Improving an Ecosystem-friendly Scallop Dredge

Farrell Davis – Coonamessett Farm Foundation, Inc.

Ronald Smolowitz – Coonamessett Farm, Inc.

David Rudders

Saltonstall-Kennedy Competitive Research Program Award Number NA15NMF4270265

Award Period: 9/01/2015 – 8/31/2017

Coonamessett Farm Foundation, Inc.
277 Hatchville Road
East Falmouth, MA 02536
508-356-3601 FAX 508-356-3603
contact@cfarm.org
www.coonamessettfarmfoundation.org

Abbreviations

ACL: Allowable Catch Limit

AIC: Akaike information criterion

AM: Accountability Measure

CFF: Coonamessett Farm Foundation, Inc.

GB: Georges Bank

GLMM: Generalized Linear Mixed Model

LPD: Low Profile Dredge

NEFMC: New England Fishery Management Council

SNE: Southern New England

TDD: Turtle deflector dredge

Executive Summary

The objective of this project was to develop sustainable fishing gear for the Northeast sea scallop (*Placopecten magellanicus*) fishery. The Northeast sea scallop fishery is one of the most valuable fisheries in the United States, estimated to be worth $440 million annually in ex-vessel value. However, the scallop fleet is vulnerable to regulators imposing reactionary measures to reduce the bycatch of certain species, such as yellowtail flounder (*Limanda ferruginea*) and windowpane flounder (*Scopthalmus aquosus*). Such global measures could reduce the overall efficiency of the scallop fleet (O'Keefe & DeCelles 2013). Technical solutions such as gear modifications provide fisheries managers with a means of meeting bycatch reduction objectives without displacing fishing effort or reducing the economic efficiency of the scallop fleet. Through the research and development of a Low Profile Dredge (LPD), this project addressed SK Themes #1-A: Maximize fishing opportunities and jobs and #1-D: Develop and/or transfer selective commercial, non-commercial, and recreational fishing gears or procedures that reduce bycatch impacts and other collateral effects.

Coonamessett Farm Foundation, Inc. (CFF) designed the LPD to be a derivative of the successful Turtle Deflector Dredge (TDD) design. The LPD maintains the forward cutting bar and open frame of the TDD, but the LPD frame has a reduced height to facilitate the vertical escapement of fish and increase tow efficiency. The development of the LPD involved the application of Computational Fluid Dynamics (CFD) analysis to test assumptions about the impacts of depressor plate angle on the hydrodynamic properties of the dredge. The use of CFD analysis is novel to the development of sea scallop dredges and shows great potential for reducing the costs of developing sustainable sea scallop dredges. The results of the CFD analysis informed the development of a prototype LPD that was subsequently tested via sea trials.

Sea trials took place aboard five commercial sea scallop vessels from New Bedford, MA and yielded a data set of 189 tow pairs for analysis. Three of the five trips tested the LPD using commercially representative tow parameters. The fourth trip investigated the effect of scope (ratio of towing warp to depth) on the relative catch performance of the LPD and control gears. A fifth trip was planned and conducted to increase the sample size of flatfish which had been relatively low on the previous four trips. Unfortunately, in the interim period between the fourth and fifth trips the LPD frame had become bent, significantly impacting the performance of the LPD. The catch data obtained during the sea trials, formed the basis to estimate the efficiency of the LPD dredge relative to the control dredge used in the study. Statistical models were developed that examine the impacts of animal length, tow parameters, and environmental conditions on relative catch efficiency.

The project was successful in achieving its objective of developing an alternative scallop dredge that reduces the bycatch and habitat impacts. Analysis of the data indicated that the LPD reduces bycatch while maintaining the catch of the target species, sea scallops and selecting for larger more valuable scallops. The novel application of CFD analysis contributed significantly to the success of this type of project and demonstrated the value this analysis has in the future design and development of alternative scallop dredges. Despite the overall success, design changes to the LPD are required to prevent the LPD from bending if the LPD frame is to be used by the scallop fishery.

Project Purpose and Overview

The objective of this project was to develop sustainable fishing gear for the Northeast sea scallop (*Placopecten magellanicus*) fishery, addressing SK Themes #1-A: Maximize fishing opportunities and jobs and #1-D: Develop and/or transfer selective commercial, non-commercial, and recreational fishing gears or procedures that reduce bycatch impacts and other collateral effects. Beginning in 1994, the US Atlantic sea scallop fishery underwent major changes which included the implementation of a Days At Sea (DAS) system, crew size restrictions, gear regulations, and the development of rotational Scallop Access Areas. Under this management regime annual landings have increased to almost 50 million pounds, nearly triple the average landings in 1994.

Despite this meteoric success, the economic efficiency of the sea scallop fishery is vulnerable to reactionary effort restrictions imposed by regulators for the reduction of overfished bycatch species such as yellowtail flounder (*Limanda ferruginea*) and windowpane flounder (*Scopthalmus aquosus*).

The Georges Bank (GB) and Southern New England (SNE) stocks of both of these flounder species are designated NOAA NMFS as being both overfished with overfishing occurring. As a result of the condition of these stocks, fisheries managers have imposed sub-Allowable Catch Limits (sub-ACL) to limit the bycatch of the species in the scallop fishery. The seasonal co-occurrence of these species on productive scalloping grounds increases the potential for the scallop fleet to exceed a sub-ACL and trigger a reactionary Accountability Measure (AM) that can take the form of area closures. While area closures can reduce bycatch, it is preferable to accomplish this reduction through the use of gear modifications in order to optimize yield (Harrington et al. 2005; Jennings and Revill 2007). Successful gear modifications within trawl and dredge fisheries tend to also reduce expenses while increasing catch selectivity and ultimately reduce impact to the environment (Kennelly and Broadhurst 1995; Broadhurst 2000; Harrington et al. 2005).

Coonamessett Farm Foundation, Inc. (CFF) has an extensive history of developing gear-based solutions for the scallop fishery. Beginning in 2009, CFF responded to an emerging issue of loggerhead sea turtle (*Caretta caretta*) interactions with scallop dredges on Mid-Atlantic scalloping grounds (Smolowitz et al. 2010 and Smolowitz et al. 2012). To eliminate fatal interactions with sea turtles, conservation engineers at CFF removed the outer bale bars typical of New Bedford dredges and moved the cutting bar from a setback position behind the depressor plate to forward of the depressor plate (Figure 1). Without the outer bales to entangle them, sea turtles are guided up and over the dredge frame by the forward cutting bar (Smolowitz et al. 2010 and Smolowitz et al. 2012). This new dredge frame, the Turtle Deflector Dredge (TDD), was mandated for use by scallop vessels fishing west of 71° under Framework Amendment 23 (NEFMC 2011). During field testing of the TDD, there was an observed reduction in flatfish bycatch for the TDD relative to a standard industry dredge (Smolowitz et al. 2010). It was hypothesized that the forward cutting bar design may have been responsible for the reduction in flatfish bycatch.

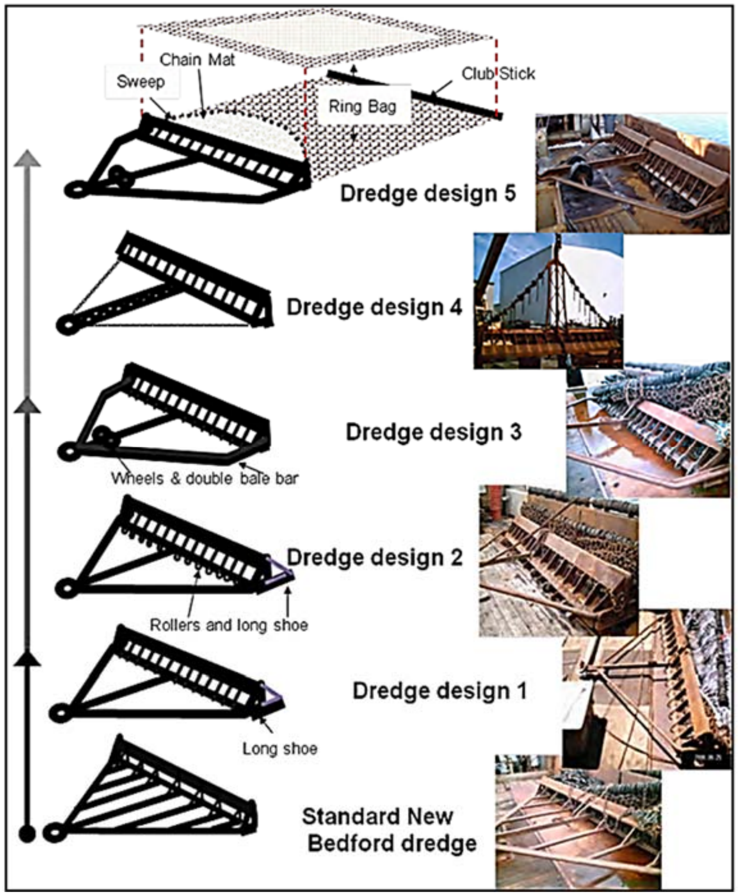


Figure 1. The evolution and development of the New Bedford dredge into the Turtle Deflector Dredge (TDD) from Smolowitz et al. 2012.

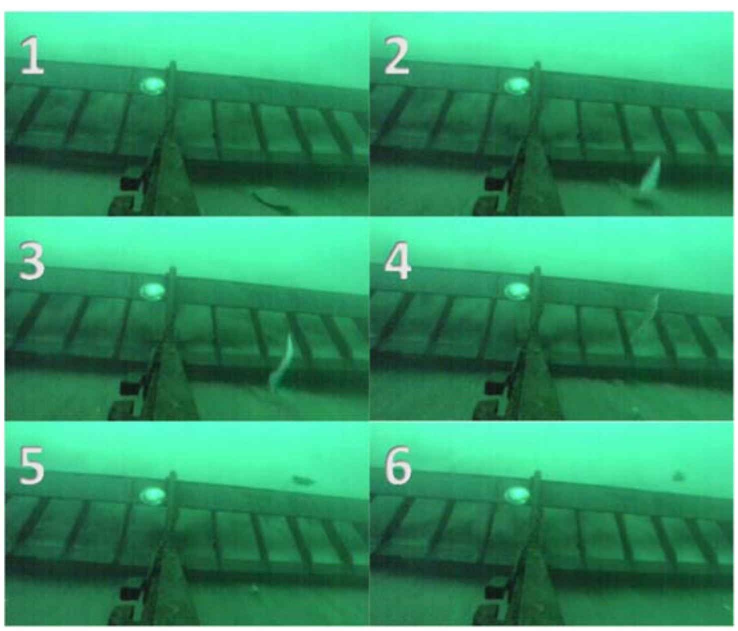


Figure 2. A yellowtail flounder (L. ferruginea) displaying vertical escape behavior ahead of a TDD. This still sequence was collected in 2013 using a camera placed on the outer frame (Davis et al. 2013).

The turbulence created by the flow of water between the cutting bar and the seafloor may be one of the stimuli that triggers flatfish to transition from a herding behavior to an escape behavior. Flatfish utilize a detection minimization strategy relying on subtle movements and intricate camouflage to avoid predators and fleeing at the last moment to further confuse predators (Ryer 2008 and Ryer et al. 2008). They also respond to trawl ground-gear at short distances, first remaining close to the seafloor while herding ahead of the footrope and then responding to the ground-gear by rising from the seafloor at the last moment, which removes them from the ground-gear's zone of influence (Ryer 2008). Similar behavior has been observed in flatfish escaping scallop dredges (**Figure 2**). Based on this evidence, CFF began developing a derivative of the TDD frame specifically designed to reduce flatfish bycatch. The new dredge maintained the forward cutting bar and open bale design of the TDD, but the overall height profile of the dredge was reduced to facilitate the escape of flatfish over the top of the dredge (Figure 3). It is from the reduced frame height that this flatfish excluder dredge earned the designation of Low Profile Dredge or LPD.

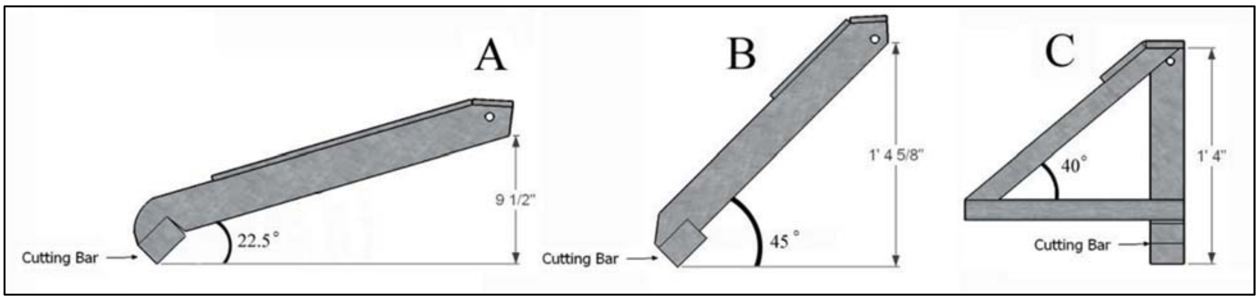


Figure 3. A) The original Low Profile Dredge (LPD); B) Turtle Deflector Dredge (TDD); C) New Bedford Dredge, typical dredge used by the fishing industry.

The first prototype of the LPD was created in 2011 and tested over a series of research trips in the SNE and GB regions. The original prototype of the LPD had a depressor plate in line with the dredge frame struts, fixed at 22.5^0 relative to the seafloor (**Figure 3**). During these research trips a number of different depressor plate widths and scopes (warp to depth ratio) were evaluated for their impact on catch efficiency. Pooled data from these sea trials demonstrated the bycatch reduction potential of the LPD (**Table 1**). There was also an indication that the LPD had increased selectivity relative to a standard dredge, catching more scallops greater than 110 mm. An increased selectivity benefits the fishery economically, as larger scallop meats fetch higher prices and a reduction in the catch of pre-recruit increases the long-term sustainability of the scallop fishery. Despite these positive results, the loss in scallop catch for the prototype LPD was too substantial for the dredge to be adopted as a viable fishing gear for the scalloping industry.

Table 1. Pooled catch data from previous LPD research. (Smolowtiz et al. 2011; Smolowitz et al. 2012; Davis et al. 2012).

Dredge Design	Benthos (bu)	Scallops (bu)	Windowpane Flounder	Yellowtail Flounder	Winter Flounder	Fluke	Barndoor Skate	Monk
LPD	419.55	3436.512	17567	2942	1147	2153	530	1807
NBD/TDD	860.5	4186.1245	25630	3997	1667	3363	739	1953
Difference	-440.95	-749.6125	-8063	-1055	-520	-1210	-209	-146
% difference	-34.45%	-9.83%	-18.67%	-15.20%	-18.48%	-21.94%	-16.47%	-3.88%

The tremendous potential of an LPD design for the reduction of flatfish bycatch and incidental mortality of pre-recruit scallops warranted further investigation of scallop dredges with reduced frame heights. However, the original LPD design with the 22.5º depressor plate had to be modified to allow the target species catch to be maintained at an acceptable level. Video observations of the original LPD showed that the cutting bar had been riding some distance above the seafloor (**Figure 4**). It was hypothesized that the cutting bar generates a turbulence that aids in the capture of sea scallops. By riding too high from the seafloor, the strength of this effect would have likely been diminished. Weight was added to the front of the frame and center bar of the dredge both for strength and in an effort to reduce the distance of the cutting bar from the seafloor. Increasing the weight of the dredge frame can come at the expense of tow efficiency and increases the habitat impacts of the gear. While the heavier dredge design appeared to have equivalent catches of sea scallops, this design was abandoned for a more ecosystem-friendly means of reducing the cutting bar distance from the seafloor.

Figure 4. The old LPD design, note that the cutting bar is some distance from the seafloor.

The primary function of the dredge depressor plate is to maintain the dredge's contact with the seafloor during the tow by exerting downward force. Both the TDD and standard industry dredge have a depressor plate at an angle between 40º and 45º, while the original LPD had a depressor plate set at a 22.5º angle (**Figure 3**). It was assumed that an angle of 22.5º was sufficient for maintaining the LPD's contact with the seafloor but, as mentioned previously *in situ* observations of the dredge indicated this assumption to be incorrect (**Figure 4**). It was from these observations and with the objective of developing an ecosystem-friendly dredge that researchers chose to incorporate a 45º depressor plate (**Figure 5**).

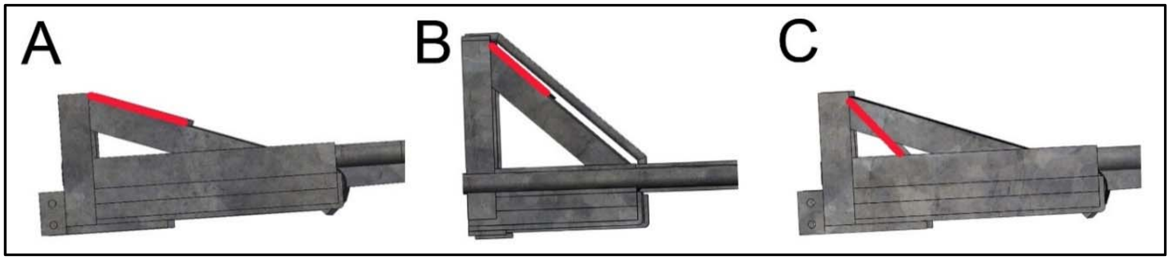


Figure 5. (A) Orignal LPD prototype (B) Turtle-deflector dredge, TDD (C) The redesigned LPD. The depressor plates are highlighted in red.

The cost of building a prototype scallop dredge is not the limiting factor in the development of new fishing gears. Instead, it is the cost of testing a prototype dredge at sea. Before the new LPD was built, conservation engineers at CFF sought a means for testing the assumptions about the hydrodynamic properties of the LPD designs without doing costly sea trials. To do this, 3-dimensional models of both the original and redesigned LPD were created using SolidWorks©, a Computer Aided Design (CAD) software. These models were then evaluated by the Centre for Sustainable Aquatic Resources (CSAR) at Memorial University in Newfoundland using Computational Fluid Dynamics (CFD) analysis to simulate water flow around the two dredge frames. These simulations confirmed that the original LPD prototype had a low drag coefficient and streamlined flow (**Figure 6A**), while the redesigned LPD generated a complex flow pattern with a strong vortex behind the cutting bar that resulted in flow up and into the dredge (**Figure 6B**). Confident about the ability of the new LPD with a 45º depressor plate to maintain proper seafloor contact, the new design was then built by East Coast Fabrications, Inc. and tested during five research trips.

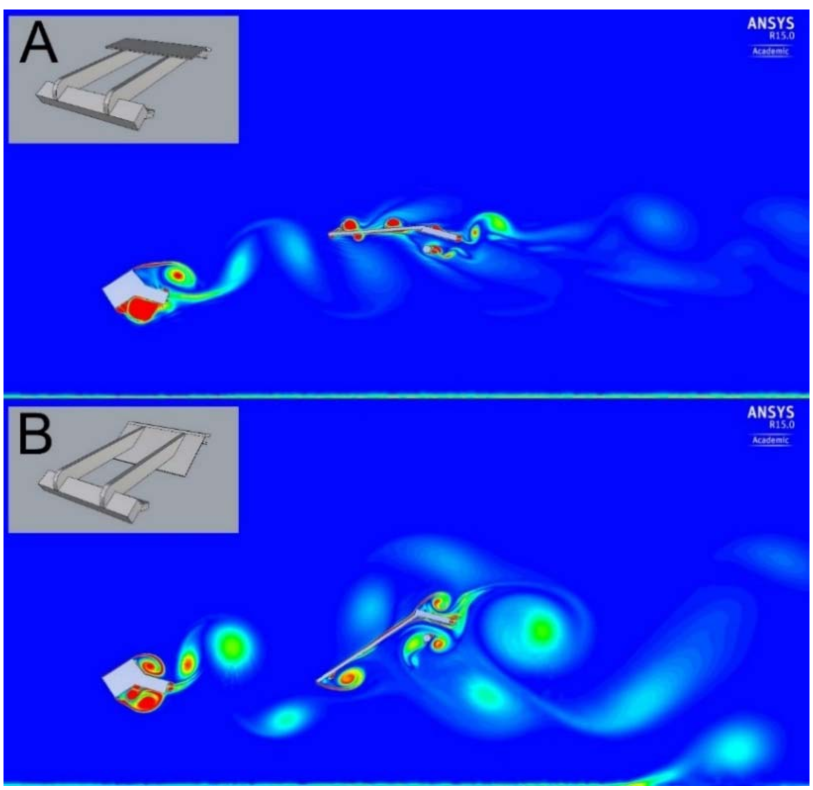


Figure 6. Output from the computational fluid dynamics simulation showing (A) the vortex contours for the original low profile dredges and (B) the vortex contours for the redesigned low profile dredge.

Project Objective

The objective of this project was to develop an ecosystem-friendly scallop dredge by improving upon a previously tested prototype LPD design. To achieve this objective, the water flow around both the old and redesigned LPD frames was modelled using CFD analysis, which had never before been used in the design of scallop dredges. Evaluation of the CFD results indicated that the new LPD design with 45º depressor plate would correct the deficits of the original LPD design and therefore was the best candidate for achieving our objective of developing an ecosystem-friendly dredge. CFF then tested the new LPD during five research trips aboard commercial scallop vessels (Table 2). Catch data for each of the trips was compared to evaluate LPD performance. The data from each of the research trips was individually modelled using a Generalized Linear Mixed Model (GLMM) to determine the impact that biological and environmental parameters had on the catch efficiency of the LPD relative to the control dredge. Since the locations and the experimental design varied from trip to trip, a GLMM analysis was carried out on each of the trips individually.

Table 2. Research trip dates, number of valid tow pairs, and the experimental design.

Vessel	Trip Start	Trip End	No. of Valid Tow Pairs	Experimental Design
Celtic	4/21/2016	4/26/2016	33	LPD vs. Ctrl
Arcturus	5/23/2016	5/27/2016	35	LPD vs. Ctrl
Wisdom	6/2/2016	6/6/2016	39	LPD vs. Ctrl
Friendship	6/20/2016	6/25/2016	38	LPD vs. Ctrl with Scope as a Variant
Westport	4/8/2017	4/12/2017	43	LPD vs. Ctrl*
*The LPD had become bent during the interim period between the 4th and 5th trips.				

Project Approach – Data Collection and Analysis

Experimental Design

All sea trials evaluating the design of the LPD were carried out aboard Limited Access (LA) scallop vessels. These vessels routinely tow two dredges simultaneously, allowing for a comparison of experimental scallop dredges without any modification to commercial fishing practices with regards to vessel operation and gear handling. In addition, simultaneous towing of a control and experimental dredge allows for the comparison of gear variants without the introduction of the variables associated with time and space. To ensure that the experiment was representative of the commercial scallop fishery, tow parameters were standardized to match commercial fishing practices. The dredge bag for both the LPD and control dredges were standardized to limit the number of gear variants that could influence catch efficiency to just the dredge frame.

Vessel speed was standardized to a range of 4.5-5.1 knots and tow scope was standardized to 3:1, with the exception of one research trip specifically evaluating the impact of scope on catch efficiency. In this instance, the control scope was 3:1 and the experimental scope was 4:1. Vessel speed was monitored and recorded using the vessel's GPS. Tows were considered invalid if the standardized tow parameters were not met or if there was a gear malfunction (e.g. dredge flipping on the seafloor). The vessel's GPS provided the tow start and end times and positions, and the tow start depth and end depth was also recorded. In addition to tow parameter data, the environmental conditions the tow took place in were also collected, including:

- The Beaufort number, a semi-quantitative scale (0-12) of wind and sea state with 0 representing calm seas and 12 representing a hurricane-like event, was collected for each tow; and
- a tidal parameter derived from when the tow took place and the time of the nearest high/low tide in that tow location.

Both the tow and environmental parameter data were used in the evaluation of the catch performance of the LPD.

Catch was sampled from each valid tow pair on all five research trips. The amount of scallops in the catch was evaluated by the number of baskets and number of scallops in a basket. Bycatch species were individually measured to the nearest centimeter. All weights were measured to a 0.01 kilogram resolution. For tows with large volumes of scallops and finfish, the catch was sub-sampled.

Catch data collected for each paired tow:

- Scallop catch rates (bushel(s)/tow/side)
- Scallop catch weight (sum of bushel(s) weight/tow/side)
- Scallop shell height frequency (one bushel/tow/side)
- Finfish catch rates (# of individuals/tow/side)
- Finfish weight (species weight/tow/side)
- Finfish and invertebrate length frequency (by species and species groups (i.e. controlled groundfish species, other groundfish species, pelagic species, and shellfish))
- Skate catch rates (# of individuals/tow/side)
- Skate weight (total weight/tow/side)
- Weight, volume and composition assessment of trash (i.e. sea star and crab species)

The working hypothesis of the study was that by redesigning the original 22.5º depressor plate to 45º, the hydrodynamics of the gear would increase the scallop catch efficiency to commercially acceptable levels while still reducing bycatch of finfish and sea turtles and produce a more knife-edged size selectivity curve for sea scallops. To test the catch performance component of this hypothesis an LPD dredge frame was tested against a control dredge (TDD) across five experimental research trips. The relative performance of the two dredge configurations tested formed the basis of the following analysis.

Catch data

Five research trips were carried out to compare the LPD to a control (i.e., TDD) dredge. While three of the research trips did test this configuration for the entire trip, one research trip introduced differential scope in an attempt to understand the effect of this factor on the relative performance of the two gears. Due to unforeseen complications during field work, not all research trips tested the initial configuration of the LPD vs. the control dredge. The fifth and final trip was intended to collect a more robust sample size of flatfish which had been lacking from the previous standard trips. Unfortunately, the frame had become bent, possibly while being stored between the fourth and fifth trips, or during cumulative use over the prior four research trips. Upon discovery of the bend during the fifth research trip, repairs were made (i.e., removing the turtle chain mat and manipulating the side pieces) in an attempt to correct the damage and return the dredge frame to the original specification, but the performance of the dredge was still suspected to be impacted. Given these differences in the research trips, it was decided to analyze each of the five research trips individually, with additional levels of analysis delineated by scope trials and LPD configuration.

Overall, this data set consisted of 189 valid tow pairs that were considered for examination in this analysis. Not all species were present in all tow pairs and for the species examined. Individual tows with zero catch for a given species were uninformative and excluded from the analysis. In addition, we also excluded species from any given research trip-level analysis if there were less than a total of 50 animals observed or five or less positive tow pairs, because this was not sufficient data to perform the analysis. **Table 1 in the attached Appendix A** shows the species analyzed by trip (and sub-trip). Of the remaining information, we focused our analysis on a subset of species that consisted of commercially important or special management concern. The species examined were: unclassified skates (little and winter *Raja spp.*), barndoor skate (*Dipturus laevis*), summer flounder (*Paralicthyes dentatus*), fourspot flounder (*Hippoglossina oblonga*), windowpane flounder (*Scophthalmus aquosus*), monkfish (*Lophius americanus*) and sea scallops (*Placopecten magellanicus*).

Statistical models

This analysis attempted to construct a model that would predict the relative efficiency of the LPD dredge relative to the TDD dredge (control) tested in the experiment based on a variety of covariates. A description of the various covariates tested is shown in Table 3. In many instances, especially with gear modifications that can possibly alter the relative size composition of the catch, using the unpooled (over length) catch data and exploring the length-based relative efficiency is informative. This analysis, utilizing the unpooled catch data, predicts the changes that the LPD dredge had on the relative catch at length for the two gears. In some cases, the change in relative catch with respect to length is not a linear function. To evaluate and capture this non-linearity, there are a number of approaches (e.g. Miller 2013, Holst and Revill, 2009). For this analysis, we used a simple approach that utilized low order polynomials to describe non-linearity in the response (Holst and Revill, 2009). For many species, however, length was not a significant predictor of relative efficiency. In these cases, an overall change in the relative total catch was possible and tested via a model specification using the pooled catch data.

Table 3. Covariates used in the GLMM model building of the LPD data.

Variable	Description
Length	Animal length - Fish(cm), Sea Scallops(mm)
Hours to Peak	Time (hours) to high/low tide peak
Tow Duration	Time (minutes) of towing time
Beaufort Value	A scale (0-12) of wind and sea conditions (0=calm, 12=Hurricane)
Depth	Depth (fathoms) where the tow was conducted
Vessel Speed	Average speed maintained by the vessel during the tow

For both approaches, the technique was the same. The catch data was brought into the SAS system. Potential fixed effects were evaluated via a forward selection process where significant terms (p=0.05) were identified and an optimal model was defined by an evaluation of the lowest

Akaike information criterion (AIC) value with PROC HPGENSELECT. The specified model was further evaluated to ascertain whether the addition of random effects (intercept, slope) improved model fit. If the addition of a random effect was justified, the final model, as identified by lowest AIC value, was evaluated to produce parameter estimates, model diagnostics and output graphics. The GLMMs were evaluated in PROC GLIMMIX. **See Appendix B** for a detailed description of the analytical framework used in the study.

Project Management
The project was managed by CFF staff, and at-sea operations and data collection was supervised by Farrell Davis. Statistical modelling was performed in collaboration with David Rudders. CFF is a non-profit organization that has been researching sustainable fisheries operations and providing resource managers with gear-based solutions for resolving fisheries issues. CFF's purpose is the development and transfer of appropriate technology in support of local communities that are environmentally sound, socially equitable, economically feasible and compatible with a sustainable future.

Results

Testing of the LPD was carried out in both the open access and rotational access areas in SNE and GB (**Figure 7**). This was done to evaluate the performance of the LPD across a range of scallop densities and substrate conditions normally encountered by the scallop fishery. The rotational access areas tend to have higher densities of scallops and a different size frequency distribution than open access areas (Hart and Rago 2004).

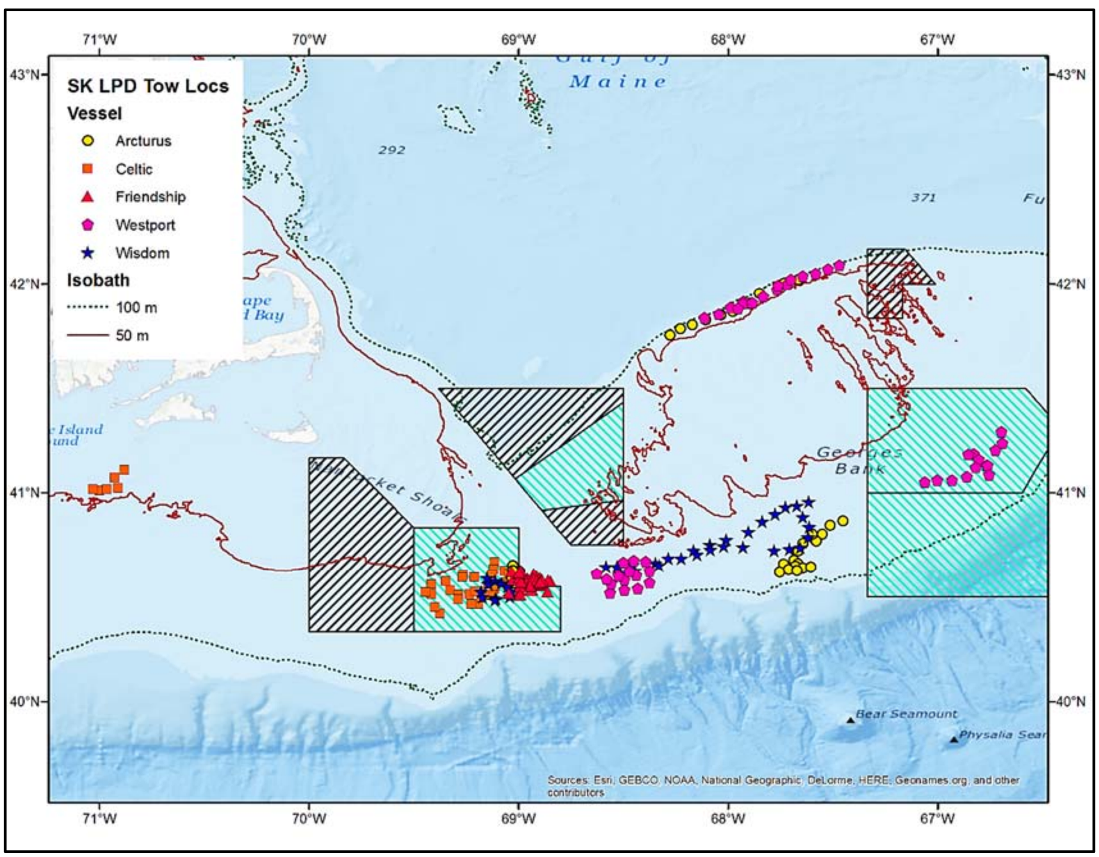


Figure 7. A map of the tow locations conducted during the five research trips.

The five trips were grouped into three different categories both intentionally and due to unforeseen circumstances regarding structural damage to the new LPD frame. The first three of the five trips utilized identical gears and tow parameters and were grouped together for a pooled analysis in addition to trip by trip analysis. Early in the development of the LPD, questions were raised about the impact of scope on the performance of the gear. For this reason, the fourth trip introduced scope as a variant. The standard scope used in the scallop fishery is roughly a 3:1 ratio of warp to depth. A longer experiment scope of 4:1 was proposed because it was believed that this would reduce the pitch of the dredge and bring the cutting bar closer to the seafloor. The fourth trip is therefore analyzed independently of the previous three trips. The fifth and final trip had intended to repeat the methods of the first three research trips; however, the new LPD had become compromised, possibly during storage. Upon discovery of the malfunction, gear work was undertaken to correct the problem. This attempt to correct the gear had fundamentally altered the gear and therefore the data from the fifth trip was also analyzed independent of the other four trips.

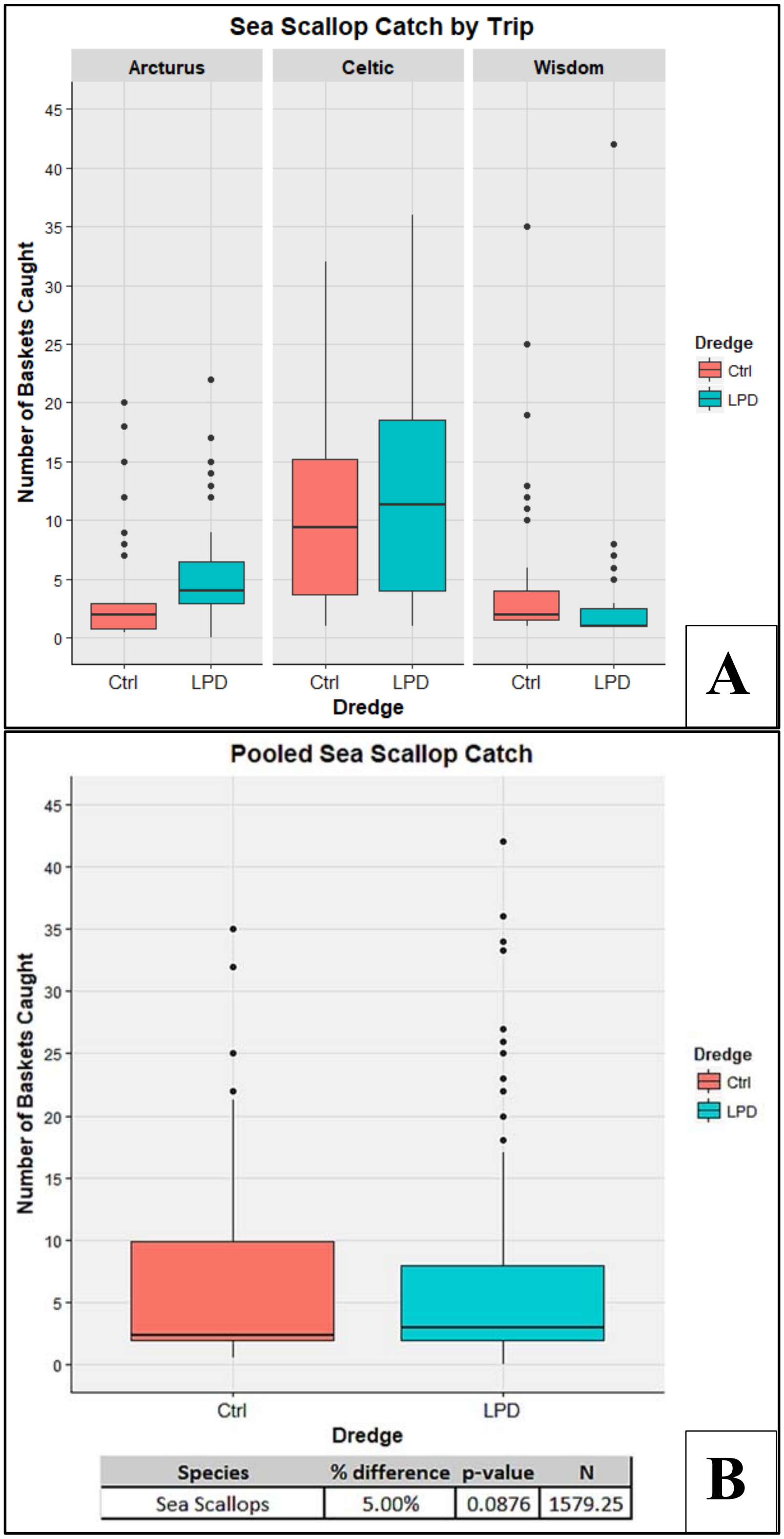
Catch Data Comparison – FV Celtic, FV Arcturus, and FV Wisdom

Because the first three research trips utilized identical gears and standardized tow parameters, they were grouped together for a pooled analysis in addition to being analyzed independently. Only a subset of the finfish species was analyzed due to small sample sizes. The species examined in this way were unclassified skates (little and winter *Raja spp.*), barndoor skate (*Dipturus laevis*), fourspot flounder (*Hippoglossina oblonga*), windowpane flounder (*Scophthalmus aquosus*), monkfish (*Lophius americanus*) and sea scallops (*Placopecten magellanicus*). The data was analyzed in R 3.3.3 using the stats package. The significance of the results were determined using a Mann-Whitney/Wilcoxon signed-rank test.

The scallop catch performance of the LPD frame varied across the three trips (**Table 4 and Figure 8A**). The increase in observed scallop bushel catch for the FV Celtic was not shown to be significant, but the increase in the observed scallop catch was significant for the FV Arcturus trip. The FV Wisdom trip observed an opposite trend in scallop catch with an 8% reduction being significant. This is likely due to spatial differences between where the individual trips took place. When pooled together, the differences in the scallop catch performance of the two dredges does not appear to be significant (Figure 8B). Based upon this result, we can conclude the LPD has scallop catch efficiency that is likely equivalent to the TDD control dredge.

Table 4. The percent difference in scallop catch for the three research trips utilizing identical gears and tow parameters. P-values were obtained using a Mann/Whitney signed-rank test.

Sea Scallops			
Vessel/Trip	**% difference**	**p-value**	**N**
F/V Celtic	7.00%	0.0878	877.5
F/V Arcturus	16.50%	0.0093	340.75
F/V Wisdom	-8.00%	0.0183	361



Species	% difference	p-value	N
Sea Scallops	5.00%	0.0876	1579.25

Figure 8. Boxplots comparing the difference in scallop catch by bushels. The bold line represents the median catch in bushels per tow. P-values were obtained using a Mann/Whitney signed-rank test. A) The three trips utilizing identical gear/tow parameters. B) Pooled comparison.

Fish catches also varied across the three trips with some trips encountering higher levels of bycatch can than others likely to due to the spatial and temporal differences between trips (**Tables 5-9 and Figures 9-13**). Like sea scallops, the significance of the observed changes in catch efficiency for the LPD varied from trip to trip but, the pooled differences were not found to be significant. P-values were obtained using a Mann/Whitney signed-rank test.

Table 5. The percent difference in unclassified skate catch for the three research trips utilizing identical gears and tow parameters.

Unclassified Skates			
Vessel/Trip	**% difference**	**p-value**	**N**
F/V Celtic	2.88%	0.8151	7718
F/V Arcturus	29.24%	<.0001	1987
F/V Wisdom	-38.43%	<.0001	1780

Table 6. The percent difference in barndoor skate catch for the three research trips utilizing identical gears and tow parameters.

Barndoor Skate			
Vessel/Trip	**% difference**	**p-value**	**N**
F/V Celtic	3.70%	0.8151	27
F/V Arcturus	43.67%	<.0001	245
F/V Wisdom	-30.48%	<.0001	420

Table 7. The percent difference in windowpane flounder catch for the three research trips utilizing identical gears and tow parameters.

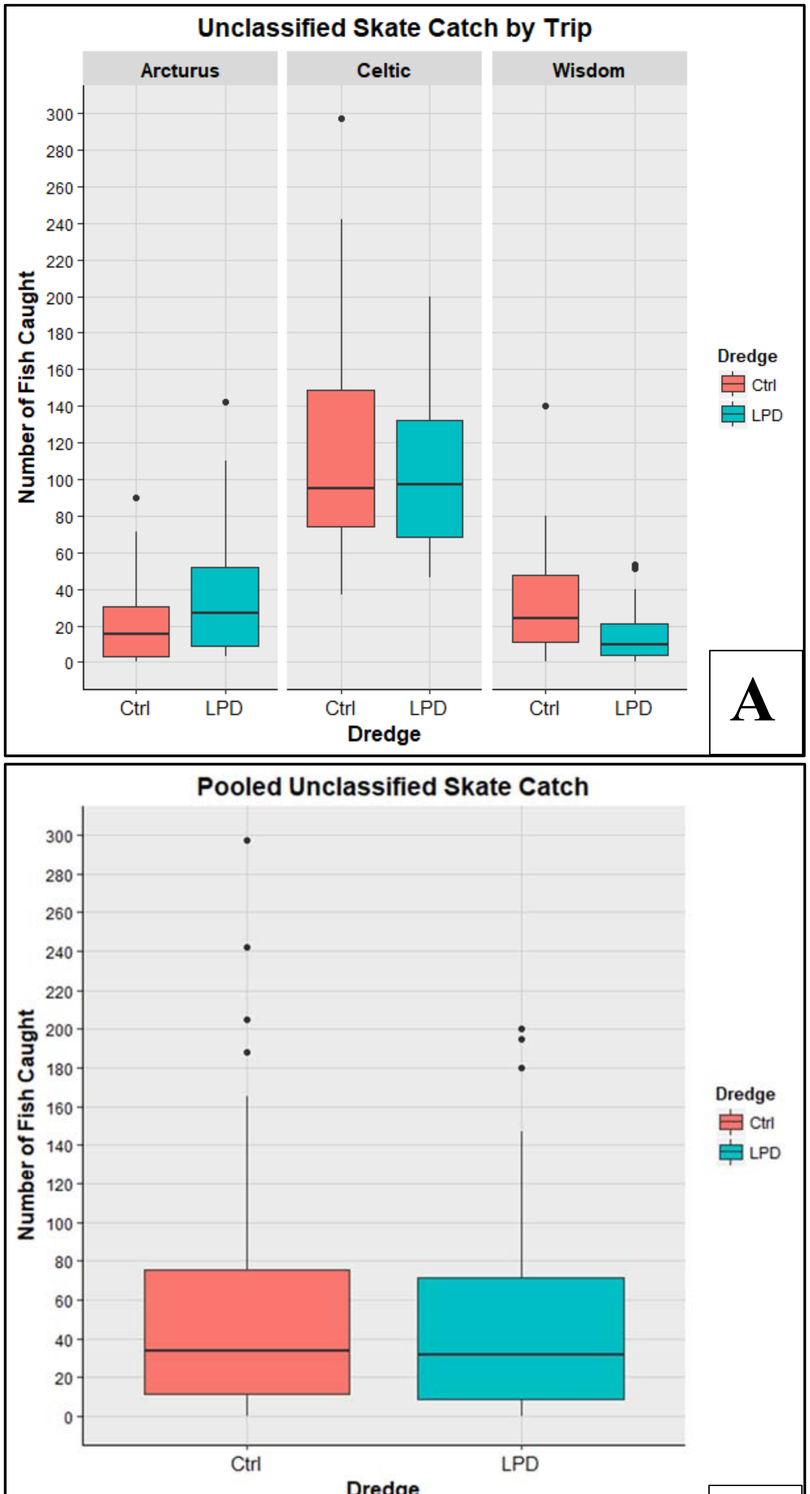
Windowpane Flounder			
Vessel/Trip	**% difference**	**p-value**	**N**
F/V Celtic	-7.72%	0.0793	1528
F/V Arcturus	44.93%	0.1696	69
F/V Wisdom	-40.00%	0.7728	5

Table 8. The percent difference in fourspot flounder catch for the three research trips utilizing identical gears and tow parameters.

Fourspot Flounder			
Vessel/Trip	**% difference**	**p-value**	**N**
F/V Celtic	28.57%	0.1198	14
F/V Arcturus	51.70%	<.0001	87
F/V Wisdom	-57.70%	<.0001	123

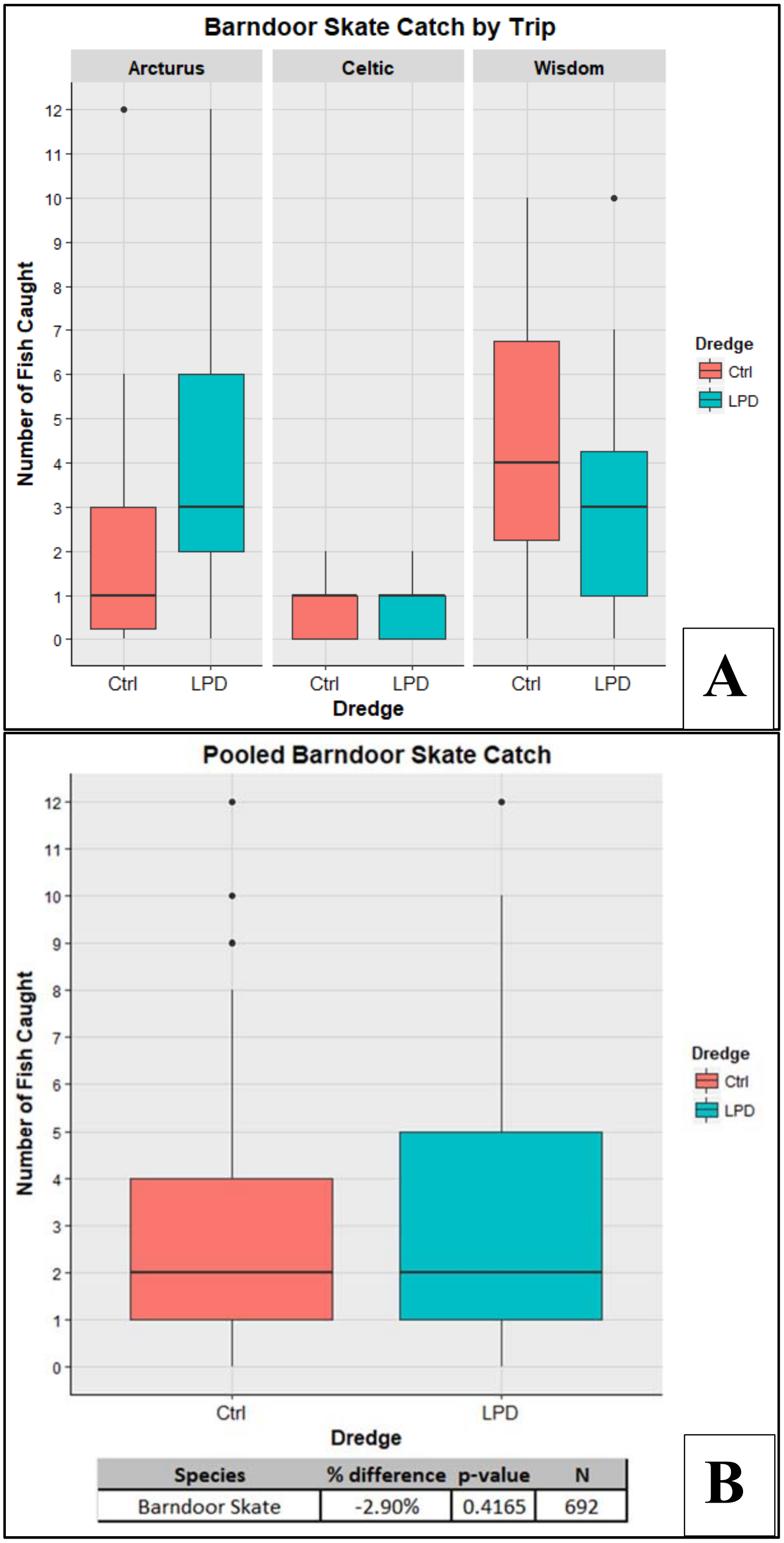
Table 9. The percent difference in monkfish catch for the three research trips utilizing identical gears and tow parameters.

Monkfish			
Vessel/Trip	**% difference**	**p-value**	**N**
F/V Celtic	8.70%	0.3992	449
F/V Arcturus	15.60%	0.0179	360
F/V Wisdom	-12.60%	0.0035	657



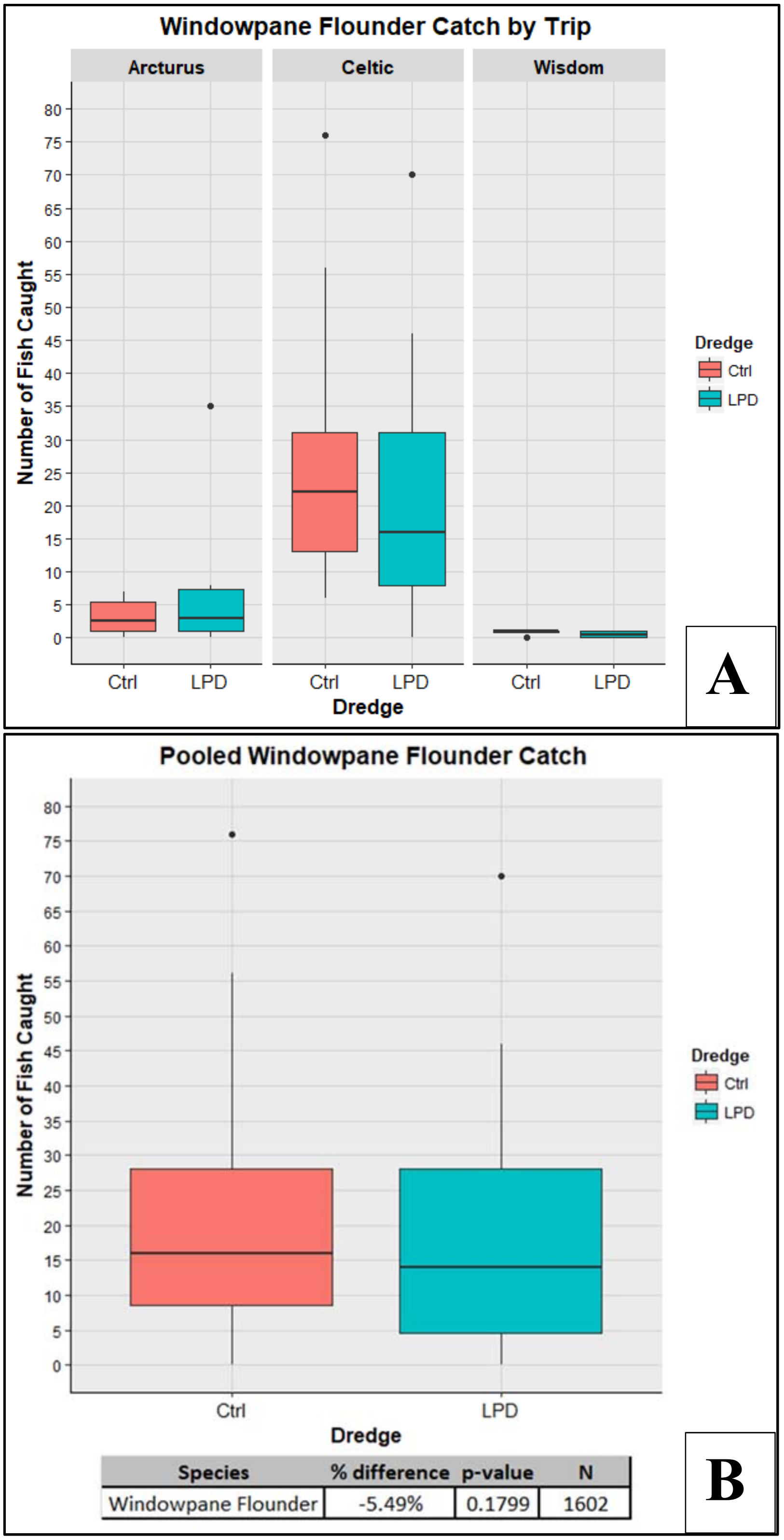
Species	% difference	p-value	N
Unclassified Skates	1.01%	0.8474	11485

Figure 9. Boxplots comparing the difference in Raja spp. catch. The bold line represents the median catch per tow. P-values were obtained using a Mann/Whitney signed-rank test. A) The three trips utilizing identical gear/tow parameters. B) Pooled comparison.



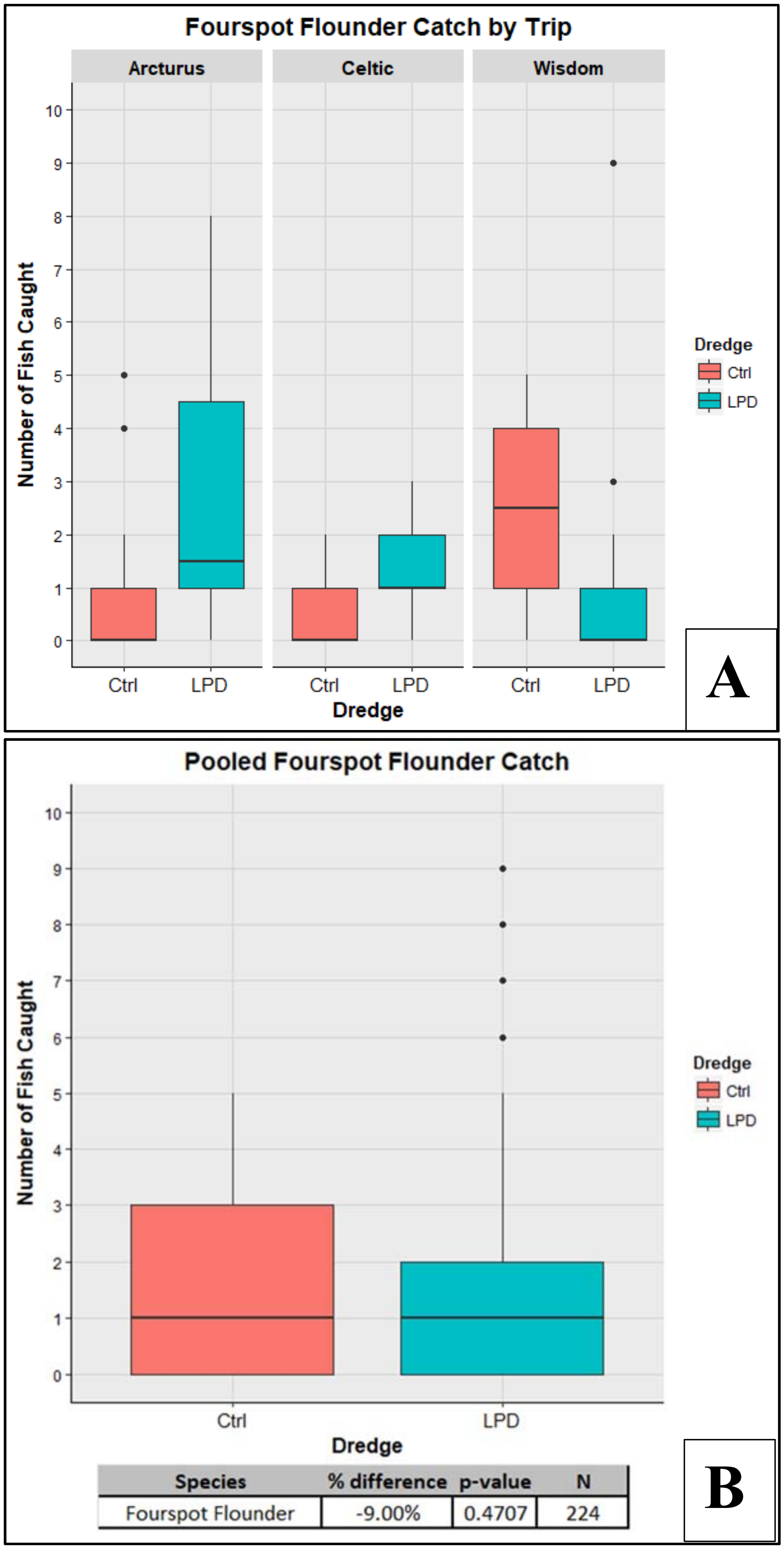
Species	% difference	p-value	N
Barndoor Skate	-2.90%	0.4165	692

Figure 10. Boxplots comparing the difference in barndoor skate catch per tow. The bold line represents the median catch per tow. P-values were obtained using a Mann/Whitney signed-rank test. A) The three trips utilizing identical gear/tow parameters. B) Pooled comparison.



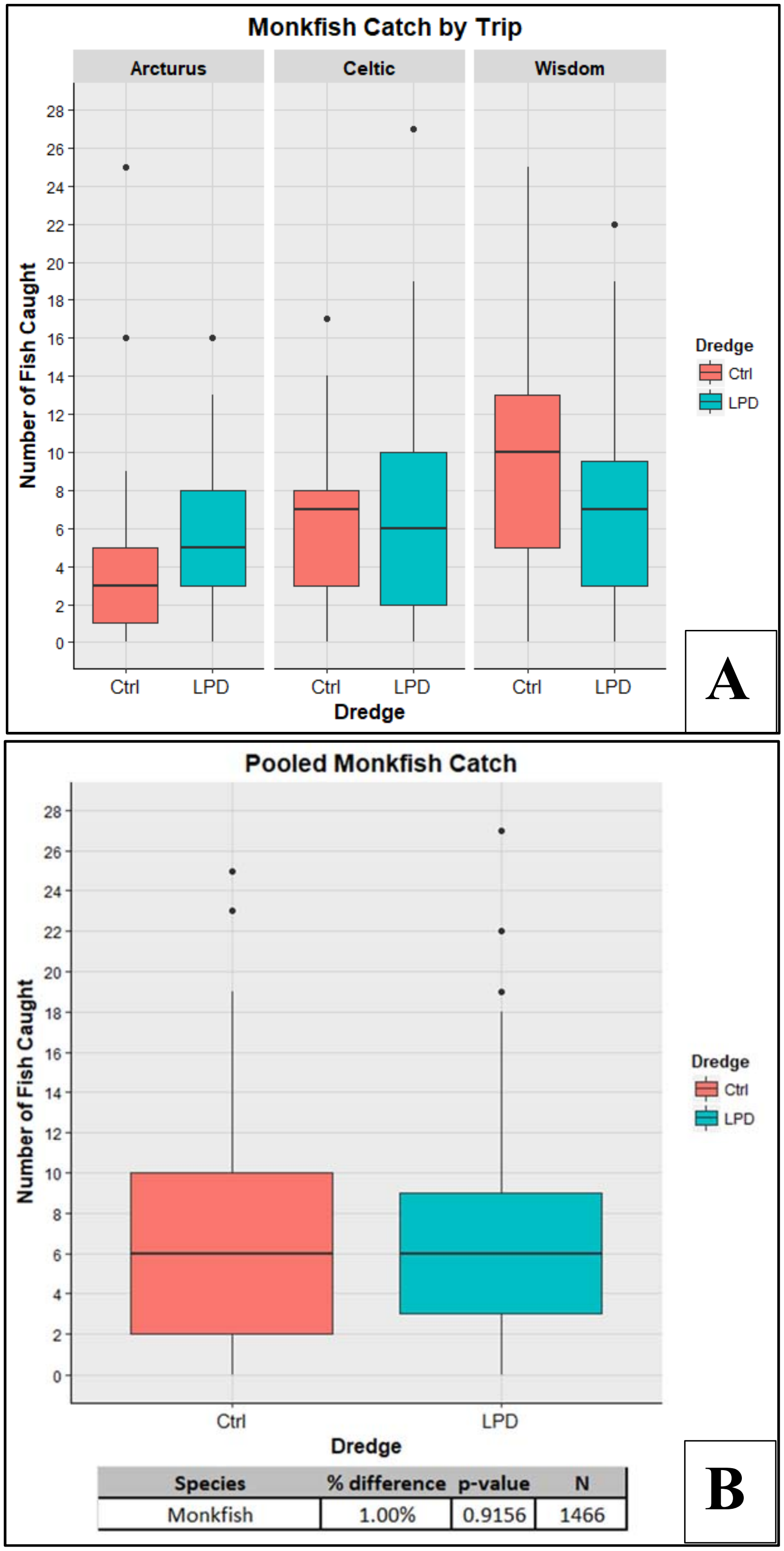
Species	% difference	p-value	N
Windowpane Flounder	-5.49%	0.1799	1602

Figure 11. Boxplots comparing the difference in windowpane flounder catch per tow. The bold line represents the median catch per tow. P-values were obtained using a Mann/Whitney signed-rank test. A) The three trips utilizing identical gear/tow parameters. B) Pooled comparison.



Species	% difference	p-value	N
Fourspot Flounder	-9.00%	0.4707	224

Figure 12. Boxplots comparing the difference in fourspot flounder catch per tow. The bold line represents the median catch per tow. P-values were obtained using a Mann/Whitney signed-rank test. A) The three trips utilizing identical gear/tow parameters. B) Pooled comparison.



Species	% difference	p-value	N
Monkfish	1.00%	0.9156	1466

Figure 13. Boxplots comparing the difference in monkfish catch per tow. The bold line represents the median catch per tow. P-values were obtained using a Mann/Whitney signed-rank test. A) The three trips utilizing identical gear/tow parameters. B) Pooled comparison.

Catch Data Comparison – FV Friendship

The fourth trip evaluated the impact of scope on the catch efficiency of both the LPD and control dredges. This was done by alternating between towing either the LPD or control at a 4:1 scope. The dredge that was not being towed at the long 4:1 was towed using a standardized scope of 3:1. A comparison of the dredge catches by scope can be found in Figures 14-19.

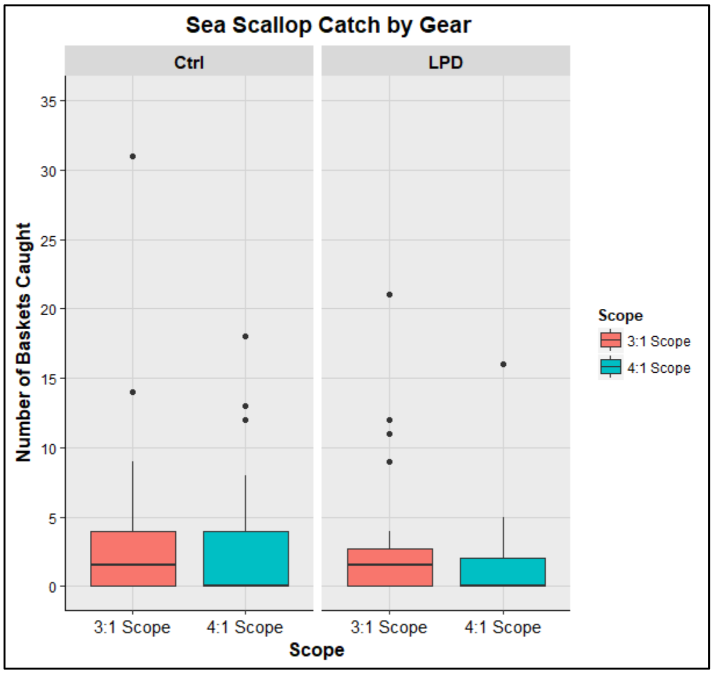


Figure 14. Boxplots comparing the difference in scallop bushel catch per tow by gear and scope.

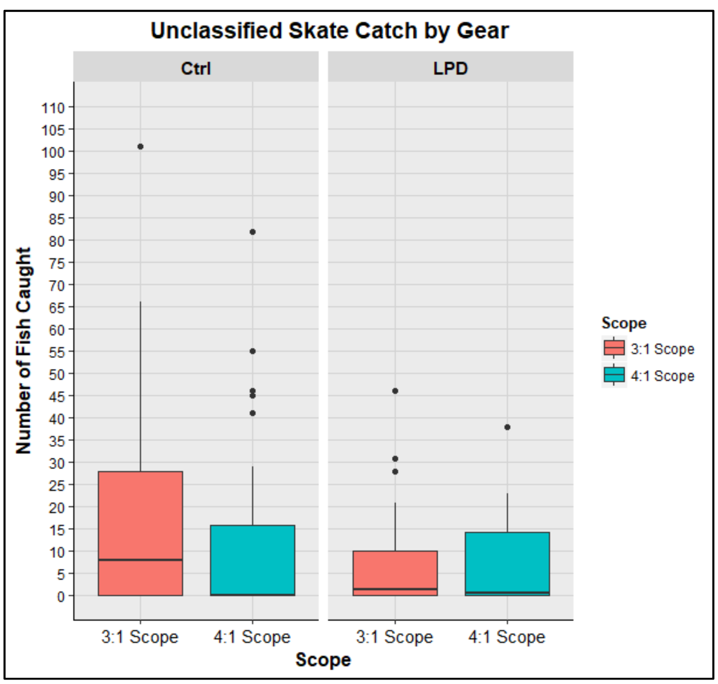


Figure 15. Boxplots comparing the difference in Raja spp. catch per tow by gear and scope.

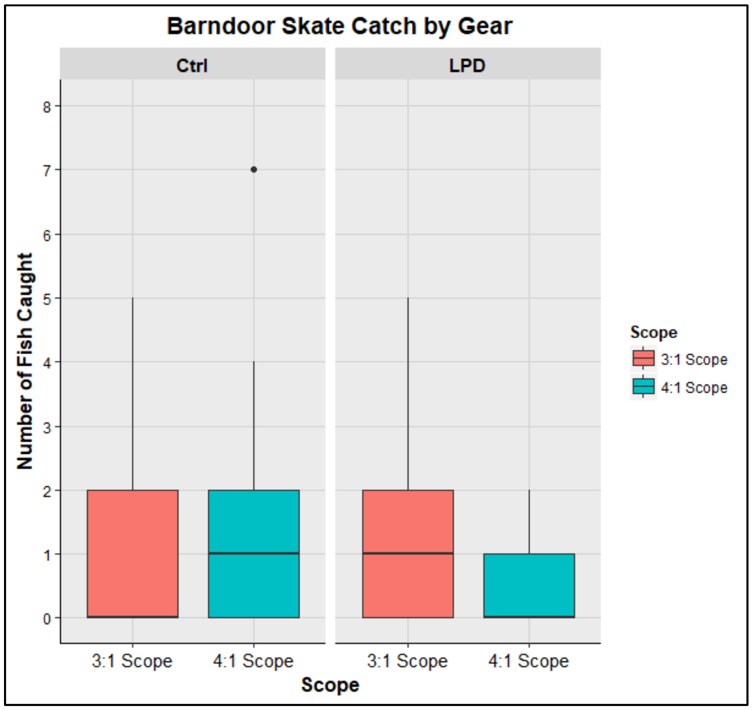


Figure 16. Boxplots comparing the difference in barndoor skate catch per tow by gear and scope.

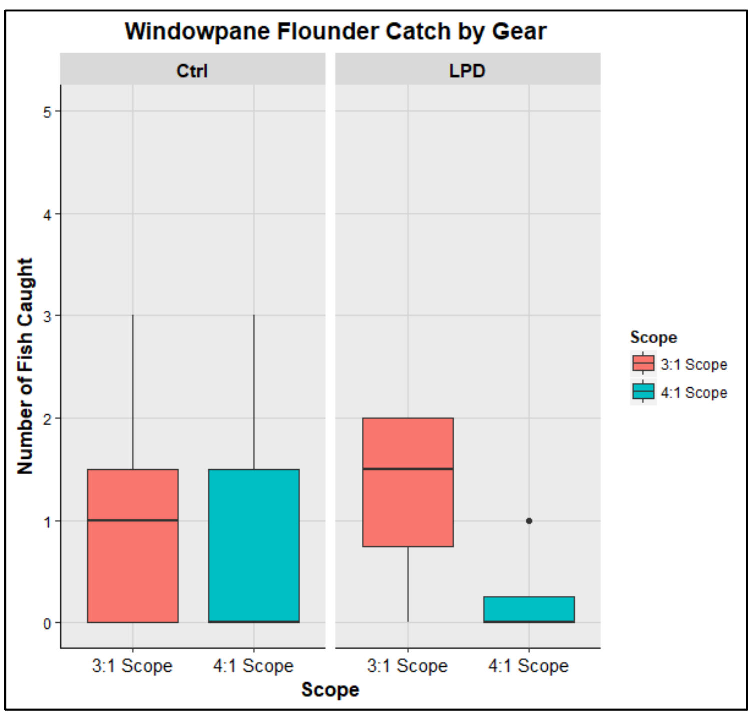


Figure 17. Boxplots comparing the difference in windowpane flounder per tow catch by gear and scope.

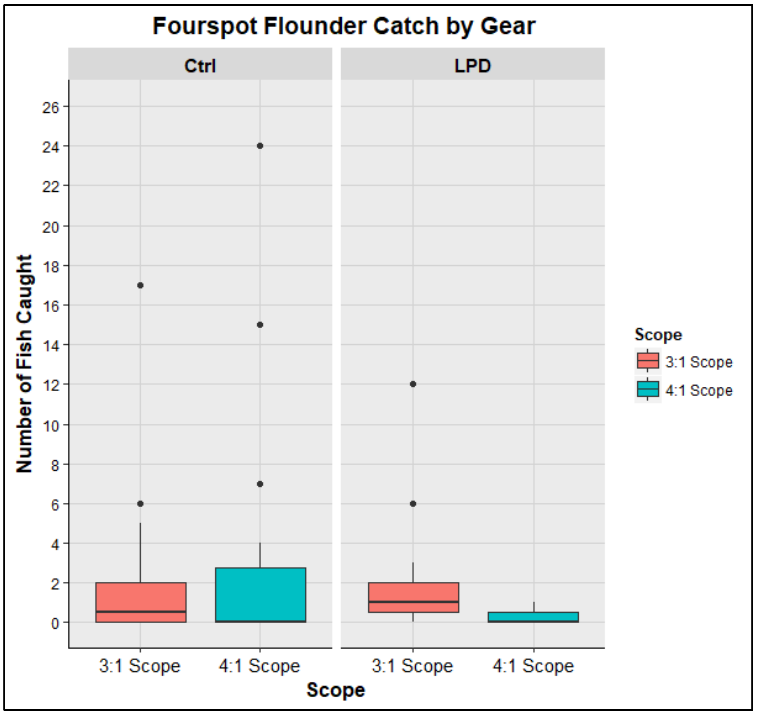


Figure 18. Boxplots comparing the difference the fourspot flounder per tow catch by gear and scope.

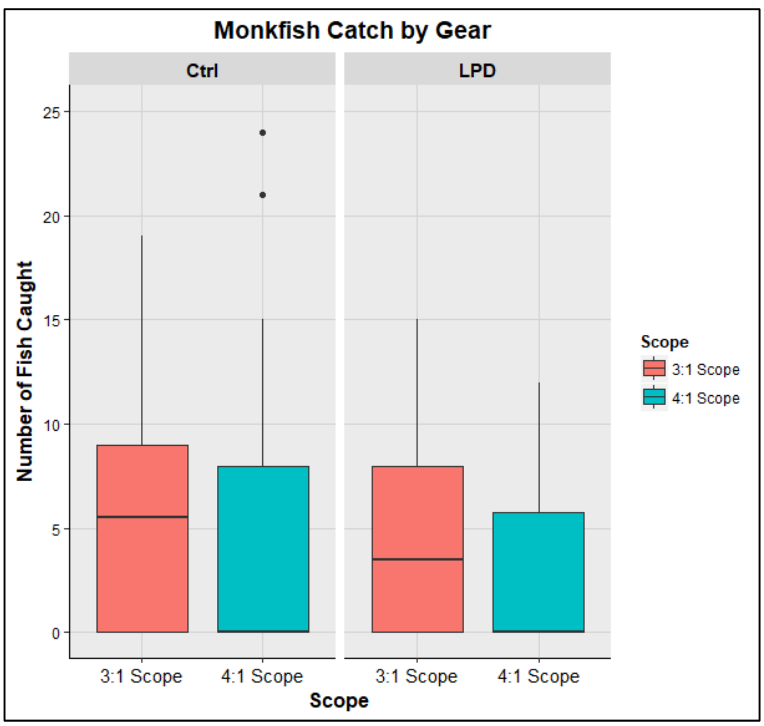


Figure 19. Boxplots comparing the difference in monkfish catch per tow by gear and scope.

Catch Data Comparison – FV Westport

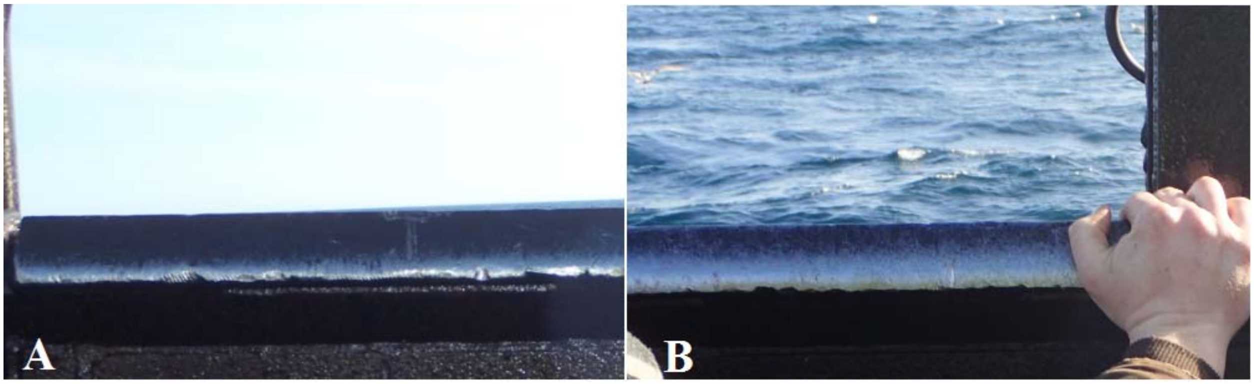


Figure 20. Picture A is the left side of the LPD dredge by the shoe and Picture B is the center of the LPD frame. The wear pattern should be relatively even across the cutting bar; however, for the LPD frame wear was greatest in the center, indicating bowing.

In the early stages of this trip it became apparent that something had happened the new LPD that was causing the scallop catches to be dramatically less than the control dredge. Based upon the evidence of holes in the twine top and an irregular wear pattern on the cutting bar and heels of the dredge it is believed that the dredge frame had at some point become bent either over the course of the experiment or being stored between the 4th and 5th research trips (**Figure 20**). The reduced frame height would make the LPD less tolerant to warping in the center of the dredge frame because of the proximity of the top of the bag to the bottom of the bag. It is likely that during the tow, links and shackle used to hold the turtle mats together would become entangled in the twine top due to the reduced height of the dredge frame. While the scallop catch had appeared to normalize after removing the turtle mats, the LPD maintained the observed reduction for windowpane flounder, hinting at the new design's bycatch reduction potential (**Table 10-11 and Figures 21-22**).

Table 10. The percent difference relative to the control dredge for sea scallop catch before corrective actions were taken (LPD1) and after corrective were taken (LPD2).

Sea Scallops			
Gear	% difference	p value	N
LPD1	-34.84%	<.0001	221
LPD2	-13.21%	0.0579	106

Table 11. The percent difference relative to the control dredge for windowpane flounder catch before corrective actions were taken (LPD1) and after corrective were taken (LPD2).

Windowpane Flounder			
Gear	% difference	p value	N
LPD1	-80.59%	<.0001	711
LPD2	-43.89%	<.0001	745

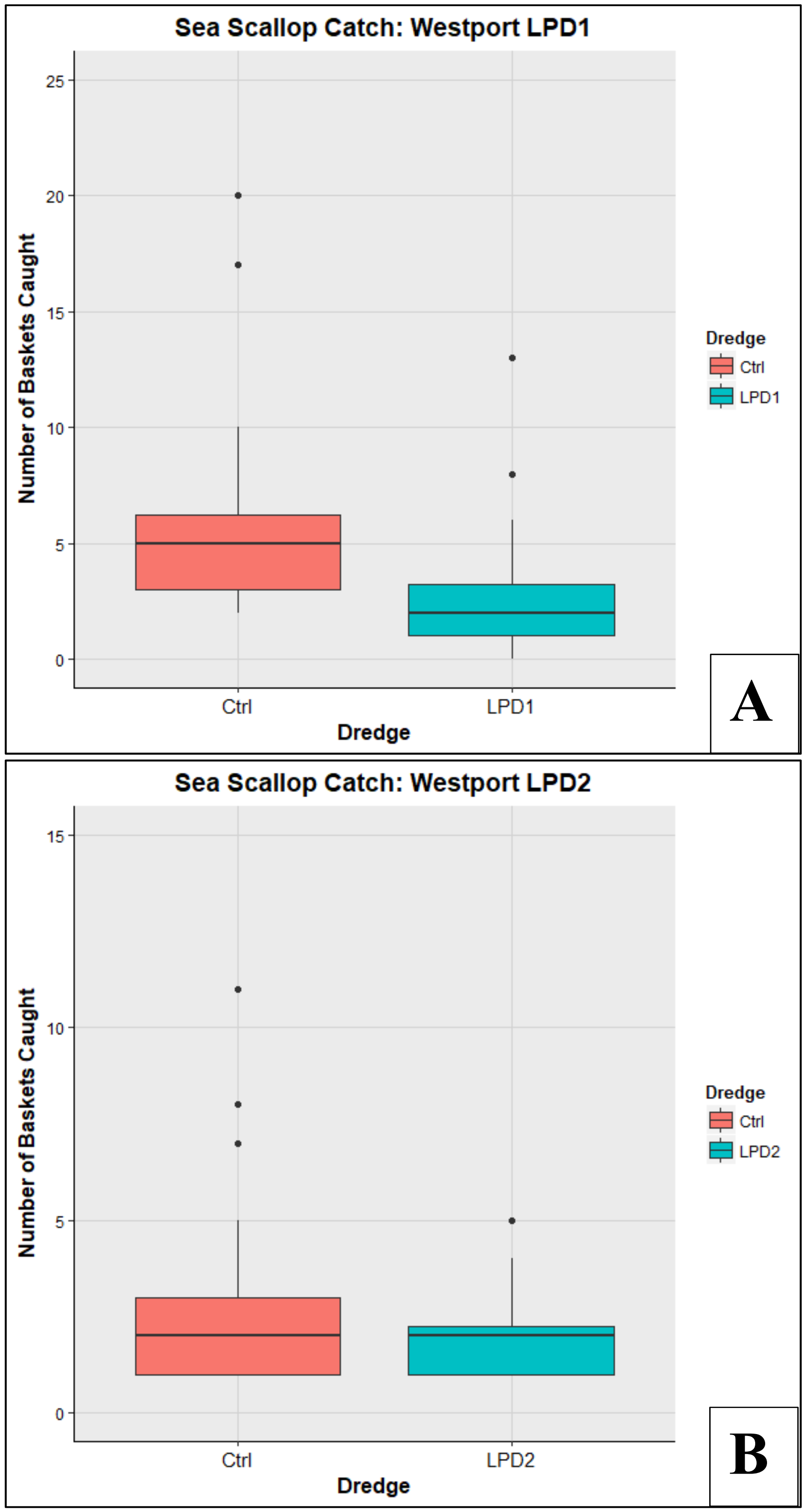


Figure 21. Boxplots comparing the difference in sea scallop catch. The bold line represents the median catch per tow. A) Prior to corrective actions (LPD1). B) After corrective actions (LPD2).

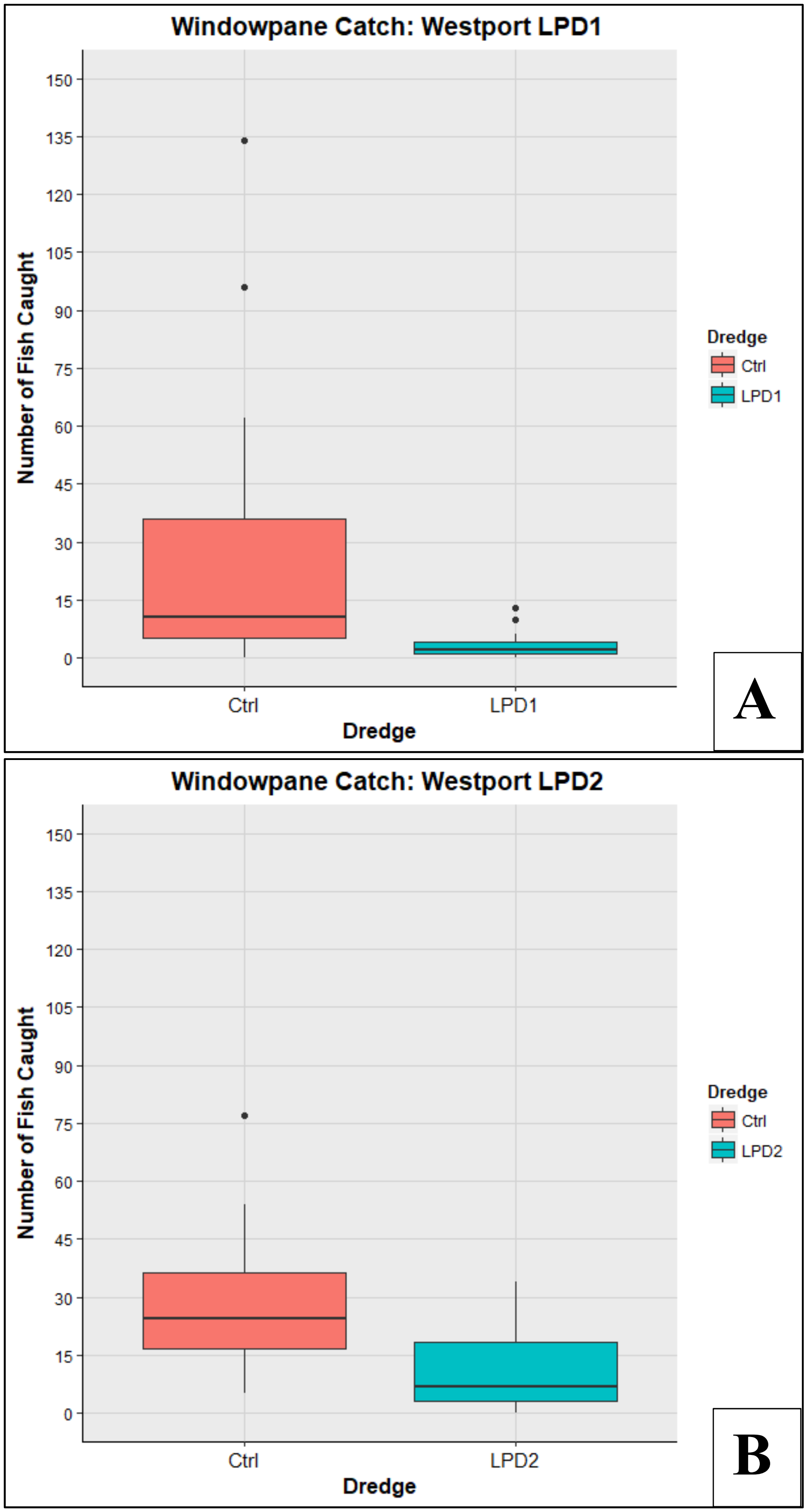


Figure 22. Boxplots comparing the difference in windowpane flounder catch. The bold line represents the median catch per tow. A) Prior to corrective actions (LPD1). B) After corrective actions (LPD2).

GLMM Model Results

As mentioned previously, the data was evaluated by cruise/gear configuration and species (**See Table 1 in the attached Appendix A**). The specific model building results can be found in **Table 2 of the attached Appendix A**. For a given cruise, the encountered species as well as the overall numbers with a species varied. Not all species were present in all tow pairs and for the species examined, individual tows with zero total catch for a given species were uninformative and excluded from the analysis. In addition, we also excluded species from a given research trip-level analysis where there were less than a total of 50 animals observed or five or less positive tow pairs. As a result, the modelled species were different for each cruise. This is likely a function of the season and geographic area sampled. Sea scallops, unclassified skates and monkfish, however, were fairly common across all cruises. Parameter estimates for the optimal model for each cruise/gear configuration/species are shown in **Tables 12-17**. Graphs depicting model output from the most parsimonious model are shown in **Figures 23-35**.

Model Results – FV Celtic

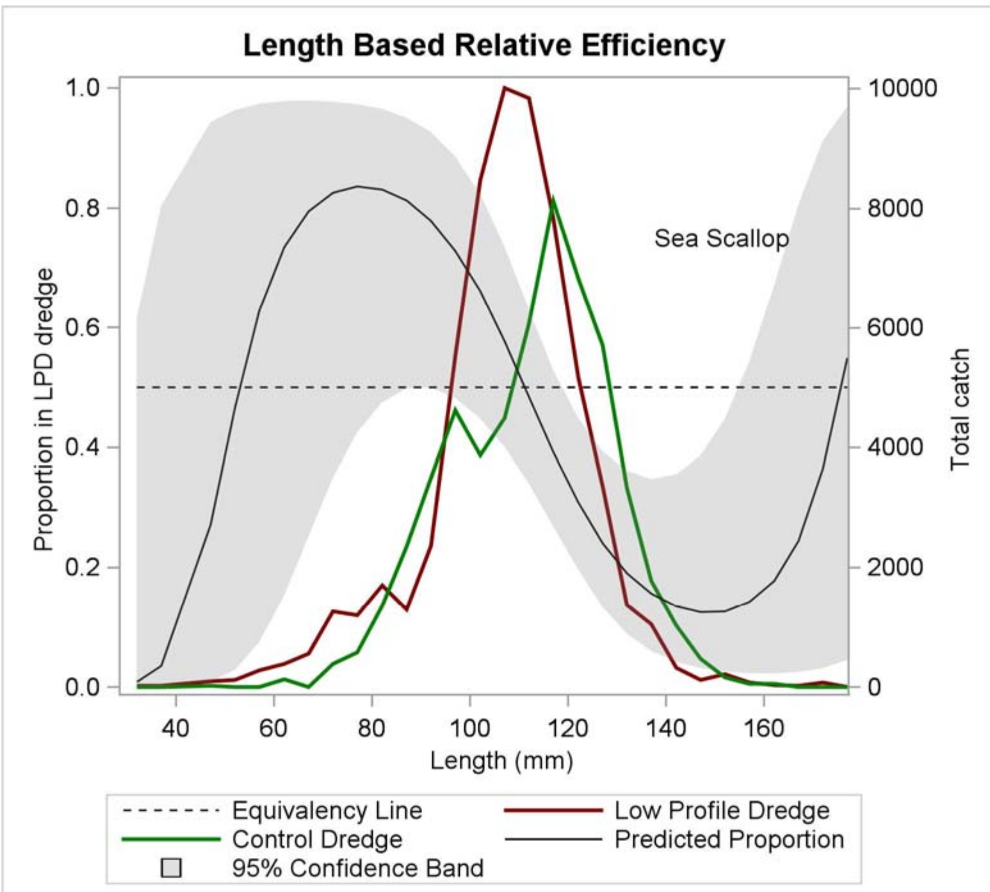


Figure 23. Length based relative efficiency for the two dredge configurations on the F/V Celtic cruise. The grey area represents the 95% confidence band for the modeled proportion (solid black line). The green and red lines represent the observed size frequency distribution with total catch on the right hand vertical axis.

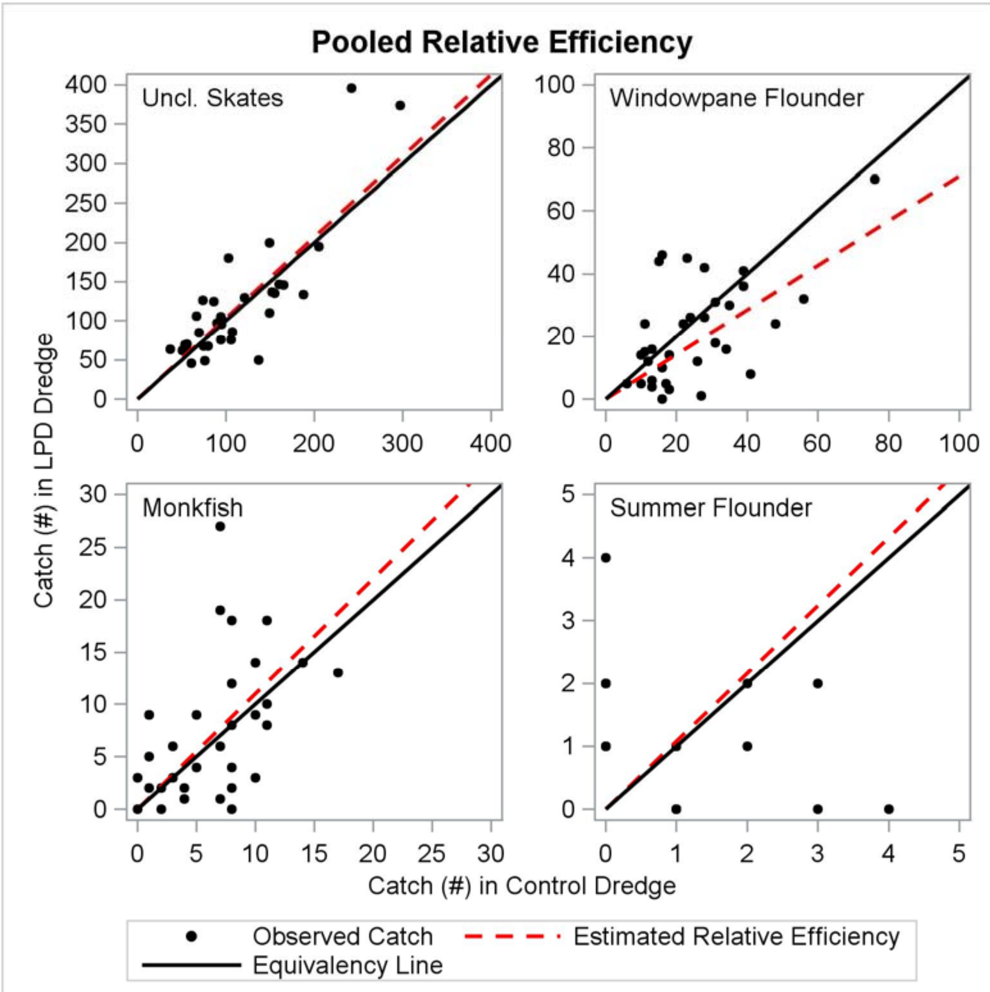


Figure 24. Total pooled catches LPD dredge vs. control dredge (CTDD) from the F/V Celtic cruise. Model output from the analysis of the unpooled data indicated that length was not a significant predictor and catch data was pooled over length. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one. For other than "intercept only" models, all covariates were held at their cruise means (continuous variable) or median (categorical variable e.g. Beaufort number))

Table 12. GLMM models examining the catch data from the F/V Celtic cruise. Results are presented from the model that provided the best fit to the data as supported by model comparison (minimum AIC value). Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale.

Species	Effect	Estimate	SE	DF	T_Value	P_Value	Lower_CL	Upper_CL
Sea Scallop	Intercept	-0.4403	0.283	29	-1.5530	0.1312	-1.0200	0.1394
	Length	-2.6270	0.801	29	-3.2790	0.0027	-4.2650	-0.9882
	Length^2	0.2726	0.191	37	1.4205	0.1563	-0.1047	0.6499
	Length^3	0.8612	0.134	37	6.4033	<0.0001	0.5967	1.1256
Unclassified Skates	Intercept	0.1441	0.214	28	0.6709	0.5078	-0.2959	0.5842
	Hours to Peak	-0.0418	0.053	28	-0.7850	0.4390	-0.1510	0.0673
	Beaufort	-0.0291	0.239	28	-0.1215	0.9041	-0.5189	0.4608
	Beaufort	-00411	0.238	28	-0.1724	0.8644	-0.5300	0.4477
	Beaufort	-0.4000	0.378	28	-1.0570	0.2996	-1.1750	0.3753
	Beaufort	0.0000	.	.	.	.	.	.
Summer Flounder	Intercept	0.0770	0.277	25	0.2773	0.7839	-0.4947	0.6486
Windowpane	Intercept	-3.7370	0.823	30	-4.5390	0.0001	-5.4190	-2.0560
	Hours to Peak	-0.0797	0.100	30	-0.7935	0.4337	-0.2850	0.1255
	Start Depth	0.0985	0.021	30	4.5410	0.0001	0.0542	0.1428
Monkfish	Intercept	0.0970	0.164	31	0.5902	0.5593	-0.2382	0.4322

Model Results – FV Arcuturus

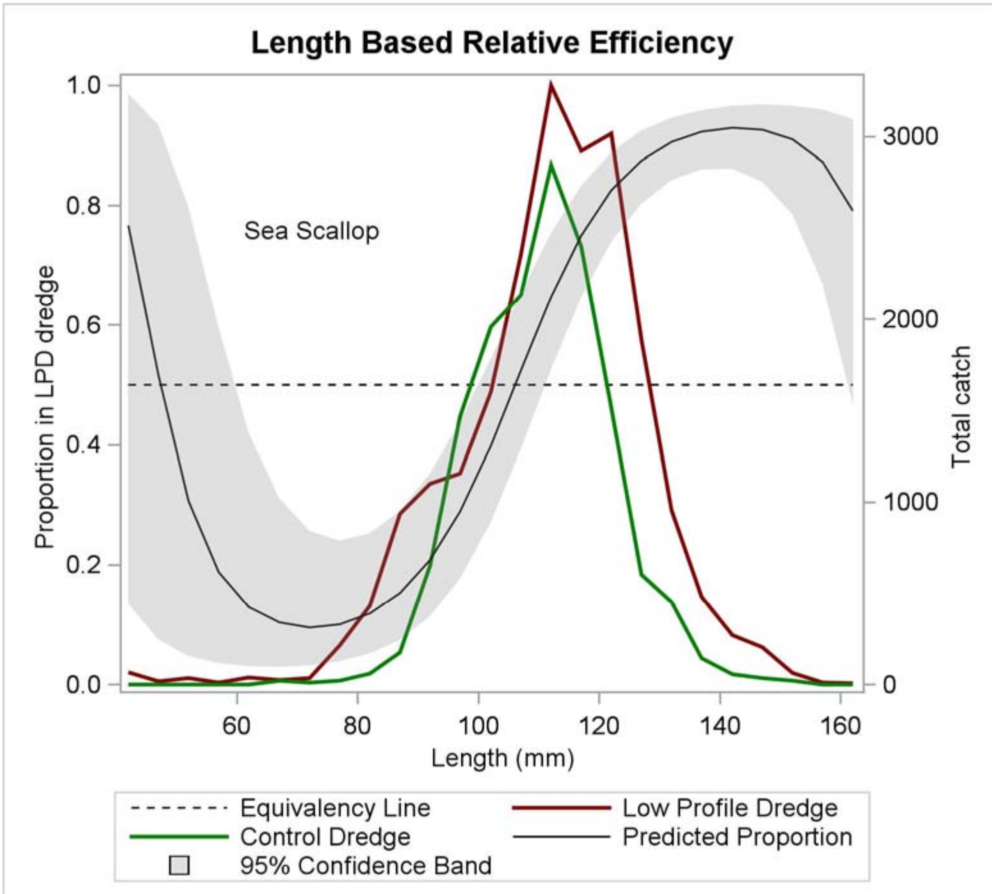


Figure 25. Length-based relative efficiency for the two dredge configurations on the F/V Arcturus cruise. The grey area represents the 95% confidence band for the modeled proportion (solid black line). The green and red lines represent the observed size frequency distribution with total catch on the right hand vertical axis.

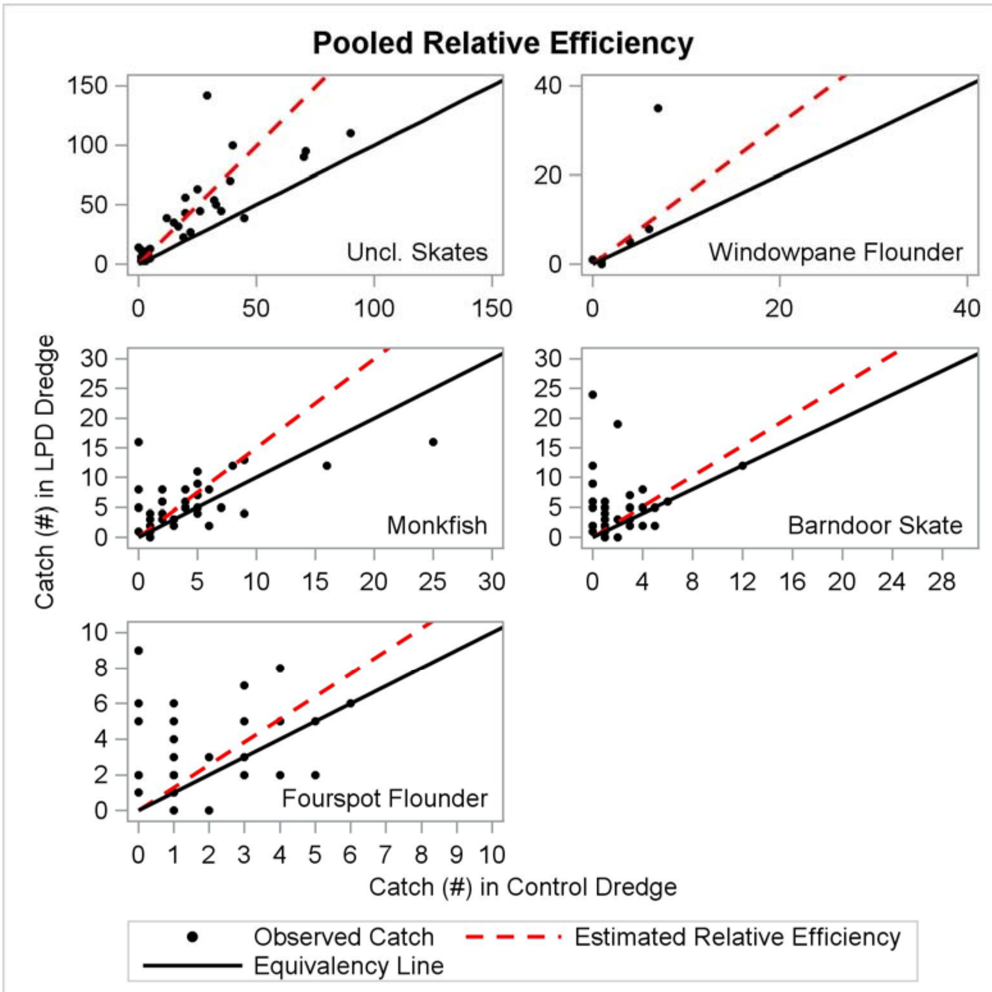


Figure 26. Total pooled catches LPD dredge vs. control dredge (CFFTDD) on the F/V Arcturus cruise. Model output from the analysis of the unpooled data indicated that length was not a significant predictor and catch data was pooled over length. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one. For other than "intercept only" models all covariates were held at their cruise means (continuous variable) or median (categorical variable e.g. Beaufort number))

Table 13. GLMM models examining the catch data from the F/V Arcturus cruise. Results are presented from the model that provided the best fit to the data as supported by model comparison (minimum AIC value). Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale.

Species	Effect	Estimate	SE	DF	T_Value	P_Value	Lower_CL	Upper_CL
Sea Scallop	Intercept	-7.8540	3.227	18	-2.4340	0.0256	-14.630	-1.0740
	Length	3.3363	0.372	21	8.9591	<0.001	2.5619	4.1107
	Length^2	-0.9408	0.205	25	-4.5840	<0.001	-1.3450	-0.5367
	Length^3	-1.1750	0.169	25	-6.9230	<0.001	-1.5090	-0.8408
	Hours to Peak	-0.6750	0.149	25	-4.5060	<0.001	-0.9699	-0.3800
	Start Depth	0.2326	0.086	25	2.6891	0.0076	0.0622	0.4029
	Beaufort	-0.7945	0.438	25	-1.8120	0.0712	-1.6580	0.0690
	Beaufort	0.0882	0.568	25	0.1550	0.8769	-1.0320	1.2082
	Beaufort	0.0000	.	.	.	.	.	.
Unclassified Skates	Intercept	0.6880	0.091	34	7.5091	<0.001	0.5018	0.8741
Barndoor Skate	Intercept	-11.850	3.945	29	-3.0040	0.0054	-19.920	-3.783
	Hours to Peak	0.3367	0.184	29	1.8237	0.0785	-0.0409	0.7142
	Start Depth	0.2966	0.098	29	3.0196	0.0052	0.0957	0.4976
	Beaufort	0.6777	0.586	29	1.1558	0.2572	-0.5215	1.8768
	Beaufort	-1.0410	0.629	29	-1.6540	0.1090	-2.3290	0.2465
	Beaufort	0.0000	.	.	.	.	.	.
Fourspot Flounder	Intercept	-13.070	7.111	24	-1.8380	0.0784	-27.750	1.6051
	Start Depth	0.3599	0.179	24	2.0057	0.0563	-0.0104	0.7302
Windowpane	Intercept	-1.1630	0.881	4	-1.3190	0.2577	-3.6120	1.2855
	Tow Duration	0.0008	0.000	4	2.4281	0.0721	-0.0001	0.0017
Monkfish	Intercept	0.4063	0.151	34	2.6741	0.0114	0.0975	0.7151

Model Results – FV Wisdom

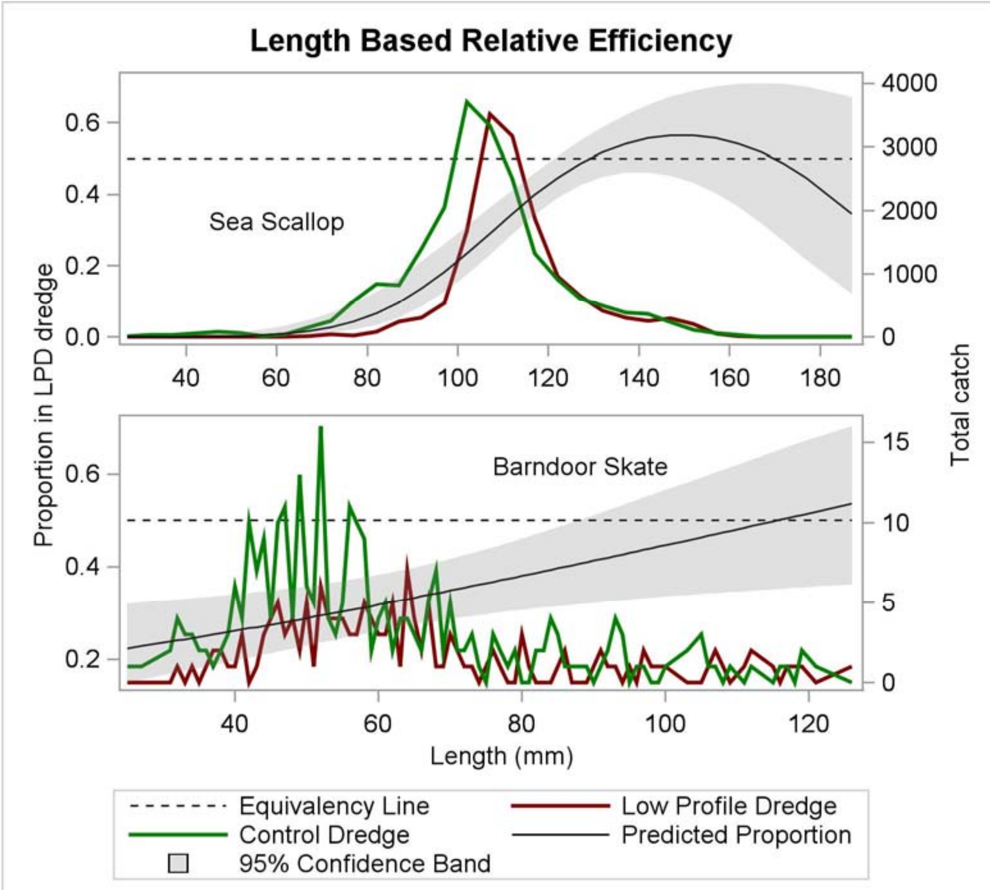


Figure 27. Length based relative efficiency for the two dredge configurations on the F/V Wisdom cruise. The grey area represents the 95% confidence band for the modeled proportion (solid black line). The green and red lines represent the observed size frequency distribution with total catch on the right hand vertical axis.

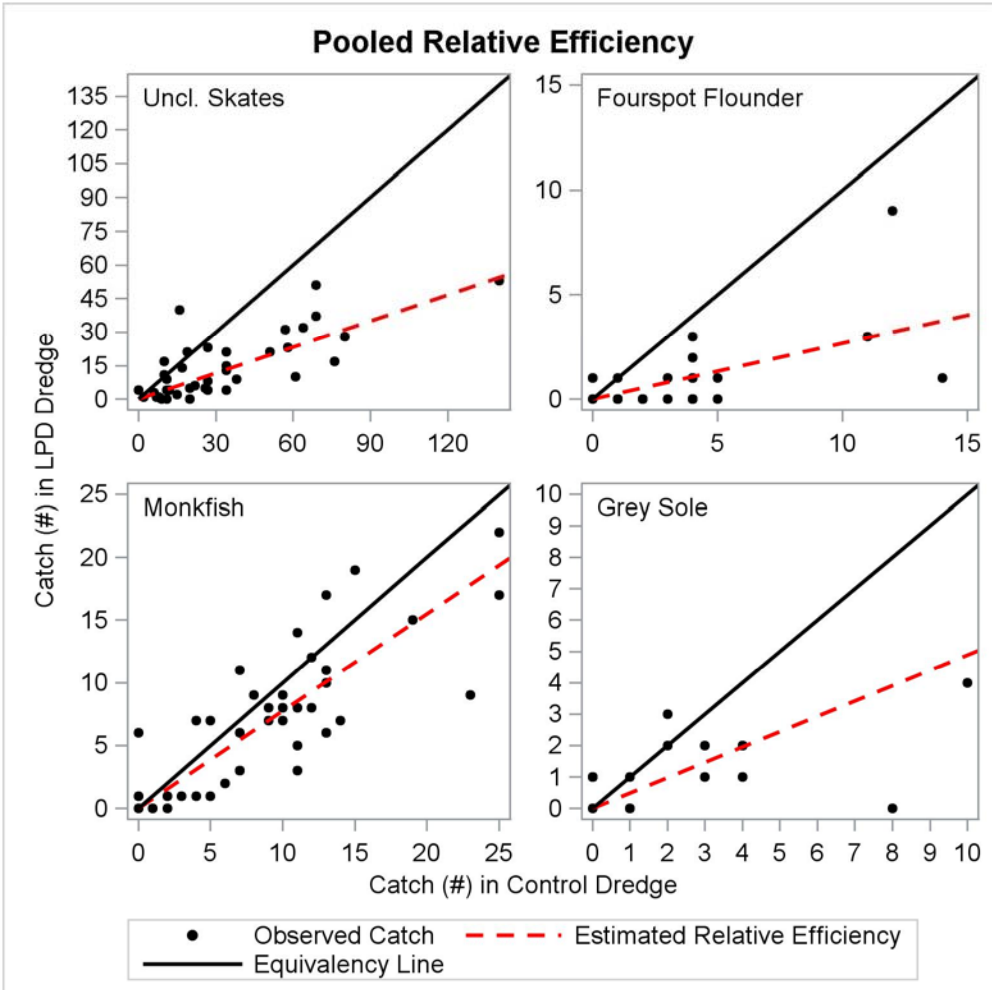


Figure 28. Total pooled catches LPD dredge vs. control dredge (CFFTDD) on the F/V Wisdom cruise. Model output from the analysis of the unpooled data indicated that length was not a significant predictor and catch data was pooled over length. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one. For other than "intercept only" models all covariates were held at their cruise means (continuous variable) or median (categorical variable e.g. Beaufort number))

Table 14. GLMM models examining the catch data from the F/V Wisdom cruise. Results are presented from the model that provided the best fit to the data as supported by model comparison (minimum AIC value). Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale.

Species	Effect	Estimate	SE	DF	T_Value	P_Value	Lower_CL	Upper_CL
Sea Scallop	Intercept	-3.7520	2.901	29	-1.2930	0.2061	-9.6860	2.1816
	Length	1.2312	0.260	32	4.7289	<0.001	0.7009	1.7616
	Length^2	-0.7844	0.140	37	-5.5930	<0.001	-1.0600	-0.5086
	Hours to	0.3297	0.110	37	2.9797	0.0031	0.1121	0.5473
	Tow Duration	-0.0003	0.000	37	-1.0010	0.3176	-0.0009	0.0003
	Vessel Speed	-0.2140	0.197	37	-1.0830	0.2797	-0.6027	0.1747
	Start Depth	0.1174	0.076	37	1.5446	0.1233	-0.0321	0.2669
Unclassified Skates	Intercept	-0.9448	0.142	37	-6.6450	0.0000	-1.2330	-0.6567
Barndoor Skate	Intercept	-1.2020	0.266	35	-4.5140	0.0001	-1.7430	-0.6615
	Length	0.3441	0.133	30	2.5783	0.0104	0.0815	0.6067
	Hours to	0.2575	0.126	30	2.0319	0.0430	0.0081	0.5069
Fourspot Flounder	Intercept	-1.3170	0.220	25	-5.9620	<0.001	-1.7710	-0.8618
Grey Sole	Intercept	-0.7166	0.266	14	-2.6920	0.0175	-1.2880	-0.1456
Monkfish	Intercept	-0.2540	0.078	37	-3.2290	0.0026	-.41340	-0.0946

Model Results – FV Friendship (3:1 Control vs. 4:1 LPD)

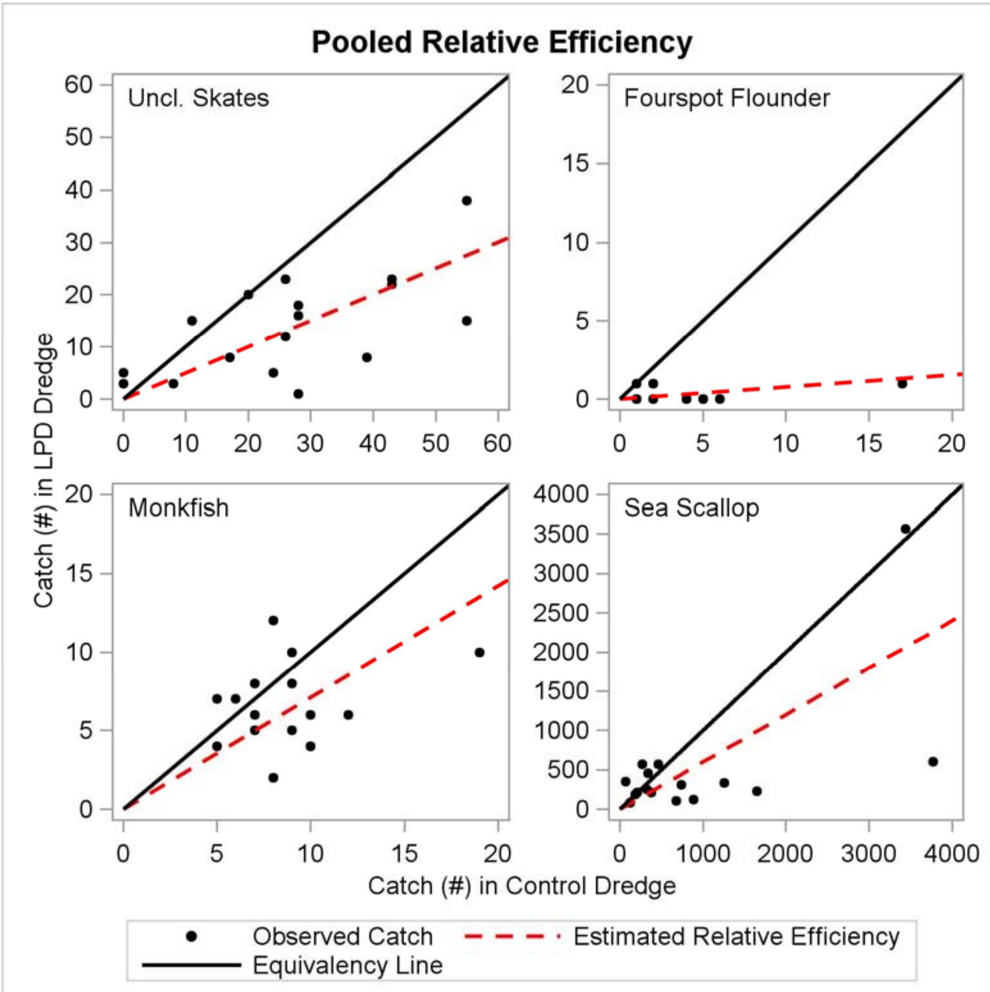


Figure 29. Total pooled catches LPD dredge vs. control dredge (CFFTDD) on the F/V Friendship cruise (3:1control) vs. 4:1 LPD). Model output from the analysis of the unpooled data indicated that length was not a significant predictor and catch data was pooled over length. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one. For other than "intercept only" models all covariates were held at their cruise means (continuous variable) or median (categorical variable e.g. Beaufort number))

Table 14. GLMM models examining the catch data from the F/V Friendship cruise (3:1control) vs. 4:1 LPD). Results are presented from the model that provided the best fit to the data as supported by model comparison (minimum AIC value). Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale.

Species	Effect	Estimate	SE	DF	T_Value	P_Value	Lower_CL	Upper_CL
Sea Scallop	Intercept	-0.5110	0.256	15	-1.989	0.0652	-1.058	0.0365
Unclassified Skates	Intercept	-5.3770	3.229	14	-1.665	0.1181	-12.30	1.5496
	Tow Duration	-0.0008	0.000	14	-2.060	0.0585	-.0016	0.0000
	Vessel Speed	1.2420	0.618	14	2.009	0.0642	-.0839	2.5680
Fourspot Flounder	Intercept	-1.2020	0.266	35	-4.514	0.0001	-1.743	-0.6615
	Length	0.3441	0.133	30	2.578	0.0104	0.081	0.6067
	Hours to	0.2575	0.126	30	2.031	0.0430	0.008	0.5069
Monkfish	Intercept	-0.3405	0.127	16	-2.680	0.0164	-.6099	-0.0711

Model Results – FV Friendship (4:1 Control vs. 3:1 LPD)

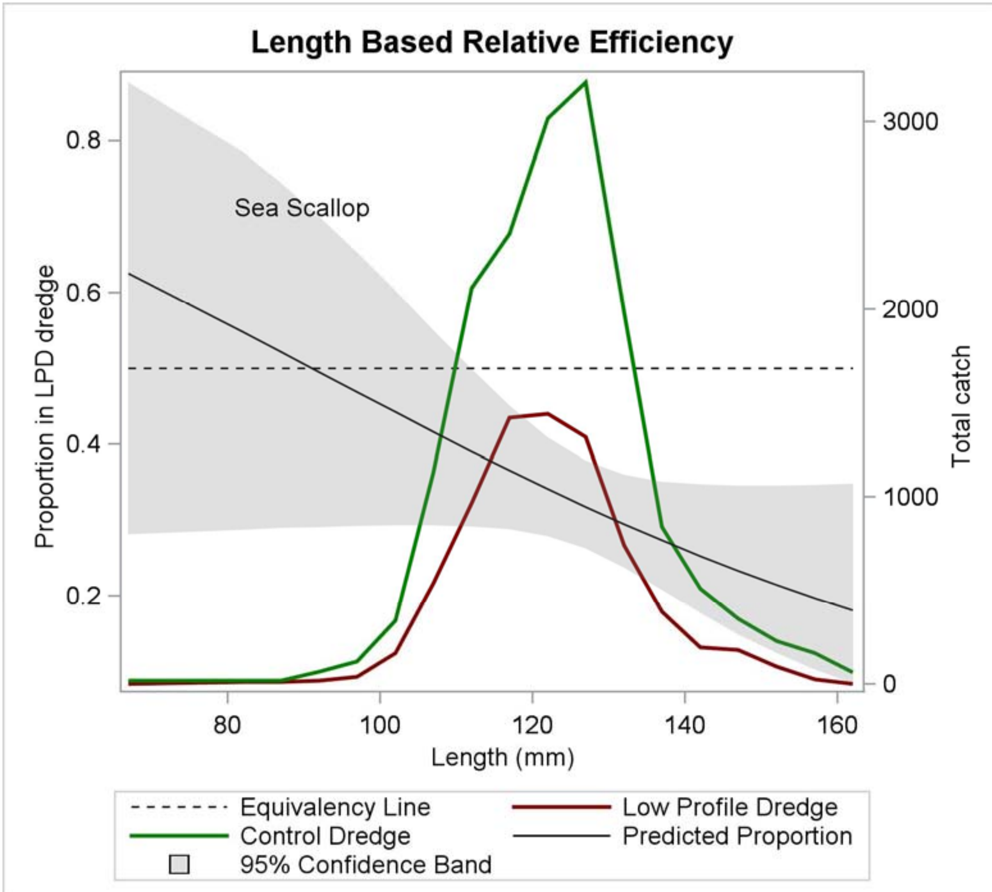


Figure 30. Length based relative efficiency for the two dredge configurations on the F/V Friendship cruise (4:1control) vs. 3:1 LPD). The grey area represents the 95% confidence band for the modeled proportion (solid black line). The green and red lines represent the observed size frequency distribution with total catch on the right hand vertical axis.

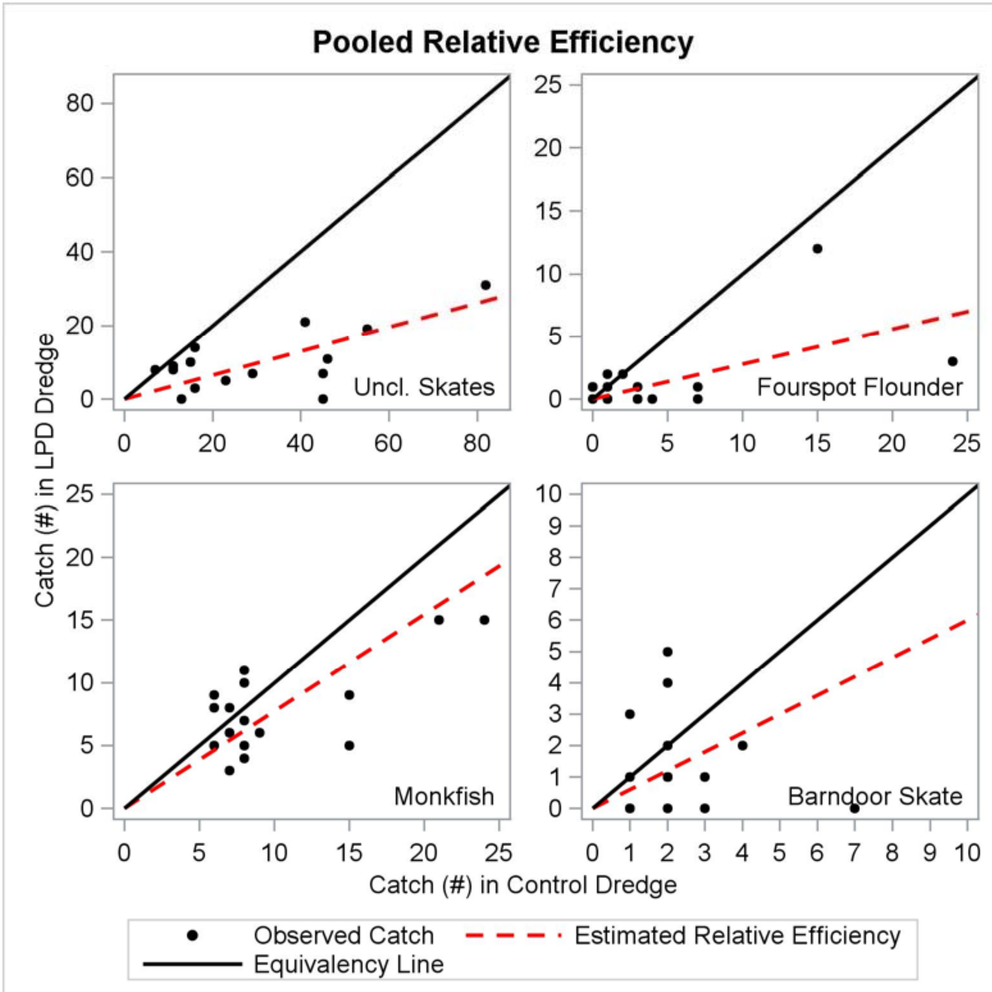


Figure 31. Total pooled catches LPD dredge vs. control dredge (CFFTDD) on the F/V Friendship cruise (4:1control) vs. 3:1 LPD). Model output from the analysis of the unpooled data indicated that length was not a significant predictor and catch data was pooled over length. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one. For other than "intercept only" models all covariates were held at their cruise means (continuous variable) or median (categorical variable e.g. Beaufort number))

Table 15. GLMM models examining the catch data from the F/V Friendship cruise (4:1control) vs. 3:1 LPD). Results are presented from the model that provided the best fit to the data as supported by model comparison (minimum AIC value). Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale.

Species	Effect	Estimate	SE	DF	T_Value	P_Value	Lower_CL	Upper_CL
Sea Scallop	Intercept	14.022	3.92	10	3.575	0.005	5.283	22.762
	Length	-0.638	0.36	12	-1.763	0.103	-1.428	0.151
	Hours to	0.326	0.19	14	1.646	0.102	-0.065	0.717
	Tow Duration	-0.004	0.00	14	-3.039	0.003	-0.006	-0.001
	Vessel Speed	-1.683	0.80	14	-2.096	0.038	-3.269	-0.096
Unclassified Skates	Intercept	-1.124	0.23	15	-4.806	<0.001	-1.623	-0.626
Barndoor Skate	Intercept	-0.511	0.27	14	-1.850	0.085	-1.103	0.081
Fourspot Flounder	Intercept	-1.274	0.41	14	-3.061	0.008	-2.166	-0.381
Monkfish	Intercept	-0.257	0.11	15	-2.170	0.046	-0.510	-0.005

Model Results – FV Westport (Prior to Corrective Actions)

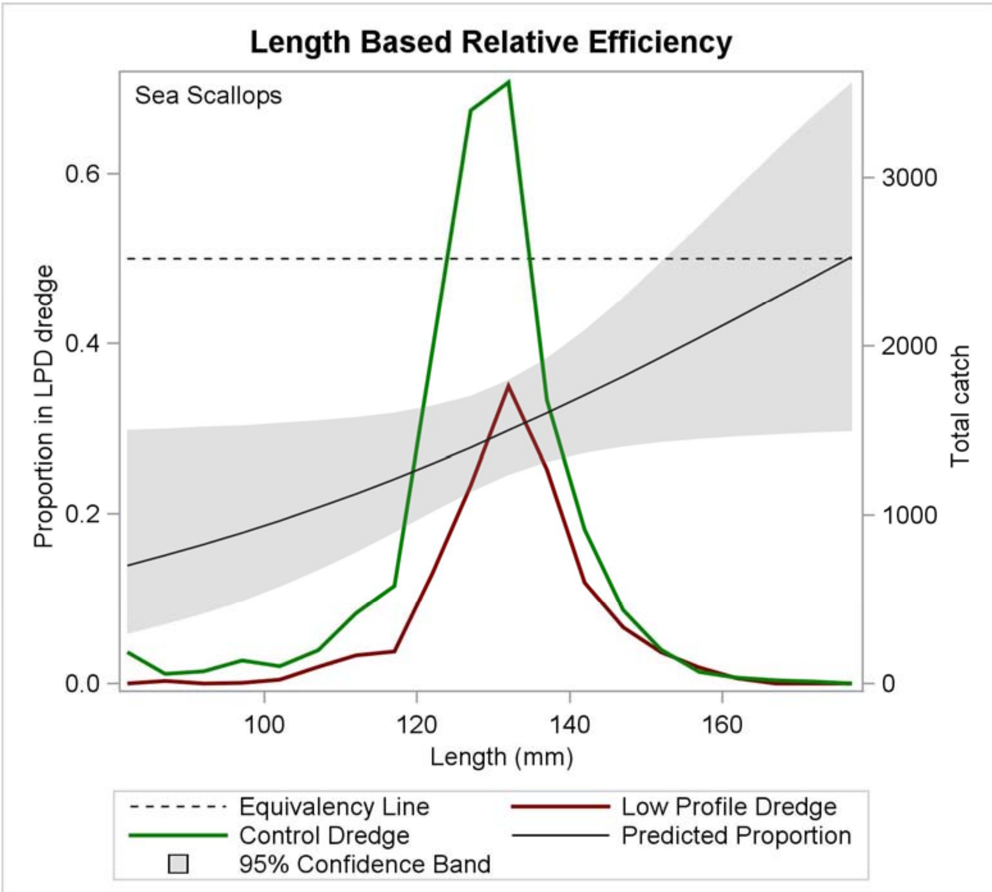


Figure 32. Length based relative efficiency for the two dredge configurations on the F/V Westport cruise (LPD2). The grey area represents the 95% confidence band for the modeled proportion (solid black line). The green and red lines represent the observed size frequency distribution with total catch on the right hand vertical axis.

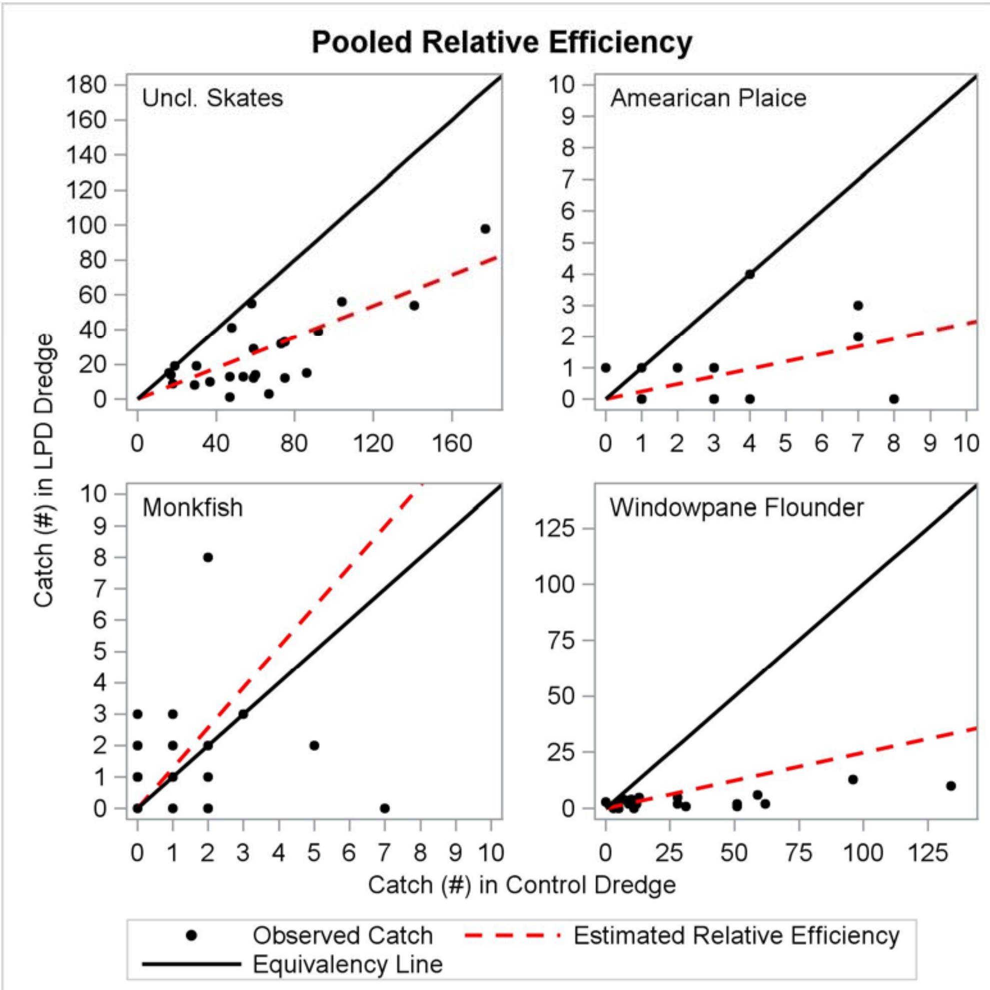


Figure 33. Total pooled catches LPD dredge vs. control dredge (CFFTDD) on the F/V Westport cruise (LPD2). Model output from the analysis of the unpooled data indicated that length was not a significant predictor and catch data was pooled over length. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one. For other than "intercept only" models all covariates were held at their cruise means (continuous variable) or median (categorical variable e.g. Beaufort number))

Table 16. GLMM models examining the catch data from the F/V Westport cruise (LPD2). Results are presented from the model that provided the best fit to the data as supported by model comparison (minimum AIC value). Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale.

Species	Effect	Estimate	SE	DF	T_Value	P_Value	Lower_CL	Upper_CL
Sea Scallop	Intercept	-0.859	0.13	22	-6.338	<0.001	-1.140	-0.578
	Length	0.578	0.28	22	2.051	0.052	-0.006	1.162
Unclassified Skates	Intercept	-3.640	2.01	19	-1.809	0.086	-7.851	0.572
	Hours to Peak	0.287	0.13	19	2.148	0.045	0.007	0.567
	Vessel Speed	0.481	0.40	19	1.186	0.250	-0.368	1.329
	Beaufort	-0.658	0.25	19	-2.574	0.019	-1.193	-0.123
	Beaufort	0.918	0.52	19	1.758	0.095	-0.175	2.012
	Beaufort	0.000	.	.	.	.	.	.
American Plaice	Intercept	-1.421	0.29	18	-4.773	<0.001	-2.047	-0.796
Windowpane	Intercept	-1.398	0.24	21	-5.637	<0.001	-1.913	-0.882
	Beaufort	-1.218	0.31	21	-3.887	0.001	-1.870	-0.566
	Beaufort	0.691	0.95	21	0.725	0.476	-1.291	2.674
	Beaufort	0.000	.	.	.	.	.	.
Monkfish	Intercept	0.251	0.41	19	0.601	0.555	-0.623	1.125

Model Results – FV Westport (After Corrective Actions)

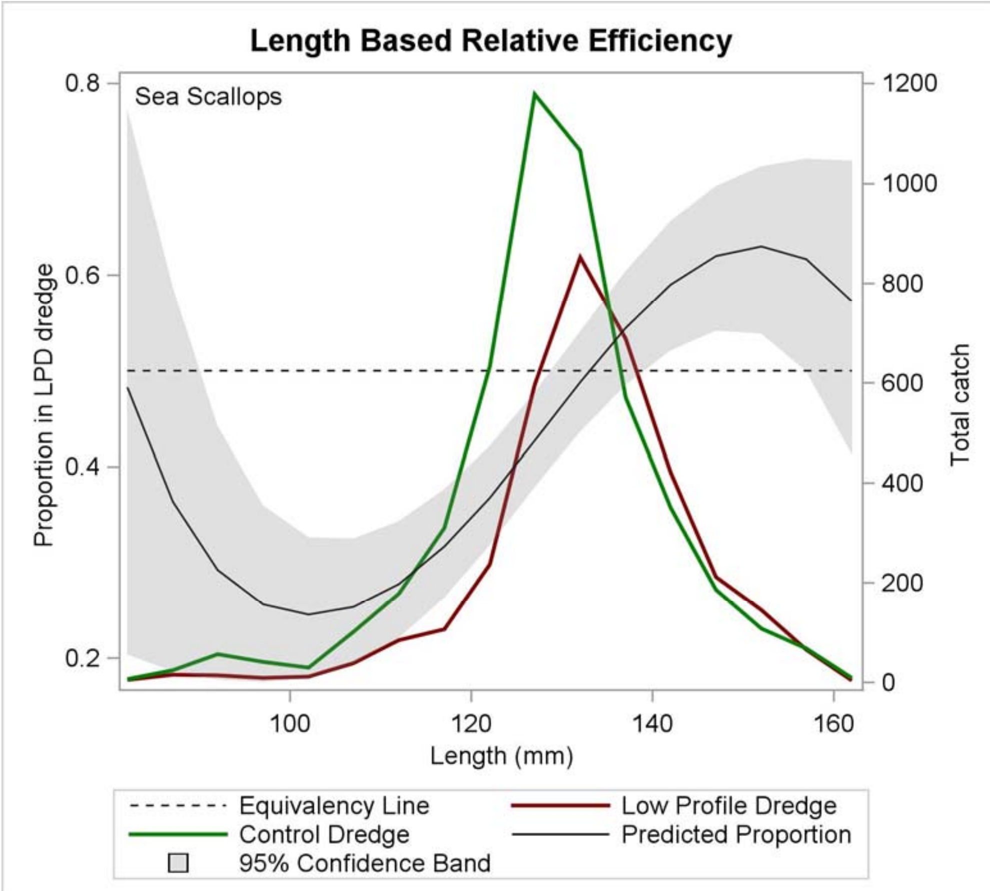


Figure 34. Length based relative efficiency for the two dredge configurations on the F/V Westport cruise (LPD3). The grey area represents the 95% confidence band for the modeled proportion (solid black line). The green and red lines represent the observed size frequency distribution with total catch on the right hand vertical axis.

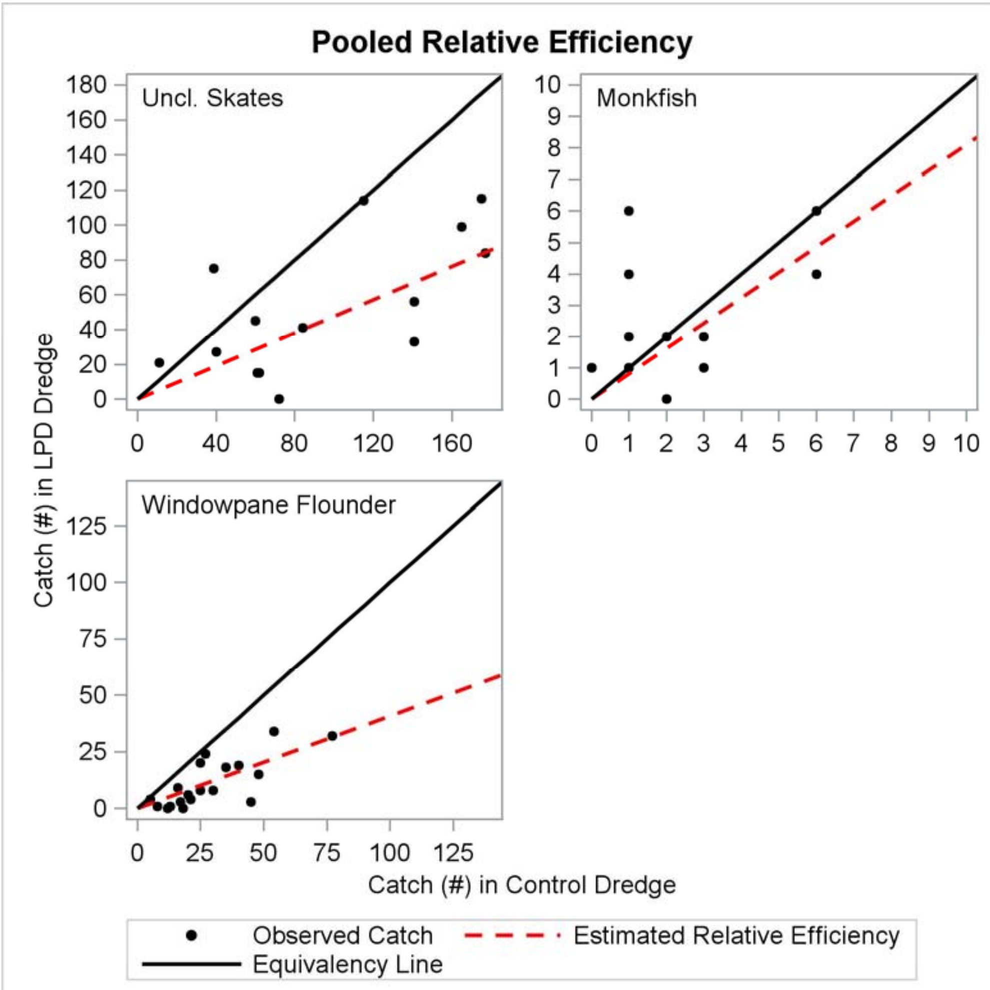


Figure 35. Total pooled catches LPD dredge vs. control dredge (CFFTDD) on the F/V Westport (LPD3). Model output from the analysis of the unpooled data indicated that length was not a significant predictor and catch data was pooled over length. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one. For other than "intercept only" models all covariates were held at their cruise means (continuous variable) or median (categorical variable e.g. Beaufort number))

Table 17. GLMM models examining the catch data from the F/V Westport cruise (LPD3). Results are presented from the model that provided the best fit to the data as supported by model comparison (minimum AIC value). Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale.

Species	Effect	Estimate	SE	DF	T_Value	P_Value	Lower_CL	Upper_CL
Sea Scallop	Intercept	-0.294	0.10	16	-2.868	0.011	-0.512	-0.077
	Length	1.505	0.24	17	6.155	<0.001	0.989	2.021
	Length^3	-0.735	0.23	16	-3.159	0.002	-1.195	-0.276
	Beaufort	-0.436	0.19	16	-2.201	0.029	-0.827	-0.045
	Beaufort	0.000	.	.	.	.	.	.
Unclassified Skates	Intercept	-0.741	0.18	18	-3.974	0.001	-1.133	-0.349
Windowpane	Intercept	4.669	1.18	14	3.930	0.002	2.121	7.217
	Hours to Peak	0.337	0.09	14	3.404	0.004	0.125	0.549
	Vessel Speed	-0.437	0.17	14	-2.528	0.024	-0.808	-0.066
	Start Depth	-0.092	0.02	14	-3.661	0.003	-0.146	-0.038
	Beaufort	-1.636	0.43	14	-3.787	0.002	-2.562	-0.709
	Beaufort	0.000	.	.	.	.	.	.
Monkfish	Intercept	3.099	1.70	15	1.817	0.089	-0.537	6.734
	Vessel Speed	-0.650	0.33	15	-1.963	0.068	-1.356	0.056

Accomplishment of the Objective

It was the intention of conservation engineers at CFF to improve upon a previously tested LPD for the purpose of developing an ecosystem friendly scallop dredge. The original LPD showed tremendous potential for the reduction of bycatch; however, there was a significant decrease in the scallop catch that had to be overcome before it could be considered a viable option for the reduction of flatfish bycatch in the scallop fishery. A redesigned version of the LPD was created with the application of CFD modelling; which, had never before been applied to the design and development of scallop dredges. This approach would increase the overall likelihood of achieving our objective of increasing the scallop catch of the LPD design to catches equivalent to that of the standard dredge. Five research trips were carried out to test the new LPD frame. Results from these trips indicate that the new LPD design achieved our objective of increasing the scallop catch to commercially acceptable levels while maintaining previously the previously observed increase in size selection. Despite this success, more improvements are needed to the LPD frame in order to prevent the frame from bowing and becoming compromised in its abilities to catch scallops. Further testing of the new LPD frame would provide for a better assessment of the frame's ability to reduce bycatch.

Evaluation and Discussion

The objective of this project was to improve upon a previously tested LPD that had shown great potential for the reduction of flatfish. The original LPD design would only be considered improved only if the scallop catch was equivalent to standard scallop dredges. Field testing of the new LPD demonstrated that overall scallop catch was not negatively impacted by this modification. Based upon this criterion the project was an overall success.

The co-occurrence of managed flatfish stocks on scallop fishing grounds and a precipitous decrease in ACLs for these species puts the scallop fishery at risk for triggering AMs; which, could take the form of area closures. If these closures were to occur during the peak of the scallop fishing year millions of dollars in potential revenue would be lost. While area closures are effective means to reducing bycatch interactions, optimized gear modifications can also accomplish this reduction without displacing fishing effort (Harrington et al. 2005; Jennings and Revill 2007). Successful gear modifications within trawl and dredge fisheries can also reduce expenses while increasing catch selectivity and ultimately reduce impact to the ecosystem (Kennelly and Broadhurst 1995; Broadhurst 2000; Harrington et al. 2005). The early design and development of optimized fishing gears can be relatively expensive due to the costs of charting and outfitting a vessel for sea trials, bottleneck the rate of development for new sustainable fishing gears.

The development of fishing gears solely using the standard method of sea trial comparisons slows the overall development of sustainable gears. Conservation engineers often have a limited number of days for which they can test an experimental gear. This means that only a limited number of attempts can be done to correct any observed deficiencies in the experimental gear. Otherwise, too many corrective attempts yields datasets without the necessary sample size to evaluate the significance of the results. Earlier projects evaluating the original LPD experienced this problem, as a number of different actions were undertaken in attempt to correct observed reductions in scallop catch. With the past project in mind, conservation engineers at CFF began investigating ways of evaluating performance of scallop dredges prior to undergoing sea trials in order to increase the likelihood of success while reducing the overall costs of development.

CFF decided to focus on the depressor plate angle and the flow pattern it created as performance predictor that could be evaluated without the need for sea trials. During the testing of the original LPD it became apparent that the reduced height and corresponding reduced depressor plate angle of 22.5º was having a significant influence on the hydrodynamics of the dredge. Based on the observations from the testing of the original LPD, CSAR in Newfoundland was contracted to model the flow of water around both the original LPD frames and the proposed prototype LPD. To do this CFF researchers employed CFD modelling; which, had never before been used for the development of scallop dredges. This approach has been used to optimize trawl gear and is capable of predicting the main performance parameters of trawls during sea trials (Meyler 2008, Hermannsson 2014 and Nguyen et al. 2015). Results from the CFD analysis demonstrated that the original LPD failed to generate the complex flow believed to facilitate the capture of scallops; while, the new LPD with a 45º depressor plate was generated a complex flow behind the cutting bar and depressor plate (**Figure 6**). After evaluating the CFD analysis a new frame was confidently built and tested. Without the application of a CFD analysis this project would not have been nearly as successful. This approach was so informative that CFF went onto submit and receive a sea scallop Research Set-Aside (RSA) grant to further develop the application for scallop dredge development. This approach has the potential to drastically reduce the cost and time it takes to develop alternative scallop dredges.

The performance of the LPD varied from trip to trip as indicated by both the simple analysis and statistical modelling. The differences in scallop catch performance could be due in part to the differences in where the trips took place. For most of the five research trips, the statistical model predicted an increased selection for scallops as length increased. However, the FV Celtic observed an opposite trend in length based efficiency, a decrease in catch efficiency for larger scallops. A majority of the FV Celtic took place in the Nantucket Lightship Access Area; which, had at the time of testing been closed to fishing. Scallop access areas tend to have higher densities of scallops than areas open to fishing year round (Hart and Rago 2004). It is possible that in this area, the high density of scallops was clogging the gear obscuring any changes in selectivity. It must also be noted that any assumptions about differences in the selective properties of the LPD are relative to the control gear and does not represent the absolute selectivity of the dredge.

The only satisfactory means of describing how selectivity has changed in the development of new towed gears is by comparing selectivity curves generated by selectivity experiments (Wileman et al. 1996). An experiment utilizing a cover net would allow for the generation of selectivity curve for the new LPD; which, could then be compared to selectivity curves for standard scallop dredges for a precise determination of differences in the selective properties LPD.

This project as well as past projects have been limited in their ability to assess the impacts gear modifications have on flatfish bycatch due to low numbers of observations. Noisy data sets and rare events like bycatch interactions often require a greater number of observations to determine the significance of the results. The application of dredge cover net could also aid conservation engineers in the development of scallop dredges for the reduction of bycatch by retaining fish escaping through the dredge bag, providing more observations. The reduced height of the LPD was designed with the intention of reducing bycatch by facilitating the ability of fish to swim over the dredge. However, when a fish is overcome by the LPD the reduced height of the frame increases the likelihood of escape through the twine top by reducing the distance from the twine top and the seafloor. A cover net has already been developed and tested, should proposed projects to further develop the cover net as a tool it will undoubtedly be used to evaluate the performance of the LPD.

The development of the new LPD was an overall success, the new LPD design catches scallops at rate equivalent to standard dredges while still appearing to have the same selective qualities observed during previous projects testing the LPD. The application of technology and analysis novel to the sea scallop fishery greatly enhanced this project and the likelihood of achieving our objective of developing an ecosystem friendly scallop dredge. However, before the dredge is to be used by the scallop fishery design changes are required to prevent the frame from bowing. Further development of the LPD would also benefit from the application of a dredge cover net.

Project Acknowledgements

The successful completion of this project could not have done without the aid and support of our fishing industry partners at Eastern Fisheries and Quinn Fisheries. Thanks to the captains and crew members of the FV Celtic, FV Arcturus, FV Wisdom, FV Friendship, FV Westport. Special thanks to Tim Lenling for overseeing the building of the new LPD. Finally, there were CFF staff members, both former and present, not formally listed on the report who volunteered time and effort to this project so special thanks to Melissa Campbell, Rachel Simpson, Liese Siemman, and Mary Newton-Lima for their support in completing this project.

Dissemination of Project Results

Results from this project will be made available to the public online at www.cfarm.org. CFF will also work collaborate with an industry periodical like Commercial Fisheries News to disseminate information about the results of this project to the fishing industry.

Literature Cited

Cadigan, N.G. and J. J. Dowden. 2009. Statistical inference about relative efficiency of a new survey protocol, based on paired-tow survey calibration data. Fish. Bull. 108:15-29.

Cadigan, N.G., S.J. Walsh, and W. Brodie. 2006. Relative efficiency of the Wilfred Templeman and Alfred Needler research vessels using a Campelen 1800 shrimp trawl in NAFO Subdivisions 3Ps and divisions 3LN. Can Sci Advis Secret Res Doc 2006/085; 59 pp.

Davis, F., Thompson, K., and Rudders, D. 2012. Testing of Scallop Dredge Bag Design for Flatfish Bycatch Reduction. NOAA-NMFS Scallop Research Set Aside Program. NA12NMF4540041.

Harrington, J. K., Myers, R.A., and Rosenberg, A. A. 2005. Wasted fishery resources: discarded bycatch in the USA. Fish and Fisheries, 6(4), 350-361.

Hermannsson, E. 2014. Hydrodynamic Shape Optimization of Trawl Doors with Three-Dimensional Computational Fluid Dynamics Models and Local Surrogates. Master's Thesis. KTH Royal Institute of Technology, Stockholm, Sweden. 241 pp.

Holst, R. and A. Revill. 2009. A simple statistical method for catch comparison studies. Fisheries Research. 95: 254-259.

Jennings, S., and Revill, A. S. 2007. The role of gear technologists in supporting an ecosystem approach to fisheries. ICES Journal of Marine Science: Journal du Conseil, 64(8), 1525-1534.

Kenelly, S. J., and Broadhurst, M. K. 1995. Fishermen and scientist solving bycatch problems: Examples from Australia and Possibilities for the Northeastern United States. Solving Bycatch: Considerations for Today and Tomorrow. Alaska Sea Grant College Program Report. No. 96-03.

Littell, R.C., G.A. Milliken, W. Stroup, R. Wolfinger, and W.O. Schabenberger. 2006. SAS for Mixed Models (2nd ed.). Cary, NC. SAS Institute Inc.

Millar, R.B., M.K. Broadhurst, and W.G. Macbeth. 2004. Modeling between-haul variability in the size selectivity of trawls. Fisheries Research. 67:171-181.

Miller TJ. 2013. A comparison of hierarchical models for relative catch efficiency based on paired-gear data for US Northwest Atlantic fish stocks. Canadian Journal of Fisheries and Aquatic Sciences 70(9):1306-1316.

Nguyen, TX, Winger, PD, Orr, D, Legge, G, Delouche, H, and Gardner, A. 2015. Computer simulation and flume tank testing of scale engineering models: How well do these techniques predict full-scale at-sea performance of bottom trawls? Fisheries Research 161: 217-225.

O'Keefe, C and DeCelles, G. 2013. Forming a partnership to avoid bycatch. Fisheries 38: 434-444.

R Core Team 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ryer, C. H. 2008. A review of flatfish behavior relative to trawls. Fisheries Research, 90(1), 138-146.

Ryer, C. H., Lemke, J. L., Boersma, K., & Levas, S. 2008. Adaptive coloration, behavior and predation vulnerability in three juvenile north Pacific flatfishes. Journal of Experimental Marine Biology and Ecology, 359(1), 62-66.

Smolowitz, R and Weeks, M. 2010. Testing of a low profile excluder dredge for winter flounder bycatch reduction. Final Report for the Challenge Grant Program for Conservation Engineering. NOAA Grant NA09NMF4720414. 19pp.

Smolowitz, R., Milliken, H., and Weeks, M. 2012. Design, evolution, and assessment of a sea turtle deflector dredge for the U.S. Northwest Atlantic sea scallop fishery: impacts on fish bycatch. N. Am. J. Fish. Manage. 32: 65-76.

Wileman, D. A., R. S. T. Ferro, R. Fonteyne & R. B. Millar. 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Coop. Res. Rep. No. 215. Copenhagen. 126 pp.

Appendix A: Data Tables

Table 1. Catch by species for each level of cruise and gear factor used to partition the data set. Minimum number of valid tow pairs (5) and minimum total catch (50) were used as thresholds for inclusion in the GLMM modelling.

Cruise	Species	Scope	LPD_Category	Tows	Control	LPD	Total
F/V Celtic	Unclassified Skates	3:1 vs. 3:1	LPD 1	33	3,748	3,970	7,718
	Summer Flounder	3:1 vs. 3:1	LPD 1	26	25	27	52
	Windowpane	3:1 vs. 3:1	LPD 1	33	823	705	1528
	Monkfish	3:1 vs. 3:1	LPD 1	33	205	244	449
	Sea Scallops	3:1 vs. 3:1	LPD 1	30	54,909	62,76	117,67
F/V Arcturus	Unclassified Skates	3:1 vs. 3:1	LPD 1	35	703	1284	1987
	Barndoor Skates	3:1 vs. 3:1	LPD 1	34	69	176	245
	Fourspot Flounder	3:1 vs. 3:1	LPD 1	26	21	66	87
	Windowpane	3:1 vs. 3:1	LPD 1	6	19	50	69
	Monkfish	3:1 vs. 3:1	LPD 1	35	152	208	360
	Sea Scallops	3:1 vs. 3:1	LPD 1	22	14,582	21,12	35,703
F/V Wisdom	Unclassified Skates	3:1 vs. 3:1	LPD 1	38	1,232	548	1780
	Barndoor Skates	3:1 vs. 3:1	LPD 1	38	274	146	420
	Fourspot Flounder	3:1 vs. 3:1	LPD 1	27	97	26	123
	Grey Sole	3:1 vs. 3:1	LPD 1	16	43	21	64
	Monkfish	3:1 vs. 3:1	LPD 1	39	370	287	657
	Sea Scallops	3:1 vs. 3:1	LPD 1	33	20,465	14,65	35,116
F/V	Unclassified Skates	3:1(control) vs.	LPD 1	17	451	235	686
	Fourspot Flounder	3:1(control) vs.	LPD 1	13	52	4	56
	Monkfish	3:1(control) vs.	LPD 1	17	149	106	255
	Sea Scallops	3:1(control) vs.	LPD 1	16	14,784	8,168	22,952
	Unclassified Skates	4:1(control) vs.	LPD 1	16	470	163	633
	Barndoor Skates	4:1(control) vs.	LPD 1	15	35	21	56
	Fourspot Flounder	4:1(control) vs.	LPD 1	16	72	24	96
	Monkfish	4:1(control) vs.	LPD 1	16	163	126	289
	Sea Scallops	4:1(control) vs.	LPD 1	13	16,583	7,539	24,122
F/V Westport	Unclassified Skates	3:1 vs. 3:1	LPD 2	24	1,488	614	2102
	American Plaice	3:1 vs. 3:1	LPD 2	19	58	14	72
	Windowpane	3:1 vs. 3:1	LPD 2	24	642	69	711
	Monkfish	3:1 vs. 3:1	LPD 2	21	30	34	64
	Sea Scallops	3:1 vs. 3:1	LPD 2	23	14,032	6,613	20,645
	Unclassified Skates	3:1 vs. 3:1	LPD 3	19	2,487	1,290	3777
	Windowpane	3:1 vs. 3:1	LPD 3	19	536	209	745

Cruise	Species	Scope	LPD_Category	Tows	Control	LPD	Total
	Monkfish	3:1 vs. 3:1	LPD 3	17	76	59	135
	Sea Scallops	3:1 vs. 3:1	LPD 3	18	4,918	3,507	8,425

Table 3. Results from model building showing fixed and random effects included in the final model as assessed via minimum AIC value. Catch data was partitioned into cruise/gear/species level groupings.

Cruise	Species	Scope	LPD	Fixed Effects	Random
F/V Celtic	Unclassified Skates	3:1 vs. 3:1	LPD1	Hours to Peak, Beaufort Number	Intercept
	Summer Flounder	3:1 vs. 3:1	LPD1	Intercept	None
	Windowpane	3:1 vs. 3:1	LPD1	Hours to Peak, Start Depth	Intercept
	Monkfish	3:1 vs. 3:1	LPD1	Intercept	Intercept
	Sea Scallops	3:1 vs. 3:1	LPD1	Length, Length^2, Length^3	Intercept,
F/V Arcturus	Unclassified Skates	3:1 vs. 3:1	LPD1	Intercept	Intercept
	Barndoor Skates	3:1 vs. 3:1	LPD1	Hours to Peak, Start Depth, Beaufort Number	Intercept
	Fourspot Flounder	3:1 vs. 3:1	LPD1	Start Depth	Intercept
	Windowpane	3:1 vs. 3:1	LPD1	Tow Duration	Intercept
	Monkfish	3:1 vs. 3:1	LPD1	Intercept	Intercept
	Sea Scallops	3:1 vs. 3:1	LPD1	Length, Length^2, Length^3, Hours to Peak , Start Depth, Beaufort	Intercept,
F/V Wisdom	Unclassified Skates	3:1 vs. 3:1	LPD1	Intercept	Intercept
	Barndoor Skates	3:1 vs. 3:1	LPD1	Length, Hours to Peak	Intercept
	Fourspot Flounder	3:1 vs. 3:1	LPD1	Intercept	None
	Grey Sole	3:1 vs. 3:1	LPD1	Intercept	Intercept
	Monkfish	3:1 vs. 3:1	LPD1	Intercept	Intercept
	Sea Scallops	3:1 vs. 3:1	LPD1	Length, Length^2, Hours to Peak, Tow Duration, Vessel Speed, Start	Intercept,
F/V	Unclassified Skates	3:1(control) vs.	LPD1	Tow Duration, Vessel Speed	Intercept
	Fourspot Flounder	3:1(control) vs.	LPD1	Intercept	None
	Monkfish	3:1(control) vs.	LPD1	Intercept	None
	Sea Scallops	3:1(control) vs.	LPD1	Intercept	Intercept
	Unclassified Skates	4:1(control) vs.	LPD1	Intercept	Intercept
	Barndoor Skates	4:1(control) vs.	LPD1	Intercept	None
	Fourspot Flounder	4:1(control) vs.	LPD1	Intercept	Intercept

Cruise	Species	Scope	LPD	Fixed Effects	Random
	Monkfish	4:1(control) vs.	LPD1	Intercept	None
	Sea Scallops	4:1(control) vs.	LPD1	Length, Hours to Peak, Tow Duration, Vessel Speed	Intercept,
F/V Westport	Unclassified Skates	3:1 vs. 3:1	LPD2	Hours to Peak, Vessel Speed, Beaufort Number	Intercept
	American Plaice	3:1 vs. 3:1	LPD2	Intercept	None
	Windowpane	3:1 vs. 3:1	LPD2	Beaufort Number	Intercept
	Monkfish	3:1 vs. 3:1	LPD2	Intercept	Intercept
	Sea Scallops	3:1 vs. 3:1	LPD2	Length	Intercept
	Unclassified Skates	3:1 vs. 3:1	LPD3	Intercept	Intercept
	Windowpane	3:1 vs. 3:1	LPD3	Hours to Peak, Vessel Speed, Start Depth, Beaufort Number	None
	Monkfish	3:1 vs. 3:1	LPD3	Vessel Speed	None
	Sea Scallops	3:1 vs. 3:1	LPD3	Length, Length^3, Beaufort Number	Intercept,

Appendix B: GLMM Model Details

Statistical Models – GLMM

Catch data from the paired tows provided the information to estimate differences in the relative efficiency for the gear combinations tested. This analysis is based on the analytical approach in Cadigan et al. 2006.

Assume that each gear combination tested in this experiment has a unique catchability. Let q_r equal the catchability of the LPD dredge and q_f equals the catchability of the CFFTDD dredge used in the study. The efficiency of the LPD dredge relative to the CFFTDD dredge will be equivalent to the ratio of the two catchabilities:

$$\rho_l = \frac{q_r}{q_f} \tag{1}$$

The catchabilities of each gear are not measured directly. However, within the context of the paired design, assuming that spatial heterogeneity in scallop/fish density is minimized, observed differences in scallop/fish catch for each vessel will reflect differences in the catchabilities of the gear combinations tested.

Let C_{iv} represent the scallop/fish catch at station i by dredge v, where $v=r$ denotes the LPD dredge and $v=f$ denotes the CFFTDD. Let λ_{ir} represent the scallop/fish density for the i^{th} station by the 5 row dredge and λ_{if} the scallop/fish density encountered by the 7 row dredge. We assume that due to random, small scale variability in animal density as well as the vagaries of gear performance at tow i, the densities encountered by the two gears may vary as a result of small-scale spatial heterogeneity as reflected by the relationship between scallop/fish patch size and coverage by a paired tow. The probability that a scallop/fish is captured during a standardized tow is given as q_r and q_f. These probabilities can be different for each vessel, but are expected to be constant across stations. Assuming that capture is a Poisson process with mean equal to variance, then the expected catch by the CFFTDD dredge is given by:

$$E(C_{if}) = q_f \lambda_{if} = \mu_i \tag{2}$$

The catch by the LPD dredge is also a Poisson random variable with:

$$E(C_{ir}) = q_r \lambda_{ir} = \rho \mu_i \exp(\delta_i) \tag{3}$$

where δ_i =log (λ_{ir}/ λ_{if}). For each station, if the standardized density of scallops /fish encountered by both dredges is the same, then δ_i=0.

If the dredges encounter the same scallop/fish density for a given tow, (i.e. λ_{ir}= λ_{if}), then ρ can be estimated via a Poisson generalized linear model (GLM). This approach, however, can be complicated especially if there are large numbers of stations and scallop/fish lengths (Cadigan et al. 2006). The preferred approach is to use the conditional distribution of the catch by the 5 row at station i, given the total non-zero catch of both vessels at that station. Let c_i represent the observed value of the total catch. The conditional distribution of C_{ir} given C_i=c_i is binomial with:

$$\Pr\left(C_{ic} = x \middle| C_i = c_i\right) = \binom{c_i}{x} p^x (1-p)^{r_i - x} \tag{4}$$

where p=ρ/(1+ρ) is the probability that a scallop/fish captured by the 5 row dredge. In this approach, the only unknown parameter is ρ and the requirement to estimate μ for each station is eliminated as would be required in the direct GLM approach (equations 2 & 3). For the binomial distribution $E(C_{ir})$=$c_i p$ and $Var(C_i r)$=$c_i p/(1-p)$. Therefore:

$$\log\left(\frac{p}{1-p}\right) = \log(\rho) = \beta \tag{5}$$

The model in equation 5, however, does not account for spatial heterogeneity in the densities encountered by the two gears for a given tow. If such heterogeneity does exist then the model becomes:

$$\log\left(\frac{p}{1-p}\right) = \beta + \delta_i \tag{6}$$

where δ_i is a random effect assumed to be normally distributed with a mean=0 and variance=σ^2. This model is the formulation used to estimate the gear effect $exp(\beta_0)$ when catch per tow is pooled over lengths.

Often, gear modifications can result in changes to the length based relative efficiency of the two gears. In those instances, the potential exists for the catchability at length (l) to vary. Models to describe length effects are extensions of the models in the previous section to describe the total scallop catch per tow. Again, assuming that between-pair differences in standardized animal density exist, a binomial logistic regression GLMM for a range of length groups would be:

$$\log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \delta_i + \beta_1 l, \delta_i \sim N(0, \sigma^2), i = 1, \ldots, n. \tag{7}$$

In this model, the intercept (*β₀*) is allowed to vary randomly with respect to station.

The potential exists, however, that there will be variability in both the number as well as the length distributions of scallops/fish encountered within a tow pair. In this situation, a random effects model that again allows the intercept to vary randomly between tows is appropriate (Cadigan and Dowden, 2009). This model is given below:

$$\log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \delta_{i0} + \beta_1 * l, \delta_{ij} \sim N(0, \sigma_j^2), i = 1,..., n, j = 0,1. \quad (8)$$

Adjustments for sub-sampling of the catch

Additional adjustments to the models were required to account for sub-sampling of the catch. In most instances, due to high scallop catch volume, particular tows were sub-sampled. This is accomplished by randomly selecting a one bushel sample for length frequency analysis. Most finfish were sampled completely without subsampling but there were some tows with large catches of windowpane flounder and the catch was also subsampled. One approach to accounting for this practice is to use the expanded catches. For example, if half of the total catch was measured for length frequency, multiplying the observed catch by two would result in an estimate of the total catch at length for the tow. This approach would overinflate the sample size resulting in an underestimate of the variance, increasing the chances of spurious statistical inference (Millar et al. 2004; Holst and Revill, 2009). In our experiment, the proportion sub-sampled was not consistent between tows as only a one bushel sub-sample was taken regardless of catch size. This difference must be accounted for in the analysis to ensure that common units of effort are compared. The subsampling offset adjusts the linear predictor of the model to account for differential scaling in the data (i.e. tow length, subsampling), in the case of most finfish that were fully sampled, the subsampling rate was 1 for both gears. Since the offset is the log of the quotient of the sampling rate of both gears and the log(1/1) = 0, nothing is added to the linear predictor for windowpane flounder.

Let q_{ir} equal the sub-sampling fraction at station *i* for the vessel *r*. This adjustment results in a modification to the logistic regression model:

$$\log\left(\frac{p_i}{1+p_i}\right) = \beta_0 + \delta_i + (\beta_1 * l_i) + \log\left(\frac{q_{ir}}{q_{if}}\right), \delta_{ij} \sim N(0, \sigma_j^2), i = 1,..., n. \quad (9)$$

The last term in the model represents an offset in the logistic regression (Littell et al. 2006).

Our analysis of the efficiency of the LPD dredge relative to the CFTDD dredge consisted of multiple levels of examination. For all species, the full model consisted of unpooled (by length) catch data:

$$\log\left(\frac{p_i}{1+p_i}\right) = \beta_0 + \delta_i + (\beta_1 * l_i) + \log\left(\frac{q_{ir}}{q_{if}}\right), \delta_{ij} \sim N(0, \sigma_j^2), i = 1..n, j = 0,1.... (10)$$

The symbol f_{ij} equals the categorical variable denoting dredge frame configuration. Model fit was assessed by AIC. If AIC and factor significance indicated that length was not a significant factor in predicting relative efficiency, the data was pooled over length. The random intercept model was evaluated to assess relative differences in total catch (see equation 6).

The approach of Holst and Revill (2009) represents a straightforward approach to model nonlinearity in the proportion at length. This method utilizes the incorporation of low order polynomials to capture deviations form a linear fit to the proportion at length. Typically 2nd order polynomials are sufficient, although at times the inclusion of 3rd order polynomials are supported

We used SAS/STAT® PROC GLIMMIX v. 9.2 to fit the generalized linear mixed effects models.