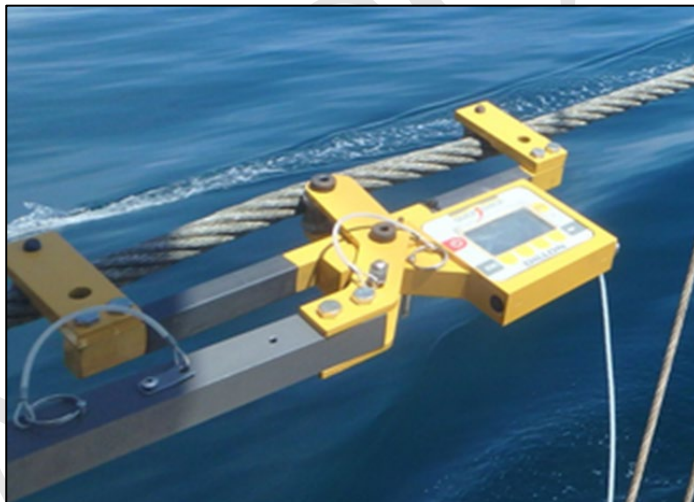


Tension in the Air: Using a Tensiometer to Assess Dredge Fullness and Loss During Haul-back Comparing Different Dredge Configurations

Final Report

**Prepared for the 2024
Sea Scallop Research Set-Aside
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Submitted By

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Executive Summary

The Atlantic sea scallop (*Placopecten magellanicus*) fishery is one of the most valuable federally managed fisheries in the United States, but its sustainability is constrained by persistent bycatch of flatfish species, particularly windowpane flounder (*Scophthalmus aquosus*) and yellowtail flounder (*Limanda ferruginea*). Under Framework Adjustment 25, the fishery is required to use a 5-row apron dredge with a 1.5:1 twine top to reduce the bycatch of these species. While effective, concerns remain regarding potential reductions in scallop retention and increased catch loss during haul back (“winnowing”), which may lead to compensatory fishing effort and reduced operational efficiency.

This study evaluated the performance of three dredge configurations, 5-row apron, traditional 7-row apron, and extended-link apron, under commercially representative conditions using paired dredge deployments across four research trips conducted between September 2024 and July 2025 on Georges Bank and adjacent areas. A key innovation of this work was the integration of a tensiometer to measure warp tension in real time, providing a novel approach to assessing dredge loading, performance, and catch loss throughout both towing and haul-back phases.

Warp tension metrics were strongly associated with catch rates and provided insight into dredge performance. Specifically, increases in the rate of tension accumulation were positively correlated with catch, while reductions in vessel speed were associated with increased catch rates. Environmental factors, including depth, substrate composition, and vessel orientation relative to wind also significantly influenced catch efficiency. These findings demonstrate that tensiometers can serve as effective tools for real-time monitoring of dredge saturation and performance, with direct applications for improving fishing efficiency.

Analysis of haul-back dynamics revealed that catch loss is strongly influenced by apron configuration, hanging duration, and scallop size. Across all gear types, larger scallops were consistently retained at higher rates, while smaller individuals were more susceptible to loss during retrieval. The 5-row apron exhibited a complex size-dependent retention pattern, indicating a post-tow redistribution process that may trap smaller scallops within the catch matrix at longer hang times. While the extended-link apron had a more intuitive size-dependent retention pattern that was enhanced with increasing sea state condition.

Overall, the additional testing of the 5-row apron configuration demonstrated that while maintained scallop catch rates are comparable to the 7-row configuration the reduction in windowpane flounder bycatch is modest relative to an extended link apron. The 5-row apron configuration as required by Framework Adjustment 25 represents an incremental improvement rather than an impactful solution for reducing windowpane flounder bycatch in the sea scallop fishery. Additionally, the application of tensiometer technology provides a powerful new tool for understanding dredge dynamics and optimizing fishing practices.

Table of Contents

1. Introduction.....	1
2. Project Objectives	2
3. Methods.....	3
3.1. Sampling design.....	3
3.2 Catch Sampling and Processing.....	5
3.3. Data Analysis	5
4. Results by Objective	9
Objective 1: Investigate the performance of a 5-row apron with a 1.5:1 twine top relative to a 7-row apron with a 2:1 twine top.....	9
Objective 2: Evaluate warp tension (pounds-force) relative to bag configuration, catch weight/composition, and relevant operational and environmental variables.....	11
Objective 3: Evaluate the impact of apron configuration on catch winnowing.....	12
5. Discussion.....	25
6. Citations	25
7. Appendix.....	27

Figures

Figure 1. Spatial distribution of tow tracks conducted during four research trips on Georges Bank, and within the Great South Channel and Nantucket Shoals. Tow tracks are colored by trip number.	3
Figure 2. Dillon Quick Check Red tensiometer used to measure warp tension (pounds-force) during scallop dredge operations.	4
Figure 3. Pooled sea scallop catch efficiency of the 5-row apron with a 1.5:1 twine top relative to the 7-row apron with a 2:1 twine top.	10
Figure 4. Pooled windowpane flounder catch efficiency of the 5-row apron with a 1.5:1 mesh twine top relative to the 7-row apron with a 2:1 mesh twine top.	10
Figure 5. Marginal effects of environmental and operational variables on predicted dredge catch rates (kg hr^{-1}). Panels show the modeled relationships between catch rate and maximum warp tension slope (N s^{-1}), vessel acceleration (m s^{-2}), percent sand substrate, depth (m), and vessel heading relative to wind direction (wind offset, degrees).....	12
Figure 6. Model-predicted relationship for the proportion of scallops at length (mm) retained in a dredge with a 7-row apron relative to hanging duration. Shaded bands represent 95% confidence intervals.	14
Figure 7. Model-predicted relationship for the proportion of scallops at length (mm) retained in a dredge with a 5-row apron relative to hanging duration. Shaded bands represent 95% confidence intervals.	14
Figure 8. Model-predicted relationship for the proportion of scallops at length (mm) retained in a dredge with a extended link apron relative to hanging duration. Shaded bands represent 95% confidence intervals.	15

Tables

Table 1. Summary of research trips, dredge configurations, number of tows, and primary study objectives addressed for each trip.	4
Table 2. Schematic of the retrieval-time experimental design	5
Table 3. Total counts and weights (kg) of species collected during research tows conducted to evaluate scallop dredge performance across apron configurations.	9
Table 4. GLMM modelling coefficient estimates for catch rate.	11
Table 5. Beta-Binomial GLM modelling coefficient estimates for each apron configuration.	13

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1. Introduction

The Atlantic sea scallop (*Placopecten magellanicus*) fishery is one of the most economically valuable federally managed fisheries in the United States, with fleet ex-vessel revenue exceeding \$333 million in 2024 (NOAA 2026). To sustain scallop productivity while limiting impacts on non-target species, the Atlantic Sea Scallop Fishery Management Plan (FMP) relies on a combination of rotational area closures, effort controls, and gear regulations. However, persistent bycatch of yellowtail flounder (*Limanda ferruginea*) and windowpane flounder (*Scophthalmus aquosus*) remains a central management challenge (NEFSC 2023, 2024).

To address these bycatch concerns, Framework Adjustment 25 established a default seven-row maximum for the dredge apron, which took effect in March 2015 (NOAA 2014). This framework also required a further reduction to five rows (with a 1.5:1 twine top hanging ratio) if the fishery exceeded its sub-Allowable Catch Limit (ACL) for windowpane and yellowtail flounder. Because the scallop fishery recently exceeded this sub-ACL, Framework 38 enacted this stricter gear-based Accountability Measure for the 2024 and 2025 fishing years (NMFS 2024).

While modifying apron lengths and linking patterns can decrease the retention of non-target species, these changes also influence scallop retention, size selectivity, and operational practices (Davis et al. 2012, 2013, 2017, 2018, 2019). Following the implementation of the 5-row configuration, industry members expressed concerns that the shortened apron causes lower scallop retention due to increased winnowing or catch loss during haul-back. Consequently, vessels may be forced to conduct additional tows to achieve their catch allocations. Although previous studies indicate that altering hauling operations (such as pausing) can affect bycatch and retention rates, most scallop gear research has focused on performance during towing (Grothues et al. 2017). Far less attention has been directed toward evaluating how apron modifications impact winnowing during haul-back (Davis et al. 2012–2019).

These concerns underscore the need to evaluate how mandated dredge configurations influence catch retention throughout the entire fishing cycle. Recent advances in gear instrumentation offer new opportunities to address this gap. Specifically, tensiometers that measure warp tension in real-time provide a reliable way to detect changes in dredge loading, resistance, and behavior (Davis et al. 2022). Applying this technology, the present study evaluated scallop dredge performance under commercially representative conditions across four research trips. Using paired deployments, we compared the performance of 7-row, 5-row, and extended-link apron designs, utilizing tensiometers to quantify warp tension during both towing and haul-back. Additionally, controlled experiments with varied durations (5–30 min) were conducted to assess how time hanging at the gallus influences catch loss across the different configurations.

2. Project Objectives

The overall objective of this study was to evaluate selectivity and retention of the 5-row and extended-link apron relative to the 7-row apron and relate warp tension to dredge fullness.

The specific objectives of this project were:

- Compare the selectivity of a 5-row apron with a 1.5:1 mesh twine top, 7-row apron with a 2:1 mesh twine top, and extended link apron with a 2:1 mesh twine top.
- Evaluate warp tension (pounds-force) relative to bag configuration, catch weight and composition, and relevant tow and environmental variables, including vessel speed and Beaufort number.
- Investigate the impact of apron configuration on catch loss during dredge haul back (“winnowing”).

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Table 1. Summary of research trips, dredge configurations, number of tows, and primary study objectives addressed for each trip.

Trip	Date	Number of tows	Dredge Configuration			Primary Goal	
			7-row apron	5-row apron	Extended-link apron	Evaluating catch loss	Catch composition
1	9/4–9/11 2024	36	X			X	
2	1/21–1/23 2025	46	X	X			X
3	6/28–6/30 2025	36			X	X	
4	7/28–7/30 2025	35		X		X	

During all research trips, two scallop dredges were towed simultaneously for 30 minutes following standard commercial fishing practices. Vessel position was tracked by GPS at 1-second intervals, and tow speeds were maintained between 9 and 11 km h⁻¹. Sea state (Beaufort number: wave height and swell period) and depth were recorded for each tow. For all trips, a Dillon Quick Check Red tensiometer was affixed to the tow warp of each dredge to record warp tension (pounds-force) at 1-second intervals (**Figure 2**). The Dillon Quick Check Red tensiometer is a static load tensiometer, and though not ideal for this application due to hysteresis, was used because it could be easily transferred between vessels without requiring any modifications.

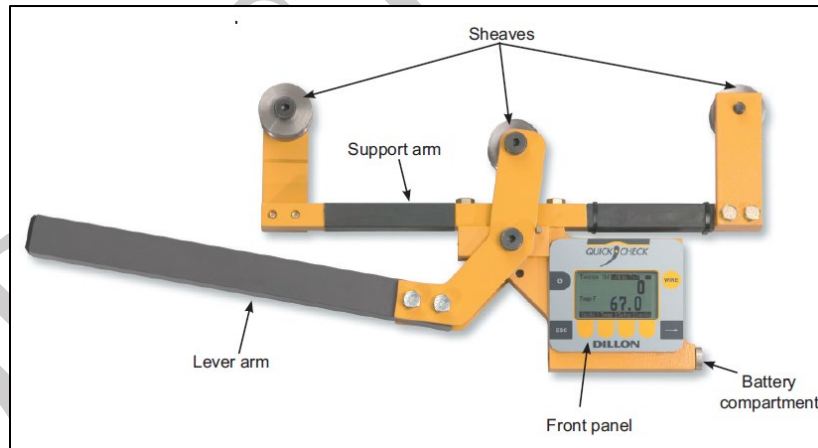


Figure 2. Dillon Quick Check Red tensiometer used to measure warp tension (pounds-force) during scallop dredge operations.

To evaluate catch loss during dredge haul back, the control dredge was retrieved immediately and emptied on deck, while the experimental dredge remained suspended in the water adjacent to the vessel for durations of 5, 15, or 30 minutes. After each duration treatment, the experimental dredge was retrieved and the catch was sampled. To minimize potential side-specific bias (Port vs. Starboard), time and control treatments were alternated using an ABBA pattern (**Table 2**). During each suspension treatment, a tensiometer collected warp tension at 1-second intervals.

Table 2. Schematic of the retrieval-time experimental design

Tow	Side	Treatment (minutes)
1	Port	5
2	Starboard	15
3	Port	30
4	Starboard	30
5	Port	15
6...46	Starboard	5

3.2 Catch Sampling and Processing

Each dredge catch was processed separately, using identical sampling protocols. For each tow and dredge, the catch was sorted by species and weighed using a Marel 1100-series motion-compensated scale. All fishes were counted and selected bycatch species, including flatfish, barndoor skate, monkfish, cod, haddock, dogfish, and other managed species, were measured to the nearest centimeter (total length). Winter (*Leucoraja ocellata*) and little skates (*L. erinacea*), and occasionally other less common skate species, were grouped as “unclassified skates.” **Table A1** lists the species and the number and weight caught during the project. The total scallop catch was quantified in bushels (bu = 35.2 L) for each tow. A one-bushel subsample of scallops was selected at random from each dredge and the cover net, from which shell height (SH) was measured for all individuals. Data for all individual lobsters caught in the dredges were collected by gear type. Carapace length, weight, sex, presence of eggs, shell hardness and incidence of shell disease was determined for each lobster. In addition to demographic data, the extent of damage caused by the dredge was recorded. Dredge damage was assessed on a scale from 0 to 5, with 0 indicating no damage and 5 indicating a fatal/dismembering crush by the dredge.

3.3. Data Analysis

Evaluation of FW 38 Windowpane Flounder Gear AM

To better determine if a 5-row apron and a 1.5:1 twine top significantly reduces flatfish bycatch relative to a dredge with a 7-row apron and a 2:1 twine top, the Generalized Linear Mixed Modelling (GLMM) approach developed in [Holst and Revill \(2009\)](#) was used to compare catches between the two gears. This approach allows for the inclusion of low order polynomials for covariates like animal length to potential nonlinear impacts of these covariates on the total catch ([Holst and Revill 2009](#)).

Evaluation of Warp Tension as a Predictor of Catch Rate ($\text{kg}\cdot\text{hr}^{-1}$)

To capture the dynamic relationship between gear performance and catch, high-frequency (1Hz) tension data were processed to extract fine-scale mechanical signatures. To mitigate sensor jitter, tension values (N) were smoothed using a 60-second centered rolling mean.

A Max Tension Slope feature was engineered to identify the peak rate of tension increase during each tow. This was calculated using a 300-second (5-minute) rolling window, where the slope was estimated via the covariance of time and tension:

$$\beta = \frac{cov(x, y)}{var(x)}$$

where x is time in seconds and y is the smoothed tension. This approach allowed for a more robust estimation of gear loading than simple global maximums. Additionally, a saturation index was calculated as the ratio of the average tension slope to the maximum tension slope, providing a proxy for how quickly the dredge reached peak loading capacity relative to its average performance.

Accumulation rates or catch rates ($kg \cdot hr^{-1}$) were modeled using a GLMM approach. Given that catch data are strictly positive and typically exhibit a right-skewed distribution where variance increases with the mean, a Gamma distribution with a log-link function was employed. The maximal model included fixed effects for peak tension ($N s^{-1}$), saturation index, acceleration/deceleration ($m s^{-2}$), substrate composition (% sand), wave height (m), depth (m), and wind offset (degrees) - the angular difference between wind direction and the vessel's heading. To account for the hierarchical nature of the sampling design and inherent variability between different survey legs, CruiseID was included as a random intercept.

A backward elimination procedure via the buildmer package was utilized to arrive at the most parsimonious model. Term deletion was determined by Likelihood Ratio Tests (LRT), systematically removing non-significant interactions and main effects until only significant predictors ($p < 0.05$) or those necessary for marginality remained. Model diagnostics were performed using the DHARMA package to inspect scaled residuals for uniformity and to check for overdispersion or outliers. Marginal effects and visualizations were generated using the ggeffects and ggplot2 suites to illustrate the predicted impact of mechanical and environmental drivers on dredge catch efficiency.

Evaluation of the Impacts of Apron Configuration on Winnowing

The proportion of scallops retained in the hanging dredge relative to the total catch was modeled using a Beta-Binomial GLM via the glmmTMB package. The Beta-Binomial distribution was selected over a standard Binomial distribution to account for overdispersion, which is common in fisheries catch data where individual observations within a tow may be correlated.

The global model for each cruise was specified as follows:

$$\text{logit}(p) = \beta_0 + \beta_1 \cdot L^2 + \beta_2 \cdot L \cdot D + \beta_3 \cdot D \cdot W$$

where:

- L represents standardized Shell Length (including a quadratic term L^2 to allow for non-linear selectivity curves).
- D represents standardized Hanging Duration.
- W represents standardized Wave Height.

To identify the most parsimonious drivers of catch proportion for each apron configuration, an automated multi-model inference approach (dredge function) was implemented using the MuMIn package. This exhaustive screening evaluated all possible sub-models derived from the global specification. The best model for each trip was selected based on the lowest Akaike Information Criterion corrected for small sample sizes (AICc).

Model fit and assumptions were verified using the DHARMA package, which utilizes a simulation-based approach to create standardized residuals. These residuals were inspected for systematic patterns, such as non-uniformity or heteroscedasticity.

To visualize the results, catch proportions were predicted across a range of shell lengths (30–180 mm) and discrete hanging durations (5, 15, and 30 minutes). During these simulations, all environmental covariates (e.g., wave height and period) were held constant at their respective trip-level means. Predicted values and their associated 95% confidence intervals ($1.96 \cdot SE$) were back transformed to the original scale for interpretation.

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4. Results by Objective

Objective 1: Investigate the performance of a 5-row apron with a 1.5:1 twine top relative to a 7-row apron with a 2:1 twine top

Paired dredge tows compared the catch performance of a 5-row apron with a 1.5:1 twine top to a 7-row apron with a 2:1 twine top configuration. A total of 45 valid paired tows were completed after excluding one tow in which gear fouling occurred. This operational failure was caught by the tensiometer and the tow was ended. Catch from both dredges was sampled following each tow, including total scallop catch weight, shell height distributions, and bycatch composition (Table 3).

Table 3. Total counts and weights (kg) of species collected during research tows conducted to evaluate scallop dredge performance across apron configurations.

Species	5-row apron		7-row apron	
	Counts	Weight (kg)	Counts	Weight (kg)
AMERICAN LOBSTER	16	28.504	26	48.85
AMERICAN PLAICE	1	1.21	5	4.71
ATLANTIC COD	1	3.02	1	1.46
BARNDOOR SKATE	71	33.27	93	31.28
FOURSPOT FLOUNDER	13	5.74	8	3.61
JONAH CRAB	-	12.44	-	17.34
LONGHORN SCULPIN	-	1.98	-	1.69
MONKFISH	23	53.04	28	73.78
RED HAKE	-	1.34	-	0.8
ROCK CRAB	-	2.59	-	1.68
SEA RAVEN	-	2.81	-	2.67
SEA SCALLOP (CLAPPER)	105	-	138	0
SEA SCALLOP	5035	6649.59	5006	6266.58
SILVER HAKE	-	-	-	0.98
SUMMER FLOUNDER	13	6.98	12	8.84
TRASH	-	401.72	-	382.75
UNCLASSIFIED SKATES	-	3698.35	-	5257.02
WINDOWPANE FLOUNDER	603	137.98	762	179.07
WINTER FLOUNDER	0	0	3	3.07
WITCH FLOUNDER	0	0	1	0.5
YELLOWTAIL FLOUNDER	12	6.3	16	10.78

Catch of sea scallops between the two dredge configurations showed a strong linear relationship across tows (Figure 3). Total catch from the 5-row apron dredge increased proportionally with catch from the 7-row apron dredge, indicating similar catch performance between configurations

over a wide range of catch magnitudes. Variability between dredges increased slightly at higher catch levels but remained within the confidence bounds of the fitted regression.

In contrast, there was a reduction in windowpane flounder associated with the 5-row apron relative to the 7-row apron (**Figure 4**). This pattern was evident across both low and moderate bycatch levels, suggesting that the reduced apron length was effective in decreasing windowpane flounder catch without a corresponding reduction in scallop catch. Despite attempts to target yellowtail flounder, catches were too low for a robust evaluation of relative gear efficiency for this species ($n = 12$ for the 5-row, and 16 individuals for the 7-row apron; **Table 3**).

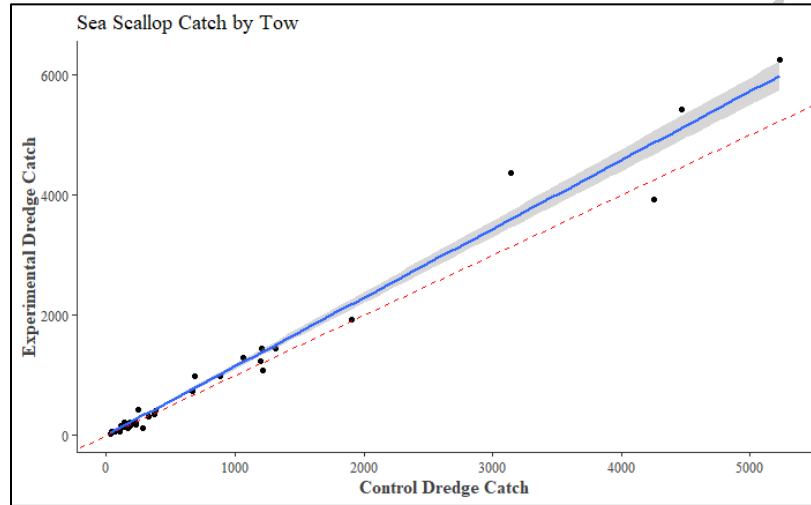


Figure 3. Pooled sea scallop catch efficiency of the 5-row apron with a 1.5:1 twine top relative to the 7-row apron with a 2:1 twine top.

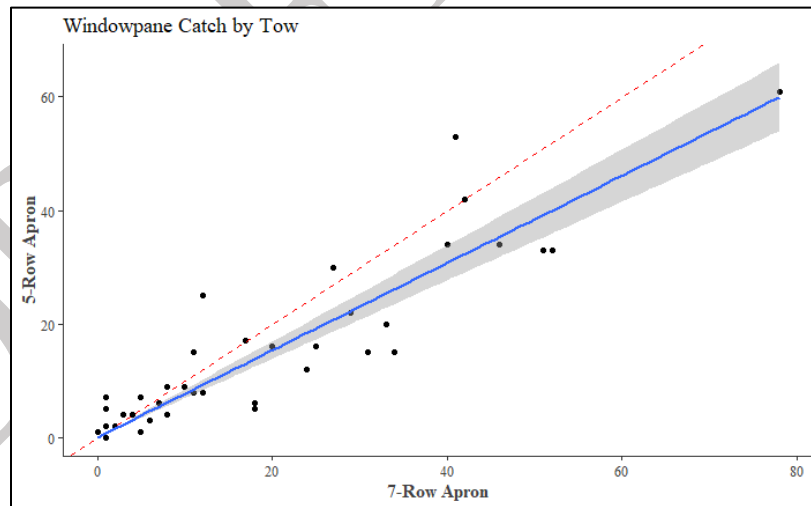


Figure 4. Pooled windowpane flounder catch efficiency of the 5-row apron with a 1.5:1 mesh twine top relative to the 7-row apron with a 2:1 mesh twine top.

Objective 2: Evaluate warp tension (pounds-force) relative to bag configuration, catch weight/composition, and relevant operational and environmental variables.

Mechanical Drivers (Tension and Speed)

Gear performance metrics were strong predictors of catch rate. The maximum tension slope had a significant positive effect ($\beta = 0.027, p = 0.0017$), indicating that more rapid increases in gear loading correlated with higher catch rates. Conversely, speed slope (centered) showed a strong negative relationship ($\beta = -1520, p < 0.001$). This suggests that even slight decelerations (negative slopes) relative to the mean towing speed were associated with increased material accumulation in the dredge (**Figure 5 and Table 4**).

Environmental and Substrate Effects

While wave height did not significantly impact catch rates, environmental factors played a critical role in catch variability. Depth was the most highly significant predictor ($\beta = 0.021, p < 0.001$), with catch rates increasing as the dredge moved into deeper waters within the study area. Percent sand had a positive influence ($\beta = 0.011, p = 0.016$), suggesting higher efficiency or higher species density or ‘trash’ accumulation in sandy habitats compared to coarser or finer sediments (**Figure 5 and Table 4**).

Finally, wind offset showed a significant positive effect ($\beta = 0.005, p < 0.001$), suggesting that surface conditions and vessel oscillation may subtly influence how the gear interacts with the seafloor (**Figure 5 and Table 4**).

Table 4. GLMM modelling coefficient estimates for catch rate.

Predictor	Estimate	Std. Error	t-value	p-value
(Intercept)	2.751	0.639	4.306	< 0.001 ***
Max Tension Slope	0.027	0.008	3.187	0.002 **
Speed Slope (c)	-1520	399.6	-3.804	< 0.001 ***
Percent Sand	0.011	0.005	2.427	0.016 *
Depth	0.021	0.004	5.396	< 0.001 ***
Wind Offset	0.005	0.001	4.004	< 0.001 ***

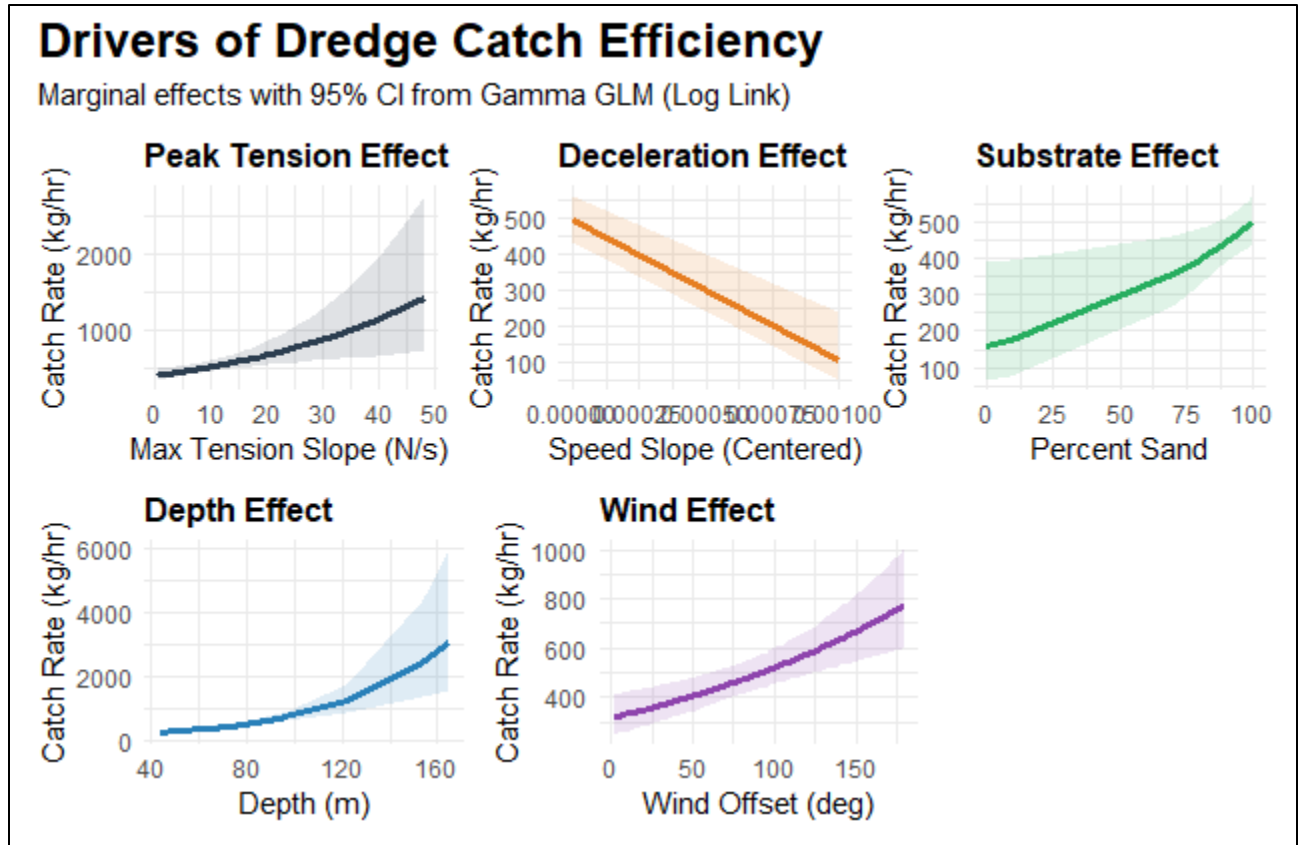


Figure 5. Marginal effects of environmental and operational variables on predicted dredge catch rates (kg hr^{-1}). Panels show the modeled relationships between catch rate and maximum warp tension slope (N s^{-1}), vessel acceleration (m s^{-2}), percent sand substrate, depth (m), and vessel heading relative to wind direction (wind offset, degrees).

Objective 3: Evaluate the impact of apron configuration on catch winnowing.

The best fitting model for the 7-row apron configuration included an interaction between wave height and hanging duration ($p = 0.002$) indicating that the effect of hanging duration varied with environmental conditions (**Table 5**). Though not significant shell height was retained by the most parsimonious model (**Figure 6**).

For the 5-row apron configuration, there was a significant interaction between shell height and hanging duration (**Table 5**), indicating that the impact of hanging duration differed among size classes, with retention increasing with shell height, resulting in a composition of between 56-80% larger scallops (>150 mm). However, unlike the 7-row apron, the effects of hanging duration were non-intuitive, with greater retention of smaller size classes (<65 mm) associated with longer hanging times (**Figure 7**) and relatively low retention of smaller scallops for the 5- and 15-minute hanging durations.

Moreover, the extended link apron configuration exhibited a strongly significant interaction between hanging duration and shell height and a marginally significant interaction between hanging duration and wave height (**Table 5**). Model predictions indicated a strong size-

dependent retention pattern like the 7-row apron but with substantial reductions in the proportion of sea scallops retained at 30 min hanging durations. During the 5 min hanging duration, predicted retention remained relatively consistent across scallop sizes, indicating minimal size-dependent loss during short retrieval times with this dredge configuration (**Figure 8**).

Table 5. Beta-Binomial GLM modelling coefficient estimates for each apron configuration.

Predictor	Estimate	Std. Error	z value	Pr(> z)
<i>7-Row Apron</i>				
(Intercept)	0.049	0.052	0.955	0.340
Hanging Duration (secs)	-0.088	0.050	-1.736	0.083
Shell Height (mm)	0.098	0.056	1.765	0.078
Wave Height (m)	0.254	0.053	4.800	0.000
Hanging Duration: Wave Height	-0.170	0.056	-3.040	0.002
<i>5-Row Apron</i>				
(Intercept)	-0.034	0.040	-0.842	0.400
Hanging Duration (secs)	-0.083	0.035	-2.333	0.020
Shell Height (mm)	0.148	0.053	2.773	0.006
I(Shell Height^2)	0.069	0.044	1.553	0.120
Hanging Duration: Shell Height	-0.160	0.043	-3.739	0.000
<i>Extended-Link Apron</i>				
(Intercept)	0.285	0.191	1.490	0.136
Hanging Duration (secs)	0.178	0.178	0.999	0.318
Shell Height (mm)	0.359	0.070	5.146	0.000
Wave Height (m)	-0.470	0.138	-3.399	0.001
Hanging Duration: Shell Height	0.191	0.063	3.013	0.003
Hanging Duration: Wave Height	-0.226	0.118	-1.911	0.056

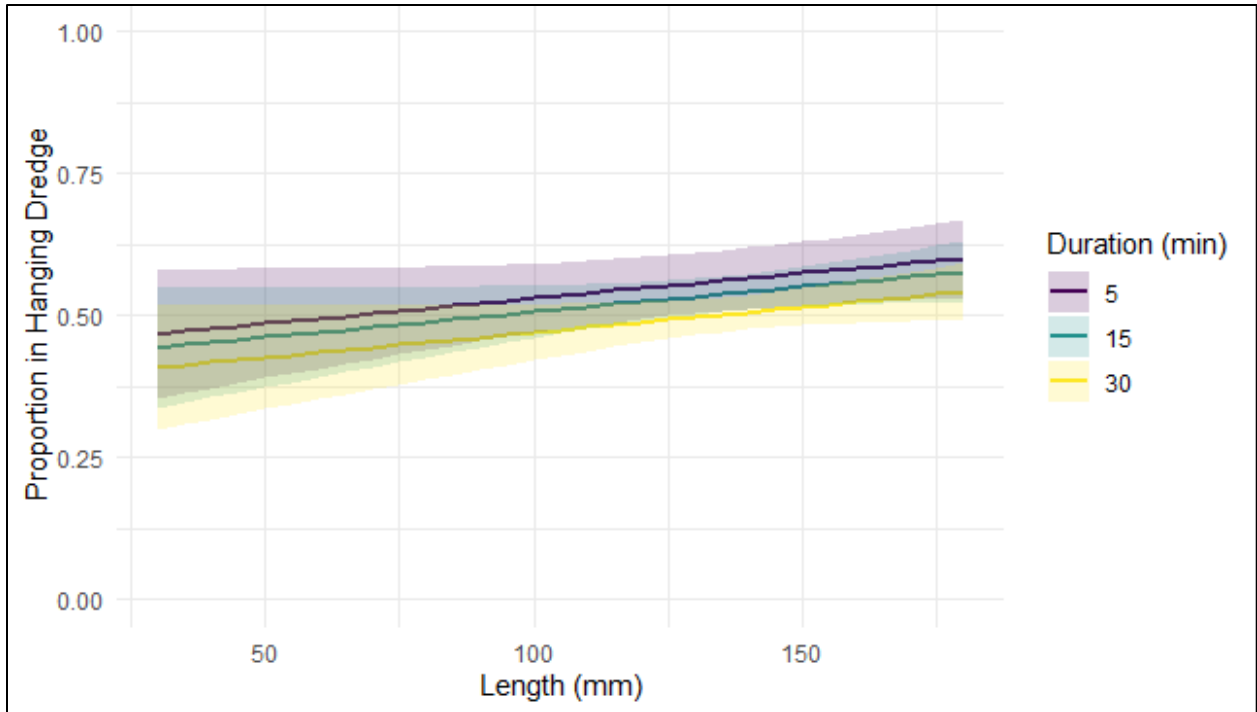


Figure 6. Model-predicted relationship for the proportion of scallops at length (mm) retained in a dredge with a 7-row apron relative to hanging duration. Shaded bands represent 95% confidence intervals.

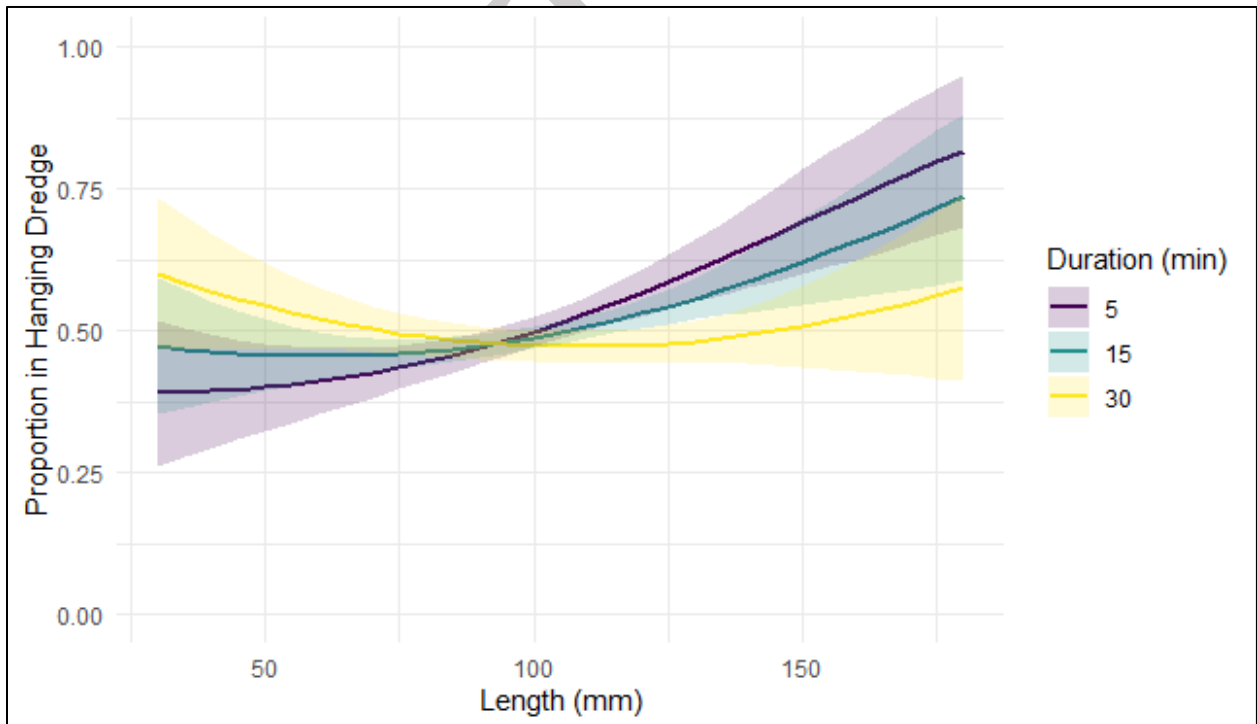


Figure 7. Model-predicted relationship for the proportion of scallops at length (mm) retained in a dredge with a 5-row apron relative to hanging duration. Shaded bands represent 95% confidence intervals.

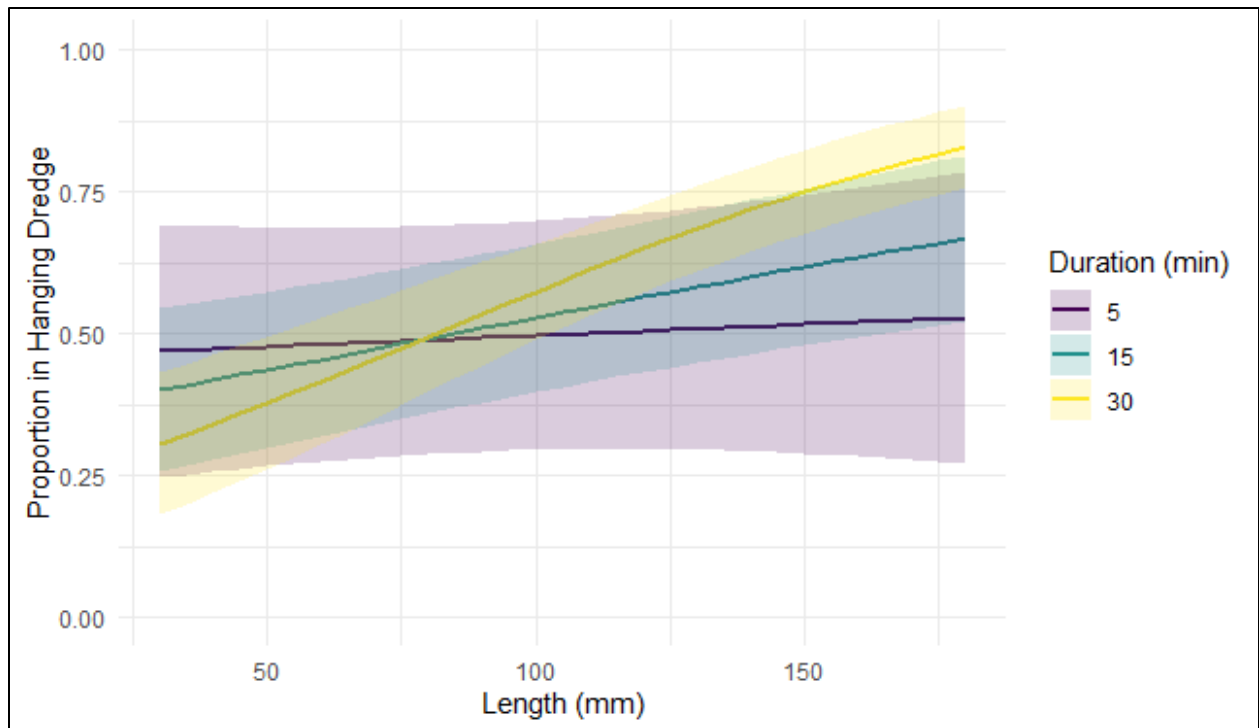


Figure 8. Model-predicted relationship for the proportion of scallops at length (mm) retained in a dredge with a extended link apron relative to hanging duration. Shaded bands represent 95% confidence intervals.

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5. Discussion

Evaluation of the 5-row apron and 1.5:1 twine top

The 5-row apron and 1.5:1 twine top was implemented under Framework 25 as a necessary reactive AMs to address urgent windowpane bycatch (NOAA 2014). While results from this project confirm that the 5-row configuration maintains scallop catch rates comparable to the 7-row standard, the bycatch reduction provided by this modification is more subtle than previous than previous testing had implied (Davis et al. 2012, 2013). As management inverted the baseline apron requirement from a 7-row minimum to a 7-row maximum, the relative benefit of dropping to 5 rows has diminished. While the 5-row apron remains a functional tool, its continued use represents a plateau in gear-based mitigation strategies with modest bycatch savings rather than the step-change needed to address increasingly stringent bycatch allocations.

In contrast to the marginal gains of the 5-row apron, the extended link apron offers a significantly higher mitigation ceiling. The extended link apron trials executed in 2018-2019 across Southern New England and Georges Bank demonstrated that this configuration reduces windowpane flounder bycatch by 29.9% while maintaining a nearly negligible impact on scallop landings (less than 4% loss; Davis et al. 2018, 2019). When compared to the subtle reductions observed during recent 5-row testing, the extended link apron's reduction parameters (0.71 for windowpane and 0.70 for yellowtail) represent a more aggressive and reliable technical solution (Davis et al. 2018, 2019). By decoupling the escapement mechanism from simple apron shortening, the extended link apron optimizes the physical interaction between the gear and flatfish, allowing for high-volume escapement without the risk of losing the target species often associated with more drastic apron reductions and twine top alterations.

The adoption of gear modifications in commercial fisheries is historically hindered by concerns over reduced catch efficiency, which can lead to increased fishing effort and higher operating costs (Suuronen 2022). Because the extended link apron achieves a ~30% bycatch reduction with only a marginal (<4%) scallop loss, it offers a more favorable efficiency-to-bycatch ratio than the 5-row apron. This high target-species retention is critical for industry acceptance. By implementing the extended link apron as a primary mitigation tool, managers can offer the fleet a way to avoid exceeding flounder sub-ACLs and reduce fishery impacts to sea scallop resources in high-density, mixed year class areas (Davis et al. 2018, 2019).

While the 5-row apron was a successful immediate response to the bycatch issues in 2014, the extended link apron represents the next logical step in the evolution of scallop gear regulations. To finalize this transition, future modeling should use seasonal fishing effort data to evaluate how a fishery-wide shift to the extended link apron would impact total landings. Ultimately, the extended link apron provides the fishery with a more precise, high-performance tool to balance

ecological sustainability with commercial viability.

Warp Tension as an Indicator of Dredge Loading

Warp tension dynamics, vessel acceleration, substrate composition, depth, and wind orientation were all associated with variation in catch rates, highlighting the complex interaction between gear mechanics, vessel operation, and seabed conditions (Davis et al. 2017, Grothues et al. 2017, Queirolo et al. 2012). In this study, a static load tensiometer was used to capture these warp tension dynamics during active towing. Static load tensiometers are typically designed for applications where both ends of a wire are anchored, allowing direct measurement under relatively stable loading (Rugged Controls, personal communication). When used on a towing warp, measurements are inherently influenced by wire strain, slack from variations in wire scope, and vessel motion due to sea state, all of which introduce short-term signal variability. To mitigate this, the tensiometer was affixed between the winch and the towing block, effectively serving as anchor points to stabilize wire motion. While this configuration successfully captured meaningful variations in dredge loading the relatively low sensitivity of the static instrument and high signal variation restricted the highly reliable predictive range of catch weights to between 460 and 1,200 kg. Despite being coarse, this relationship proved sufficient for identifying optimal haul-back windows and detecting pronounced operational failures, such as crossed dredges.

Several environmental variables were strongly associated with increased catch rates, primarily driven by the underlying ecology of the benthic communities. The positive relationship between catch and percent sand highlights how substrate composition dictates both mobile gear interaction and species distribution (Valentine & Lough 1991). Previous studies on Georges Bank indicate that echinoderms, including the common sand dollar (*Echinarachnius parma*), account for nearly half of the regional macrobenthic biomass (Rosellon-Druker & Stokesbury 2019). Because sand dollars and sea scallops both prefer moderately fine to medium-grained sand habitats (Brown 1983, Hart 2004), their dominance in these widespread Northwest Atlantic environments explains the higher catch rates observed over sand substrates. Notably, when caught in these areas, sand dollars comprised approximately 80% of the total catch volume.

Depth also emerged as a strong ecological predictor, with predicted catches increasing substantially across the observed depth range. In the Northwest Atlantic, invertebrate and demersal fish assemblages vary across depth gradients in response to temperature and current regimes (Collie et al. 1997, Kostylev et al. 2001, Kaiser et al. 2002). Because this analysis grouped multiple species, the positive depth-catch relationship likely reflects spatial variation in the local abundance of seasonally dominant taxa, including the depth-associated habitat preferences of Atlantic sea scallops and sand dollars (Brown 1983, Hart 2004).

While the significance of depth is likely driven by ecology, it introduces distinct operational challenges that would influence dredge performance. As depth decreases or increases, the wire needs to be adjusted to maintain a consistent scope (wire-to-depth ratio) which impacts the sensitivity of the tensiometer ([Rugged Controls, personal communication](#)). The static Dillon Quick Check tensiometer used in this study does not account for wire sliding through the block as depth changes, nor does it allow for dynamic adjustments to maintain a consistent scope. While running line tensiometers or hanging block load cells can account for these subtle depth transitions, they require permanent vessel alterations limiting their application in proof-of-concept studies like this one. The ability to adjust scope while providing operators with real-time tension readings would reduce variability associated with depth making running line tensiometers or hanging block load cells more accurate and precise instruments for monitoring dredge loading while towing.

Beyond depth, vessel kinematics related to weather conditions not only impacted dredge efficiency but also the sensitivity of the tensiometer. Towing directly into prevailing winds transfers kinetic energy from the pitching vessel down the tow wire, disrupting the dredge's hydrodynamic behavior and bottom-tending capability while also imparting greater variability in tension readings. Conversely, towing with or across the wind improves stability, minimizing vertical movement, allowing the operator to hold a more consistent speed and the tensiometer to collect more stable readings. Vessel acceleration was negatively associated with catch rate, reinforcing that maintaining an optimal, stable towing speed is vital for maximum gear efficiency ([Davis et al. 2017](#); [O'Neill & Ivanović, 2016](#)). Operators compensate for the natural drag of an accumulating catch by increasing engine revolutions per minute (RPMs) to maintain this speed. However, when towing with the wind and tide, excess vessel momentum masks this deceleration, making it difficult for operators to infer dredge saturation from RPMs alone until a massive volume of material has already accumulated.

Ultimately, these behavioral, environmental, and mechanical nuances underscore the value of integrating high-resolution sensor data with traditional catch metrics. The positive relationship observed between maximum tension slope and catch rate aligns with previous work showing that tension increases reflect changes in bottom contact and catch accumulation ([O'Neill & Summerbell 2016](#); [Engas 1994](#)). Real-time tension data can eliminate the guesswork of inferring gear saturation from RPMs and momentum alone. By knowing exactly when the gear is full, fishermen can optimize haul-back times, avoiding excessively long tows that cause unnecessary benthic impacts. Furthermore, tension data can immediately identify fouled or entangled gear, allowing operators to correct performance mid-tow, avoid rocky seafloor hazards, and prevent wasted fishing effort.

Mechanisms of Catch Loss During Retrieval

Size-dependent retention is a hallmark of scallop dredge fisheries, as the removal of towing tension during haul-back causes the dredge bag to relax and reconfigure ([Millar 1992](#)). Across all

apron configurations in this study, shell height emerged as the primary predictor of retention, with larger scallops consistently exhibiting a higher probability of remaining in the bag than smaller individuals. This suggests that as the bag loses its taut, elongated shape during retrieval, smaller scallops can more easily pass through the apron or twine top (Holst & Reville 2009). However, the specific geometry of the apron determines the initial escape window; the 5-row apron, with its five rows of rings and 1.5:1 twine top, has a longer twine top compared to the 7-row or extended-link configurations, facilitating a higher rate of initial escapement for all size classes.

Notably, an unexpected pattern was observed in the 5-row apron configuration, where the model predicted an increased proportion of smaller scallops at 30 min hang durations. This trend contradicts the general expectation that longer hangs lead to greater catch loss. This could indicate a two-stage catch redistribution process within the bag. Immediately after towing ends, the initial shaking and reconfiguration of the bag allow smaller scallops near the openings to escape. Following this initial loss, the remaining catch likely stabilizes; larger individuals settle and compress, trapping smaller scallops within the interior of the catch mass and debris. Consequently, the higher retention predicted at longer durations likely reflects a shift in the relative composition of the remaining catch, where intermediate and larger scallops continue to drop out gradually through the 1.5:1 twine top, rather than an absolute increase in the number of small scallops. This trapping effect was absent in the 7-row and extended-link configurations, likely because their smaller openings limit the pathways available for small scallops to reach the escape zone before the catch stabilizes.

Wave height significantly influenced retention, though the influence of this effect was dictated by gear geometry. For both the 7-row and the extended link aprons, increased wave height was associated with reduced retention. This aligns with the mechanism proposed by Grothues et al. (2017), where wave-induced vessel motion causes the dredge bag to oscillate. For the extended-link gear, increased wave height improves size selectivity independent of hanging duration. In contrast, size selectivity was not influenced by wave height for the 7-row apron and instead increased wave heights strengthened the effect of hanging duration on catches.

Management Implications

Transitioning to the Extended Link Apron

The findings of this study suggest that the 5-row apron configuration does not reduce flatfish bycatch as efficiently as extended link aprons. For this reason, the latter should be considered as a superior regulatory alternative or a primary successor to the currently mandated 5-row apron. While the 5-row apron served as a critical reactive measure under Framework 25, it has reached a performance plateau relative to the current industry baseline.

- **Performance Advantage:** Managers can use the extended-link apron as a more effective

bycatch mitigation tool, as it provides greater reductions in windowpane flounder (~30%) while maintaining scallop catch closer to standard configurations. This allows compliance with increasingly strict bycatch limits without the target-species losses and reduced efficiency often associated with more aggressive apron shortening.

- **Industry Acceptance:** Because the extended link apron preserves scallop landings (less than 4% loss), its implementation reduces the economic risk of increased fishing effort and can facilitate higher industry compliance and acceptance compared to less efficient gear.
- **High Density/Mixed-Year Class Areas:** With improved selectivity, the extended link apron can be used to reduce incidental mortality of sea scallops in high density/mixed-year class areas.

Integration of Real-Time Tension Monitoring

The positive relationship between warp tension slope and catch rate provides a pathway for increased catch efficiency and improved sustainability.

- **Dredge Saturation:** Management should encourage the adoption of tensiometers (specifically running line tensiometers or load cells for more precise depth-adjusted data) to monitor dredge loading. This eliminates the operators reliance on estimating saturation via RPMs and vessel momentum, which can be masked by wind and tide.
- **Reduced Benthic Impact:** By identifying exactly when a dredge is full or fouled, operators can optimize haul-back timing. This reduces unnecessarily long tow durations, thereby minimizing total gear interaction with the seabed and non-target species

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7. Appendix

Table A1. Species captured during this project. Scallop and trash catch is quantified in bushels and fish/crustacean in number of individuals.

Common Name	Scientific Name	Weight (kg)	Number Caught
American lobster	<i>Homarus americanus</i>	319.794	191
American plaice	<i>Hippoglossoides platessoides</i>	7.74	9
Atlantic cod	<i>Gadus morhua</i>	4.48	2
Barndoor skate	<i>Dipturus laevis</i>	1185.93	1609
Butterfish	<i>Peprilus triacanthus</i>	0.21	3
Chain dogfish	<i>Scyliorhinus retifer</i>	0.34	1
Fourspot flounder	<i>Paralichthys oblongus</i>	52.6	178
Gulfstream flounder	<i>Citharichthys arctifrons</i>	1.42	23
Haddock	<i>Melanogrammus aeglefinus</i>	2.11	2
Hagfish	<i>Myxine glutinosa</i>	1.06	11
Illex squid	<i>Illex illecebrosus</i>	0.58	4
Jonah crab	<i>Cancer borealis</i>	291.61	977
Loligo squid	<i>Doryteuthis pealeii</i>	0.08	1
Longhorn sculpin	<i>Myoxocephalus octodecemspinosus</i>	8.05	21
Monkfish	<i>Lophius americanus</i>	3088.7	1884
Red hake	<i>Urophycis chuss</i>	35.9	229
Rock crab	<i>Cancer irroratus</i>	12.26	71
Sea raven	<i>Hemitripterus americanus</i>	23.37	16
Sea scallop	<i>Placopecten magellanicus</i>	33375	1,042
Silver hake	<i>Merluccius bilinearis</i>	13.41	115
Smooth skate	<i>Malacoraja senta</i>	4.64	11
Squid uncl	<i>Teuthida</i>	1.66	1
Summer flounder	<i>Paralichthys dentatus</i>	15.82	25
Unclassified skates	<i>Rajidae</i>	19853	100527
White hake	<i>Urophycis tenuis</i>	1.09	9
Windowpane flounder	<i>Scophthalmus aquosus</i>	320.08	1376
Winter flounder	<i>Pseudopleuronectes americanus</i>	36.01	21
Witch flounder	<i>Glyptocephalus cynoglossus</i>	14.8	27
Yellowtail flounder	<i>Limanda ferruginea</i>	20.51	33
Trash		27,306	853