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Scallop dredge design using computational fluid dynamics and flume tank testing and the application of both methods to improving a low profile dredge

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ABSTRACT

The Atlantic sea scallop (*Placopecten magellanicus*) is the focus of one of the most valuable fisheries on the east coast of the United States, but the incidental bycatch of flounder species could have negative impacts on the long-term sustainability of the scallop fishery. The low profile dredge (LPD) was conceived as a modified dredge that would reduce flounder bycatch by decreasing the vertical distance to the top of the dredge, allowing the fish to more easily swim over the top to escape. During initial development, two prototypes were tested at sea, and each reduced flounder catch with minimal reductions in scallop catch. To make continued refinement of the LPD more efficient and cost effective, we incorporated computational fluid dynamics (CFD) analysis and flume tank testing into our design strategy. The use of CFD analysis was validated with comparisons to flume tank tests and data from at-sea trials through examination of turbulent flow patterns and particle trajectories. There was a strong correspondence between the CFD simulation outputs and the results of the flume tank tests and at-sea gear trials, supporting the use of computer simulations during the early stages of gear design to speed up and reduce the cost of new gear development.

1. Introduction

The Atlantic sea scallop (*Placopecten magellanicus*) is the focus of one of the most valuable fisheries on the east coast of the United States (National Marine Fisheries Service (NMFS, 2020). Yet the incidental bycatch of non-target species could have negative impacts on the long-term sustainability of the scallop fishery. Bycatch of certain species by the scallop fishery, such as yellowtail flounder (*Limanda ferruginea*) and windowpane flounder (*Scopthalmus aquosus*), are managed via a quota system. The decline of these species decreases quota allocations to the scallop fishery, putting its continued sustainability at risk (O'Keefe and DeCelles, 2013).

The turtle-deflector dredge (TDD) was designed to deal with high bycatch rates of protected sea turtles by the scallop fishery in the early 2000s (Smolowitz et al., 2010). The TDD frame has two major differences from a traditional New Bedford dredge (NBD): the cutting bar is in front of the depressor plate to create a sloping face at the front of the dredge frame and the number of bale bars is reduced to one center supporting bale bar to leave openings for turtles to escape (Fig. 1). In addition to reducing injury to and bycatch of sea turtles while maintaining commercially acceptable levels of scallop catch, use of a TDD in place of the commonly used NBD resulted in significantly lower bycatch of several fish species, including yellowtail flounder and winter flounder (*Pseudopleuronectes americanus*)(Smolowitz et al., 2012). It was theorized that use of the TDD reduced flatfish bycatch because the forward cutting bar encouraged fish to swim upwards and over the dredge, whereas flatfish that encountered the cutting bar of an NBD contacted the depressor plate if they swam up and were directed into the dredge bag.

The low profile dredge (LPD) was conceived as a modified TDD that would further reduce flatfish bycatch by reducing the vertical distance to the top of the dredge, allowing flatfish to more easily swim over the dredge (Fig. 2). The height of the dredge was lowered to make it easier for fish to swim over the oncoming frame. The original LPD prototype (LPD v1) had the depressor plate attached along the top side of the struts, resulting in a depressor plate angle of 22 degrees (Fig. 2A). A

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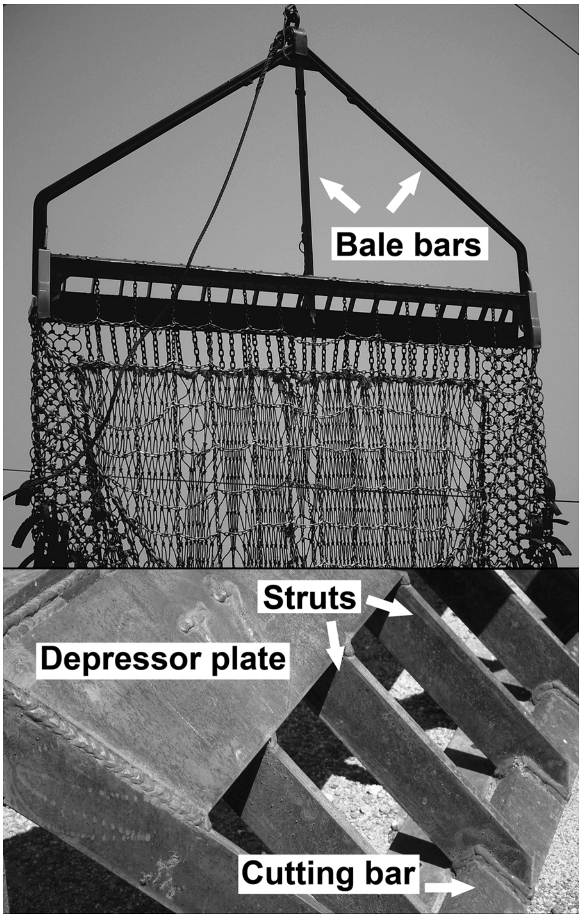

Fig. 1. Parts of a scallop turtle-deflector dredge (TDD) frame. Important features of the TDD include the open spaces between the center and outer bale bars and the cutting bar located in front of the depressor plate.

second version of the LPD (LPD v2) was designed to improve performance by dropping the depressor plate between the struts to increase the angle of the depressor plate to 45 degrees, matching the angle in standard-height dredges like the TDD (Fig. 2**B-C**). Although field tests using variations of the LPD, with modifications to the depressor plate length and angle as well as the dredge bag, have been conducted since 2011, none of the tested dredge frame/dredge bag combinations have consistently reduced flatfish catch while maintaining scallop catch (unpublished data).

To reach the final design of the TDD currently used by the scallop fishery, a sequence of incremental dredge modifications were tested during 37 trips conducted over three years of research efforts (NEFMC, 2011; Smolowitz et al., 2012). Development of bag modifications currently implemented in the Sea Scallop Fishery Management Plan to reduce fish bycatch, including twine-top minimum mesh sizes, twine-top hanging ratios, and minimum apron sizes, also required significant research effort aboard fishing vessels to evaluate the potential impacts of these gear-based measures (New England Fisheries Management Council (NEFMC, 1999, 2014). Consequently, developing and testing gear modifications to reduce bycatch in the scallop fishery costs hundreds of thousands of dollars due to expensive at-sea testing.

Computer simulation packages offer rapid and low-cost alternatives to field testing of preliminary gear modifications (Winger et al., 2006). When trawl-specific simulation software and flume tank studies have been conducted on trawl designs, both methods predicted key performance parameters of the trawls, like the relationship between wing-end spread and door spread, during at-sea fishing trials (Nguyen et al., 2015). Programs that run computational fluid dynamics (CFD) analysis are not limited to simulating the behavior of a specific fishing gear type. Flow around any gear can be simulated using these software packages if computer-aided design (CAD) drawings are available. CFD analysis has been used to optimize trawl door designs and characterize flow around trawl nets, with net shapes determined from flume tank tests (Meyler, 2008; Hermannsson, 2014).

To make continued refinement of the LPD more efficient and cost effective, we incorporated CFD analysis and flume tank testing into our design strategy. The use of CFD analysis was validated with comparisons to flume tank tests and data from at-sea trials. Based on the success of these efforts, we propose a new multipronged approach for designing and testing scallop gear.

2. Materials and methods

2.1. At-sea gear trials

Survey trips testing variations of the LPD were conducted between 2011 and 2017, and a subset of those trips compared catch in an LPD with catch in a TDD using identical dredge bags. Paired tow comparisons with modified bags on the LPD, with a different control dredge, or with wire scope alterations were excluded from our analysis. The data set used for comparisons included paired tows conducted in 2011 using the LPD v1 as the experimental dredge and a TDD as the control dredge and paired tows conducted in 2016 with the LPD v2 as the experimental dredge and a TDD as the control dredge. The TDD had a 9-inch depressor plate, while the LPD v1 had a 10-inch depressor plate and the LPD v2 had an 8-inch depressor plate. Dredge specifications are shown in Table 1.

All sea trials evaluating the design of the LPD using paired tows were

Table 1
Dredge specifications.

Specification	Details
Rings	Commercial 4-inch
Width	15 feet
Bag	10-by-40 ring
Apron	2011: 8-by-40 ring, 2016–2017: 7-by-40 ring
Side length	2011: 10 rows, 2016–2017: 11 rows
Twine top	10.5 inch stretched mesh
Hanging ratio	2:1
Depressor plate	TDD: 9 inch, LPD v1: 10 and 13 inch, LPD v2: 8 inch

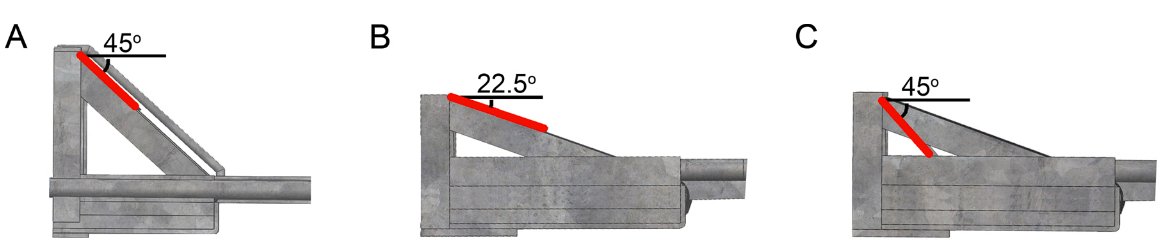

Fig. 2. Turtle deflector (TDD) and low profile dredge (LPD) frames with the depressor plates highlighted in black. (A) Standard-height TDD. (B) First LPD prototype with a 22.5° depressor plate (C) Redesigned LPD with a 45° depressor plate.

carried out aboard Limited Access (LA) scallop vessels. These vessels routinely tow two dredges simultaneously, allowing for a comparison of experimental scallop dredges without any modification to commercial fishing practices with regards to vessel operation and gear handling. In addition, simultaneous towing of a control and experimental dredge allows for the comparison of gear variants without the introduction of the variables associated with time and space. To ensure that the experiment was representative of the commercial scallop fishery, tow parameters were standardized to match commercial fishing practices. During each survey, two dredges were towed from the vessel: a standardized 4.6 m-wide TDD and a 4.6 m-wide LPD variant. Tows were conducted at speeds of 4.5–5.1 knots with a 3:1 tow scope in waters south of Martha's Vineyard in Massachusetts and across Georges Bank (Fig. 3). After each tow, scallops and commercially important bycatch species were sorted. All flatfish were counted and measured for each dredge type. Scallop bushel counts were recorded for each dredge type, and all scallops in a representative bushel from each dredge were counted and measured. Total scallop catch by tow and dredge type was calculated by expanding the catch data for each measured bushel by the corresponding total number of bushels.

2.2. Flume tank testing of scaled dredge models

Scaled dredges were built by Reidar's Manufacturing, a company that builds full-sized dredges used for commercial fishing (Fig. 4). The LPD had top units that could be exchanged to represent two versions of this dredge (LPD v1 and LPD v2). None of the dredge frames included the wheels that are often present on full-scale dredges. The dredges were designed to be fished at realistic scaled fishing speeds in the flume tank at the Marine Institute Centre for Sustainable Aquatic Resources (CSAR) at Memorial University (Winger et al., 2006; Moret and Legge, 2014). This flume tank has a maximum flow speed of ~2.2 knots. Therefore, in order to test a model dredge at scaled fishing speeds of 4.8–5.5 knots, our model had to be approximately 1/6th normal size (scaled speed = speed x $\sqrt{\text{scale}}$) (scaled by Froude number - Heller, 2011). The linear dimensions of the dredges were scaled to 1/6th the size of a commercial dredge, with the weights also scaled as close as possible to this ratio. In addition, a 7-row apron bag, scaled to the correct 1:6 size and weight, was built to allow testing of the dredges with a bag attached (Fig. 4).

The scaled dredges were tested with and without the dredge bag attached at scaled speeds of 3, 4, 5, and 5.5 knots with a 3:1 wire scope. The wire used during testing was scaled to be equivalent to a 1 1/8″ diameter wire commonly used with scallop dredges. To visualize the flow and any turbulence behind the dredge frames, fluorescent dye tablets were glued to the frames on the bale bars and on the cutting bar. Tests using dye tablets were conducted with a 2.5:1 scope to increase the distance between the dredges and the back of the tank for viewing turbulence behind the dredge. The bale angle for the dredge was measured during each test using a calibrated camera on a trolley, and a load cell was attached between the side of the tank and the wire to measure changes in wire tension with dredge type and speed. Dredge behavior during the tests was observed by the authors and two commercial fishers who provided important perspectives from their experiences fishing for scallops.

2.3. CFD modelling

Flow around the TDD and LPD dredges was modeled with the Flow Simulation package for SOLIDWORKS using CAD drawings for each of the full-sized dredges. It uses Cartesian-based meshes with rectangular cells that can arbitrarily intersect with the solid bodies, and the CFD equations are solved using modified k-ε models focused on turbulent kinetic energy (Sobachkin & Dumnov 2014). These time-dependent simulations used 2D computational domains, and flow simulation settings are shown in Table 2.

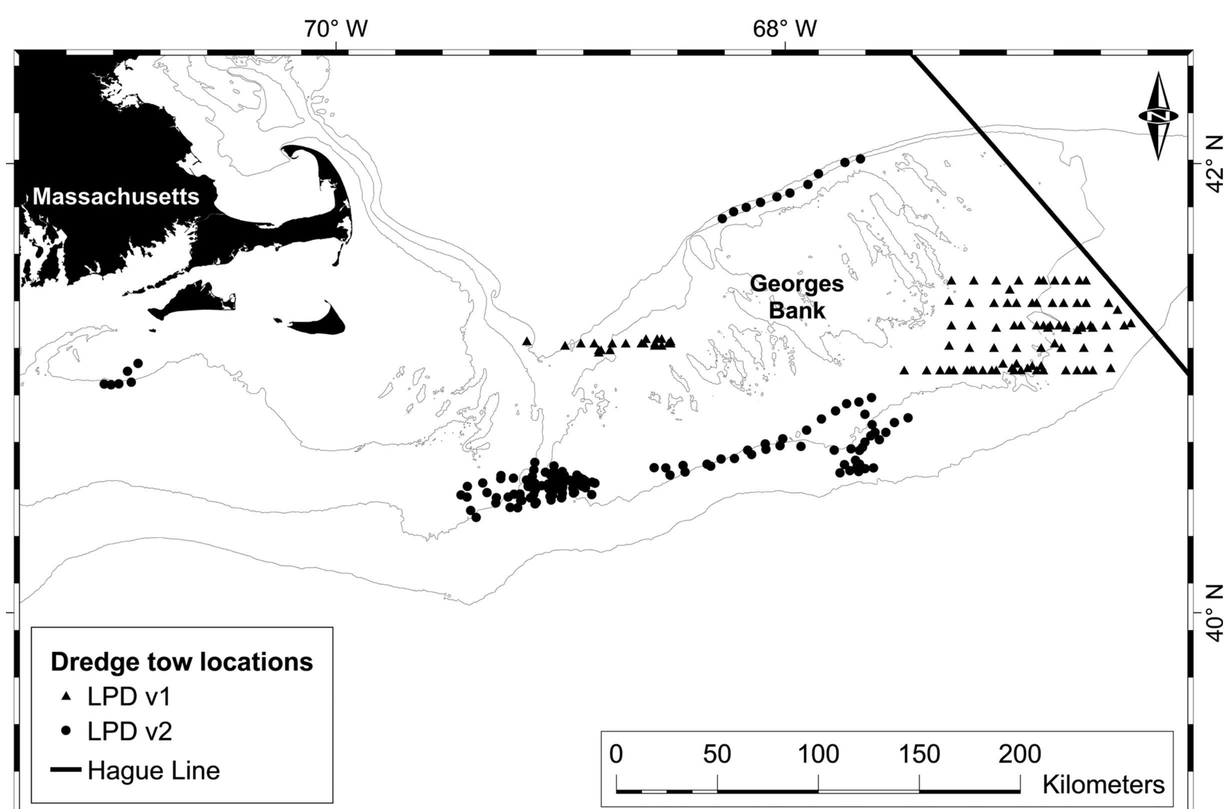

Fig. 3. Map of locations where at-sea tests of low profile dredge variants were conducted.

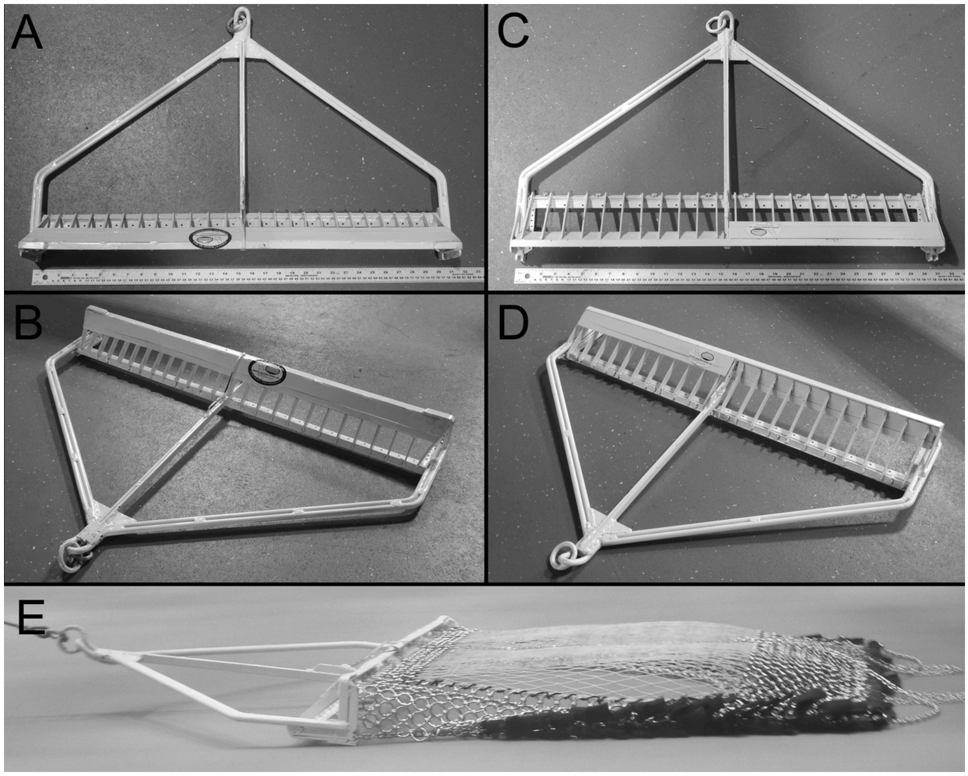

Fig. 4. Scaled dredges used for flume tank testing, with a meter stick shown for scale. All dredges were built to 1/6th scale to allow testing a scaled commercial fishing speeds. (A-B) The TDD. (C-D) The LPD with the 22.5° and 45°depressor plates, shown highlight the difference between these configurations. During flume tank tests, the two halves of the LPD matched. (E) The scaled dredge bag towed behind the TDD.

Table 2
Summary of Flow Simulation settings.

Simulation setting	Details
2D computational domain	4 m in front and 6 m behind the dredge point of contact with the bottom. 2.8 to −0.2 m from the bottom boundary (domain extended into the bottom). 2D-slice passed between struts.
Global mesh	600 cells long by 180 cells high with adaptive refinement up to level 7 (single cell subdivided into four cells up to seven times)
Local meshes	On the depressor plate, top bar, and cutting bar surfaces with adaptive refinement uo to level 7
Time setting	Time dependent 4 s with 1/24 s intervals
Boundary conditions	Bottom as ideal wall

2.3.1. Comparing CFD model output to flume tank tests

To assess if the results of the CFD models approximated flow around models of a dredge, we ran simulations at 5 knots with each dredge (TDD, LPD v1, and LPD v2) outfitted with a 9-inch depressor plate matching the ones on the scaled models. The bale angles were set to match those observed in the flume tank during dye tests. Because turbulent flow is clearly visualized by examining turbulent energy contours, cut plots of turbulent energy from CFD model outputs for each dredge type were compared to video imagery and stills from the dye tests.

2.3.2. Comparing CFD model output to catch data from at-sea trials

The goal for using CFD models during dredge design would be accurately predicting catch with different dredges. Therefore, we compared catch data from at-sea trials with predicted particle trajectories for the TDD and each of the LPD variants tested during gear trials. The models used for the simulations matched those used during paired gear tests; specifically, the depressor plate lengths were 9 in. for the TDD, 10 in. for the LPD v1, and 8 in. for the LPD v2.

Only spherical particles are available in SOLIDWORKS for particle studies, although a range of pre-defined materials with different densities is included. Because particle study output depends on particle size and density (Dassault Systemes, 2018), we used particle sizes that were volume equivalent spheres of scallops and fish when simplified to ellipsoid shapes (Table 3) and materials that matched densities for sea scallops and benthic fish as closely as possible. Scallops particles, representing 125-mm and 150-mm scallops, were spheres of 4-layer PC spheres B material with a density of 2.15 g/cm^3, within the range of measured scallop densities of 2.01 ± 0.44 g/cm^3 (unpublished data). Fish particles, representing 30-cm and 40-cm flatfish, were spheres of polystyrene with a density of 1.08 g/cm^3, close to published estimated for benthic fish densities of 1.06–1.07 g/cm^3 (Webb, 1990). Scallop particles were placed from 2 cm below to 3 cm above the point where the dredge makes contact with the sea floor (zero on the model Y-axis) to simulate scallops that are recessed in the sediment or resting on the surface (Fig. 5**A** and Table 3). Fish particles were placed in two groups (Fig. 5**A** and Table 3). The first group included fish that passed under the cutting bar, placed from 2 cm below to 10 cm above the point where the dredge makes contact with the sea floor to simulate fish that are buried, resting on the bottom, and starting to swim up in response to the dredge as it approaches. The second group represented fish that swam up in front of the dredge above the height of the cutting bar, from 10 cm to 60 cm above the bottom.

Scallop and fish particles 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 (Fig. 5**B** and Table 4). Particles that went over the dredge or under the dredge bag escaped from the dredge. The fates of particles that went toward the twine top or into the dredge bag were based on the proportions retained by those parts of the gear using the pair of equations:

Table 3
Summary of injections for the particle studies. Scallops and flatfish volumes were estimated using the formula for the volume of an ellipsoid. Scallop shell height to width and depth conversions were based on published morphometric relationships (Grant et al., 1993; Northeast Fisheries Science Center (NEFSC, 2014). Flatfish volumes were estimated without including fins or tail, with morphometric relationships based on published data (He, 2007) and measurements done on images of yellowtail and windowpane flounder and 3D models (unpublished data). Zero on the X-axis was the center of the cutting bar, while zero on the Y-axis was the bottom of the dredge foot.

Particle name	Dimensions (L × W×D) in cm	Equal volume sphere diameter	Number of particles	Vertical range (m)	Horizontal range (m)
125-mm scallop	125 × 123 × 41.7	86	1000	−0.02 to 0.03	−0.3 to 1.0
150-mm scallop	125 × 123 × 41.7	104	1000	−0.02 to 0.03	−0.3 to 1.0
30-cm fish on bottom	240 × 115.2 × 28.8	94	1000	−0.02 to 0.1	−0.3 to 1.0
40-cm fish on bottom	320 × 153.6 × 38.4	124	1000	−0.02 to 0.1	−0.3 to 1.0
30-cm fish on bottom	240 × 115.2 × 28.8	94	1000	0.1 to 0.6	−0.3 to −0.1
40-cm fish on bottom	320 × 153.6 × 38.4	124	1000	0.1 to 0.6	−0.3 to −0.1

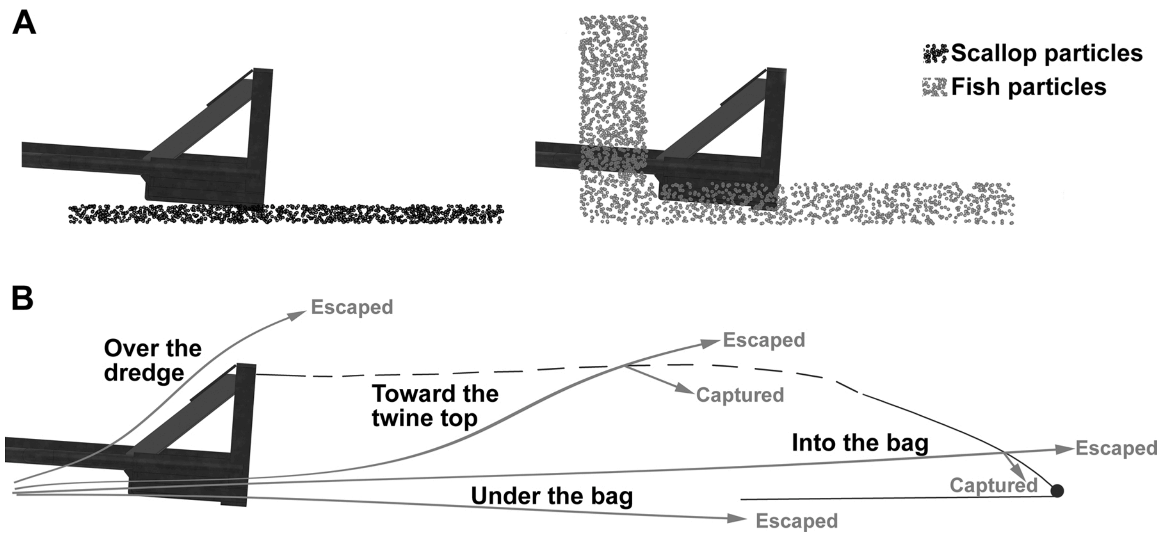

Fig. 5. Particle study details. (A) Locations of the initial particle injection locations for scallops and fish. (B) Schematic showing scallop and fish fates based on the trajectories derived from the particle studies using results of flow simulations. The locations of the top of the dredge frame, the start and end of the twine top, and the start of the sweep are based on the dimensions of each frame and a dredge bag with a 7-row apron. Drawing is not to scale.

Table 4
Criteria for classifying fate of scallops and fish from particle studies.

Fate	Caught	Trajectory path
Into the dredge bag	Depends on selectivity	Particle was above the bottom and under the height of the top of the bag at the sweep location
Over the dredge	No	Particle passed over the dredge frame
Through the twine top	Depends on selectivity	Particle passed through the dredge frame and above the height of the dredge in the space where the twine top would be located
Under the dredge bag	No	Particle hit the bottom before the sweep location

$$\text{Captured} = \text{Ret}_{B}*\text{Bag} + \text{Ret}_{TT}*\text{TT}$$

$$\textit{Escaped} = \textit{Over} + (1\text{-}\textit{Ret}_{B})*\textit{Bag} + (1\text{-}\textit{Ret}_{TT})*\textit{TT}$$

Where Bag is the number of particles that went into the bag, TT is the number of particles that went toward the twine top, Ret_B is the proportion retained by the bag, and Ret_{TT} is the proportion retained by the twine top. For 150-mm scallop and 30-cm fish particles, $\text{Ret}_B = 1$ because the ring openings and inter-ring spacings in a dredge ring bag are 10.2 cm or less. In these cases, the above equations are simplified, and particles are captured based on the proportion that are retained by the twine top. Therefore, comparisons between model output and the results of at-sea trials included only large scallops (>110-mm shell heights) and fish with widths greater than 11 cm (yellowtail and fourspot flounder lengths>32 cm and windowpane flounder lengths>24; He, 2007, unpublished data). To avoid including tows where one of the dredges was not operating normally, extreme outliers were removed from each data set if the difference in scallop catch between the dredges exceeded an outlier fence set at three times the interquartile range. This left 89 valid tow pairs for the 2011 gear trials with the LPD v1 and 96 valid tow pairs for the 2016 gear trials with the LPD v2. Because there are no published estimates for the percentage of scallops or fish that are retained by the twine top, Ret_{TT} was set to 0, 0.25, and 0.5 for comparisons to field data.

3. Results

3.1. Scallop catch and bycatch in LPD variants

While the LPD v1 caught significantly fewer large flounder relative to standard-height TDDs (29–34 % reductions for fourspot, windowpane, and yellowtail flounders), large scallop catch was also reduced by 6% in the LPD v1 relative to the TDD (Table 5). Changing the depressor plate design for the LPD v2 improved catch of large scallops, with a reduction of only 4% relative to the TDD that was not significant. Catch of large windowpane flounder was significantly reduced by 23 % (Table 5). However, the observed reductions in yellowtail and fourspot flounder catch were not significant because catch rates were low and there was considerable variability between trips.

Table 5
Catch totals for paired tows using a control TDD with a 9-inch depressor plate and an experimental LPD with the depressor plates as listed. Percent reduction in catch was calculated as $Catch_{TDD}$-$Catch_{LPD}$/$Catch_{TDD}$. The significance of the differences in catch was tested using paired Wilcoxon signed-rank tests. Degrees of freedom (df) vary by species because not all were caught in every tow.

TDD 9 inch vs LPD v1 10 inch						
Number of Tows = 89	TDD	LPD v1	% Reduction	df	Z value	p-value
Scallops	84,687	79,488	6.09%	78	−2.053	0.020
Yellowtail flounder	651	464	28.73%	85	−4.070	<0.001
Windowpane flounder	163	108	33.74%	31	−2.066	0.019
Fourspot flounder	147	99	32.65%	68	−2.581	0.005
TDD 9 inch vs LPD v2 8 inch						
Number of Tows = 96	TDD	LPD v2	% Reduction	df	Z value	p-value
Scallops	42,535	40,829	4.01%	88	−0.061	0.524
Yellowtail flounder	24	16	33.33%	18	−0.721	0.236
Windowpane flounder	481	372	22.66%	34	−1.686	0.046
Fourspot flounder	33	22	33.33%	29	−1.096	0.137

3.2. Flume tank data used for simulations

Bale angles collected during the flume tank tests were used to set parameters for the CFD simulations used for comparisons to flume tank observations and data from at-sea gear trials. For comparisons between dye tests conducted at the flume tank and CFD simulation output, bale angles observed for dredge frames without bags and wire scopes of 2.5:1 were used (Table 6). For the simulations used for comparisons to catch data, bale angles were set to 4 degrees because observed angles fluctuated around this value during tests in the flume tank for all three dredge types with bags attached (Table 6).

3.3. Flume tank tests and CFD models of turbulence

Examination of the turbulence behind each dredge frame, highlighted by the dye tablets, showed low turbulence behind the LPD v1, moderate turbulence behind the TDD, and high turbulence behind the LPD v2 (Fig. 6). The trends in the magnitude of the turbulence predicted by the CFD models for each dredge type were consistent with what was observed in the flume tank. The same relative levels of turbulence were predicted from the simulations of flow behind each dredge frame, with the turbulent energy plots looking similar to the dye tracks (Fig. 6).

3.4. CFD simulations and adaptive refinement of meshes

The initial mesh of 600 by 180 included 108,000 cells. This included 16–22 cells located along the depressor plates, with that number varying depending on the depressor plate angle and length, 5–6 located along the top bar, and 10–12 located along the front edges of the cutting bar, with the latter numbers varying depending on the orientation of the bars. After adaptive refinement of the local meshes, the number of cells along the front surfaces increased eightfold, resulting in 128–176 cells along the depressor plates, 40–48 cells along the top bar, and 80–96 cells on the front surfaces of the cutting bar. Adaptive refinement of the global meshes increased the number of cells along the other surfaces of the dredges by twofold. The total increase in the number of cells was below the maximum allowed by the refinement settings, indicating that further refinement did not change the results significantly.

Table 6
Bales angles measured in the flume tank.

Dredge	Speed (kn)	Scope	Bale angle without bag	Bale angle with bag
TDD	5	2.5:1	3.0	
TDD	3	3:1	−1.6	1.9
TDD	4	3:1	−1.6	1.0
TDD	5	3:1	−1.6	4.0
LPD v1	5	2.5:1	−0.6	
LPD v1	3	3:1	−2.7	2.7
LPD v1	4	3:1	−2.7	4.1
LPD v1	5	3:1	1.4	3.6
LPD v2	5	2.5:1	1.0	
LPD v2	3	3:1	−2.7	2.7
LPD v2	4	3:1	−2.7	4.5
LPD v2	5	3:1	1.6	4.2

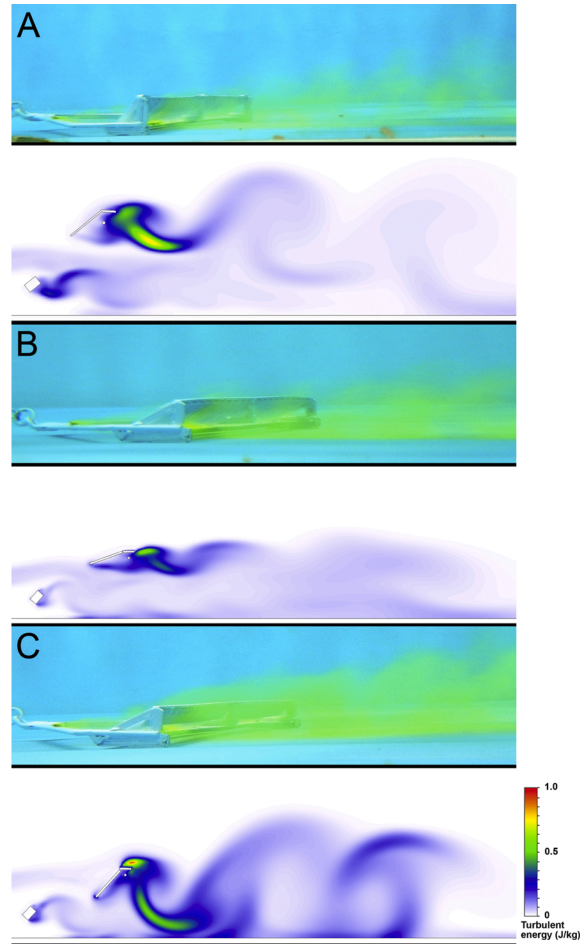

Fig. 6. Turbulence highlighted by dye tablets during flume tank tests and turbulent energy contours predicted by the CFD models. Each pair of images shows the dye tracks in the flume tank on the top panel and contours from the model on the bottom panel. (A) Turbulence around and behind the TDD. (B) Turbulence around and behind the LPD v1. (C) Turbulence around and behind the LPD v2. Turbulence in front of the dredge cutting bars and depressor plates is caused by water passing around the bale bars (not shown).

3.5. CFD model particle studies and data collected at sea

The particle studies predicted that the TDD would catch over 99 % of the scallops included in the injection, while catch would be reduced in both LPDs, with this reduction estimated to be higher if the scallops were recessed for LPD v1 and on the surface for the LPD v2 (Table 7 and Fig. 7). Examination of the flow fields behind each dredge indicate that some recessed scallops would not be lifted as they traveled under the LPD v1, while scallops could be entrained behind the LPD v2 then transported high into the water column behind the dredge frame and

Table 7
Proportion of particles that went into the bag (Bag), toward the twine top (Ttop), over the dredge (Over), or under the dredge (Under) based on their trajectories relative to the locations of dredge frame and bag parts. Dredge bags with 8-row aprons were standard in 2011, while bags with 7-row aprons were the maximum size allowed in 2015.

	TDD 8-row apron				TDD 7-row apron				LPD v1 8-row apron				LPD v2 7-row apron			
Scallops	Bag	Ttop	Over	Under	Bag	Ttop	Over	Under	Bag	Ttop	Over	Under	Bag	Ttop	Over	Under
Recessed	0.994			0.006	0.994			0.006	0.929	0.008		0.063	0.977	0.009		0.014
Surface	0.987			0.013	0.987			0.013	0.955	0.018		0.027	0.933	0.019		0.048
Flounder																
Buried	1.000				1.000				0.931			0.069	0.917	0.076		0.007
Surface	1.000				1.000				0.991	0.001		0.008	0.926	0.054		0.020
5–10cm	0.984	0.012		0.004	0.984	0.012		0.004	0.995	0.003		0.002	0.951	0.020		0.029
10–20cm	0.993	0.002		0.005	0.988	0.007		0.005	0.416	0.014	0.568	0.002	0.506	0.012	0.469	0.013
20–30cm	1.000				1.000				0.229		0.764	0.007	0.727	0.046	0.216	0.011
30–40cm	1.000				1.000				0.060		0.939	0.002	0.192	0.008	0.799	0.001
40–50cm	0.240		0.756	0.004	0.240		0.756	0.004			1.000				1.000	
50–60cm			1.000				1.000				1.000				1.000	

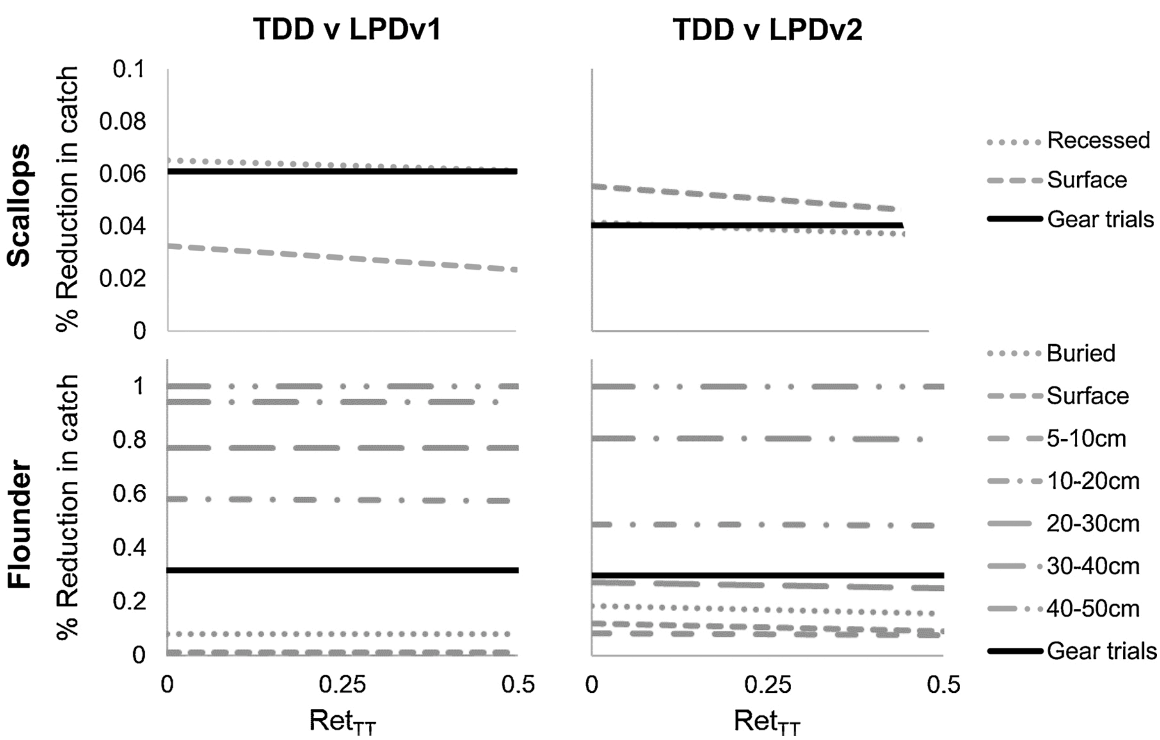

Fig. 7. Predicted and observed reductions in scallop and flounder catch ($Catch_{TDD}$-$Catch_{LPD}$/$Catch_{TDD}$). Predicted reductions are grouped by the starting vertical distance of each particle and are shown with the percent retained by the twine top (Ret_{TT}) set to 0, 0.25, and 0.50.

back to the surface (Fig. 8). Scallops were lost under the dredge and through the twine top with both LPDs (Table 7). Consequently, as Ret_{TT} increased, the predicted percent reduction decreased (Fig. 7). The observed percent reduction in catch during gear trials fell between the values predicted by the model for scallops that were recessed and scallops on the surface (Fig. 7).

The observed percent reductions in flounder catch during the gear trials fell between those predicted for flounder near bottom and flounder >10 cm off bottom (Fig. 7). The predicted reduction in catch of flounder particles was low when flounder were <10 cm from the bottom and tended to increase until the flounder particles were 50 cm or more off the bottom in front of the dredge and all flounder escaped over the dredge frames (Table 7). The particle studies estimated that over 75 % of the flounder escaped over the top of the LPD v1 if they were more than 20 cm off the bottom, with the escape percentage increasing as the particle height increased (Table 7). The same general trend occurred for catch in the LPD v2 with one exception; catch increased when particles were placed 20–30 cm off the bottom (Table 7). Flounder particles at this height entered the flow field in the region between the cutting bar and the lower part of the depressor plate where they could be pulled down under the depressor plate of the LPD v2 to enter the bag (Fig. 8). Because most of the flounder escaped over the depressor plate, the percent reduction in flounder catch decreased slightly or remained constant as Ret_{TT} increased (Fig. 7).

4. Discussion

Both of the LPDs significantly reduced fish catch with minimal reductions in scallop catch during gear trials, and these reductions were predicted using the CFD models. The results of the simulations suggest that, despite their similar designs, the two variations of the LPD may impact scallop catch relative to the TDD through different mechanisms. Recessed scallops may pass under the dredge bag more often behind the LPD v1 because the turbulent wake behind this dredge frame does not lift scallops off the bottom as effectively as flow behind the TDD. On the other hand, scallops on the surface may pass under the dredge bag more

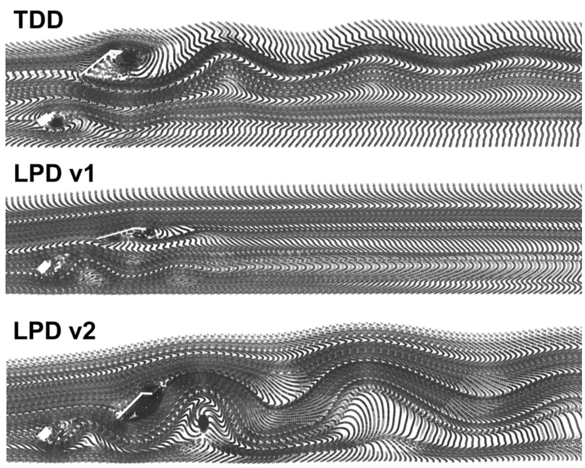

Fig. 8. Flow trajectories around each dredge frame.

frequently behind the LPD v2 because they are lifted and then transported back to the surface by the more turbulent flow behind this dredge frame.

The LPD frame was designed to reduce flounder catch by making it easier for the fish to swim up over the top of the frame. Scallop dredges are typically towed at 4.8–5.5 knots, and in order for flounder to escape to the side or over the top of a scallop dredge, their reaction times and swimming speeds would have to be sufficient to respond to a scallop dredge approaching at this high speed. The results of the CFD simulations, which used passive particles, support this possibility and suggest that both LPDs could reduce flounder catch by redirecting flounder that do not swim high or fast enough to escape over the dredge on their own to still pass over the dredge. Moreover, the flow patterns behind both LPD variants send a higher proportion of passive flounder particles toward the twine top or under the dredge bag when they are close enough to the bottom to pass under the cutting bar.

The results of the particle studies must be viewed with caution. While the SOLIDWORKS Flow Simulation package offers several advantages to users including a relatively affordable price and a user-friendly interface for running flow simulations and particle studies, there are drawbacks. The package includes only one turbulence model and particle simulations are simplified by assuming that the particles themselves do not impact flow. Furthermore, the use of passive particles does not account for scallop or fish active behaviors in the presence of scallop dredges. Like analyses using CFD for other applications, the studies of the three dredge designs simulated the particles of interest, scallops and flounder, using equal volume spheres. This simplification of particle structure can impact results in complicated ways due to the impacts of particle shape on drag and lift forces (Yin et al., 2004; Zastawny et al., 2012). Yet use of the passive spherical particles yielded results that predict relative catch rates observed in the field, suggesting the simplification is acceptable for use in the early stages of gear design.

Computer models and flume tank studies have been used to predict at-sea behavior of trawl nets (Nguyen et al., 2015), but we are not aware of any previous efforts to predict relative catch in fishing gear using flume tank studies or computer models. Scallop dredges, with their fixed-geometry frames and modular bags made of 4-inch rings, are ideal for testing the validity of using computer simulations for estimating the impacts of gear modifications on catch. The coordinates of key cutoff points, necessary for tracing particle trajectories and determining their fates, can be determined based on measurements of the dredge frame and details about the construction of the dredge bag. For this study, cutoff points like the start and end of the twine top and location of the sweep, were determined based on specifications of the dredges used in the at-sea gear trials, but these values could be changed to investigate the impacts of changing bag length or apron size.

The flume tank tests were critical components of this research because they validated the shape and strength of the turbulent flow behind each dredge frame and they provided realistic estimates of parameters needed to set up the CFD simulations. For example, bale angles depend on both towing speed and wire scope. Because the scaled speeds and wire scopes used at the flume tank corresponded with those used during the gear trials, the flume tank test results provided realistic estimates for bale angles that were needed to compare simulation results to the field data from the gear trials. Yet fishing parameters like towing speed and wire scope can vary based on environmental conditions and vessel captain preferences. Just as CFD simulations could be used to investigate the impacts of changing dredge geometries, it could also be used to look at the impacts of changes to fishing conditions.

The TDD and the NBD are the standard dredge frames used by most of the scallop fishery. The success of modifications to these dredge frames is judged by performance, generally maintenance of scallop catch and reduced bycatch relative to unmodified dredge frames. By using CFD simulations, it will be possible to make changes to the LPD, or any other dredge frame or part, and quickly determine if scallop or fish catch will be impacted. While this model-based approach cannot replace testing of new gear in the field, it could be used to eliminate bad designs and identify promising ones. For the LPD, this would include testing the impact of different depressor plate sizes and angles, towing speeds, and wire scopes to determine the best combinations to retain scallop catch but continue to reduce catch of flounder.

Fishing gear innovation is an incremental process, and acceptance of new designs can take time. Yet successful new gear designs have been adopted by the scallop industry if they improve gear efficiency or reduce bycatch (Smolowitz et al., 2012; Walsh, 2008). CFD simulations are not routinely used when developing fishing gear modifications, even though they are routinely used in other industries (Norton and Sun, 2006; Kaijima et al., 2013; Pinto et al., 2017). This project demonstrated a strong correspondence between CFD simulation outputs and the results of at-sea gear trials, supporting the use of computer simulations during the early stages of gear design. Routine use of computer simulation studies could speed up and reduce the cost of new gear development, providing benefits for both industry and conservation efforts.

CRediT authorship contribution statement

Liese A. Siemann: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Farrell H. Davis:** Conceptualization, Methodology, Investigation, Data curation, Writing - review & editing, Project administration, Funding acquisition. **Tor A. Bendiksen:** Methodology, Investigation, Resources, Writing - review & editing. **Ronald J. Smolowitz:** Conceptualization, Methodology, Investigation, Resources, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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