A Modified Flounder Sweep for Flatfish Bycatch Reduction in the LAGC Scallop Fishery

Final Report

Prepared for the 2016
Sea Scallop RSA Programs
(NOAA Award NA16NMF4540035)
May 2018

Submitted By

Ricky Alexander and Farrell Davis - Coonamessett Farm Foundation, Inc.

Coonamessett Farm Foundation, Inc

277 Hatchville Road
East Falmouth, MA 02536

508-356-3601 FAX 508-356-3603
contact@cfarm.org

www.cfarm.org

General Information

Report Title: A Modified Flounder Sweep for Flatfish Bycatch Reduction in the LAGC Scallop Fishery

Report Author(s): Ricky Alexander and Farrell Davis

Organization: Coonamessett Farm Foundation, Inc.

Grant Number: NA16NMF4540035

Date: 5/29/2018

Executive Summary

The reauthorized Magnuson-Stevens Act (U.S. DOC 2007) established new requirements to end and prevent overfishing through the implementation of Annual Catch Limits (ACLs) and Accountability Measures (AMs) (Section 303(a)(15)) for all stocks and stock areas. For the United States (US) Atlantic sea scallop fishery, this applies to the target species (scallops), as well as two yellowtail flounder stocks and Southern New England windowpane flounder. The Atlantic sea scallop fishery is divided into two fleets; the Limited Access (LA) fleet and the Limited Access General Category (LAGC) fleet, with LA vessels being larger (generally >80’ LOA). Due to this size difference, LAGC fishing effort is typically more limited by foul weather and fuel storage capacity; thus, the LAGC fishing season is typically a function of fishing conditions rather than management restrictions. In the event of an AM closure, these vessels are more likely to be affected due to an inability to fish elsewhere. Further, because the sea scallop industry is well-managed, a scallop vessel is far more likely to be shut down as a result of AMs on bycatch, rather than scallops. Therefore, it is prudent to find alternative approaches that would allow these vessels to continue fishing in the event an AM is triggered. This project examines one possible gear solution; the use of a flounder cookie sweep (FCS) to deter flatfishes from entering the dredge.

Despite high variability in trends, the FCS was largely successful in reducing undesirable bycatch and filtering out sub-commercial size scallops. A total of 138 paired tows were conducted in 2016/2017 comparing the use of an FCS to an identical unmodified dredge. Tows were conducted on two vessels representing a cross-section of the LAGC fleet. These vessels varied greatly (different length overall, horsepower, dredge size, fishing areas), with the most notable difference being tow strategy; one vessel tows two dredges simultaneously while the other tows a single dredge. Due to these differences, results from each vessel were treated as independent data sets. For both vessels, catch (scallops) and bycatch were weighed, counted (number of individuals), and measured, as appropriate for each species. While a diversity of bycatch species were encountered, we focused our analyses on a subset of species that consisted of species of commercial importance or species with special management concern. These species not only have intrinsic importance to the fishery, but also were typically observed in numbers sufficient to return results from selected statistical models. For both vessels, the FCS dredge captured fewer small scallops relative to the control dredge. As scallop size increased, the proportion of catch became roughly equivalent with some suggestion that the FCS dredge

was more efficient at larger sizes. The FCS significantly reduced windowpane flounder catches (21.26%) on alternate tow trips, while skate catches (winter and little combined) were significantly reduced (30.24%) on paired tow trips In addition, both vessels observed modest (non-significant) reductions in summer flounder (2.03% and 9.52%) and increases in monkfish (7.51% and 15.52%), which some vessels are permitted to retain for sale. Windowpane and yellowtail flounder presence was highly variable, which likely impacted the results.

In support of statistical analysis of the catch data, video observations revealed that in both cases the FCS fished variably. In some instances, the FCS made even, consistent bottom contact, while at other times the center portion of the FCS flew off the bottom so that only the edges of the FCS made consistent bottom contact. This is a likely source of high between-tow variability observed in FCS performance.

1. **Purpose**

1.1 Description of Problem

The reauthorized Magnuson-Stevens Act (U.S. DOC 2007) established new requirements to end and prevent overfishing through the implementation of Actual Catch Limits (ACLs) and Accountability Measures (AMs) (Section 303(a)(15)) for all stocks and stock areas. For the US sea scallop fishery, these requirements apply to the target stock, Atlantic sea scallops, as well as to non-target species that are commonly captured as bycatch. These species include two yellowtail flounder stocks (Georges Bank and Southern New England/Mid Atlantic). To comply with the new requirements, the scallop fishery is limited by a cap on removals for all fishing areas by a yellowtail flounder sub-ACL set annually by the New England Fishery Management Council (NEFMC) (NEFMC 2009).   In addition to yellowtail flounder, the NEFMC has implemented a sub-ACL and associated gear-based AM for SNE windowpane flounder (5-row apron; 1.5:1 twine top hanging ratio) based on findings from previous gear research done by CFF (NEFMC 2014).

The Limited Access General Category (LAGC) fishing season is typically a function of fishing conditions rather than management restrictions. The LAGC fishing season may overlap with inshore migrations of fish species in the region; however, LAGC vessels have less spatial and temporal flexibility due to vessel characteristics (e.g. size and fuel storage capacity). For these reasons, the LAGC scallop fishery is vulnerable to being adversely impacted by seasonal inshore area closures that may not affect the more mobile Limited Access (LA) scallop fleet. Spatio-temporal closures are a common approach to crafting AMs. These types of closures, if implemented in nearshore areas, could potentially exclude the LAGC fleet from the scallop fishery altogether. An alternative AM approach that includes gear modifications to mitigate the impact of LAGC bycatch would offer an attractive alternative to seasonal closures of inshore fishing grounds for the LAGC fishery. This project examined the use of a FCS as a possible gear solution to this issue.

1.2 Objectives

The project addresses 2016 Sea Scallop RSA **High Priority #2 Bycatch Research**: "Identification and evaluation of methods to reduce the impact of the scallop fishery with respect to bycatch. . . [including] gear modifications to reduce bycatch." The goal of this project was to test the effectiveness of a modified flounder cookie sweep (FCS) in reducing flatfish bycatch in the LAGC fleet. Video of FCS modifications and fish behavior were documented using GoPro cameras mounted on the dredges.

2 Approach

2.1 Experimental Design

An advantage of utilizing a commercial sea scallop vessel to conduct comparative gear experiments 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. The objective of this experiment was the characterization of the addition of the FCS to the dredge frame of the typical gear used in the LAGC fishery. In many cases, this fishery is comprised of smaller vessels relative to their LA counterparts, and these vessels typically only have the ability to tow one dredge. This attribute necessitates the modification of the aforementioned experimental design to an alternate tow design, where gear variant A (e.g., the control dredge) is fished for one tow and the subsequent tow is made over a similar tow path as soon as operationally possible with gear variant B (e.g., the FCS dredge). The following tows are then performed in ABBA manner to introduce a randomization with respect to gear configuration, but also to allow for operational efficiency.

For the current study, both experimental designs were utilized and represented a cross-section of vessels in the LAGC component of the fishery. Fourteen single-day trips were conducted aboard the F/V *Mister G.*, a vessel capable of towing only one dredge. For these trips, the alternate tow experimental design was used. In addition to the F/V *Mister G.*, a larger vessel, the F/V *Let it Ride*, was also used on one multi-day experimental cruise. This vessel had the ability to tow two dredges simultaneously and, given this characteristic, the paired design was utilized. While the two components of the experiment had similarities, differences in tow strategy, FCS size/design, dredge size/design, vessel size, horsepower, and sampling areas supported the treatment of the collected data as two separate data sets. The resulting analyses will be referred to as "alternate experimental design" for the analysis of the data collected on the F/V *Mister G* and data collected aboard the larger F/V *Let it Ride* will be referred to as "paired experimental design".

Testing began on 9/26/2016 on F/V *Mister G* out of Point Judith, RI. Tows were performed in an ABBAAB fashion, where A is an experimental tow (dredge with FCS attached; see **Figure 1A**) and B is a control tow (dredge with no FCS attached). The vessel captain (Mike Marquetti) was instructed to tow in the same path within a given A-B set. Given the difficulty in locating dense aggregations of yellowtail and windowpane flounder (n = 17 yellowtail flounder and n = 427 windowpane flounder over 53 paired tows), we decided to outfit the F/V *Let It Ride* (New Bedford, MA) with an FCS. This required building a new FCS (**Figure 1B**) to fit an 11' dredge. F/V *Let It Ride* fishes two identical dredges, allowing twice as many tows in a given time frame. This allowed us to obtain more tows (93 of 75 anticipated total pairs) in less days (22 of 25 anticipated DAS) than proposed. Additionally, using F/V *Let It Ride* allowed us to get a little further offshore in search of yellowtail and windowpane flounder (n = 2 yellowtail flounder and n = 395 windowpane flounder over 40 paired tows). An aggregation of windowpane flounder was located towards the end of this trip, capturing 37% (303 of 822 individuals) of the windowpane flounder observed during this project in just 7.5% of tows (7 of 93 tow pairs). GoPro video was recorded on both vessels to observe FCS performance *in situ* and to observe fish behaviors when interacting with the FCS.

2.2 Flounder Cookie Sweep Design

This project utilized two different styles of scallop dredge; a 9 foot wide Provincetown scallop dredge and an 11 foot wide New Bedford style dredge. Each was modified with a FCS on the outer bale bars (**Figure 1**). The FCS was designed for rapid removal and installation for flexibility during trips and to minimize the need to purchase an additional dredge frame. The FCS attaches to the dredge via split links welded at regular intervals along the outer bale bars, and is constructed of 2 ¾” (7 cm) rubber and lead “cookies” strung over ½” (1.3 cm) stainless steel cable. Lead cookies were used approximately 3 every foot (30.5 cm), along the length of the FCS. The FCS features chain link attachments approximately every 12 inches (30.5 cm) along its length to match the split link attachments welded to the outer bale bars. A steel eyelet is welded on either end to shackle the ends of the FCS to the dredge. These end eyes are about 6” long each, making the total length of the F/V *Mister G* FCS 10 foot 4 inches (315 cm) and the F/V *Let It Ride* FCS 12 foot 10 inches (391) cm. To account for the tilt of the dredge as it fishes, the FCS features staggered lengths of chain affixed along its length so that the chains near the gooseneck are longer than those closer to the frame. The terminal link of each chain is a quick link that matches to corresponding links welded at roughly even intervals along the bale bars.

2.3 Catch data

Tow parameters were held constant between pairs with speeds of ~4.2 kts and a tow wire scope of 4:1. On sampled tows the entire catch (including bycatch) was sorted by species and weighed in bushel baskets on an M1100 60 kg Marel Marine Scale. A one basket subsample of scallops was retained from each tow for shell height frequency (5 mm bins). Commercially important finfish were measured, by species, to the nearest cm. All bycatch was returned to the sea and all marketable scallops were shucked and sold. Each trip aboard F/V *Mister G* achieved a minimum of 6 tows (3 pairs) and tows were generally 45-60 minutes, depending on catch rates. Tow path length was recorded using integrated GPS on the data collection tablet. This was used to calculate swept area.

Overall, the partitioned data set consisted of 138 valid tow pairs that were examined in the analysis. The alternate experimental design used on F/V *Mister G* consisted of 89 tows over 14 trips. Typically, 3 pairs (A, B) were completed on a given trip; however, two trips recorded 4 pairs. For the paired experimental design used on F/V *Let It Ride*, 49 valid tow pairs were completed on a single cruise. Not all species were present in all tow pairs and, for the species examined, individual tows with zero total catch were uninformative and excluded from the analysis. While a broad cross-section of bycatch species were encountered, we focused our analysis on a subset of species encountered that consisted of commercially important or species with special management concern. The species examined were: unclassified skates (little and winter *Raja spp.*), summer flounder (*Paralicthyes dentatus*), fourspot flounder (*Hippoglossina oblonga*), yellowtail flounder (*Limanda ferruginea*), winter flounder (*Pseudopleuronectes americanus*), windowpane flounder (*Scophthalmus aquosus),* monkfish (*Lophius americanus*), and sea scallops (*Placopecten magellanicus*). These species not only have intrinsic importance to the fishery, but also were typically observed in numbers sufficient to return results from the statistical models.

The raw catch numbers of all species encountered during the study (**Tables 1-2**), as well as length frequencies and pooled relative catches for the species of interest (see above) are shown (**Figures 2-5**).

2.4 Statistical models

This analysis attempted to construct a statistical model that would predict the relative efficiency of the FCS dredge (experimental) relative to the control dredge (identical dredge but without the FCS) tested in the experiment as a function of a suite of covariates. In many instances, especially with gear modifications that can alter the relative size composition of the catch, using the unpooled catch data to explore the length-based relative efficiency is informative. The analysis utilizing the unpooled catch data predicts the changes that the FCS dredge had on the relative catch at length for the two gears. 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 (over length) catch data. See Appendix A for a detailed description of the analytical framework used in the study.

3 Project Management

Field testing and data management – Ricky Alexander and Farrell Davis
GLMM Analysis – David Rudders
Technical Advisor – Ron Smolowitz

4 Findings

4.1 Model Results

Length-based estimates

For the analysis that tested for a difference in relative efficiency of the two gear variants as a function of fish/scallop size, we used the catch data unpooled over length. The initial step in the analysis was to test whether length was a significant predictor of the relative efficiency of the two gears. If that model supported animal size as a significant predictor, then for that species additional model specifications using the unpooled data were evaluated. In these cases, additional covariates of interest were introduced and explored to ascertain whether there was support to include them as explanatory factors. For species best described by the length-based models, in addition to length, the second order polynomial of length (to capture potential non-linearity in the length term (see Holst and Revill, 2009), depth and a semi-quantitative measure of sea state/wind (Beaufort Scale) were included as predictors. In addition to the fixed effects, the inclusion of a random intercept and slope were also evaluated. Given this suite of covariates, the model that provided the best fit to the data, as evaluated by Akaike Information Criterion (AIC), was put forward as the selected model for that experimental design/species. For both vessels (i.e., experimental designs), only sea scallops were shown to include length as a significant predictor of the efficiency of the FCS relative to the control configuration (**Tables 3** and **4**).

For F/V *Mister G*, model building results for sea scallops returned a model that included length, the second order polynomial of length, Beaufort scale, and depth with a random intercept and slope as the best fit to the data (model building results in **Table 5** and parameter estimates in **Table 6**). While the relative efficiency for any combination of size, depth, and Beaufort number can be calculated from the parameter estimates, a visualization model was created to show the effect of scallop size on relative efficiency while holding Beaufort scale and depth at their averages (**Figure 6**). For F/V *Let It Ride*, model building results were similar to the alternate tow design (**Table 7**) where the model that included length, the second order polynomial of length, Beaufort scale, and depth with a random intercept and slope was selected as the best fit to the data (parameter estimates in **Table 8**). Similarly, a visualization model was created to illustrate the effect of scallop size on relative efficiency while holding Beaufort scale and depth at their averages for the paired data set (**Figure 7**).

In the case of sea scallops, both vessels produced similar results. While the length frequency distributions were overall quite similar, the FCS dredge did capture fewer small scallops relative to the control dredge. As scallop size increased, the proportion of catch became roughly equivalent with some suggestion that the FCS dredge was more efficient at larger sizes. Given the length composition of the catch for both experiments, however, there is considerable uncertainty in the estimates for both large and small scallops. This can be seen in the wide confidence bands at the tails of the size distributions.

Pooled-over-length estimates

Animal length was not a significant predictor of relative efficiency for many of the species analyzed, likely due to the low numbers at length across many of the species. Since this was the case, the data was pooled (for each vessel, respectively) to examine the relative efficiency of the two dredge configurations with respect to total catch (number of individuals). In these cases, a similar procedure was followed for the model building and resulting parameter estimates. For the pooled data, Beaufort scale and depth were explored as covariates of interest and models with or without a random intercept term were also fit. In some cases, the number of positive observations was low and the addition of covariates produced similar AIC values. In these instances, if there was no clear support from the resulting AIC values and all values were within 3 units, we selected the simplest model, which was typically the "intercept only" model (**Tables 9** and **10**). The pooled data from species across both experimental designs were best fit by different model specifications. In many situations, the "intercept only" was the best fitting model, however some species were better described by the addition of one or more covariates. While the selected models may represent the best fit to the data, this does not imply that there was a significant difference in the relative efficiency of the two gear variants.

Based on the model building exercise, the best fitting models were selected for the alternate (**Tables 11-13**) and paired tow (**Tables 14** and **15**) experimental designs. As in the unpooled analysis, a visualization of the data was attempted that, for the purposes of examining the pooled data and model results, an intercept only model was shown, and, if for a given species a covariate was selected in the final model, that covariate was held at its average (**Figures 8-9** for the alternate and paired data set, respectively). In terms of bycatch, the FCS significantly reduced windowpane flounder catches (21.26%; **Table 16**) on one vessel (but not the other), while skate catches (winter and little combined) were significantly reduced (30.24%, **Table 17**) on the other vessel. Interestingly, both vessels observed modest (non-significant) reductions in summer flounder (2.03% and 9.52%) and increases in monkfish (7.51% and 15.52%), which some vessels are permitted to sell. Further, while not significant, there was some indication that the FCS might reduce yellowtail flounder catches in some instances; the experimental dredge reduced catch numbers by 27.3% (n=19 total individuals; **Tables 1** and **2**).

4.3 Results from video documentation

GoPro Hero 4 HD action cameras were affixed to the interior corners of the dredge frame (**Figure 10**). This location was selected because it offered maximum protection of the camera and enabled a forward view of the FCS. This view allowed for review of FCS bottom contact and fish behavior as they interact with the FCS. Video review revealed that the forward portion of the FCS was being blown up and back with the force of drag created by towing the dredge. The extent of this effect was more dramatic on initial tows on F/V *Let It Ride*. To correct this, we affixed an additional length of sweep chain to FCS to weigh the unit down in an attempt to overcome drag somewhat. This was successful in forcing the FCS to make more bottom contact (**Figure 11**) and minimized interactions between fish and the FCS; however, when flatfish did interact with the FCS, they initiated a swimming response, and were occasionally able to escape the dredge (**Figure 12**). Unfortunately, it seemed that, although the FCS was effective in alerting fish to the presence of the dredge, the burst swimming speeds of fishes were not generally great enough to actively avoid recruitment to the dredge. Fish that initiated an upward swimming response, however, escaped more often, although the nature of this data did not allow for proper quantification of this effect. Compared to flatfish, skates were far better equipped for escapement once alerted to the presence of the dredge. For example, some skates were observed curling their pectoral fins over and rolling out of the way of the dredge (**Figure 13**) while others simply swam straight away from the dredge.

4.4 Discussion

Our results indicate that in some cases, the addition of the FCS to the dredge frame resulted in differences in the catch of both the target species as well as the analyzed bycatch species encountered during the experiment. Across both experimental designs the modeling efforts for sea scallops showed significant differences in the length composition of the catches between the two dredge configurations, while for all other species length was not a significant predictor of relative efficiency. This was likely due to relatively low numbers of fish at length for some species. These results provide insight into how modifying the dredge frame can affect the catch of individual species. With this insight, further modifications can be made in an attempt to facilitate additional reductions in bycatch.

While there was variability across the experiment with respect to individual species (i.e. windowpane flounder reduced in one instance and not the other), one trend was stable across the experimental designs; the impact on scallops. Our results suggest that the FCS reduced the catch of smaller scallops without sacrificing the capture of larger animals. It is worth noting that there were fairly limited number of smaller scallops in the populations sampled, but the trend was encouraging.

4.5 Problem Areas and Future Work

FCS performance was variable throughout the project, with noticeable reductions of bycatch during some tows, while bycatch seemed to increase in other tows. This is likely a function of hydrodynamics and vessel operations; if the FCS is bouncing lightly off the bottom, it is likely that bycatch is reduced. However, if the FCS is digging into the bottom, it is likely that the FCS is kicking animals into the dredge, rather than bumping them forward. This could be an effect of tide strength and direction relative to the tow path, foul weather, or amount of wire used (i.e., angle of the dredge relative to the incline of the seafloor).

The primary issue we encountered was a lack of available flatfish present on scallop grounds. Flatfish are known to aggregate on scallop grounds in some areas during certain times of the year. Unfortunately, this combination is difficult to predict and plan around. For example, yellowtail flounder was virtually non-existent on scallop grounds near Block Island, RI, and windowpane flounder occurred sporadically throughout the project, and was never captured in high numbers (most yellowtail captured in a single tow on F/V *Mister G* = 3; most windowpane captured in a single tow = 21). We were able to target windowpane flounder more effectively on F/V *Let It Ride*, with some tows capturing in excess of 30 individuals. In fact, 37% (303 of 822 individuals) of the windowpane flounder observed during this project was captured in just 7.5% of tows (7 of 93 tow pairs) while aboard F/V *Let It Ride*. When windowpane flounder density was high, the FCS was effective and the result was statistically significant. It is possible that flatfish encounters were higher than observed but individuals escaped through the twine top, as is the intention of this dredge design feature. In this event, the use of a dredge cover net might shed additional light of the performance of the FCS.

The primary issue we encountered was the loss of bottom contact from the FCS. The force of drag from pulling the dredge was so great that it caused the weighted FCS to “fly”, pushing it up and back towards the dredge frame. On F/V *Mister G*, the FCS was mounted from the forward-centermost portion of the drag along the outer bale bars back towards the cutting bar (**Figure 1**), whereas, on F/V *Let It Ride*, the FCS was mounted from behind the roller and out to the outer bale bars, then back towards the cutting bar (**Figure 1**). Adding weight corrected this to some extent (sweep chain was added to F/V *Let It Ride* FCS), increasing scallop catches (5.05% reduction on F/V *Let It Ride* compared to 9.52% reduction on F/V *Mister G*), and, in some cases, decreasing undesired bycatch (windowpane flounder was reduced 21.26% on F/V *Let It Ride* compared to a 15.13% increase in windowpane catches on F/V *Mister G*). This was not always the case; for example, fourspot flounder catches increased 15.52% when using the FCS on F/V *Let It Ride*, but were reduced 33.65% on F/V *Mister G*. Additionally, it is possible that the additional weight added drag, decreasing fuel efficiency, and possibly caused physical damage to bycatch species and/or the seafloor. Furthermore, on several occasions on F/V *Let It Ride* operations were paused to repair mounting points that had broken off during a tow, which is likely the result of using a heavier FCS. Future research (funded through the NOAA Bycatch Reduction Engineering Program) will focus on a FCS featuring various sized (thickness and diameter) rubber cookies that, together, create a vibration that has been shown to induce upward swimming in flatfish when attached to a trawl net. If this concept works on a dredge, we hypothesize that flatfishes will swim up, and avoid being retained by the dredge.

Between-tow variability was high; for example, a ~16% increase in windowpane flounder observed on F/V *Mister G* was not statistically significant. This is likely due to large reductions during some tows. Some of this variability is inherent in either experimental design approach. For example, during alternate tows it is possible that mobile schools of flounder moved out of the tow path after the dredge passed through initially, so that on the second leg of the AB pattern, the school was no longer present, skewing tow-to-tow comparisons. Alternatively, during paired tows that feature a turn, one dredge digs into the bottom more than the other, which could influence flounder catchability. While vessel captains are asked to avoid turns whenever possible, the location of scallop beds and seafloor obstructions often warrant mid-tow course corrections.

5 Evaluation

5.1 Attainment of Goals and Objectives

The goal of this project was to test the effectiveness of a modified FCS in reducing flatfish bycatch in the LAGC fleet. By utilizing F/V *Let It Ride*, we were able to obtain more data (138 valid tow pairs accomplished vs. 75 proposed) in less time (22 DAS utilized vs. 25 DAS proposed) than proposed, satisfying our goals for this project.

5.2 Dissemination of Results

The CFF works closely with Mike Marquetti, captain of the F/V *Mister G* and the president of the Eastern New England Scallop Association (ENESA). The ENESA is one of the largest associations of LAGC scallop dredge fishermen. Their participation in this work will ensure that the interests and concerns of the industry are represented through collaboration in the scientific process. The results of this project will be disseminated to all members of the LAGC scallop fleet. This has been shown to be an effective approach with the Coonamessett Farm Turtle Deflector Dredge as over 100 dredges of this design have been placed into use prior to the regulatory requirement. An article will be prepared for Commercial Fisheries News and a publication will be prepared for peer reviewed literature as results warrant. As with our current practice, all catch data is entered into a custom designed Microsoft Access database and will be available online to researchers and managers. Gear results from previous projects have been presented to the NEFMC Research Steering Committee as well as the scallop and groundfish PDTs. We expect a similar process for this project.

6 References

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Tables

Table 1. Catch totals of all species encountered for the alternate tow design portion of the study.

Common Name	Scientific Name	Control Dredge	FCS Dredge
SPINY DOGFISH	*Squalus acanthias*	2	2
UNCLASSIFIED SKATES	*Rajidae*	5120	3676
BARNDOOR SKATE	*Dipturus laevis*	7	2
SILVER HAKE	*Merluccius bilinearis*	16	17
RED HAKE	*Urophycis chuss*	2	2
SPOTTED HAKE	*Urophycis regia*	6	4
SUMMER FLOUNDER	*Paralichthys dentatus*	168	139
FOURSPOT FLOUNDER	*Paralichthys oblongus*	65	46
YELLOWTAIL FLOUNDER	*Limanda ferruginea*	10	7
BLACKBACK FLOUNDER	*Pseudopleuronectes americanus*	25	27
WINDOWPANE FLOUNDER	*Scopthalmus aquosus*	198	229
GULFSTREAM FLOUNDER	*Citharichthys arctifrons*	28	19
NORTHERN PIPEFISH	*Syngnathus fuscus*	0	1
BLACK SEA BASS	*Centropristis striata*	27	22
SCUP	*Stenotomus chrysops*	12	2
LONGHORN SCULPIN	*Myoxocephalus octodecemspinosus*	0	2
NORTHERN SEAROBIN	*Prionotus carolimus*	160	82
MONKFISH	*Lophius americanus*	330	356
JONAH CRAB	*Cancer borealis*	1	1
HORSESHOE CRAB	*Limulus polyphemus*	1	0
SEA SCALLOP (RETAINED)	*Placopecten magellanicus*	36291	34340
LOLIGO SQUID	*Doryteuthis pealeii*	6	4

Table 2. Catch totals of all species encountered for the paired tow design portion of the study.

Common Name	Scientific Name	Control Dredge	FCS Dredge
SPINY DOGFISH	*Squalus acanthias*	1	0
UNCLASSIFIED SKATES	*Rajidae*	3420	3536
BARNDOOR SKATE	*Dipturus laevis*	0	3
SILVER HAKE	*Merluccius bilinearis*	9	9
RED HAKE	*Urophycis chuss*	206	127
SPOTTED HAKE	*Urophycis regia*	70	65
AMERICAN PLAICE	*Hippoglossoides platessoides*	1	0
SUMMER FLOUNDER	*Paralichthys dentatus*	48	47
FOURSPOT FLOUNDER	*Paralichthys oblongus*	50	62
YELLOWTAIL FLOUNDER	*Limanda ferruginea*	1	1
BLACKBACK FLOUNDER	*Pseudopleuronectes americanus*	6	5
WINDOWPANE FLOUNDER	*Scopthalmus aquosus*	221	174
GULFSTREAM FLOUNDER	*Citharichthys arctifrons*	21	3
BUTTERFISH	*Peprilus triacanthus*	0	1
BLACK SEA BASS	*Centropristis striata*	0	1
LONGHORN SCULPIN	*Myoxocephalus octodecemspinosus*	0	1
NORTHERN SEAROBIN	*Prionotus carolimus*	6	9
NORTHERN SAND LANCE	*Ammodytes dubius*	7	0
MONKFISH	*Lophius americanus*	153	182
AMERICAN LOBSTER	*Homarus americanus*	1	3
HORSESHOE CRAB	*Limulus polyphemus*	0	1
SEA SCALLOP (RETAINED)	*Placopecten magellanicus*	48060	44146
ILLEX SQUID	*Illex illecebrosus*	1	6
LOLIGO SQUID	*Doryteuthis pealeii*	8	3

Table 3. Model results for the assessment of animal size as a significant predictor of relative efficiency for the alternate tow experimental design. Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale. Significant (α=0.05) length effects are highlighted in bold.

Common Name	Effect	Estimate	SE	DF	t value	p value	LCL	UCL
BLACKBACK FLOUNDER	Intercept	-0.252	2.50	46	-0.101	0.9203	-5.289	4.785
	Size	0.011	0.08	46	0.138	0.8911	-0.149	0.171
FOURSPOT FLOUNDER	Intercept	0.213	0.96	94	0.223	0.8238	-1.683	2.110
	Size	-0.024	0.03	94	-0.681	0.4978	-0.093	0.045
MONKFISH	Intercept	-0.166	0.43	435	-0.387	0.6987	-1.011	0.678
	Size	0.007	0.01	435	0.700	0.4842	-0.013	0.026
SEA SCALLOP (RETAINED)	Intercept	-0.750	0.18	605	-4.177	<0.0001	-1.103	-0.397
	Size	**0.006**	**0.00**	**605**	**3.789**	**0.0002**	**0.003**	**0.009**
SUMMER FLOUNDER	Intercept	0.138	0.60	252	0.232	0.8168	-1.034	1.310
	Size	-0.008	0.01	252	-0.600	0.5492	-0.035	0.019
WINDOWPANE FLOUNDER	Intercept	1.202	1.20	194	1.006	0.3157	-1.155	3.559
	Size	-0.040	0.04	194	-0.893	0.3729	-0.128	0.048
YELLOWTAIL FLOUNDER	Intercept	12.430	24.13	14	0.515	0.6145	-39.32	64.184
	Size	-0.369	0.70	14	-0.527	0.6067	-1.872	1.134

Table 4. Model results for the assessment of animal size as a significant predictor of relative efficiency for the paired tow experimental design. Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale. Significant (α=0.05) length effects are highlighted in bold.

Common Name	Effect	Estimate	SE	DF	t value	p value	LCL	UCL
BLACKBACK FLOUNDER	Intercept	13.223	9.839	9	1.344	0.2119	-9.034	35.480
	Size	-0.383	0.272	9	-1.405	0.1936	-0.999	0.233
FOURSPOT FLOUNDER	Intercept	-1.675	1.331	103	-1.259	0.2108	-4.315	0.964
	Size	0.072	0.050	103	1.429	0.1559	-0.028	0.171
MONKFISH	Intercept	-0.112	0.579	279	-0.194	0.8461	-1.252	1.027
	Size	0.006	0.014	279	0.459	0.6468	-0.021	0.033
SEA SCALLOP (RETAINED)	Intercept	-0.604	0.189	909	-3.196	0.0014	-0.975	-0.233
	Size	**0.005**	**0.002**	**909**	**2.973**	**0.0030**	**0.002**	**0.008**
SUMMER FLOUNDER	Intercept	-1.101	1.160	83	-0.949	0.3454	-3.408	1.206
	Size	0.022	0.024	83	0.928	0.3561	-0.025	0.069
WINDOWPANE FLOUNDER	Intercept	1.965	1.187	182	1.656	0.0995	-0.377	4.307
	Size	-0.082	0.044	182	-1.862	0.0642	-0.168	0.005

Table 5. Length based model building for species that showed length as a significant predictor in the alternate tow experimental design. Hierarchical models ranked based upon minimum AIC values. The selected model is shown in bold. Given the large amount of length data associated with sea scallops, the addition of a low order polynomial term for length was explored.

Model	Fixed Effects	Random Effects	AIC Value	Delta AIC
M8	**INTERCEPT, SIZE, SIZE^2, BEAUFORT, DEPTH**	**INTERCEPT, SLOPE**	**2484.8**	**0.00**
M7	INTERCEPT, SIZE, SIZE^2, BEAUFORT, DEPTH	INTERCEPT	2527.3	42.50
M6	INTERCEPT, SIZE, SIZE^2, BEAUFORT, DEPTH	NONE	2692.6	207.85
M4	INTERCEPT, SIZE, SIZE^2, BEAUFORT	NONE	2747.9	263.12
M5	INTERCEPT, SIZE, SIZE^2, DEPTH	NONE	2767.4	282.67
M3	INTERCEPT, SIZE, SIZE^2	NONE	2821.5	336.77
M2	INTERCEPT, SIZE	NONE	2828.4	343.65
M1	INTERCEPT ONLY	NONE	2829.8	345.01

Table 6. Parameter estimates from the models examining the unpooled catch data. Results are presented from the model that provided the best fit (intercept, size, size^2, Beaufort number, and depth) to the sea scallop data as supported by model comparison (minimum AIC value) from the alternate tow experimental design. Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale.

Effect	Beaufort	Estimate	SE	DF	t value	p value	LCL	UCL
Intercept	.	-1.819	0.690	39	-2.635	0.0120	-3.216	-0.422
Size	.	0.175	0.086	43	2.022	0.0495	0.000	0.349
Size^2	.	-0.134	0.072	517	-1.862	0.0631	-0.275	0.007
Depth	.	0.044	0.015	517	3.001	0.0028	0.015	0.073
Beaufort	1	-0.381	0.279	517	-1.367	0.1722	-0.930	0.167
	2	-0.378	0.205	517	-1.840	0.0664	-0.781	0.026
	3	-0.507	0.210	517	-2.421	0.0158	-0.919	-0.096
	4	-0.021	0.242	517	-0.086	0.9317	-0.497	0.455
	5	0.000	.	.	.	.	.	.

Table 7. Length based model building for species that showed length as a significant predictor in the paired tow experimental design. Hierarchical models ranked based upon minimum AIC values. The selected model is shown in bold. Given the large amount of length data associated with sea scallops, the addition of a low order polynomial term for length was explored.

Model	Fixed Effects	Random Effects	AIC Value	Delta AIC
M8	**INTERCEPT, SIZE, SIZE^2, BEAUFORT, DEPTH**	**INTERCEPT, SLOPE**	**18260**	**0.00**
M7	INTERCEPT, SIZE, SIZE^2, BEAUFORT, DEPTH	INTERCEPT	18383	122.82
M6	INTERCEPT, SIZE, SIZE^2, BEAUFORT, DEPTH	NONE	18406	146.17
M5	INTERCEPT, SIZE, SIZE^2, DEPTH	NONE	18426	165.90
M4	INTERCEPT, SIZE, SIZE^2, BEAUFORT	NONE	18446	185.92
M3	INTERCEPT, SIZE, SIZE^2	NONE	18462	202.04
M2	INTERCEPT, SIZE	NONE	18462	202.63
M1	INTERCEPT ONLY	NONE	18478	218.19

Table 8. Parameter estimates from the models examining the unpooled catch data. Results are presented from the model that provided the best fit (intercept, size, size^2, Beaufort number, and depth) to the sea scallop data as supported by model comparison (minimum AIC value) from the paired tow experimental design. Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale.

Effect	Beaufort Number	Estimate	SE	DF	t value	p value	LCL	UCL
Intercept	.	0.389	0.425	41	0.916	0.3649	-0.469	1.247
Size	.	0.151	0.132	46	1.143	0.2590	-0.115	0.416
Size^2	.	-0.028	0.058	817	-0.490	0.6242	-0.141	0.085
Depth	.	-0.016	0.007	817	-2.242	0.0252	-0.031	-0.002
Beaufort	2	0.385	0.309	817	1.248	0.2124	-0.221	0.991
	3	0.624	0.306	817	2.040	0.0417	0.024	1.224
	4	0.463	0.270	817	1.716	0.0866	-0.067	0.992
	5	0.000	.	.	.	.	.	.

Table 9. Pooled-over-length model building the alternate tow experimental design. Hierarchical models ranked based upon minimum AIC values. In cases where the delta AIC value was less than 3 units, the simpler model was chosen. The selected model is shown in bold.

Species	Model	Fixed Effects	Random Effects	AIC Value	Delta AIC
Fourspot Flounder	**M5**	**INTERCEPT ONLY**	**INTERCEPT**	**81.86**	**0.00**
	M7	DEPTH	INTERCEPT	83.86	2.00
	M8	BEAUFORT, DEPTH	INTERCEPT	83.86	2.00
	M1	INTERCEPT ONLY	NONE	84.31	2.45
	M6	BEAUFORT	INTERCEPT	84.76	2.90
	M3	DEPTH	NONE	86.29	4.43
	M2	BEAUFORT	NONE	86.76	4.90
	M4	DEPTH BEAUFORT	NONE	88.60	6.75
Monkfish	M3	DEPTH	NONE	183.98	0.00
	M1	**INTERCEPT ONLY**	**NONE**	**183.99**	**0.01**
	M4	DEPTH BEAUFORT	NONE	184.01	0.03
	M6	BEAUFORT	INTERCEPT	184.27	0.29
	M2	BEAUFORT	NONE	184.27	0.29
	M5	INTERCEPT ONLY	INTERCEPT	185.49	1.51
	M7	DEPTH	INTERCEPT	185.86	1.88
	M8	BEAUFORT, DEPTH	INTERCEPT	185.86	1.88
Summer Flounder	M6	BEAUFORT	INTERCEPT	141.56	0.00
	M2	**BEAUFORT**	**NONE**	**141.56**	**0.00**
	M4	DEPTH BEAUFORT	NONE	142.98	1.43
	M1	INTERCEPT ONLY	NONE	145.92	4.36
	M5	INTERCEPT ONLY	INTERCEPT	147.67	6.12
	M3	DEPTH	NONE	147.91	6.36
	M7	DEPTH	INTERCEPT	149.67	8.11
	M8	BEAUFORT, DEPTH	INTERCEPT	149.67	8.11
Unclassified Skates	**M7**	**DEPTH**	**INTERCEPT**	**401.63**	**0.00**
	M8	BEAUFORT, DEPTH	INTERCEPT	401.63	0.00
	M5	INTERCEPT ONLY	INTERCEPT	405.94	4.31
	M6	BEAUFORT	INTERCEPT	407.02	5.40
	M4	DEPTH BEAUFORT	NONE	523.74	122.12
	M2	BEAUFORT	NONE	550.34	148.71
	M3	DEPTH	NONE	571.72	170.10
	M1	INTERCEPT ONLY	NONE	598.18	196.55
Windowpane Flounder	**M2**	**BEAUFORT**	**NONE**	**143.99**	**0.00**
	M6	BEAUFORT	INTERCEPT	143.99	0.00
	M4	DEPTH BEAUFORT	NONE	144.98	0.99
	M3	DEPTH	NONE	145.10	1.12
	M7	DEPTH	INTERCEPT	146.10	2.11

Species	Model	Fixed Effects	Random Effects	AIC Value	Delta AIC
	M8	BEAUFORT, DEPTH	INTERCEPT	146.10	2.11
	M5	INTERCEPT ONLY	INTERCEPT	147.51	3.52
	M1	INTERCEPT ONLY	NONE	149.29	5.30
Winter Flounder	M3	DEPTH	NONE	54.45	0.00
	M1	**INTERCEPT ONLY**	**NONE**	**54.65**	**0.20**
	M5	INTERCEPT ONLY	INTERCEPT	56.44	1.99
	M7	DEPTH	INTERCEPT	56.44	1.99
	M8	BEAUFORT, DEPTH	INTERCEPT	56.44	1.99
	M4	DEPTH BEAUFORT	NONE	57.65	3.20
	M2	BEAUFORT	NONE	60.01	5.56
	M6	BEAUFORT	INTERCEPT	61.85	7.40
Yellowtail Flounder	M3	DEPTH	NONE	22.26	0.00
	M1	**INTERCEPT ONLY**	**NONE**	**23.19**	**0.93**
	M5	INTERCEPT ONLY	INTERCEPT	23.69	1.43
	M7	DEPTH	INTERCEPT	23.89	1.63
	M8	BEAUFORT, DEPTH	INTERCEPT	23.89	1.63
	M6	BEAUFORT	INTERCEPT	24.77	2.51
	M4	DEPTH BEAUFORT	NONE	25.60	3.34
	M2	BEAUFORT	NONE	26.90	4.64

Table 10. Pooled-over-length model building the paired tow experimental design. Hierarchical models ranked based upon minimum AIC values. In cases where the delta AIC value was less than 3 units, the simpler model was chosen. The selected model is shown in bold.

Species	Model	Fixed Effects	Random Effects	AIC Value	Delta AIC
Fourspot Flounder	**M1**	**INTERCEPT ONLY**	**NONE**	**89.83**	**0.00**
	M3	DEPTH	NONE	89.95	0.11
	M5	INTERCEPT ONLY	INTERCEPT	90.31	0.48
	M7	DEPTH	INTERCEPT	91.15	1.32
	M8	BEAUFORT, DEPTH	INTERCEPT	91.15	1.32
	M2	BEAUFORT	NONE	94.21	4.37
	M6	BEAUFORT	INTERCEPT	95.12	5.29
	M4	DEPTH BEAUFORT	NONE	95.75	5.91
Monkfish	**M5**	**INTERCEPT ONLY**	**INTERCEPT**	**166.09**	**0.00**
	M7	DEPTH	INTERCEPT	168.01	1.91
	M8	BEAUFORT, DEPTH	INTERCEPT	168.01	1.91
	M1	INTERCEPT ONLY	NONE	168.82	2.72
	M3	DEPTH	NONE	170.77	4.67
	M6	BEAUFORT	INTERCEPT	171.49	5.40
	M2	BEAUFORT	NONE	172.59	6.49
	M4	DEPTH BEAUFORT	NONE	174.18	8.08
Summer Flounder	**M1**	**INTERCEPT ONLY**	**NONE**	**36.20**	**0.00**
	M3	DEPTH	NONE	37.94	1.73
	M5	INTERCEPT ONLY	INTERCEPT	38.20	2.00
	M2	BEAUFORT	NONE	38.20	2.00
	M4	DEPTH BEAUFORT	NONE	39.84	3.64
	M7	DEPTH	INTERCEPT	39.92	3.71
	M8	BEAUFORT, DEPTH	INTERCEPT	39.92	3.71
	M6	BEAUFORT	INTERCEPT	40.20	4.00
Unclassified Skates	**M4**	**DEPTH BEAUFORT**	**NONE**	**327.85**	**0.00**
	M5	INTERCEPT ONLY	INTERCEPT	332.02	4.18
	M6	BEAUFORT	INTERCEPT	333.59	5.75
	M7	DEPTH	INTERCEPT	333.76	5.92
	M8	BEAUFORT, DEPTH	INTERCEPT	333.76	5.92
	M2	BEAUFORT	NONE	353.36	25.51
	M3	DEPTH	NONE	379.64	51.79
	M1	INTERCEPT ONLY	NONE	380.45	52.61
Windowpane Flounder	**M1**	**INTERCEPT ONLY**	**NONE**	**80.17**	**0.00**

Species	**Model**	**Fixed Effects**	**Random Effects**	**AIC Value**	**Delta AIC**
	M5	INTERCEPT ONLY	INTERCEPT	80.17	0.00
	M3	DEPTH	NONE	80.27	0.10
	M7	DEPTH	INTERCEPT	80.27	0.10
	M8	BEAUFORT, DEPTH	INTERCEPT	80.27	0.10
	M2	BEAUFORT	NONE	83.07	2.90
	M6	BEAUFORT	INTERCEPT	83.07	2.90
	M4	DEPTH BEAUFORT	NONE	83.98	3.81
Winter Flounder	M4	DEPTH BEAUFORT	NONE	12.63	0.00
	M2	BEAUFORT	NONE	14.68	2.05
	M6	BEAUFORT	INTERCEPT	14.68	2.05
	M1	**INTERCEPT ONLY**	**NONE**	**14.96**	**2.34**
	M5	INTERCEPT ONLY	INTERCEPT	14.96	2.34
	M3	DEPTH	NONE	16.45	3.83
	M7	DEPTH	INTERCEPT	16.45	3.83
	M8	BEAUFORT, DEPTH	INTERCEPT	16.45	3.83

Table 11. Models examining the pooled-over-length catch data from the alternate tow experiment. 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.

Species	Effect	Estimate	SE	DF	t value	p value	LCL	UCL
Fourspot Flounder	Intercept	-0.353	0.193	28	-1.830	0.0780	-0.748	0.042
Yellowtail Flounder	Intercept	-0.388	0.493	10	-0.787	0.4497	-1.488	0.711
Blackback Flounder	Intercept	0.081	0.278	25	0.292	0.7727	-0.491	0.654
Monkfish	Intercept	0.077	0.077	42	1.006	0.3199	-0.077	0.232

Table 12. Models examining the pooled-over-length catch data from the alternate tow experiment. Results are presented from the model that provided the best fit (intercept, Beaufort number) 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	Beaufort	Estimate	SE	DF	t value	p value	LCL	UCL
Summer Flounder	Intercept	.	0.852	0.867	38	0.983	0.3319	-0.903	2.608
	Beaufort	1	-13.62	340.47	38	-0.040	0.9683	-702.9	675.63
		2	-0.825	0.881	38	-0.937	0.3549	-2.608	0.958
		3	-1.500	0.891	38	-1.683	0.1005	-3.305	0.304
		4	-0.946	0.962	38	-0.983	0.3316	-2.895	1.002
		5	0.000	.	.	.	.	.	.
Windowpane Flounder	Intercept	.	-1.100	0.559	34	-1.966	0.0575	-2.236	0.037
	Beaufort	1	1.189	0.615	34	1.933	0.0616	-0.061	2.440
		2	1.415	0.579	34	2.444	0.0199	0.239	2.591
		3	0.933	0.595	34	1.569	0.1258	-0.275	2.141
		4	1.727	0.619	34	2.791	0.0086	0.469	2.984
		5	0.000	.	.	.	.	.	.

Table 13. Model examining the pooled-over-length catch data from the alternate tow experiment. Results are presented from the model that provided the best fit (intercept, depth) to the data as supported by model comparison (minimum AIC value). Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale.

Species	Effect	Estimate	SE	DF	t value	p value	LCL	UCL
Unclassified Skates	Intercept	-3.372	1.161	42	-2.904	0.0059	-5.716	-1.029
	Depth	0.063	0.024	42	2.602	0.0128	0.014	0.112

Table 14. Models examining the pooled-over-length catch data from the paired tow experiment. 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.

Species	Effect	Estimate	SE	DF	t value	p value	LCL	UCL
Fourspot Flounder	Intercept	-0.353	0.193	28	-1.830	0.0780	-0.748	0.042
Blackback Flounder	Intercept	0.081	0.278	25	0.292	0.7727	-0.491	0.654
Monkfish	Intercept	0.077	0.077	42	1.006	0.3199	-0.077	0.232

Table 15. Models examining the pooled-over-length catch data from the paired tow experiment. Results are presented from the model that provided the best fit (intercept, Beaufort number) 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	Beaufort	Estimate	SE	DF	t value	p value	LCL	UCL
Unclassified Skates	Intercept	.	0.866	0.233	44	3.711	0.0006	0.396	1.337
	Beaufort	2	0.131	0.089	44	1.475	0.1474	-0.048	0.311
		3	1.049	0.152	44	6.892	0.0000	0.742	1.355
		4	0.451	0.075	44	5.976	0.0000	0.299	0.603
		5	0.000	.	.	.	.	.	.
	Depth	.	-0.026	0.005	44	-5.219	0.0000	-0.035	-0.016

Table 16. 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 paired tow experiment. Statistical significance (alpha=0.05 level) is specific to that model and may not be the most parsimonious model from the analysis.

Species	FCS	Control	Percent Difference	Model Estimate	Significance
Blackback Flounder	5	6	-16.67	-16.66	NO
Fourspot Flounder	62	50	24.00	25.98	NO
Monkfish	182	153	18.95	15.52	NO
Sea Scallop (Retained)	44,146	48,060	-8.14	-5.05	NO
Summer Flounder	47	48	-2.08	-2.03	NO
Unclassified Skates	3,536	3,420	3.39	8.94	NO
Windowpane Flounder	**174**	**221**	**-21.27**	**-21.26**	**YES**

Table 17. 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 alternate tow experiment design. Statistical significance (alpha=0.05 level) is specific to that model and may not be the most parsimonious model from the analysis.

Species	**FCS**	**Control**	**Percent Difference**	**Model Estimate**	**Significance**
Blackback Flounder	27	25	8.00	9.43	NO
Fourspot Flounder	46	65	-29.23	-33.65	NO
Monkfish	356	330	7.88	7.51	NO
Sea Scallop (Retained)	34,340	36,291	-5.38	-9.52	NO
Summer Flounder	139	168	-17.26	-19.05	NO
Unclassified Skates	**3,676**	**5,120**	**-28.20**	**-30.24**	**YES**
Windowpane Flounder	229	198	15.66	15.13	NO

7 Figures

Figure 1. A 9' sea scallop dredge equipped with a flounder cookies sweep (FCS) attached along the outer bale bars aboard F/V *Mister G* (**A**) and an 11' sea scallop dredge equipped with a FCS attached behind the roller extending out to the outer bale bars aboard F/V *Let It Ride* (**B**).

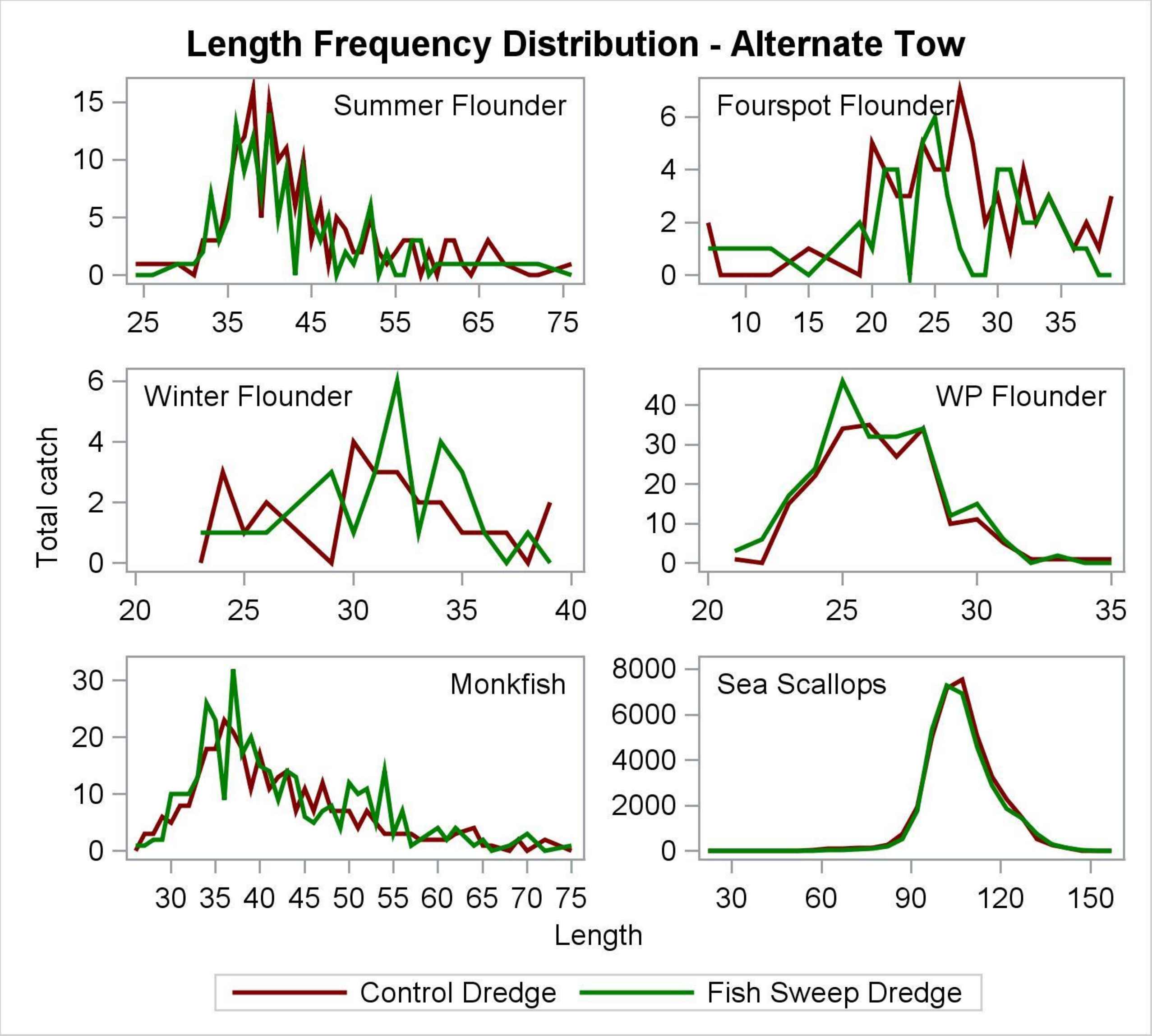

Figure 2. Length frequency distributions for the selected species in the alternate tow experimental design.

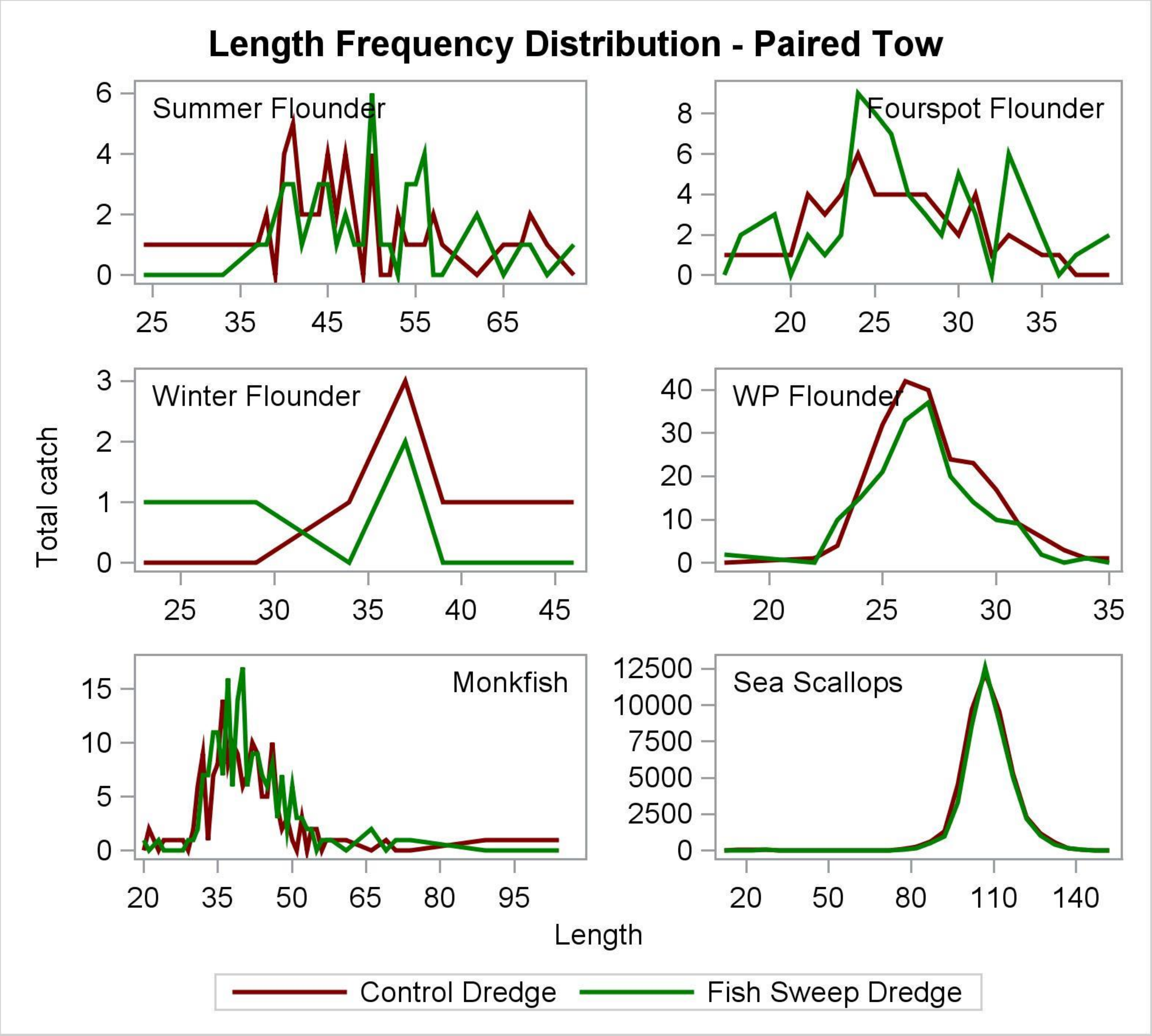

Figure 3. Length frequency distributions for the selected species in the paired tow experimental design.

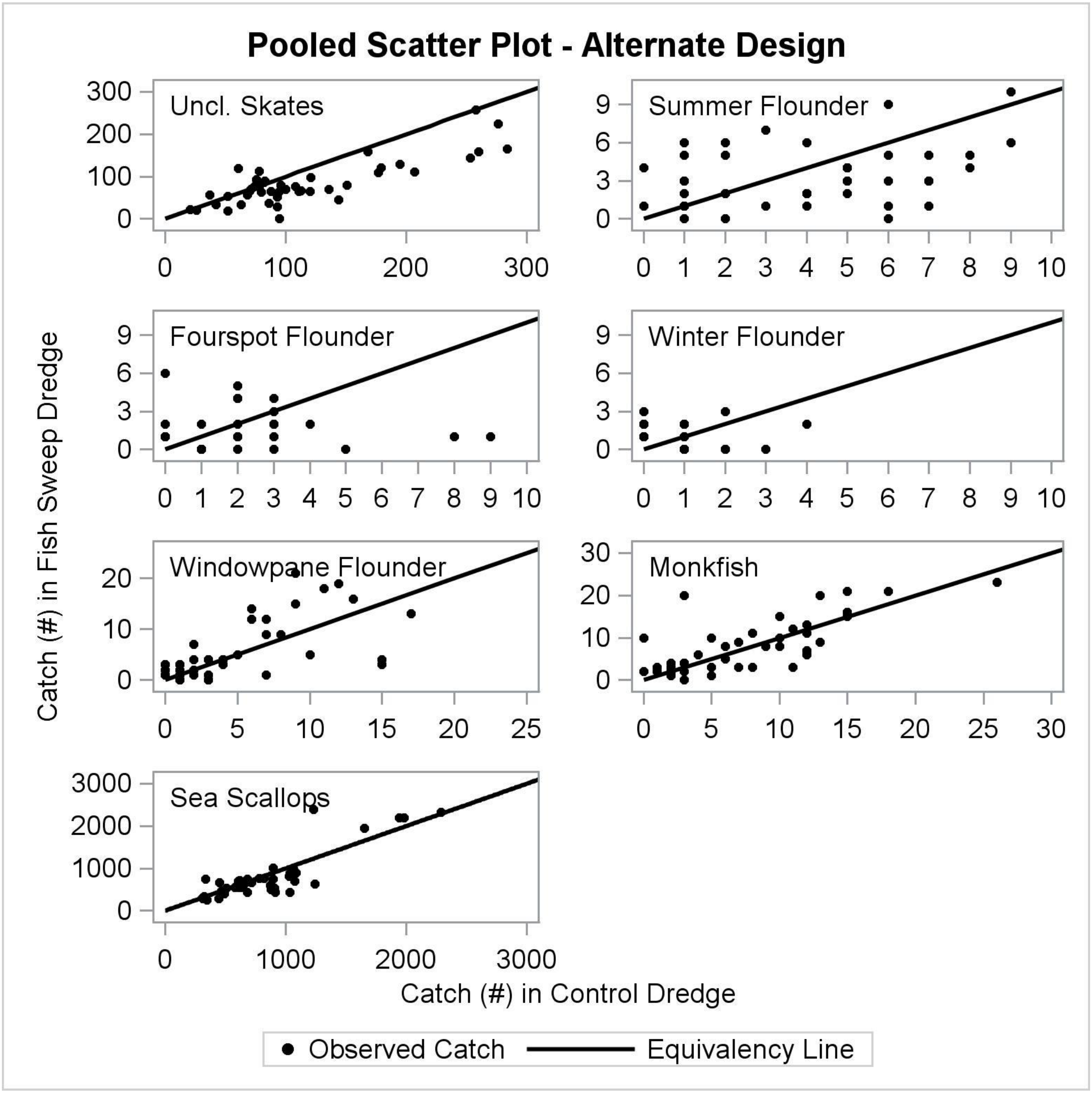

Figure 4. Scatter plot of pooled catches for the selected species in the alternate tow experimental design.

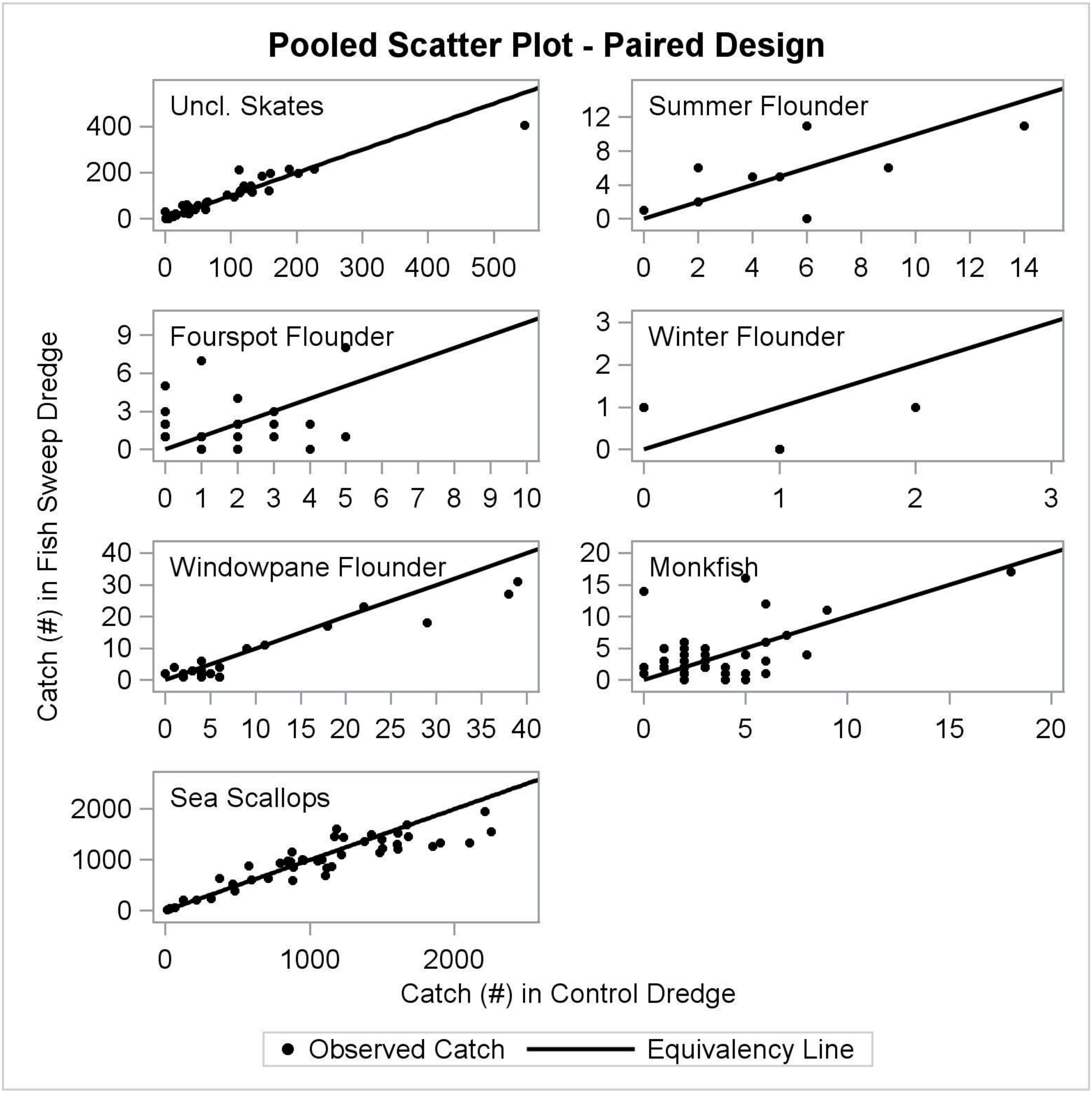

Figure 5. Scatter plot of pooled catches for the selected species in the alternate tow experimental design.

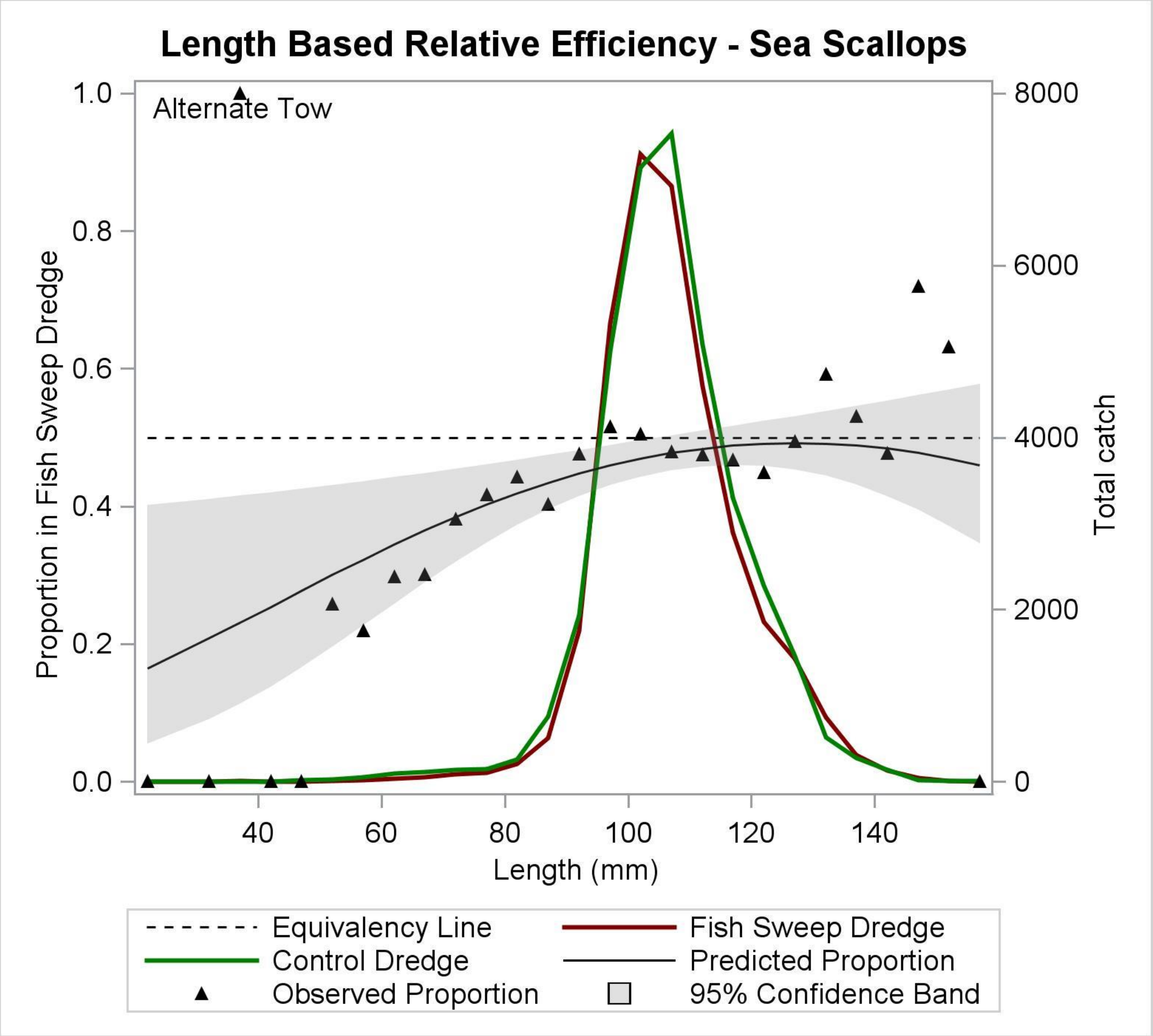

Figure 6. Relative sea scallop catch by the two dredge configurations from the alternate tow experimental design. The triangles represent the observed proportion at length ($Catch_{fis}/(Catch_{fis} + Catch_{crt})$), with a proportion >0.5 representing more animals at length captured by the FCS dredge. The grey area represents the 95% confidence band for the modeled proportion (solid black line).

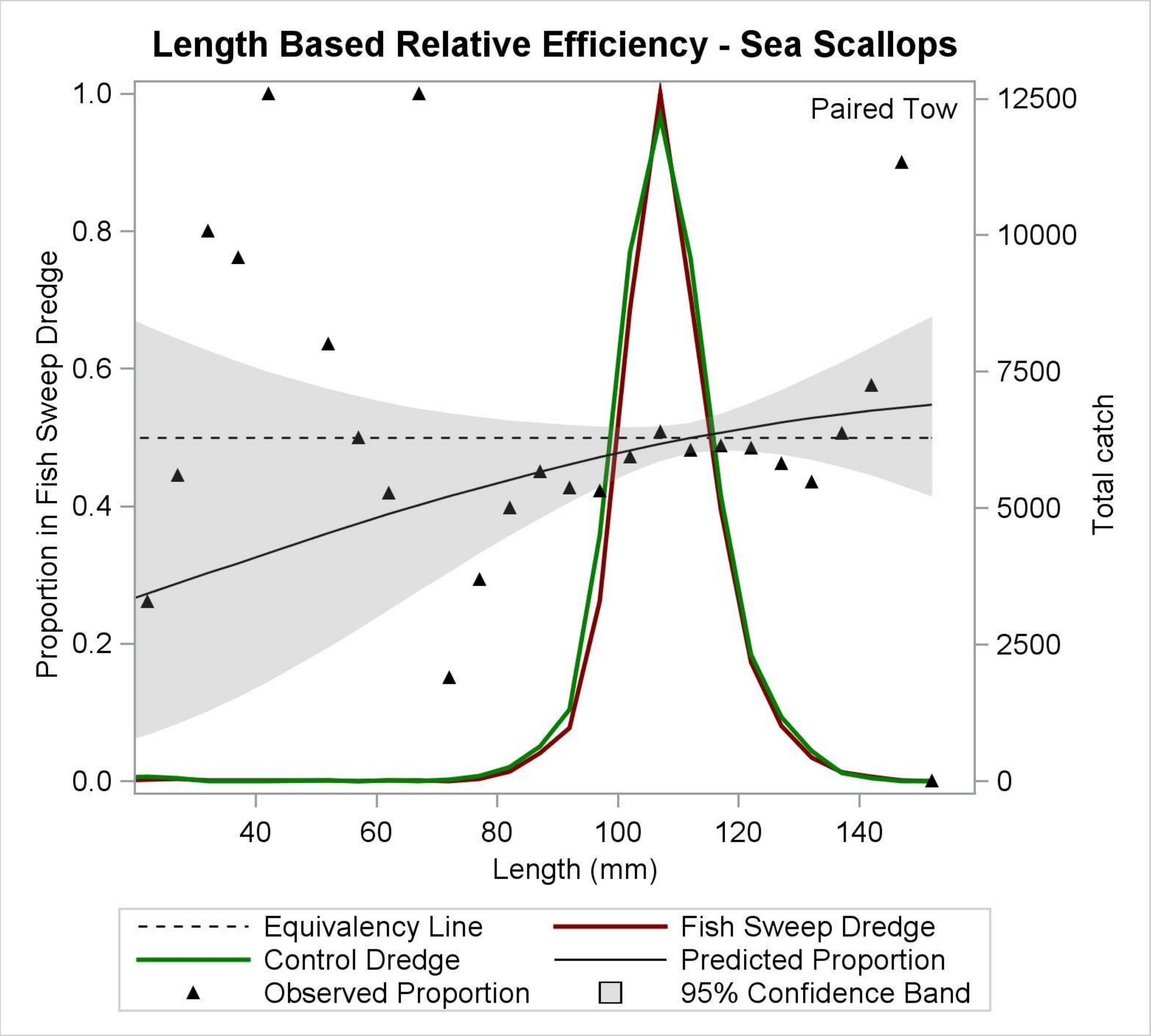

Figure 7. Relative sea scallop catch by the two dredge configurations from the paired tow experimental design. The triangles represent the observed proportion at length ($Catch_{fis}/(Catch_{fis} + Catch_{crt})$), with a proportion >0.5 representing more animals at length captured by the FCS dredge. The grey area represents the 95% confidence band for the modeled proportion (solid black line).

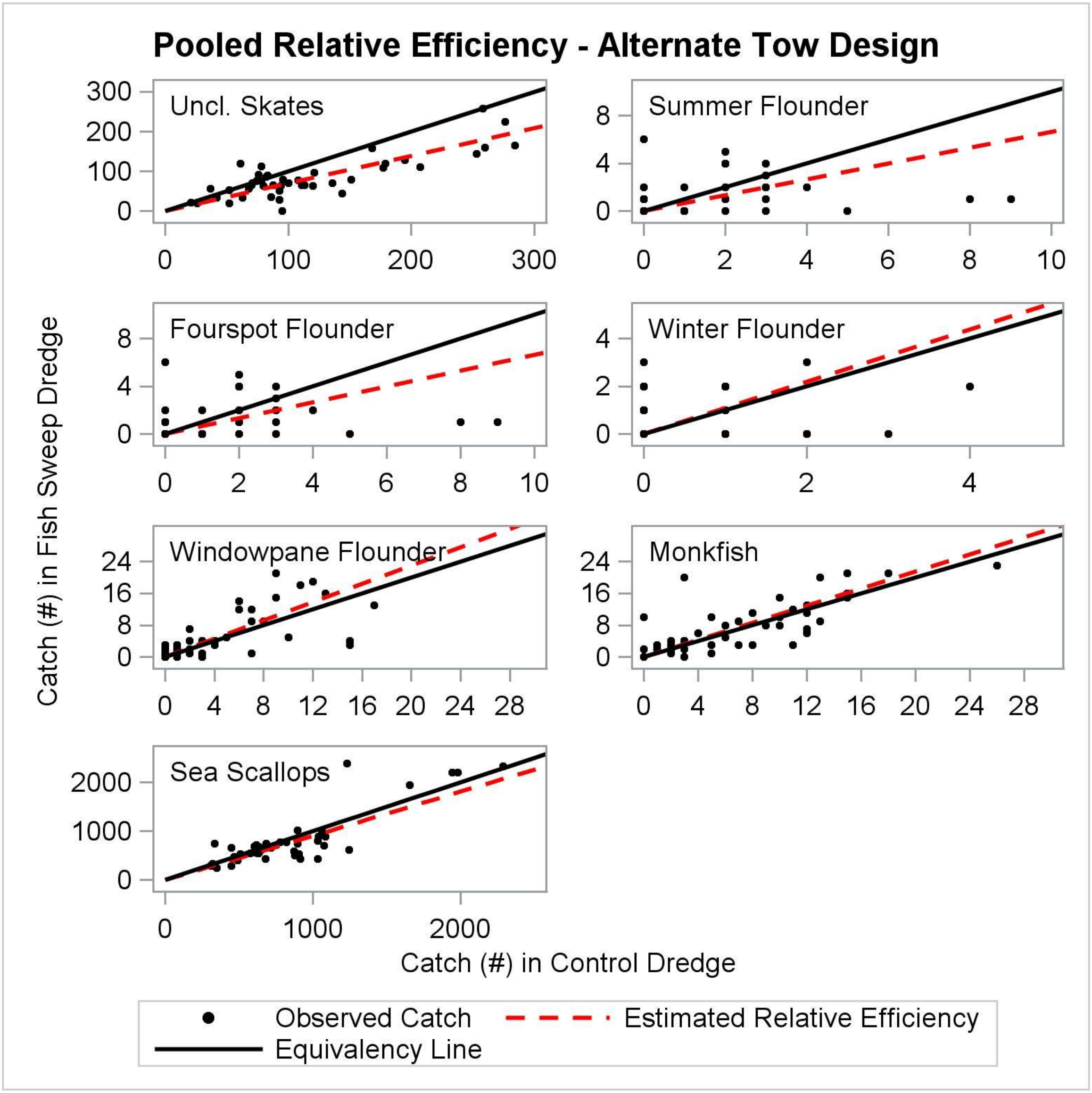

Figure 8. Total pooled catches for unclassified skates, summer flounder, fourspot flounder, winter flounder, windowpane flounder, monkfish and sea scallops for the FCS dredge vs. the control dredge from the alternate tow experimental design. The visualization of these data is represented by the intercept only model even though this model may not represent the most parsimonious specification. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one.

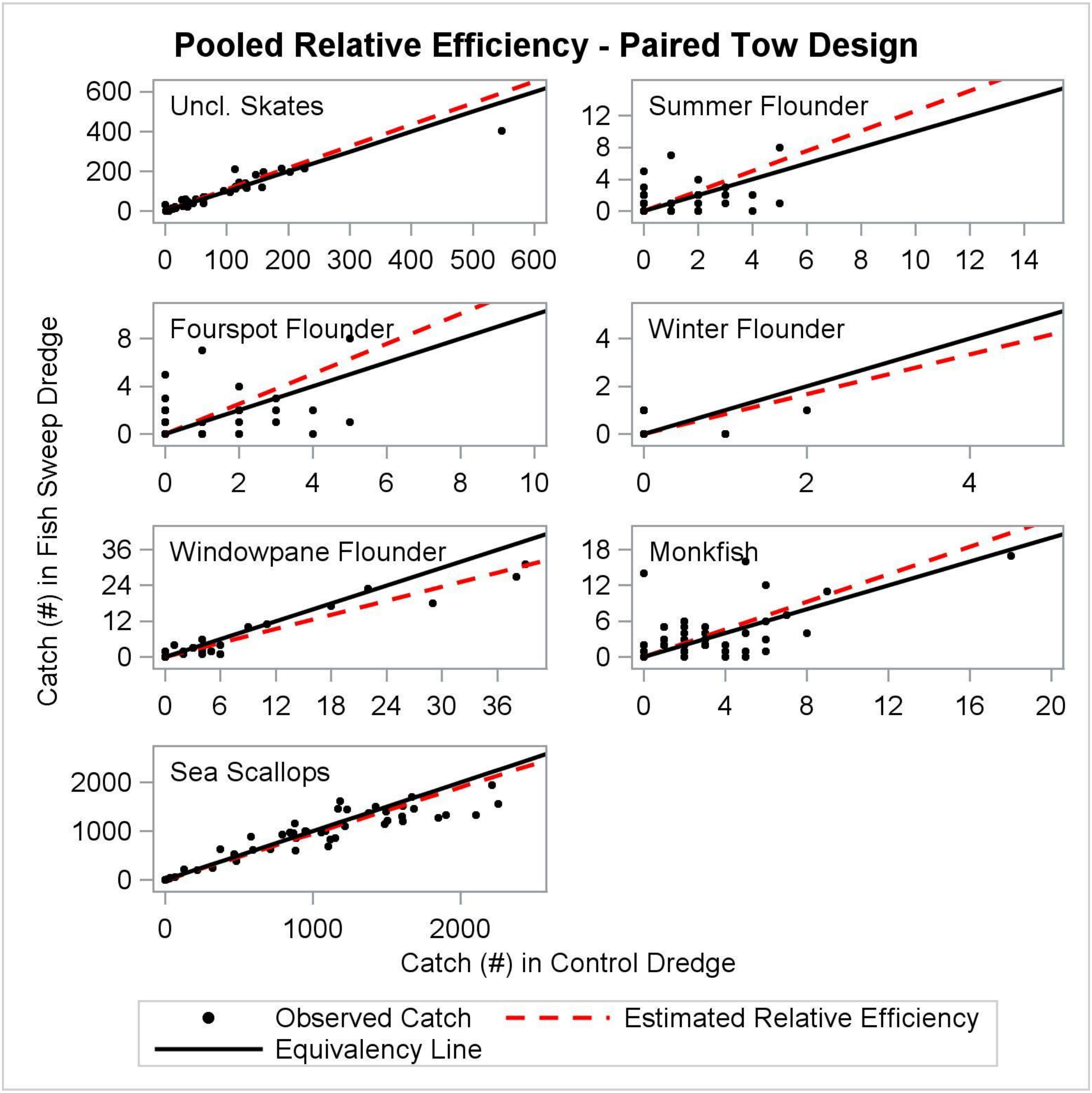

Figure 9. Total pooled catches for unclassified skates, summer flounder, fourspot flounder, winter flounder, windowpane flounder, monkfish and sea scallops for the FCS dredge vs. the control dredge from the paired tow experimental design. The visualization of these data is represented by the intercept only model even though this model may not represent the most parsimonious specification. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one.

Figure 10. Image highlighting placement of GoPro HD action camera (**A**) and dive light (**B**) on F/V *Let It Ride* used to document FCS behavior in situ and fish interactions with the FCS. Camera and dive light were set up similarly on F/V *Mister G*.

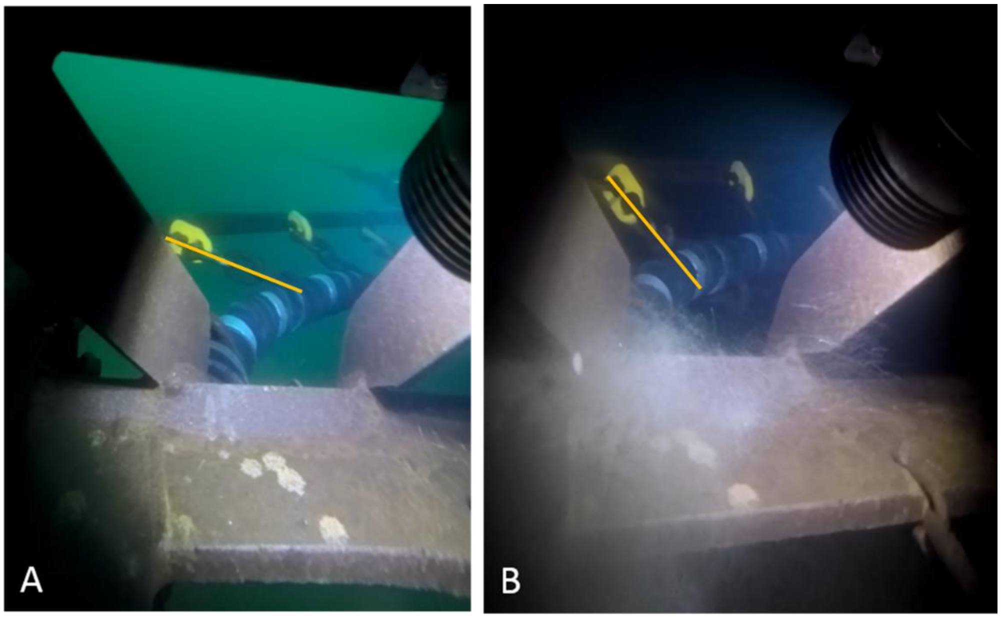

Figure 11. GoPro image capture from before adding sweep chain (**A**) and after adding sweep chain (**B**) to the FCS on F/V *Let It Ride*. In image **B**, sand is kicked up by the FCS, and the angle of the attachment chain has grown steeper (angles highlighted in yellow).

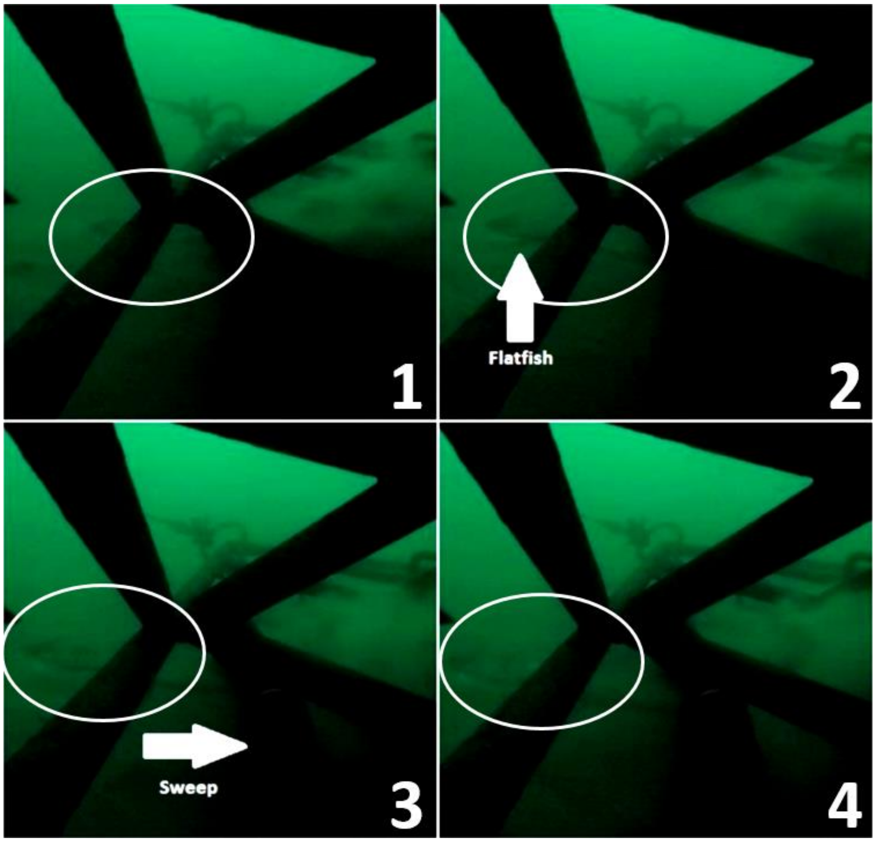

Figure 12. GoPro image capture series showing a flatfish (circled) swimming away from the dredge. Fish and FCS are labelled for reference.

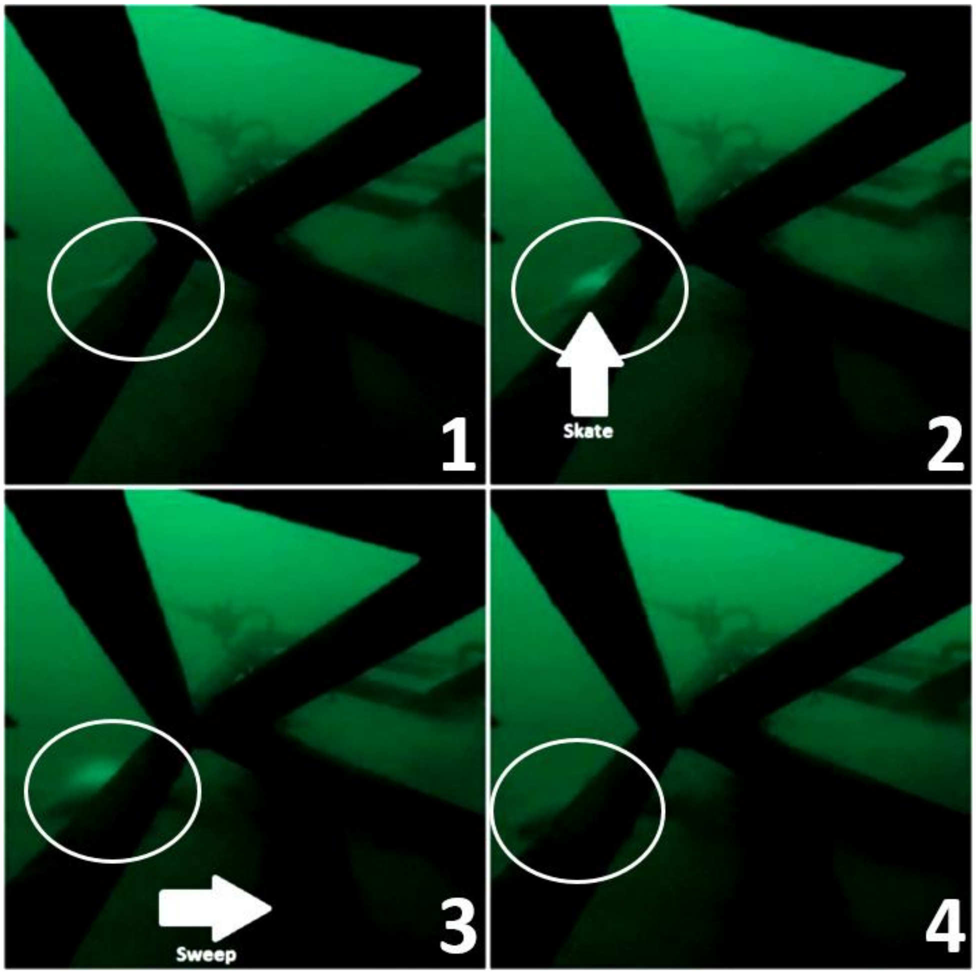

Figure 13. GoPro image capture series showing a skate (circled) curling into a ball to escape the dredge. Fish and FCS are labelled for reference.

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 FCS dredge and q_f equals the catchability of the control dredge used in the study. The efficiency of the FCS dredge relative to the control 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 gear will reflect differences in the catchabilities of the gear combinations tested.

Let C_{iv} represent the scallop/fish catch at tow pair i by dredge v, where $v{=}r$ denotes the FCS dredge and $v{=}f$ denotes the control dredge. Let λ_{ir} represent the scallop/fish density for the i^{th} tow by the FCS 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 pair 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 are expected to be constant across tows. Assuming that capture is a Poisson process with mean equal to variance, then the expected catch by the control dredge is given by:

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

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

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

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

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

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

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

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

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

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

In this model, the intercept (β_0) is allowed to vary randomly with respect to tow.

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:

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

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 shell height (length) frequency analysis. Most finfish were sampled completely without subsampling. 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, however, 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). 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. In addition to subsampling of the catch, in our alternate haul experiment, the offset term also includes a term to account for the differences in the area swept by the gear.

Let q_{ir} equal the sub-sampling fraction at tow *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 FCS 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:

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

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.

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