Determination of the Impacts of Dredge Speed on Bycatch Reduction and Scallop Selectivity

Final Report

Prepared for the 2015

Sea Scallop Research Set-Aside Program

June 2016

Submitted By

Farrell Davis, Christopher Parkins and Liese Siemann - Coonamessett Farm Foundation, Inc (CFF)
David Rudders- Virginia Institute of Marine Sciences (VIMS)

Coonamessett Farm Foundation, Inc
277 Hatchville Road
East Falmouth, MA 02536
508-356-3501 FAX 508-356-3503
contact@cfarm.org
www.coonamessettfarmfoundation.org

NOAA Grant Number: NA15NMF4540057

A. Grantee: Coonamessett Farm Foundation, Inc.

B. Project Title: **Determination of the Impacts of Dredge Speed on Bycatch Reduction and Scallop Selectivity**

C. Amount of Grant: $237,528

D. Award Period: 4/01/2015-3/31/2016

E. Reporting Period: 4/01/2015-3/31/2016

Project Summary

The Coonamessett Farm Turtle Deflector Dredge (TDD) has proven to be successful in reducing the bycatch of loggerhead sea turtles (*Carretta carreta*) without a significant reduction in scallop catch. However, some fishermen have reported that the TDD is more efficient at higher speeds (5.5 knots compared to the traditional 4.5 knots). Towing at higher speeds can potentially have significant impacts on CPUE, scallop size selectivity, and fish bycatch rates. To determine the impact of tow speed on catch efficiency we towed a TDD and a New Bedford Dredge (NBD) simultaneously at both Fast (5.5-6.0 knots) and Slow (4.5-5.0 knots) speeds and compared the catches from both the dredges. Four Limited Access scallop vessels were used for this project. Overall there was a small but significant increase in the relative efficiency of the TDD at higher speeds. However, when analyzed individually this effect was not observed throughout all of the trips. Yet when the two dredges were fished at their preferred tow speeds - Slow speeds for the NBD and Fast speeds for the TDD - scallop catch per hour was similar. Moreover, when both dredges were fished at the other speed, scallop catch per hour decreased. This verified the observations made by scallop fishermen that the TDD may be more efficient per unit time at higher tow speeds than the NBD. With the information provided by this project, we hope that gear technologists will factor in the impact of speed when developing alternative scallop dredge frames.

Introduction

The environmental impacts of fishing have become more easily definable through the use of ecosystem-based models, increasing the necessity of research and development of sustainable fishing gear (Jennings and Revill, 2007). The Altantic sea scallop (*Placopecten magellanicus*) populations on Georges Bank and in the Mid-Atlantic region of the United States support one of the world's most lucrative fisheries (Hart and Jacobson, 2013). This high level of economic productivity, lasting for almost a decade, is due in part to the successful collaboration of the fishing community, managers and scientists through the Sea Scallop Research Set-Aside (RSA) program (O'Keefe and Stokesbury, 2009; Adams *et al*., 2014). The scallop RSA program has allowed for the research and development of sustainable scallop dredges. One of the more important gear developments to come out of the scallop RSA program is the CFarm Turtle Deflector Dredge (TDD), which has successfully minimized fatal interactions between scallop dredges and sea turtles foraging on the seafloor.

Gear-based bycatch solutions can be a cost effective means to achieving a long-term solution for bycatch avoidance within a fishery (Jennings and Revill, 2007). Seasonal changes in bycatch rates as well as management uncertainty make it difficult to optimize time and area closures. Fishing area closures in the late 2000's due to exceeding the yellowtail flounder (*Limanda ferruginea*) Total Allowable Catch (TAC) prevented the economic maximization of the scallop resource (O'Keefe and DeCelles, 2013). Area closures can also displace fishing effort leading to localized overfishing of productive fishing grounds (Hiddink et al., 2006). The use of environmentally responsible fishing gear, which has a greater species and size selectivity than current traditional fishing gear, can be used independently or in conjunction with area closures through the creation of Gear Restricted Areas (GRA) to reduce bycatch within a fishery.

Prior to the implementation of TDD under Framework (FW) 23 of the Atlantic Scallop Fishery Management Plan, scallop fishermen used a variation of the New Bedford dredge (NBD) frame. The TDD is a derivative of the NBD, retaining many of the same structural elements of the NBD frame like the outer bale, center bar and shoes while removing the inner bale bars and moving the cutting bar forward of the depressor plate (Smolowitz et al., 2012). **Figure 1** displays the differences between the two dredge frames as well as the design evolution of the TDD. The NBD frame was traditionally towed at speeds between 4.5 and 5.0 knots. It was largely assumed that the tow parameters to maximize catch efficiency for the TDD were the same as those for the NBD. However, in the years since FW 23 some scallopers have observed that higher tow speeds (> 5.0 knots) may maximize the scallop catch efficiency of the TDD.

Increased tow speed allows a scallop vessel to cover more area in a shorter amount of time. A majority of the Limited Access (LA) fishing effort is dependent upon the number of Days At Sea (DAS) allocated to a permit holder by fishery managers each fishing year. By covering more fishing ground in a shorter amount of time, a scalloper can potentially maximize their catch for each of their allocated DAS. In addition to affecting scallop Catch Per Unit Effort (CPUE), increased tow speed could impact bycatch of finfish and scallop size selectivity. There may also be impacts to habitat due to an increase in the frequency and intensity of fishing effort in a localized area. Finally, increasing vessel tow speed would increase fuel consumption during the course of the tow. While at the time of the submission of this report fuel prices are relatively low, an increase in fuel prices could potentially offset any gains that result from an increased tow speed. Therefore understanding how tow speeds impact catch efficiency of scallop dredge is important to the long term sustainability of the scallop fishery because it can inform the development of ecologically and economically sustainable scallop dredges.

While the original goal of the proposal was to investigate the impact of speed on the efficiency of a 5 row apron with a 1.5:1 twine top, it was decided instead to examine the impact of speed on the catch efficiency of the two headbale designs used by the fleet. The primary goal of this project then became to determine if there is a difference in catch efficiency of the TDD and the NBD at historic tow speeds ranging from 4.5-5.0 knots and high speeds ranging from 5.5-6.0 knots. Throughout the remainder of this report, the historic tow speeds (4.5-5.0 knots) will be referred to as Slow and the high speeds (5.5-6.0 knots) will be referred to as Fast. This decision to deviate from the objectives set forth in the proposal because the fundamental hypothesis that the TDD is more efficient at higher speeds than an NBD needed to be tested prior to investigating the impact of speed on bag modifications to the TDD as this hypothesis was the genesis for the project. We also wanted to determine the ideal or most efficient tow speed for both the TDD and NBD dredge frames by pairing Fast tows with Slow tows and comparing the Fast tow catch to the Slow tow catch. This would also allow us to determine if the TDD is more efficient at higher speeds than the NBD at slower speeds and verify the observations of the fishermen who initially posed this question.

We towed a NBD and a TDD simultaneously at either Fast or Slow speeds and compared the scallop and finfish catches of the frames. Data collection for this project took place during four research trips in the summer and fall to minimize the potential of severe weather limiting the vessels ability to consistently maintain both Fast and Slow speeds. This is also the time when meat yields are the highest for the region and therefore when a majority of the fishing effort takes place (Huntsberger *et al.*, 2015). All four trips were conducted aboard commercial fishing vessels, in collaboration with skilled and respected industry members. The first trip was aboard the F/V Diligence, and tow duration for this trip was between 50 and 60 minutes (typical of fleet practice). During the second trip, aboard the F/V CB Keane, tow duration was shortened to between 25 and 30 minutes due to excessive quantities of sand dollars in the area. On this trip, we also utilized the Notus Dredgemaster© system to monitor and record the dredge pitch, roll, and distance from the vessel in real time. The third and fourth trips took place aboard the F/V Concordia and the F/V Westport with tow durations again between 25 and 30 minutes. **Figure 2** displays the locations where fishing took place during each of the trips.

Methods

The only variable being tested for this project was vessel speed and its relation to headbale design (NBD and TDD), all other variables including scope and dredge bag configuration were standardized. To determine the impact of speed on dredge efficiency, tow speeds were binned into two categories: Fast and Slow tows. Tow speeds between 5.5-6.0 knots were categorized as Fast and tow speeds between 4.5-5.0 knots were categorized as Slow. Both an NBD and a TDD were towed simultaneously at Fast or Slow speeds, and the catches from each tow were sampled for paired-dredge comparisons. Fast and Slow speeds were alternated, and when possible, dredges were swapped between the port and starboard side of the vessel to account for potential vessel effects and daily changes in tidal velocity and direction. Tow time was adjusted proportionally to the tow speed to ensure that the swept area for Fast and Slow tows was as similar as possible. During the first trip, the average tow durations for the Fast tows were reduced 50 minutes to be comparable to hour-long Slow tows. For the final three trips, the average tow durations for the Fast tows were reduced to 25 minutes to be comparable to 30-minute Slow tows. This design allowed for both 1) a paired-towed analysis of the NBD and TDD catches at each speed and 2) an alternate paired-tow comparison of Fast and Slow catches.

On all directed research trip tows, the entire scallop catch was counted for each side in bushel baskets and weighed to the nearest 0.01 kg using a Marel® scale. A randomly selected one basket subsample from each side was measured in 5-mm increments. A one-bushel subsample has been found to accurately represent the size frequency of scallops in a commercial catch (4-inch ring dredge bag) based on our previous research. The fish catch was sorted by species, counted, weighed to the nearest 0.01 kg, and measured in 1-cm increments. In cases where there were large catches of fish, a subsample was collected for size frequency data. The trash or benthos was also counted by bushels and weighed to the nearest 0.01 kg. Tow parameter data was recorded using CFF's OLRAC Electronic Monitoring System, which records the vessel's position, heading, and speed in 15-second intervals using the vessel's onboard GPS system. Environmental data was also recorded using the OLRAC system; this included a Beaufort value, wind direction, wind speed, and sea conditions. Tows were considered to be invalid if the towing parameters were not followed or if there was a gear malfunction with one of the dredges (e.g. tangled twine top or the dredge flipping during setting out).

Data collected for each paired Limited Access tow is summarized below.

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

Preliminary data analysis was done in R using base functions and the "lattice" graphics package (Sarkar, 2008; R Core Team, 2015).

Statistical Models – GLMM

Catch data from the paired tows provided the information to estimate differences in the relative efficiencies of the two gear combinations we tested.   This analysis is based on the analytical approach in Cadigan *et al.*, 2006. Our analysis of the efficiency of the NBD relative to the TDD consisted of multiple levels of examination. Additional details about the derivation of the model can be found in **Appendix A**.

The model assumes that each gear combination has a unique catchability and differences in scallop or fish catch between paired dredges will be reflected in the ratio of the catchability of the NBD (q_r) to the catchability of the TDD (q_f). The probability that a scallop or fish is captured by the TDD is $p=\rho/(1+\rho)$, where $\rho = q_r/ q_f$.

If binomial regression is used to compare tows, a common practice because fishing catch data is typically over dispersed, and spatial heterogeneity of animal densities is incorporated, the logit (log of the odds) function of the binomial probability p is:

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

After additional terms are added to account for catchability at length (l) and subsampling of the catch, the full initial model using unpooled by length catch data becomes:

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

The Alkaike Information Criteria (AIC) was used to select the best model configuration (Akaike, 1973). If AIC and factor significance indicated that length was not a significant factor in predicting relative efficiency, the data was pooled over length and the random intercept model was evaluated to assess relative differences in total catch (**Equation 1**).

We used SAS/STAT® PROC GLIMMIX v. 9.2 to fit the generalized linear mixed effects models (Littell, *et al*., 2006).

Results

The Impact of Speed on Scallop Catch Efficiency

A total of 168 tows were used for this analysis, with 86 Fast tows and 82 Slow tows. While the sample size for all trips combined is low, there was a detectable effect of tow speed on scallop catch efficiency with a small but significant ($p = 0.0002$) increase in scallop catch across all size classes for the TDD relative to the NBD at Fast speeds (**Table 1**). When catch was adjusted for tow length, catch was higher in the TDD during Fast tows (**Figure 3**). At Slow speeds, the catch in the two dredges was similar, with the observed difference in scallop catch efficiencies between the NBD and TDD due to a shift in the relative efficiency at the 105 mm size class, with the TDD appearing to catch more 90-105 mm scallops, and the NBD catching more 105-120 mm scallops (**Figure 4**). However, when each trip was individually analyzed, the impact of speed on scallop catch efficiency was not ubiquitous.

Speed was found to have a significant impact on scallop catch for only two of the four trips, the CB Keane ($p < 0.0001$) and the Diligence ($p = 0.042$) trips (**Tables 2 and 3**). For the CB Keane trip, the effect of tow speed on scallop catch appeared to be driven by a low overall catch of scallops in the NBD during Fast tows (**Figures 5 and 6**). Yet for the Diligence trip, the effect was caused by a strong shift in the relative efficiency at the 105-110 mm size class of scallops

(**Figures 7 and 8**). The Diligence trip was also the only trip for which size was found to have a significant impact on the scallop catch with the TDD having a greater catch of smaller scallops (**Figures 7 and 8**). Neither speed nor size was found to have a significant impact on scallop catch for the two dredges during the Concordia and Westport trips.

The Impact of Speed on Finfish Catch Efficiency

For many of the finfish species, the catches were too low and sparse to determine if there was an impact of speed on catch efficiency for these species (**Table 4**). The species with large enough catches to analyze were unclassified skates, windowpane flounder (*Scopthalmus aquosus*) and monkfish (*Lophius americanus*). For all trips combined, speed did not have a significant effect on the catch of these species. However, when each trip was analyzed independently, speed did have a significant effect ($p = 0.003$) on windowpane flounder catches during the CB Keane trip but not for the other three trips (**Table 5**). The TDD caught more windowpane flounder at Fast speeds during the CB Keane trip (**Figure 9**).

Investigation of Preferred Tow Speeds (Fast TDD and Slow NBD)

The genesis of this project was the observation from scallop fishermen that the TDD preferred higher tow speeds than a NBD. When fished at their preferred tow speeds - Slow speeds for the NBD and Fast speeds for the TDD - scallop catch per hour was similar for both dredges (**Table 6**). Moreover, when both dredges were fished at the other speed, scallop catch per hour decreased. This verifies the observations made by scallop fishermen that TDD prefers higher tow speeds than a NBD; however, there is no indication that the TDD is more efficient at higher tow speeds than a NBD at slower speeds (**Figure 10**). In terms of bycatch there was a significant difference in windowpane flounder catch by size, with the TDD catching more small fish than the NBD (**Figure 11**). Examination of the dredge pitch data collected using the Notus Dredgemaster© system aboard shows that when towed at their preferred speeds the dredges pitch is roughly the same angle (**Figure 12**). This suggests that there are likely underlying hydrodynamic forces related to the angle of the dredge affecting scallop catch efficiency.

Development and Testing of a Low Resistance Dredge Shoe

In the proposal the testing of a low resistance UHMW plastic shoe was discussed and at the time of writing the proposal a final design of the shoe had been built but remained untested. In the interim period between submission of the proposal and its receipt the shoe design was tested aboard the FV Celtic during a compensation trip from the previous year. During this trip, the alternative shoe design failed after completing only one 55 minute tow (**Figure 13**). For this reason the alternative shoe design was not developed any further in order to focus time and resources on answering questions regarding tow speed and catch efficiency.

Additional model outputs, tables and figures can found in **Appendix B**.

Discussion

Coonamessett Farm Foundation, Inc. has worked with the scalloping industry over the past decade to design and develop alternative fishing gear to mitigate the environmental impact of the fishery. With RSA funding, we were able to develop a scallop dredge that successfully minimized interactions between sea turtles and the scalloping industry. The TDD did not require any change in fishing practices nor did it reduce scallop catch, two factors that contributed to the successful uptake and implementation of the TDD frame. Keeping those factors in mind, we began testing alternative bag design configurations for the reduction of bycatch and the mitigation of recruitment overfishing in areas with high densities of pre-recruit scallops. However, this year's project was unique; rather than developing and testing an alternative piece of fishing gear we decided to conduct a mensuration study of the impacts of speed. While this research is not immediately applicable by fisheries managers, it does provide valuable information for fishing gear developers.

The small but significant increase in scallop catch predicted by the model was driven by two of the four trips: the CB Keane and Diligence. The procedural details of these two trips were slightly different from the Concordia and Westport trips which may the reason for these results. During the Diligence trip, Slow tows were one hour in length and Fast tows were 50 minutes in length. The longer tow times are more typical of fleet practices; however, the increased catch of scallop and benthos decreases sampling efficiency. The increased volume of benthos from longer tow times could have been decreasing the mechanical sorting ability of the dredge resulting in a larger catch of smaller scallops that would have likely been expelled through the apron of the bag.

During the CB Keane trip, technical circumstances prevented us from using the two 15-foot dredges used for the other three trips and two 13-foot dredges were provided by the fishing vessel instead. Additionally, rather than moving from area to area across a wide geographic range, fishing took place in a relatively localized area area south of Martha's Vineyard known as the "The Claw" (**Figure 2**). When commercially fishing, scallopers will tend to work a bed of scallops until densities are too low to justify the cost of remaining in the area. In some ways, one could argue that remaining in one area is more representative of fleeting practices than moving from area to area. When these two trips are dropped from the analysis, the significant increase in scallop catch for the TDD during Fast tows disappears for the Concordia and Westport trips, which used half hour and 25 minute tow lengths, the same 15-foot dredges, and similar wide-area coverage. However, given the number of factors that influence the efficiency of scallop dredges, it is not outside the realm of possibility that longer tow lengths and a smaller dredge frames may not be responsible for the unique results observed during the CB Keane and Diligence trips.

For our part, all possible variables and parameters were standardized and accounted for to the best of our ability. With more observations it is possible that we could strengthen the signal of tow speed observed during this project or even push the CB Keane and Diligence trips into the realm of outliers, finding that tow speed has no effect at all on catch efficiency. Further, it must be noted that the standard bag design used by CFF is but one of many bag designs observed throughout the fleet, and it is not impossible that changes to the bag design could cancel out the influence of tow speed on catch efficiency. Each variation of the bag design from the standardized bag would require its own experiment to determine if the effect of tow speed is equal across all bag configurations. Additionally, scope could counteract the effect of tow speed or compound the effect. Speed, dredge configuration and scope could all influence each other so that for any given dredge configuration, there is an ideal speed and scope that maximizes efficiency. There are many variables that influence and contribute to the success of a piece fishing gear, and therefore trying to draw fleet-wide conclusions from a study of this nature is tenuous. However, the costs associated with collecting a large enough sample size using traditional experimental designs to draw fleet-wide conclusions are prohibitive.

What if there was a cost-effective means of collecting a large enough sample size to make fleet-wide inferences about the impact of a particular gear design? By using recent advancements in at-sea data collection technology, like electronic measuring boards, and working with fishing communities to collect accurate and reliable fishery dependent data, fisheries technologists can investigate the plethora of gear designs within the scallop fleet and look for trends and identify promising gear configurations that warrant a more detailed controlled study. Initial investment in data collection and storage infrastructure may be high and participation by fishing communities might be deterred by the idea of being monitored. Furthermore, there would be a delay in the applicability of the collected data to assess gear because baseline efficiencies for a vessel/gear would have to be established during the first couple of years after the system is put in place. However, such a system could provide immediate benefits like real-time identification of areas with diseased scallops, areas with high levels of bycatch, and places where recruitment overfishing might occur because of large sets of scallops. Fleet owners could capitalize upon the data collected by such a platform by directing effort to areas with better meat yields and lower bycatch rates. Finally, this hypothetical system could allow adaptive gear restrictions by identifying where and when a given gear configuration is most effective at mitigating negative impacts to the environment. This approach has the potential to increase the rate at which ecologically, socially and economically sustainable fishing gear is produced and shorten the time from concept and design to application by fisheries managers.

References Cited

Adams, E.K., K.D.E. Stokesbury, and D. Georgianna. 2014. User based fisheries funding and its impact on fisheries management. 144th Annual Meeting of the American Fisheries Society. August 17-21, Quebec City, Canada.

Akaike, H. 1973. Information theory as an extension of the maximum likelihood principle. In: Second international symposium on information theory. B.N. Petrov and F. Csaki (eds.) Budapest, Hungary: Akademiai Kiado. pp. 267-281.

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. Canadian Science Advisory Secretariat Research Document 2006/085. 63 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. Fisheries Bulletin 108: 15-29.

Hiddink, J.G., T. Hutton, S. Jennings, and M.J. Kaiser. 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.

Huntsberger, C, K. Thompson, M. Winton, and L. Siemann. 2015. Seasonal Bycatch Survey of the Georges Bank Scallop Fishery. Final Report for the 2013 Sea Scallop Research Set-Aside. NOAA grant NA13NMF4540011. 107 pp.

Jennings, S., and A. S. Revill. 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. 840 pp.

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.

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

O'Keefe, C.E. and K.D.E. Stokesbury. 2009. From bust to boom: the success of industry collaboration in US sea scallop research. Proceedings of the 2009 ICES Annual Science Conference. ICES CM 2009/L:05. 9 pp.

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

Sarkar, D. 2008. Lattice: Multivariate Data Visualization with R. Springer, New York. ISBN 978-0-387-75968-5.

Smolowitz, R., H.O. Milliken, and M. Weeks. 2012. Design, Evolution, and Assessment of a SeaTurtle Deflector Dredge for the U.S. Northwest Atlantic Sea Scallop Fishery: Impacts on Fish Bycatch, North American Journalof Fisheries Management, 32: 65-76

Tables and Figures

Table 1: GLMM Model Results for all trips combined.

Solutions for Fixed Effects (Scallops)									
Effect	**DESIGNATION**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Alpha**	**Lower**	**Upper**
Intercept		0.1787	0.1283	2165	1.39	0.1640	0.05	-0.07301	0.4304
SIZE		-0.00131	0.000893	2165	-1.46	0.1437	0.05	-0.00306	0.000445
DESIGNATION	Fast	0.3462	0.08991	2165	3.85	0.0001	0.05	0.1699	0.5225
DESIGNATION	Slow	0	.	.	.	.	.	.	.

Table 2: GLMM Model Results for the Diligence trip.

Solutions for Fixed Effects (Scallops)									
Effect	**DESIGNATION**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Alpha**	**Lower**	**Upper**
Intercept		0.9960	0.2815	445	3.54	0.0004	0.05	0.4427	1.5492
SIZE		-0.00810	0.001884	445	-4.30	<.0001	0.05	-0.01180	-0.00439
DESIGNATION	Fast	0.4730	0.2314	445	2.04	0.0416	0.05	0.01818	0.9278
DESIGNATION	Slow	0	.	.	.	.	.	.	.

Table 3: GLMM Model Results for the CB Keane trip.

Solutions for Fixed Effects (Scallops)									
Effect	**DESIGNATION**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Alpha**	**Lower**	**Upper**
Intercept		0.08211	0.2558	583	0.32	0.7484	0.05	-0.4204	0.5846
SIZE		0.000984	0.001757	583	0.56	0.5757	0.05	-0.00247	0.004435
DESIGNATION	Fast	0.8978	0.1853	583	4.84	<.0001	0.05	0.5338	1.2618
DESIGNATION	Slow	0	.	.	.	.	.	.	.

Table 4: Total finfish catch weight in kilograms for each trip by dredge.

Trip	Headbale	Monkfish	Haddock	Yellowtail Flounder	Four Spot Flounder	Windowpane Flounder	Winter Flounder	American Plaice	Barndoor Skate	Spiny Dogfish	Grey Sole	Fluke
CB Keane	TDD	576.2	0	40.53	33.819	59.852	20.59	0	14.69	0	0	21.13
	NBD	308.6	0	21.05	14.77	47.44	11.6	0	3.61	0	0	23.05
Concordia	TDD	395.85	4.19	74.91	34.3	105.38	30.96	0	24.38	2.34	0	97.26
	NBD	455.7	2.83	85.69	22.16	118.16	26.53	0	37.83	4.98	0	80.21
Diligence	TDD	603.22	11.56	9.7	42.21	50.18	22.8	1.55	108.72	17.16	0.64	2.14
	NBD	405.11	4.77	4.97	37.43	33.86	30.5	0.2	239.6	12.57	0.49	5.26
Westport	TDD	182.53	0.64	67.41	17.54	21.84	15.04	0	16.55	2.65	0	78.44
	NBD	234.45	0.08	37.84	18.73	19.39	13.52	0	33.12	2.96	0	54.81

Table 5: GLMM Model Results for the CB Keane trip.

Solutions for Fixed Effects (Windowpane Flounder)									
Effect	DESIGNATION	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
Intercept		2.5040	1.4758	188	1.70	0.0914	0.05	-0.4073	5.4153
SIZE		-0.08437	0.05033	188	-1.68	0.0953	0.05	-0.1836	0.01491
DESIGNATION	Fast	0.9044	0.3073	188	2.94	0.0037	0.05	0.2981	1.5107
DESIGNATION	Slow	0	.	.	.	.	.	.	.

Table 6: Scallop Catch Per Unit Effort both in terms of tow, area and time, (Coefficient of Variation).

Speed	Dredge	Tow Duration (hr) (CV)	Swept Area (km2) (CV)	Scallop catch per tow (CV)	Scallop catch per hour (CV)	Scallop catch per km2 (CV)
Fast	NBD	0.52 (34%)	0.0247 (34%)	99.46 (111%)	206.61 (118%)	4339.07 (118%)
Slow	NBD	0.62 (35%)	0.0252 (35%)	140.41 (125%)	223.21 (106%)	5464.32 (106%)
Fast	TDD	0.52 (34%)	0.0247 (34%)	117.66 (103%)	244.24 (114%)	5106.53 (114%)
Slow	TDD	0.62 (35%)	0.0252 (35%)	131.64 (118%)	210.91 (102%)	5167.20 (102%)

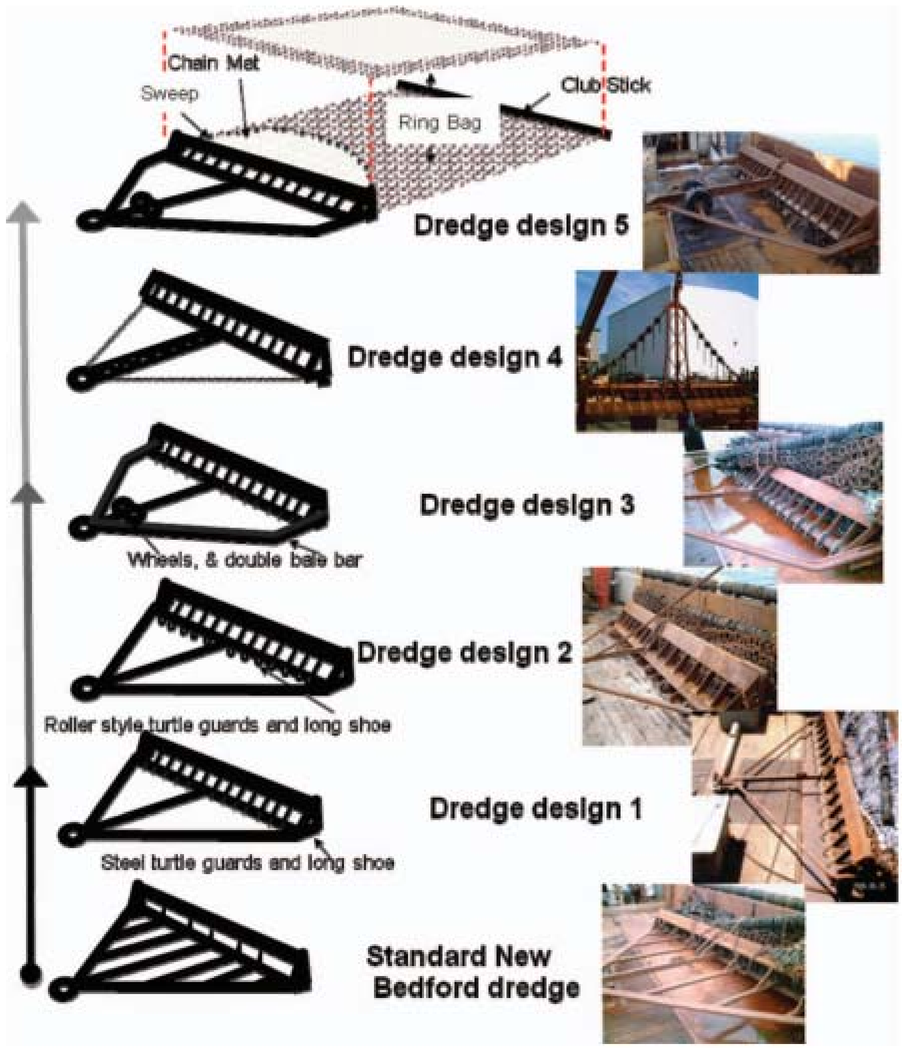

Figure 1: The design evolution of the Turtle Deflector Dredge (Smolowitz et al,. 2012).

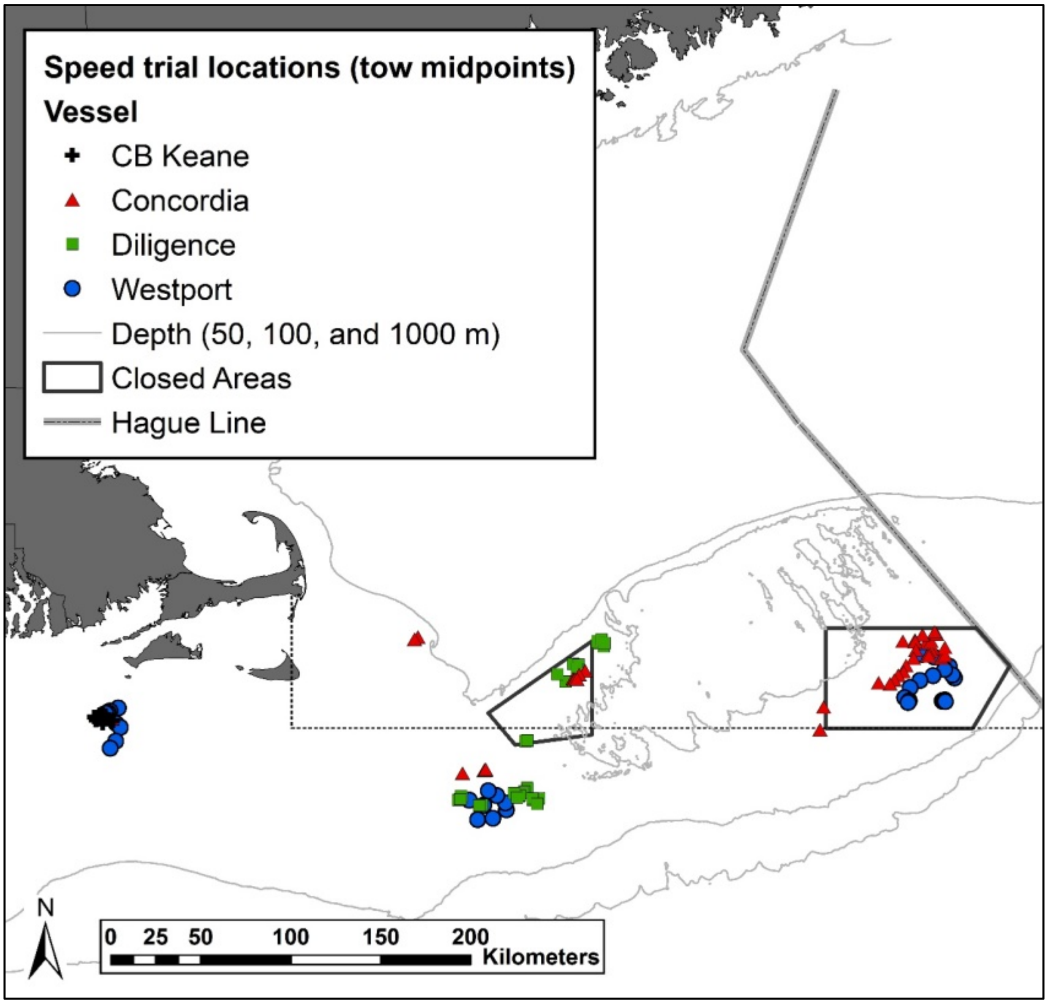

Figure 2: Tow locations for the 2015 RSA Gear Testing Project.

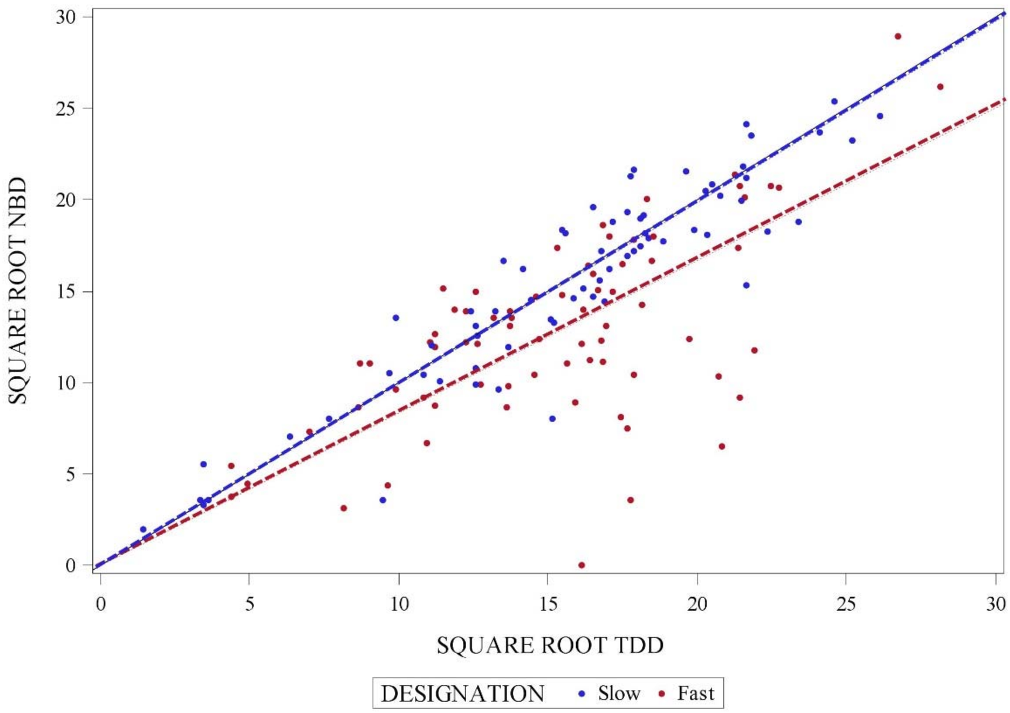

Figure 3: Scallop catch in the TDD versus the NBD for all four trips. The catch in the TDD vs. NBD for each tow is shown as a solid circle, and the linear regression lines for Slow and Fast tows are shown as dashed lines. ***At Fast speeds, scallop catch was higher in the TDD than the NBD (red line below equivalency line), while at Slow speeds, scallop catch was similar for both dredge frames (blue line on equivalency line).*** *The axis units are the square root of the scallop catch (kg) for each tow.*

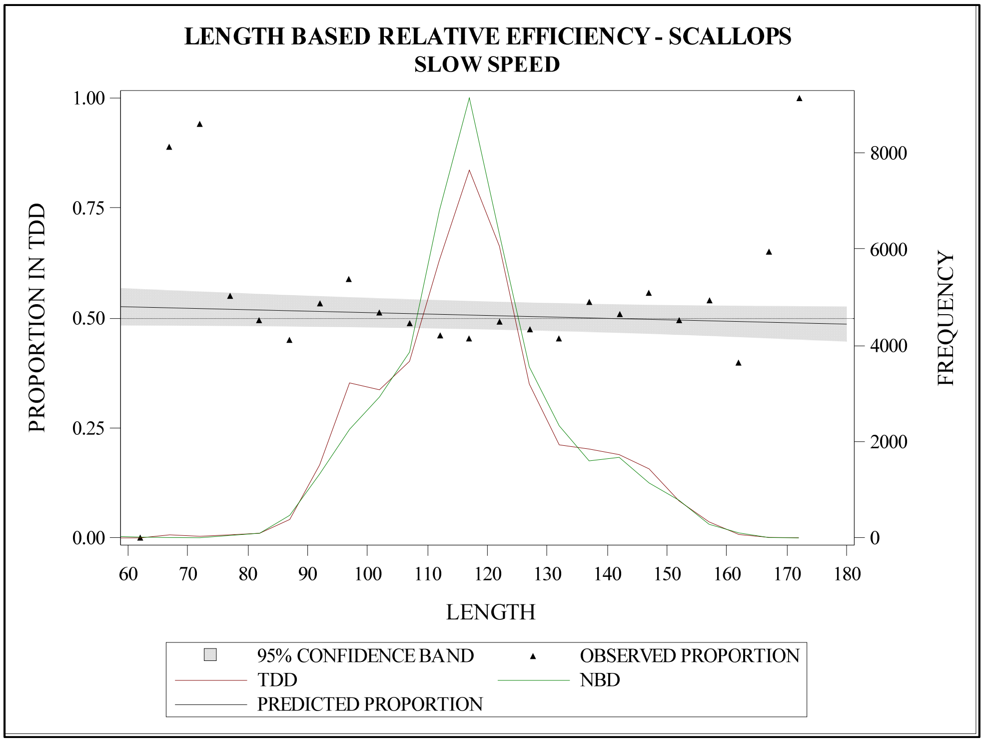

Figure 4: Length-based relative efficiency for scallops during Slow tows. The observed proportion of the catch per tow in the TDD (TDD catch/Total catch) at each scallop length (black triangles) is overlaid with the model predicted proportion by length (black line) and confidence band (gray area). The length frequency curves for the TDD (red line) and NBD (green line) are also shown. ***There was a noticeable but not significant shift in the relative efficiencies of the two dredges when the scallop SH = 105 mm.***

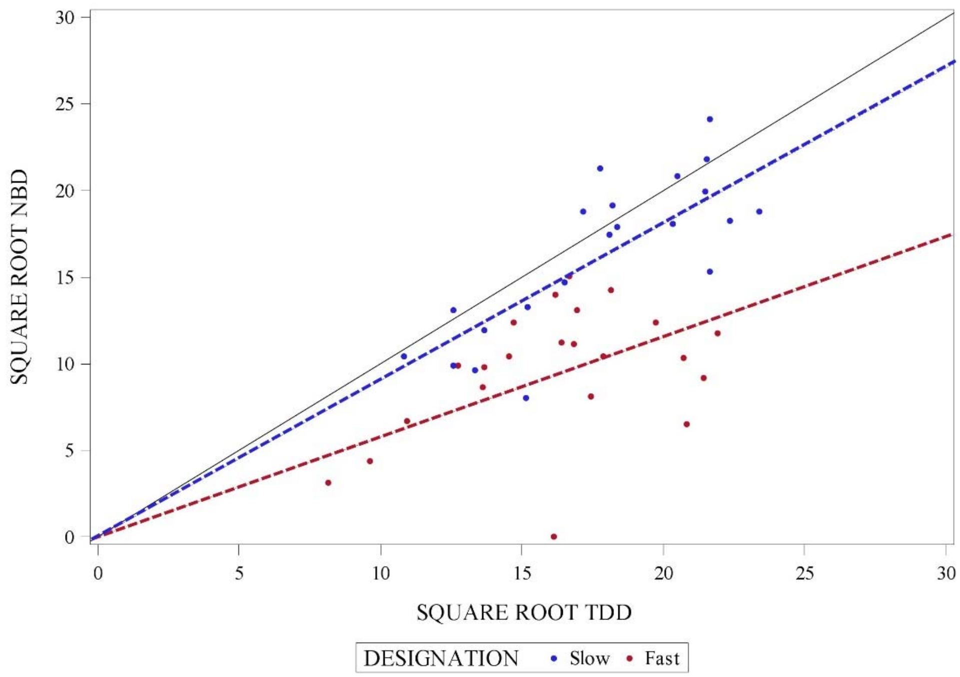

Figure 5: Scallop catch in the TDD versus the NBD for the CB Keane trip. ***At Fast and Slow speeds, scallop catch was higher in the TDD than the NBD (red and blue lines below equivalency line), although this increase in the relative efficiency of the TDD was greater at Fast speeds.*** *Additional details in Figure 3 caption.*

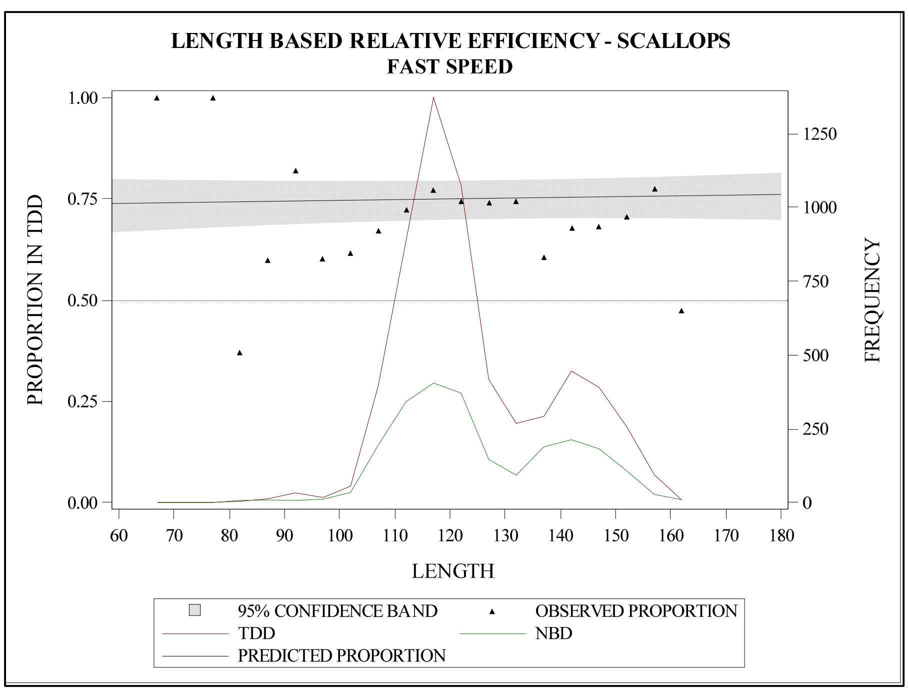

Figure 6: Length-based relative efficiency for scallops during Fast tows on the CB Keane. ***Scallop catch in the NBD was significantly lower than catch in the TDD.*** *Additional details in Figure 4 caption.*

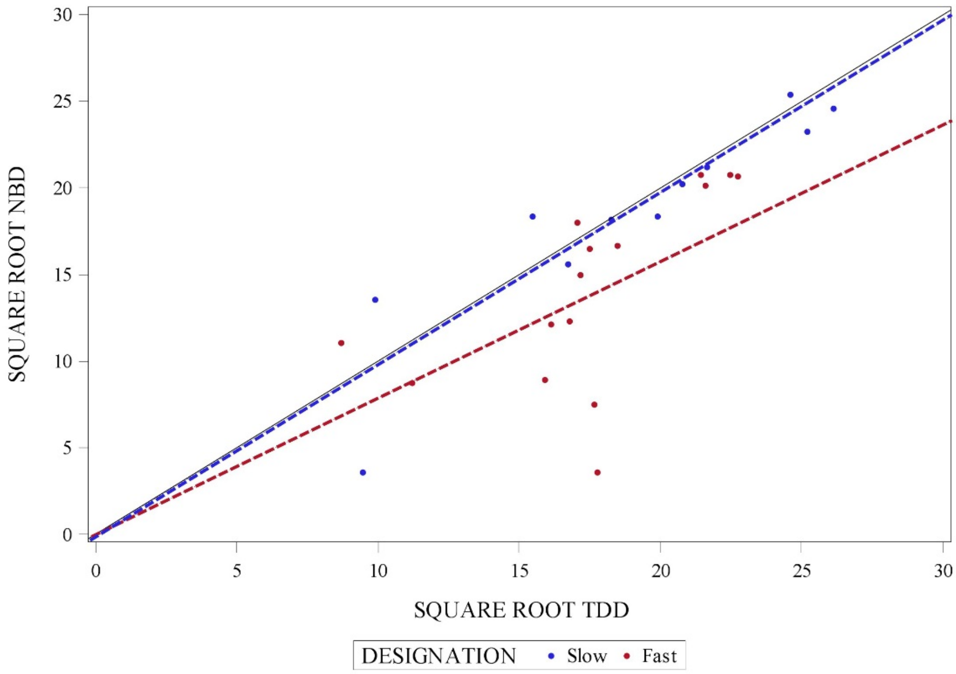

Figure 7: Scallop catch in the TDD versus the NBD for the Diligence trip. ***At Fast speeds, scallop catch was higher in the TDD than the NBD (red line below equivalency line), while at Slow speeds, scallop catch was similar for both dredge frames (blue line on equivalency line).*** *Additional details in Figure 3 caption.*

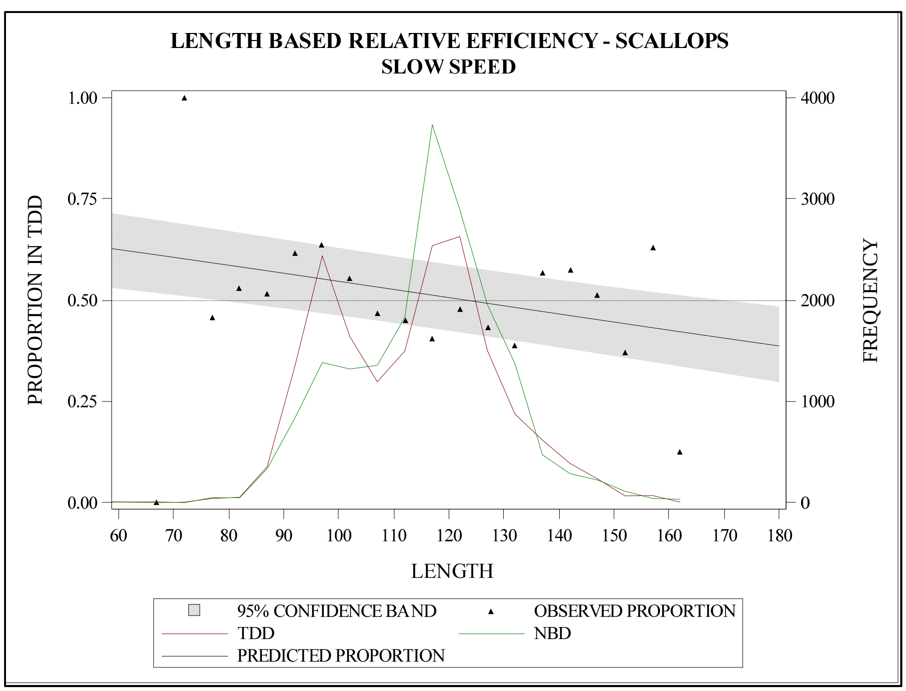

Figure 8: Length-based relative efficiency for scallops during Slow tows on the Diligence. ***There was a strong shift in catch relative efficiency at scallop SH=105 mm.*** *Additional details in Figure 4 caption.*

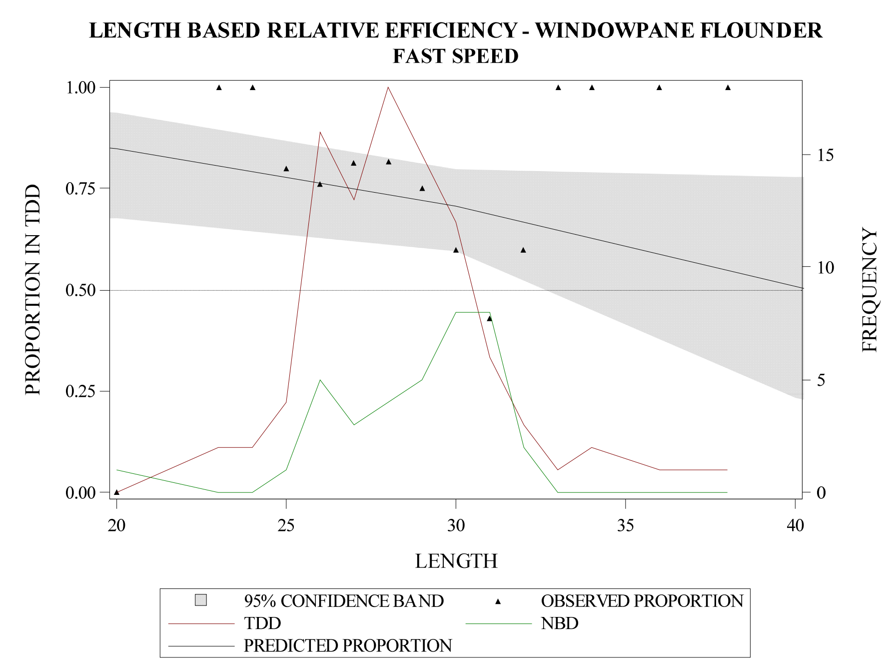

Figure 9: Length-based relative efficiency for windowpane flounder during Fast tows on the CB Keane. ***Windowpane flounder catch in the NBD was significantly lower than catch in the TDD.*** *Additional details in Figure 4 caption.*

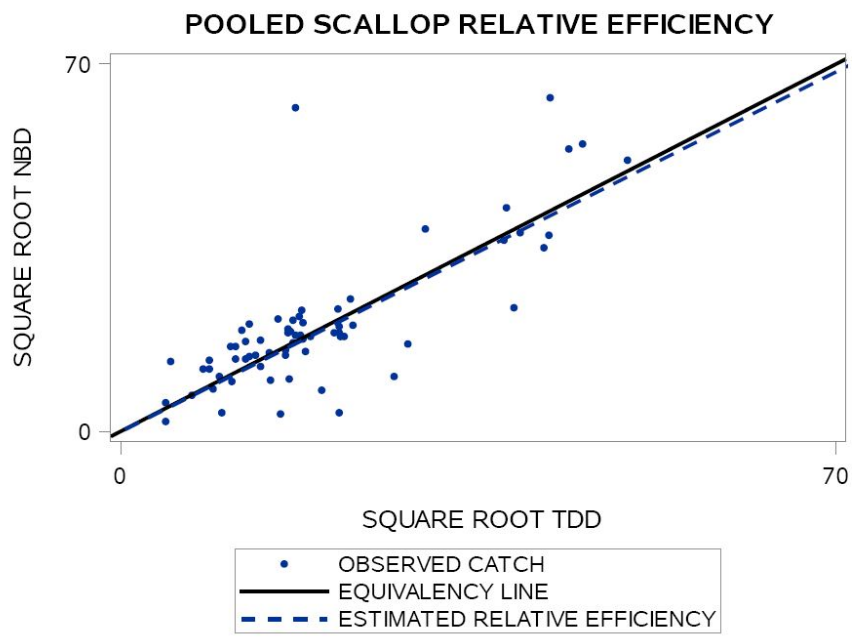

Figure 10: Scallop catch in the Fast TDD versus the Slow NBD for all four trips. The catch in the TDD vs. NBD for each consecutive paired tow is shown as a solid circle, and the linear regression lines cross gear comparison is shown as a dashed line. ***Scallop catch for the Fast TDD versus the Slow NBD was equivalent (dashed line on equivalency line).***

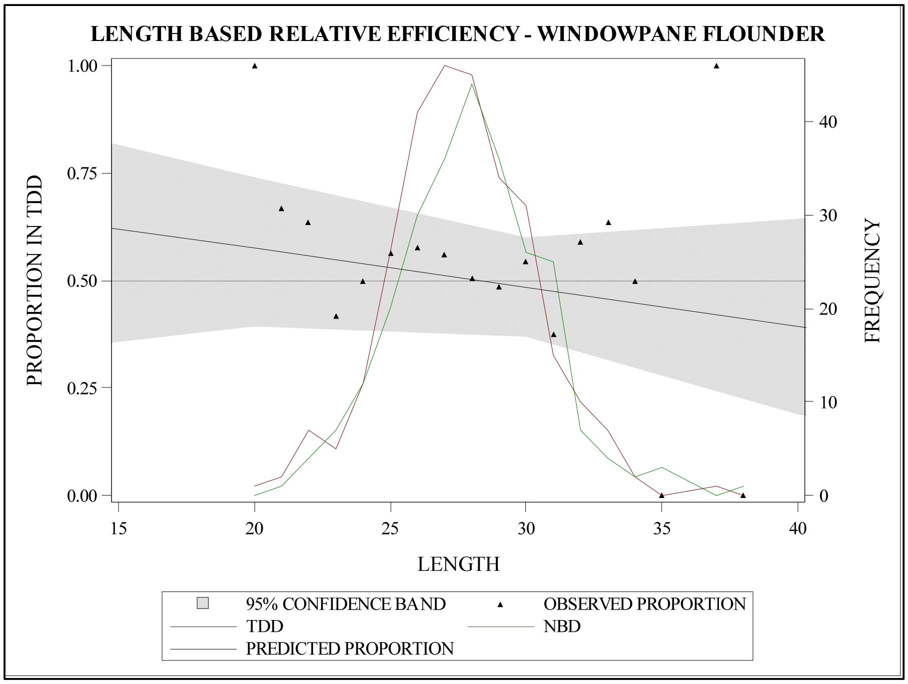

Figure 11: Length-based relative efficiency for windowpane flounder for Fast TDD tows and Slow NBD tows. ***The TDD caught more smaller windowpane flounder than the NBD****. Additional details in Figure 4 caption.*

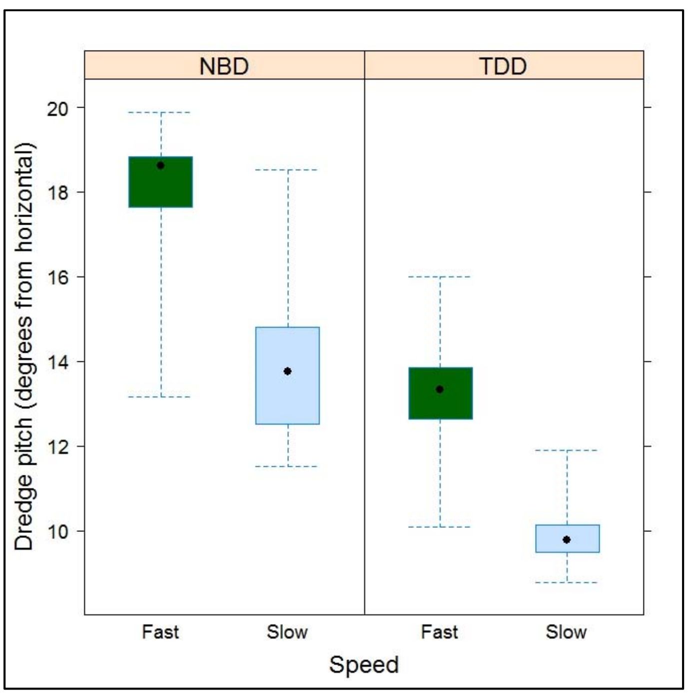

Figure 12: Dredge pitch at Fast and Slow speeds for the NBD and TDD during the CB Keane trip. The black dot represents the median dredge pitch, the box extends from the first to third quartile of the pitch values, and the whiskers extend minimum and maximum values. ***The dredge pitch at the preferred speeds for each headbale (Slow for NBD and Fast for TDD) were roughly the same.***

Figure 13:The wear after one 55 minute was too excessive to warrant any further testing of the UHMW plastic shoe.

Appendix A

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 TDD dredge and q_f equals the catchability of the NBD dredge used in the study. The efficiency of the TDD dredge relative to the NBD dredge 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/fish and fish density is minimized, observed differences in scallop/fish catch for each vessel will reflect differences in the catchabilities of the gear combinations tested.

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

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

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

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

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

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

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

where $p=\rho/(1+\rho)$ is the probability that a scallop/fish captured by the TDD dredge. In this approach, the only unknown parameter is ρ and the requirement to estimate μ for each station is eliminated as would be required in the direct GLM approach (equations 2 & 3). For the binomial distribution $E(C_{ir})=c_ip$ and $Var(C_ir)=c_ip/(1-p)$. 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 station.
The potential exists, however, that there will be variability in both the number as well as the length distributions of scallops/fish encountered within a tow pair. In this situation, a random effects model that again allows the intercept to vary randomly between tows is appropriate (Cadigan and Dowden, 2009). This model is given below:

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

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

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

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

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

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

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

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

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

Appendix B

GLIMMIX output for