**Project Title:** Development of Ecosystem-Friendly Scallop Dredge Bags: Tools for Long-Term Sustainability

**Project Duration:** One year

**Applicant:** Coonamessett Farm Foundation, Inc
277 Hatchville Road
East Falmouth, MA 02536
Phone: 508-564-5516
FAX: 508-564-5073
Email: cfarm@capecod.net

**Project Management:**
Field testing and analysis: Farrell Davis and Liese Siemann
GLMM Analysis: Dave Rudders
Technical Advisor: Ronald Smolowitz

## Project Summary

Multiple years of high sea scallop (*Placopecten magellanicus*) recruitment has led to a situation where pre-recruit scallops and harvestable scallop resources are concurrently distributed in high densities within some of the rotational access areas. Therefore, the incidental bycatch and discard mortality of pre-recruit scallops could have negative impacts on the long term sustainability of the scallop fishery. Additionally, accountability measures (AM) for yellowtail (*Limanda ferruginea*) and windowpane (*Scopthalmus aquosus*) flounder further jeopardize the economic viability of this fishery. The goal of this project was to develop an alternative gear design to reduce the impact of fishing effort on pre-recruit scallops and flatfish species.

To reduce the capture of pre-recruit scallops, Coonamessett Farm Foundation, Inc. (CFF) investigated approximately doubling the inter-ring spacing of the apron by using two links joined end-to-end (rather than two side-by-side links) to connect the rings. This non-standard configuration yielded promising preliminary results on research compensation trips (**Figure 1)**. The most extreme configuration, extending the inter-ring spacing in both the horizontal and vertical directions, was the primary gear configuration tested for this project. A total of five trips were conducted throughout Southern New England (SNE), the New York Bight (NYB), and the Mid-Atlantic Access (MAA) areas to compare this experimental gear configuration to a standardized control dredge (i.e., side-by-side links). Two additional trips were conducted to assess the selective properties of the control and experimental dredge bags through paired-tow comparisons with a lined survey dredge. A final trip utilized a dredge bag cover net to estimate the numbers and sizes of scallops and fishes passing through the twine top and apron.

Results from field testing of the extended link indicate that this configuration is effective at reducing the catch of pre-recruit scallops with a minimal reduction in catch efficiency of larger, more marketable scallops. Increasing the inter-ring spacing may also reduce the bycatch of skate species and finfish. The cover net showed great potential for providing conservative estimates of flatfish catchability in scallop dredges.

## Introduction

The Northwest Atlantic sea scallop (*Placopecten magellanicus*) fishery is currently one of the most lucrative wild-harvest fisheries in the United States (NMFS 2014). Beginning in 1994, fisheries managers, with the use of effort controls and area management, were able to increase the recovery rate of the sea scallop stocks and rapidly rebuild what was once a severely depleted fishery into a lucrative, sustainable example of a successfully managed fishery (Hart & Rago 2006). The success of the scallop fishery is due in part to the collaboration of industry, management, and science in developing resource stewardship practices through collaborative research programs like the scallop Research Set-Aside (RSA) program (Adams 2015, Repetto 2001). The RSA program has funded the research and development of sustainable sea scallop harvesting technologies that mitigate the negative impacts of fishing and allow for sustained access to the resource (Jennings & Revill 2007). These technologies can be used independently or in conjunction with spatial management to address issues that jeopardize the economic viability and sustainability of the scalloping industry.

Variability in sea scallop recruitment in the Mid-Atlantic has yielded areas where pre-recruit scallops are mixed with high densities of harvestable scallops. Prior to Amendment 4 of the Sea Scallop Fisheries Management Plan, and in the absence of a minimum landing size for scallops shucked at sea, managers used maximum meat counts in an attempt to increase the age of recruitment (NEFMC 1994). The meat count system was woefully inadequate for preventing growth or recruitment overfishing of sea scallop resources. As early as 1987, researchers began to propose technical measures, such as a minimum ring size, as an alternative approach (Repetto 2001, Smolowitz & Serchuk 1987). In 1994, regulations were put in place to reduce effort and fishing mortality, including an incremental increase of the minimum ring size from 3.25” to 3.5” over a three-year period (NEFMC 1994). Increased size selectivity of the gear, in combination with extraordinary recruitment events in the Mid-Atlantic, increased the sea scallop biomass to an extent where managers, in 2001, reopened portions of the Mid-Atlantic that had been closed since 1998. In 2004, managers implemented a 4” minimum ring size and a 10” minimum twine top. Implementation of minimum ring size further reduced catch of pre-recruit scallops, while the twine top minimum reduced scallop-fishery impact on groundfish.

The 2003 year-class of scallops was estimated to be larger than the entire scallop stock in any given year between 2004 and 2009. However, this exceptional year class experienced a sharp and sudden decline in the MAA areas, which is widely believed to be the result of recruitment overfishing (Stokesbury et al. 2011a, b). High densities of the 2003 year-class and the unfortunate coincidental opening of the MAA areas to fishing increased the exposure and vulnerability of the 2003 year-class to capture, desiccation, and thermal shock as they were being culled from the pile on deck, ultimately leading to increased discard mortality (Stokesbury et al. 2011a, b). Resource surveys of the MAA and SNE areas in 2015 indicated that high recruitment over multiple years has led to areas with large numbers of both pre-recruit scallops and harvestable scallops (Boelke 2015). Closures of these areas to protect pre-recruit scallops could result in significant economic losses due to natural mortality (Stokesbury et al. 2007). To avoid a repeat of the recruitment overfishing that decimated the 2003 year-class, a technical solution is needed to sift pre-recruit scallops and prevent them from being captured. Extending inter-ring spacing, which would allow more pre-recruit scallops to escape, could accomplish this goal

(**Figure 1**).


***Figure 1:*** *(Left) A side-by-side comparison of a row of rings from a normal apron and the extended link apron. (Right) The inter-ring spacing in a normal apron and a two-way extended link apron.*

**Methods**

Multiple gear configuration tests were conducted during RSA compensation research trips aboard participating scallop vessels for this project (**Table 1**).

***Table 1****: List of gear configurations tested during compensation research trips.*

| **Description of Potential Bag Modifications** |
|---|
| Extended Link Apron (Vertical) |
| Extended Link Apron (Horizontal) |
| Extended Link Apron (Two-way) |
| "Daylight" Skirt (Skirt replaced with 12" square windows) |

While extending the links in a single direction either horizontally or vertically appeared to decrease catch loss, the two-way (horizontal and vertical) extended link apron configuration was also tested because it was radically different from a normal apron configuration and would potentially result in the most dramatic changes. After analyzing the data, the two-way extended link apron configuration was confirmed to be the most effective for reducing retention of pre-recruit scallops, and, thereby, reducing discard mortality.

*Research trips*

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

To assess how the two-way extended link apron impacts the efficiency of a scallop dredge, the study was divided into two parts: sea trials with paired control and experimental dredges, and a selectivity experiment utilizing a lined survey dredge. A final trip utilized a dredge bag cover net that extended from the top of the dredge headbale to the clubstick, to estimate the numbers and sizes of scallops and fishes passing through the twine top and apron. The sea trials compared the two-way extended link configuration to a control dredge configured with a standard apron. Dredges were towed simultaneously for 30 to 60 minutes at 4.8 – 5.1 knots to simulate commercial fishing conditions. At least once during each trip, the control dredge and experimental dredges were switched to reduce any effects resulting from towing a given dredge on the port or starboard side of the vessel. The selectivity study utilized a standard survey dredge (8' with a 38-mm mesh liner) as the non-selective gear. Tow parameters for the selectivity study deviated from the sea trial and commercial tow parameters with shorter tow durations and slower speeds ((15-minute tows at 4 - 4.5 knots). Catch data from the sea trials were analyzed to assess the impact the two-way extended link apron had on catch efficiency relative to the control dredge. Data collected during the selectivity experiment were used to generate and compare length-based retention probability curves.

**Figure 3:** *The preliminary dredge cover net.*

For all research tows, the entire catch for each side was sorted into bushel baskets (basket) and weighed to the nearest 0.01 kg using a 60 kg Marel® scale (as described in **Table 2**). Scallop baskets were counted and weighed. All scallops in a randomly selected one-basket subsample from each side were measured in 5-mm increments. Based on previous CFF research, a one-bushel subsample accurately represents the size frequency of scallops in commercial catches using a 4-inch ring dredge bag. Fish catch was sorted by species, counted, and weighed to the nearest 0.01 kg. Each fish was measured in 1-cm increments. In cases where there were large catches of fish, a subsample was collected for size-frequency data. Trash and benthos were also counted by bushel and weighed to the nearest 0.01 kg. Environmental data, including bottom depth, Beaufort value, wind direction, wind speed, and sea conditions, was also recorded. Tow parameter data was recorded using an onboard GPS system and included vessel position, heading, and speed in 15-second intervals (see **Figure 2** for tow locations). Tows were considered invalid if the research tow parameters were not followed or if a gear malfunction occurred on one or both of the dredges (e.g. tangled twine top or the dredge flipping during setting out).

***Table 2:*** *Catch data collected for each tow during the sea trials and selectivity experiment*

| |
|---|
| 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) |
| Skate catch rates (# of individuals/tow/side) |
| Skate weight (total weight/tow/side) |
| Weight, volume, and composition assessment of trash (e.g. sea star and crab species) |

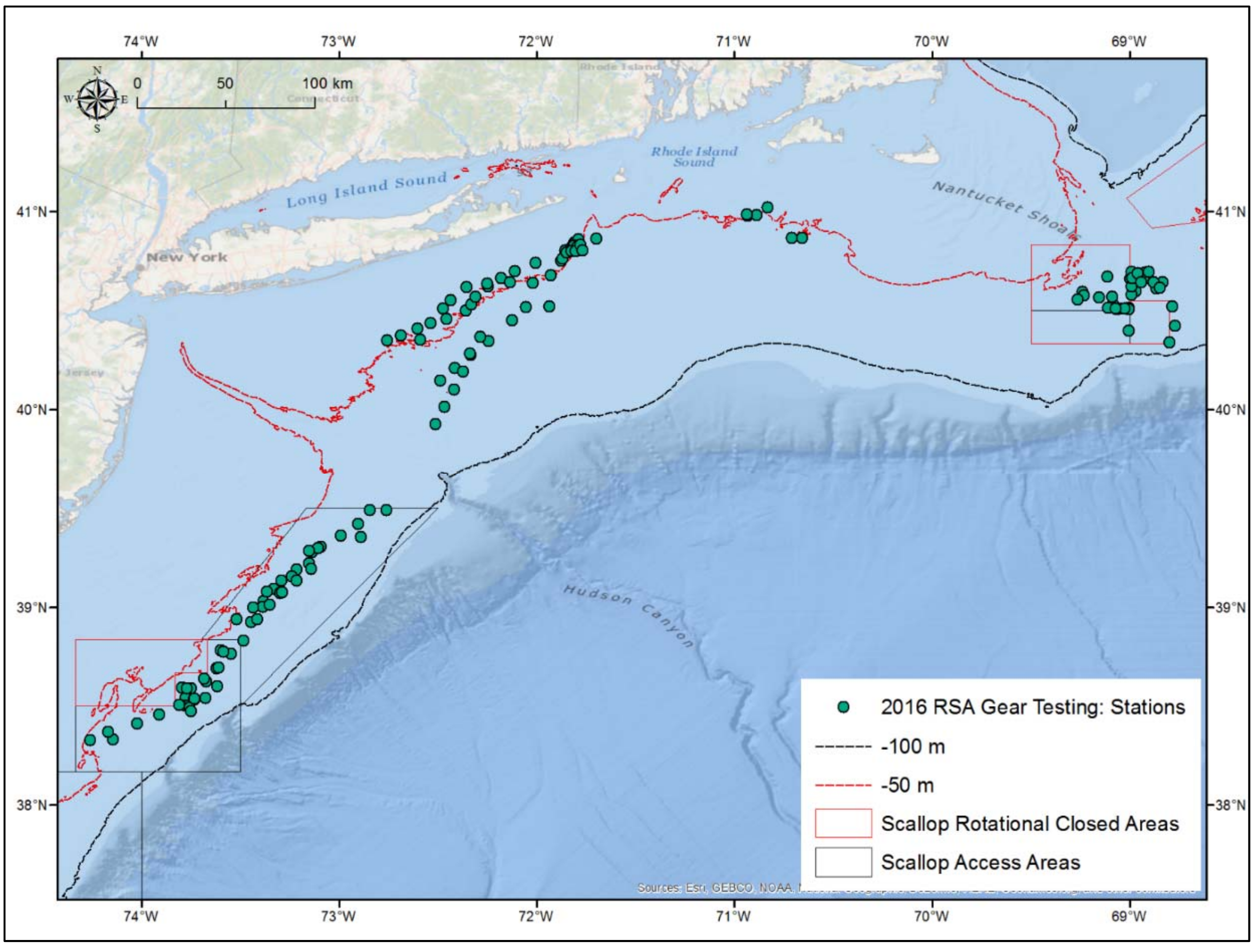


***Figure 2:*** *Map of the tow locations for this project.*

*Sea trial analysis using generalized linear mixed models (GLMM)*

Overall, a data set consisting of five separate cruises with 232 validated tow pairs were examined in the analysis. 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 excluded from the analysis. While the objective of the study was to examine the effect that two-way extended links had on the length-based catch of sea scallops, we also examined a subset of fish species that are of special management concern or commercially important. The species examined were: unclassified skates, barndoor skate (*Dipturus laevis*), fourspot flounder (*Hippoglossina oblonga*), windowpane flounder (*Scophthalmus aquosus*), monkfish (*Lophius americanus*) and sea scallops.

This analysis attempted to construct a model that would predict the relative efficiency of the two-way extended link apron dredge (experimental) relative to the standard link apron dredge (control) using a variety of covariates (see **Appendix A** for a detailed description of the analytical framework used in the study). The model assumes that each gear combination has a unique catchability, and differences in scallop or fish catch between paired dredge tows is reflected in the ratio of the catchability of the two-way extended link apron to the catchability of the standard apron. Catch data from the sea trials provided the data to estimate differences in the relative efficiencies of the two-way extended link and standard aprons. This analysis is based on the analytical approach in Cadigan et al. (2006) and Holst & Revill (2009). Our analysis of the efficiency of the two-way extended link apron relative to the standard apron consisted of multiple levels of examination. We examined animal size, trip, Beaufort value, and bottom depth as possible factors predicting relative efficiency. Following Holst & Revill (2009), we also included low order polynomial terms to parameterize any non-linearity on the observed proportions at length. In many instances, especially with gear modifications that can possibly alter the relative size composition of the catch, using the unpooled catch data and exploring the length-based relative efficiency predicts the changes that the two-way extended link apron has on the relative catch at length for the two gear types. 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.

*Selectivity experiment analysis using the SELECT model*

The scallop catch-at-length data for each tow from the selectivity experiment was analyzed using the SELECT model (Millar 1992; see **Appendix B**). Selectivity of an experimental dredge can be estimated by towing it paired with a control dredge that is assumed to be non-selective. The resulting curve highlights estimates of two important parameters used to define dredge selectivity. It is symmetrical around the 50%-retention-length (L50), the size (shell height) at which a scallop has a 50% chance of being retained in the dredge if caught. The steepness of the curve reflects the selection range (SR), or the difference between the 25%- and 75%-retention-lengths. For this project, the control (standard) and experimental (two-way extended link) aprons were towed with a lined survey dredge, allowing estimation of the selectivity of gear with both apron types.

**Results**

Overall, the experimental dredge caught less than the control dredge across the suite of species encountered on the research trips. Although tow locations were chosen based on reports from fishermen and previous CFF research-trip catch data, for many species the catches were too low and infrequent to permit an in-depth analysis (**Table 3**). Furthermore, because the primary focus of the study was testing the impact of the two-way extended links on pre-recruit scallops, we had to compromise in our choice of trip locations by concentrating our efforts in areas with small scallops that have few fish. Due to these low fish catches, only the catch data for sea scallops, windowpane flounder, monkfish, and fourspot flounder were analyzed in greater detail.

***Table 3:*** *Pooled raw catch data for the standard apron (CTRL) and the extended link apron (EXTL).*

| Common name | CTRL | EXTL | Difference (EXTL-CTRL) | % Change (Difference/CTRL) |
|---|---|---|---|---|
| Sea scallops (bushels) | 1545 | 1255 | -290 | -18.77% |
| Sea scallops (expanded) | 307313 | 233517 | -73796 | -24.01% |
| Fourspot flounder | 260 | 174 | -86 | -33.08% |
| Summer flounder | 4 | 3 | -1 | -25.00% |
| Windowpane flounder | 157 | 73 | -84 | -53.50% |
| Winter flounder | 18 | 8 | -10 | -55.56% |
| Yellowtail flounder | 18 | 13 | -5 | -27.78% |
| Monkfish | 2261 | 1608 | -653 | -28.88% |
| Haddock | 25 | 27 | 2 | 8.00% |
| Barndoor skate | 127 | 85 | -42 | -33.07% |
| Unclassified skates | 13268 | 9805 | -3463 | -26.10% |

*Scallop Catch Efficiency*

Analysis of the scallop catch data from the sea trials showed a reduction in the total scallop catch when using a two-way extended link apron (**Figure 4**). However, a closer investigation of the data indicates that the reduction in scallop catch is mostly a result of reduced efficiency on smaller size classes that produce a meat yield of greater than 20-count scallops per pound (**Table 4** and **Figure 5**). Meat yields were calculated using the Stock Assessment Review Committee (SARC) shell-height-to-meat-weight models. Sampling took place across a range of areas and depths, and for this reason, the shell height of 20-count scallops varied, with the minimum shell height close to 112-mm. The scallop meat yield in the two-way extended link apron had a higher relative proportion of scallops with shell heights ≥ 112 mm, suggesting that the extended link apron is more efficiently sifting scallops < 112 mm from the catch with minimal reduction in the catch of larger scallops (**Figure 4** and **Figure 5A**). Thus, the two-way extended link apron appeared to have less impact on pre-recruit scallops than a standard apron.

***Table 4:*** *Pooled average scallop catch (pounds/tow) with standard error binned by meat count categories: Smaller than 20 count scallops (scallops/pound) and larger than 20 count scallops. Meat yields were estimated using SARC models. * indicates a statistically significant difference. Standard apron = CTRL and the extended link apron = EXTL.*

| Scallop size | CTRL | EXTL | Difference (EXTL-CTRL) | % Change (Difference/CTRL) |
|---|---|---|---|---|
| **Small (> 20 count)** | 49.91 (8.10) | 34.20 (7.49) | -15.71 * | -31.48% * |
| **Large (≤ 20 count)** | 23.52 (1.37) | 21.80 (1.56) | -1.72 * | -7.31% * |

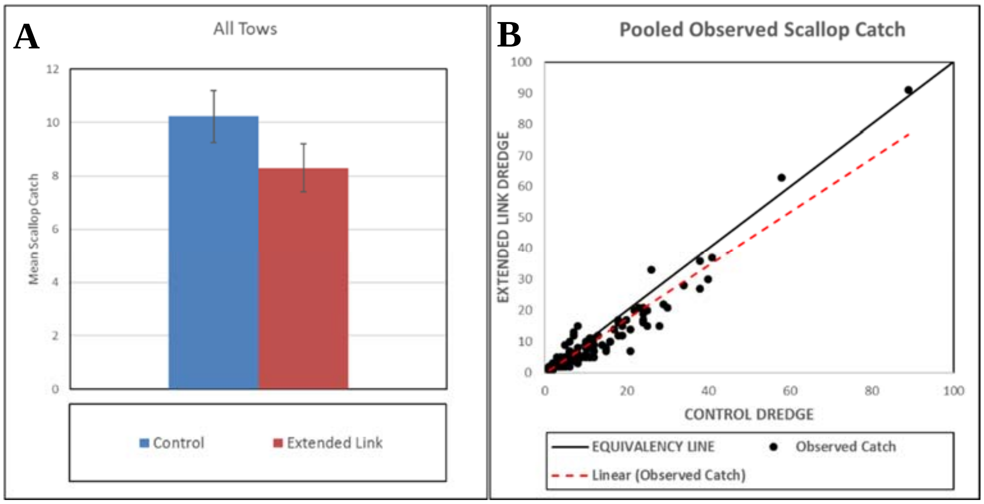


***Figure 4:*** *The pooled scallop catch results. (A) Mean scallop catch in bushels for each gear type. (B) Scallop catch data pooled over lengths for each paired tow.*

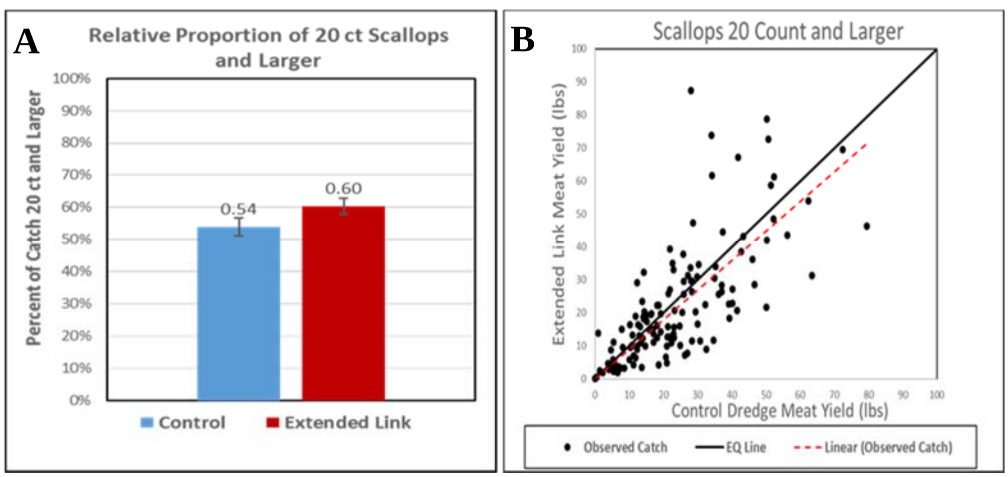


***Figure 5:*** *(A) Proportion of meat yield from 20 count and larger scallops to yield from all scallops. (B) Meat yield from 20 count or larger scallops for each paired tow.*

*<u>Finfish and skate catch efficiency</u>*

Overall the catches of finfish during the sea trials were quite low (**Table 3**). The species that had catches sufficient enough to warrant further analysis were windowpane flounder, unclassified skates, monkfish, and fourspot flounder. For these species, the two-way extended link apron decreased relative efficiency (**Figure 6**). The reductions in unclassified skates, fourspot flounder and monkfish were statistically significant. Interestingly, a robust size range of monkfish were encountered on this project, allowing changes in dredge relative efficiency with size to be observed, which is usually not possible. Based on the results, it is likely that the two-way extended link apron has some efficacy for reducing bycatch of finfish as well as reducing the capture of pre-recruit scallops.

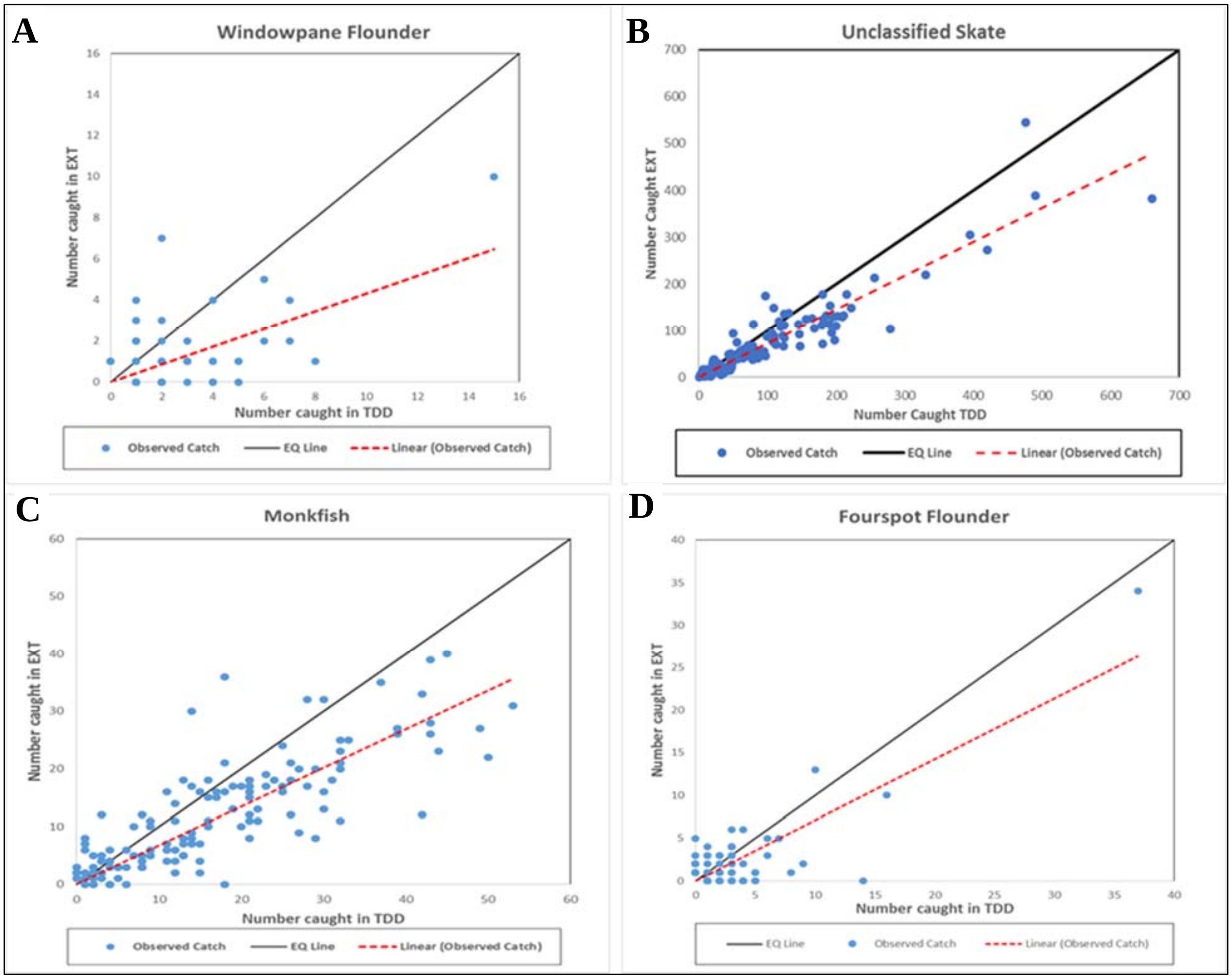


***Figure 6:*** *Catch data, pooled over length for each paired tow, for (A) windowpane flounder, (B) unclassified skate, (C) monkfish, and (D) fourspot flounder. The black line is the equivalency line (slope = 1), while the red line shows the linear relationship between the catches. In all cases, the slope of the red line was less than one, indicating that the dredge with the extended link apron tended to catch fewer fish than the dredge with a standard apron.*

## <u>GLMM Model Results</u>

### *Length-based estimates*

For the analysis that tested for a difference in relative efficiency as a function of fish/scallop size, we used the catch data coupled with length-frequency information for each species. Since the experiment was conducted over five individual cruises, it is informative to examine whether the length-based relative efficiency varied between trips, which can highlight potential vessel-specific conditions impacting the relative performance of the two gears. The covariates tested in this analysis were scallop/fish size, trip, Beaufort value, depth, and an interaction between animal size and trip (this effect tested for different slopes between trips). For some species, there was not enough data to provide meaningful results from the more complex models. In most cases, this failure resulted from a small number of tow pairs where there were non-zero observations and the model failed to converge. **Table C1**, shown in **Appendix C**, shows the model building/selection results to find the most parsimonious model for each species. Parameter estimates associated with the selected model specification for each species are also shown in **Tables C2** to **C5** in **Appendix C**.

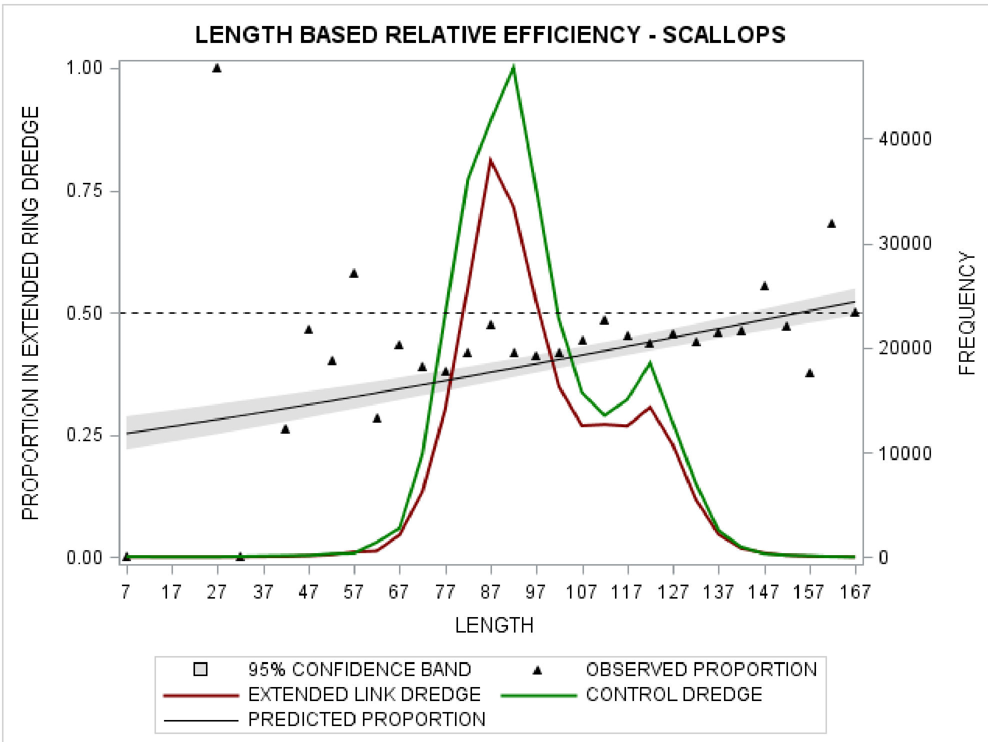


***Figure 7:*** *Relative sea scallop catch in the two dredge configurations. The triangles represent the observed proportion at length ($Catch_{ext}/(Catch_{ext} + Catch_{stand})$, with a proportion >0.5 representing more animals at length captured by the extended link apron dredge. The grey area represents the 95% confidence band for the modeled proportion (solid black line).*

For the length-based model, windowpane flounder and sea scallops were the only species where length represented a significant predictor of relative efficiency ($p < 0.05$). In addition, for sea scallops, the polynomial term was a significant factor, suggesting that there was significant nonlinearity to the observed proportions. Furthermore, the significant interaction terms (size*trip) suggest that the relative efficiency of the two-way extended link apron varied by research trip. In the case of monkfish, factor of size was marginally non-significant ($p = 0.065$), so we examined the length-based results. The predicted proportion increased with length, and catch of smaller scallops was lower in the two-way extended link apron (**Figure 7**). The trip-specific analysis showed similar results, where, in the majority of cases, the two-way extended link apron captured fewer small scallops and was more efficient at capturing larger scallops (**Figure C1** in **Appendix C**). For windowpane flounder and monkfish, the estimated slope was also positive, suggesting the extended link apron allowed smaller fish to escape (**Figures C2** and **C3** in **Appendix C**).

*Pooled-over-length estimates*
Animal length was not a significant predictor of relative efficiency for barndoor skate or fourspot flounder. Since this was the case, the catch data was pooled over length to examine the relative efficiency of the two dredge configurations with respect to total catch (numbers caught). Changes in the relative efficiencies for these two species were statistically significant (**Figures C4** and **C5** in **Appendix C)**. For unclassified skates, trip was a significant factor for predicting the relative efficiency between the two dredge configurations (**Figure C6** in **Appendix C)**. When viewing all species in the context of total catch (i.e. pooled over length analysis), significant decreases of the catch by the two-way extended link apron relative to the standard link apron was observed. Across all species evaluated, the reduction ranged from 27 - 60%. A comparison of model-generated estimates and the percent changes from the raw catch data area shown in **Table 5** in **Appendix C**.

***Table 5:*** *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** | **Extended Link** | **Standard Link** | **Percent Difference** | **Model Estimate (RE)** | **Statistical Significance** |
|---|---|---|---|---|---|
| Uncl. Skates | 9,583 | 13,031 | -26.46 | -27.13 | Yes |
| Barndoor Skates | 80 | 118 | -32.20 | -31.37 | Yes |
| Fourspot Flounder | 169 | 259 | -34.75 | -44.68 | Yes |
| Windowpane Flounder | 71 | 152 | -53.29 | -59.41 | Yes |
| Monkfish | 1,563 | 2,204 | -29.08 | -29.78 | Yes |
| Sea Scallops | 233,517 | 307,313 | -24.01 | -27.21 | Yes |

SELECT Model Results

Analysis of the data from the selectivity experiment yielded somewhat surprising and unexpected results for scallop selectivity of the two dredges (**Figure 8**). We hypothesized the two-way extended link apron would have a greater L50 and a smaller SR, but the SELECT model results show that the L50 of the two-way extended link and the control apron are equivalent and the SR for the two-way extended link apron has a larger selection range (**Figure C7**). The broader selection observed with the two-way extended link apron appears to be consistent with observations made by researchers investigating the impacts of increasing the scallop dredge ring size (Dr.William DuPaul, personal comm.) and may be a result of variations in the conditions that allow for the flushing of the dredge bag during haul-back of the scallop dredge. When flushing occurs, more scallops will be expelled from the bag than under conditions that do not allow for the flushing of the dredge bag.

Due to differences between the tow parameters required for the lined survey dredge and commercial fishing practices, in addition to low overall catches of finfish, the SELECT model was not used to evaluate finfish data from the selectivity experiment.

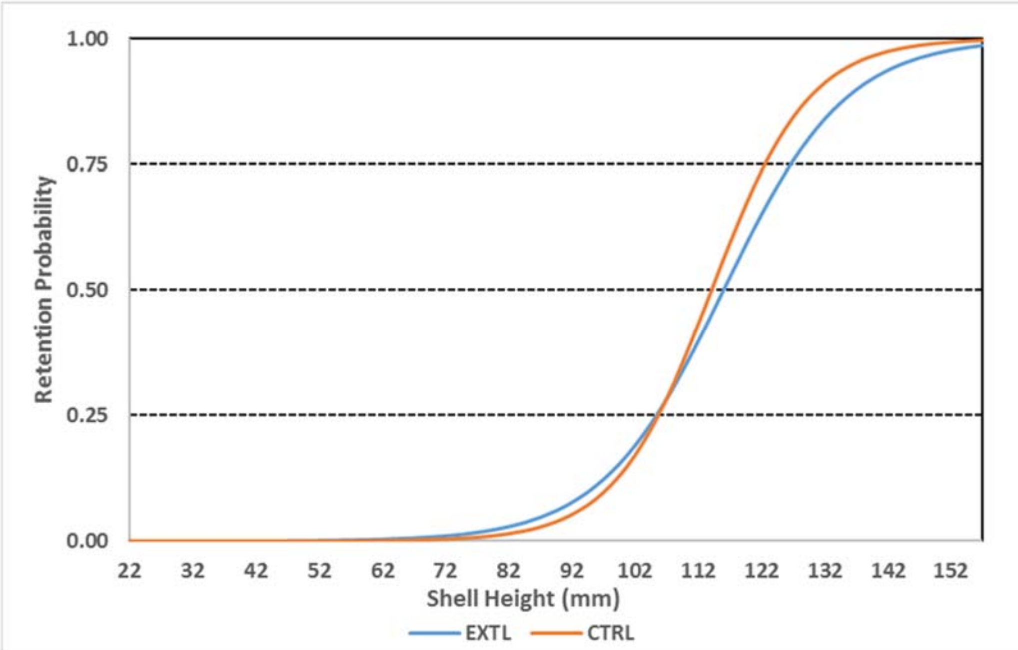


***Figure 8**: The probability of retention at length curves generated by the SELECT model.*

**Table 6** displays the results of the selectivity experiment compared to the findings of Yochum & DuPaul (2008). The smaller sample size and lack of a robust range of size classes observed in this experiment could be responsible for the differences in the standard apron relative to their findings using a standard 4" ring apron. Therefore, conducting more tows across a wider range of conditions could likely result in a more knife-edge selection curve. More tows would allow for a better assessment of how a two-way extended link apron impacts dredge selectivity, but based on the current data, the SELECT model indicates that the two-way extended link apron does have different selective properties than a traditional dredge apron.

***Table 6:** Parameter estimates and outputs of the SELECT model for the two-way extended link apron and a standard apron. The results of the Yochum & DuPaul (2008) study are also shown for comparison.*

| | Extended Link Apron | | Standard Apron | | Yochum & DuPaul 2008 | |
|---|---|---|---|---|---|---|
| **Lengths** | 62 - 142 mm | | 87 - 137 mm | | 22.5-162.5 mm | |
| ***a*** | -12.00 | | -14.91 | | -9.32 | |
| ***b*** | 0.10 | **S.E.** | 0.13 | **S.E.** | 0.09 | **S.E.** |
| $p_c$ | 0.82 | 0.04 | 0.75 | 0.05 | 0.77 | 0.60 |
| $l_{50}$ **(mm)** | 116.03 | 4.74 | 114.08 | 4.98 | 100.11 | 0.59 |
| **SR:** | 21.24 | 1.72 | 16.81 | 2.70 | 23.61 | |
| **L** | -29142.95 | | -4428.67 | | -311035.00 | |
| **REP** | 35.87 | | 19.42 | | 7.98 | |
| **No. tows** | 31 | | 13 | | 173 | |

*Preliminary results with the cover net*

The preliminary test of the cover net indicated that the cover net can be towed at commercially representative speeds to provide an estimate of flatfish relative catchability and selectivity (**Figures 9** and **C8**). However, a more in-depth study is needed to determine the efficacy of this technique for providing reliable estimates of the relative catchability of scallop dredges.

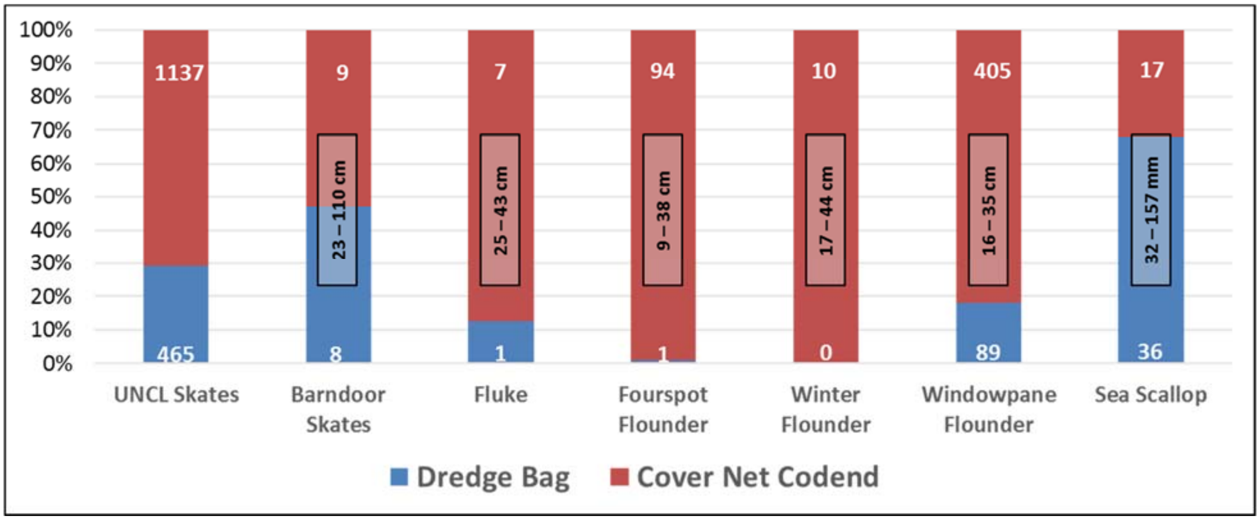


***Figure 9:*** *Catch data from the cover net test. The catch numbers for the dredge bag and cover net (white) and the observed size ranges for each species are indicated in each of the bars.*

**Discussion**

Our results indicate that modifying the links between the rings in the apron of the dredge resulted in differences in the catch of both the target species and common bycatch species encountered during the experiment. For a number of species, modeling efforts indicated significant differences in the length composition of the catches between the two dredges, while, in other cases, only the total numbers of animals differed. These results provide insight into how apron modifications can affect the catch of individual species. The modification was hypothesized to reduce the capture of an incoming year class of sea scallops and small (i.e., low-length) individuals of some bycaught species. While it did appear to function in this manner, the analyses suggest that there was an overall reduction of catch efficiency irrespective of size. With this insight, further modifications can be made in an attempt to facilitate additional reductions in bycatch.

Scallop management is predicated on the protection of small scallops in an effort to improve yield-per-recruit and reproductive potential. This is accomplished in a number of ways, including gear modification (effort control and spatial management are two other examples). While the gear modification in this study does appear to be effective in reducing the relative catch of small scallops, the catch of larger animals is also impacted, although to a lesser degree. Of primary importance for any gear modification is the maintenance of target catch. Reductions of harvestable animals may be unpalatable to the industry. However, this reduction must be tempered with concomitant reductions in important bycatch species and the specific management objectives that are being pursued.

During most of the trips, high densities of small scallops with shell heights under 110 mm (peak between 87 and 97 mm) were encountered. Scallops within this range do not produce the optimal meat size of 10-20 and U10 count scallops. While there is a minor reduction in catch efficiency of the larger individual scallops, the largest decrease in efficiency occurred in these smaller size classes. A hypothetical estimate of the potential reduction in the loss of small scallops from using the two-way extended link apron versus a standard apron that retains pre-recruit scallops can be generated using data collected during this project (**Table 11**). Using our observed ratios of small (> 20 count) to large (≤ 20 count) scallops for dredges using a standard control apron versus a two-way extended link apron, we can estimate the weight of small scallops that might be brought on deck during a trip where 18,000 lbs of 20 count or larger scallops are landed. Fishing with a two-way extended link apron would leave ~10,000 lbs on small scallops on the bottom. If these scallops double in size over the following year, almost 20,000 lbs of scallops are left for future harvest.

***Table 11:*** *Hypothetical estimates of the catch in a dredge with a standard apron vs an extended link apron if a vessel lands 18,000 lbs of 20 count or larger scallops. The ratios between large and small scallops were determined using catch data from this project. Standard apron = CTRL and the extended link apron = EXTL.*
** The weight of small scallops after one year assumes the scallops will double in weight.*

| Scallop size | CTRL | EXTL | Small scallops not caught (CTRL-EXTL) | Weight of small scallops not caught after one year * |
|---|---|---|---|---|
| Small (> 20 count) | 38196 | 28239 | 9958 | 19916 |
| Large (≤ 20 count) | 18000 | 18000 | | |

High scallop densities may have impacted the selectivity experiment. When scallops are in high densities, a dredge may "bulldoze" and this can happen in a relatively short time with a 38-mm mesh liner in the survey dredge. Additionally, because the tow parameters for the selectivity experiments differed drastically from those during the sea trails and commercial tows, the lined dredge is not an appropriate tool for assessing how flatfish catchability changes due to different gear modifications. For this reason, we investigated the use of a dredge bag cover net (**Figure 3**). We expect it to be a valuable tool for determining how different dredge modifications impact the catchability of flatfish and to provide managers with a better estimate of the impact the scallop fishery has on other species.

Gear modifications adopted by the scallop industry in recent years have led to needed reductions in sea turtle and fish bycatch, while allowing the continued sustainable and lucrative harvest of scallops. Gear research, like the work conducted during this project, has been critical for developing and testing these modifications. As fish abundances decrease, leading to strict new management quotas, rigorous testing of gear modifications has also become increasingly difficult. Due to known, but not fully understood, factors like the patchiness of the scallop resources, spatiotemporal changes in fish and sea turtle abundances, variable bottom types, and already low bycatch rates, testing new gear modifications requires many tows in different areas during different seasons. Multiple management goals like simultaneously reducing catch of pre-recruit scallops and bycatch of flatfish further increase the need for field-testing gear changes across a range of time and space. By taking advantage of compensation research trips to collect preliminary data and focusing more expensive dedicated research trips on the most promising gear modifications, CFF has continued its cost-effective yet consistently successful approach to developing improved scallop dredges.

*Outreach*

Coonamessett Farm Foundation, Inc. has made electronic versions of the report available online and presented the findings from this project to the joint AP and PDT RSA Share Day Meeting May 4, 2017. The results of the research were also shared at the 2017 International Pectinid Workshop attended by both researchers and industry members. In addition to past presentations, CFF is working to produce an article to be circulated in an industry publication like National Fishermen or Commercial Fisheries News summarizing and highlighting the outcomes for this project as well as past gear projects. As always, data and findings can be obtained by industry members, managers, and other researchers upon request.

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## Appendix A: GLMM Model Details

Assume that each gear combination tested in this experiment has a unique catchability. Let $q_r$ equal the catchability of the extended link apron dredge and $q_f$ equals the catchability of the standard link apron dredge used in the study. The efficiency of the extended link apron dredge relative to the standard link apron 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 extended link apron dredge and $v=f$ denotes the standard link apron dredge. Let $\lambda_{ir}$ represent the scallop/fish density for the $i^{th}$ station by the extended link apron dredge and $\lambda_{if}$ the scallop/fish density encountered by the standard link apron 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 standard link apron dredge is given by:

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

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

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

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

If the dredges encounter the same scallop/fish density for a given tow, (i.e. $\lambda_{ir}=\lambda_{if}$), then $\rho$ 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:

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

where $p=\rho/(1+\rho)$ is the probability that a scallop/fish captured by the 5 row dredge. In this approach, the only unknown parameter is $\rho$ and the requirement to estimate $\mu$ 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:

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

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:

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

where $\delta_i$ is a random effect assumed to be normally distributed with a mean=0 and variance=$\sigma^2$. 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:

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

In this model, the intercept ($\beta_0$) 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 & Dowden 2009). This model is given below:

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

Often, depending upon the modifications to the experimental gear, the selective properties can change resulting in a non-linearity of the observed proportions. Following Holst & Revill (2009) the above model can be extended to include low order polynomials to capture the nonlinear characteristics of the observed proportions at length.

*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 (Holst & Revill 2009, Millar et al. 2004). 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 all finfish 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 fish species.

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 extended link apron dredge relative to the standard link apron dredge consisted of multiple levels of examination. For all species, the full model consisted of unpooled (by length) catch data:

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

The symbol $f_{ij}$ equals the categorical variable denoting dredge apron 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 (**Equation 6**).

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

**Appendix B: SELECT model details**

The scallop catch-at-length data for each tow from the selectivity experiment was analyzed using the SELECT model (Millar 1992). This model can be used to estimate the selectivity of fishing gear (in this project, the control or experimental dredge) by towing with a paired non-selective dredge (Yochum & DuPaul 2008). The model evaluates the proportion of scallops at length *l* that are caught in the fishing gear out of the total catch **($\phi_c(l)$)** from both gears (fishing and non-selective) (**Equation 1)**.

$$\phi_c(l) = \frac{p_c r_c(l)}{p_c r_c(l) + (1 - p_c)} \tag{1}$$

Scallop dredge selectivity tends to reflect the logistic function (Yochum & DuPaul 2008). **Equation 2** demonstrates the logistic model for dredge selection.

$$r_c(l) = \frac{\exp(a + bl)}{1 + \exp(a + bl)} \tag{2}$$

Substituting the logistic model into the SELECT model yields **Equation 3**, where *a* and *b* are the logistic selectivity parameters and $p_c$ is the split-parameter; which, describes the relative efficiency of the two-way extended link or control dredge (Millar 1992).

$$\phi_c(l) = \frac{p_c \exp(a + bl)}{(1 - p_c) + \exp(a + bl)} \tag{3}$$

Parameter estimates were generated by maximizing the likelihood:

$$(a, b, pc|data) = \prod_{l=7}^{177} \left( \frac{pc\,\exp(a + bl)}{(1 - pc) + \exp(a + bl)} \right)^{C_c} \left( 1 - \frac{pc\,exp(a + bl)}{(1 - pc) + exp(a + bl)} \right)^{C_s} \tag{4}$$

In order to account for uncontrolled variation like wind speed, water depth, scallop density etc. from one tow to the next a test for over dispersion was done using the replication estimate of between-haul variation (REP) combined hauls (Millar et al. 2004). The REP value is the Pearson chi-square statistic for model goodness of fit divided by the degrees of freedom, or the number of terms in the summation minus the number of fitted parameters. In order to avoid over-inflating the degrees of freedom and following the methods put forth in Yochum & DuPaul 2008, only length classes where, when all tows combined, one dredge has caught at least 20 scallops were used.

The selectivity experiment data were evaluated using the R-Statistical Program using the SELECT package (Millar 1992; Millar et al 2004, and R Core Team 2015).

## Appendix C: Additional Tables and Figures

*Table C1: Model building for length based models. Hierarchical models ranked based upon minimum AIC values. A forward selection process was used in model selection, however since size was the primary variable of interest, if non-significant, then no additional covariates were added for that species. An exception was made for monkfish where size was marginally non-significant.*

| **Species** | **Model** | **AIC** | **Delta AIC** |
|---|---|---|---|
| Monkfish | Size (p=0.065) | 3,268.02 | 0.00 |
| | Size, Size$^2$ | 3,268.32 | 0.30 |
| | Intercept | 3,269.04 | 1.02 |
| | Size, Depth | 3,270.01 | 1.99 |
| | Size, Tripnum | 3,274.34 | 6.32 |
| | Size, BeaufortNumber | 3,277.00 | 8.98 |
| | | | |
| Windowpane Flounder | Size (p=0.004) | 228.17 | 0.00 |
| | Size, Depth | 229.46 | 1.29 |
| | Size, Size$^2$ | 230.13 | 1.96 |
| | Size, BeaufortNumber | 234.01 | 5.84 |
| | Size, Tripnum | 234.97 | 6.80 |
| | Intercept | 235.51 | 7.34 |
| | | | |
| Barndoor Skate | Size (p=0.15) | 247.32 | 0.00 |
| | Intercept | 247.51 | 0.19 |
| | | | |
| Fourspot Flounder | Intercept | 475.83 | 0.00 |
| | Size (p=0.75) | 477.73 | 1.90 |
| | | | |
| Sea Scallop | Size, Size$^2$, Size*Tripnum, Size$^2$*Tripnum | 11,231.40 | 0.00 |
| | Size, Size$^2$, Tripnum, Size*Tripnum, Size$^2$*Tripnum | 11,233.93 | 2.53 |
| | Size, Size$^2$, Tripnum, Size*Tripnum | 11,289.98 | 58.58 |
| | Size, Size$^2$, Tripnum | 11,441.27 | 209.87 |
| | Size, Size$^2$, Tripnum, Depth | 11,442.09 | 210.69 |
| | Size, Size$^2$, Tripnum, BeaufortNumber | 11,447.62 | 216.22 |
| | Size, Size$^2$ | 11,454.58 | 223.18 |
| | Size (p=0.001) | 11,468.13 | 236.73 |
| | Intercept | 11,531.81 | 300.41 |

*Table C2: Models examining the unpooled catch data. Results are presented from the model that provided the best fit (intercept and length) 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. Statistical significance is evaluated at the alpha=0.05 level.*

| **Species** | **Effect** | **Estimate** | **SE** | **DF** | **t-value** | **p-value** | **LCI** | **UCI** |
|---|---|---|---|---|---|---|---|---|
| Windowpane Flounder | Intercept | -6.922 | 2.098 | 160 | -3.29 | 0.001 | -11.065 | -2.779 |
| | Size | 0.210 | 0.072 | 160 | 2.92 | 0.004 | 0.068 | 0.353 |
| | | | | | | | | |
| Monkfish | Intercept | -0.608 | 0.145 | 1650 | -4.20 | <0.001 | -0.892 | -0.324 |
| | Size | 0.007 | 0.004 | 1650 | 1.84 | 0.065 | 0.000 | 0.015 |

*Table C3: Model examining the unpooled catch data for sea scallops. Results are presented from the model that provided the best fit for this species (intercept, size, size$^2$,trip and interactions) 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. For the categorical variable "trip" the variable with a parameter estimate of zero is a reference category and other estimates for that variable are relative to that trip. Statistical significance is evaluated at the alpha=0.05 level.*

| **Species** | **Effect** | **Trip** | **Estimate** | **SE** | **DF** | **t-value** | **p-value** | **LCI** | **UCI** |
|---|---|---|---|---|---|---|---|---|---|
| Sea Scallops | Intercept | | -0.348 | 0.038 | 1962 | -9.049 | 0.000 | -0.423 | -0.272 |
| | Size | | 0.211 | 0.064 | 1962 | 3.292 | 0.001 | 0.085 | 0.337 |
| | Size$^2$ | | -0.113 | 0.098 | 1962 | -1.150 | 0.250 | -0.306 | 0.080 |
| | Size * Trip | Diligence | 0.394 | 0.091 | 1962 | 4.333 | 0.000 | 0.216 | 0.572 |
| | Size * Trip | Concordia | 0.623 | 0.130 | 1962 | 4.786 | 0.000 | 0.368 | 0.879 |
| | Size * Trip | Wisdom | 0.278 | 0.091 | 1962 | 3.048 | 0.002 | 0.099 | 0.457 |
| | Size * Trip | Westport | -0.315 | 0.085 | 1962 | -3.713 | 0.000 | -0.482 | -0.149 |
| | Size * Trip | Norseman | 0.000 | | | | | | |
| | Size$^2$ * Trip | Diligence | 0.481 | 0.125 | 1962 | 3.853 | 0.000 | 0.236 | 0.726 |
| | Size$^2$ * Trip | Concordia | -0.377 | 0.149 | 1962 | -2.525 | 0.012 | -0.670 | -0.084 |
| | Size$^2$ * Trip | Wisdom | 0.257 | 0.126 | 1962 | 2.049 | 0.041 | 0.011 | 0.503 |
| | Size$^2$ * Trip | Westport | 0.679 | 0.132 | 1962 | 5.158 | 0.000 | 0.421 | 0.937 |
| | Size$^2$ * Trip | Norseman | 0.000 | | | | | | |

*Table C4: Models examining the pooled-over-length catch data. Results are presented from the model that provided the best fit (intercept only) 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. Statistical significance is evaluated at the alpha=0.05 level.*

| **Species** | **Effect** | **Estimate** | **SE** | **DF** | **t-value** | **p-value** | **LCI** | **UCI** |
|---|---|---|---|---|---|---|---|---|
| Fourspot Flounder | Intercept | -0.592 | 0.159 | 93 | -3.714 | 0.000 | -0.909 | -0.276 |
| Barndoor Skate | Intercept | -0.376 | 0.158 | 32 | -2.377 | 0.024 | -0.699 | -0.054 |

*Table C5: Models examining the pooled-over-length catch data. Results are presented from the model that provided the best fit (intercept, trip) 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. For the categorical variable "trip" the variable with a parameter estimate of zero is a reference category and other estimates for that variable are relative to that trip. Statistical significance is evaluated at the alpha=0.05 level.*

| **Species** | **Effect** | **Trip** | **Estimate** | **SE** | **DF** | **t-value** | **p-value** | **LCI** | **UCI** |
|---|---|---|---|---|---|---|---|---|---|
| Unclassified Skates | Intercept | | -0.215 | 0.075 | 138 | -2.856 | 0.005 | -0.364 | -0.066 |
| | Trip | Diligence | -0.106 | 0.113 | 138 | -0.942 | 0.348 | -0.330 | 0.117 |
| | Trip | Concordia | 0.009 | 0.109 | 138 | 0.084 | 0.933 | -0.206 | 0.224 |
| | Trip | Wisdom | -0.311 | 0.105 | 138 | -2.955 | 0.004 | -0.518 | -0.103 |
| | Trip | Westport | -0.076 | 0.111 | 138 | -0.682 | 0.497 | -0.295 | 0.144 |
| | Trip | Norseman | 0 | | | | | | |

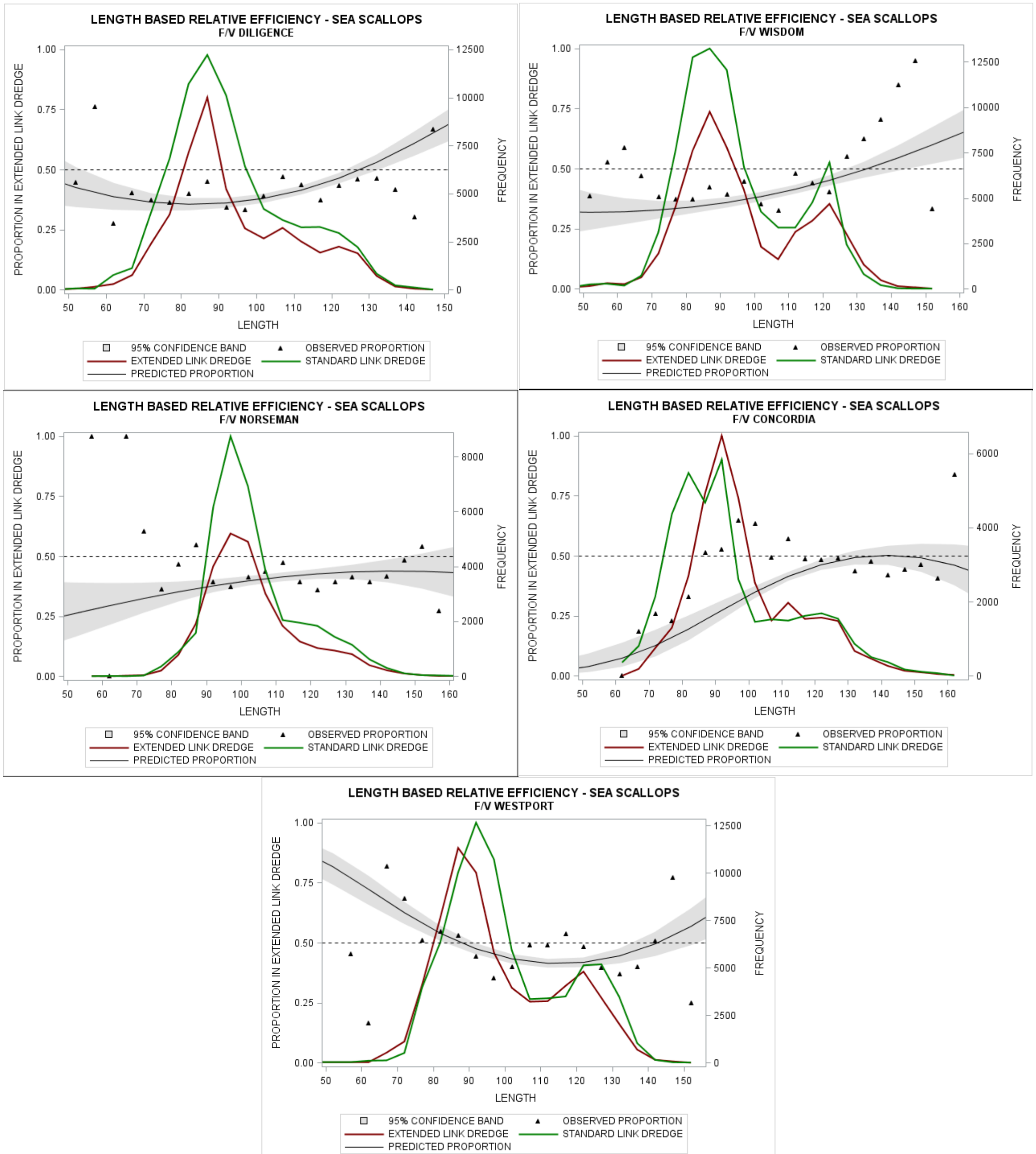


*Figure C1: Relative sea scallop catch by the two dredge configurations. The triangles represent the observed proportion at length ($Catch_{ext}/(Catch_{ext} + Catch_{stand})$, with a proportion >0.5 representing more animals at length captured by the extended link apron dredge. The grey area represents the 95% confidence band for the modeled proportion (solid black line). The model that provided the best fit to the data included a factor that accounted for individual slopes for each cruise.*

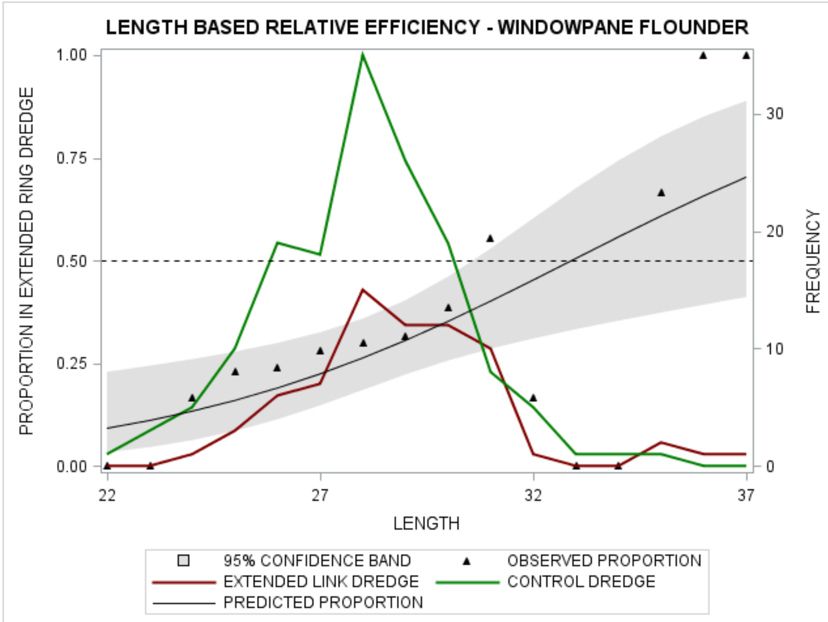


*Figure C2: Relative windowpane flounder catch by the two dredge configurations. The triangles represent the observed proportion at length ($Catch_{ext}/(Catch_{ext} + Catch_{stand})$, with a proportion >0.5 representing more animals at length captured by the extended link apron dredge. The grey area represents the 95% confidence band for the modeled proportion (solid black line).*

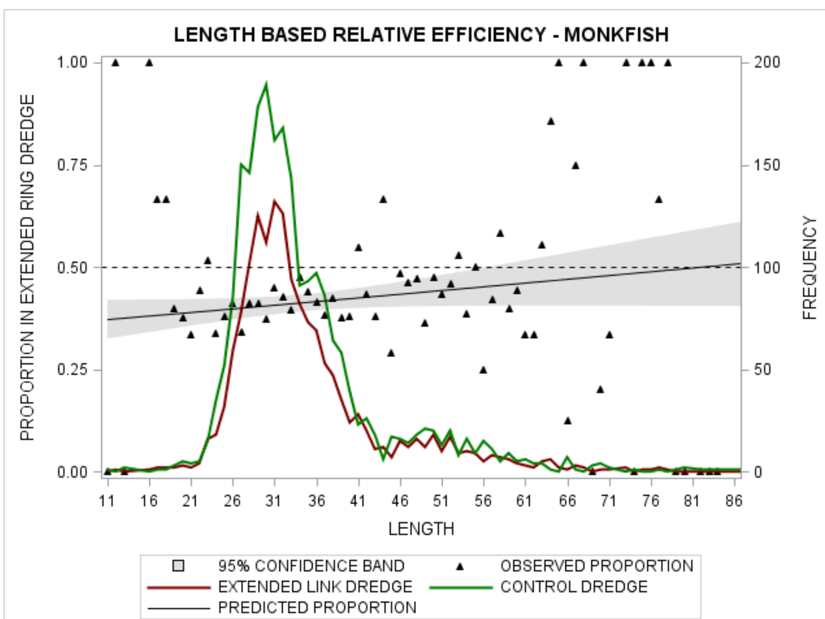


*Figure C3: Relative monkfish catch by the two dredge configurations. The triangles represent the observed proportion at length ($Catch_{ext}/(Catch_{ext} + Catch_{stand})$, with a proportion >0.5 representing more animals at length captured by the extended link apron dredge. The grey area represents the 95% confidence band for the modeled proportion (solid black line).*

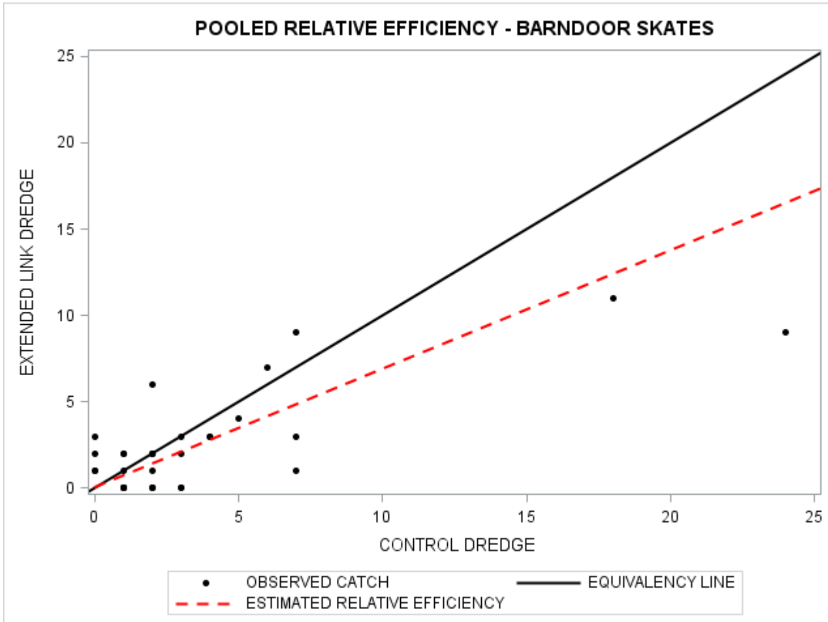


*Figure C4: Total pooled catches for barndoor skate for the extended link apron dredge vs. the standard link apron dredge. Model output from the analysis of the pooled data indicated that the intercept only model was the most appropriate specification. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one.*

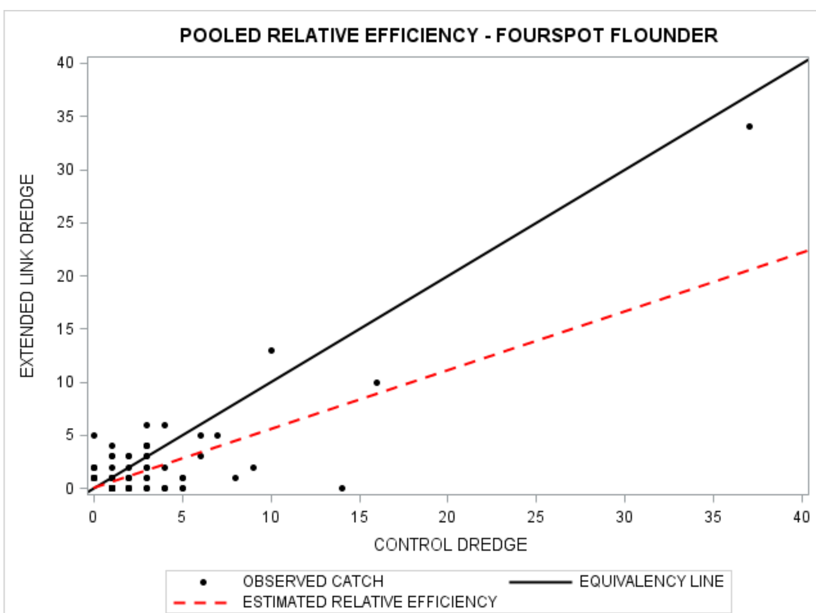


*Figure C5: Total pooled catches for fourspot flounder for the extended link apron dredge vs. the standard link apron dredge. Model output from the analysis of the pooled data indicated that the intercept only model was the most appropriate specification. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one.*

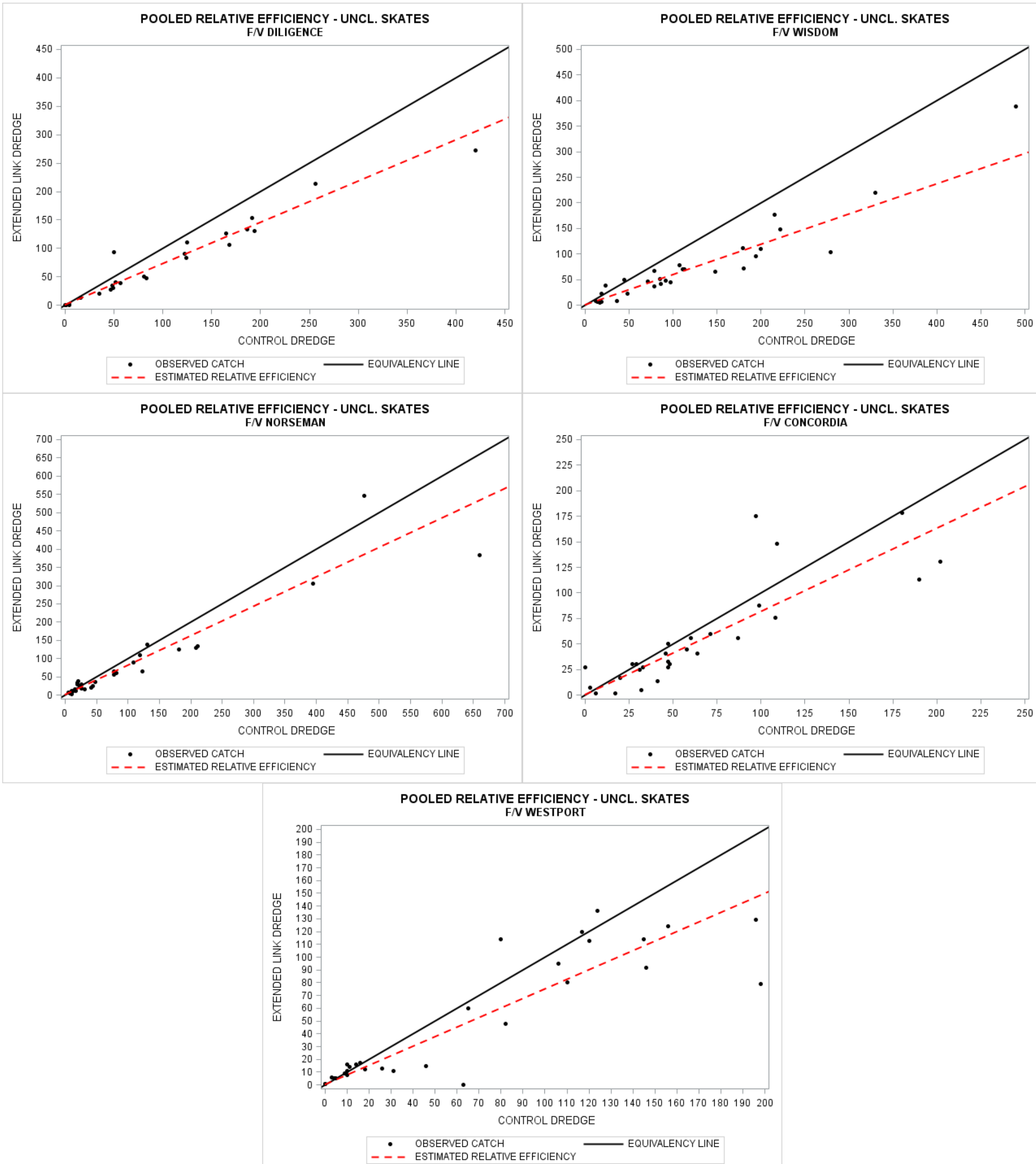


*Figure C6: Total pooled catches for unclassified skates for the extended link apron dredge vs. the standard link apron dredge. Model output from the analysis of the pooled data indicated that the model that included cruise as a factor was the most appropriate specification. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one.*

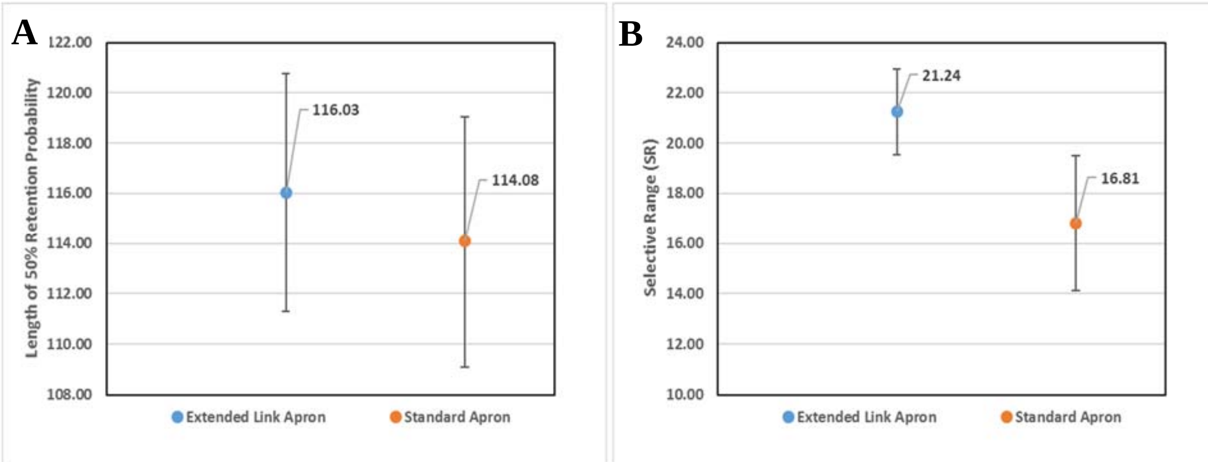


*Figure C7: (A) The length of 50% retention probability (L50) and (B) the selection range (SR) for the extended link apron and the standard link apron based on results from the SELECT model.*

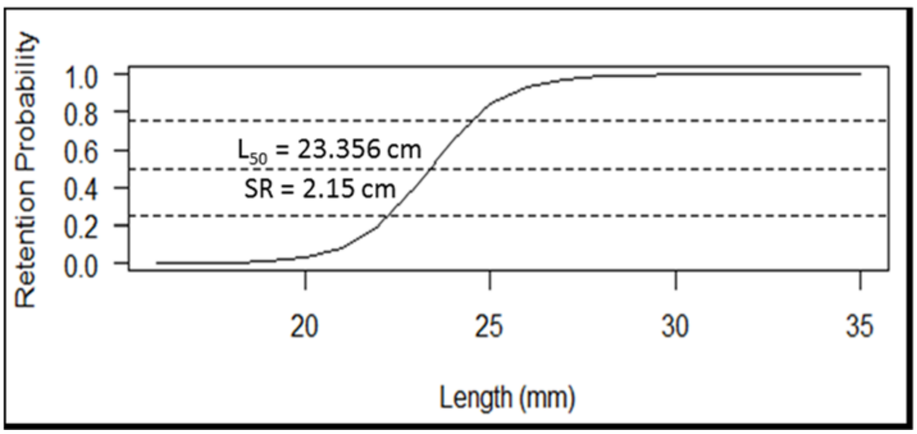


*Figure C8: Selectivity curve for windowpane flounder generated using the data from the testing of the cover net and the SELECT model.*