Development of an Extended Link Apron: A Broad Range Tool for Bycatch Reduction

Final Report

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Submitted By

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Project Title: Development of an Extended Link Apron: A Broad Range Tool for Bycatch Reduction

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Organization: Coonamessett Farm Foundation, Inc.

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Executive Summary

In 2016, Coonamessett Farm Foundation, Inc. (CFF) developed and tested an extended link apron with increased inter-ring spacing in both the horizontal and vertical directions. By increasing the inter-ring spacing of the dredge apron, mechanical sorting of the catch should improve, thereby reducing the bycatch of finfish and pre-recruit sea scallops. Results from this study indicated that extended link aprons warranted further research; however, changes to the apron were necessary to improve scallop catch efficiency. We hypothesized that increasing the inter-ring spacing in just the vertical direction would have equivalent catches of commercial-sized scallops while maintaining the bycatch reductions previously observed and improving sea scallop size selection.

During this project, the vertically extended link apron was tested during four research cruises aboard commercial sea scallop vessels. With the exception of the first research cruise, the participating vessel supplied their dredges for the gear comparison study, and the experimental gear for these cruises was the vessel's dredge modified to incorporate the extended link apron. Two dredges were towed simultaneously using commercially representative parameters. Upon completion of the tow, both dredges were emptied on deck and catch was sorted by scientists with assistance from the vessel's crew. Scallop and finfish catch was counted, weighed, and measured for each valid tow. Following the completion of all four cruises, the tow data were analyzed using appropriate statistical analyses.

Our results demonstrate that the vertically extended link apron is capable of significantly reducing windowpane flounder bycatch while having an equivalent or greater catch efficiency for larger scallops compared to a standard apron. There was a trend of reduced bycatch of other flatfish species like yellowtail flounder despite relatively low catches of these species. The overall performance of this modification satisfied our research objective of improving the extended link apron scallop catch efficiency while reducing the bycatch of non-target species.

The findings from this study provide fisheries managers with a gear-based solution for the reduction of incidental mortality to small scallops and the bycatch of flatfish in the sea scallop fishery. Our results in combination with findings from other studies investigating the seasonal and spatial distribution of scallop dredge bycatch can be used by fisheries managers to sustainably exploit exceptional recruitment events while minimizing fishery impacts to incoming year classes of scallops and non-target species.

Project timeline

Funding period: March 1, 2017 – May 29, 2018

Field Testing and Data Collection: September 9, 2017 – May 3, 2018

Background

Valued at $486.1 million USD in 2016, landings of sea scallops (*Placopecten magellanicus*) represent a significant portion of fisheries revenue in the Northeast US (NMFS 2016). Despite a reduction in fishing effort, landings have increased due to the rotational management of sea scallop access areas (Rago & Hart 2006, He et al. 2004, Howard 2004). The establishment of the rotational management of sea scallop areas would not have been possible without a close collaboration between the fishing industry, managers, and research.

Through the Research Set-Aside (RSA) program, the sea scallop fishery has funded research initiatives to develop and optimize resource surveys, understand the ecology of protected species on scalloping grounds, and reduce bycatch and incidental mortality within the scallop fishery. This progressive program enabled the sea scallop fishery to efficiently respond to emergent bycatch problems, thereby limiting economic disruptions from emergency management actions. Exceptional and unpredicted sea scallop recruitment events in recent years have highlighted the need for the continued development of sustainable harvest technology in the sea scallop fishery.

Fisheries managers must balance the harvest of sea scallops with the protection of both the resource and non-target species thereby optimizing the fishery. Sea scallop resources are not guaranteed and forgoing the exploitation of exceptional recruitment events results in a decreased economic potential for the fishery (Bethoney et al. 2016, Stokesbury et al. 2007). Multiple large recruitment events within access areas and the co-occurrence of scallop fishing can lead to the mass mortality of pre-recruit scallops (Stokesbury et al. 2011a, Stokesbury et al. 2011b). Furthermore, many important bycatch species appear to have seasonal patterns of distribution and abundance on sea scallop fishing grounds (Leavitt et al. 2018, Winton et al. 2017). Spatial management through time/area closures can be used to restrict fishing effort on bycatch hotspots, but these strategies are challenged by density-dependent effects, the diversity of non-target species on fishing grounds, and increased operational costs (Winton et al. 2017, Smolowitz et al. 2016, Pastoors et al. 2000, Murray et al. 2000). Gear modifications are a win-win solution to mitigating fishery impacts to habitat, juveniles of the species, and non-target species, while still allowing for the sustainable harvest of the target species (Jennings & Revill 2007, Valdermarsen & Suuronen 2003).

Previous research

Coonamessett Farm Foundation, Inc. (CFF) has almost a decade of experience working collaboratively with the commercial scallop fishery to develop gear solutions for the mitigation of dredge impacts to marine ecosystems (Davis et al. 2016, Davis et al. 2015, Davis et al. 2014, Davis et al. 2013, Smolowitz et al. 2012, Smolowitz et al. 2010). In 2016, we began researching ways to use materials readily found on scallop vessels to develop practical gear modifications to reduce bycatch and incidental mortality in the fishery. No additional operating costs would be incurred by the fishery when using a modification created using this strategy.

The 4” (10.16 cm) steel rings of a scallop dredge bag are connected together using open steel links squeezed shut using hand squeezers. Links and hand squeezers are as ubiquitous on scallop vessels as twine and mending needles are on trawl vessels. To build an extended link apron, one simply joins the steel rings together with two interconnected links without the need of additional tools or training (**Figure 1**). This simple cost-effective modification increases the inter-ring spacing of the apron, thereby increasing mechanical sorting which, in turn, could facilitate the escape of fish and small scallops (**Figure 1**).

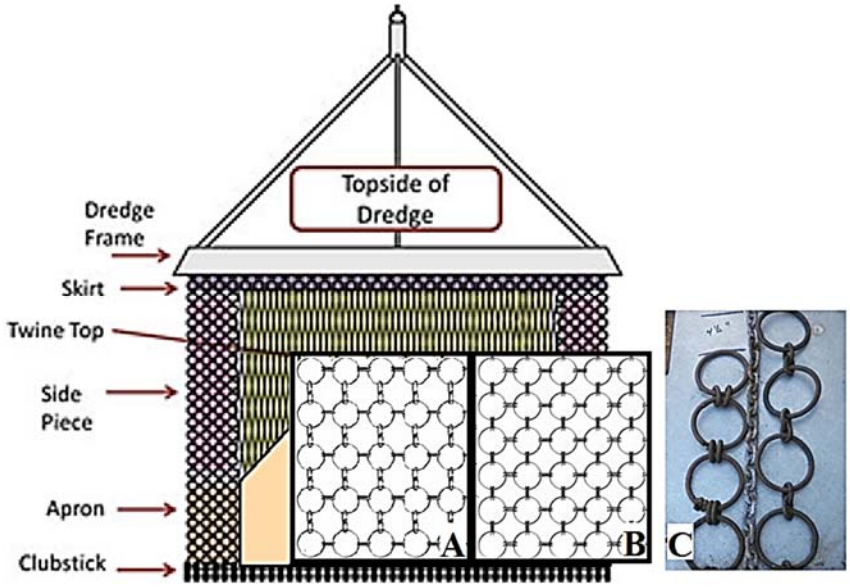

***Figure 1**: Diagram of the topside of a dredge illustrating the difference between an extended link apron (A) and a standard linked apron (B). Chain or shackles are used to connect standard linked portions of the bag to the extended link (C).*

Previous extended link apron research focused on an extreme version of the modification which used extended links in both the horizontal and vertical directions (Davis et al. 2016). Field testing of this configuration took place in Southern New England (SNE) and the Mid-Atlantic Access Areas (MAA) due to concerns about high densities of pre-recruit scallops in these regions. Testing of the apron included a gear comparison study and a selectivity study. During the gear comparison study, catches from a commercially representative control dredge were compared to catches from a dredge modified with the two-way extended link apron in order to assess how the modification would impact scallop catches. The selectivity study used a lined survey dredge, towed in tandem with the experimental dredge, to examine of the absolute selective properties of the two-way extended link apron.

***Table 1:** Estimated differences in catch for the two-way extended link apron relative to a control apron. From Davis et al. 2016.*

Species		Two-Way Extended Link	Control Apron	Percent Difference	Model Estimate (RE)	Statistical Significance
UNCLASSIFIED SKATES	*Rajidae spp.*	9,583	13,031	-26.46%	-27.13	**Yes**
BARNDOOR SKATE	*Dipturus laevis*	80	118	-32.20%	-31.37	**Yes**
FOURSPOT FLOUNDER	*Paralichthys oblongus*	169	259	-34.75%	-44.68	**Yes**
WINDOWPANE FLOUNDER	*Scopthalmus aquosus*	71	152	-53.29%	-59.41	**Yes**
MONKFISH	*Lophius americanus*	1,563	2,204	-29.08%	-29.78	**Yes**
SEA SCALLOP (RETAINED)	*Placopecten magellanicus*	233,517	307,313	-24.01%	-27.21	**Yes**

While the two-way extended link apron functioned as hypothesized, reducing the capture of incoming year classes of scallops and smaller bycatch species, there was an observed overall reduction in sea scallop catch, irrespective of animal length (**Table 1** and **Figure 2**). Unfortunately, the loss of sea scallop catch for the two-way extended link apron was too high because preservation of target species catch is essential for successful gear modifications (Jennings & Revill 2007, Valdermarsen & Suuronen 2003). Despite this setback, the results using the two-way extended link apron were promising enough to warrant further examination of a less extreme version of an extended link apron. We hypothesized that an apron with only vertically extended links would have scallop catches similar to a standard apron while still reducing bycatch.

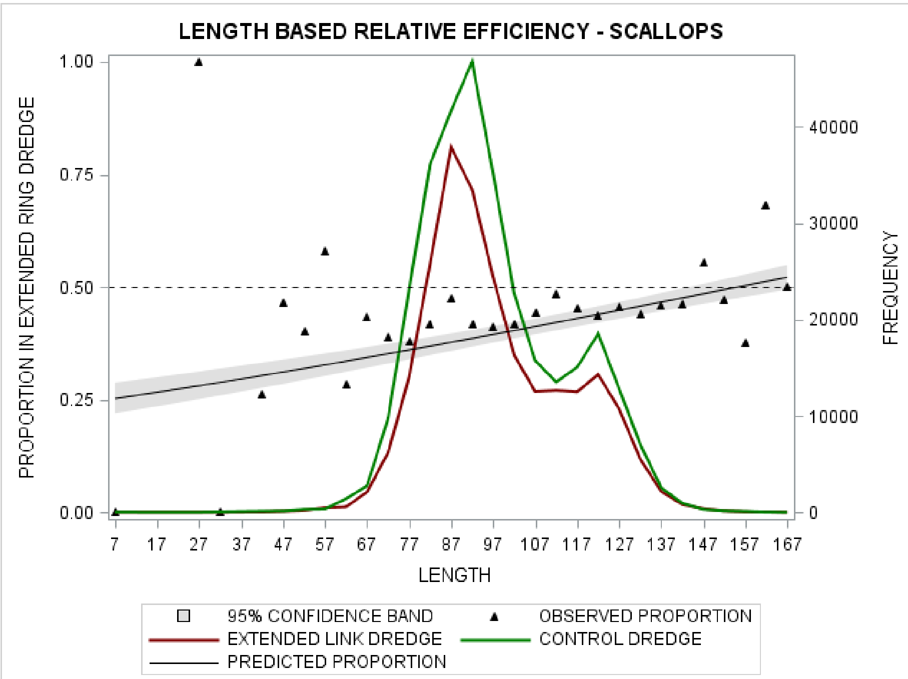

Figure 2: *Relative sea scallop catch from an experimental (two-way extended link apron) and control (standard link apron) dredge in 2016. Triangles represent the observed proportion at length ($Catch_{ext}/(Catch_{ext} + Catch_{stand})$), with a proportion >0.5 (dotted line) representing more animals at length captured by the extended link apron dredge. The grey area represents the 95% confidence band for the modeled proportion (solid line).*

Objectives

The project objectives included:

(1) Improve the relative sea scallop catch efficiency of an extended link apron while still reducing dredge impacts to incoming year scallop classes.

(2) Evaluate the efficacy of an extended link apron to reduce scallop dredge impacts to critical bycatch species like windowpane (*Scopthalmus aquosus*) and yellowtail (*Limanda ferruginea*) flounder.

(3) Explore the mechanisms behind changes to dredge efficiency when using an extended link apron.

Methods by Objective

Improvement of the Extended Link Apron

It was hypothesized that the large deficit in scallop catch observed with the two-way extended link apron was due to the extreme nature of this configuration. By using extensions only in the vertical direction, mechanical sorting would still be improved while fewer scallops would be lost. From previous testing of the configuration, we had found that a seven row apron linked together using the standard method was equivalent in height to five rows of rings held together with extended links. A three by forty row extended link apron was built by East Coast Fabrication, Inc. The links of the apron were welded shut to reduce the likelihood of stretching or breaking. To incorporate the extended link apron into a dredge bag, five rows of rings are removed from the middle of a standard seven row apron, leaving behind a row of rings attached to the bottom of the twine top and the clubstick. A shackle and a single link were used to attach the three row extended link apron section to the rings on the twine top and the clubstick. The final product has five rows of steel rings with three rows of extended links. A scallop dredge can be outfitted with the improved extended link apron in under an hour.

Evaluation of the Vertically Extended Link Apron

An advantage of utilizing commercial sea scallop vessels to conduct research operations is the ability to simultaneously tow two dredges. This allows for the comparison of gear variants without the introduction of the variables associated with time and space.

Four dedicated research cruises were conducted on board commercial scallop vessels to evaluate the performance of the vertically extended link apron. With the exception of the first cruise aboard the *FV Celtic*, the participating vessels supplied the dredges, and one vessel dredge was modified with the experimental extended link apron. The first cruise utilized dredge frames provided by Coonamessett Farm Foundation Inc. The control dredge was a turtle deflector headbale with a commercially representative bag configuration. The experimental was the control dredge modified to include an extended link apron. Vessel-supplied dredges were used to examine how a regulation requiring the use of an extended link apron would impact the commercial fishery. There is a diversity of dredge bag configurations found within the scallop fishery, and evaluating extended link apron performance across multiple bag configurations would indicate how this modification would impact the fleet as a whole.

The tow started when the winch was locked, and the dredge was fished for a target duration of 30 minutes before being hauled back. If tow parameters were not followed or if the gear malfunctioned (e.g. dredges fishing upside down), the tow was declared invalid and a new tow was initiated. Vessel speed, heading, and position during the tow were recorded for each tow using GPS recorded directly from the vessel or by an external GPS unit. An average depth and a Beaufort number (a semi-quantitative measure of sea and wind conditions) was also recorded for each tow. Following the completion of a valid tow, the catch was emptied on deck and sorted for sampling.

Scallops, commercially important finfish species, and lobsters were sorted, counted, and measured following each tow. Scallop catch, for control and experimental gear, was evaluated by the number of baskets, the number of scallops within a single basket subsample, and total unshucked scallop basket weight to the nearest 0.2 kilograms. Scallops within the single basket subsample were measured in 5-millimeter increments. Bycatch species were individually measured to the nearest centimeter, and finfish bycatch weights were measured to the nearest 0.01 kilogram.

Data collected for each paired tow included:

- 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)

Exploration of the Mechanisms Effecting Catch Efficiency

Following the completion of all cruises, a simple statistical analysis of the data was carried out using R Statistical Software to evaluate the performance (R Core Team 2015). Statistical analysis was conducted on pooled data as well as data from each of the individual cruises.

Additional analysis attempted to construct a model that would predict the efficiency of the extended link apron relative to the control dredge as a function of a variety of covariates. In many instances, especially with gear modifications that can possibly alter the relative size composition of the catch, exploring the relative catch at length is informative. For many species, however, length may not be a significant predictor of relative efficiency. In these cases, the overall change in the relative total catch was tested using the pooled catch data (summing catch over all lengths for a given tow).

Since the experiment was conducted over four individual cruises, it was informative to examine whether length-based relative efficiency varied between cruises. The covariates tested in this analysis were length, a second order polynomial of length (to capture potential non-linearity in the length term, cruise, Beaufort number, and the interaction between cruise and length (this effect tested for different slopes between cruises). See **Appendix A** for a detailed description of this analytical framework.

While the variability in length-based efficiency trends by cruise provides insight about the impact of temporal and spatial differences between research cruises, evaluating the overall impact of the extended link apron on scallop catch regardless of location and vessel is of greater importance to fisheries managers. A length-based model was used to evaluate the pooled cruise scallop catch at length data using the R packages “MASS” and “nlme” (Pinheiro et al 2018, Venables & Ripley 2002). The covariates tested in this analysis were length, a second-order polynomial of length, and a third-order polynomial of length with tow as a random effect (Holst & Revill 2009).

Project management and participation

Project management: Farrell Davis

Data Collection and Management: Farrell Davis

Statistical Analysis: David Rudders and Farrell Davis

Technical Support: Ricky Alexander, Liese Siemman, and Ronald Smolowitz

Results

Pooled Data Analysis

The four research cruises were conducted throughout the Southern New England and Georges Bank scallop fishing grounds in both open and rotational access areas (**Figure 3**). Overall, this data set consisted of 196 valid tow pairs that were examined in the analysis. Pooled data from the field testing of the improved extended link apron indicates that the performance of this modification is better than the two-way version tested during the previous study (**Tables 2 and 3**). There was an observed reduction in the bycatch of many of the species encountered during field testing (**Table 3**). Barndoor skate (*Dipturus laevis*) were the only bycatch species with increased catch in the extended link apron (**Tables 2 and 3**). However, the increase in barndoor skate was not found to be statistically significant. The reduction of bycatch was statistically significant for unclassified skates (*Rajidae spp.*) and windowpane flounder, the two most commonly encountered bycatch species (**Table 3**). Skate bycatch was reduced by 7.91% (Wilcoxon signed-rank test, $V = 12374$, $p < 0.001$) and windowpane flounder bycatch was reduced by 29.99% (Wilcoxon signed-rank test, $V = 7876$, $p < 0.001$). There was also a minimal (0.58%) but significant reduction in scallop catch with the vertically extended link apron (Wilcoxon signed-rank test, $V = 4235.5$, $p = 0.003$).

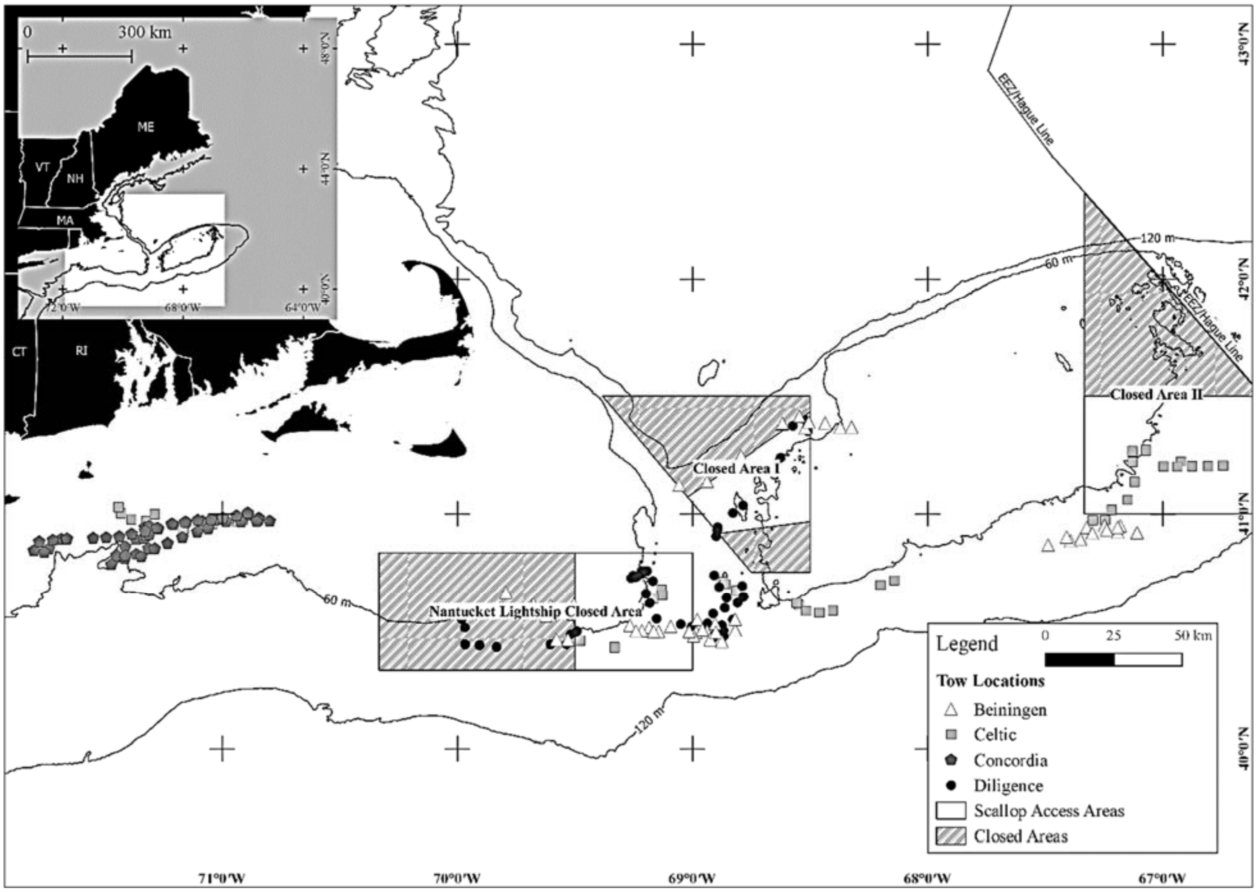

Figure 3: *Tow location of the four research cruises.*

Table 2: *Pooled catch (counts) data from 196 valid tow pairs sampled during this project.*

Species Name	Scientific Name	Control Apron			Extended Link Apron		
		N	Mean	Std. Dev	N	Mean	Std. Dev
UNCLASSIFIED SKATES	*Rajidae spp.*	21416	115.14	96.98	19723	104.35	96.93
BARNDOOR SKATE	*Dipturus laevis*	159	2.69	2.18	197	2.59	2.36
AMERICAN PLAICE	*Hippoglossoides platessoides*	45	2.50	1.86	29	1.93	1.22
SUMMER FLOUNDER	*Paralichthys dentatus*	122	2.18	1.72	108	2.20	1.96
FOURSPOT FLOUNDER	*Paralichthys oblongus*	153	2.32	1.50	142	2.15	1.92
YELLOWTAIL FLOUNDER	*Limanda ferruginea*	68	1.62	0.94	47	1.27	0.56
WINTER FLOUNDER	*Pseudopleuronectes americanus*	38	1.41	0.89	26	1.24	0.62
WITCH FLOUNDER	*Glyptocephalus cynoglossus*	32	1.60	0.75	26	1.53	0.72
WINDOWPANE FLOUNDER	*Scopthalmus aquosus*	2861	20.88	20.23	2003	15.65	15.71
MONKFISH	*Lophius americanus*	1007	6.85	5.21	949	6.83	5.15
SEA SCALLOP (BASKETS)	*Placopecten magellanicus*	2426	12.57	22.64	2412	12.56	24.07

__Table 3:__ Comparison of the control and experimental catches. A positive value indicates a reduction in catch for the extended link apron. Significance was obtained using a Wilcoxon signed-rank test.

Species Name	Control - Experimental	%	Significant
UNCLASSIFIED SKATES	1693	7.91%	**Yes**
BARNDOOR SKATE	-38	-23.90%	No
AMERICAN PLAICE	16	35.56%	No
SUMMER FLOUNDER	14	11.48%	No
FOURSPOT FLOUNDER	11	7.19%	No
YELLOWTAIL FLOUNDER	21	30.88%	No
WINTER FLOUNDER	12	31.58%	No
WITCH FLOUNDER	6	18.75%	No
WINDOWPANE FLOUNDER	858	29.99%	**Yes**
MONKFISH	58	5.76%	No
SEA SCALLOP (BASKETS)	14	0.58%	**Yes**

We hypothesized that the average shell height of scallops captured by the extended link apron would be larger due to the increased inter-ring spacing. A comparison of the shell height frequencies indicates that the extended link apron has a distribution shifted to the right of the control apron and fewer smaller scallops less than 110 mm were retained (Two sample Kolmogorov-Smirnov test, $D = 0.072$, $p < 0.0001$; **Figure 4**). The mean shell height was significantly larger for the extended link apron, 119.21 mm versus 116.90 mm (Welch two sample t-test, $t(562{,}150) = -65.817$, $p < 0.0001$).

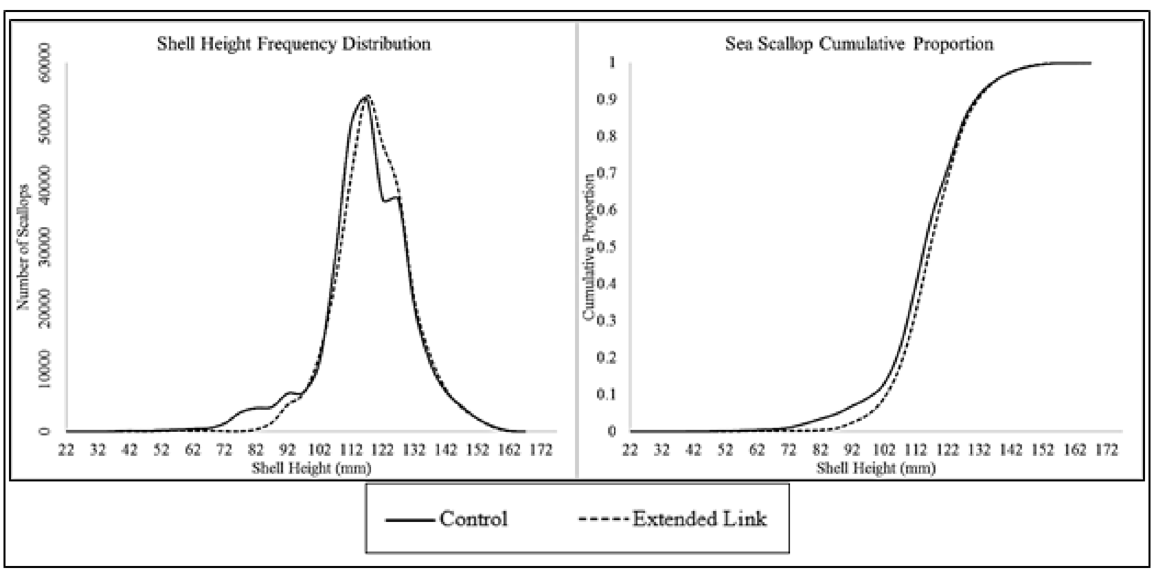

***Figure 4:** The pooled scallop shell height frequency distribution and cumulative proportion curves for the control dredge (solid line) and the extended link apron (dashed line).*

Individual Cruise Analysis

While results from the pooled data analysis are informative regarding the overall performance of the improved extended link apron, an analysis of the individual cruise results provides insight on how variation in the spatial distribution of sampling effort and industry supplied dredge configuration impacts dredge performance.

<u>*Sea Scallop Catch*</u>

The impact of the vertically extended link apron to sea scallop catch varied by cruise (**Table 4**). For half of the cruises there was a non-significant increase in the number of baskets of scallops retained by the vertically extended link apron (**Table 4**). For two of the cruises, *FV Celtic* and *FV Beiningen*, there was a slight decrease in the number of baskets retained by the vertically extended link apron which was significant (**Table 4**).

Table 4: *Comparison of the control and experimental sea scallops catches. A negative value/percentage indicates a reduction in catch for the extended link apron. Significance was obtained using a paired Wilcoxon signed-rank test.*

Cruise	Control	Extended Link Apron	difference	%	V Statistic	p-value
FV Celtic	130	108	-22	-16.92%	237	0.001
FV Concordia	171	173	2	1.17%	156	0.862
FV Diligence	1143	1189	46	4.02%	258.5	0.843
FV Beiningen	982	942	-40	-4.07%	460	0.005

An examination of the mean sea scallop shell height for the vertically extended link apron indicates that the modification may more efficiently retain larger scallops (**Table 5**). For two of the cruises, *FV Diligence and FV Beiningen*, there was a significant increase in the mean scallop shell height for the vertically extended link apron (**Table 5**). During the *FV Concordia* and *FV Celtic* cruises, the mean shell height was slightly reduced for the extended link apron (**Table 5**). The reduction in shell height was only significant for the *FV Concordia* cruise (**Table 5**). **Figures 5-8** show the shell height frequency distributions and cumulative proportion curves for each of the four research cruises

Table 5: *Comparison of the control and experimental mean retained sea scallop shell height. Significance was obtained using a Welch two sample t-test.*

Cruise	Control Shell Height (mm)	Extended Link Shell Height (mm)	difference (mm)	df	t-value	p-value
FV Celtic	122.75	122.71	-0.04	23676	0.239	0.811
FV Concordia	114.04	113.25	-0.79	46969	8.706	<0.001
FV Diligence	116.64	120.63	3.99	277620	-84.215	<0.001
FV Beiningen	117.06	118.07	1.01	201870	-16.187	<0.001

Unclassified Skate Catch

During all four research cruise there was an observed reduction in the bycatch of little (*Leucoraja erinacea*) and winter (*Leucoraja ocellata*) skates, combined and analyzed as unclassified skate (**Table 6**). The reduction in unclassified skate was found to be significant for three of the four research cruises (**Table 6**).

Table 6: *Comparison of the control and experimental unclassified skate catches. A negative value/percentage indicates a reduction in catch for the extended link apron. Significance was obtained using a paired Wilcoxon signed-rank test.*

Cruise	Control	Extended Link Apron	difference	%	V Statistic	p-value
FV Celtic	4233	3837	-396	-9.36%	505.5	0.02
FV Concordia	6849	6627	-222	-3.24%	865	0.2935
FV Diligence	5370	4668	-702	-13.07%	1055.5	0.0002
FV Beiningen	4964	4591	-373	-7.51%	781.5	0.0216

Windowpane Flounder Catch

Windowpane flounder bycatch reduction varied from 26.22-61.54% during the four research cruises (**Table 7**). The reduction in windowpane catch was significant on three of the four cruises (**Table 7**). The *FV Celtic* cruise was the only cruise where the reduction in was not significant and it was also the trip with the lowest overall bycatch of windowpane flounder (**Table 7**).

Table 7: *Comparison of the control and experimental windowpane flounder catches. A negative value/percentage indicates a reduction in catch for the extended link apron. Significance was obtained using a paired Wilcoxon signed-rank test.*

Cruise	Control	Extended Link Apron	difference	%	V Statistic	p-value
FV Celtic	13	5	-8	-61.54%	41.5	0.1446
FV Concordia	843	622	-221	-26.22%	951.5	<0.0001
FV Diligence	984	687	-297	-30.18%	1058	<0.0001
FV Beiningen	1021	689	-332	-32.52%	388.5	0.0002

Yellowtail Flounder Catch

Overall very few yellowtail flounder were observed during this project (**Table 8**). For a majority of the cruises, yellowtail flounder bycatch was reduced by the vertically extended link apron and for the *FV Celtic* cruise the reduction was significant (**Table 8**).

Table 8: *Comparison of the control and experimental yellowtail flounder catches. A negative value/percentage indicates a reduction in catch for the extended link apron. Significance was obtained using a paired Wilcoxon signed-rank test.*

Cruise	Control	Extended Link Apron	difference	%	V Statistic	p-value
FV Celtic	28	13	-15	-53.57%	51.5	0.0142
FV Concordia	20	21	1	5.00%	101.5	0.6202
FV Diligence	9	6	-3	-33.33%	48	0.4644
FV Beiningen	11	7	-4	-36.36%	10	0.072

Modelling Results

Length-based estimates

Since the experiment was conducted over four cruises, we examined the relationship between the length-based relative efficiency and cruise. The covariates tested in this analysis were length, the second-order polynomial of length (to capture potential non-linearity in the length term), cruise, Beaufort number (a semi-quantitative measure of sea and wind conditions), and the interaction between cruise and length (Holst & Revill 2009). For some species, there was simply not enough data to provide meaningful results for the more complex models. In most of these cases this failure resulted from a small number of tow pairs where there were non-zero observations and the model failed to converge or produce parameter estimates that were unrealistic. While it was hypothesized that weather sea state and wind conditions (Beaufort number) had a negative impact on catch due to increased mechanical sorting, the Beaufort number was not a significant predictor for dredge efficiency. Appendix **Table B1** shows the most parsimonious model for each species. Parameter estimates associated with the selected model specification for each species where length was an included factor in the selected model are shown in in **Table 9**.

For the length-based model, sea scallops, barndoor skate, summer flounder, and monkfish were the only species where length represented a significant or marginally significant predictor of relative efficiency. In addition, sea scallops also exhibited differences in the slope of the length-based relationship as a function of cruise. Looking across the landscape of species that showed significant length-based estimates, there was no consistent directionality across species and cruises. For example, cruise-specific curves generated for sea scallops were highly variable (**Figure 9**). During some of the cruises, the extended link dredge captured fewer smaller scallops and efficiency increased as scallop size increased, while during other cruises, this pattern was reversed (**Figure 9**).

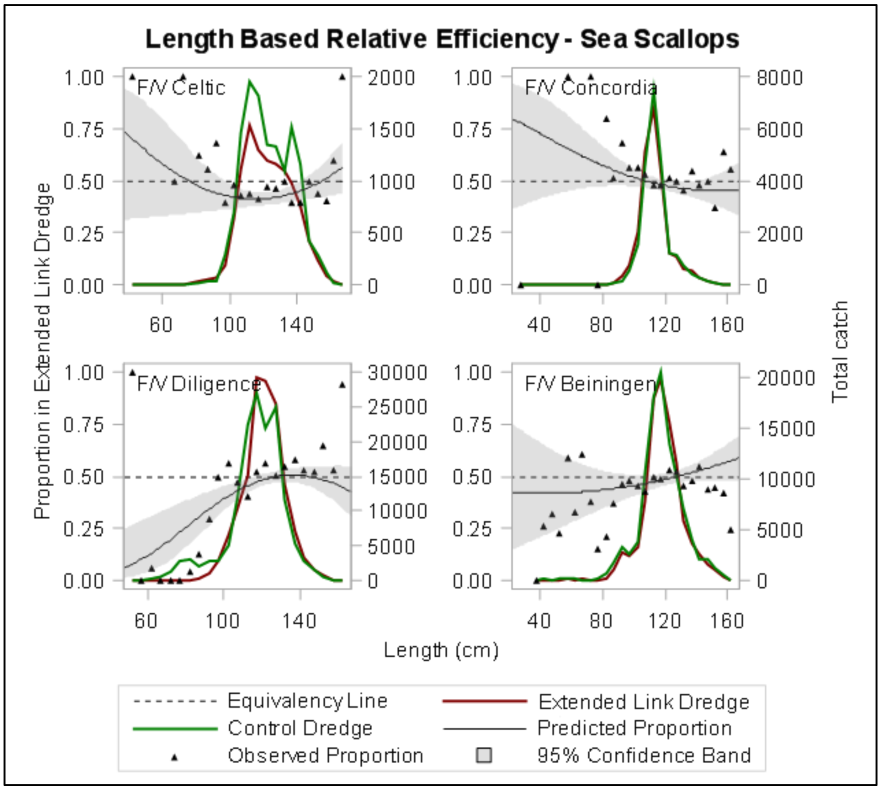

Figure 9: *Relative sea scallop catch by the two dredge configurations by cruise as supported by the selected length-based model. The grey area represents the 95% confidence band.*

For the analysis using data pooled over cruise, the model containing the second order polynomial of length was most representative of the data based on the standard errors and p-values of the fixed effects (**Table 10**). The curve generated by the model containing the second-order polynomial showed a trend of increasing efficiency with scallop length with catches of scallops >120 mm being similar between the two gears (**Figure 10**).

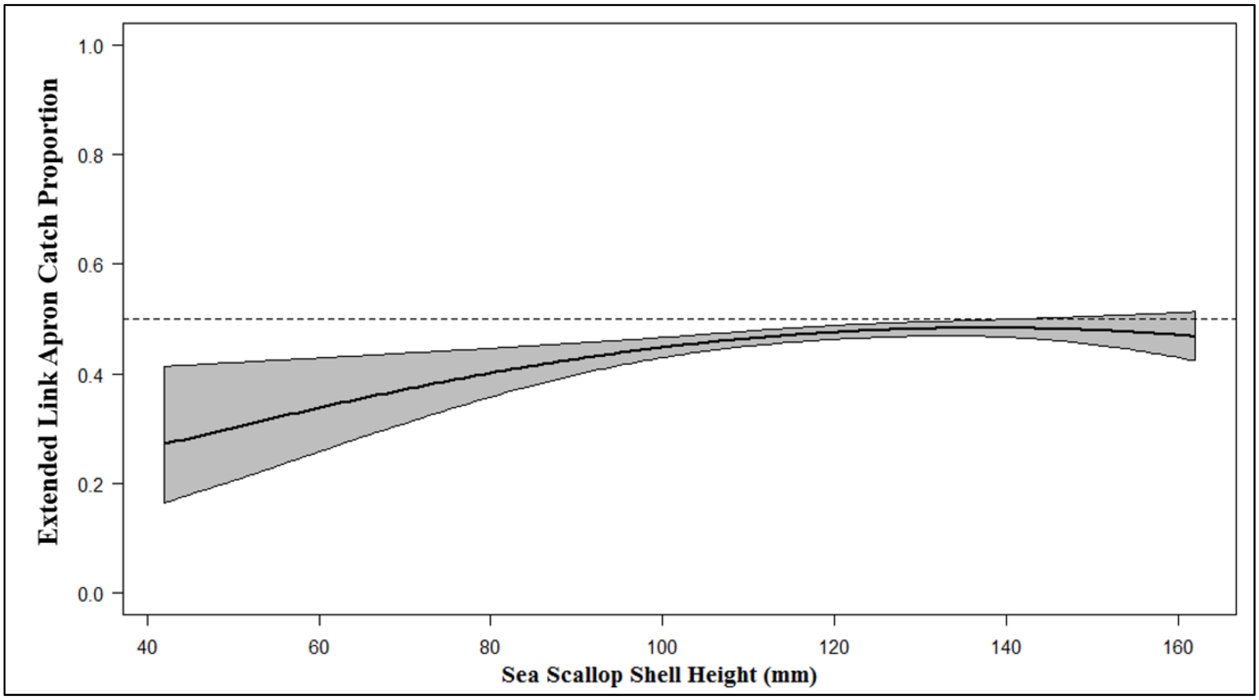

Figure 10: *Pooled relative sea scallop catch by the two dredge configurations as supported by the second order polynomial model. The grey area represents the 95% confidence band.*

Pooled-over-length estimates

Animal length was not a significant predictor of relative efficiency for fourspot, yellowtail, and windowpane flounders. Length measurements were not taken for unclassified skates. For these three flounder species, the catch data was pooled over length to examine the relative efficiency of the two dredge configurations with respect to total catch (numbers). Graphical representations of the observed, pooled catches and predicted relative efficiencies derived from the model output are shown in **Figures 11-13**. For all species except yellowtail flounder, the model that included cruise as a predictor was the most appropriate. For unclassified skates, fourspot flounder and windowpane flounder, cruise was a significant factor predicting the relative efficiency between the two dredge configurations. Although cruise was a factor in the preferred model for windowpane flounder, catch was reduced in the extended link dredge during all four cruises. The species where cruise was included in the preferred model (fourspot flounder and unclassified skates), catch was reduced in the extended link dredge during most of the cruises. For the other species where cruise was included in the preferred model (fourspot flounder and unclassified skates), catch was reduced in the extended link dredge during most of the cruises. Appendix Table B2 shows the most parsimonious model for each species using the pooled data.

The intercept only model for the catch of sea scallops predicted a decrease in the extended link dredge of 9.5%; however, this is not the most parsimonious model for the species and the actual observed reduction was less than 4% (**Table 11 and Table B1**). For all of the flatfish species, monkfish, and unclassified skate, there was a consistent reduction of catch by the extended link dredge with reductions ranging from 6-30% (**Table 11**). This reduction was statistically significant for windowpane flounder and unclassified skates. Surprisingly, barndoor skate catch increased in the experimental dredge, but this change was not significant.

Table 11: *A comparison of the relative efficiencies estimated from the intercept only model for the analyzed species and the observed percent differences from the catch data collected during the experiment. Statistical significance (alpha=0.05 level) is specific to that model and may not be the most parsimonious model from the analysis.*

Species	Extended Link Dredge	Control Dredge	Percent Difference	Model Estimate	Significance
Uncl. Skates	19,253	21,761	-11.53%	-11.46%	**YES**
Barndoor Skate	197	159	23.90%	34.16%	NO
Summer Flounder	107	122	-12.30%	-12.29%	NO
Fourspot Flounder	141	151	-6.62%	-10.32%	NO
Yellowtail Flounder	46	66	-30.30%	-30.30%	NO
Windowpane Flounder	2,003	2,861	-29.99%	-34.47%	**YES**
Monkfish	933	996	-6.33%	-7.82%	NO
Sea Scallops	279,774	291,103	-3.89%	-9.58%	**YES**

Evaluation

Accomplishments by objective

All objectives were accomplished with few modifications. Accomplishments by objective are described below.

(1) Improve the relative sea scallop catch efficiency of an extended link apron while still reducing dredge impacts to incoming year scallop classes.

A vertically extended link apron has improved scallop catch efficiency relative to the two-way extended link apron tested in previous research. There was a minimal reduction in overall scallop catch and the extent of the reduction varied from cruise to cruise. There was increase of 2.31 mm in the mean scallop shell height for the extended link apron and modelling indicates that fewer smaller scallops were being retained (**Figures 4, 9, and 10**). Given these results, we can conclude that the vertically extended link apron is an improvement over the previously tested two-way extended link apron.

(2) Evaluate the efficacy of an extended link apron to reduce scallop dredge impacts to critical bycatch species like windowpane (*Scopthalmus aquosus*) and yellowtail (*Limanda ferruginea*) flounder.

There was an observed reduction in windowpane flounder bycatch during all four research cruises and the reduction was statistically significant for three of the four cruises. Modelling of the pooled catch data for windowpane flounder found the reduction in bycatch to be significant for all cruises (Figure 12). Unfortunately, catches of yellowtail flounder were low and highly variable, making it difficult to determine the significance of the observed reduction in bycatch.

(3) Explore the mechanisms behind changes to dredge efficiency when using an extended link apron.

Length was found to be a significant or marginally significant predictor for sea scallops, barndoor skate, summer flounder, and monkfish. This suggests that a difference in the selectivity of the extended link apron and the control dredge could be responsible for the changes in efficiency when using the extended link apron.

Discussion

One of the most significant conclusions of this work is the overall reduction of windowpane bycatch by the extended link apron dredge with minimal loss of scallop catch (**Table 3 and 10**). While overall scallop catch by numbers were reduced, the length-based analysis suggests this loss is due to a decreased retention of small scallops with a concomitant maintenance or slight increase in relative efficiency for larger scallops (**Figure 9 and 10**). Sea state (Beaufort value) was not found to be a significant predictor of dredge efficiency; however, a majority of the observations were made during periods of relatively calm weather. Winnowing of the extended link scallop catch may be further increased in larger seas and in greater depths due to the dredge being suspended in the water column for a longer period of time (Grothues et al. 2017). The first cruise was conducted aboard the *FV Celtic*, the only vessel in the group of research vessels to tow their dredges from midship as opposed to towing from the stern. This could have impacts on the flushing of water through the dredge during the haul back process, providing a possible explanation for the observed differences in extended link performance relative to the other trips. More testing would be needed to specifically evaluate this hypothesis. Overall, our results validate our hypothesis that an improved extended link apron could reduce bycatch of flatfish and pre-recruit scallops with a scallop catch similar to a standard apron.

The continued research and development of sustainable dredge and dredge bag configurations is essential to the long-term viability of the sea scallop fishery. The unpredictable nature of scallop recruitment can lead to unforeseen interactions between non-target species, incoming scallop year classes, and the scallop fishery. Scallop resources within a closed area are also not guaranteed and the delayed harvest of the resource can result in millions of dollars in lost revenue (Bethoney et al. 2016, Stokesbury et al. 2007). Gear modifications are a solution for the reduction of bycatch that enables the harvest of the resource with limited to no interruption to fishing (Jennings & Revill 2007, Valdermarsen & Suuronen 2003). Seasonal bycatch surveys can provide fisheries managers with accurate information about the seasonal and spatial distribution of bycatch species on scallop fishing grounds (Leavitt et al. 2018, Winton et al. 2017, Smolowitz et al. 2016). The extended link apron can then be utilized by fisheries managers to reduce windowpane flounder bycatch in areas/times of year when the species is most abundant as identified by seasonal bycatch surveys. Additionally, the extended link apron can be used to reduce the incidental mortality of incoming scallop year classes in areas that also have exploitable scallops.

Additional work

In order to properly establish bycatch limits and implement gear restrictions, fisheries managers and conservation engineers need a way to obtain accurate efficiency estimates for non-target species. While traditional gear comparison experiments can provide accurate information about relative scallop catch efficiency, low catches of flatfish have limited our ability to access with accuracy the impact gear modifications have on the overall catch and length-based efficiency of flatfish. Therefor an innovative approach is necessary for assessing dredge efficiency for non-target species.

In order to gain a better grasp of the flatfish selectivity and catchability, CFF developed a cover net to retain fish and scallops that pass through the top of the dredge bag. The net was built to be non-selective using 50-mm mesh and extended the full length and width of the dredge bag, from the headbale to the clubstick and over both side pieces. The cover net is designed to retain any fish and scallops that passed through the apron, twine top, skirt, and sides. Nine tows were conducted in both the open access area and the Nantucket Lightship Access Area where both flatfish and commercially viable scallop densities were present. Tow parameters were representative of commercial practices, and video observations and catch data suggested that the dredge fishes properly with the cover net in place. Surprisingly, over 70% of the windowpane flounder and skate catch was retained in the cover net, and therefore passed through the dredge bag at some point during the tow. Assuming that the sum of the catch in the dredge bag and the cover net is a conservative estimate of the biomass in the dredge tow path (conservative because it does not account for animals in the dredge path that avoid the dredge), we estimated the upper bound of dredge efficiency for windowpane flounder was 0.17 ± 0.13 (average ± standard deviation). The SELECT model (Millar 1992) for estimating gear selectivity was also used to estimate a windowpane flounder 50% retention size of L50 = 23.36 cm in the dredge bag. Through the application of the cover net and paired haul methods, CFF seeks to simultaneously demonstrate the value a dredge cover net has for scallop dredge research and the bycatch reduction potential of a one-way extended link apron.

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Tables and Figures

Table 1: *A comparison of the relative efficiencies estimated from the intercept only model for the analyzed species and the observed percent differences from the catch data. Statistical significance (alpha=0.05 level) is specific to that model and may not be the most parsimonious model from the analysis.*

Species		Two-Way Extended Link	Control Apron	Percent Difference	Model Estimate (RE)	Statistical Significance
UNCLASSIFIED SKATES	*Rajidae spp.*	9,583	13,031	-26.46%	-27.13	**Yes**
BARNDOOR SKATE	*Dipturus laevis*	80	118	-32.20%	-31.37	**Yes**
FOURSPOT FLOUNDER	*Paralichthys oblongus*	169	259	-34.75%	-44.68	**Yes**
WINDOWPANE FLOUNDER	*Scopthalmus aquosus*	71	152	-53.29%	-59.41	**Yes**
MONKFISH	*Lophius americanus*	1,563	2,204	-29.08%	-29.78	**Yes**
SEA SCALLOP (RETAINED)	*Placopecten magellanicus*	233,517	307,313	-24.01%	-27.21	**Yes**

Table 2: *Pooled catch (counts) data from 196 valid tow pairs sampled during this project.*

Species Name	Scientific Name	Control Apron			Extended Link Apron		
		N	Mean	Std. Dev	N	Mean	Std. Dev
UNCLASSIFIED SKATES	*Rajidae spp.*	21416	115.14	96.98	19723	104.35	96.93
BARNDOOR SKATE	*Dipturus laevis*	159	2.69	2.18	197	2.59	2.36
AMERICAN PLAICE	*Hippoglossoides platessoides*	45	2.50	1.86	29	1.93	1.22
SUMMER FLOUNDER	*Paralichthys dentatus*	122	2.18	1.72	108	2.20	1.96
FOURSPOT FLOUNDER	*Paralichthys oblongus*	153	2.32	1.50	142	2.15	1.92
YELLOWTAIL FLOUNDER	*Limanda ferruginea*	68	1.62	0.94	47	1.27	0.56
WINTER FLOUNDER	*Pseudopleuronectes americanus*	38	1.41	0.89	26	1.24	0.62
WITCH FLOUNDER	*Glyptocephalus cynoglossus*	32	1.60	0.75	26	1.53	0.72
WINDOWPANE FLOUNDER	*Scopthalmus aquosus*	2861	20.88	20.23	2003	15.65	15.71
MONKFISH	*Lophius americanus*	1007	6.85	5.21	949	6.83	5.15
SEA SCALLOP (BASKETS)	*Placopecten magellanicus*	2426	12.57	22.64	2412	12.56	24.07

Table 3: *Comparison of the control and experimental catches. A positive value/percentage indicates a reduction in catch for the extended link apron. Significance was obtained using a Wilcoxon-Signed Rank Test.*

Species Name	Control - Experimental	%	Significant
UNCLASSIFIED SKATES	1693	7.91%	**Yes**
BARNDOOR SKATE	-38	-23.90%	No
AMERICAN PLAICE	16	35.56%	No
SUMMER FLOUNDER	14	11.48%	No
FOURSPOT FLOUNDER	11	7.19%	No
YELLOWTAIL FLOUNDER	21	30.88%	No
WINTER FLOUNDER	12	31.58%	No
WITCH FLOUNDER	6	18.75%	No
WINDOWPANE FLOUNDER	858	29.99%	**Yes**
MONKFISH	58	5.76%	No
SEA SCALLOP (BASKETS)	14	0.58%	**Yes**

Table 4: *Comparison of the control and experimental sea scallops catches. A negative value/percentage indicates a reduction in catch for the extended link apron. Significance was obtained using a paired Wilcoxon signed-rank test.*

Cruise	Control	Extended Link Apron	difference	%	V Statistic	p-value
FV Celtic	130	108	-22	-16.92%	237	0.001
FV Concordia	171	173	2	1.17%	156	0.862
FV Diligence	1143	1189	46	4.02%	258.5	0.843
FV Beiningen	982	942	-40	-4.07%	460	0.005

Table 5: *Comparison of the control and experimental mean retained sea scallop shell height. Significance was obtained using a Welch two sample t-test.*

Cruise	Control Shell Height (mm)	Extended Link Shell Height (mm)	difference (mm)	df	t-value	p-value
FV Celtic	122.75	122.71	-0.04	23676	0.239	0.811
FV Concordia	114.04	113.25	-0.79	46969	8.706	<0.001
FV Diligence	116.64	120.63	3.99	277620	-84.215	<0.001
FV Beiningen	117.06	118.07	1.01	201870	-16.187	<0.001

Table 6: *Comparison of the control and experimental unclassified skate catches. A negative value/percentage indicates a reduction in catch for the extended link apron. Significance was obtained using a paired Wilcoxon signed-rank test.*

Cruise	Control	Extended Link Apron	difference	%	V Statistic	p-value
FV Celtic	4233	3837	-396	-9.36%	505.5	0.02
FV Concordia	6849	6627	-222	-3.24%	865	0.2935
FV Diligence	5370	4668	-702	-13.07%	1055.5	0.0002
FV Beiningen	4964	4591	-373	-7.51%	781.5	0.0216

Table 7: *Comparison of the control and experimental windowpane flounder catches. A negative value/percentage indicates a reduction in catch for the extended link apron. Significance was obtained using a paired Wilcoxon signed-rank test.*

Cruise	Control	Extended Link Apron	difference	%	V Statistic	p-value
FV Celtic	13	5	-8	-61.54%	41.5	0.1446
FV Concordia	843	622	-221	-26.22%	951.5	<0.0001
FV Diligence	984	687	-297	-30.18%	1058	<0.0001
FV Beiningen	1021	689	-332	-32.52%	388.5	0.0002

Table 8: *Comparison of the control and experimental yellowtail flounder catches. A negative value/percentage indicates a reduction in catch for the extended link apron. Significance was obtained using a paired Wilcoxon signed-rank test.*

Cruise	Control	Extended Link Apron	difference	%	V Statistic	p-value
FV Celtic	28	13	-15	-53.57%	51.5	0.0142
FV Concordia	20	21	1	5.00%	101.5	0.6202
FV Diligence	9	6	-3	-33.33%	48	0.4644
FV Beiningen	11	7	-4	-36.36%	10	0.072

Table 9: *Parameter estimates for the selected model examining the unpooled catch data for Sea Scallops. Results are presented from the model that provided the best fit (intercept, length, length^2, cruise and vessel*cruise) 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	Vessel	Estimate	SE	DF	t value	p value	LCL	UCL
Barndoor Skate	Intercept		-0.422	0.361	308	-1.168	0.2436	-1.133	0.289
	Length		-0.002	0.167	308	-0.01	0.9919	-0.331	0.328
	Length^2		0.026	0.041	308	0.633	0.527	-0.054	0.106
	Cruise	Beiningen	0.87	0.401	308	2.171	0.0307	0.081	1.659
		Celtic	0.049	0.417	308	0.118	0.9059	-0.771	0.869
		Concordia	1.365	0.445	308	3.07	0.0023	0.49	2.24
		Diligence	0	.	.	.	.	.	.
Summer Flounder	Intercept	-0.044	0.135	201	-0.3	0.7447	-0.311	0.223	
	Length	-0.313	0.172	201	-1.8	0.0712	-0.652	0.027	
Monkfish	Intercept	-0.119	0.055	1442	-2.1	0.0322	-0.227	-0.01	
	Length	0.166	0.067	1442	2.48	0.0132	0.035	0.297	
	Length^2	0.123	0.067	1442	1.83	0.0681	-0.009	0.254	
Sea Scallop	Intercept		-0.049	0.055	186	-0.891	0.3743	-0.157	0.059
	Length		0.295	0.113	186	2.615	0.0097	0.072	0.518
	Length*Cruise	Beiningen	-0.084	0.158	1827	-0.534	0.5936	-0.394	0.225
		Celtic	-0.201	0.165	1827	-1.219	0.2231	-0.525	0.123
		Concordia	-0.462	0.15	1827	-3.072	0.0022	-0.756	-0.17
		Diligence	0	.	.	.	.	.	.
	Length^2		-0.312	0.114	1827	-2.748	0.0061	-0.535	-0.09
	Length^2*Cruise	Beiningen	0.351	0.129	1827	2.728	0.0064	0.099	0.604
		Celtic	0.516	0.151	1827	3.413	0.0007	0.219	0.812
		Concordia	0.395	0.144	1827	2.736	0.0063	0.112	0.679
		Diligence	0	.	.	.	.	.	.
	Cruise	Beiningen	0.005	0.079	1827	0.065	0.9479	-0.149	0.16
		Celtic	-0.297	0.084	1827	-3.529	0.0004	-0.462	-0.13
		Concordia	-0.056	0.075	1827	-0.744	0.4572	-0.202	0.091
		Diligence	0	.	.	.	.	.	.

Table 10: *Parameter estimates for the selected models examining the pooled catch data for sea scallops.*

Model	Effect	Estimate	SE	DF	t value	p value
TEST/(TEST+CTRL)~1+MLL+offset(log(qTEST/qCTRL)	Intercept	-0.512	0.142	1491	-3.59	0.0003
	Length	0.003	0.001	1491	2.861	0.0043
TEST/(TEST+CTRL)~1+MLL+I(MLL^2)+offset(log(qTEST/qCTRL)	Intercept	-1.974	0.739	1490	-2.669	0.0077
	Length	0.027	0.012	1490	2.277	0.0229
	Length^2	-0.0001	0.00005	1490	-2.017	0.0439
TEST/(TEST+CTRL)~1+MLL+I(MLL^2)+I(MLL^3)+offset(log(qTEST/qCTRL)	Intercept	-5.65	2.469	1489	-2.287	0.0223
	Length	0.126	0.064	1489	1.978	0.0481
	Length^2	-0.0009	0.0005	1489	-1.761	0.0784
	Length^3	0.000003	0.000001	1489	1.593	0.1112

Table 11: *A comparison of the relative efficiencies estimated from the intercept only model for the analyzed species and the observed percent differences from the catch data collected during the experiment. Statistical significance (alpha=0.05 level) is specific to that model and may not be the most parsimonious model from the analysis.*

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Monkfish	933	996	-6.33%	-7.82%	NO
Sea Scallops	279,774	291,103	-3.89%	-9.58%	**YES**

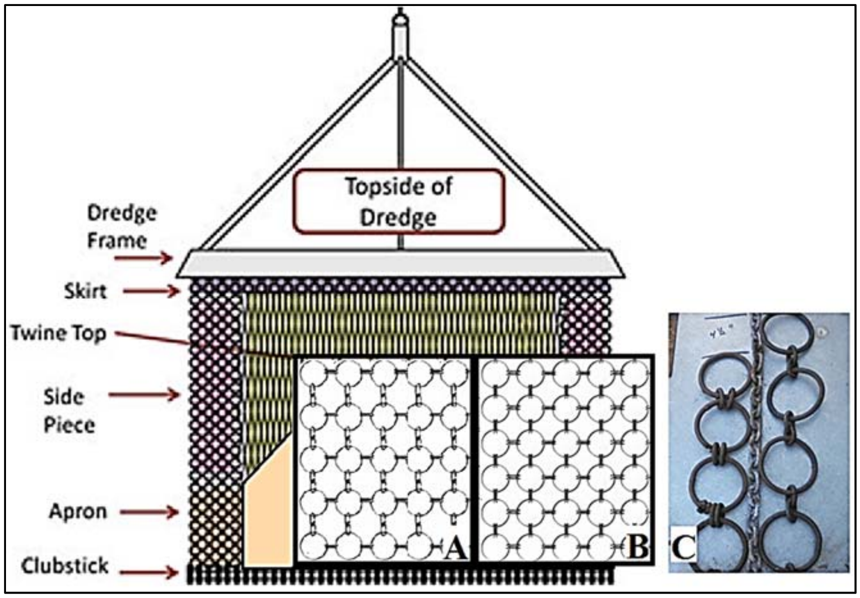

***Figure 2**: Diagram of the topside of a dredge illustrating the difference between an extended link apron (A) and a standard linked apron (B). Chain or shackles are used to connect standard linked portions of the bag to the extended link (C).*

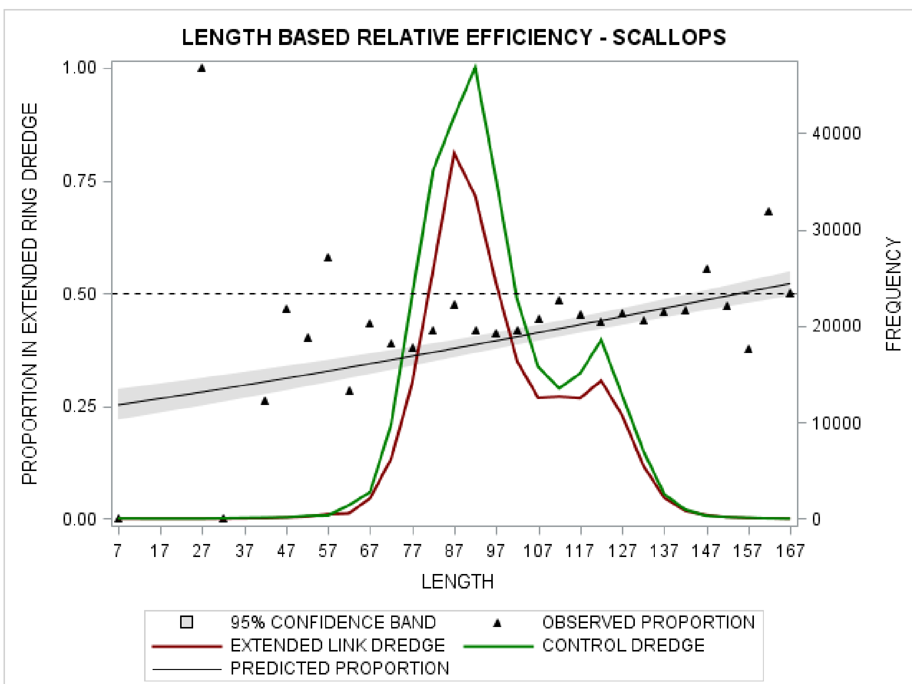

***Figure 2:** Relative sea scallop catch from an experimental (two-way extended link apron) and control (standard link apron) dredge in 2016. Triangles represent the observed proportion at length ($Catch_{ext}/(Catch_{ext} + Catch_{stand})$, with a proportion >0.5 (dotted line) representing more animals at length captured by the extended link apron dredge. The grey area represents the 95% confidence band for the modeled proportion (solid line).*

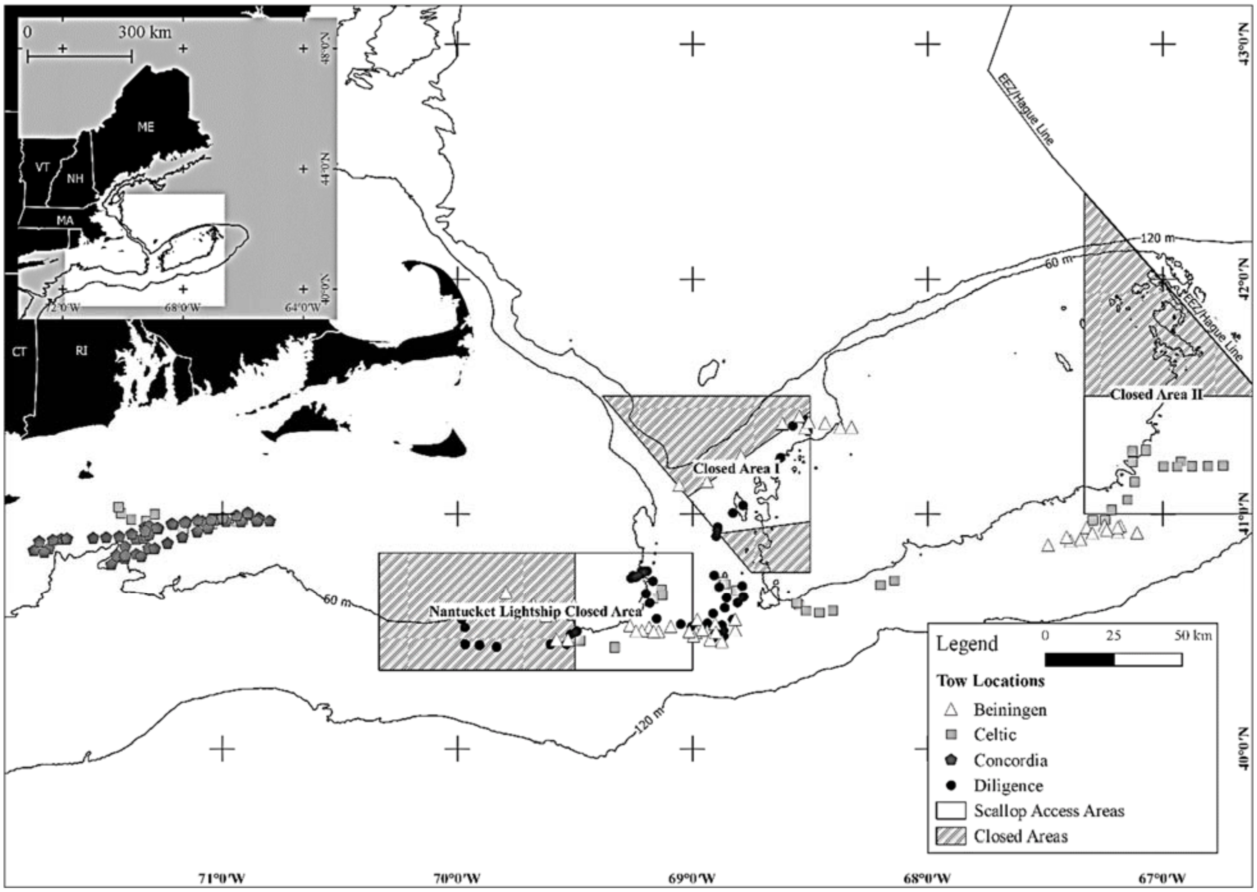

Figure 3: *Tow location of the four research cruise.*

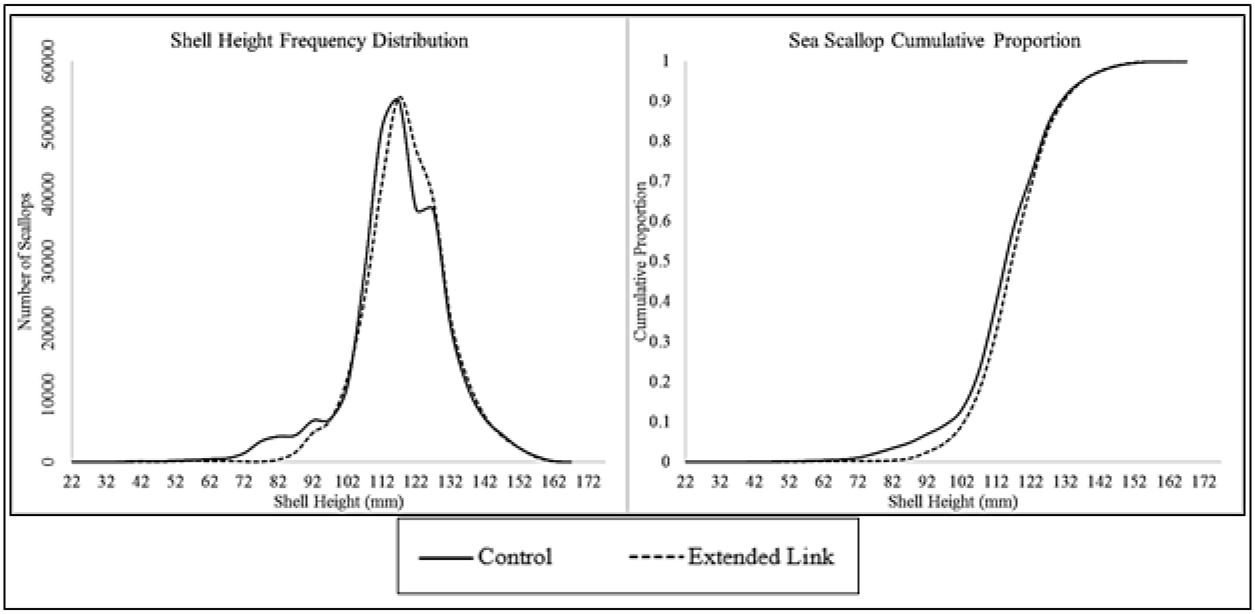

Figure 4: *The pooled scallop shell height frequency distribution and cumulative proportion curves for the control dredge (solid line) and the extended link apron (dashed line).*

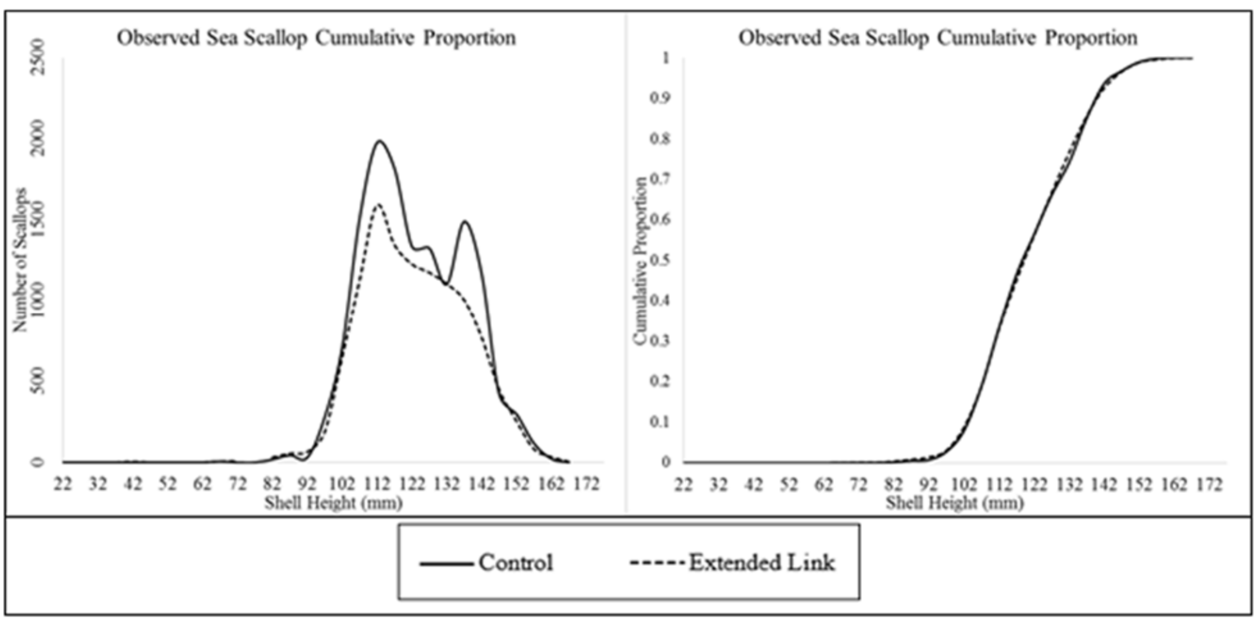

Figure 5: *The pooled scallop shell height frequency distribution and cumulative proportion curves for the control dredge (solid line) and the extended link apron (dashed line) for the FV Celtic cruise.*

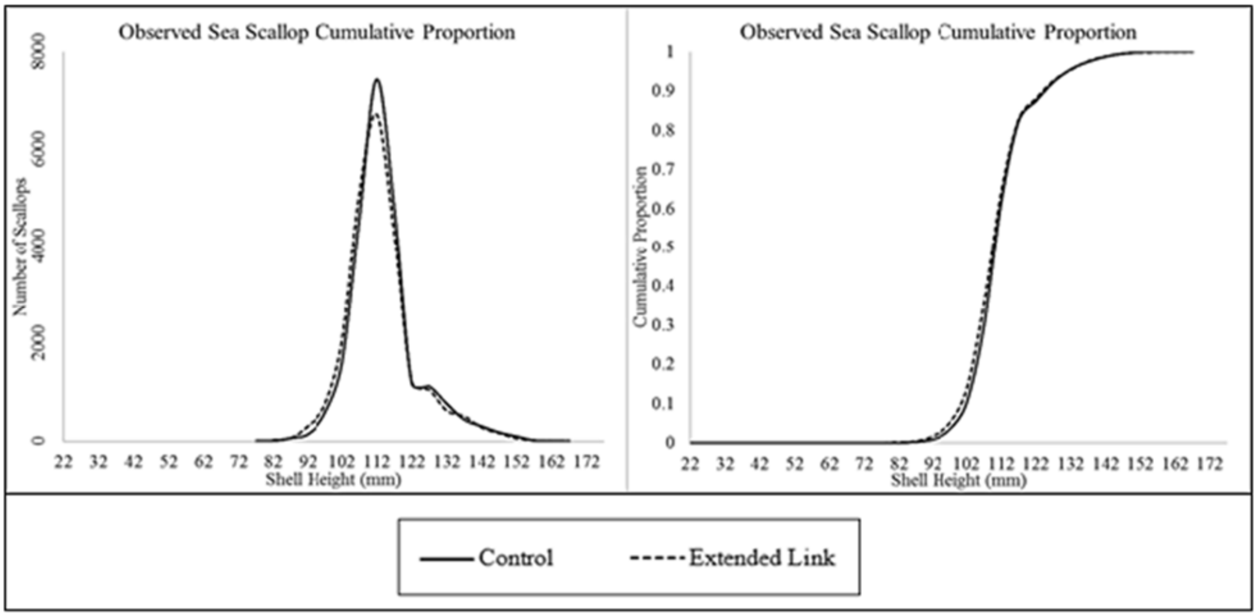

Figure 6: *The pooled scallop shell height frequency distribution and cumulative proportion curves for the control dredge (solid line) and the extended link apron (dashed line) for the FV Concordia cruise.*

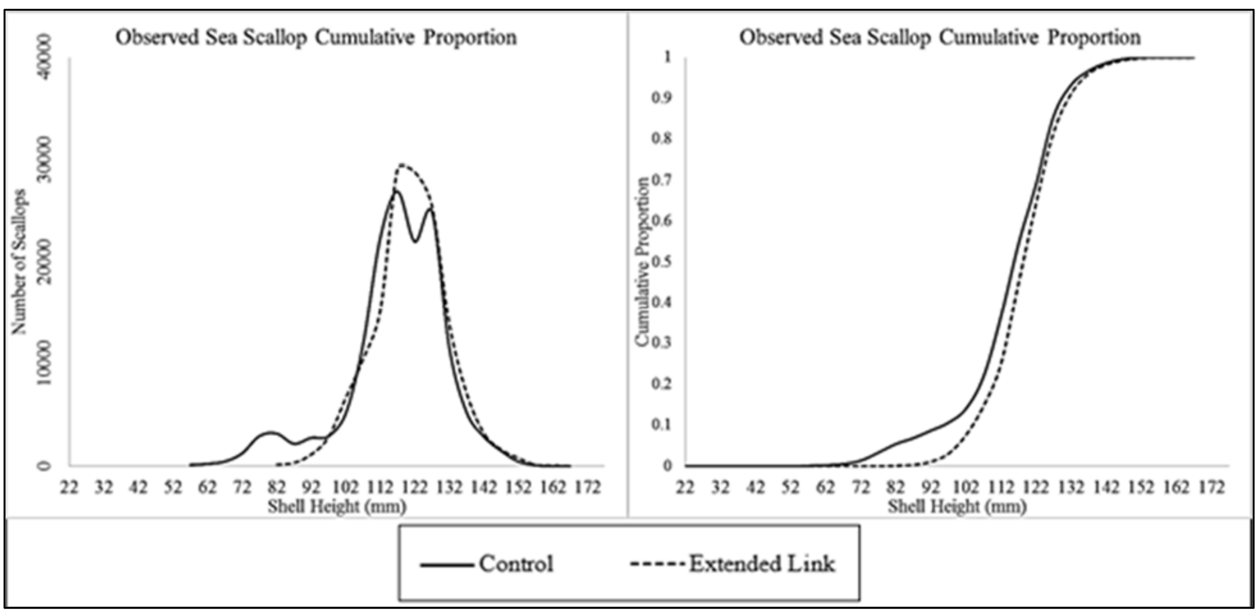

Figure 7: *The pooled scallop shell height frequency distribution and cumulative proportion curves for the control dredge (solid line) and the extended link apron (dashed line for the FV Diligence cruise).*

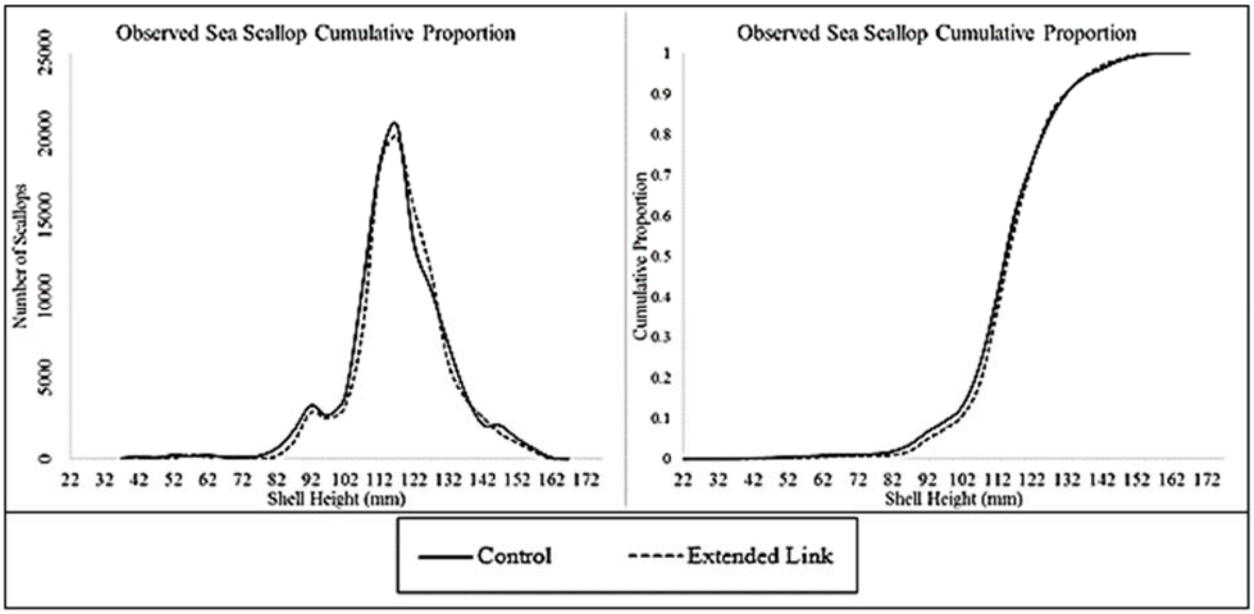

Figure 8: *The pooled scallop shell height frequency distribution and cumulative proportion curves for the control dredge (solid line) and the extended link apron (dashed line) for the FV Beiningen cruise.*

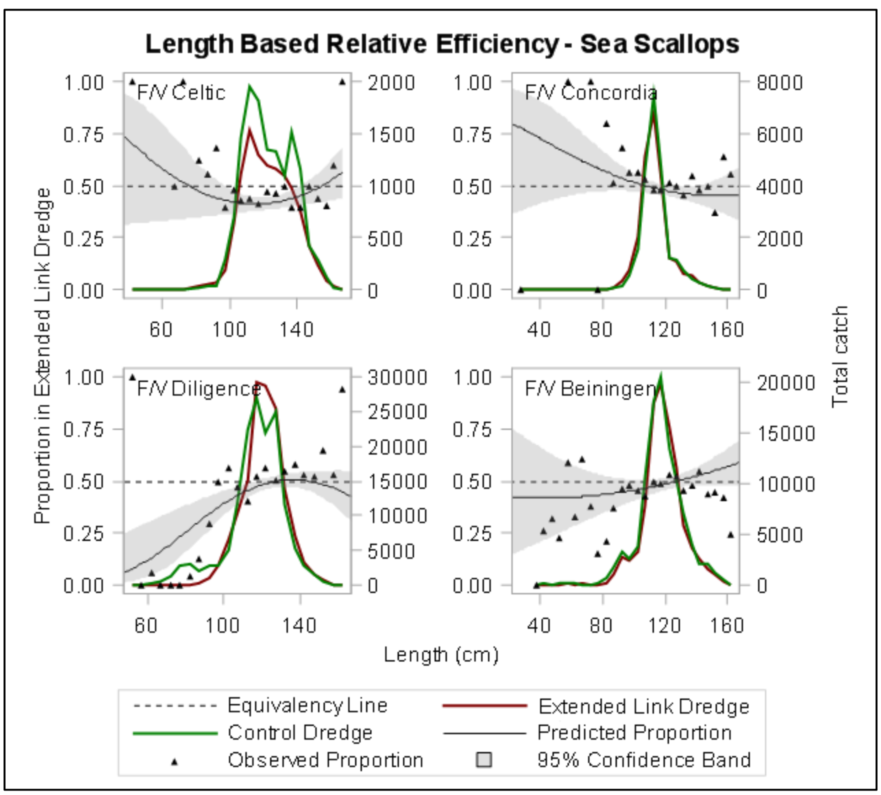

Figure 9: *Relative sea scallop catch by the two dredge configurations by cruise as supported by the selected length-based model. The grey area represents the 95% confidence band.*

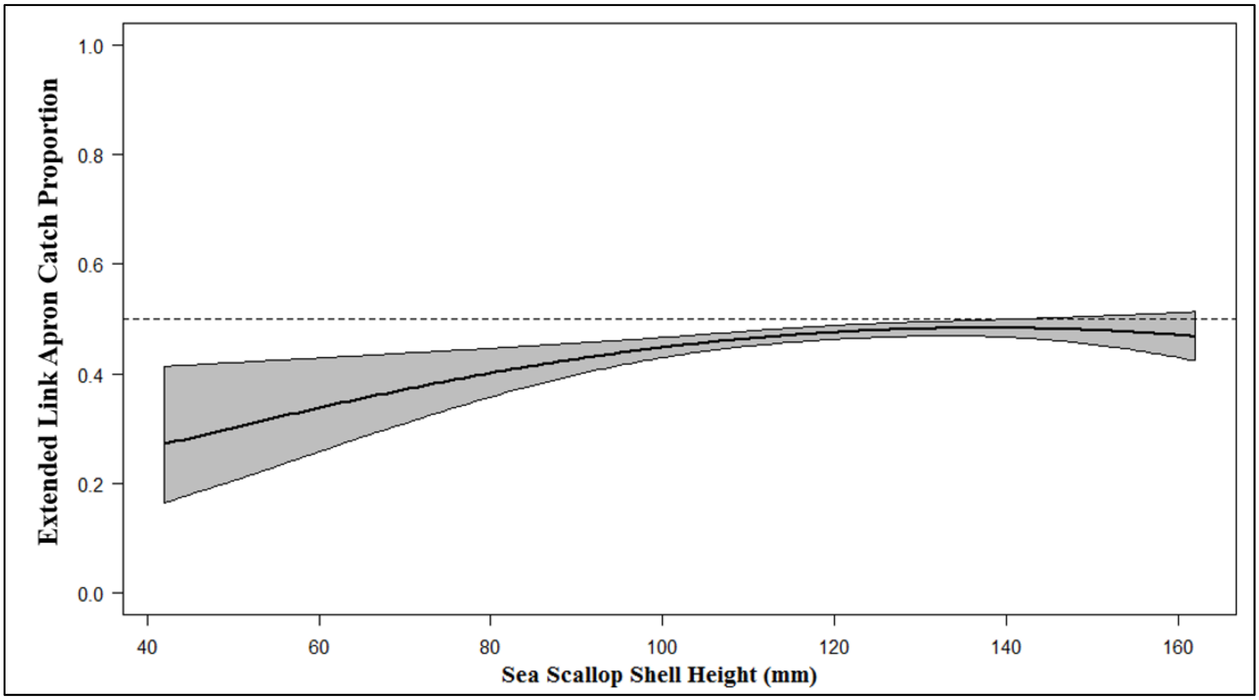

Figure 10: *Relative sea scallop catch by the two dredge configurations as supported by the second order polynomial model. The grey area represents the 95% confidence band.*

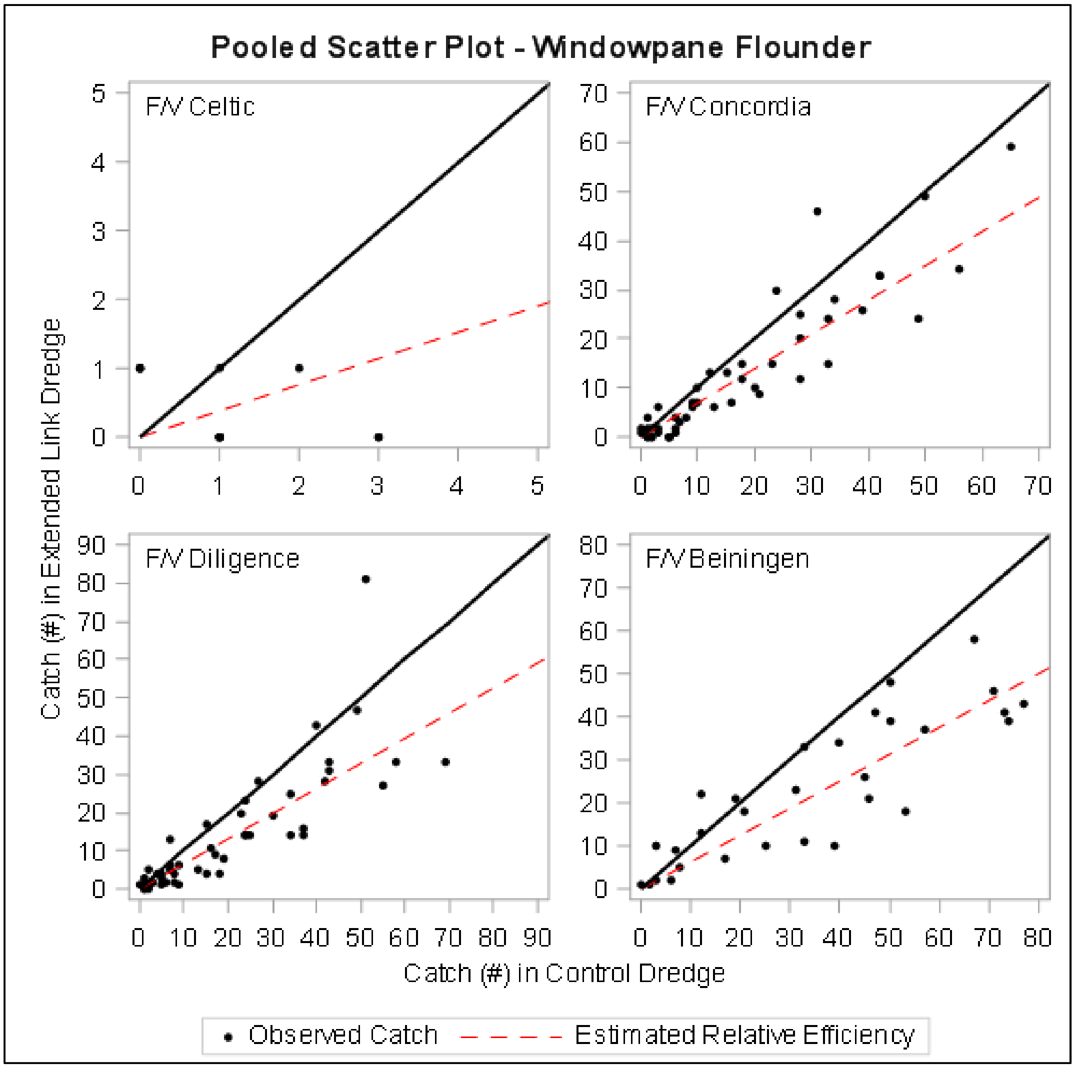

Figure 11: *Total pooled catches for windowpane flounder for the extended link dredge vs. the control dredge. The visualization of these data is represented by the selected model from the pooled over length data. For this species, cruise was a significant predictor of the relative efficiency. The estimated relative efficiency (model prediction) is show as the red dashed line. The black (equivalency) line has a slope of one.*

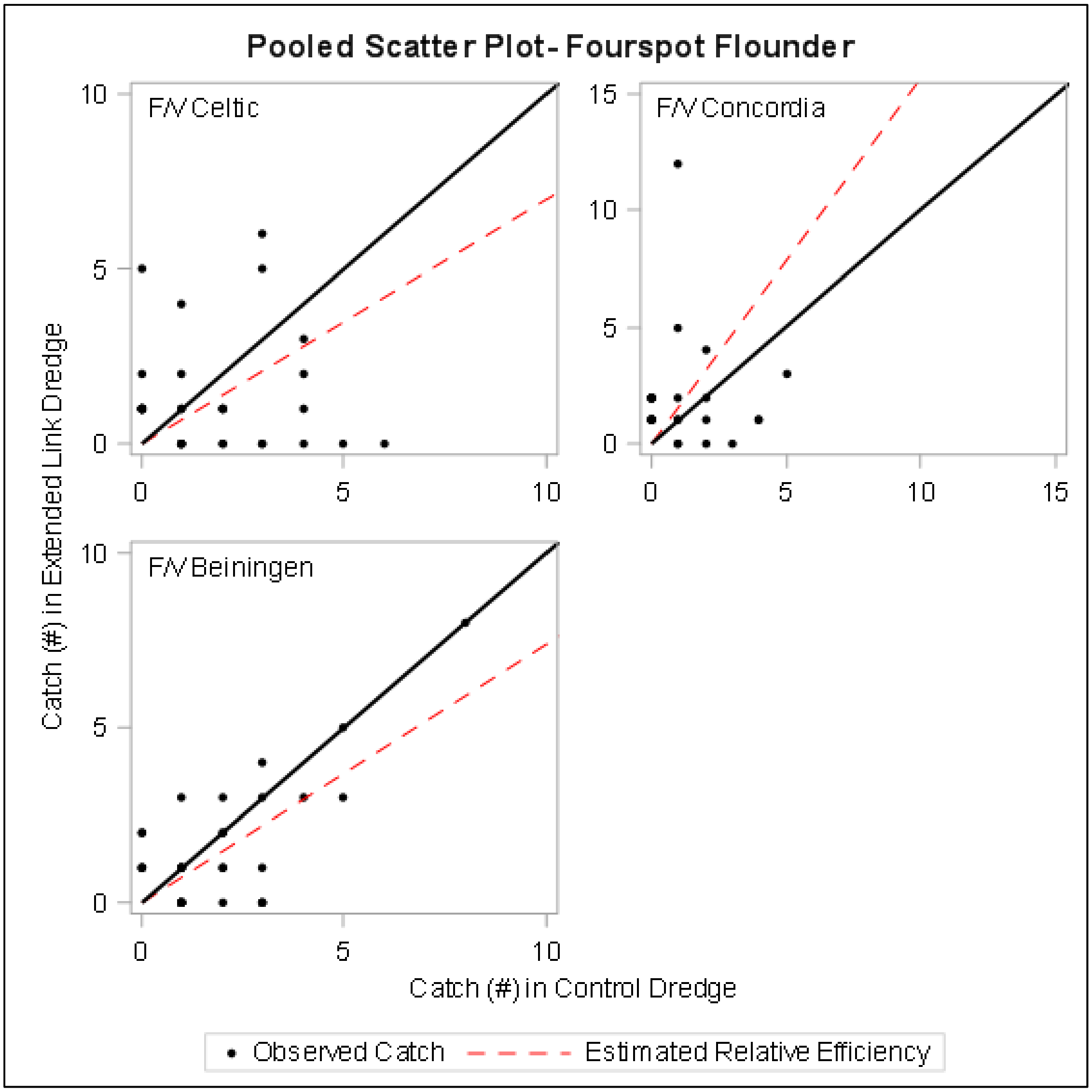

Figure 12*: Total pooled catches for fourspot flounder for the extended link dredge vs. the control dredge. The visualization of these data is represented by the selected model from the pooled over length data. For this species, cruise was a significant predictor of the relative efficiency. The estimated relative efficiency (model prediction) is show as the red dashed line. The black (equivalency) line has a slope of one. Due to the absence of this species on the F/V Diligence cruise, that graph was ommitted.*

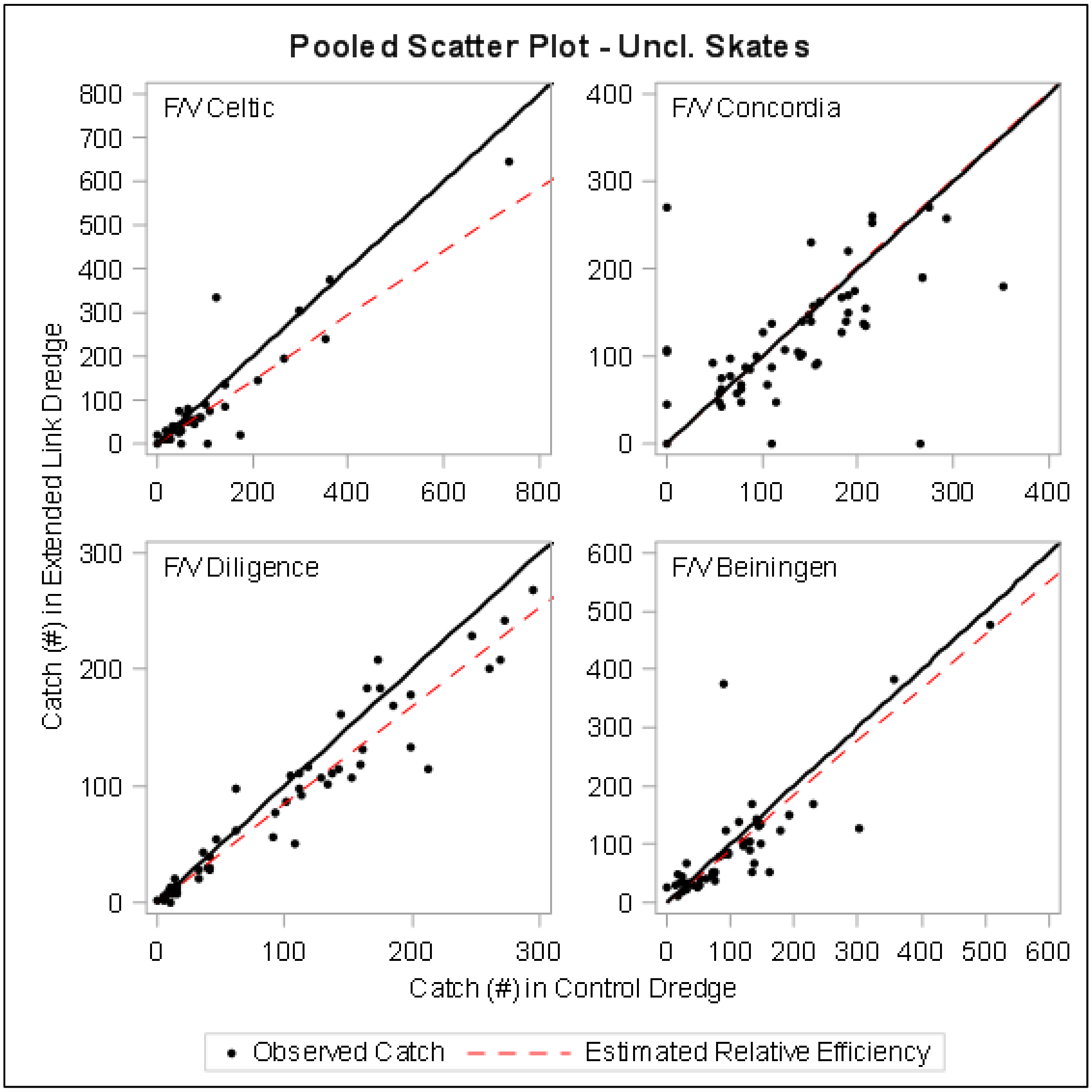

Figure 13: *Total pooled catches for unclassified skates for the extended link dredge vs. the control dredge. The visualization of these data is represented by the selected model from the pooled over length data. For this species, cruise was a significant predictor of the relative efficiency. The estimated relative efficiency (model prediction) is show as the red dashed line. The black (equivalency) line has a slope of one.*

Appendix A: 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 extended link dredge and q_f equals the catchability of the control dredge used in the study. The efficiency of the extended link dredge relative to the control dredge will be equivalent to the ratio of the two catchabilities:

$$\rho_l = \frac{q_r}{q_f} \quad (1)$$

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 extended link dredge and $v=f$ denotes the control dredge. Let λ_{ir} represent the scallop/fish density for the i^{th} station by the extended link dredge and λ_{if} the scallop/fish density encountered by the control 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 control dredge is given by:

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

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

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

where δ_i =log ($\lambda_{ir}/ \lambda_{if}$). 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. $\lambda_{ir}= \lambda_{if}$), 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 extended link 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:

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

where p=ρ/(1+ρ) is the probability that a scallop/fish captured by the extended link 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:

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

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:

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

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:

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

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:

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

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 subsampled. In these cases the model caught the tows that were subsampled and treated them accordingly. 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 windowpane flounder the subsampling rate was 1 on both sides. Since the offset is the log of the quotient of the sampling rate of both sides 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:

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

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

Our analysis of the efficiency of the extended link dredge relative to the control 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).

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

Appendix B

Table 1: *Model building for length-based models. Hierarchical models ranked based upon minimum AIC values. Some species have fewer candidate models as a function of non-convergence of individual models. In cases where random effects were included and insufficient variation within the slope or intercept existed, the models converged, however the inclusion of the random effects were not warranted and those model specifications were not included in the table. In cases where the delta AIC value was less than 3 units, the simpler model was chosen. Parameter estimates from these models were shown for species where length was included in the preferred model. The selected model is shown in bold.*

Species	Model	Fixed Effects	Random Effects	AIC Value	Delta AIC
Barndoor Skate	**M4**	**Length, Length^2, Cruise**	**NONE**	**451.5**	**0**
	M10	Length, Length^2, Cruise	INTERCEPT	452.32	0.85
	M15	Length, Length^2, Cruise	INTERCEPT, SLOPE	452.85	1.39
	M18	Length, Length^2, Cruise, Length*Cruise	INTERCEPT, SLOPE	459.7	8.23
	M6	Length, Length^2, Cruise, Beaufort Number	NONE	460.01	8.54
	M12	Length, Length^2, Cruise, Beaufort Number	INTERCEPT	461.4	9.94
	M17	Length, Length^2, Cruise, Beaufort Number	INTERCEPT, SLOPE	462.16	10.7
	M7	INTERCEPT ONLY	INTERCEPT	462.69	11.22
	M11	Length, Length^2, Beaufort Number	INTERCEPT	464.41	12.94
	M5	Length, Length^2, Beaufort Number	NONE	465.76	14.29
	M13	Length	INTERCEPT, SLOPE	465.95	14.49
	M16	Length, Length^2, Beaufort Number	INTERCEPT, SLOPE	465.97	14.5
	M9	Length, Length^2	INTERCEPT	466.13	14.67
	M1	INTERCEPT ONLY	NONE	467.76	16.3
	M14	Length, Length^2	INTERCEPT, SLOPE	467.92	16.46
	M2	Length	NONE	467.99	16.53
	M8	Length	INTERCEPT	467.99	16.53
	M3	Length, Length^2	NONE	469.61	18.14
Fourspot Flounder	**M7**	**INTERCEPT ONLY**	**INTERCEPT**	**368.1**	**0**
	M13	Length	INTERCEPT, SLOPE	368.87	0.82
	M10	Length, Length^2, Cruise	INTERCEPT	369.39	1.34
	M9	Length, Length^2	INTERCEPT	369.9	1.86
	M15	Length, Length^2, Cruise	INTERCEPT, SLOPE	370.77	2.73
	M14	Length, Length^2	INTERCEPT, SLOPE	370.87	2.82
	M1	INTERCEPT ONLY	NONE	372.81	4.77
	M4	Length, Length^2, Cruise	NONE	372.91	4.87

	M2	Length	NONE	374.56	6.51
	M8	Length	INTERCEPT	374.56	6.51
	M3	Length, Length^2	NONE	375.19	7.14
	M5	Length, Length^2, Beaufort Number	NONE	380.84	12.79
	M6	Length, Length^2, Cruise, Beaufort Number	NONE	380.92	12.87
Monkfish	**M9**	**Length, Length^2**	**INTERCEPT**	**2273**	**0**
	M10	Length, Length^2, Cruise	INTERCEPT	2277.6	4.57
	M7	INTERCEPT ONLY	INTERCEPT	2280.2	7.19
	M11	Length, Length^2, Beaufort Number	INTERCEPT	2284	10.98
	M12	Length, Length^2, Cruise, Beaufort Number	INTERCEPT	2287.4	14.36
	M3	Length, Length^2	NONE	2287.5	14.49
	M2	Length	NONE	2288.9	15.89
	M8	Length	INTERCEPT	2288.9	15.89
	M4	Length, Length^2, Cruise	NONE	2290.6	17.59
	M1	INTERCEPT ONLY	NONE	2293.4	20.38
	M5	Length, Length^2, Beaufort Number	NONE	2296.9	23.9
	M6	Length, Length^2, Cruise, Beaufort Number	NONE	2298.5	25.41
Sea Scallops	**M18**	**Length, Length^2, Cruise, Length*Cruise**	**INTERCEPT, SLOPE**	**9177**	**0**
	M15	Length, Length^2, Cruise	INTERCEPT, SLOPE	9186.6	9.72
	M13	Length	INTERCEPT, SLOPE	9192.8	15.88
	M14	Length, Length^2	INTERCEPT, SLOPE	9194	17.09
	M17	Length, Length^2, Cruise, Beaufort Number	INTERCEPT, SLOPE	9200.6	23.71
	M16	Length, Length^2, Beaufort Number	INTERCEPT, SLOPE	9206.8	29.86
	M10	Length, Length^2, Cruise	INTERCEPT	9441.1	264.15
	M12	Length, Length^2, Cruise, Beaufort Number	INTERCEPT	9452.2	275.25
	M9	Length, Length^2	INTERCEPT	9452.8	275.84
	M11	Length, Length^2, Beaufort Number	INTERCEPT	9464.8	287.85
	M7	INTERCEPT ONLY	INTERCEPT	9479.9	302.95
	M6	Length, Length^2, Cruise, Beaufort Number	NONE	9893.3	716.41
	M4	Length, Length^2, Cruise	NONE	9906.1	729.21
	M5	Length, Length^2, Beaufort Number	NONE	9969.1	792.22
	M3	Length, Length^2	NONE	9980	803.1
	M2	Length	NONE	9994.5	817.58
	M8	Length	INTERCEPT	9994.5	8817.58
	M1	INTERCEPT ONLY	NONE	10010	833.08
Summer Flounder	**M2**	**Length**	**NONE**	**299.2**	**0**
	M8	Length	INTERCEPT	299.21	0
	M3	Length, Length^2	NONE	300.66	1.45
	M1	INTERCEPT ONLY	NONE	300.68	1.47
	M4	Length, Length^2, Cruise	NONE	305.94	6.72

	M5	Length, Length^2, Beaufort Number	NONE	307.57	8.36
	M6	Length, Length^2, Cruise, Beaufort Number	NONE	311.74	12.53
Windowpane Flounder	**M7**	**INTERCEPT ONLY**	**INTERCEPT**	**2611**	**0**
	M13	Length	INTERCEPT, SLOPE	2613.3	2.05
	M9	Length, Length^2	INTERCEPT	2613.8	2.59
	M14	Length, Length^2	INTERCEPT, SLOPE	2614.8	3.59
	M10	Length, Length^2, Cruise	INTERCEPT	2618.1	6.83
	M15	Length, Length^2, Cruise	INTERCEPT, SLOPE	2619.1	7.85
	M11	Length, Length^2, Beaufort Number	INTERCEPT	2622.3	11.11
	M16	Length, Length^2, Beaufort Number	INTERCEPT, SLOPE	2623.4	12.15
	M18	Length, Length^2, Cruise, Length*Cruise	INTERCEPT, SLOPE	2624.9	13.64
	M12	Length, Length^2, Cruise, Beaufort Number	INTERCEPT	2626.8	15.53
	M17	Length, Length^2, Cruise, Beaufort Number	INTERCEPT, SLOPE	2627.8	16.62
	M1	INTERCEPT ONLY	NONE	2640.7	29.45
	M2	Length	NONE	2641.3	30.1
	M8	Length	INTERCEPT	2641.3	30.1
	M3	Length, Length^2	NONE	2643	31.78
	M4	Length, Length^2, Cruise	NONE	2644.2	32.95
	M5	Length, Length^2, Beaufort Number	NONE	2646.3	35.09
	M6	Length, Length^2, Cruise, Beaufort Number	NONE	2649.5	38.28
Yellowtail Flounder	**M1**	**INTERCEPT ONLY**	**NONE**	**155.2**	**0**
	M3	Length, Length^2	NONE	156.13	0.89
	M2	Length	NONE	157.19	1.94
	M8	Length	INTERCEPT	157.19	1.94
	M4	Length, Length^2, Cruise	NONE	160.61	5.37
	M5	Length, Length^2, Beaufort Number	NONE	166.85	11.61
	M6	Length, Length^2, Cruise, Beaufort Number	NONE	171.13	15.89

Table 2: Model building for pooled over length models. Hierarchical models ranked based upon minimum AIC values. Some species have fewer candidate models as a function of non-convergence of individual models. In cases where random effects were included and insufficient variation within the slope or intercept existed, the models converged, however the inclusion of the random effects were not warranted and those model specifications were not included in the table. In cases where the delta AIC value was less than 3 units, the simpler model was chosen. Parameter estimates from these models were shown for species where length was included in the preferred model. The selected model is shown in bold.

Species	Model	Fixed Effects	Random Effects	AIC Value	Delta AIC
Fourspot Flounder	**M6**	**CRUISE**	**INTERCEPT**	**228.94**	**0**
	M3	CRUISE	NONE	231.63	2.69
	M1	INTERCEPT ONLY	NONE	234.14	5.2
	M5	BEAUFORT	INTERCEPT	234.37	5.43
	M8	INTERCEPT ONLY	INTERCEPT	236.64	7.69
	M2	BEAUFORT	NONE	239.13	10.19
	M4	BEAUFORT, CRUISE	NONE	239.6	10.65
Uncl. Skates	**M6**	**CRUISE**	**INTERCEPT**	**1875.4**	**0**
	M5	BEAUFORT	INTERCEPT	1877.9	2.51
	M8	INTERCEPT ONLY	INTERCEPT	1882.8	7.32
	M7	BEAUFORT, CRUISE	INTERCEPT	1882.8	7.32
	M4	BEAUFORT, CRUISE	NONE	3728	1852.5
	M2	BEAUFORT	NONE	3730	1854.5
	M3	CRUISE	NONE	3774	1898.6
	M1	INTERCEPT ONLY	NONE	3777.9	1902.4
Windowpane Flounder	**M6**	**CRUISE**	**INTERCEPT**	**669.21**	**0**
	M5	BEAUFORT	INTERCEPT	673.67	4.46
	M7	BEAUFORT, CRUISE	INTERCEPT	678.22	9.01
	M8	INTERCEPT ONLY	INTERCEPT	678.22	9.01
	M4	BEAUFORT, CRUISE	NONE	738.7	69.5
	M2	BEAUFORT	NONE	742.12	72.92
	M3	CRUISE	NONE	742.66	73.45
	M1	INTERCEPT ONLY	NONE	750.6	81.39
Yellowtail Flounder	**M1**	**INTERCEPT ONLY**	**NONE**	**105.07**	**0**
	M6	CRUISE	INTERCEPT	107.85	2.78
	M3	CRUISE	NONE	107.85	2.78
	M2	BEAUFORT	NONE	114.52	9.45
	M5	BEAUFORT	INTERCEPT	114.52	9.45
	M7	BEAUFORT, CRUISE	INTERCEPT	115.77	10.7
	M8	INTERCEPT ONLY	INTERCEPT	115.77	10.7
	M4	BEAUFORT, CRUISE	NONE	115.77	10.7