 5-drop chain. Though only briefly tested at sea, the results revealed that the drop chain footgears were promising in both engineering and catch performance. Underwater video observations demonstrated that the drop chain trawling system, with greatly reduced bottom contact on the seabed, could help reduce potential disturbance of marine ecosystems, in particular minimizing encounters with snow crab (*Chionoecetes opilio*).

KEYWORDS

Shrimp trawl; Drop chain footgear; Rockhopper footgear

INTRODUCTION

Concerns over the impact of fishing practices on the ocean environment have been expressed at the local, national, and international scale [Morgan and Chuenpagdee, 2003; Rice, 2006; and Fuller et al., 2008]. The entire global seafood industry is facing public pressure to amend its fishing practices, particularly bottom trawling, in an effort to reduce by-catch and negative impacts on the seabed. Evidence that fishing gears harm benthic organisms, reduce habitat complexity, and reduce biodiversity has appeared in scientific literature [Kaiser et al., 2003; Valdemarsen and Suuronen, 2003; Valdemarsen et al., 2007; He and Winger, 2010; Pham et al., 2014] and popular media with increasing frequency [Gilkinson et al., 2006]. Current consumer trends and the growing demand for certification by eco-labels such as the Marine Stewardship Council indicate that the public is increasingly concerned with the environmental footprint of fisheries, particularly for bottom trawling. While physical alterations of the seabed by bottom trawling and dredging are evident [e.g., Jones, 1992; Løkkeborg, 2005; Rice, 2006; He and Winger, 2010], the effect of the alterations on the benthic organisms and recovery rates associated with gear alterations depend on substrate type, depth, and natural disturbance in the area.

The northern shrimp (*Pandalus borealis*) and snow crab (*Chionoecetes opilio*) fisheries are important contributors to the local economy of the province of Newfoundland and Labrador, Canada [DFA, 2014]. However, snow crab and shrimp fishing grounds are known to overlap considerably from the southern Labrador shelf to the northern Grand Bank, particularly in northern regions such as Northwest Atlantic Fisheries Organization (NAFO) Divisions 3KL [Dawe et al., 2007]. 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 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 (*C. bairdi*) and snow crab (*C. opilio*), respectively. These findings suggest that minimizing potentially negative encounters through the use of trawl modifications is a valuable research agenda as it can promote stock productivity through the reduction of unaccounted fishing mortality.

The primary objective of this study was to examine the effectiveness of a novel footgear for reducing the seabed impacts of shrimp trawls off the east coast of Newfoundland and Labrador, Canada. This footgear, referred to as a drop chain footgear, consists of only a few drop chains in contact with the seafloor. The use of drop chain footgear technology has been previously investigated or adopted in different fisheries in Australia [Ramm et al., 1993; Brewer et al., 1996] and the United States [Hannah and Jones, 2000; Pol, 2003; Sheppard et al., 2004]. In this study we evaluated two experimental footgear designs, the 9-drop

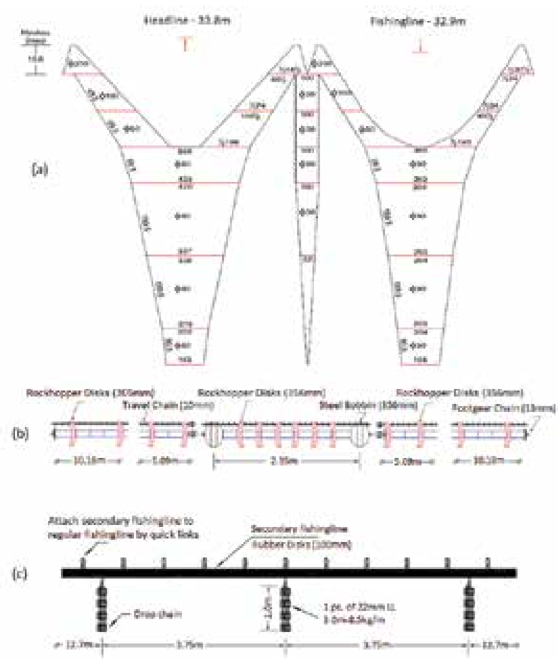


Figure 1: Schematic netplan of the Vónin 2007-1570 shrimp trawl (a), rigged with a traditional rockhopper footgear (b), and experimental drop chain footgear (c).

chain and 5-drop chain, in a flume tank to estimate contact area with the seabed. We also conducted two comparative fishing experiments, evaluating catch rates of target and non-target species, trawl geometry, fuel consumption, and trawling resistance (i.e., warp tension) to determine the differences between the traditional and experimental trawls (i.e., rockhopper vs. drop chain).

MATERIALS AND METHODS

Fishing Gear

In the current study, the trawl design used for the traditional (control) and experimental trawls was the 4-seam, Vónin 2007-1570 shrimp trawl with 33.8 m headline and 32.9 m fishing line (Figure 1a). The traditional and experimental trawls were identical in every way, except for modifications to the footgear and four fewer floats on the fishing line of the experimental trawl. The traditional trawl was rigged with a 32.9 m rockhopper footgear commonly used throughout the fishing fleet. The rockhopper footgear, with a weight of 354 kg, is constructed from different components including wires, travel chains, spacers, bobbins, and rubber discs/wheels. This consisted of 28 rockhopper disks with a diameter of 356 mm, 38 disks with a diameter of 305 mm, and two 356 mm diameter steel bobbins linked together by a 13 mm long-link footgear chain, a 10 mm long-link travel chain, and a 10 mm long-link weight chain (Figure 1b). Flotation was provided using 203 mm trawl floats, with 100 floats on the headline, 18 floats on the fishing line, and five floats on each of the upper selvedges. The trawls were constructed with 25-100 mm mesh and were equipped with two 5.0 m^2 Injector Scorpion steel trawl doors (1,350 kg each) made by Injector Door Limited™ and high-density polyethylene Nordmøre grids.

We tested two experimental footgear designs: the 9-drop chain and 5-drop chain. Both drop chain footgear arrangements were devoid of all rockhopper components and consisted of nine or five drop chains spaced from wing to wing. Each chain was 1.0 m in length, 25.6 kg in weight, and was constructed of 22 mm long-link steel chain (Figure 1c). The total footgear weight of the 9-drop chain and 5-drop chain was 334 and 223 kg, respectively. This weight included the weight of a secondary fishing line which was a combination of chains, spacers, and 100 mm diameter of rubber disks and attached directly to the original fishing line by quick links (Figure 1c).

Scaled engineering models (1:8) of both the traditional and experimental trawls were constructed and evaluated using a flume tank

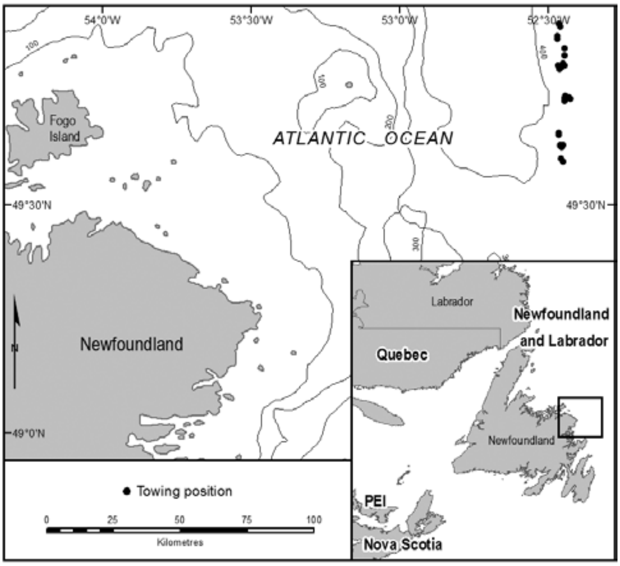


Figure 2: The experimental study area in NAFO Division 3K (SFA6) on the northeast coast of Newfoundland, Canada. Black box denotes the towing area.

[Winger et al., 2006]. The percentage of contact area with the seabed was estimated visually by filming the models while under test in the flume tank.

Comparative Fishing Experiments

Prior to sea trials, we followed the quality-control protocol outlined in DFO [1998] to ensure the trawl nets did not differ in size or shape, with the exception of the footgear (i.e., rockhopper vs. drop chain). The comparative fishing experiments were conducted aboard the F/V *Nautical Legend*, a 20 m commercial trawler, from July 25 to August 1, 2014. Fishing experiments were conducted on the northeast coast (i.e., NAFO Division 3K) of Newfoundland, Canada, with average water depths ranging from 357-390 m (Figure 2).

Prior to the comparative fishing experiments, we conducted engineering trials with an opened cod-end. This was to verify that all instrumentation and equipment used to monitor trawl performance, geometry, resistance, and footgear rigging were functioning properly. We conducted two separate fishing experiments. Experiment 1 consisted of a comparison of the traditional footgear trawl against the experimental 9-drop chain footgear trawl. A total of 10 tows (five pairs) was successfully carried out and included in the analysis. Experiment 2 consisted of a comparison of the traditional footgear trawl against the experimental 5-drop chain footgear trawl. A total of 12 tows (six pairs) was successfully carried out and included in the analysis. The alternate tow method [DFO, 1998] was used to compare catches among paired tows. Paired tows were fished in the same direction to minimize variation in environmental conditions. The warp length was appropriately adjusted for the experimental 5-drop chain footgear trawl to maintain a stable footgear contact with the bottom. Towing speed was approximately 2.3 knots and towing order followed the ABBA-BAAB protocol [DeAlteris and Castro, 1991]. (Editor's Note: ABBA-BAAB protocol is a comparative study by which a control net and experimental net are fished and compared using an alternating, paired methodology. In this case, A = control/traditional net; B = experimental gear.) Tow duration varied between one and two hours.

Data Collection and Analysis

Trawl monitoring equipment, including a combination of E-Sonar™ and Netmind™ technology, was used to record measurements of trawl net geometry during sea trials. Trawl geometry parameters measured included door spread (m), wing spread (m), and headline height (m). Hand-held tension meters (i.e., VTM 502 10K developed by Cooper Instruments & Systems) were installed on the warps aft of the winches to measure warp tension (kilogram-force, kgf) for both trawl types. Vessel fuel consumption (L h^{-1}) was also documented for each tow using the vessel's fuel meter located on the bridge. Differences in engineering trawl performance (i.e., trawl geometry, resistance/warp tension) and fuel consumption between the traditional rockhopper and experimental drop chain footgear trawls were compared using paired *t*-tests.

The number of bags of shrimp captured from each tow, with an average weight of 13.6 kg per bag, was recorded. These data were used to compare the differences in catch rates of shrimp (kg min^{-1}) caught by the traditional and experimental footgear trawls using paired *t*-tests. Power analysis was performed to determine the statistical power and the extent to which the proposed sample size (number of paired tow comparisons for our future experiments) would be adequate to detect the differences in the catch rates of shrimp between the experimental and traditional trawls. We based our power calculations on the assumption of power level (0.95), significant level (0.05), and the population effect size as obtained in the current study. Sub-samples of shrimp were also taken back to the laboratory to estimate the number of individuals per kg (an assessment of average body size).

For each tow, the number and cumulative weight of each major fish species with at least 2.5% of total catch captured incidentally (by-catch) were recorded and individual body lengths were obtained. Miscellaneous by-catch species captured infrequently and in low abundance were only counted and weighed. Differences in catch rates (numbers per hour, N h^{-1}) of major by-catch species between the traditional and experimental footgear trawls were analyzed using paired *t*-tests. The proportion of catch at each length class for major by-catch species from the control and experimental trawls was analyzed using the Generalized Linear Mixed Models (GLMM) with fish length as the explanatory variable (fixed effect) and individual tow as the random effect, following the technique described by Holst and Revill [2009]. Underwater video footage was recorded during the experiments using a low-light TrawlCamera manufactured by JT Electric. The camera was attached to the fishing line of the trawl in the manner similar to Nguyen et al. [2014]. The video footage was used to determine the performance of the drop chain footgear relative to the seabed and its herding effects on shrimp and by-catch species; in particular, the interaction or encounter of snow crab with the drop chains.

All of the statistical procedures regarding paired *t*-tests were performed using the IBM SPSS Statistics software package. 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]. Statistical power analyses were conducted using G*Power 3.1 [Faul et al., 2009]. Analysis of the video footage was conducted using AVS video editor software on a high definition monitor.

RESULTS

Flume Tank Tests

Results from the flume tank testing demonstrated that the traditional and

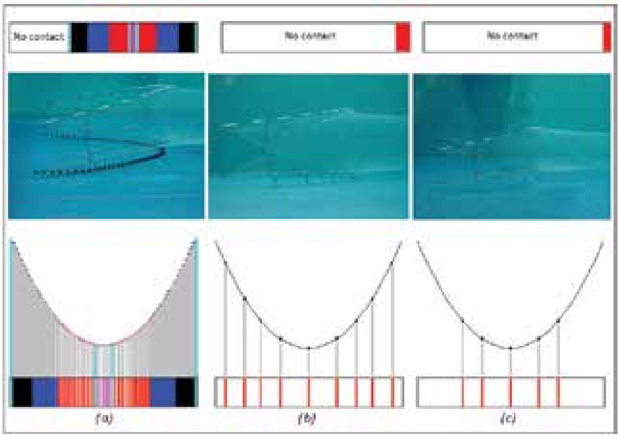


Figure 3: Schematic of the estimated percentage of seabed contact for a traditional rockhopper footgear (a), experimental 9-drop chain footgear (b), and experimental 5-drop chain footgear (c). The colour coding of seabed contact is described for different footgear components/sections. For traditional footgear which made 69% of seabed contact: Bobbin (Green), Wingtip sections (Black), Wing sections (Blue), Bunt wing sections (Red), Bosom section (Purple). For experimental footgears which made only 11% (9-drop chain) and 6% (5-drop chain) of seabed contact: Drop chains (Red).

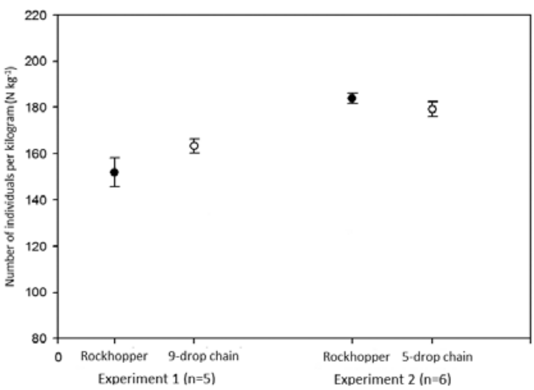


Figure 4: Number of individuals per kilogram (N kg^{-1}) for northern shrimp caught by the traditional rockhopper and experimental drop chain footgear trawls. Error bars represent ± 1 S.E.

experimental trawls were similar in net geometry and performance, but the experimental drop chain footgear trawls had substantial reductions in contact area with the seabed, as expected. The footgear (rockhopper) of the traditional trawl consisted of 68 contact points with the seabed (Figure 3a). This produced a footprint that made contact with 69% of the seabed in the path of the trawl. The experimental footgear (9-drop chain and 5-drop chain) (Figures 3b and c) produced footprints that made contact with only 11% and 6%, respectively, of the seabed in the path of the trawl.

Engineering Trawl Performance

Mean door spread, wing spread, and headline height recorded in Experiment 1 were significantly different between the experimental trawl (9-drop chain footgear) and the traditional rockhopper footgear trawl, but the differences were generally less than 10% (Table 1). Whereas, the warp tension (kgf) and fuel consumption (L h^{-1}) were not significantly different between the trawl types (Table 1). In Experiment 2, mean door spread of the experimental trawl with 5-drop chains was on average 4% higher than that recorded for the traditional footgear trawl and this difference was statistically significant (Table 1). Mean wing spread, headline height, warp tension and fuel consumption were not significantly different between the experimental and traditional footgear trawls in Experiment 2 (Table 1).

We observed some unexpected technical challenges during fishing operations for the experimental footgear trawls. On two occasions the trawl net body of the experimental 9-drop chain trawl was damaged resulting in significant tears in the netting of the first and second side panels. Repairs were completed at sea and fishing operations were resumed. An operational issue regarding the drop chains causing tangles during the trawl shooting away or hauling back was also noticed.

	Pair	Door spread		Wing spread		Headline height		Warp tension		Fuel consumption	
		Control	D. chain	Control	D. chain	Control	D. chain	Control	D. chain	Control	D. chain
EXPERIMENT 1	1	58.47	58.43	19.16	21.54	5.04	4.7	6945	6793	64.75	67.25
	2	59.52	61.19	19.45	20.87	5.02	4.38	6713	6733	67.13	69.50
	3	59.71	61.97	19.48	NA	5.32	4.68	5888	6368	54.38	58.63
	4	58.53	62.28	19.74	21.85	4.87	NA	6293	5861	67.75	64.25
	5	58.68	60.75	19.09	21.05	4.79	NA	6491	6663	65.62	65.00
	Mean	58.98	60.92	19.36	21.33	5.10	4.59	6466.00	6483.60	63.92	64.93
	SE	0.3	0.7	0.1	0.2	0.1	0.1	180.9	171.9	2.4	1.8
	% change	+3.3		+10.0		-8.4		-0.3		+1.6	
	df	4		3		2		4		4	
	t-statistic	-3.195		-9.734		5.4		-0.115		-0.730	
	p-value	**0.033**		**0.002**		**0.033**		0.914		0.506	
EXPERIMENT 2	6	60.61	62.77	NA	21.63	5.16	NA	5790	5885	58.00	56.75
	7	60.38	62.9	19.46	21.06	5.13	4.63	5960	5800	56.75	58.00
	8	60.91	63.7	19.48	21.75	5.21	5.06	5580	5450	53.75	50.50
	9	63.48	65.97	20.37	23.25	5.13	NA	5735	5900	52.25	53.25
	10	60.84	63.55	20.06	NA	NA	NA	6185	6085	63.50	65.25
	11	61.61	64.72	19.96	22.61	NA	NA	6245	6030	55.75	55.00
	Mean	61.3	63.93	19.81	22.16	5.17	4.84	5915.83	5858.33	56.67	56.46
	SE	0.5	0.5	0.2	0.5	0.0	0.2	107.1	91.9	1.6	2.1
	% change	+4.3		+11.9		-6.4		-1.0		-0.4	
	df	5		3		1		5		5	
	t-statistic	-20.073		-8.397		1.857		0.928		0.269	
	p-value	**0.000**		**0.004**		0.314		0.396		0.799	

Note: NA means the data were not available as the sensors did not function. Experiment 1 and Experiment 2 represent a comparison of the traditional rockhopper footgear trawl against the experimental 9-drop chain and 5-drop chain footgear trawl, respectively.

Table 1: Tow-by-tow comparison of trawl geometry, trawling resistance, and fuel consumption. Mean in metre (m) for door spread, wing spread and headline height, kilogram force for warp tension (kgf) and litre per hour (Lh^{-1}) for fuel consumption, standard error of the mean (SE), percent change (% change), degrees of freedom (df), *t*-statistic, and *p*-value denoted in bold are statistically significant based on an alpha of 0.05.

Catch Comparison Results

Shrimp catch

In Experiment 1, there was no difference in the mean catch rate for shrimp between the traditional footgear trawl and experimental 9 drop-chain trawl (*t*-statistic=0.646, df=4, *p*=0.553) (Table 2). However, the statistical power to detect this effect was low (0.25) (Table A1 in Appendix) given low number of paired tow comparisons and the highly variable shrimp catch rates observed for the 9-drop chain footgear. For Experiment 2, mean shrimp catch rates decreased approximately 52% from the traditional footgear trawl (6.84 kg min^{-1}) to the experimental 5-drop chain footgear trawl (3.29 kg min^{-1}), and this difference was statistically significant (*t*-statistic=5.162, df=5, *p*=0.004) (Table 2).

In both experiments, there were no differences in the size of shrimp caught between the traditional and experimental trawls. In Experiment 1, the mean ($\pm$ 1 S.E.) number of shrimp per kilogram was 151.9 $\pm$ 6.27 individuals kg^{-1} in the traditional trawl, and 163.3 $\pm$ 3.10 individuals kg^{-1} in the experimental trawl (*t*-statistic=1.497, df=21,

	Pair	Northern shrimp		Turbot		Atlantic cod		American plaice		Miscellaneous	
		Control	D. chain	Control	D. chain	Control	D. chain	Control	D. chain	Control	D. chain
EXPERIMENT 1	1	3.29	10.09	85	272	34	1	50	0	60	9
	2	7.03	5.67	143	585	29	24	46	9	23	25
	3	3.74	1.36	246	65	29	77	5	74	16	59
	4	9.53	7.14	838	472	23	27	9	34	33	29
	5	11.11	2.49	1195	1381	50	27	7	3	55	39
	Mean	6.94	5.35	501.40	555.00	33.00	31.20	23.40	24.00	37.40	32.20
	SE	1.5	1.6	219.3	224.8	4.6	12.4	10.1	13.9	8.7	8.3
	% change	-22.9		+10.7		-5.5		+2.6		-13.9	
	df	4		4		4		4		4	
	t-statistic	0.646		-0.371		0.128		-0.028		0.343	
	p-value	0.553		0.729		0.904		0.979		0.749	
EXPERIMENT 2	6	6.58	2.72	773	445	23	12	17	3	14	32
	7	5.44	1.59	786	664	21	5	5	0	19	22
	8	7.03	1.81	473	481	16	6	6	2	19	8
	9	7.03	3.86	209	129	19	5	4	5	5	3
	10	5.44	4.99	0	20	330	93	24	11	20	5
	11	9.53	4.76	162	34	30	8	25	4	7	19
	Mean	6.84	3.29	393.83	297.17	73.17	21.50	13.50	4.17	14.00	14.83
	SE	0.6	0.6	131.4	110.7	51.4	14.3	4.0	1.5	2.7	4.6
	% change	-51.9		-24.5		-70.6		-69.1		+6.0	
	df	5		5		5		5		5	
	t-statistic	5.162		2.173		1.392		2.834		-0.159	
	p-value	**0.004**		0.082		0.223		**0.036**		0.88	

Note: Experiment 1 and Experiment 2 represent a comparison of the traditional rockhopper footgear trawl against the experimental 9-drop chain and 5-drop chain footgear trawl, respectively.

Table 2: Tow-by-tow comparison of northern shrimp, major by-catch species, and miscellaneous species. Total catch mean in kilogram per minute (kg min^{-1}) for northern shrimp, number of individuals per hour (Nh^{-1}) for turbot, Atlantic cod, American plaice, and miscellaneous species, standard error of the mean (SE), percent change (% change), degrees of freedom (df), *t*-statistic, and *p*-value denoted in bold are statistically significant based on an alpha of 0.05.

Species group	Species included	Scientific name	% of total by-catch, by counts
Major by-catch species	Turbot	*Reinhardtius hippoglossoides*	82.0-87.0
	Atlantic cod	*Gadus morhua*	5.0-10.0
	American plaice	*Hippoglossoides platessoides*	2.5-4.0
Miscellaneous species	Redfish	*Sebastes fasciatus*	0.3-0.5
	Capelin	*Mallotus villosus*	0.5-0.7
	Sandlance	*Ammodytes spp.*	1.3-1.7
	Eelpout	*Zoarces spp.*	0.5-0.7
	Sculpin	*Myoxocephalus octodecimspinosus*	0.4-0.6
	Grey sole	*Glyptocephalus cynoglossus*	0.1-0.2
	Alligator fish	*Aspidophoroides monopterygius*	0.1-0.3
	Snow crab	*Chionoecetes opilio*	0.1-0.2
	Wolf fish	*Anarhichas denticulatus*	0.1-0.4
	Skate	*family Rajidae*	0.2-0.4

Table 3: Catch composition of non-target species caught by the traditional and experimental footgear trawls.

	Species	Model	Parameter	Estimate	SE	df	*t*-value	*p*-value
EXPERIMENT 1	Turbot	Constant	β_0	0.163	0.468	73	0.348	0.728
	Atlantic cod	Constant	β_0	62.545	32.063	22	1.950	0.063
	American plaice	Constant	β_0	11.288	6.559	9	1.721	0.119
EXPERIMENT 2	Turbot	Cubic	β_0	-9.524	3.718	69	-2.562	**0.012**
			β_1	1.602	0.667	69	2.215	**0.019**
			β_2	-0.089	0.039	69	-2.090	**0.024**
			β_3	0.001	0.000	69	1.923	**0.035**
	Atlantic cod	Cubic	β_0	41.743	14.551	20	2.869	**0.009**
			β_1	-8.689	3.210	20	-2.706	**0.013**
			β_2	0.568	0.231	20	2.460	**0.023**
			β_3	-0.012	0.005	20	-2.228	**0.037**
	American plaice	Quadratic	β_0	43.944	10.682	6	4.113	**0.006**
			β_1	-4.451	1.074	6	-4.143	**0.006**
			β_2	0.110	0.026	6	4.115	**0.006**

Note: Experiment 1 and Experiment 2 represent a comparison of the traditional rockhopper footgear trawl against the experimental 9-drop chain and 5-drop chain footgear trawl, respectively. The analyses were preceded by fitting the highest order polynomials (third) followed by subsequent reductions until all terms showed significance (p < 0.05), based on Wald's test, with removal of one term at each step to determine the best-fit model [Holst and Revill, 2009].

Table 4: Generalized linear mixed model parameters for: turbot, Atlantic cod, and American plaice; where model and parameter are the chosen model (either constant, linear, quadratic, or cubic), estimate is the value of the slope or intercept, SE is the standard error of the mean, df is the degrees of freedom, *t*-statistic, and *p*-value denoted in bold are statistically significant based on an alpha of 0.05.

p=0.149). In Experiment 2, the numbers of shrimp per kilogram were: 183.9 ± 2.12 individuals kg^{-1} in the traditional trawl, and 179.2 ± 3.34 individuals kg^{-1} in the experimental trawl (*t*-statistic=-1.099, df=32, *p*=0.280) (Figure 4).

By-catch

The predominant by-catch species caught by the traditional and experimental footgear trawls was turbot (*Reinhardtius hippoglossoides*), comprising 82.1% and 87.1% of the total by-catch on average by count, respectively (Table 3). Atlantic cod (*Gadus morhua*) and American plaice (*Hippoglossoides platessoides*) were also frequently caught by both the experimental and traditional trawls. These species accounted for 10.1% and 3.6% of the total by-catch on average respectively for the traditional

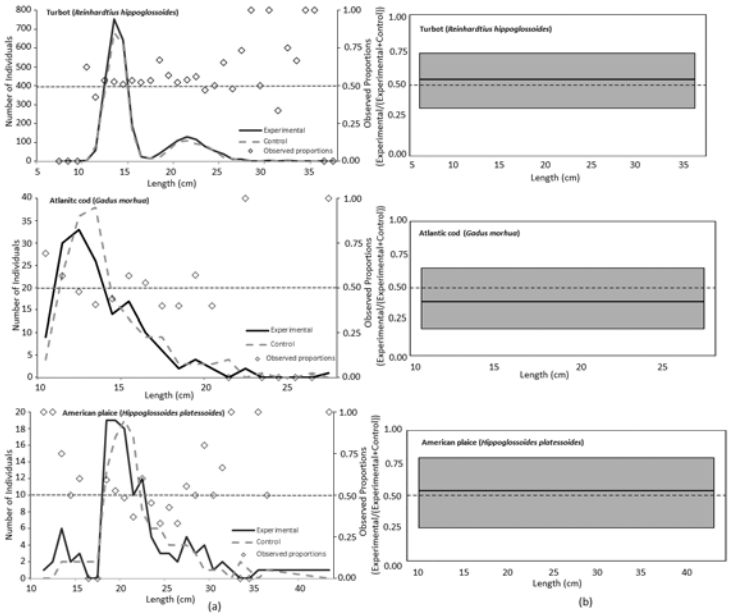


Figure 5: Experiment 1 – Pooled length frequency and observed proportions (experimental / (experimental + control)) of the total catches caught in the experimental 9-drop chain footgear trawl (a). Generalized linear mixed model (GLMM) modelled proportion of the total catches caught in the experimental 9-drop chain footgear trawl. Interpretation: a value of 0.5 indicates an even split between the two trawls, whereas a value of 0.25 indicates that 25% of the total fish at that length were caught in the drop chain footgear trawl and 75% were caught in the traditional rockhopper footgear trawl. The shaded areas around the mean curves (bold lines) are the 95% confidence regions (b).

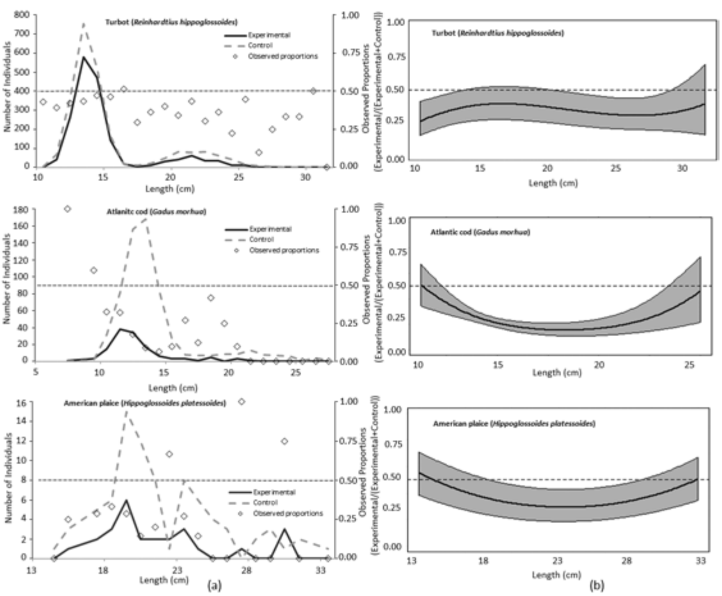


Figure 6: Experiment 2 – Pooled length frequency and observed proportions (experimental / (experimental + control)) of the total catches caught in the experimental 5-drop chain footgear trawl (a). Generalized linear mixed model (GLMM) modelled proportion of the total catches caught in the experimental 5-drop chain footgear trawl. Interpretation: a value of 0.5 indicates an even split between the two trawls, whereas a value of 0.25 indicates that 25% of the total fish at that length were caught in the drop chain footgear trawl and 75% were caught in the traditional rockhopper footgear trawl. The shaded areas around the mean curves (bold lines) are the 95% confidence regions (b).

footgear trawl, 4.8% and 3.9% respectively for the experimental 9-drop chain footgear trawl, and 6.4% and 2.6% respectively for the experimental 5-drop chain footgear trawl (Table 3). In Experiment 1, differences in the mean catch rates (numbers per hour) of major by-catch species were generally less than 10% between the traditional footgear trawl and experimental 9-drop chain footgear trawl and these differences were not statistically significant (Table 2). The observed proportions at length of the total catches of each of the major by-catch species in the experimental 9-drop chain footgear trawl were found to be independent of fish length, owing to the fact that length was not a significant factor in the curve fitting of the GLMM procedure (Table 4, Figure 5). In Experiment 2, the experimental 5-drop chain footgear trawl had statistically lower by-catch catch rates for American plaice (69.1%) compared to the traditional trawl rigged with rockhopper footgear (t-statistic=2.834, df=5, p=0.036). The experimental 5-drop chain footgear trawl produced a lower average catch of cod (22 vs. 73) and turbot (297 vs. 394) but neither difference was statistically significant (cod: t-statistic=1.392, df=5, p=0.223; turbot: t-statistic=2.039, df=5, p=0.097) (Table 2). The results from the GLMM analyses showed that the experimental trawl (5 drop-chain footgear) was less efficient in catching turbot, Atlantic cod, and American plaice (Table 4 and Figure 6). The relative efficiency of the experimental trawl was approximately 0.10 to 0.50, depending on fish length. For Atlantic cod and American plaice, the shape of the curve (i.e., bowl shaped) indicates that the experimental trawl was less efficient at catching fish in the middle of the size distribution but was nearly equal to the traditional trawl for fish at the ends of the distribution (i.e., very small and very large fish).

Figure 7: Images from an underwater video camera attached to the fishing line of the experimental-9 drop chain footgear trawl. Images show shrimp (a), turbot (b), and snow crab (c) in response to the approaching drop chain footgear.

Miscellaneous by-catch species captured infrequently by the traditional and experimental footgear trawls accounted for approximately 4.6% of the total by-catch (Table 3). Differences in overall mean catch rates of miscellaneous species were not statistically significant (Table 2).

Underwater observations

A total of 125 minutes of underwater video was recorded on the experimental 9-drop chain footgear in Experiment 1, but only 60 minutes of video was usable for analysis; the rest was too cloudy or the trawl was not on bottom. Video observations revealed the drop chain, which was attached directly to the secondary fishing line at the centre of the footgear, was in stable contact with the seabed. Shrimp, snow crab, American plaice, and turbot were observed distributed near or on the seabed (Figure 7). A total of 64 crabs were observed. In all cases, snow crab easily passed under the fishing line of the experimental trawl and out of the path of capture (see video in Appendix). The majority (92%) of the crabs observed had no direct encounters (i.e., collisions) with the drop chain (i.e., went under fishing line and between the drop chains). The remaining 8% came into contact with the chain.

DISCUSSION

Results from our flume tank testing and comparative fishing experiments demonstrated the promising engineering features of drop chain footgears. Compared to the traditional bottom trawl equipped with rockhopper footgear, we found that experimental trawls equipped with drop chain footgears had substantial reductions in the predicted contact area with the seabed and only minor differences in trawl geometry and resistance.

One of our interesting findings is that both of the experimental footgear trawls had greater mean door spread and wing spread compared to the traditional trawl. With this additional spread came a corresponding reduction in headline height, which is known to have an inverse linear relationship with door spread and wing spread [Godø and Engås, 1989]. Such trawl geometry differences were unexpected results as the trawls were the same design, with the exception of the footgear components (drop chain vs. rockhopper). In addition, the flume tank testing did not provide evidence for large differences in trawl geometry. Previous authors have discussed that increased horizontal opening should result in increased catch rate of shrimp [SINTEF, 2004; Munden et al., 2013]; however, this effect was not observed in this study. Functional explanations for why the drop chain trawls experienced greater spread during sea trials are speculative at this point. We hypothesize that the removal of the large rockhopper footgear may have reduced friction with the seabed, which reduced the inward pull on the doors and wings, allowing them to spread to a greater extent.

Our results revealed that the catch rate for shrimp by the experimental 9-drop chain footgear trawl used in Experiment 1 was not significantly different from the catch rates of the traditional rockhopper footgear trawl, despite a mean difference of 23%. This non-significant finding may be explained by the highly variable shrimp catch rates observed at sea together with the low number of paired tows, which led to the low statistical power necessary for detecting a difference. Therefore, further commercial fishing trials are recommended to provide sufficient paired tows (30-40 paired comparisons, see Table A1 in Appendix) for demonstrating whether the real-world differences in shrimp catch rates between experimental and traditional trawls are statistically different.

Our underwater video observations revealed that shrimp and by-catch species were distributed near the seabed, providing easy opportunity for escape underneath the fishing line and between the drop chains (see video in Appendix). While this study did not measure the height of the fishing line off the seabed under fishing conditions, previous studies have shown that this parameter can significantly affect the overall catchability of shrimp and by-catch species [Beardsley, 1973; Hannah and Jones, 2003; He et al., 2006; Hannah et al., 2011; Hannah and Jones, 2013]. Given the reduced catch rates of shrimp and by-catch observed in Experiment 2, we hypothesize that reducing the number of chains caused the trawl to operate further from the seabed.

Developing and ultimately implementing footgears with reduced bottom contact remains a desirable goal for stakeholders. One of the primary concerns raised by the fishing industry is their contention that shrimp trawling represents an important source of unaccounted mortality, negatively affecting the snow crab population and habitat (Monty Way, Unifor-FFAW, personal communication). In a previous study we found about 54% of the crabs observed experienced an encounter with the rockhopper (either disks or spacer/chain) [see Nguyen et al., 2014]. By contrast, our trawl-mounted video camera observations in this study demonstrated that, at least around a single drop chain, only 8% of the crabs observed were found to experience an encounter with the drop chain. This suggests that the likelihood of snow crab mortality in relation with drop chains is expected to be low or minimized. Admittedly, these video observations were focused only on the centre of the footgear (one drop chain was in the field of view) thus limiting our ability to evaluate interactions in other regions of the trawl.

Assessing any fishing gear requires that researchers study the impact of the gear on target and non-target species, as well as the practicality of the gear for use in a fishery. While our study focused on the former, we did identify several pathways for further improvement of this gear. First, the drop-chain-equipped trawl net experienced two tear-ups over the course of the study. It is unclear whether these tear-ups were due to the footgear or chance alone. The application of drop chain footgear to reduce by-catch in the ocean shrimp (*Pandalus jordani*) trawl fishery off the west coast of the United States has been investigated and no tear-ups reported [Hannah and Jones, 2000], suggesting that the drop chain footgear is not fundamentally flawed. Second, operational safety issues may exist as crews grow accustomed to using this gear. Specifically, when shooting the gear and during haulback, the drop chains swing off the drum in a manner that could impact fishers on deck. From a safety point of view, it is likely that vessel crew would require a certain period of time to adjust to or become comfortable with the drop chain operations.

ACKNOWLEDGMENT

This project was funded by the Canadian Centre for Fisheries Innovation, the province of Newfoundland and Labrador, the Fisheries and Marine Institute of Memorial University of Newfoundland, NL Research and Development Corporation, the Canadian Fisheries Research Network, and Vónin Canada Ltd. Special thanks to Lindsay Petten and the crew of the F/V *Nautical Legend* for their kind assistance and hospitality while out at sea. We are grateful to several individuals (Harold DeLouche, Tara Perry, and Craig Hollett) who provided technical assistance during the flume tank evaluations and Shannon M. Bayse who assisted with the GLMM analysis. We also express our sincere gratitude and appreciation to anonymous reviewers and the editor Dawn Roche for their valuable comments and recommendations for the previous manuscript.

t tests - Means: Difference between two dependent means (matched pairs)			
Analysis:	Post hoc: Compute achieved power		
Input:	Tail(s)	=	Two
	Effect size dz	=	0.4554976
	α err prob	=	0.05
	Total sample size	=	10
Output:	Noncentrality parameter δ	=	1.4404099
	Critical t	=	2.2621572
	Df	=	9
	Power (1-β err prob)	**=**	**0.2518603**

t tests - Means: Difference between two dependent means (matched pairs)			
Analysis:	A priori: Compute required sample size		
Input:	Tail(s)	=	Two
	Effect size dz	=	0.4554976
	α err prob	=	0.05
	Power (1-β err prob)	=	0.95
Output:	Noncentrality parameter δ	=	3.6723391
	Critical t	=	1.9977297
	Df	=	64
	Total sample size	**=**	**65**
	Actual power	=	0.9512130

Table A1: Statistical summary of power analysis for shrimp catch in Experiment 1 (9-drop chain footgear vs. rockhopper footgear).

APPENDIX

Video: Video demonstrating snow crab and by-catch in response to the approaching experimental 9-drop chain footgear. This is an engineering clip which was glued together (not a raw video). [To view video, click here]

Table A1: Statistical summary of power analysis for shrimp catch in Experiment 1 (9-drop chain footgear vs. rockhopper footgear).

REFERENCES

Beardsley, A.J. [1973]. *Design and evaluation of a sampler for measuring the near-bottom vertical distribution of pink shrimp* (Pandalus jordani). Fishery Bulletin, Vol. 71, No. 1, pp. 243-253.

Breslow, N.E. and Clayton, D.G. [1993]. *Approximate inference in generalized linear models*. Journal of the American Statistical Association, Vol. 88, No. 421, pp. 9-25.

Brewer, D.; Eayrs, S.; Mounsey, R.; and Wang, Y.G. [1996]. *Assessment of an environmentally friendly, semi-pelagic fish trawl*. Fisheries Research, Vol. 26, Issues 3-4, pp. 225-237. doi:10.1016/0165-7836(95)00433-5.

Dawe, E.G.; Gilkinson, K.D.; Walsh, S.J.; Hickey, W.; Mullowney, D.R.; Orr, D.C.; and Forward, R.N. [2007]. *A study of the effect of trawling in the Newfoundland and Labrador northern shrimp* (Pandalus borealis) *fishery on mortality and damage to snow crab* (Chionoecetes opilio). Canadian Technical Report of Fisheries and Aquatic Sciences, No. 2752, p. 43.

DeAlteris, J.T. and Castro, K. [1991]. *Experimental designs and data analysis methodologies for the evaluation of bottom trawl performance based on catch* *comparisons.* In: Proceedings of the Fisheries Conservation Engineering Workshop, J.T. DeAlteris and M. Grady (Eds.). Rhode Island Sea Grant, Kingston, pp. 60-70.

DFA – Department of Fisheries and Aquaculture [2014]. *Landings and landed value 2013 preliminary*. Government of Newfoundland and Labrador, Canada. Retrieved from: www.fishaq.gov.nl.ca/stats/landings/2013%20-%20Preliminary%20Landings%20and%20Landed%20Value%20Table%20Design.pdf.

DFO – Department of Fisheries and Oceans [1998]. *Protocol for conducting selectivity experiments with trawls: alternate haul*. St. John's, Newfoundland. AQUAPROJECTS Inc.

Faul, F.; Erdfelder, E.; Buchner, A.; and Lang, A.-G. [2009]. *Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses*. Behavior Research Methods, Vol. 41, No. 4, pp. 1149-1160. doi:10.3758/BRM.41.4.1149.

Fuller, S.D.; Picco, C.; Ford, J.; Tsao, C.F.; Morgan, L.E.; Hangaard, D.; and Chuenpagdee, R. [2008]. *How we fish matters: addressing the ecological impacts of Canadian fishing gear*. Ecology Action Centre, Living Oceans Society, and Marine Conservation Biology Institute.

Gilkinson, K.; Dawe, E.; Forward, B.; Hickey, B.; Kulka, D.; and Walsh, S. [2006]. *A review of Newfoundland and Labrador region research on the effects of mobile fishing gear on benthic habitat and communities*. Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Research Document, 2006/055.

Godø, O.R. and Engås, A. [1989]. *Swept area variation with depth and its influence on abundance indices of groundfish from trawl surveys*. Journal of Northwest Atlantic Fishery Science, No. 9, pp. 133-139.

Hammond, C.F.; Conquest, L.L.; and Rose, C.S. [2013]. *Using reflex action mortality predictors (RAMP) to evaluate if trawl gear modifications reduce the unobserved mortality of Tanner crab* (Chionoecetes bairdi) *and snow crab* (C. Opilio). ICES Journal of Marine Science, Vol. 70, No. 7, pp. 1308-1318. doi:10.1093/icesjms/fst085.

Hannah, R.W. and Jones, S.A. [2000]. *By-catch reduction in an ocean shrimp* (Pandalus jordani) *trawl from a simple modification to the trawl footrope*. Journal of Northwest Atlantic Fishery Science, Vol. 27, pp. 227-234.

Hannah, R.W. and Jones, S.A. [2003]. *Measuring the height of the fishing line and its effect on shrimp catch and by-catch in an ocean shrimp* (Pandalus jordani) *trawl.* Fisheries Research, Vol. 60, Issues 2-3, pp. 427-438. doi:10.1016/S0165-7836(02)00138-8.

Hannah, R.W.; Jones, S.A.; Lomelli, M.J.M.; and Wakefield, W.W. [2011]. *Trawl net modifications to reduce the by-catch of eulachon* (Thaleichthys pacificus) *in the ocean shrimp* (Pandalus jordani) *fishery*. Fisheries Research, Vol. 110, Issue 2, pp. 277-282. doi:10.1016/j.fishres.2011.04.016.

Hannah, R.W. and Jones, S.A. [2013]. *Tests of trawl footrope modifications to reduce the by-catch of eulachon* (Thaleichthys pacificus) *and other small demersal fishes in the ocean shrimp* (Pandalus jordani) *trawl fishery*. Oregon Department of Fish and Wildlife (Fish Division), Information Report Series, No. 2013-02.

He, P.; Hamilton, R.; Littlefield, G.; and

Syphers, R. [2006]. *Design and test of a semi-pelagic shrimp trawl to reduce seabed impact*. Final report submitted to the Northeast Consortium, University of New Hampshire. UNH-FISH-REF-2006-029.

He, P. and Winger, P. [2010]. *Effect of trawling on the seabed and mitigation measures to reduce impact*. In: Behaviour of Marine Fishes: Capture Processes and Conservation Challenges, P. He (Ed.). Wiley-Blackwell, pp. 295-314. doi:10.1002/9780813810966.ch12.

Holst, R. and Revill, A. [2009]. *A simple statistical method for catch comparison studies*. Fisheries Research, Vol. 95, Issues 2-3, pp. 254-259.

Jones, B.J. [1992]. *Environmental impact of trawling on the seabed: a review*. New Zealand Journal of Marine and Freshwater Research, Vol. 26, pp. 59-67.

Kaiser, M.J.; Collie, J.S.; Hall, S.J.; Jennings, S.; and Poiner, I.R. [2003]. *Impacts of fishing gear on marine benthic habitats*. In: Responsible Fisheries in the Marine Ecosystem, M. Sinclair and G. Valdimarsson (Eds.). Cabi Publishing, pp. 197-218.

Løkkeborg, S. [2005]. *Impacts of trawling and scallop dredging on benthic habitats and communities*. Food and Agriculture Organization of the United Nations, Fisheries Technical Paper 472.

Morgan, L. and Chuenpagdee, R. [2003]. Shifting gears: addressing the collateral impacts of fishing methods in US waters. PEW Foundation.

Munden, J.; Grant, S.; Winger, P.; Legge, G.; and Nguyen, T. [2013]. *Comparative fishing to determine the commercial viability of a low impact shrimp bottom trawl*. M.Sc. Thesis. Memorial University of Newfoundland. pp. 16-75.

Nguyen, T.X.; Winger, P.D.; Legge, G.; Dawe, E.G.; and Mullowney, D.R. [2014]. *Underwater observations of the behaviour of snow crab* (Chionoecetes opilio) *encountering a shrimp trawl off northeast Newfoundland*. Fisheries Research, Vol, 156, pp. 9-13. doi:10.1016/j.fishres.2014.04.013.

Pham, C.K.; Diogo, H.; Menezes, G.; Porteiro, F.; Braga-Henriques, A.; Vandeperre, F.; and Morato, T. [2014]. *Deep-water longline fishing has reduced impact on vulnerable marine ecosystems*. Nature Publishing Group, Scientific Reports 4, Article No. 4837, doi:10.1038/srep04837.

Pol, M. [2003]. *Turning gear research into effective management: a case history* (poster). Managing our Nation's Fisheries. November 13-15. Washington, DC.

R Development Core Team [2014]. *R: a language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from: www.R-project.org.

Ramm, D.C.; Mounsey, R.P.; Xiao, Y.; and Poole, S.E. [1993]. *Use of a semi-pelagic trawl in a tropical demersal trawl fishery*. Fisheries Research, Vol, 15, No. 4, pp. 301-313. doi:10.1016/0165-7836(93)90081-H.

Rice, J. [2006]. *Impacts of mobile fishing gears on seafloor habitats, species, and communities: a review ams synthesis of selected international reviews*. Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Research Document, 2006/057.

Rose, C.S.; Hammond, C.F.; Stoner, A.W.; Munk, E.J.; and Gauvin, J.R. [2013]. *Quantification and reduction of unobserved* *mortality rates for snow, southern Tanner, and red king crabs* (Chionoecetes opilio, C. bairdi, and Paralithodes camtschaticus) *after encounters with trawls on the seafloor*. Fishery Bulletin, Vol. 111, No. pp. 42-53.

Sheppard, J.; Pol, M.; and McKiernan, D. [2004]. *Expanding the use of the sweepless raised footrope trawl in small-mesh whiting fisheries*. NOAA/NMFS Cooperative Research Partners Initiative, Unallied Science Grant NA16FL2261, Final Report.

SINTEF [2004]. *A new ground gear for bottom trawls, incorporating spreading features*. SINTEF Fisheries and Aquaculture, Hirtshals, Denmark.

Valdemarsen, J.W. and Suuronen, P. [2003]. *Modifying fishing gear to achieve ecosystem objectives*. In: Responsible Fisheries in the Marine Ecosystem, M. Sinclair and G. Valdimarsson (Eds.). Food and Agriculture Organization of the United Nations, pp. 321-334.

Valdemarsen, J.W.; Jorgensen, T.; and Engas, A. [2007]. *Options to mitigate bottom habitat impact of dragged gears*. Food and Agriculture Organization of the United Nations, Fisheries Technical Paper No. 506.

Venables, W.N. and Ripley, B.D. [2002]. *Modern applied statistics with S*. Fourth Edition. Springer, New York. ISBN 0-387-95457-0.

Winger, P.D.; DeLouche, H.; and Legge, G. [2006]. *Designing and testing new fishing gears: the value of a flume tank*. Marine Technology Society Journal, Vol. 40, No. 3, pp. 44-49.