Developing an effective foot sweep to reduce flounder bycatch in scallop dredges using computational fluid dynamics and field testing with paired dredges

Final Report

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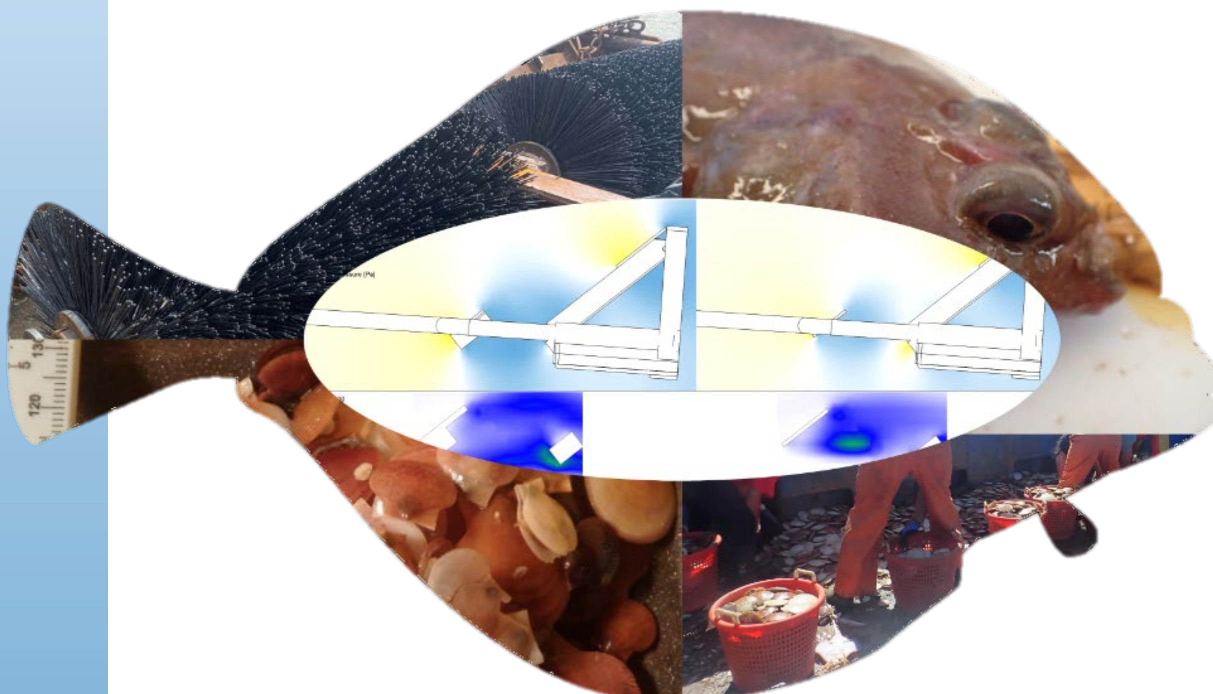

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Project Title: Developing an effective foot sweep to reduce flounder bycatch in scallop dredges using computational fluid dynamics and field testing with paired dredges

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Organization: Coonamessett Farm Foundation, Inc.

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Executive Summary

Working with a panel comprised of sea scallop industry members, CFF designed and tested a street sweeper sweep. Development of this modification utilized CFD analysis to visualize flow around the modification and predict the path of particles interacting with the modification. A visual comparison of the CFD simulations for the previously tested rubber disc sweep indicated that fewer sea scallops would travel over the dredge with the street sweeper sweep and sea scallop catch may not be as impacted. Field testing revealed that a street sweeper sweep reduces flatfish bycatch by ~45% with a ~20% reduction in sea scallop catch. Similar to what had been observed when testing the rubber disc sweep. While the CFD particle study did not predict as great of a reduction in sea scallop catch, this difference may be the result of software limitations and differences between the CAD drawing and the real-world street sweeper sweep. Overall, CFD analysis was able to identify key factors influencing the performance of the street sweeper sweep and going forward this tool could be used to optimize sweep designs for reducing flatfish bycatch in the sea scallop fishery.

Project timeline

Research period: June 1, 2021 - August 31, 2022

Industry design meeting: October 20, 2021

CFD simulations: June 2021 through March 2022

Sweep development: October 2021 – April 2022. The final gear was completed April 5, 2022.

Field testing: May 2022 – August 2022 (F/V Contender: 5/23-5/28 and F/V Concordia: 8/16-8/20)

Project management and participation

Project management: Farrell Davis.

CFD simulations: Liese Siemann.

Sweep design and construction: Tim Lenling with assistance from Farrell Davis and Ronald Smolowitz

Field testing: Farrell Davis, Nathan Shivers, Victoria Oriole (CFF – Sea tech.), Ryan Munnelly (CFF – Sea tech.). The F/V Contender and F/V Concordia are owned by Brian Kvilhaug and operated by Lloyd Jacobsen.

Analysis of catch data: Farrell Davis and Nathan Shivers

Background

Bycatch of yellowtail flounder (*Limanda ferruginea*) and windowpane flounder (*Scopthalmus aquosus*) in the sea scallop (*Placopecten magellanicus*) fishery is, in part, managed through the implementation of gear restricted areas (GRA). Currently, within the sea scallop GRAs, a sea scallop dredge cannot have an apron exceeding five rows of rings and a twine top exceeding a hanging ratio of 1.5 meshes per ring. This gear restriction reduces flatfish bycatch by making it easier for the animal to escape from the dredge bag through the twine top (**Figure 1**; Davis et al. 2012, Davis et al. 2013). However, this modification only works to reduce bycatch after the animal has entered the dredge.

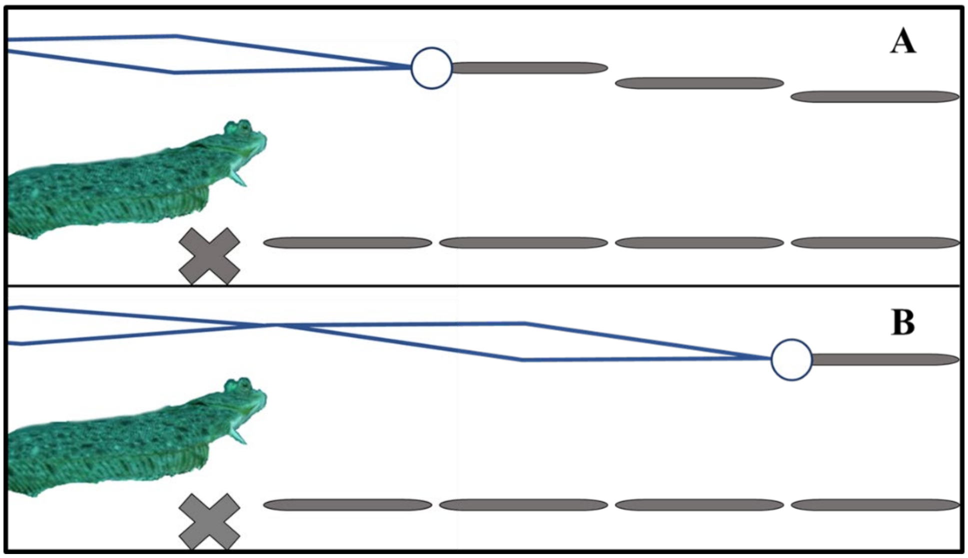

Figure 1: Top (A) the relative position of apron/twine boundary for a dredge bag with a seven row apron and an eight row belly. Bottom (B) a dredge with a five row apron and an eight ring belly.

A dredge bag is a hostile environment for flatfish, and to escape the animal must pass through the twine top or rings. A "clean" escape, without contacting the dredge bag, is very unlikely because a flatfish would need to swim at an impossible speed of 357 cm/s (He 1993). Based on previous research using dredge covers, significantly more flatfish are escaping through the dredge than are being retained (Davis et al. 2019). Without research about the fate of escapees, improving the posterior selectivity of fishing gear may not be the most appropriate way of protecting non-target species (Chopin & Arimoto 1995, Broadhurst et al. 2006). Intuitively, the highest mortality of escapees would occur in the dredge bag, therefore selective mechanisms should focus on facilitating escape ahead of the dredge bag in the absence of research about the fate of escapees.

For most bottom-tending mobile gears, a sweep or series of sweeps is used to make the target species available to the codend or dredge. While sweeps are most often used this way, the relatively short height of sea scallop dredges provide an opportunity to develop sweeps into flatfish deflectors i.e. a device to stimulate escape over the dredge. By stimulating flatfish to escape over the dredge, the animal's overall interaction with the dredge is reduced. Encouraging flatfish to escape in this way capitalizes on a behavioral type of selection. Relative to mechanical sorting, a behavioral-type escape would be less likely to result in escapee damage or mortality (Broadhurst et al. 2006). Water flow is a key factor influencing escape through behavioral-type mechanisms and can be manipulated to guide animals towards escape locations (Broadhurst et al. 2002). Previous research testing sweeps to reduce flatfish bycatch in sea scallop dredges indicated that flow and not direct contact may be eliciting an escape response in flatfish (Alexander & Davis 2018; Alexander & Davis 2019).

Advances in software during the last two decades have allowed for the development of flow simulation packages capable of simulating flow around fishing gears. By predicting key performance parameters, these software packages can provide a rapid, low-cost alternative to field testing when optimizing fishing gears (Winger et al. 2006, Meyler 2008, Hermannsson 2014, Nguyen et al. 2015, and Siemann et. al 2021). While computational fluid dynamics (CFD) analysis is routinely used by other industries to aid design, it has yet to be widely used to aid in designing fishing gear (Siemann et. al 2021). CFD analysis is ideal for evaluating modifications to a scallop dredge because it is rigid and does not have many moving parts unlike a dredge bag. The performance of a low-profile dredge predicted by CFD particle studies were similar to what had been observed during gear trials but, this method has not been used to inform the design of gear prior to field testing (Siemann et. al 2021).

When tested in the field, a rubber disc sweep reduced the bycatch of yellowtail and windowpane flounder catches by 68.9% and 77.6%, albeit with a 20% reduction in sea scallop catch (Alexander & Davis 2019). Modeling of the sea scallop data indicates that animal length is a significant predictor for the relative efficiency of the rubber cook sweep (Alexander & Davis 2019). A majority of the reduction in sea scallop catch was for animals less than 110 mm and catches of larger, more marketable scallops were similar (Alexander & Davis 2019). Flow around the rubber disc sweep may be a key factor influencing the performance of this modification. By using CFD analysis to evaluate the rubber disc sweep, the performance of similar modifications can be predicted and the design optimized before field testing takes place.

Objectives

The project objectives included:

(1) Utilize CFD models to test variations on two types of modifications to dredge frames: simplified rubber disc sweeps and a secondary depressor plate mounted forward of and parallel to the cutting bar.

(2) Work with an industry advisory panel to determine which modifications to test in the field.

(3) Modify and test a 15-foot (4.6-m) commercial Turtle Deflector Dredge (TDD) with the most promising modifications.

Methods by Objective

(1) Utilize CFD models to test variations on two types of modifications to dredge frames: simplified rubber disc sweeps and a secondary depressor plate mounted forward of and parallel to the cutting bar.

Flow around a TDD dredge frame with a simplified version of the rubber disc sweep tested previously (Alexander & Davis 2019) and a TDD frame with a secondary depressor plate located at the bend in the bale bars (**Figure 2**) was modelled and compared to flow around a TDD with no modifications and field data collected during trials with the rubber disc sweep. The Flow Simulation package in SolidWorks was used to run the CFD models using the parameters shown in **Table 1**. Tow speed was set to 5 knots and the bale angle was set to 4° based on flume tank testing of a scaled model TDD towed at a scaled speed of 5 knots (Siemann et al. 2021).

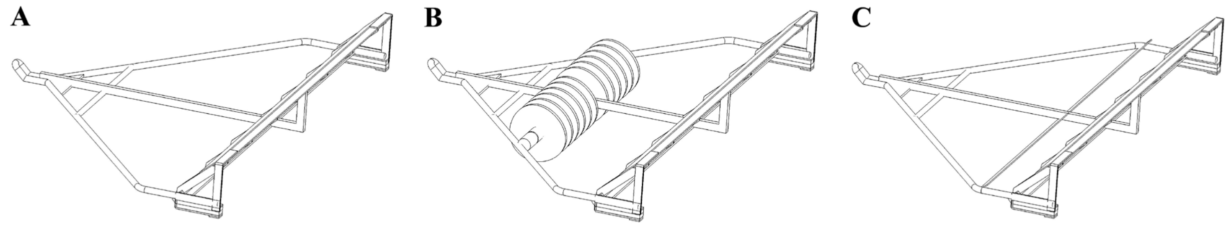

Figure 2: (A) Control TDD. (B) TDD with a simplified version of the rubber disc sweep. (C) TDD with an secondary depressor plate at the bend in the bale bars.

Dredge catch was modelled using particle injections of equivalent-volume spheres with densities that approximated those of scallops and fish. Injections of particles in front of the dredge frame were designed to represent scallops that were buried or sitting on the surface (-2 to 3cm) and flounder that were buried, on the surface, or up in the water column (-2 to 30 cm). Scallops and flounder were classified as going into the dredge bag, over the dredge, toward the twine top, or under the dredge bag based on the trajectory between the front of dredge frame and the start of the sweep or the end of the twine top. A range of catch values were estimated with the particle studies because 50-100% of the particles that headed toward the twine top were assumed to pass through the mesh and out of the dredge. Comparisons between model output and the results of at-sea trials conducted with the rubber disc sweep included only large scallops (>110-mm shell heights) and flounder with widths greater than 11 cm (yellowtail and fourspot flounder lengths>30 cm and windowpane flounder lengths>24 cm) to exclude sizes that could pass through the dredge bag (for additional details, see Siemann et al. 2021). Modelled scallop sizes were 100 mm, 130 mm, and 150 mm; and modelled flounder sizes were 30 cm and 45 cm to include a range of sizes typically observed in dredge hauls.

(2) Work with an industry advisory panel to determine which modifications to test in the field.

CFD results were presented to an industry advisory panel whose membership includes fishing vessel owners, operators, gear manufacturers, and engineers. Modifications were assessed by the industry panel in terms of operational feasibility, likelihood of effectiveness, and likelihood of voluntary uptake by the industry. Based on sustained input from the industry panel, a final modification was selected to be built and tested in the field.

(3) Modify and test a 15-foot (4.6-m) commercial Turtle Deflector Dredge (TDD) with the most promising modifications.

(3.1) Field Testing of Street Sweeper

Average tow speeds ranged from 3.6-5.6 kts, the tow wire scope was 3:1+10 fathoms for both the control and experimental dredge, and tow duration ranging from 15-66 minutes. On most tows, the entire scallop catch was weighed in bushel baskets and a one basket sub-sample from each side was measured to the nearest millimeter. When catch volume was too large to weigh entirely, the volume of catch was estimated, and a representative sample was weighed to extrapolate scallop catch weights. For all tows, the entire fish catch was weighed by species, and commercially important species were measured in one-cm increments. All catch was returned to the sea following sampling. Distance covered by each tow was recorded using an internal GPS program to record dredge path distance.

Biological data collected from each dredge for each tow included:

- Scallop catch rates (total weight and # of baskets)
- Scallop shell height frequency (one bushel/side/tow)
- Commercial finfish and invertebrate length frequency and total weight (by species)
- Other finfish and invertebrate total weight and number caught.
- Weight and composition assessment of trash (i.e. sea stars, crabs, sponges, etc.).

(3.2) GLMM Analysis of Catch Data

Catch data (number of individuals) from paired tows was analyzed with a generalized linear mixed model (GLMM) as developed in Holst and Revill (2009). Comparative fishing experiments generate binomial data and allow for the estimation of the expected proportions at length captured by the experimental gear. While the underlying process (i.e. true selectivity characteristics of the gear) cannot be estimated from comparative fishing experiments, this method offers a number of advantages. This approach accounts for between-haul variability and effects related to sub-sampling the catch to accurately represent the degrees of freedom for more reliable statistical inference (Fryer 1991, Millar et. al. 2004). Depending upon the underlying selectivity characteristics of the gear, the inclusion of low order polynomials to describe observed non-linearity of the response, can accurately describe the mean proportion of the total catch caught by the experimental gear at length (Holst & Revill, 2009).

Following the completion of all cruises, a simple statistical analysis of the data was carried out using R Statistical Software to evaluate the performance (R Core Team 2021). Statistical analysis was conducted on pooled data as well as data from each of the individual cruises to identify and exclude outlying and invalid tows.

The GLMM analysis attempted to construct a model that would predict the efficiency of the flounder sweep dredge relative to the control dredge as a function of a variety of covariates. In many instances, especially with gear modifications that can possibly alter the relative size composition of the catch, exploring the relative catch at length is informative. For many species, however, length may not be a significant predictor of relative efficiency. In these cases, the overall change in the relative proportion (Test/(Test + Ctrl)) was tested using the pooled catch data (summing catch over all lengths for a given tow).

In addition to length, tow duration and tow speed were also included in the modelling exercise as covariates. The volume of catch within the dredge can impact the angle of a dredge and the performance of a dredge (Rudders et al. 2020). Catch volume is impacted by tow duration i.e. longer tows will have more catch than shorter tows when fished in the same area. Tow speed was evaluated in the model because of the impacts this parameter has on flow around the dredge. Overall catches of individual flatfish species were low and flatfish species were aggregated for this analysis. Therefore, a species covariate was tested when modelling the flatfish data in addition to length, tow duration, and tow speed. All models included haul as a random effect (Holst & Revill 2009). The models developed for this report used the R package "lme4" (Bates et al. 2015).

Results

(1) Utilize CFD models to test variations on two types of modifications to dredge frames: simplified rubber disc sweeps and a secondary depressor plate mounted forward of and parallel to the cutting bar.

During field trials, observed catch of large scallops was reduced by 14.8% relative to the control dredge when the rubber disc sweep was used (data from Alexander & Davis 2019), a result that was close to the predicted 14.2% reduction in scallop catch if all scallops heading toward the twine top pass through the mesh (**Table 2**). Trajectories from the particle studies indicated that a large proportion of scallops were sent over the top of the dredge frame when the sweep was used (**Figure 3**). Catch of large flounder was reduced by 67.7-68.9% during field trials using the rubber disc sweep, but the model predicted catch reductions of only 17.0-20.9%. However, if the model inputs assumed that all flounder would swim up off the bottom in response to an approaching sweep, reductions predicted by the model were 62.3-64.4%, approaching results from the field trials (**Table 2**).

Model results from the secondary depressor plate indicated that this dredge modification could be more effective than a rubber disc sweep, with no reductions in catch of large scallops and a 14.8 – 22.8% reduction in flounder catch (**Table 2**). Particle studies indicated that large scallops remained on the bottom and a larger proportion of large flounder were sent over the top of the dredge frame (**Figure 3**). Because a secondary depressor plate would be unlikely to stimulate flounder to swim off bottom, catch reductions if all flounder were off bottom as the dredge approached were not tested.

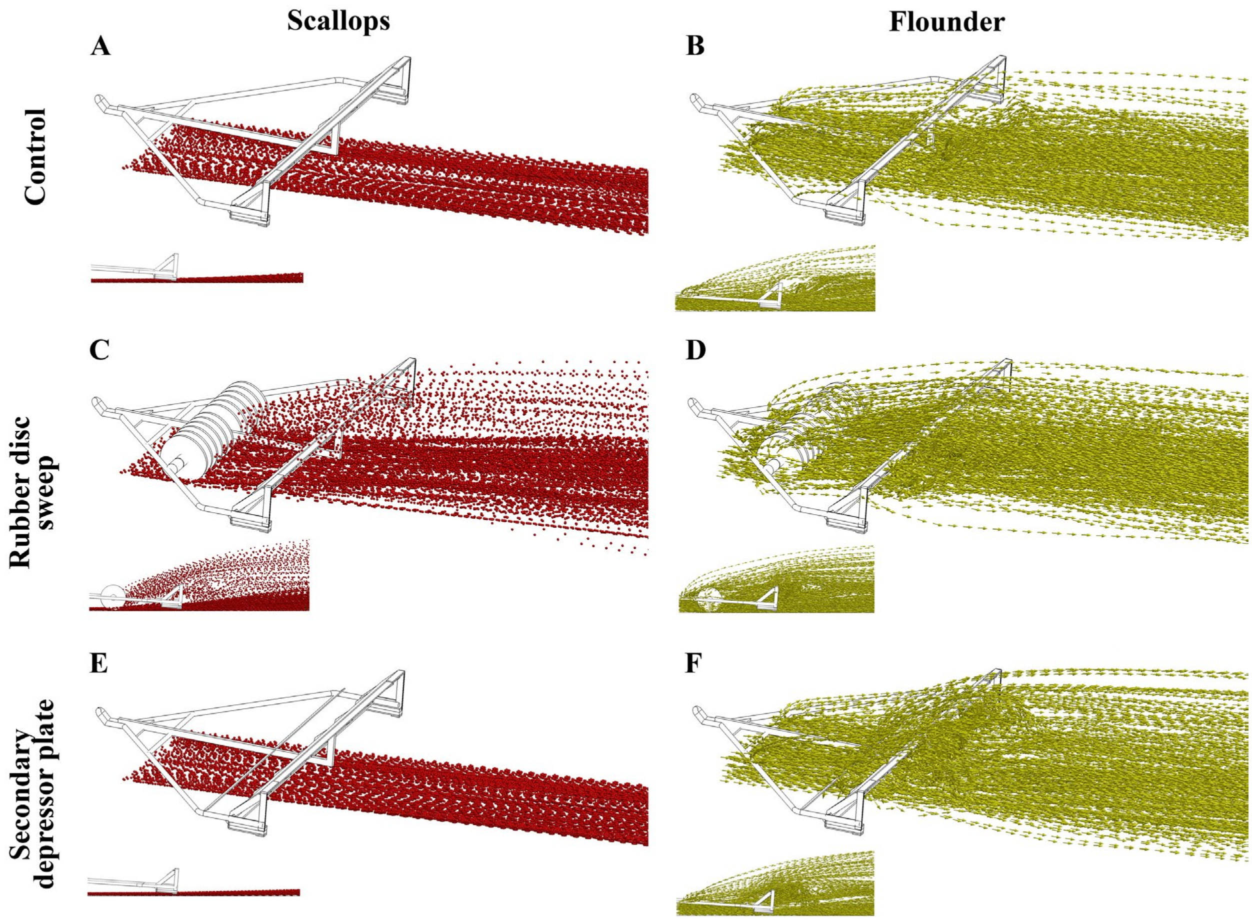

Figure 3: Trajectories of large scallop and flounder particles as predicted based on flow around the control and modified dredges: (A) scallop particles and the control TDD, (B) flounder particles and the control TDD, (C) scallop particles and the TDD with a rubber disc sweep, (D) flounder particles and the TDD with a rubber disc sweep, (E) scallop particles and the TDD with a secondary depressor plate, and (F) flounder particles and the TDD with a secondary depressor plate.

(2) Work with an industry advisory panel to determine which modifications to test in the field.

During a majority of the research period, restrictions were in place to prevent the spread of COVID-19 which limited our ability to host meetings with an industry panel. CFF was able to convene with members of the industry advisory panel on October 20, 2021. This meeting was attended by Peter Anthony (Eastern Fisheries, Inc.), Ronnie Enoksen (Eastern Fisheries, Inc.), Mark Buron (Eastern Fisheries, Inc.), Charlie Quinn (Quinn Fisheries, Inc.), Mike Quinn (Quinn Fisheries, Inc.), Charlie Quinn, Jr. (Quinn Fisheries, Inc. and Operator of F/V Incentive), and Jay Elsner (Mass Fabrication, Inc.).

At the meeting, attendees were presented results from past projects testing bycatch avoidance devices ahead of the cutting bar and the CFD simulations of simplified rubber disc sweeps and a secondary 3/8" (9.525 mm) depressor plate mounted forward of and parallel to the cutting bar (**Figure 2**). The CFD predictions of catch with the simplified rubber disc sweep were remarkably similar to what had previously been observed in the field, providing the attending industry members with the confidence to select promising gear designs using CFD simulations. At the end of the meeting, the industry members advised CFF to further investigate bycatch avoidance devices placed ahead of the cutting bar using CFD analysis. Specifically, it was advised that we investigate the impacts of reinforcing the secondary plate forward of the cutting bar, the most promising simulation presented at the meeting. The consensus at the meeting was that the 3/8" secondary depressor plate was too fragile to be tested in the field. Repeated towing and contact with seafloor obstructions would likely cause the thin plate to bend inward reducing its effectiveness. Our industry advisors suggested that the plate be thickened to 5/8" (15.875 mm) and a 2" (50.8 mm) x 3" (76.2 mm) cutting bar be attached to the plate's leading edge to create a reinforced depressor plate. Flanges spaced 12" (30.48 cm) were also added to further strengthen the frame.

The reinforced depressor plate was analyzed using CFD models with the same parameters as those used in earlier simulations (**Table 1**). Relative to the 3/8" secondary depressor plate, the reinforced design had the same predicted impact on scallops ≥ 110 mm but no impact on flatfish bycatch (**Table 3**). CFD simulations revealed a continuous region of low pressure between the plate and the cutting bar that did not form in simulations of the thin forward depressor plate. This region may explain why the reinforced design was not predicted to reduce flounder bycatch (**Figure 4**). Because the reinforced design was not predicted to reduce flatfish bycatch, this design was not selected for field testing after discussion with members of the industry panel.

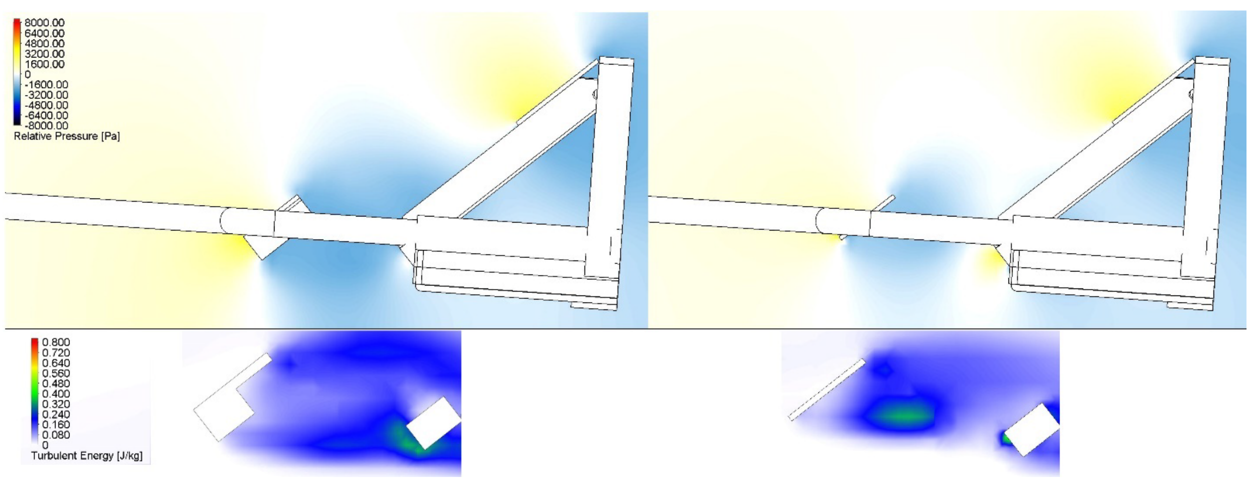

Figure 4: A comparison of the predicted relative pressure (top) and turbulent energy (bottom) of the reinforced depressor plate (left) and the 3/8" secondary depressor plate (right).

During the development of the rubber disc sweep, a design using street sweeper brushes had been proposed; however, the researchers had difficulty finding a supplier of street sweeper brushes (Alexander & Davis 2019). Attaching and removing sweeps to the front of the dredge frame can be easy and require only a few simple modifications to the dredge frame (Alexander & Davis 2018, Alexander & Davis 2019). Relative to the rubber cookie and disc sweeps, a street sweeper brush would have more surfaces to contact flatfish and possibly encourage them to escape upwards. The similarity between the CFD simulations of the simplified rubber disc sweep and the rubber disc sweep tested in the field provided the confidence to use this method to predict how a sweep comprised of street sweeper brushes would behave in the field. Street sweeper brushes were located, purchased, and a 3D CAD drawing approximating the wafers and the whole brush unit was made. Attempts to simulate flow for a TDD with street sweeper brushes exceeded the limitation of the SolidWorks Flow Simulation package and simulations could not be done for a complete model due to the complexity of the street sweeper brush CAD drawing geometry. Instead, flow was simulated for a simplified street sweeper brush consisting of five street sweeper wafers and half of the simplified rubber disc sweep (not attached to a dredge). Comparison of large scallop particle trajectories behind the rubber disc sweep and the street sweeper brush indicated that a much smaller proportion of scallops would be sent over the dredge if a street sweeper brush was used instead of the rubber disc sweep (**Figure 5**). Trajectories of flounder particles behind each unit were not identical (**Figure 5**), but making predictions about catch reductions based on a visual examination of the trajectories was difficult. However, examination of the vertical locations of flounder particles behind each unit and comparing these to height-dependent particle fates (Siemann et al. 2021) indicated that flounder catch reduction may be less with the street sweeper brushes because a higher proportion of flounder would be at heights where they were likely to be caught behind the street sweeper brush than behind the rubber cookie sweep (**Figure 5**). However, the difference would depend on the proportion of fish that successfully escape through the twine top mesh.

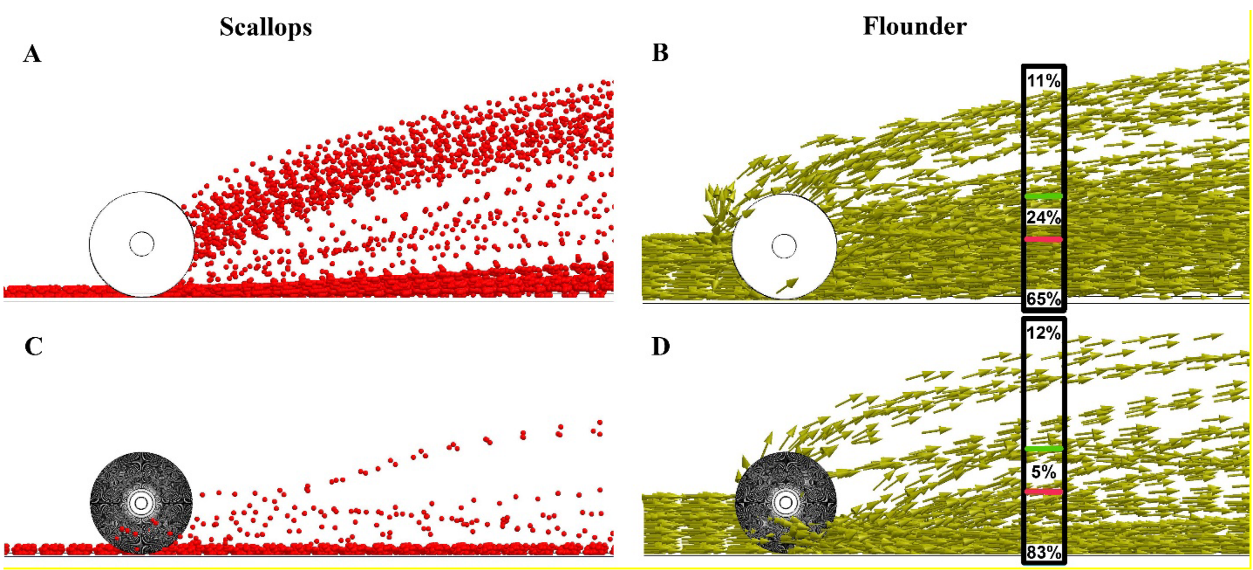

Figure 5: Trajectories of large scallop and flounder particles as predicted based on flow around the rubber disc sweep (top) and street sweeper brush (bottom): (A) scallop particles and the rubber disc sweep, (B) flounder particles and the rubber disc sweep, (C) scallop particles and the street sweeper brush, and (D) flounder particles and the street sweeper brush. The black boxes behind the sweeps in the flounder column show the approximate location of the space just before the dredge frame. The values inside the boxes show the estimated percentages of fish that would escape over the dredge (value above the green line), get caught (value below the red line), or interact with the twine top (middle value).

Given the ease of installing and removing sweeps, the significant reduction of flatfish bycatch observed when testing the rubber disc sweep, and the predicted lessened impact to sea scallop particles behind the street sweeper brushes, a sweep constructed of street sweeper brushes was chosen as the most promising candidate for field testing.

(3) Modify and test a 15-foot (4.6-m) commercial Turtle Deflector Dredge (TDD) with the most promising modifications.

(3.1) Gear Design

The street sweeper sweep tested in the field was designed with the assistance of Tim Lenling and fabricated by Dockside Repairs, Inc. It was constructed using thirty-six brush wafers with 20" (50.8 cm) polypropylene bristles riveted to a ring with a 5" (12.7-cm) interior diameter for mounting. The sweep consists of two sections of eighteen brush wafers mounted on a tube with a 5" outer diameter, and there is a 1.384" (3.52-cm) spacer between each brush wafer. The street sweeper brushes were then mounted ~38" (96.5 cm) forward of the cutting bar (**Figure 6A**). The brushes were mounted to frame using pipes flanges and nuts and bolts which allowed for the brushes to be easily installed and removed (**Figure 6B**).

Figure 6: The street sweeper sweep mounted to a TDD (A) and a close up view of the mounting mechanism (B).

(3.2.1) Field Testing Results

Testing of the street sweeper sweep took place aboard the F/V Contender and F/V Concordia. The first trip, aboard the F/V Contender, took place from May 23 to May 28, 2022 and the second trip, aboard the F/V Concordia, took place from August 16 to August 19, 2022. Data collected from seventy-two valid tows were used to evaluate the performance of the street sweeper sweep. Catch of all species was reduced by the street sweeper sweep, with the exception of monkfish, and this trend was consistent for both trips (**Tables 4 and 5**).

(3.2.2) GLMM Modeling Results

The covariates evaluated for this report were animal length, tow duration, and tow speed. A second-order polynomial of animal length was also examined to capture potential non-linearity in this term (Holst & Revill 2009). Tow duration and speed were not found to be significant predictors of the street sweeper sweep relative efficiency for any species. Due to insufficient data to model the individual flatfish species encountered during field trials **(Table 4)**, these species were modeled in aggregate and a species covariate was examined for significance to account for relative differences in morphology and behavior between species that may impact the performance of the street sweeper sweep. In addition to sea scallops and flatfish, the analysis was also used to evaluate barndoor skate and monkfish. All models included haul as a random effect to allow the intercept to vary randomly between hauls. The most parsimonious model and parameter estimates associated with the selected model specification for each species are shown in **Table 6**.

Sea scallops and flatfish were the only species for which animal length was a significant predictor in the performance of the street sweeper sweep. For both sea scallops and flatfish, the predicted proportion of catch retained by the street sweeper sweep increased with increasing animal length (**Table 6; Figures 7 and 8**). The second-order polynomial of animal length was also significant for sea scallops (**Table 6**). The combined linear and U-shaped relationship indicated significantly lower catches of smaller sea scallops. As length increased, the proportion of catch converged on 0.5 at ~140 mm (i.e. catch efficiency between the control and street sweeper sweep are similar for larger animals; **Figure 7**). Animal length was not found to be a significant predictor of barndoor skate and monkfish bycatch (**Table 6**). However, for barndoor skate, the difference in overall relative efficiency was significant while it was not for monkfish (**Table 6**).

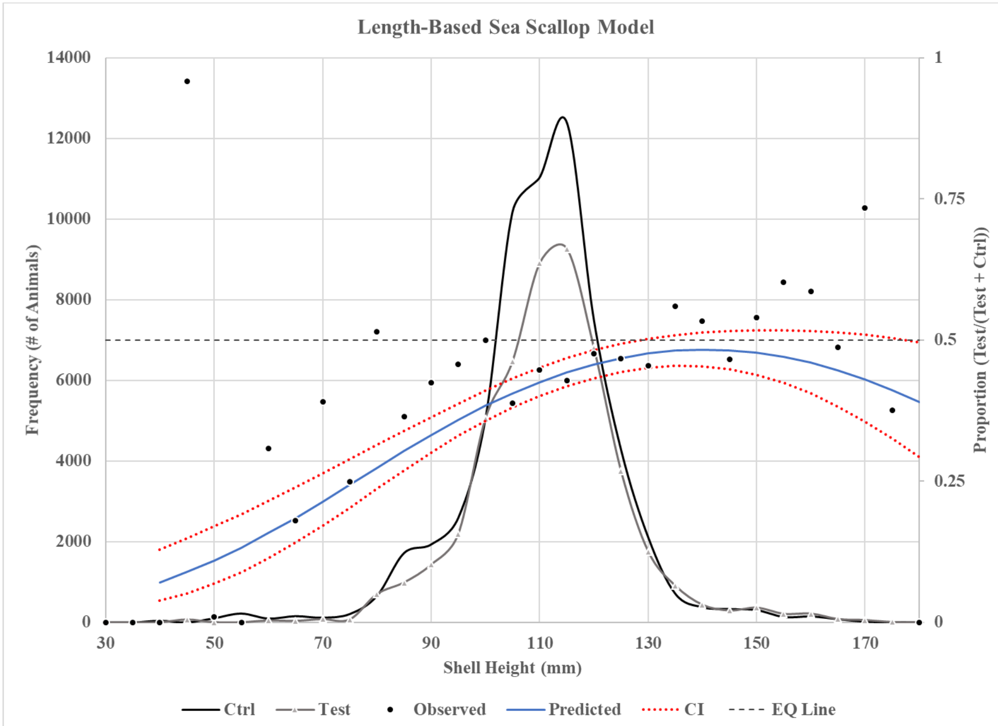

Figure 7: Observed sea scallop catch proportions at shell height in the street sweeper sweep dredge and size frequencies relative to the modeled predicted proportion retained at shell height.

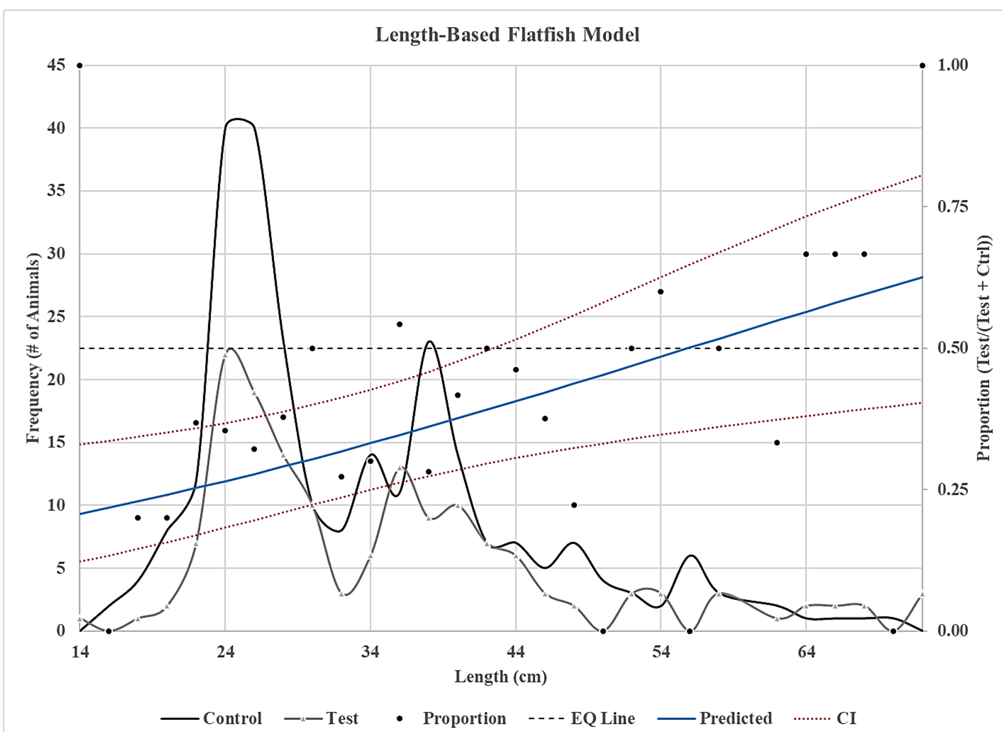

Figure 8: Observed fish catch proportions at fish length in the street sweeper sweep dredge and size frequencies relative to the modeled predicted proportion retained at shell height.

Evaluation

Accomplishments by objective

All objectives were accomplished with few modifications. Accomplishments by objective are described below.

(1) Utilize CFD models to test variations on two types of modifications to dredge frames: simplified rubber disc sweeps and a secondary depressor plate mounted forward of and parallel to the cutting bar.

CFD models for these modifications were completed and they provided valuable information for discussing these modifications with members of the scallop industry. Flow around TDDs equipped with a simplified rubber disc sweep and two versions of a secondary depressor plate were modelled using CFD simulations, and particle studies based on the modelled flow provided clear visualizations of the likely impacts of these modifications on scallop and flounder catch.

(2) Work with an industry advisory panel to determine which modifications to test in the field.

This objective was accomplished by working closely with a panel comprised sea scallop vessel owners, captains, crew, and dredge fabricators to identify and design the street sweeper sweep tested in the field. CFD simulations of a rubber disc sweep presented to the panel provided them with the confidence to attempt to design a reinforced secondary depressor plate, predicted to reduce bycatch without impacting scallop catch. When simulations of the reinforced depressor plate indicated that this modification would not have a predicted reduction of flounder catch, panel members worked with us to a design a secondary depressor plate using the 3/8" plate that could be sufficiently rugged. However, this design would not be easy to install or uninstall, violating a key design criterion of the industry panel. Sweeps had been previously tested and demonstrated to be easy to install and remove, and a group decision was made to test a new sweep in the field.

CFD analysis of dredge modifications is fairly novel and was not a tool available to researchers evaluating forward sweeps in the past. The industry panel was interested in CFD analysis as a tool to predict the performance of dredge modifications prior to field testing. A post-hoc comparison of a simplified rubber disc sweep and the one tested in the field indicated that CFD analysis may be a good tool for predicting the performance of similar modifications. The street sweeper sweep was predicted to behave similarly to the rubber disc sweep, reducing both sea scallop and flatfish catches (**Table 2; Figures 3 and 5**). With assistance from members of the panel, a street sweeper sweep was designed and built, providing an opportunity to further evaluate the use CFD analysis to predict gear performance prior to field testing.

(3) Modify and test a 15-foot (4.6-m) commercial Turtle Deflector Dredge (TDD) with the most promising modifications.

We were able to accomplish this objective by testing a street sweeper sweep during two research trips which collected and analyzed data from 72 valid tows. CFD analysis of the street sweeper sweep indicated it would reduce flounder catch similar to the rubber disc sweep while reducing scallop catch less thyan the rubber disc sweep **(Figure** 5). However, field testing found sea scallop catch to be reduced by ~20% with the street sweeper sweep, with a majority of the reduction occurring in sea scallops <110 mm (**Tables 4 and 7**). Aggregated flatfish bycatch was reduced by 45.6% (**Table 4**). These results are similar to the previously tested rubber disc sweep (Alexander & Davis 2019).

Discussion

Prior to developing the street sweeper sweep, the panel considered returning to the 3/8" secondary depressor plate design which could be reinforced using just flanges. Using the flanges would also facilitate connecting a secondary depressor plate to the struts of a TDD which would further strengthen the design. This attachment method would require that the modification be welded to the TDD frame. To avoid damaging both the secondary depressor plate and the TDD frame, a cutting wheel would be required to remove the secondary depressor plate. Our industry panel advised that we take into consideration how difficult it may be to install and/or remove modifications when developing them. Currently, gear modifications to reduce flounder bycatch in the sea scallop fishery are implemented seasonally and spatially. Unless bycatch reducing gear improves sea scallop catch, it is unlikely to be used outside of the season or area requiring the gear. A 3/8" secondary depressor plate would require more effort to install and remove than the current gear restrictions and therefore this modification was not selected for field testing.

Installing and removing the street sweeper sweep was relatively easy, but the complex shape of the sweep made modelling flow around it challenging. A rubber disc sweep is comprised of varying sized discs that are relatively smooth and uniform compared to a street sweeper wafer which has many bristles pitched at random angles. As a result, the street sweeper sweep has a greater overall surface area interacting with the flow around it. As object complexity increases, modelling flow around the object becomes computationally challenging. For this reason, the CAD drawing of the street sweeper was dramatically simplified and relative to the real street sweeper sweep, the bristles with in the CAD drawing are not as bushy (**Figure 9**). Differences between CAD drawings and the real-world object may explain why the sea scallop reductions observed in the field did not agree with the trend predicted by the CFD analysis (**Table 8**). While the complexity of the street sweeper sweep pushed SolidWorks to its limits, more sophisticated software and more accurate CAD drawings could provide better CFD predictions of dredge modifications.

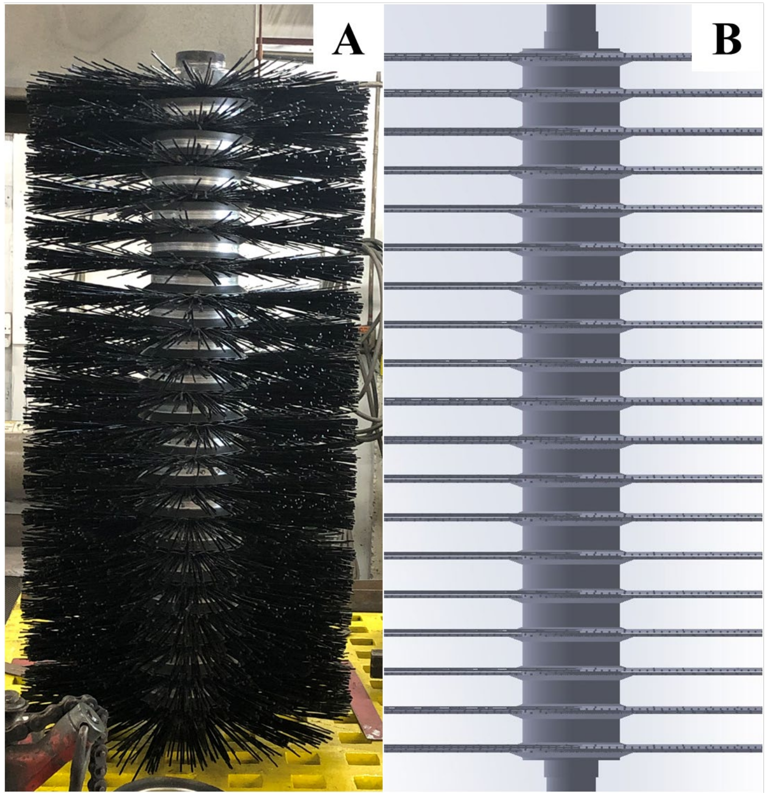

Figure 9: A comparison of (A) the real-world street sweeper brush and (B) the CAD drawing.

CFD particle studies are limited in their ability to account for animal behavior around fishing gears. For sea scallops this may not be not a significant issue, but for animals capable of sensing and utilizing flow to escape, CFD particle studies must be interpreted with animal behavior in mind. Relative to the rubber disc sweep, the street sweeper sweep is predicted to direct more flatfish downward which would be retained in the dredge bag; however, slightly more flatfish particles are also being directed over the dredge frame (**Figure 5).** With the dredge bags being identical, any observed changes in selectivity, species or size, is not likely the result of a mechanical sorting. Placing sweeps forward of the cutting bar is believed to provoke a behavioral-type escape in flatfish. While CFD particle studies of both the rubber disc and street sweeper sweeps predict that more flatfish particles will interact with the dredge bag, real flatfish may be more likely to swim and go over the dredge after interacting with sweeps.

Despite the loss in sea scallop catch, bycatch with the street sweeper sweep was substantially reduced. Previous research indicates that significantly more flatfish are escaping through the bag than are being retained by a typical dredge (Davis et al. 2019). With the street sweeper sweep, fewer flatfish are being retained and interacting with the dredge bag which results in lower discarding and lower escape mortality. Therefore, efforts to develop sweeps or other devices to reduce flatfish interactions with the dredge bag should be sustained. Going forward, CFD analysis can be used to optimize sweeps by predicting the likelihood that particles simulating sea scallop or flatfish will be flung over the dredge frame. An optimal sweep design would be predicted to fling fewer sea scallops over the dredge frame while predicting more flatfish would go over the dredge frame, maximizing scallop catch and reducing flatfish bycatch through a method that would minimize fish interactions with the dredge bag and therefore escape mortality of non-target species.

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Table 1: Summary of Flow Simulation settings for full dredge models.

Simulation setting	Details
3D computational domain	4 meters in front and 6 meters behind the dredge point of contact with the bottom. 8 meters wide, with 1.72 meters on each side of the dredge frame. 2.8 to -0.2 meters from the bottom boundary (domain extended into the bottom). 2D-slice passed between struts.
Mesh	Highest resolution automatic mesh (setting = 7) with adaptive meshing around dredge parts to improve accuracy.
Time setting	Time dependent 4 seconds with 1/24 second intervals
Boundary conditions	Bottom as ideal wall

Table 2: Summary of catch reductions using a rubber disc sweep or secondary depressor plate.

	Number caught in field trials	Reduction in field trials	Reductions with modelled sweep	Reductions with modelled secondary depressor plate
Large scallops	39,326	14.8%	10.4 – 14.2%	-1.0%
Large windowpane flounder	411	67.7%	17.0 – 20.9%	14.8 – 22.8%
Large other flounder	232	68.9%	17.0 – 20.9%	14.8 – 22.8%
Large flounder 20-50cm off bottom			62.3% – 64.4%	

Table 3: Summary of catch reductions using the secondary depressor plate (3/8”) and the reinforced depressor plate.

	Reductions with modelled secondary depressor plate	Reductions with modelled reinforced depressor plate
Large scallops	-1.0%	-1.0%
Large flounder	14.8 – 22.8%	-1.0 – 1.6%

Table 4: A summary of the pooled catch data comparing the street sweeper sweep to the control dredge.

Species	*Control*	*Street Sweeper Sweep (Test)*	*% change*
Barndoor Skate	239	169	-29.3%
American Plaice	23	8	-65.2%
Summer Flounder	57	35	-38.6%
Fourspot Flounder	122	67	-45.1%
Yellowtail Flounder	2	0	-100.0%
Grey Sole	20	23	15.0%
Windowpane Flounder	35	21	-40.0%
Monkfish	264	312	18.2%
Sea Scallops	62702	50131	-20.0%

Table 5: A summary of the two research trips testing the street sweeper sweep.

	F/V Contender		*F/V Concordia*	
Species	*Control*	*Test*	*Control*	*Test*
Barndoor Skate	223	168	16	1
American Plaice	23	8	0	0
Summer Flounder	56	35	1	0
Fourspot Flounder	79	28	43	39
Yellowtail Flounder	2	0	0	0
Grey Sole	20	23	0	0
Windowpane Flounder	32	14	3	7
Monkfish	213	245	51	67
Sea Scallops	31625	24992	30937	25148

Table 6: GLMM modelling estimates for the most parsimonious models.

Species	*Fixed Effect*	*Estimate*	*Std. Error*	*t-value*	*p-value*
Sea Scallops	(Intercept)	-0.299	0.063	-4.719	**2.37E-06**
	Length	12.421	1.606	7.733	**1.05E-14**
	$Length^2$	-7.862	1.871	-4.201	**2.66E-05**
Flatfish	(Intercept)	-1.787	0.455	-3.925	**8.60E-05**
	Length	0.032	0.011	2.803	**0.005**
Barndoor Skate	(Intercept)	-0.461	0.175	-2.628	**8.59E-03**
Monkfish	(Intercept)	0.121	0.134	0.9	0.368

Table 7: Sea scallop catch broken down by scallop shell heights.

Shell Height	*Catch Data*				*Modelled Data*	
	Control	**Test**	**Proportion**	**Std. Error**	**Proportion**	**Std. Error**
>110 mm	23106	17113	0.393	0.001	0.383	0.060
110-129 mm	35202	28711	0.438	0.001	0.447	0.052
130-150 mm	3539	3390	0.473	0.003	0.475	0.056
<150 mm	715	926	0.502	0.005	0.464	0.107

Table 8: Summary of predicted and observed trends in catch reductions using street sweeper brushes instead of a rubber disc sweep.

	Predicted trend with street sweeper brushes	**Reduction in field trials rubber disc sweep**	**Reductions in field trials of the street sweeper brushes**	**Observed trend with the street sweeper brushes**
Large scallops	Smaller reduction in catch	14.8%	16.1%	Larger reduction in catch
Large windowpane flounder	Smaller reduction in catch	67.7%	27.6%	Smaller reduction in catch
Large other flounder	Smaller reduction in catch	68.9%	33.6%	Smaller reduction in catch