Testing of Scallop Dredge Bag Design Changes for Flatfish Bycatch Reduction

Final Report

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Project Summary

In this project, four Limited Access (LA) research trips and 24 Limited Access General Category (LAGC) trips were completed from March 1, 2013 through May 29, 2014. In the LA portion of the project, paired tows were conducted to compare a commercial dredge supplied by the vessel (control dredge) to a standardized dredge consisting of a Coonamessett Farm Turtle Deflector Dredge (TDD) hung with an experimental bag (5 ring apron, 45 mesh twine top; 5R apron dredge). In the LAGC portion of the study, an alternate tow strategy was employed with control gear used on 12 trips and experimental gear used on the remaining 12 trips. The results indicate that the experimental dredge bag reduced flatfish bycatch with variable effects on sea scallop catch. This project is a continuation of a 2012 Gear Testing RSA Project (NA12NMF4540041).

2014 Trip Summary

Vessel	Start Date	End Date	Number of Tows	Fishery
Freedom	6/24/2013	6/28/2013	69	LA
Celtic	7/10/2013	7/14/2013	68	LA
Diligence	7/30/2013	8/3/2013	55	LA
Concordia	9/7/2013	9/11/2013	61	LA
Mister G	August 2013 - May 2014		69	LAGC

Introduction

One factor that has made the Georges Bank sea scallop (*Placopecten magellanicus*) fishery such an economic success is the involvement and cooperation of the commercial scallop fishing industry in the development of bycatch avoidance methods. Yellowtail flounder (*Limanda ferruginea*) and other commercially valuable flatfish are bycatch species of particular concern in the sea scallop fishery. In the past, areas were closed in response to the fleet exceeding bycatch quotas, thus preventing the scallop fishery from maximizing its economic potential (O'Keefe and DeCelles 2013). While time/area closures can be an effective means of reducing bycatch, seasonal trends in bycatch rates differ between species of concern (CFF Seasonal Bycatch Survey 2011-2013), making it difficult to optimize closures. In the current system, the scallop fleet is allocated an Actual Catch Limit for bycatch species (sub-ACL) and Accountability Measures (AMs) are enacted when sub-ACLs are exceeded. Gear modifications designed to increase species or size selectivity provide an alternative to area closures that may simultaneously reduce bycatch of multiple species with similar characteristics, such as flatfish. In conjunction with other bycatch mitigation efforts, gear modifications can serve as an AM option that reduces bycatch with minimal economic impact to the scallop fishery.

One successful gear modification already implemented in the scallop industry is the Coonamessett Farm Turtle Deflector Dredge (TDD). In field trials, the TDD reduced the bycatch of loggerhead sea turtles (*Carretta carreta*) without loss in scallop catch efficiency (Smolowitz et al. 2012). The dredge frame was designed to smoothly guide turtles over the top of the dredge by moving the cutting bar forward and eliminating most of the bale bars so not to impede escape (Smolowitz et al. 2010; Smolowitz et al. 2012). The New England Fishery Management Council (NEFMC) implemented use of the TDD west of 71° W longitude from May 1 through October 31 under Framework 23 beginning in the 2013 fishing year (NEFSC 2011). This allowed the scallop fishery to operate in areas where sea turtle and scallop habitat overlap. The success of the TDD in reducing sea turtle bycatch was due to three main factors: the modification had a low implementation cost to the fishery, it was easily enforceable by regulators, and it did not decrease the catch efficiency of the target species.

Keeping these factors in mind, dredge bag modifications were tested to reduce flatfish bycatch during the 2012 RSA Gear Testing Project (NA12NMF4540041). Bag modifications were chosen because the potential implementation cost to the fishery would be low and they would also be easy to enforce. A trend of reduced flatfish bycatch in dredges with an apron shorter than 8 rings was observed during the 2011 RSA Bycatch Survey (NA11NMF4540027). This reduction in flatfish may be due in part to the fact that a shorter apron changes the position of the bottom of the twine top relative to the sweep. A reduced apron causes the twine top bottom to extend behind the sweep and may decrease the distance fish have to swim to successfully escape from the dredge bag. Based on this observation, an experimental bag was built with a 5-row apron and a 1.5:1 twine top hanging ratio (5R apron bag) for experimentation in 2012.

The TDD design reduced flatfish bycatch as compared to the traditional New Bedford-style Dredge (NBD) (Smolowitz et al. 2012); however, given recent reductions in yellowtail flounder quota, improvements to current gear designs must be investigated to further mitigate bycatch (O'Keefe et al., 2013). The goal of this project was to reduce flatfish bycatch by lowering the profile of the TDD. The Low Profile Dredge (LPD) is a variation of the TDD with a lower-angled depressor plate which reduces head bale height off the seafloor and enables fish to avoid capture by swimming over the dredge. These modifications to the TDD design were adopted based on observations made by placing video cameras on a scallop dredge in a previous gear testing study.

The 5R apron bag was simultaneously fished alongside a TDD with a standardized bag on four research trips during the 2012 RSA Gear Testing Project. The first two of these trips tested a 5R apron bag attached to a TDD; on the final two trips, the 5R apron bag was attached to a LPD frame. The results suggested that, when attached to a TDD, the 5R apron bag significantly reduced bycatch of windowpane flounder (*Scophthalmus aquosus*) (45%) without significantly decreasing sea scallop catch. Reduction in other species of flatfish sampled on these trips ranged from 33- 44%. There was also a reduction in flatfish bycatch in the 5R apron bag on the LPD; however, the scallop catch was significantly decreased (31%). Based on these results, the LPD as originally designed was not considered a viable solution and only a modified version was tested in 2013 aboard a Limited Access (LA) vessel.

The federal sea scallop fishery is managed as two fleets: Limited Access (LA) and Limited Access the General Category (LAGC). The main difference between these two fleets is that the LA fleet is a Days At Sea (DAS) fishery with no daily weight limit of scallops and the LAGC fishery is an ITQ fishery with a daily weight limit. Without a daily weight limit, the LA fishery has evolved to maximize landings in the allotted number of DAS by utilizing large boats (greater than 90' length overall and 1000 HP) and, in the case of full-time LA permit holders, two dredges often exceeding ten feet in width. The LAGC fishery consists of smaller vessels (less than 60' length overall and 400 HP) towing a single dredge usually less than ten feet in width. Fishing effort for the LAGC fleet is often spread out over the fishing year until the vessel's yearly scallop quota is reached.

The 2012 RSA Gear Testing Project (NA12NMF4540041) only tested the 5R apron bag aboard LA vessels. Since the research from the 2012 project was used to inform the creation of the SNE/MA windowpane flounder AMs, testing was expanded to the LAGC fleet in 2013 to account for the differences between the two fleets. Testing of the LPD was continued aboard LAGC vessels because anecdotal evidence from captains participating in past LPD projects suggested that the LPD has a greater tow efficiency than both a TDD and a typical commercial dredge frame. The goal of this project was to determine if the 5R apron bag could reduce bycatch rates without negatively impacting scallop catch in the LA and LAGC fisheries. This objective aligns with National Standard 1, the prevention of overfishing while achieving optimal yield, and National Standard 9, the reduction of bycatch and incidental mortality, as defined in the Magnuson-Stevens Fisheries Conservation and Management Act SEC. 301a (MSFCMA).

Methods

Limited Access Experimental Design

The 5R apron bag was attached to a TDD and tested offshore throughout Southern New England (SNE) and Georges Bank against four industry-supplied dredges under standardized tow conditions (Figure 1). The LA vessels towed both the 5R apron bag and a vessel-supplied commercial dredge simultaneously following standardized tow parameters. Standardized tow parameters were to maintain vessel heading and vessel speed of 4.6-4.8 knots while towing the dredges with a 3:1 wire scope (wire length: depth). The tows were 30 minutes in duration unless lengthened to one hour in bad weather and rough seas. All tow parameters were recorded, including start and end positions, depth, and sea conditions. Tows where one or both of the dredges experienced a technical failure (*e.g.* twine top fouled in tail chain hook) were declared invalid and eliminated from the analysis. Dredge bag specifications for each commercial dredge were recorded prior to vessel departure (Table 1).

Limited Access General Category Experimental Design

Given that vessels in the LAGC fishery may only use one dredge, an alternating tow strategy was employed in order to compare the LPD and TDD frames as well as bag design. On the first day, one of the two dredge frames was selected, and eight to ten 50-minutes tows were completed. Within two days, and usually within 24 hrs, the second dredge was fished in an identical manner in the same tow locations at roughly the same time of day as the first dredge. A control bag with an 8R apron was used on both the LPD and TDD frames for half of the 24 days at sea (DAS) and the 5R apron bag was used for the remaining 12 DAS. This allowed for comparison of both the frames and the bags. Tows were conducted inshore near Block Island (Figure 2).

Biological Sampling Protocols

Following each tow, the catch from each dredge was sorted by species. The entire scallop catch was recorded in bushels (1 bu = 35.2 liters). A one bushel subsample of scallops from each dredge was picked at random from each tow; for tows where the scallop catch was less than one bushel the entire scallop catch was measured. The subsample was measured in 5 millimeter length bins to estimate the length frequency of the entire catch. The size frequency of the entire catch was estimated by expanding the catch at each shell height of the subsample by the total scallop catch. The commercially important finfish species and barndoor skates were measured to the nearest centimeter. Winter and little skates were counted together, but not measured, and categorized as “unclassified skates.” Table 2 lists all species that were measured and/or counted by common and scientific name. Composition and estimated quantity of “benthos” (including rocks, sand dollars, crabs, sea stars, clams and shell debris) were also noted. This biological sampling protocol was used in both the LA and LAGC portion of the study.

In Situ Videography of Fishing Gear

GoPro® Hero 3 Plus High Definition cameras were used throughout the course of the experiment to film the scallop dredges during tows. A variety of reinforced housings were designed and built in collaboration with Quinn Fisheries Inc. and tested over the course of the experiment. These housing were mounted at different locations on the dredge to observe different aspects of the dredge while fishing. Filming was limited to the hours between 10 AM and 3 PM on days with optimum visibility in order to take advantage of ideal lighting conditions. Data collected from the video was purely qualitative but was used to inform the redesign of the LPD frame.

Gear Comparisons

A Generalized Linear Mixed Model (GLMM) was used to analyze the paired catch data and test for differences in both the catch and the length composition of the catch. The GLMM was used to analyze catch as numbers of animals. Within this modeling framework, the random effects acknowledge the potential for differences that may have occurred at both the trip and individual tow levels. The GLMM groups all the data and gives an overall perspective on how the two gears compare. This analytical approach can account for the variability that is characteristic of paired tow experiments. Tow by tow differences in biotic, abiotic, and procedural factors all contribute to variability at the haul level. The GLMM modeling approach detailed in the next section better accounts for this variability and allows for a more broad inference to be made.

Statistical Models – GLMM

Catch data from the paired tows provided the information to estimate differences in the relative efficiency for the gear combinations tested. Overall, the analytical approach used here is based on the method presented 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 5R apron dredge and q_f equal the catchability of the control dredge used in the study. The efficiency of the 5R apron bag relative to the control bag will be equivalent to the ratio of the two catchabilities:

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

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

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

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

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

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

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). However, this approach can be complicated 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 5 ring 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 5R apron dredge. In this approach, the only unknown parameter is ρ and the requirement to estimate μ for each tow is eliminated as would be required in the direct GLM approach (equations 2 & 3). For the binomial distribution $E(C_{ir}) = c_i p$ and $Var(C_i r) = c_i p/(1-p)$. Therefore:

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

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

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

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

Often, gear modifications can result in changes to the length based relative efficiency of the two gears. In those instances, the potential exists for the catchability at length (*l)* to vary. Models to describe length effects are extensions of the models described in the previous section to compare 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 and Dredge Width

Additional adjustments to the models were required to account for sub-sampling of the catch and dredge width. 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. Finfish were always sampled 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 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.

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:

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

In addition, there was an instance where the widths of the two dredges used on a given cruise were not the same. In this instance, for the same reasons outlined above for subsampling of the catch, the difference in dredge width must be accounted for. Let w_{ir} equal the width of the dredge used at tow *i* for vessel *r*. Further adjustment to the model is shown below:

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

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

Our analysis of the efficiency of the 5R apron 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. Model fit was assessed by AIC. If AIC and factor significance indicated that length was not significant in predicting relative efficiency, the data was pooled over length. The random intercept model was evaluated to assess the relative differences in total catch invariant to animal length (see Equation 6).

For the LA portion of the analysis, there existed significant variability in the designs of the dredges supplied by the vessel (dredge specifications shown in Table 1). From an analytical perspective there are several ways to approach this analysis. One approach would be to include the variations in dredge design as fixed effects in a model to predict relative efficiency. Table 1 shows that the manner in which components of the individual dredge designs were combined precluded this approach. An alternative approach would be posit that the dredge designs in the study were a representative sample of the designs used by the fishery and draw inference to the entire universe of dredge designs in this fishery by including vessel as a random effect. However, the inclusion of only four dredge designs precluded reliable inference to the fleet. The models employed assume that random effects vary stochastically about a mean selection curve (Fryer et al. 2003); therefore, this was necessary to avoid the potentially confounding effects of using different industry-supplied dredges as the “control” for our analysis. As a result, we approached the data set on a trip-by-trip basis and present the analysis in this manner. We used SAS/STAT® PROC GLIMMIX v. 9.2 to fit the generalized linear mixed effects models for LA trips.

The control and experimental dredge configurations were consistent for all LAGC trips; therefore all trips were analyzed together. The analysis followed that described above except for the inclusion of a categorical variable to denote bag design (*i.e*. 8R or 5R apron). Models for LAGC trips were fit using the “mgcv” package (Wood 2006, 2011) in R (R Core Team 2013). Model fit was evaluated as described above.

Results

LA Results

Catch data
Overall, this data set consisted of 249 valid paired tows. While a suite of non-target species was encountered over the course of the experiment, many were caught in low numbers or in a low number of tow pairs. Given this, we focused on a subset of species. The species included in the analysis were: sea scallops, unclassified skates (winter & little), barndoor skates, summer flounder, fourspot flounder, yellowtail flounder, winter flounder, windowpane flounder and monkfish. Not all species were present in all tow pairs. Individual tows with zero total catch for a given species were uninformative and excluded from the analysis. Table 3a shows the aggregate catch for each species by trip and Table 4a the mean per tow.

From June 24 to June 28, 2013, 69 tow pairs were conducted throughout Georges Bank and parts of Southern New England aboard the F/V *Freedom*. The vessel provided a New Bedford Dredge (NBD) that had a more heavily built bag than the experimental 5R apron bag, which is typical of dredge bag configurations used on rocky bottom. The second LA trip aboard the F/V *Celtic* collected data from 68 tow pairs from July 10 to July 14, 2013. The dredge provided for the comparison by the F/V *Celtic* was a 14-foot TDD with a bag that was of lighter build than the dredge provided by the F/V *Freedom*. Aboard the third designated research trip on the F/V *Diligence* that took place from July 30 to August 3, 2013, a total of 55 valid tow pairs were used for the analysis. The *F/V Diligence* provided a NBD with rock chains and also with a bag of a heavier build than the experimental 5R apron bag. The final LA research trip was done aboard the F/V *Concordia* between September 7 and September 11, 2013 and yielded 57 valid tow pairs. The dredge provided by the F/V *Concordia* was a TDD with a similarly built bag configuration to that of the experimental 5R apron bag. Table 1 details the differences between the bag configurations of the vessel supplied dredges and the experimental 5R apron bag.

Model Results

For some species, there was simply not enough data to provide meaningful results from the model. Most of these cases involved a small number of tow pairs where there were non-zero observations and the model failed to converge. Table 5a shows the best model fit as determined by AIC for the various species in the analysis. Parameter estimates associated with the best model fit are shown in Tables 6a and 7a. Graphical representations of the observed catches (either pooled or unpooled depending upon best model fit) and predicted relative efficiencies derived from the model output are shown in Figures 3-8; only the trip-species combinations where effects were significant are presented.

For the length based model, sea scallops were significant only for the F/V *Freedom* and F/V *Diligence* trips. Length was a significant predictor for barndoor skate and monkfish also on the F/V *Freedom* trips. Figure 3 shows the graphical results for scallops on the two trips as a function of length. Interestingly, the relationship for these two trips with respect to length based relative efficiency for scallops is quite different. On the F/V *Freedom* trips, the estimated curve was logistic-like. This implies that the 5R apron dredge captured significantly fewer small scallops and more large scallops (> 140 mm) than the industry-supplied dredge; while aggregate catches were reduced, the relative proportion of large scallops retained in the 5R apron dredge was greater (Table 4a & 6a). For the F/V *Diligence* trip, the 5R apron dredge caught more scallops for all size classes, with greater efficiency at the smaller end of the size range (Table 6a). For barndoor skate and monkfish on the F/V *Freedom* trip, relative efficiency of the 5R apron dredge increased as a function of increasing fish length (Figure 4), but overall catches of both species were reduced (Table 6a).

Examining the parameter estimates for the pooled output (Table 7a) as well as the graphics depicting the scatter plots of catches and the estimated relative efficiency (Figures 5-8), it is clear that, with the exception of the F/V *Diligence* trip, the 5R apron dredge reduced bycatch overall. This can be seen in the negative parameter estimates for the pooled model as well as the calculation on the probability scale of the relative efficiencies. With respect to species of great interest, the 5R apron bag reduced the bycatch of yellowtail flounder (45%, 41%, 26% and 12%), winter flounder (35%, 61%, 22% and 26%) and windowpane flounder (63%, 45%, 3% and 49%) chronologically over the four cruises, (see Table 7a for trip-specific reductions and significance at the trip level). Catch of other species (*i.e.* fourspot, summer flounder, monkfish, barndoor skates) was more variable, likely due to small sample size; however, catch of these species appeared to be reduced in the 5R apron dredge (Table 7a).

LAGC Results

A total of 69 valid (38 conducted with the 8R-LPD and 31 with the 5R-LPD) alternating tow pairs were used for this portion of the analysis. The size range of scallops caught was similar between dredge frames (Figure 9). For all bycatch species, there were simply not enough data to provide meaningful results from the model; on average, less than one of each species of interest was caught per dredge per tow pair in which they were encountered in at least one of the dredges (Table 4b). The models converged in all cases, but residual plots indicated inadequate fit. Table 5b shows the best model fit as determined by AIC for the various species in the analysis. Parameter estimates associated with the best model fit for bycatch species are shown in Tables

6b and 7b. There was no evidence of difference in catches of bycatch species between the LPD (with either bag design) and the TDD (Table 7b).

Sea scallops were the only species for which the data were best fit by a length-based model that included apron as a fixed effect. The best fitting model included an interaction term between length and apron type, suggesting difference in size selectivity between the two bag configurations (Table 6b). For the LPD with an 8R apron, there was an overall increase in relative scallop catch efficiency (Table 6b), with the LPD catching more small scallops and fewer large scallops than the TDD dredge (Figure 10). There was an overall reduction in relative scallop catch efficiency using the experimental dredge configuration with the 5R apron dredge relative to the control dredge (Table 6b). However, relative catches per size class were similar, and confidence intervals overlapped the equivalency line for all size classes except for shell heights from approximately 100-150 mm (Figure 10), suggesting limited differences in relative catches.

In Situ Videography of Fishing Gear

The use of GoPro® cameras was extremely helpful in gathering information about the influence of gear modifications on the fishing performance of the gear. Cameras were used throughout the testing of a modified LPD frame to inform gear design process. During the 2012 RSA Gear Testing Project, the LPD frame was bent by a collision with a boulder during the final trip. The LPD frame was repaired and then modified in collaboration with East Coast Fabrication and Quinn Fisheries, based on video footage taken during LPD testing. Wear on the dredge shoes indicates the angle at which the head bale was towed and the height of the cutting bar above the seafloor. The ideal height of the cutting bar above the seafloor is around 2 to 3 inches, as observed through video footage of the TDD and commercial dredges, allowing it to contact the seafloor on uneven bottom. When the 2012 LPD frame was lifted on deck to match the shoe wear, it was apparent that the cutting bar was fishing too high off the seafloor, ~5 inches. Based on this information, the LPD frame was reinforced and weight was added to the front of the frame to lower the fishing angle of the head bale at the suggestion of our collaborators (Figure 13).

The modified LPD was tested aboard the F/V *Celtic* during a commercial fishing trip in the Nantucket Lightship Access Area. With high definition video cameras, the modified LPD was filmed and the footage was reviewed at sea to determine if the modifications had the intended effect. Throughout the first half of this trip the modified LPD frame had a 20” depressor plate and scallop catch was lower in the LPD compared to the commercial dredge provided by the F/V *Celtic*. Video footage showed that restricted flow caused by the wide depressor plate may have negatively impacted scallop catch. After the depressor plate was reduced to 10” by removing the extension, the modified LPD frame had equivalent scallop catches compared to the commercial dredge. Video showed that all the modifications tested aboard the F/V *Celtic* during the commercial recording trip had their intended effect. The modified LPD was then tested under standardized conditions on a designated research trip. Preliminary analysis of the data from the second LPD trip suggests that there is minimal loss in scallop catch with the modified LPD frame.

Video footage can also be used to observe general fish behavior in relation to scallop dredges. Figures 11 and 12 show the escape sequences of what appears to be a yellowtail flounder and a silver hake (*Merluccius bilinearis*). These sequences were obtained during the final LA trip aboard the F/V *Concordia*. Video analysis from these trips is ongoing.

Discussion

The ideal scallop dredge modification would unequivocally reduce bycatch of all non-target species while having no effect on catches of harvestable-size scallops. The results of this project were not conclusive, but did suggest that the experimental 5R apron bag reduces flatfish bycatch, sometimes quite substantially. Sea scallop dredges are typically towed at speeds greater than 4 knots (much faster than most towed gear), which increases the probability of catching non-target species due to short response time. Therefore, we focused on a bycatch mitigation method that would release fish after capture, rather than deterring fish before capture. The 5R apron and 1.5:1 twine top bag configuration was developed to facilitate the post-capture escapement of flatfish by extending the twine top and increasing the mesh openings.

In both the LA and LAGC trips, there was generally an observed reduction in bycatch species of interest (Tables 3 & 4). However, the extent of the reduction did vary from trip to trip and was in some cases negligible (Tables 6 & 7). On LA trips, yellowtail flounder catches were reduced by 12-45%, winter flounder by 22-61% and windowpane flounder 3-63%. The trend for reduced bycatch was less distinct for LAGC trips. Although overall catches of most non-target species were reduced, in no case was there evidence of significant difference between experimental and control dredges (Table 7b). For most bycatch species, overall catches in both LA and LAGC trips were too low for statistical inference regarding size selectivity. Even for the pooled catch models, model diagnostics suggested inadequate fit, indicating insufficient sample sizes. Indeed, for most species less than one individual of each non-target species was caught per tow on average (Table 4b). While the overall results of this project suggest that the 5R apron may effectively reduce flatfish bycatch, the relatively small number of vessels and gear variations tested precluded generalization of our conclusions to the entire LA and LAGC fleets. Future studies should seek to increase sample sizes to more reliably estimate differences and provide fleet-wide inference.

Modifications that give fish an opportunity to escape (i.e. more chance to contact the large meshes of the twinetop) can also allow for the escapement of scallops. The reduction of sea scallop catch due to an extended twine top was observed in previous projects (NA12NMF4540041) as well as to varying degrees in this study. While this study demonstrated the efficacy of the 5R apron bag in reducing flatfish bycatch, the relatively small number of vessels and gear variations tested precluded generalization of our conclusions to the entire fleet. Given the variability of the results in terms of both scallop and bycatch species, it is difficult to assess the overall efficacy of this modification with the present data.

Given the variability of the results, it is important to take into consideration how the bag modifications may impact the two federally managed fleets (LA and LAGC) differently. Applying a gear modification to both fleets without adequately addressing their differences may negatively impact one of the fleets. For the LAGC portion of the experiment, scallop length was found to have a significant effect for the LPD with the control bag. The LPD was more efficient at catching smaller scallops with the control bag than the TDD with the control bag. The control bag may be more efficient at retaining smaller scallops because the increase in the twine top surface area caused by the 5R apron combined with the 1.5:1 twine top hanging ratio would increase the mechanical sorting ability of the dredge.

Anecdotal evidence from LAGC fisher Captain Mike Marchetti suggests that scallop catch "maxes out" in the 5R apron bag on the nine-foot dredge faster than the control 8R apron bag. He hypothesizes that instead of the bag filling up to the sweep, like in the control 8R apron bag, the 5R apron bag catch is only filling to the back of the twine top resulting in a loss of scallop catch. Dredge widths observed in the LAGC fishery are typically less than 10 feet and catch loss due to "maxing out" might occur more often in this fishery due to the utilization of smaller dredges. For fish catches length was not found to be significant and there is no evidence of difference in catches by number or length. However, the scope of our inference regarding non-target species is limited by sample size.

Fishers usually adapt their gear to account for changes in catch efficiency due to uncontrollable variables such as weather, bottom type and tide. Since the control gear varied in the LA portion, some of the industry-supplied dredges may have been more efficient at catching scallops than the 5R apron dredge in different weather and tidal conditions. For example, the F/V *Freedom* utilized a heavy control dredge and the trip occurred during strong spring tides, possibly explaining the large difference in scallop catch compared to the other three LA trips. The dredge supplied by the F/V *Freedom* would typically be used for fishing hard, rocky bottom, whereas the bag configurations of the 5R apron dredge would be used to fish on soft to intermediate bottom. The F/V *Freedom*'s control dredge may have been heavy enough to hold bottom during the erratic acceleration and deceleration caused by trying to maintain a tow speed of 4.8 knots in the strong spring tides.

In traditional gear testing experiments, tow parameters are standardized and fail to capture the effect of all variables due to small sample size. A long time series of data would have to be collected over a variety of fishing conditions in order to adequately represent gear performance. This is not always feasible given funding and time restrictions. Though not yet feasible for this use, fleet wide Electronic Vessel Trip Reporting (EVTR) and Electronic Monitoring (EM) could be a means of collecting the data necessary to determine the significance of variables (e.g. weather) to draw fleet-wide inferences about the efficacy of a gear modification.

Video footage collected during this project proved to be invaluable in informing the gear design process. GoPro® cameras were purchased and additional protective housings were built and tested. These cameras are small, easy to use and are relatively inexpensive. Future research will continue to use cameras to provide information about fishing gear performance. In the future, precise video methods might yield quantitative data about fish interactions with scallop dredges, video data from trawls has already yielded quantitative data about fish behavior that can inform conservation engineers (Bubilitz 1996).

Modified gear AMs provide a less severe solution to mitigating excessive bycatch by providing an alternative to retroactive area closures. Time and area closures serve to prevent overfishing, reduce bycatch and minimize degredation of essential fish habitat (EFH). However, retroactive area closures like those triggered by AMs can have negative consequences by preventing the fishery from achieving optimal yield (O'Keefe and DeCelles 2013). Area closures in some cases also displace and consolidate fishing effort, increasing the likelihood of localized overexploitation of fish stocks and a reduction in productivity (Hiddink et al. 2006). Well researched fishing gear regulations and proper marine spatial planning can prevent overfishing and reduce bycatch without impacting the economic sustainability of the fishery (Jennings and Revill 2007). The "reactive" and "proactive" SNE windowpane AMs of Framework Adjustment 25 combine marine spatial planning with gear regulations to create a gear restricted area (GRA). The "reactive" AM establishes a GRA west of 71°W requiring fishers to use a 5 ring apron and 1.5:1 twine top during February and March when SNE/MA windowpane overages less than 20%. The "proactive" AM prohibits fishers from using an apron exceeding 7 rings in the same area. This AM allows fishers to continuing fishing in area while reducing bycatch of windowpane flounder.

CONCLUSIONS

Although the results were variable, there was evidence to suggest that dredges with a modified 5R apron dredge caught less flatfish than other dredge configurations. Future studies investigating the 5R apron and 1.5:1 twine top configuration should increase sample size to draw fleet-wide inference about gear modifications. Escape windows in the side piece will be the focus of the 2014 RSA Gear Testing Project. Continued research will be done to determine the tow efficiency of the LPD and investigate other ways to increase the energy efficiency.

PRESENTATIONS

Davis F., Rudders D., and Smolowitz R. Testing of Bag Design Modification to Reduce Flatfish Bycatch in the Northwest Altantic Sea Scallop Fishery. 19th International Pectinid Workshop. Florianopolis, Santa, Catarina, Brazil. April 10-16, 2013.

Davis F., Rudders D., and Smolowitz R. Potential Gear Modifications for the Reduction of Windowpane Flounder Bycatch in SNE/MA. Sea Scallop PDT Meeting. Boston, Massachusetts. May 22, 2013

Smolowitz R. and Davis F. An Overview of Coonamessett Farm Foundation Scallop RSA Projects. Northeast Fishery Management Council Meeting. Newport, RI. November 13, 2012.

REFERENCES

Bublitz, C.G. 1996. Quantitative evaluation of flatfish behavior during capture by trawl gear. Fish. Res. 25, 293–304.

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

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

Fryer, R.J., A.F. Zuur, and N. Graham. 2003. Using mixed models to combine smooth size-selection and catch-comparison curves over hauls. Can J Fish Aquat Sci 60:448-459.

Hiddink, J. G., Hutton, T., Jennings, S., and Kaiser, M. J. 2006. Predicting the effects of area closures and fishing effort restrictions on the production, biomass, and species richness of benthic invertebrate communities. ICES Journal of Marine Science, 63: 822-830.

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

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

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

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

New England Fishery Management Council (NEFMC). 2011. Framework 23 to the Atlantic Sea Scallop Fishery Management Plan Including an Environmental Assessment. October 2011.

O'Keefe, C. E., S.X. Cadrin, & K.D. Stokesbury. 2013. Evaluating effectiveness of time/area closures, quotas/caps, and fleet communications to reduce fisheries bycatch. ICES Journal of Marine Science: Journal du Conseil.

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

R Core Team. 2013. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/

Smolowitz, R., H. Haas, H.O. Milliken, M. Weeks, and E. Matzen. 2010. Using Sea Turtle Carcasses to Assess the Conservation Potential of a Turtle Excluder Dredge. N. Amer. J. Fish. Manage. 30: 993-100.

Smolowitz, R.J., H.O. Milliken, and M. Weeks. 2012. Design, Evolution, and Assessment of a Sea Turtle Deflector Dredge for the U.S. Northwest Atlantic Sea Scallop Fishery: Impacts on Fish Bycatch. N. Amer. J. Fish. Manage. 32: 65–76.

Wood, S.N. 2006. Generalized additive models: an introduction with R. Chapman and Hall/CRC, Boca Raton, FL.

Wood, S.N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. J. R. Statist. Soc. B 73(1):3-36.

TABLES

Table 1. Gear specifications for dredges used in the Limited Access portion of the study.

Dredge Designation	Experimental Dredge	FV Freedom Dredge	FV Celtic Dredge	FV Diligence Dredge	FV Concordia Dredge
Frame	CFTDD	NBD	TDD	NBD	TDD
Type of Chain for Turtle Mat/Rock Chains	3/8" Grade 70	1/2"	3/8"	1/2"	3/8"
Up and Downs	13	19	11	3 Main, 20 Secondary	13
Tickler Chain	9	9	6	10	9
Type of Chain for Sweep	Long Link Grade 80	5/8" Trawlex	5/8" Trawlex	5/8" Long Link	5/8" Long Link
Number of Links in Sweep	121 long links	137	129	113	121
Chain Sweep Hanging	Dog Chains all around	Shackles	Shackles	Shackles	Shackles on the diamonds and dog chain on the belly
Twine Top	1.5:1 (10.5X45)	2:1 (7.5X60)	2:1 (8X60)	3:1 (8X82)	3:1 (6X82)
Diamonds	14	14	14	14	13
Skirt	2X28 or 2X40	2 links trawlex	2X32	Dog Chain and Shackles	4 links trawlex
Sides	6X18 or 6X20	5X20	6X16	5X20	7X17
Apron	5 X 40	8X40	8X40	7X40	7X36
Bag	10 X 40	9X40	10X40	8X40	9X36
Chaffing Gear	Sewn in three rows down from the sweep for the bag and on the diamonds	Three rows of extra rings below sweep. Sewn in three rows down from the sweep for the bag and on the diamonds	Sewn in three rows down from the sweep for the bag and on the diamonds	Sewn in three rows down from the sweep for the bag and on the diamonds	Sewn in three rows down from the sweep for the bag and on the diamonds
Club Stick	20 link dog chains	20 link dog chains	20 link dog chains	20 link dog chains	20 link dog chains

Table 2. Species List.

Common Name	Scientific Name
Invertebrates	
Sea Scallop	*Placopecten magellanicus*
Fish	
Yellowtail Flounder	*Limanda ferruginea*
Winter Flounder	*Pseudopleuronectes americanus*
Windowpane Flounder	*Scophthalmus aquosus*
Summer Flounder (Fluke)	*Paralichthys dentatus*
Fourspot Flounder	*Paralichthys oblongus*
Monkfish	*Lophius americanus*
Skates	
Barndoor Skates	*Dipturus laevis*
Little Skates	*Leucoraja erinacea*
Winter Skates	*Leucoraja ocellata*

Table 3. Aggregate catch data by trip type and species for (A) Limited Access and (B) Limited Access General Category trips. Percent change is shown relative to the control dredge.

(A)

		Total Catch		
Trip	**Species**	**5R Apron Dredge**	**Control Dredge**	**Percent Change**
F/V *Freedom*	Unclassified Skates	3,152	3,764	-16.26
F/V *Freedom*	Barndoor Skate	112	157	-28.66
F/V *Freedom*	Summer Flounder	15	14	7.14
F/V *Freedom*	Fourspot Flounder	66	120	-45.00
F/V *Freedom*	Yellowtail Flounder	84	150	-44.00
F/V *Freedom*	Winter Flounder	30	45	-33.33
F/V *Freedom*	Windowpane Flounder	60	159	-62.26
F/V *Freedom*	Monkfish	176	207	-14.98
F/V *Freedom*	Sea Scallop (bu)	279.23	362.35	-22.94
F/V *Celtic*	Unclassified Skates	8,878	10,497	-15.42
F/V *Celtic*	Barndoor Skate	75	66	13.64
F/V *Celtic*	Summer Flounder	4	8	-50.00
F/V *Celtic*	Fourspot Flounder	91	77	18.18
F/V *Celtic*	Yellowtail Flounder	236	379	-37.73
F/V *Celtic*	Winter Flounder	27	64	-57.81
F/V *Celtic*	Windowpane Flounder	40	69	-42.03
F/V *Celtic*	Monkfish	367	312	17.63
F/V *Celtic*	Sea Scallop (bu)	308.2	287.45	7.22
F/V *Diligence*	Unclassified Skates	3,384	2,854	18.57
F/V *Diligence*	Barndoor Skate	185	122	51.64
F/V *Diligence*	Summer Flounder	0	1	-100.00
F/V *Diligence*	Fourspot Flounder	19	22	-13.64

F/V *Diligence*	Yellowtail Flounder	306	403	-24.07
F/V *Diligence*	Winter Flounder	55	72	-23.61
F/V *Diligence*	Windowpane Flounder	12	13	-7.69
F/V *Diligence*	Monkfish	380	312	21.79
F/V *Diligence*	Sea Scallop	129.8	102	27.25
F/V *Concordia*	Unclassified Skates	4,271	4,567	-6.48
F/V *Concordia*	Barndoor Skate	156	130	20.05
F/V *Concordia*	Summer Flounder	55	80	-31.25
F/V *Concordia*	Fourspot Flounder	43	52	-17.31
F/V *Concordia*	Yellowtail Flounder	470	534	-11.96
F/V *Concordia*	Winter Flounder	66	91	-27.07
F/V *Concordia*	Windowpane Flounder	91	161	-43.48
F/V *Concordia*	Monkfish	194	175	10.70
F/V *Concordia*	Sea Scallop	192.16	193.61	-0.75

(B)

		Total Catch		
Trip	**Species**	**Low profile dredge**	**Turtle deflector dredge**	**Percent Change**
8R apron	Barndoor Skate	2	5	-60.00
8R apron	Summer Flounder	48	53	-9.43
8R apron	Fourspot Flounder	22	35	-37.14
8R apron	Yellowtail Flounder	36	45	-20.00
8R apron	Winter Flounder	12	12	0.00
8R apron	Windowpane Flounder	88	128	-31.25
8R apron	Monkfish	87	94	-7.45
8R apron	Sea Scallop (bu)	192	187	2.67
5R apron	Barndoor Skate	5	9	-44.44
5R apron	Summer Flounder	8	22	-63.64

5R apron	Fourspot Flounder	1	7	-85.71
5R apron	Yellowtail Flounder	20	24	-16.67
5R apron	Winter Flounder	4	1	300.00
5R apron	Windowpane Flounder	25	19	31.58
5R apron	Monkfish	24	24	0.00
5R apron	Sea Scallop (bu)	109	136	-19.85

Table 4. Mean and standard deviation of barndoor skate, winter, monkfish, windowpane and yellowtail flounder (in numbers) and sea scallop catch (in bushels) for (A) Limited Access and (B) Limited Access General Category trips.

(A)

F/V Freedom

DREDGE	BARNDOOR SKATE	WINTER FLOUNDER	MONKFISH	WINDOWPANE FLOUNDER	YELLOWTAIL FLOUNDER	SEA SCALLOP
5R Apron	1.62 (2.93)	0.43 (0.83)	2.55 (3.14)	0.87 (1.42)	1.22 (1.85)	4.05 (3.32)
Commercial Dredge	2.28 (4.49)	0.65 (0.92)	3.00 (3.29)	2.30 (2.84)	2.17 (2.56)	5.25 (4.52)
Difference	-0.65	-0.22	-0.45	-1.43	-0.96	-1.20
% Difference	-28.66%	-33.33%	-14.98%	-62.26%	-44.00%	-22.93%

F/V Celtic

DREDGE	BARNDOOR SKATE	WINTER FLOUNDER	MONKFISH	WINDOWPANE FLOUNDER	YELLOWTAIL FLOUNDER	SEA SCALLOP
5R Apron	1.12 (1.27)	0.39 (0.75)	5.43 (3.91)	0.59 (1.05)	3.49 (3.51)	4.53 (3.64)
Commercial Dredge	0.99 (1.19)	0.93 (1.17)	4.64 (2.79)	1.01 (1.54)	5.51 (5.47)	4.23 (3.19)
Difference	0.13	-0.54	0.80	-0.42	-2.01	0.31
% Difference	13.24%	-57.81%	17.19%	-41.43%	-36.58%	7.22%

F/V Diligence

DREDGE	BARNDOOR SKATE	WINTER FLOUNDER	MONKFISH	WINDOWPANE FLOUNDER	YELLOWTAIL FLOUNDER	SEA SCALLOP
5R Apron	2.87 (3.15)	0.99 (1.49)	6.14 (4.38)	0.22 (0.51)	6.75 (7.97)	2.36 (1.17)
Commercial Dredge	1.99 (2.34)	1.48 (2.08)	5.17 (3.61)	0.26 (0.83)	8.67 (8.83)	1.86 (0.91)
Difference	0.88	-0.49	0.97	-0.04	-1.91	0.51
% Difference	44.53%	-33.33%	18.77%	-16.67%	-22.07%	27.22%

F/V Concordia

DREDGE	BARNDOOR SKATE	WINTER FLOUNDER	MONKFISH	WINDOWPANE FLOUNDER	YELLOWTAIL FLOUNDER	SEA SCALLOP
5R Apron	2.67 (4.11)	1.11 (1.65)	3.33 (2.38)	1.60 (5.91)	7.91 (9.68)	3.43 (1.87)
Commercial Dredge	1.90 (2.88)	1.38 (1.95)	2.67 (2.06)	2.62 (8.07)	7.22 (9.73)	3.46 (1.82)
Difference	0.77	-0.27	0.67	-1.03	0.69	-0.03
% Difference	40.46%	-19.72%	25.00%	-39.14%	9.63%	-0.75%

(B)

LPD

DREDGE	BARNDOOR SKATE	WINTER FLOUNDER	MONKFISH	WINDOWPANE FLOUNDER	YELLOWTAIL FLOUNDER	SEA SCALLOP
8R Apron	0.05 (0.23)	0.32 (0.53)	2.29 (3.06)	2.32 (2.34)	0.95 (1.18)	5.05 (1.85)
CFTDD	0.13 (0.41)	0.32 (0.57)	2.47 (4.03)	3.37 (3.56)	1.18 (1.87)	4.93 (1.66)
Difference	-0.08	0.00	-0.18	-1.05	-0.24	0.12
% Difference	-61.54%	0.00%	-7.45%	-31.25%	-20.00%	2.43%

LPD

DREDGE	BARNDOOR SKATE	WINTER FLOUNDER	MONKFISH	WINDOWPANE FLOUNDER	YELLOWTAIL FLOUNDER	SEA SCALLOP
5R Apron	0.16 (0.37)	0.13 (0.34)	0.77 (1.09)	0.81 (1.42)	0.65 (0.77)	3.52 (1.22)
CFTDD	0.29 (0.59)	0.03 (0.18)	0.77 (0.96)	0.61 (0.84)	1.05 (1.12)	4.38 (0.95)
Difference	-0.13	0.10	0.00	0.19	-0.13	-0.86
% Difference	-44.44%	300.00%	0.00%	31.58%	-16.67%	-19.63%

Table 5. Model building results for (A) Limited Access and (B) Limited Access General Category trips for each species examined in the analysis. Fixed effects included in the model indicate the specification that resulted in the lowest AIC value for that particular species; * indicates an interaction term. Random effects are shown in brackets and were included at the tow level. Species where the model failed to converge are indicated. Note that while the best fitting model for bycatch species for the LAGC is presented below, in all cases the intercept was not significant, suggesting no evidence of difference in relative catch between experimental and control dredges.

(A)

Vessel	Date	Species	Model Specification
F/V *Freedom*	June, 2013	Sea Scallops	RE_{5R} ~ intercept + length + [tow]
F/V *Freedom*	June, 2013	Unclassified Skates	RE_{5R} ~ intercept +[tow]
F/V *Freedom*	June, 2013	Barndoor Skates	RE_{5R} ~ intercept + length + [tow]
F/V *Freedom*	June, 2013	Summer Flounder	RE_{5R} ~ intercept +[tow]
F/V *Freedom*	June, 2013	Fourspot Flounder	RE_{5R} ~ intercept +[tow]
F/V *Freedom*	June, 2013	Yellowtail Flounder	RE_{5R} ~ intercept +[tow]
F/V *Freedom*	June, 2013	Winter Flounder	RE_{5R} ~ intercept +[tow]
F/V *Freedom*	June, 2013	Windowpane Flounder	RE_{5R} ~ intercept +[tow]
F/V *Freedom*	June, 2013	Monkfish	RE_{5R} ~ intercept + length + [tow]
F/V *Celtic*	July, 2013	Sea Scallops	RE_{5R} ~ intercept +[tow]
F/V *Celtic*	July, 2013	Unclassified Skates	RE_{5R} ~ intercept +[tow]
F/V *Celtic*	July, 2013	Barndoor Skates	RE_{5R} ~ intercept +[tow]
F/V *Celtic*	July, 2013	Summer Flounder	Did not converge
F/V *Celtic*	July, 2013	Fourspot Flounder	Did not converge
F/V *Celtic*	July, 2013	Yellowtail Flounder	RE_{5R} ~ intercept +[tow]
F/V *Celtic*	July, 2013	Winter Flounder	RE_{5R} ~ intercept +[tow]
F/V *Celtic*	July, 2013	Windowpane Flounder	RE_{5R} ~ intercept +[tow]
F/V *Celtic*	July, 2013	Monkfish	RE_{5R} ~ intercept +[tow]
F/V *Diligence*	July, 2013	Sea Scallops	RE_{5R} ~ intercept + length + [tow]
F/V *Diligence*	July, 2013	Unclassified Skates	RE_{5R} ~ intercept +[tow]
F/V *Diligence*	July, 2013	Barndoor Skates	Did not converge
F/V *Diligence*	July, 2013	Summer Flounder	RE_{5R} ~ intercept +[tow]
F/V *Diligence*	July, 2013	Fourspot Flounder	RE_{5R} ~ intercept +[tow]
F/V *Diligence*	July, 2013	Yellowtail Flounder	RE_{5R} ~ intercept +[tow]
F/V *Diligence*	July, 2013	Winter Flounder	RE_{5R} ~ intercept +[tow]
F/V *Diligence*	July, 2013	Windowpane Flounder	RE_{5R} ~ intercept +[tow]
F/V *Diligence*	July, 2013	Monkfish	RE_{5R} ~ intercept +[tow]
F/V *Concordia*	Sept., 2013	Sea Scallops	RE_{5R} ~ intercept +[tow]
F/V *Concordia*	Sept., 2013	Unclassified Skates	RE_{5R} ~ intercept +[tow]
F/V *Concordia*	Sept., 2013	Barndoor Skates	Did not converge
F/V *Concordia*	Sept., 2013	Summer Flounder	Did not converge
F/V *Concordia*	Sept., 2013	Fourspot Flounder	Did not converge

F/V *Concordia*	Sept., 2013	Yellowtail Flounder	RE_{5R} ~ intercept +[tow]
F/V *Concordia*	Sept., 2013	Winter Flounder	RE_{5R} ~ intercept +[tow]
F/V *Concordia*	Sept., 2013	Windowpane Flounder	RE_{5R} ~ intercept +[tow]
F/V *Concordia*	Sept., 2013	Monkfish	RE_{5R} ~ intercept +[tow]

(B)

Species	**Model Specification**
Barndoor Skate	RE_{5R} ~ intercept + [tow]
Monkfish	RE_{5R} ~ intercept +[tow]
Summer Flounder	RE_{5R} ~ intercept +[tow]
Yellowtail Flounder	RE_{5R} ~ intercept +[tow]
Winter Flounder	RE_{5R} ~ intercept +[tow]
Windowpane Flounder	RE_{5R} ~ intercept +[tow]
Fourspot Flounder	RE_{5R} ~ intercept +[tow]
Sea Scallops	RE_{5R} ~ intercept + length*bag + [tow]

Table 6 Mixed effects model for sea scallop catch using the unpooled catch data for (A) Limited Access and (B) Limited Access General Category trips. Results are for from the model that provided the best fit (intercept, length and apron) 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.

(A)

Cruise	Species	Effect	Estimate	SE	t-value	p-value	LCI	UCI
F/V *Freedom*	Barndoor Skate	Intercept	-1.398	0.434	-3.221	0.001	-2.254	-0.543
		Length	0.023	0.008	2.861	0.005	0.007	0.039
F/V *Freedom*	Monkfish	Intercept	-1.365	0.570	-2.393	0.017	-2.487	-0.243
		Length	0.025	0.012	2.141	0.033	0.002	0.048
F/V *Freedom*	Sea Scallop	Intercept	-4.626	0.200	-23.100	<0.001	-5.019	-4.233
		Length	0.034	0.001	22.937	<0.001	0.031	0.037
F/V Diligence	Sea Scallop	Intercept	0.843	0.208	4.053	<0.001	0.435	1.251
		Length	-0.004	0.001	-2.643	0.008	-0.007	-0.001

(B)

Species	Effect	Apron	Estimate	SE	z-value	p-value	LCI	UCI
Sea Scallop	Intercept		0.881	0.242	3.633	<0.001	0.407	1.355
	Length		-0.007	0.002	-3.765	<0.001	-0.011	-0.003
	Length*Apron		0.007	0.003	2.573	0.01	0.001	0.013
	Apron	5R	-1.042	0.339	-3.072	0.002	-1.706	-0.378

Table 7. Mixed effects model using the pooled catch data for (A) Limited Access and (B) Limited Access General Category trips. Results are for 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 and the exp(Est) is the estimated relative efficiency on the probability scale. Percent change represents the average percentage change in the catch of the 5R apron dredge relative to the industry/control dredge as predicted by the model. Significant values are indicated in bold.

(A)

Trip	Species	Effect	Estimate	SE	t-value	p-value	LCI	UCI	Exp(Est)	% Change
F/V *Freedom*	**Unclassified Skates**	**Intercept**	**-0.276**	**0.061**	**-4.541**	**0.000**	**-0.398**	**-0.155**	**0.759**	**-24.14**
F/V *Freedom*	Summer Flounder	Intercept	0.072	0.389	0.186	0.855	-0.767	0.912	1.075	7.49
F/V *Freedom*	**Fourspot Flounder**	**Intercept**	**-0.598**	**0.169**	**-3.530**	**0.001**	**-0.937**	**-0.259**	**0.550**	**-45.01**
F/V *Freedom*	**Yellowtail Flounder**	**Intercept**	**-0.608**	**0.155**	**-3.916**	**<0.001**	**-0.921**	**-0.296**	**0.544**	**-45.58**
F/V *Freedom*	Winter Flounder	Intercept	-0.444	0.266	-1.670	0.103	-0.983	0.094	0.641	-35.88
F/V *Freedom*	**Windowpane Flounder**	**Intercept**	**-1.003**	**0.178**	**-5.649**	**<0.001**	**-1.361**	**-0.646**	**0.367**	**-63.34**
F/V *Celtic*	**Unclassified Skates**	**Intercept**	**-0.271**	**0.037**	**-7.237**	**<0.001**	**-0.346**	**-0.196**	**0.763**	**-23.75**
F/V *Celtic*	Barndoor Skate	Intercept	0.059	0.184	0.319	0.751	-0.310	0.427	1.060	6.03
F/V *Celtic*	Summer Flounder	Intercept	-0.762	0.612	-1.245	0.242	-2.127	0.602	0.467	-53.33
F/V *Celtic*	Fourspot Flounder	Intercept	0.098	0.155	0.633	0.529	-0.213	0.409	1.103	10.30
F/V *Celtic*	**Yellowtail Flounder**	**Intercept**	**-0.542**	**0.116**	**-4.690**	**<0.001**	**-0.773**	**-0.311**	**0.582**	**-41.84**
F/V *Celtic*	**Winter Flounder**	**Intercept**	**-0.946**	**0.245**	**-3.856**	**<0.001**	**-1.442**	**-0.450**	**0.388**	**-61.17**
F/V *Celtic*	**Windowpane Flounder**	**Intercept**	**-0.614**	**0.200**	**-3.077**	**0.004**	**-1.017**	**-0.212**	**0.541**	**-45.91**
F/V *Celtic*	Monkfish	Intercept	0.072	0.093	0.773	0.443	-0.114	0.258	1.075	7.45
F/V *Celtic*	**Sea Scallop**	**Intercept**	**-0.157**	**0.045**	**-3.465**	**0.001**	**-0.248**	**-0.067**	**0.854**	**-14.55**
F/V *Diligence*	**Unclassified Skates**	**Intercept**	**0.158**	**0.038**	**4.193**	**<0.001**	**0.082**	**0.233**	**1.171**	**17.09**
F/V *Diligence*	**Barndoor Skate**	**Intercept**	**0.416**	**0.117**	**3.570**	**0.001**	**0.182**	**0.651**	**1.516**	**51.64**
F/V *Diligence*	Fourspot Flounder	Intercept	-0.145	0.338	-0.427	0.673	-0.839	0.550	0.865	-13.46
F/V *Diligence*	**Yellowtail Flounder**	**Intercept**	**-0.303**	**0.094**	**-3.238**	**0.002**	**-0.491**	**-0.115**	**0.738**	**-26.15**
F/V *Diligence*	Winter Flounder	Intercept	-0.250	0.207	-1.208	0.238	-0.675	0.175	0.779	-22.11
F/V *Diligence*	Windowpane Flounder	Intercept	-0.027	0.436	-0.062	0.952	-0.977	0.923	0.973	-2.65
F/V *Diligence*	**Monkfish**	**Intercept**	**0.197**	**0.077**	**2.545**	**0.014**	**0.042**	**0.352**	**1.218**	**21.77**

F/V *Concordia*	**Unclassified Skates**	**Intercept**	**-0.077**	**0.038**	**-2.007**	**0.049**	**-0.154**	**0.000**	**0.926**	**-7.41**
F/V *Concordia*	Barndoor Skate	Intercept	0.179	0.120	1.491	0.143	-0.063	0.420	1.196	19.59
F/V *Concordia*	**Summer Flounder**	**Intercept**	**-0.375**	**0.175**	**-2.139**	**0.038**	**-0.728**	**-0.022**	**0.688**	**-31.25**
F/V *Concordia*	Fourspot Flounder	Intercept	-0.190	0.206	-0.922	0.362	-0.606	0.226	0.827	-17.31
F/V *Concordia*	Yellowtail Flounder	Intercept	-0.132	0.073	-1.814	0.076	-0.279	0.015	0.876	-12.39
F/V *Concordia*	Winter Flounder	Intercept	-0.307	0.163	-1.889	0.066	-0.635	0.021	0.736	-26.43
F/V *Concordia*	**Windowpane Flounder**	**Intercept**	**-0.681**	**0.191**	**-3.563**	**0.002**	**-1.078**	**-0.284**	**0.506**	**-49.39**
F/V *Concordia*	Monkfish	Intercept	0.104	0.108	0.966	0.338	-0.112	0.321	1.110	10.98
F/V *Concordia*	Sea Scallop	Intercept	-0.055	0.034	-1.611	0.113	-0.124	0.014	0.946	-5.38

(B)

Species	Effect	Estimate	SE	z-value	p-value	LCI	UCI	Exp(Est)	% Change
Barndoor Skate	Intercept	-0.392	0.212	-1.848	0.065	-0.818	0.024	0.676	-32.43
Yellowtail Flounder	Intercept	-0.168	0.222	-0.757	0.449	-0.603	0.267	0.845	-15.46
Windowpane Flounder	Intercept	-0.239	0.154	-1.557	0.119	-0.541	0.063	0.787	-21.26
Winter Flounder	Intercept	0.208	0.374	0.556	0.578	-0.525	0.941	1.231	23.12
Fourspot Flounder	Intercept	-0.516	0.450	-1.146	0.252	-1.398	0.366	0.597	-40.31
Monkfish	Intercept	-0.012	0.178	-0.068	0.945	-0.361	0.337	0.988	-1.19

FIGURES

Figure 1. Map of Limited Access tows made aboard the F/V *Freedom* (blue), F/V *Celtic* (red), F/V *Diligence* (green), and F/V *Concordia* (grey).

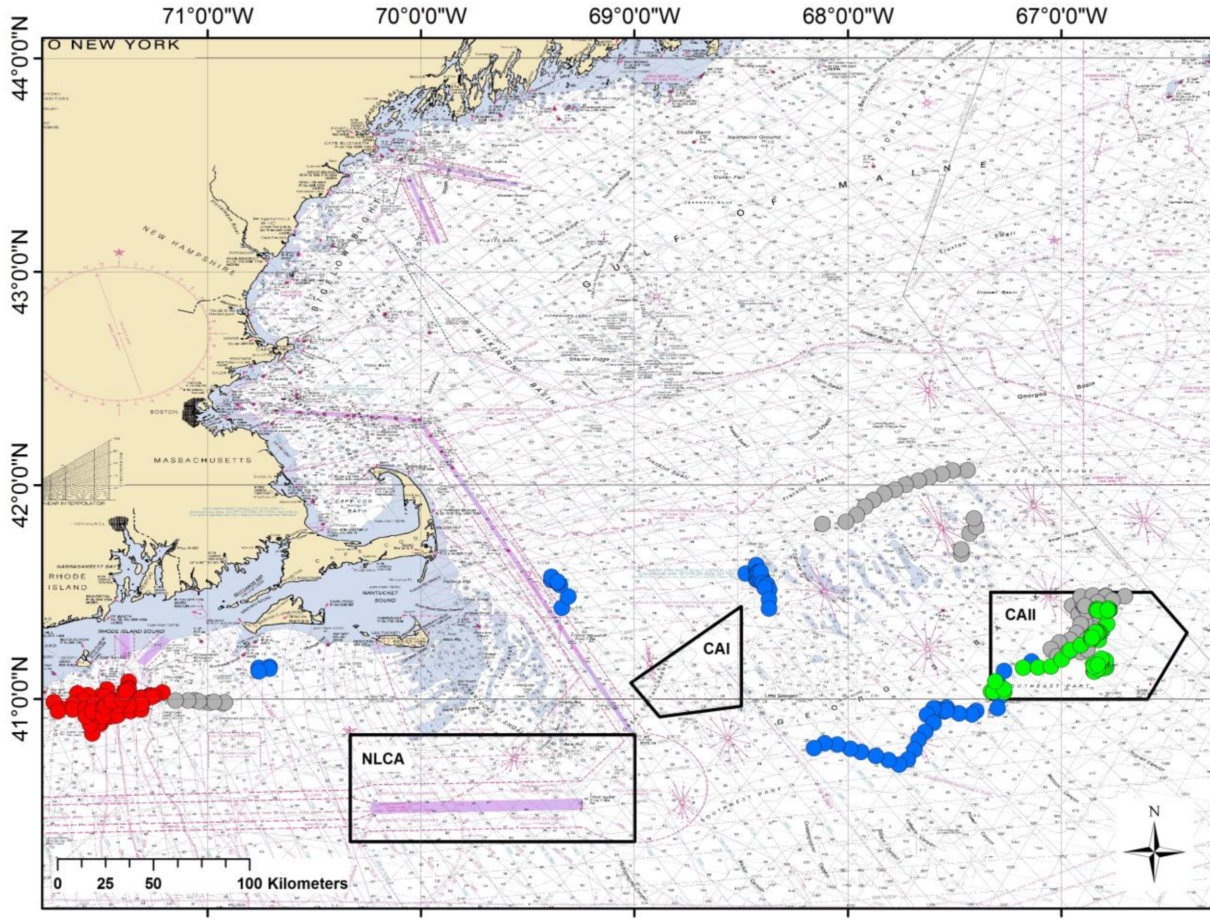


Figure 2. Map of Limited Access General Category tow locations (black).

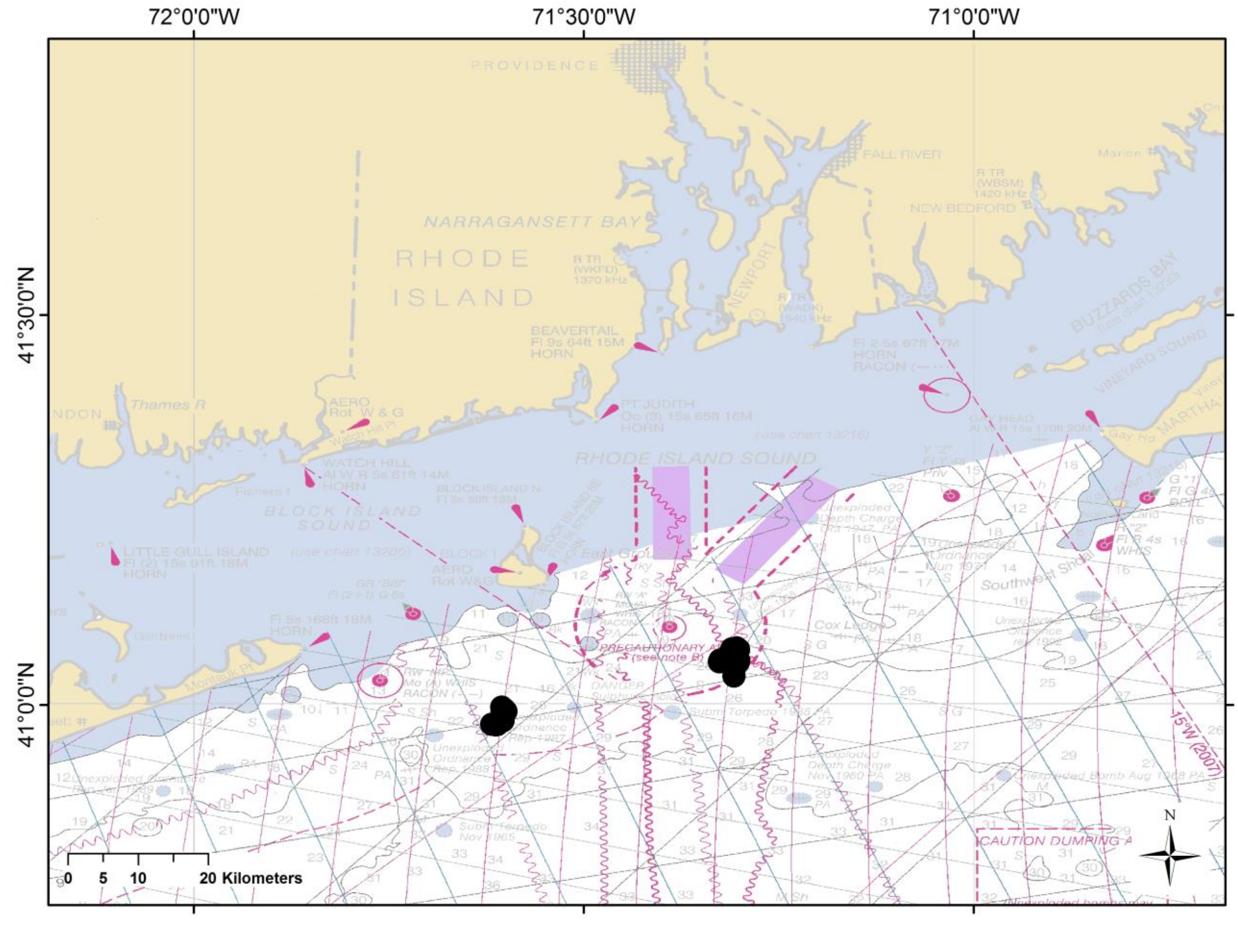
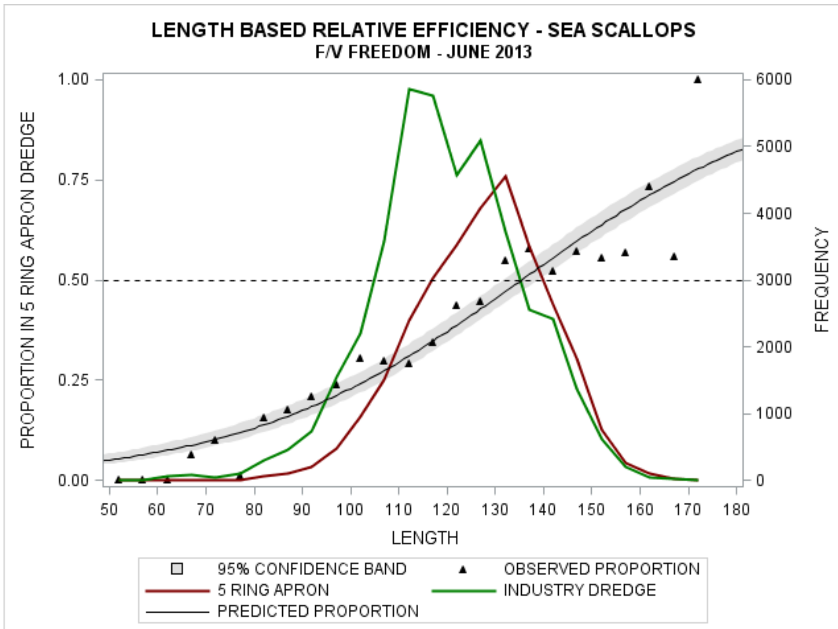


Figure 3. Relative Sea Scallop catch by the two dredge configurations on cruises where length was a significant predictor of relative efficiency. The triangles represent the observed proportion at length ($Catch_{5R}/(Catch_{5R} + Catch_{I})$), with a proportion >0.5 representing more animals at length captured by the 5R apron dredge. The grey area represents the 95% confidence band for the modeled proportion (solid black line).



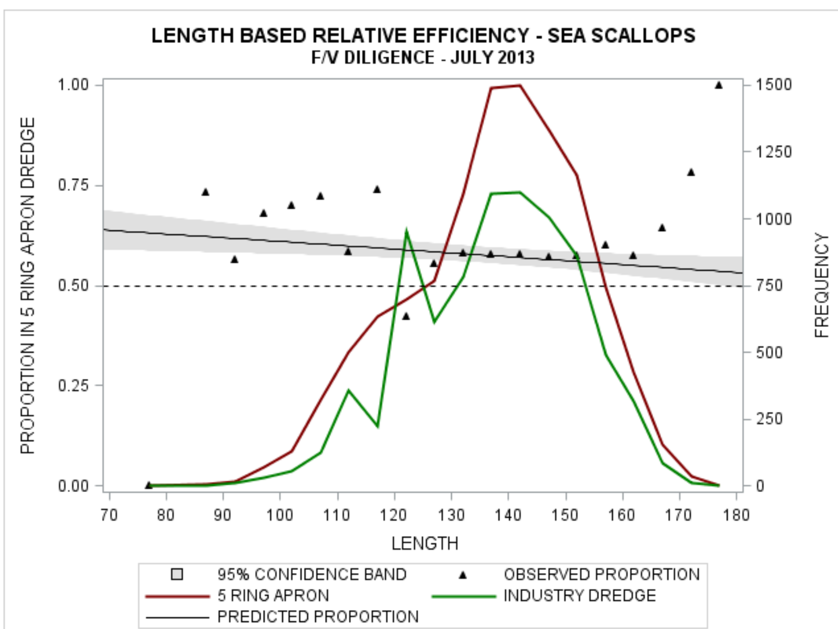
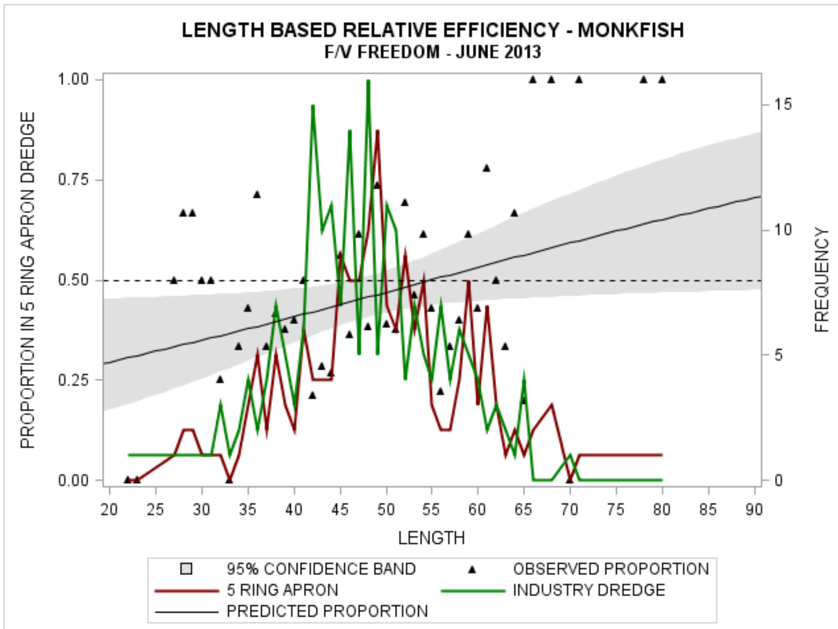


Figure 4. Relative finfish catch by the two dredge configurations on cruises and for species where length was a significant predictor of relative efficiency. The triangles represent the observed proportion at length ($Catch_{5R}/(Catch_{5R} + Catch_{I})$), with a proportion >0.5 representing more animals at length captured by the 5R apron dredge. The grey area represents the 95% confidence band for the modeled proportion (solid black line).



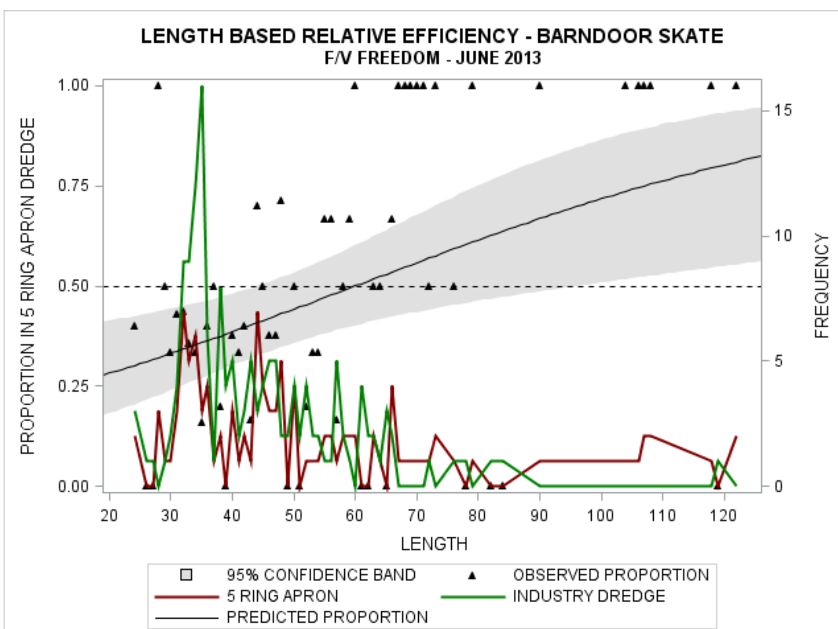
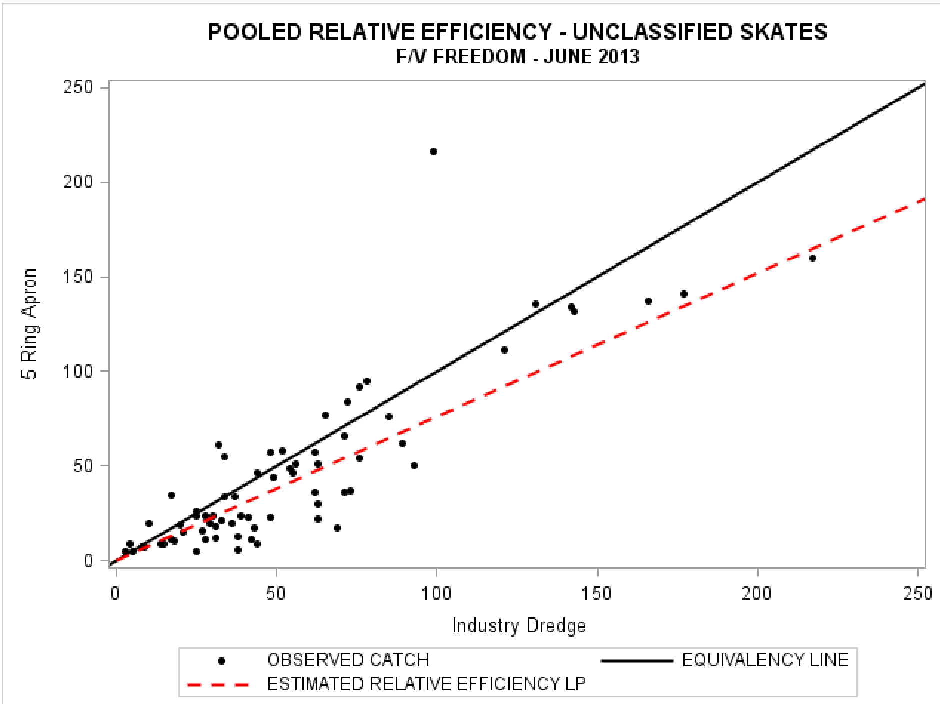
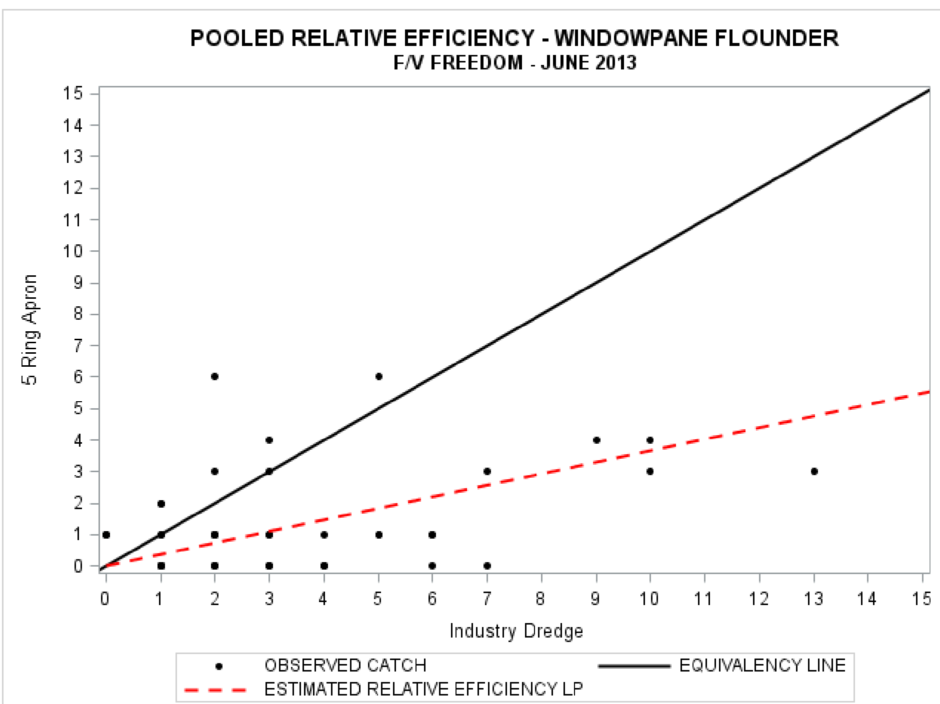
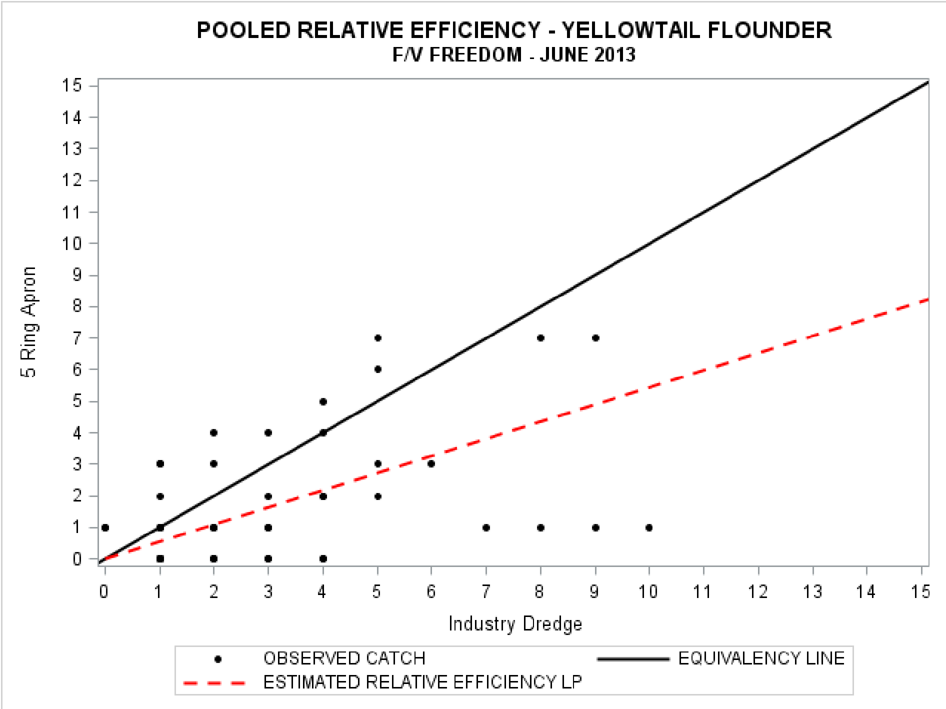


Figure 5. Results from the F/V *Freedom* cruise where model output from the analysis of the pooled data indicated that the intercept only model was the most appropriate specification. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one.






POOLED RELATIVE EFFICIENCY - YELLOWTAIL FLOUNDER
F/V FREEDOM - JUNE 2013
5 Ring Apron
Industry Dredge
OBSERVED CATCH
EQUIVALENCY LINE
ESTIMATED RELATIVE EFFICIENCY LP

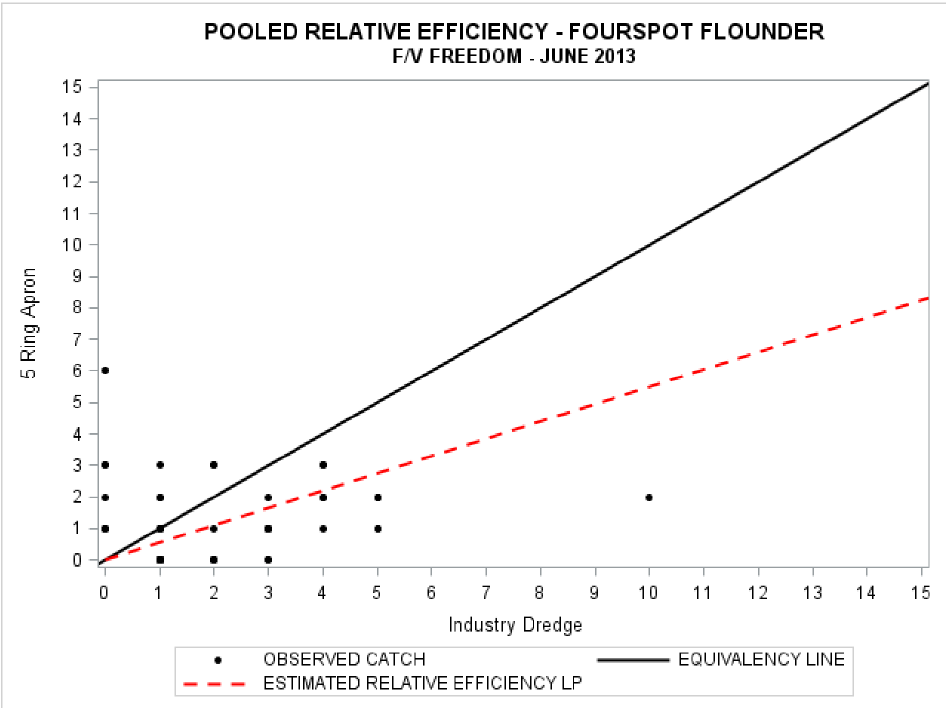
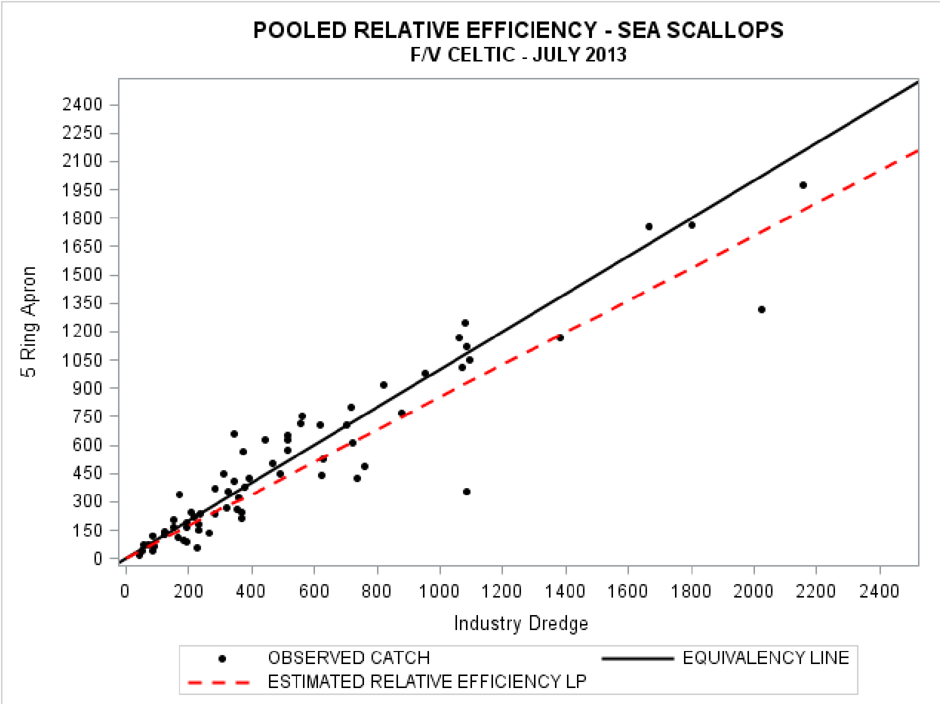
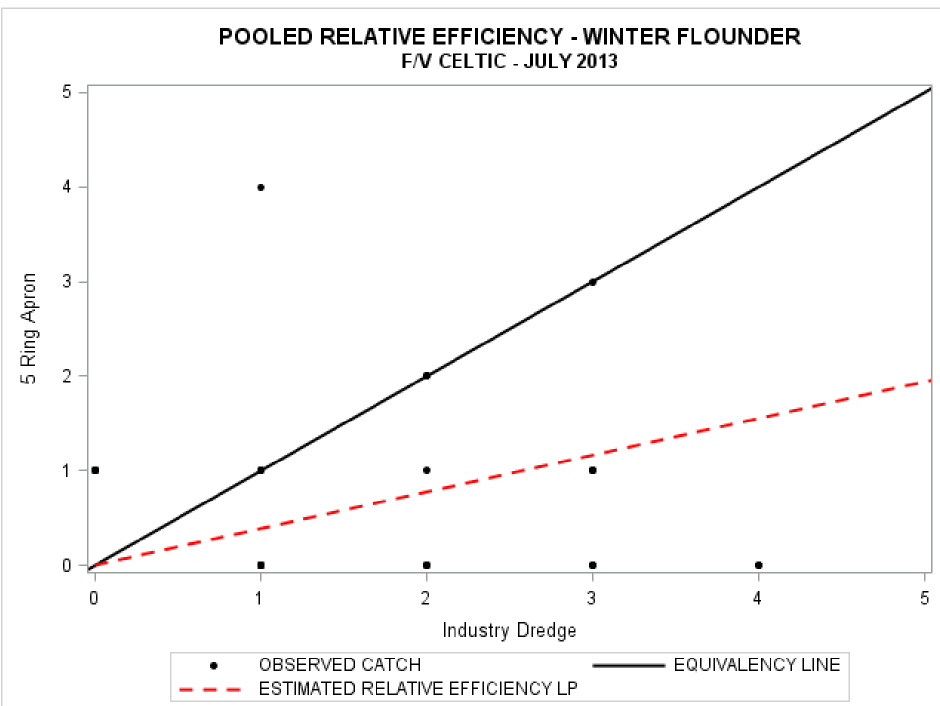
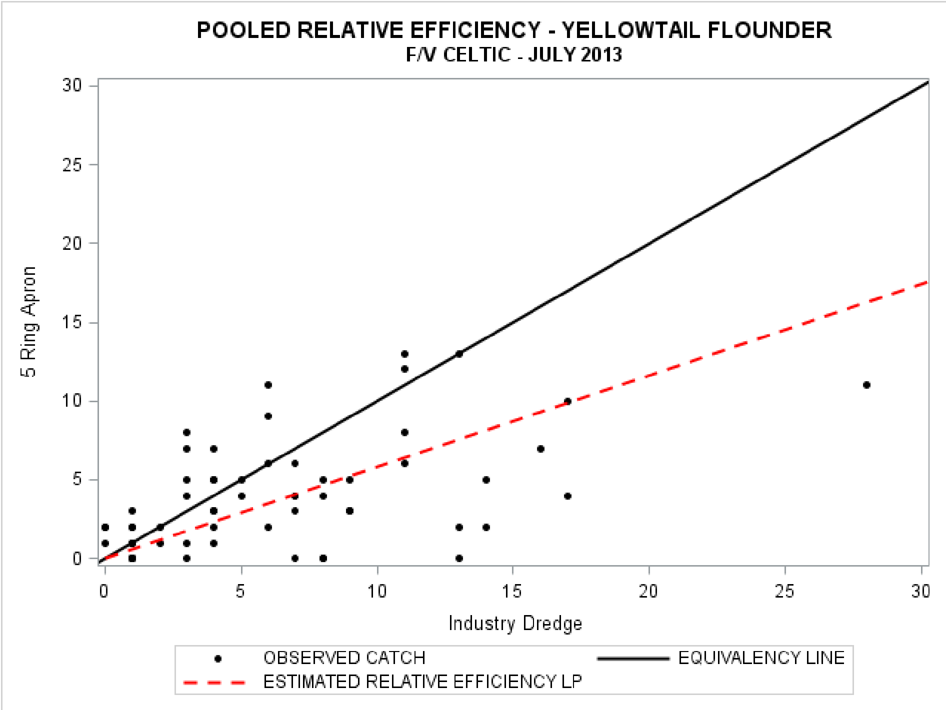
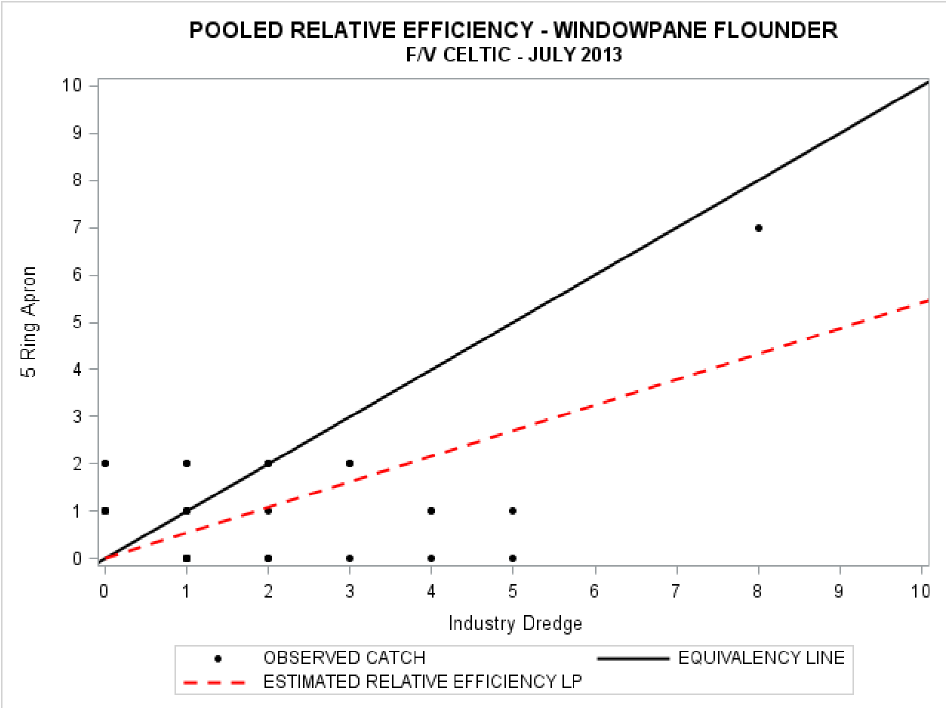

POOLED RELATIVE EFFICIENCY - FOURSPOT FLOUNDER
F/V FREEDOM - JUNE 2013
5 Ring Apron
Industry Dredge
OBSERVED CATCH
EQUIVALENCY LINE
ESTIMATED RELATIVE EFFICIENCY LP

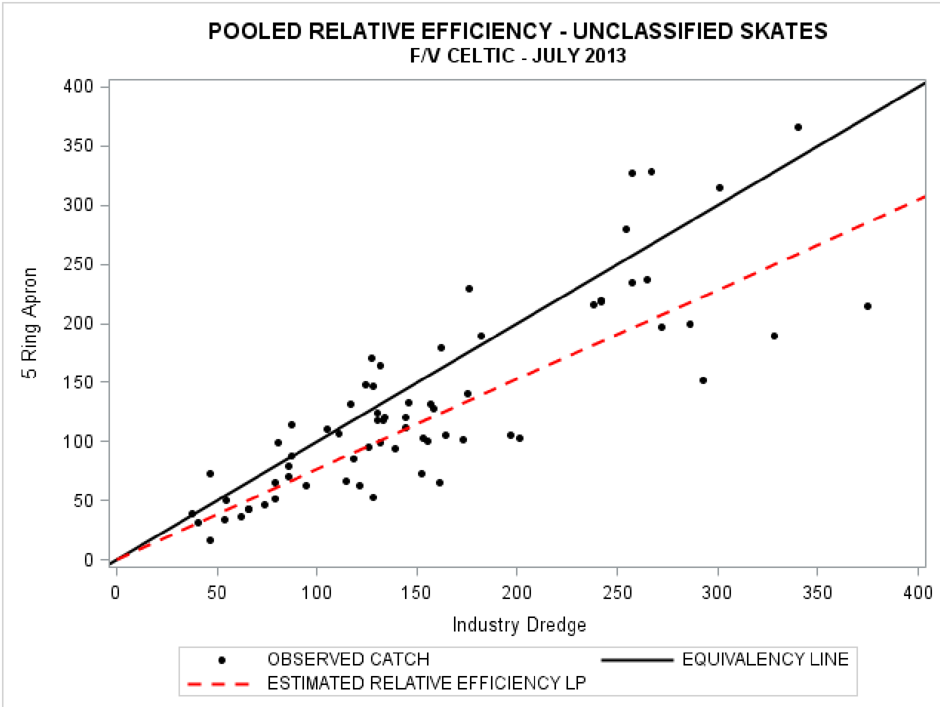
Figure 6. Results from the F/V *Celtic* cruise where model output from the analysis of the pooled data indicated that the intercept only model was the most appropriate specification. The estimated relative efficiency is show as the red dashed line. The black line has a slope of one.



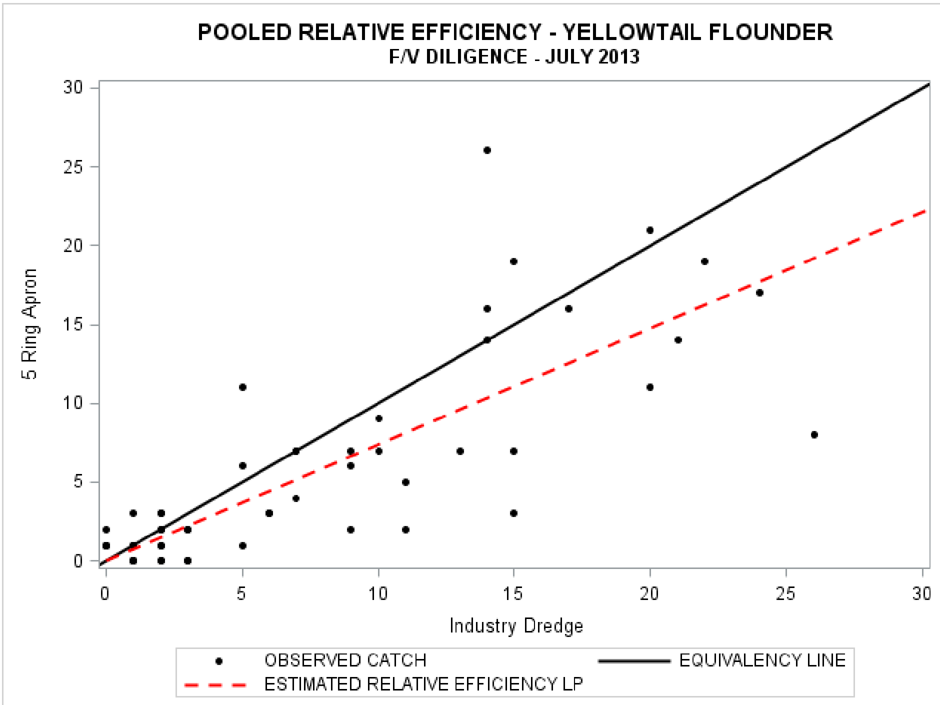


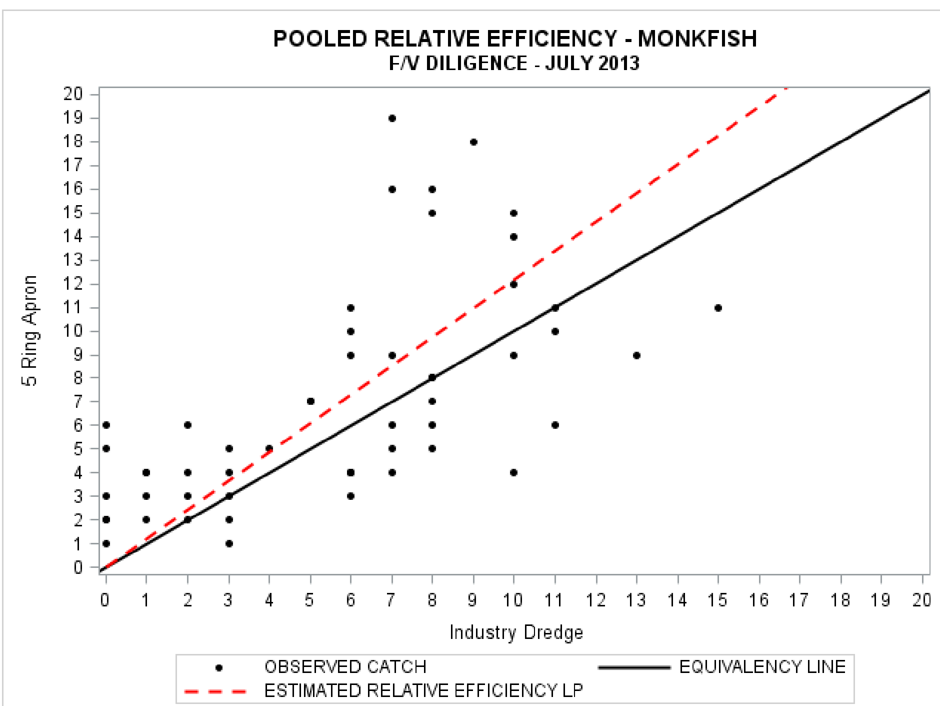

POOLED RELATIVE EFFICIENCY - YELLOWTAIL FLOUNDER
F/V CELTIC - JULY 2013
5 Ring Apron
Industry Dredge
OBSERVED CATCH
EQUIVALENCY LINE
ESTIMATED RELATIVE EFFICIENCY LP

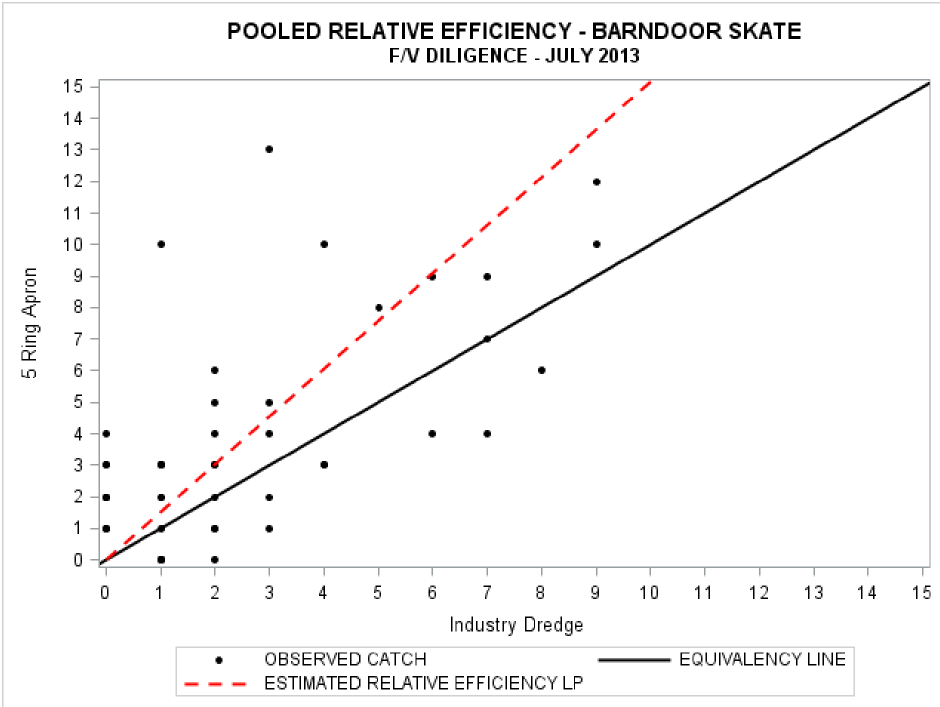

POOLED RELATIVE EFFICIENCY - WINDOWPANE FLOUNDER
F/V CELTIC - JULY 2013
5 Ring Apron
Industry Dredge
OBSERVED CATCH
EQUIVALENCY LINE
ESTIMATED RELATIVE EFFICIENCY LP


POOLED RELATIVE EFFICIENCY - UNCLASSIFIED SKATES
F/V CELTIC - JULY 2013
5 Ring Apron
Industry Dredge
0
50
100
150
200
250
300
350
400
OBSERVED CATCH
EQUIVALENCY LINE
ESTIMATED RELATIVE EFFICIENCY LP

<u>Figure 7.</u> Results from the F/V *Diligence* cruise where 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.






POOLED RELATIVE EFFICIENCY - BARNDOOR SKATE
F/V DILIGENCE - JULY 2013
5 Ring Apron
Industry Dredge
OBSERVED CATCH
EQUIVALENCY LINE
ESTIMATED RELATIVE EFFICIENCY LP

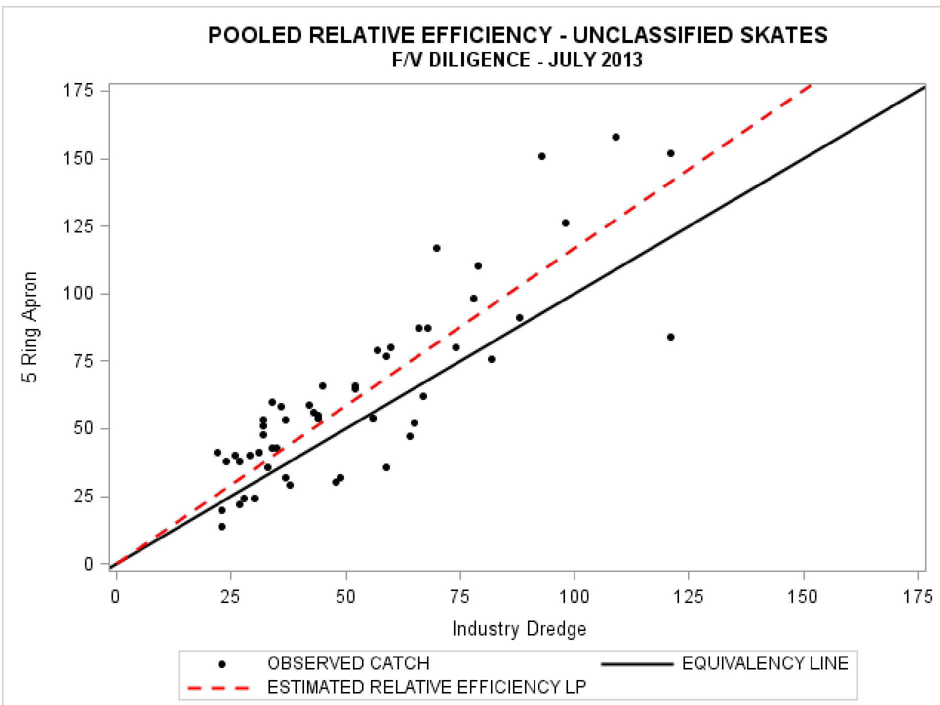
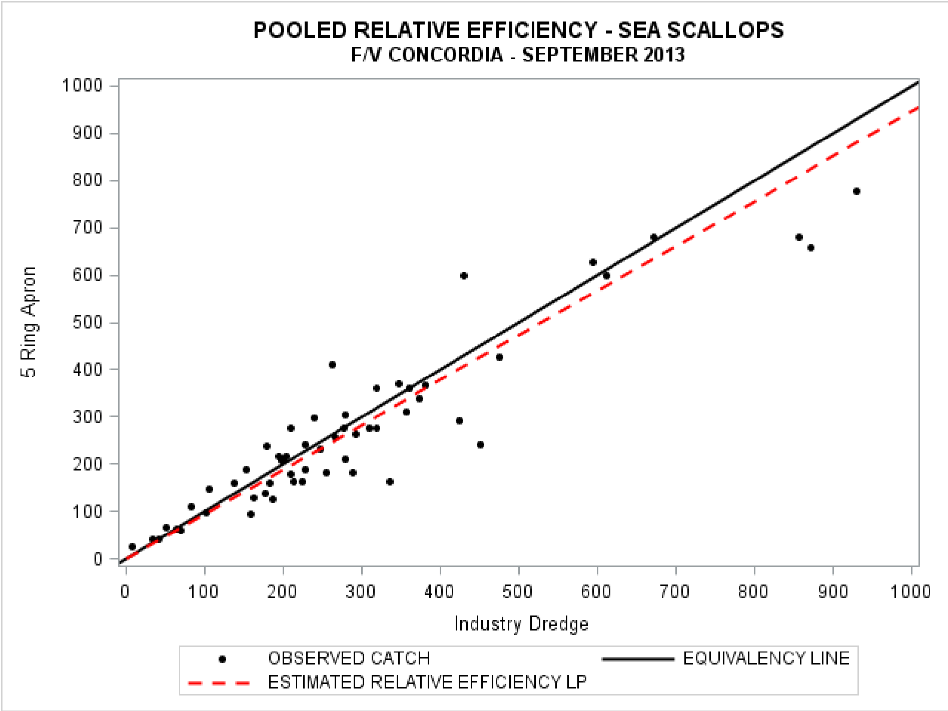
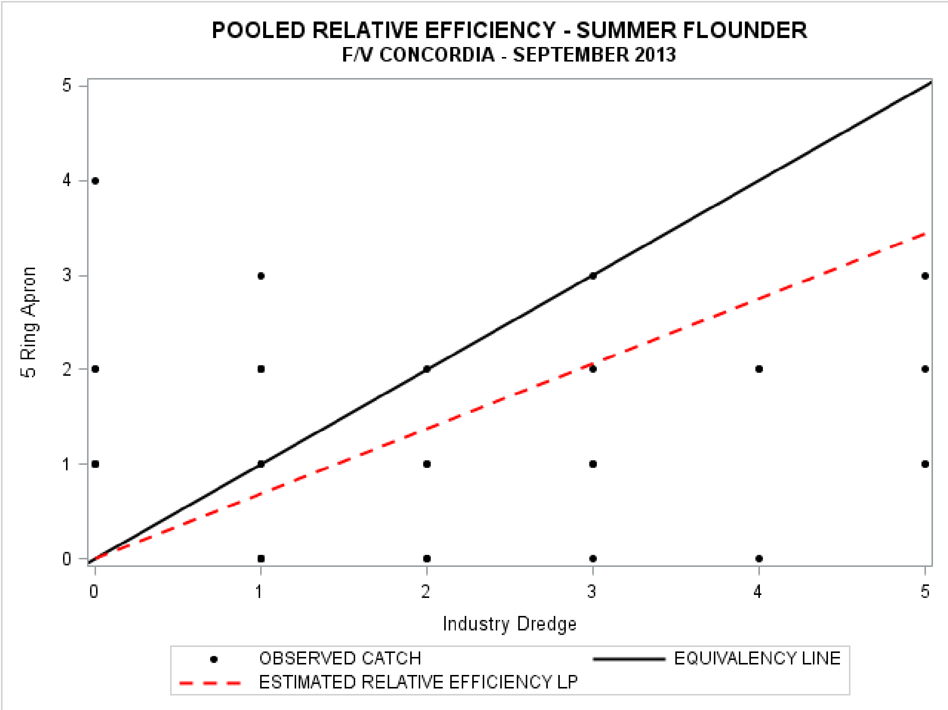
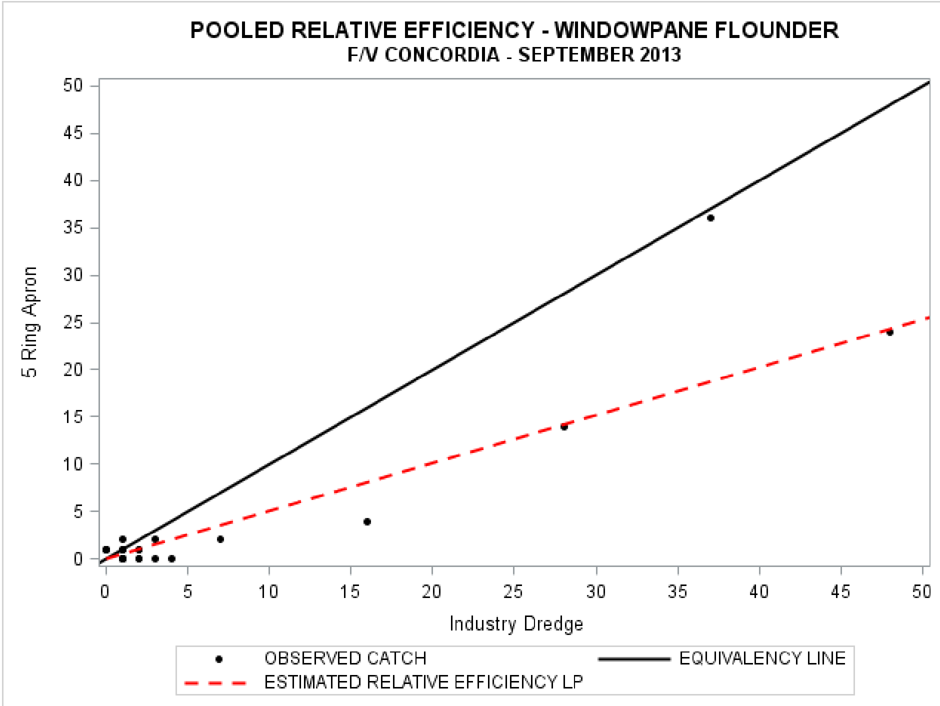

POOLED RELATIVE EFFICIENCY - UNCLASSIFIED SKATES
F/V DILIGENCE - JULY 2013
5 Ring Apron
Industry Dredge
OBSERVED CATCH
EQUIVALENCY LINE
ESTIMATED RELATIVE EFFICIENCY LP

Figure 8. Results from the F/V *Concordia* cruise where 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.






POOLED RELATIVE EFFICIENCY - WINDOWPANE FLOUNDER
F/V CONCORDIA - SEPTEMBER 2013
5 Ring Apron
Industry Dredge
OBSERVED CATCH
EQUIVALENCY LINE
ESTIMATED RELATIVE EFFICIENCY LP

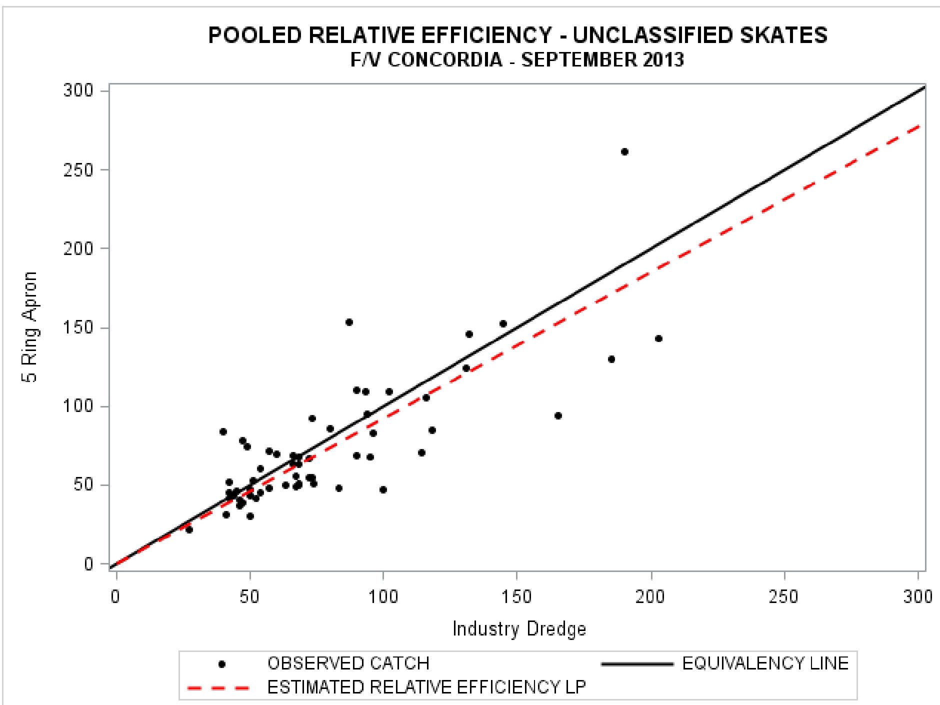
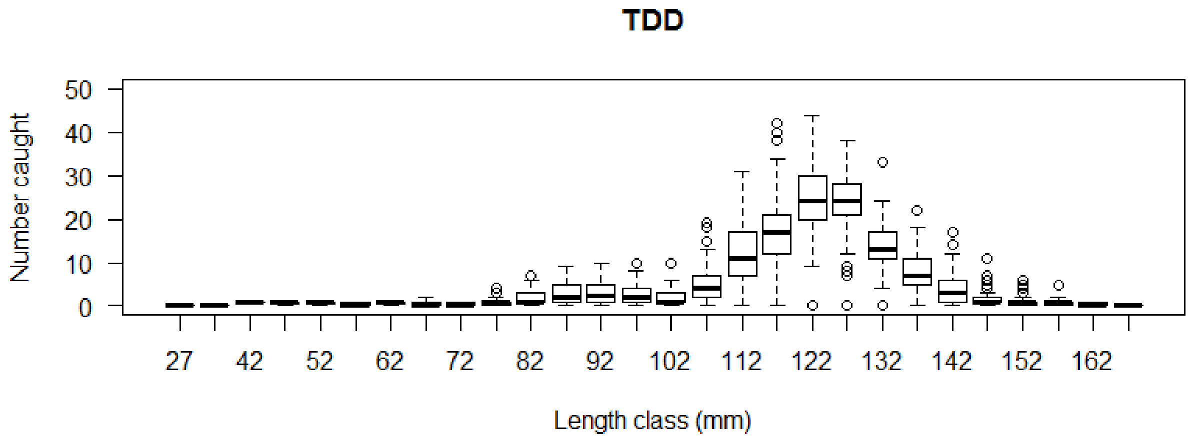

POOLED RELATIVE EFFICIENCY - UNCLASSIFIED SKATES
F/V CONCORDIA - SEPTEMBER 2013
5 Ring Apron
Industry Dredge
OBSERVED CATCH
EQUIVALENCY LINE
ESTIMATED RELATIVE EFFICIENCY LP

Figure 9. Boxplot of sea scallop catch per tow by the two Limited Access General Category (LAGC) dredge frame configurations.



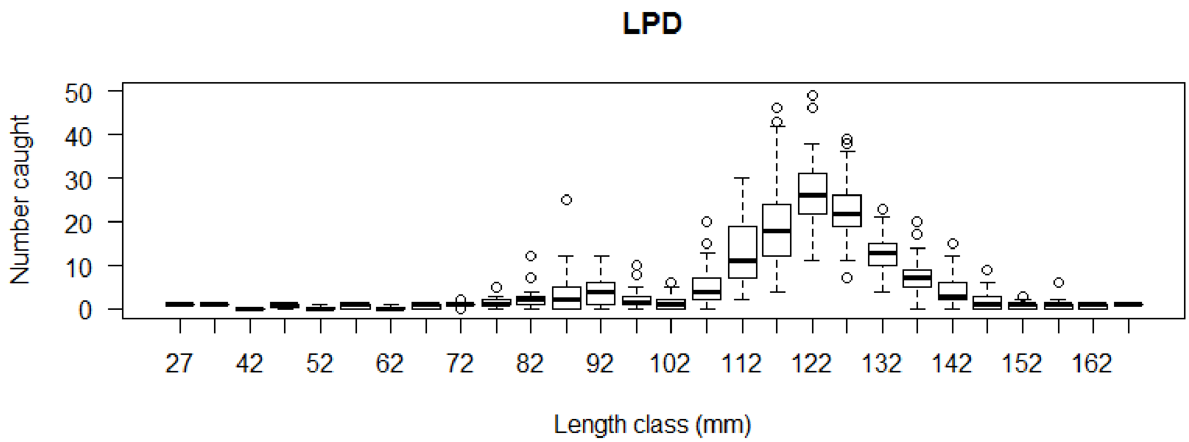
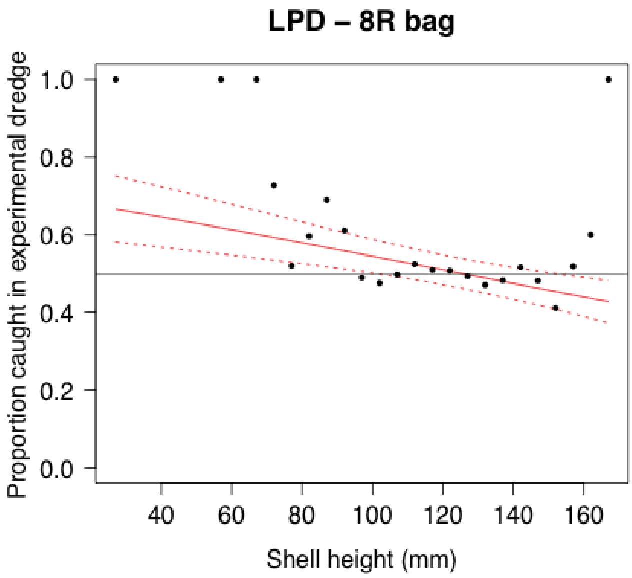


Figure 10. Relative sea scallop catch by the two LAGC dredge configurations. Circles represent the pooled observed proportion at length ($Catch_{LPD}/(Catch_{LPD} + Catch_{TDD})$, with a proportion > 0.5 representing more animals at length captured by the experimental dredge. The dotted lines represent the 95% confidence band for the modeled proportion (solid line). The top panel depicts results from the 8R LPD with respect to the TDD frame and the bottom panel represents the results from the analysis of the 5R LPD.



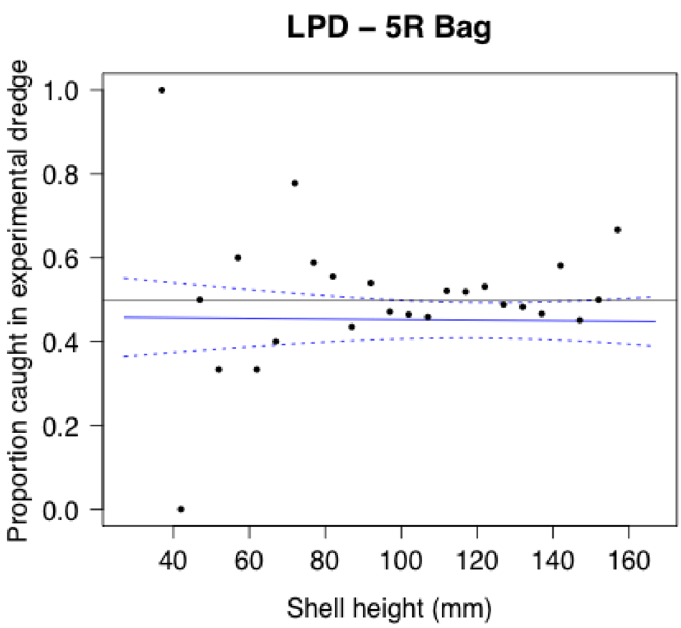


Figure 11. A flatfish escaping successfully ahead of the dredge.

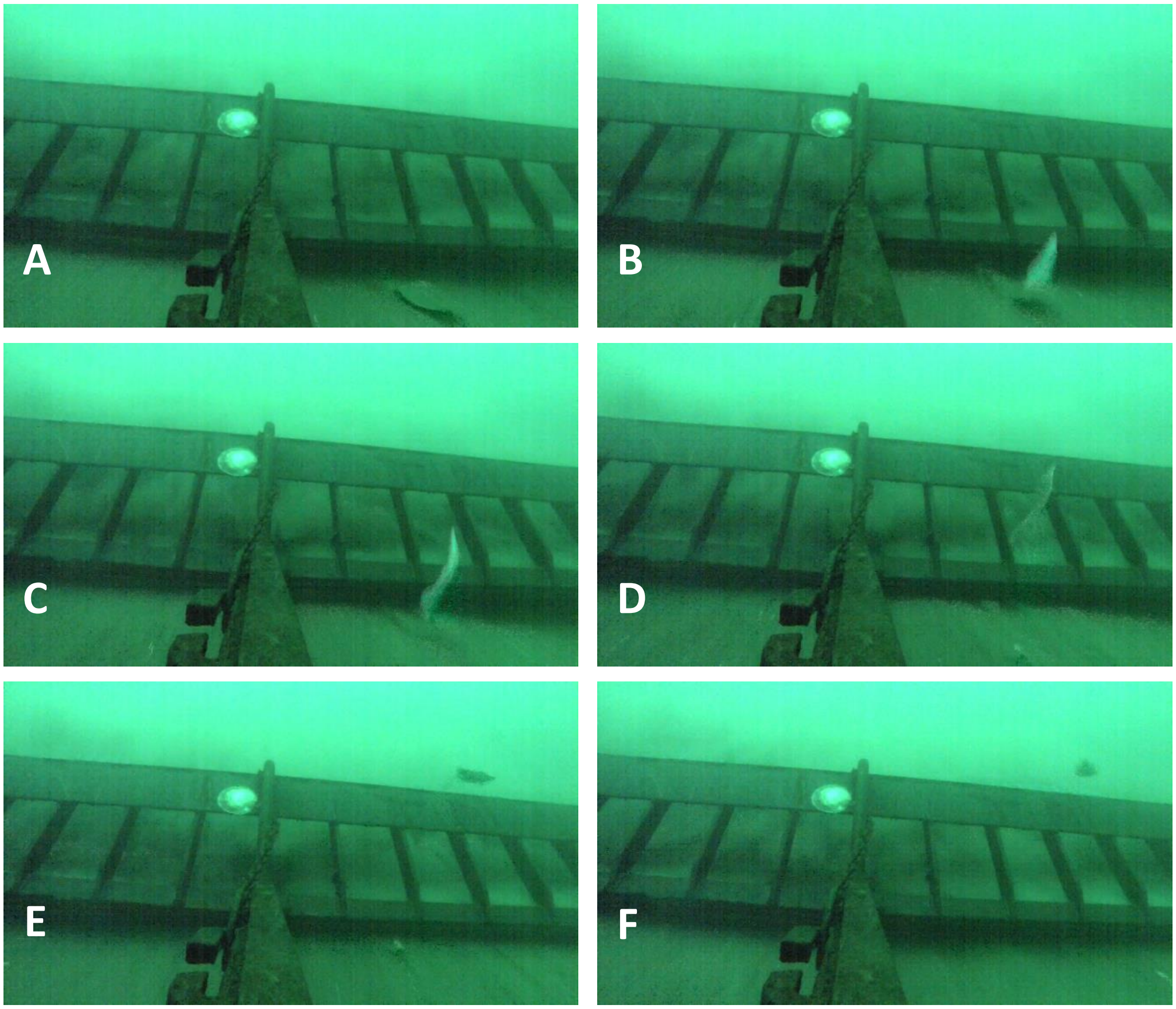


Figure 12. A silver hake (*Merluccius bilinearis)* escaping successfully ahead of the dredge.

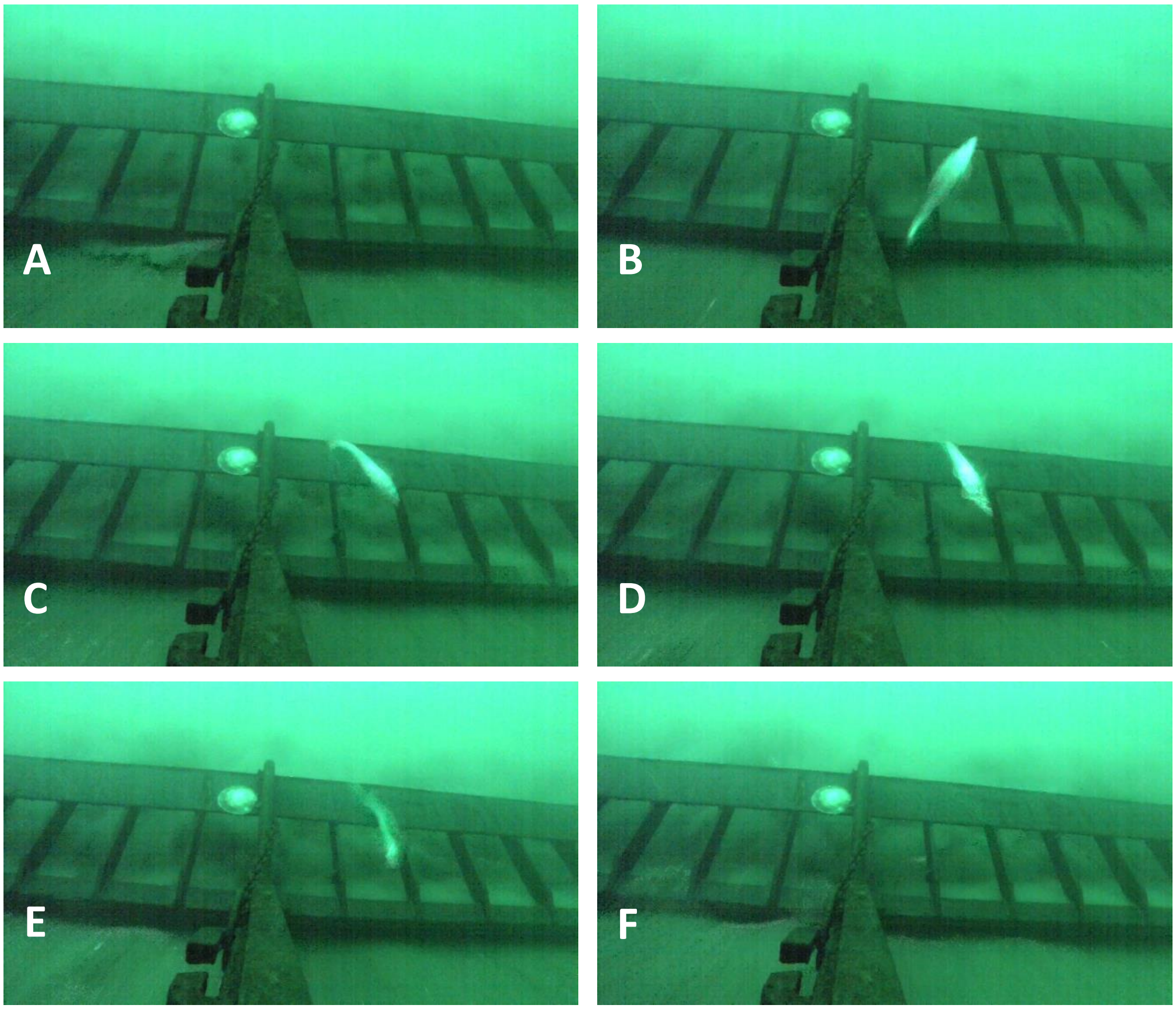


Figure 13. The 2012 LPD frame (left) and the modified LPD frame (right).