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ARTICLE

Design, Evolution, and Assessment of a Sea Turtle Deflector Dredge for the U.S. Northwest Atlantic Sea Scallop Fishery: Impacts on Fish Bycatch

Ronald Smolowitz*
Coonamessett Farm, Inc., 277 Hatchville Road, East Falmouth, Massachusetts 02536, USA

Henry O. Milliken
National Marine Fisheries Service, Northeast Fisheries Science Center, 166 Water Street, Woods Hole, Massachusetts 02543, USA

Matthew Weeks
Coonamessett Farm, Inc., 277 Hatchville Road, East Falmouth, Massachusetts 02536, USA

Abstract
Between May 2006 and November 2009 we tested five sequential dredge modifications during 37 trips on 13 different sea scallop fishing vessels. The testing evaluated the impacts of these modifications on the catch of sea scallops *Placopecten magellanicus*, the bycatch of fish and sea turtles in the families Cheloniidae and Dermochelyidae, and frame durability. We tested the modified dredges and an original New Bedford dredge (control) by conducting paired, side-by-side tows using identical tow parameters. A total of 4,059 paired tows were conducted in which tow data, scallop catch, and bycatch were recorded; data from 44% of the tows were sufficiently sampled for comparisons of bycatch. The dredge catches showed a significant 3% increase in sea scallop catch and significant decreases in the bycatch of many species, including yellowtail flounder *Limanda ferruginea* (46%), winter flounder *Pseudopleuronectes americanus* (69%), barndoor skate *Dipturus laevis* (18%), and winter skate *Leucoraja ocellata* (20%). The final design, the CFarm turtle deflector dredge, proved effective at guiding turtle carcasses over the top of the dredge by eliminating most of the bale bars and forming a ramp with a forward-positioned cutting bar and closely spaced struts leading back at a 45° angle. The final design also proved effective in reducing bycatch for a number of nontarget fish species. Flow characterizations in a flume tank provided insight into the cutting bar and frame hydrodynamics that may explain the field trial results.

Sea turtles in the families Cheloniidae and Dermochelyidae have long been subject to worldwide dangers from traditional and commercial fisheries (Parsons 1962; Witzell 1994), including incidental capture or injury in the sea scallop *Placopecten magellanicus* fishery (K. Murray 2004, K. T. Murray 2004, 2005, 2007). Decreases in nesting abundance and uncertainties in sea turtle population stability (Limpus and Limpus 2003) indicate an increasing need to mitigate these dangers. However, it is also important to consider the impacts of any proposed bycatch mitigation measures on fishermen and local economies. The scallop fishery was valued at US$385 million in 2007 (NMFS 2008) and is critical to communities in the northeastern USA.

Historically, fisheries stocks were managed by maximizing the sustainable catch of target species, regardless of the catch composition of nontarget species (Pikitch et al. 2004). In recent years, fisheries management has been moving toward more specific control of catch composition through gear innovations to achieve more ecologically sustainable fisheries (Smolowitz and Serchuk 1989; Kennelly and Broadhurst 2002). More than 15 years of continuous research has gone into preventing fish

*Corresponding author: cfarm@capecod.net
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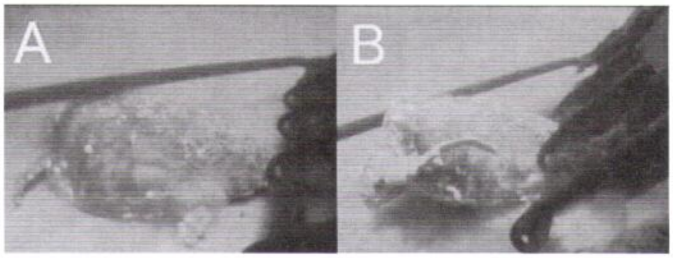


FIGURE 1. Illustration of a turtle carcass being run over by a scallop dredge. The dredge shown is an earlier prototype of the turtle excluder dredge. The experiment both highlighted the advantages of reducing the bale bars and revealed a flaw in this design, namely, the possibility of turtles being caught in the frame corner (**A** and **B**), which led to the extension of the outer bale and removal of the turtle guards. Adapted from Milliken et al. (2007). [Figure available in color online.]

bycatch in the New Bedford–style sea scallop dredge (Walsh 2008). However, only within the last 10 years has an effort been made to reduce the impacts of dredge interactions with loggerhead sea turtles *Carretta carreta* (Milliken et al. 2007; Smolowitz et al. 2010). Initially, the focus was on preventing loggerheads from entering the dredge through the implementation of turtle chains, which have been shown to be effective (DuPaul et al. 2004; Murray 2011).

However, many stakeholders were concerned that even with turtle chains in place the design of the New Bedford–style sea scallop dredge could inflict injuries on loggerheads. These concerns first arose when observers and fishermen reported that loggerheads were becoming wedged in the space between the depressor plate and the cutting bar on the dredge frame. In this position, loggerheads are at risk of injury if the dredge frame encounters the side of the vessel or they are dislodged while a dredge is up in the air over the vessel's deck. Video experiments in 2005, 2006, and 2009 using the carcasses of loggerheads that had become stranded and died indicated further potential for injury for carcasses placed in the path of a towed scallop dredge (Milliken et al. 2007; Smolowitz et al. 2010). These simulations showed that sea turtles could be run over by the dredge and become trapped beneath it. Video analysis and direct inspection of the carcasses offered insights into the type of injuries sustained as well as the paths or trajectories associated with those injuries, highlighting the areas on the dredge that were in need of modification (Figure 1). We determined that closely spaced bale bars were preventing the sea turtles from escaping upward before encountering a flat-faced cutting bar (Milliken et al. 2007). This observation indicated the need for additional measures to prevent loggerhead bycatch.

This paper chronicles the evolution of the design modifications that were tested to develop a sea scallop dredge that maximizes both scallop catch and the exclusion of sea turtle. These modifications focused on the changes to frame design that seemed likely to mitigate documented concerns about factors critical to sea turtle safety. The basic changes consisted of moving the cutting bar forward, removing all the interior bale bars except the center bar, increasing the opening between the outer bale and the frame, and decreasing the spaces between struts (Figures 2, 3). As is common when one is modifying fishing equipment, the changes created new challenges (e.g., maintaining viable catch results), all of which are addressed in this paper.

METHODS

Each of the five experimental dredge designs tested during this study represented a sequential variation on a standard New Bedford dredge (Figure 3). The experimental and control dredges had uniform measurements and outfitting, measured 4.6 m wide, and were configured with similar chain bags. The modifications consisted of four major design changes to prevent interaction with sea turtles that were guided by previous work and observations (Smolowitz et al. 2010). First, we moved the cutting bar forward of the depressor plate and placed it at a 45° angle. We then reduced the strut spacing, added turtle guards, and rotated the struts from the standard 90° angle to tow direction to a 45° angle to allow easier deflection of objects. In dredge designs 3 and 5, the outer bale was extended straight forward from the cutting bar before turning toward the tow point. In dredge 4 there was a major change to a center truss in lieu of a traditional bale. This was a prototype of a new dredge concept that was not pursued after preliminary tests. Lastly, the number

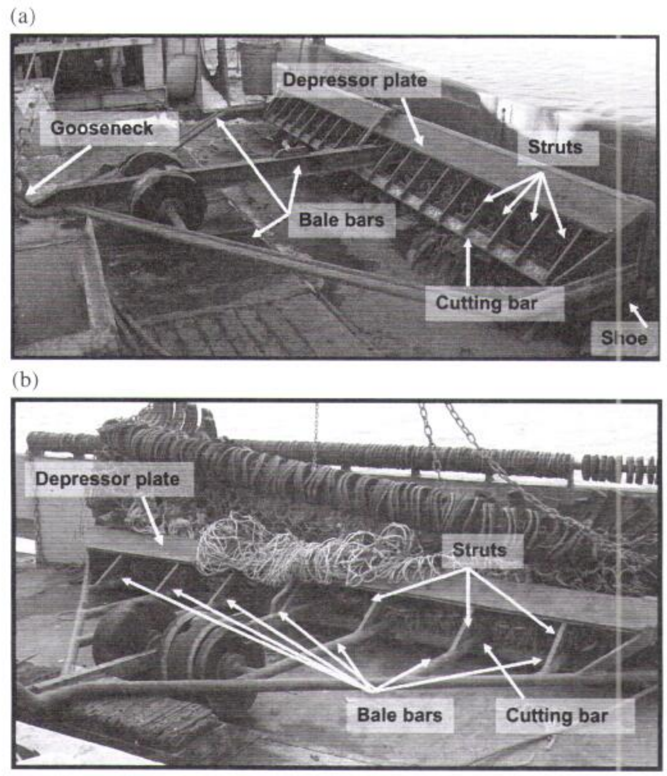


FIGURE 2. **(A)** The CFarm turtle deflector dredge frame and **(B)** the standard New Bedford scallop dredge. The chain bags of the two gears are similar. [Figure available in color online.]

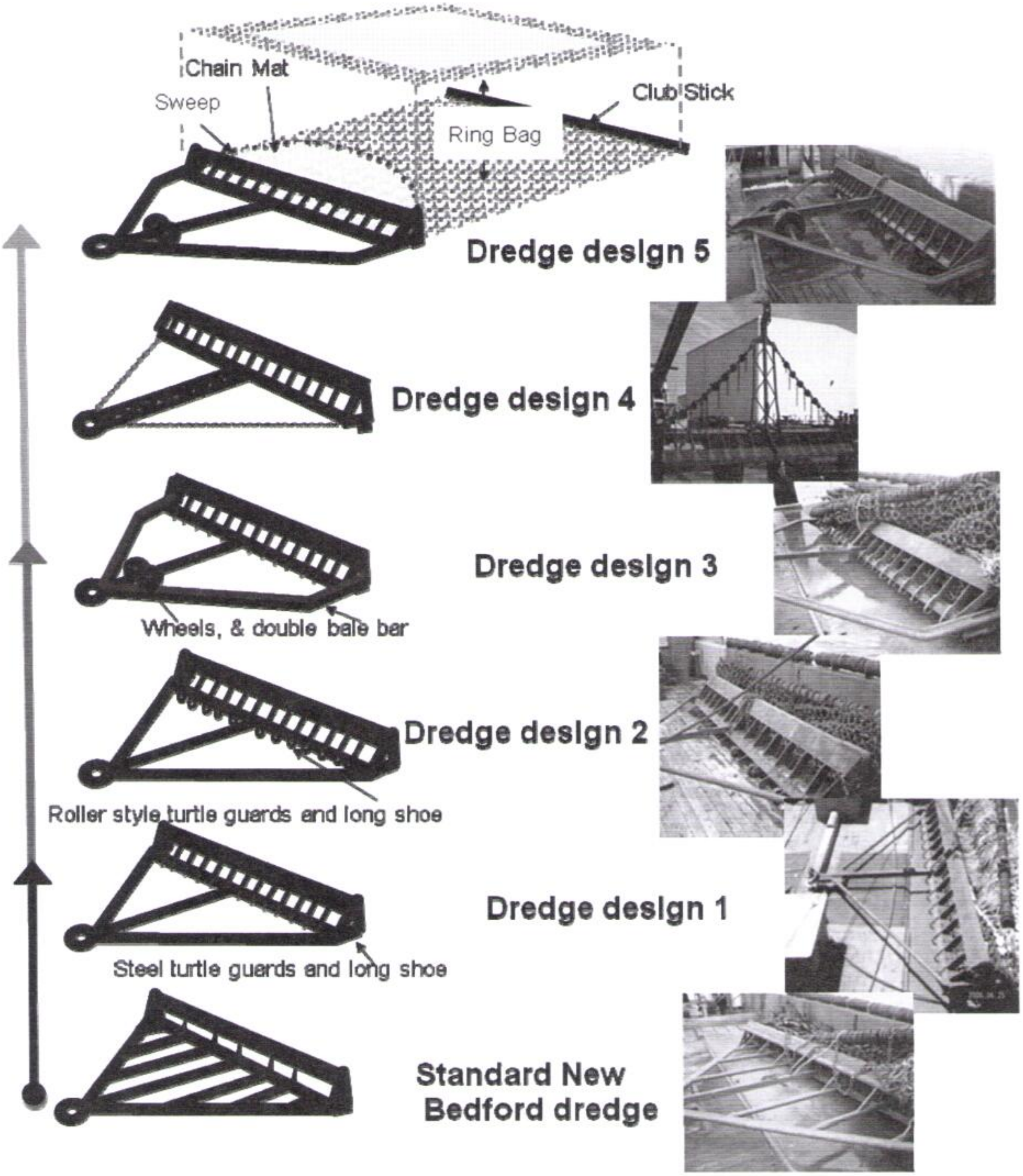
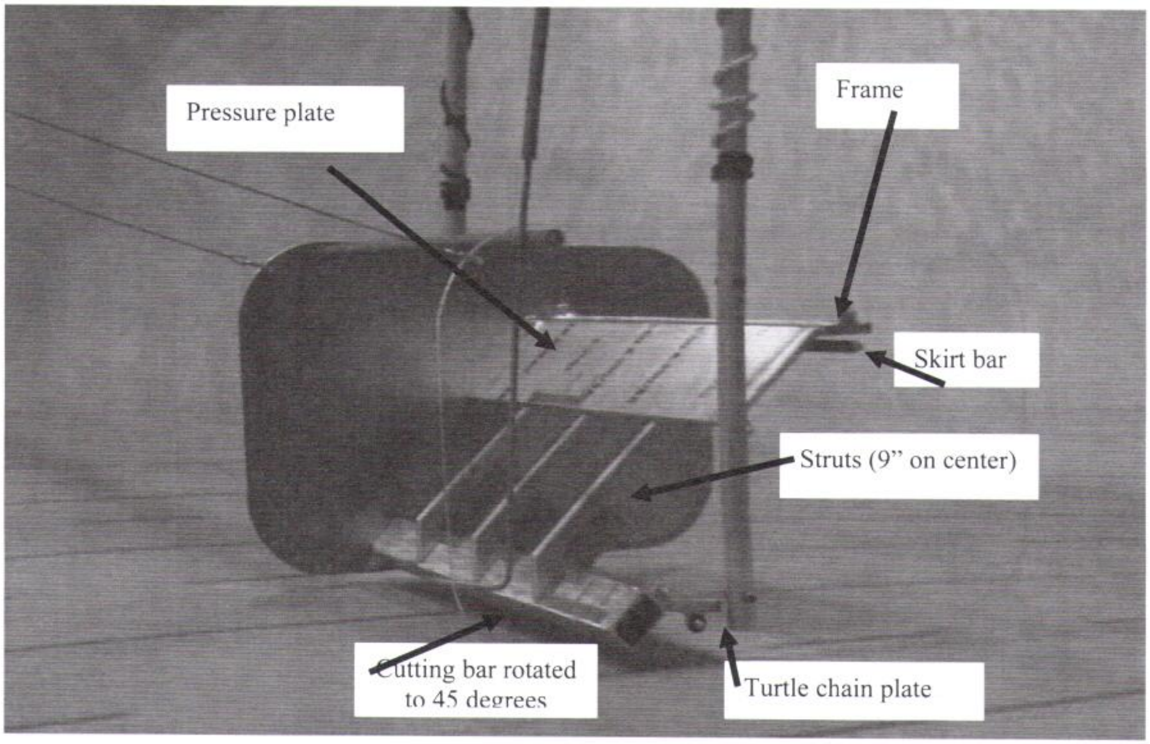


FIGURE 3. The standard New Bedford–style scallop dredge (bottom) and the progression of dredge designs tested during this study. [Figure available in color online.]

of bale bars were reduced from nine to three (except for dredge 4, which had a center truss) to allow sea turtles to escape upward. Figure 4 illustrates elements as tested in the flume tanks. These changes, combined with the elimination of many of the doublers and gusset plates used for structural reinforcement, enabled the modified dredges to be as lightweight as possible while still being able to fish in areas with low levels of boulders. These reductions in frame weight may also reduce fuel consumption and the impacts on benthic habitats.

The individual experimental design models were numbered sequentially as experimental dredges 1–5. Each model represented a minor modification of the design features while the

(a)



(b)

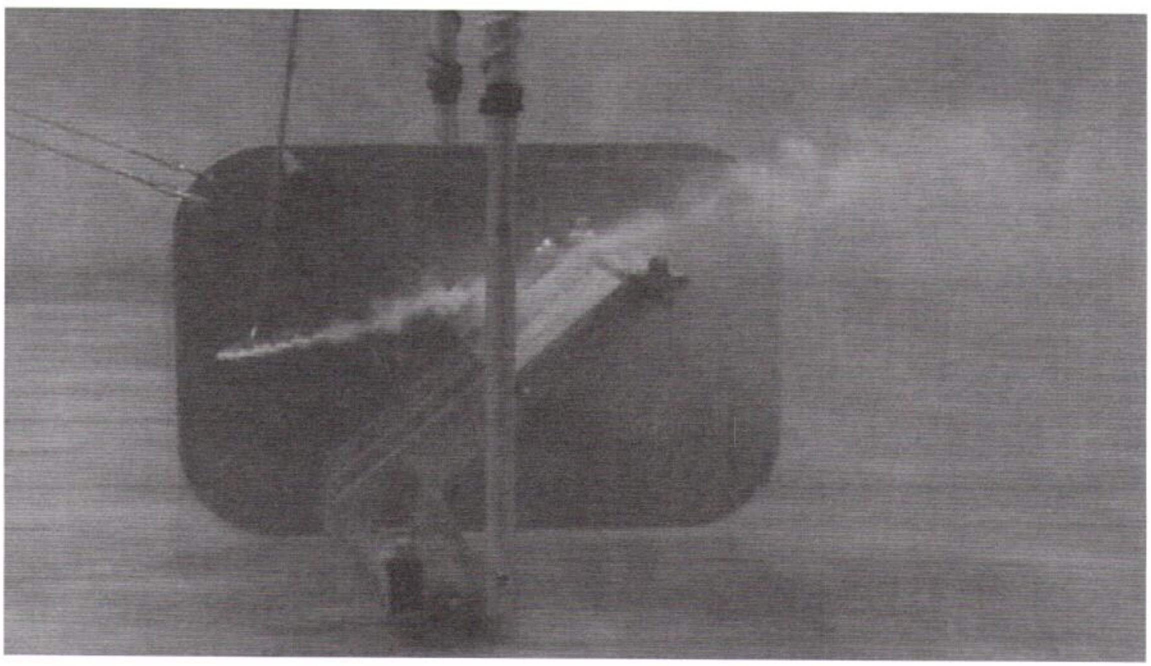


FIGURE 4. Panel (**A**) shows the experimental dredge frame design used in the flume tank tests. The major components are labeled for reference. Panel (**B**) shows a dye injection test that illustrates the hydrodynamic flow around the depressor plate; the water flow hits the plate and is ramped up and over the dredge. [Figure available in color online.]

TABLE 1. Results of cruises testing various sea scallop dredge designs (see Figure 3). Closed Area I (CAI), Closed Area II (CAII), and the Nantucket Lightship Area (NLSA) are scallop access areas within areas closed to groundfish fishing. The Hudson Canyon Access Area (HCAA), Elephant Trunk Access Area (ETAA), and Delmarva Access Area (DMAA) are scallop rotational-access areas. Areas fished outside of the scallop access areas included the Northern Edge (NE), the Southeast (SE), and southern New England (SNE).

Vessel	Cruise	Date sailed	Area	Total tows	Observed tows	Dredge frame
Celtic	2006-1	May 19, 2006	SNE	11	11	1
Celtic	2006-2	May 25, 2006	SE	218	92	1
Westport	2006-1	Jul 31, 2006	CAII	27	9	1
Celtic	2006-3	Oct 6, 2006	CAII	114	76	2
Westport	2006-2	Sep 14, 2006	CAII	162	75	2
Resolution	2006-1	Nov 7, 2006	NLSA	25	14	4
Resolution	2006-2	Nov 13, 2006	CAII	91	30	4
Resolution	2006-3	Dec 9, 2006	NE	186	74	2
Nordic Pride	2007-1	Jan 6, 2007	NE	252	98	2
Nordic Pride	2007-2	Feb 9, 2007	NE	295	76	2
Westport	2007-1	Mar 28, 2007	ETAA	68	45	3
Celtic	2007-1	Apr 10, 2007	ETAA	32	16	3
Friendship	2007-1	May 15, 2007	HCAA	100	53	3
Friendship	2007-2	Jun 5, 2007	HCAA	184	89	3
Friendship	2007-3	Jun 27, 2007	HCAA	161	43	3
Friendship	2007-4	Jul 5, 2007	HCAA	116	55	3
Friendship	2007-5	Aug 22, 2007	ETAA	42	19	3
Diligence	2007-1	Sep 20, 2007	CAI	88	50	3
Diligence	2007-2	Aug 20, 2007	CAI	93	54	3
Celtic	2007-6	Nov 5, 2007	ETAA	109	60	3
Westport	2007-2	Nov 20, 2007	ETAA	100	60	3
Kathy Ann	2008-2	Aug 6, 2008	ETAA	107	12	5
Tradition	2008-1	Aug 6, 2008	ETAA	92	57	5
Grand Larson	2008-1	Aug 19, 2008	ETAA	63	0	5
Elizabeth	2008-1	Oct 31, 2008	ETAA	60	0	5
Araho	2009-1	Jun 4, 2009	ETAA	111	46	5
Celtic	2009-1	Jun 11, 2009	ETAA	106	8	5
Generation	2009-1	Jun 17, 2009	ETAA	38	17	5
Kathy Ann	2009-2	Jun 22, 2009	ETAA	118	61	5
Generation	2009-2	Jul 8, 2009	ETAA	41	23	5
Kathy	2009-4	Jul 17, 2009	ETAA	203	106	5
Westport	2009-1	Aug 25, 2009	ETAA	130	39	5
Kathy Ann	2009-7	Sep 19, 2009	ETAA	239	109	5
Diligence	2009-3	Sep 30, 2009	ETAA	127	54	5
Tradition	2009-2	Oct 9, 2009	DMAA	159	82	5
Celtic	2009-4	Oct 13, 2009	DMAA	118	76	5
Diligence	2009-4	Oct 13, 2009	DMAA	152	79	5

primary modifications (as described above) remained. Dredge 5 represents the final accepted dredge design developed via an evolutionary progression starting with dredge 1.

Sea trials.—Testing occurred over a 42-month period starting in 2006 involving 37 trips on 13 vessels capable of towing two dredges simultaneously (Table 1). Each trip compared a single experimental dredge design with a single New Bedford–style dredge as the control. Except for the testing of dredge 5, which was used in an area of presumed high sea turtle numbers, fishing occurred in traditional sea scallop areas as part of typical commercial operations and under a variety of weather conditions. Tow times averaged 30–60 min for each pair of dredge comparisons depending on the location, and tow speed ranged from 2.3 to 2.6 m/s. The gear was switched from one side of the vessel to the other approximately half way through each trip to reduce any potential bias resulting from a particular side.

After an observed tow, the catch from each dredge was separated by species and individually counted; sea scallop catches

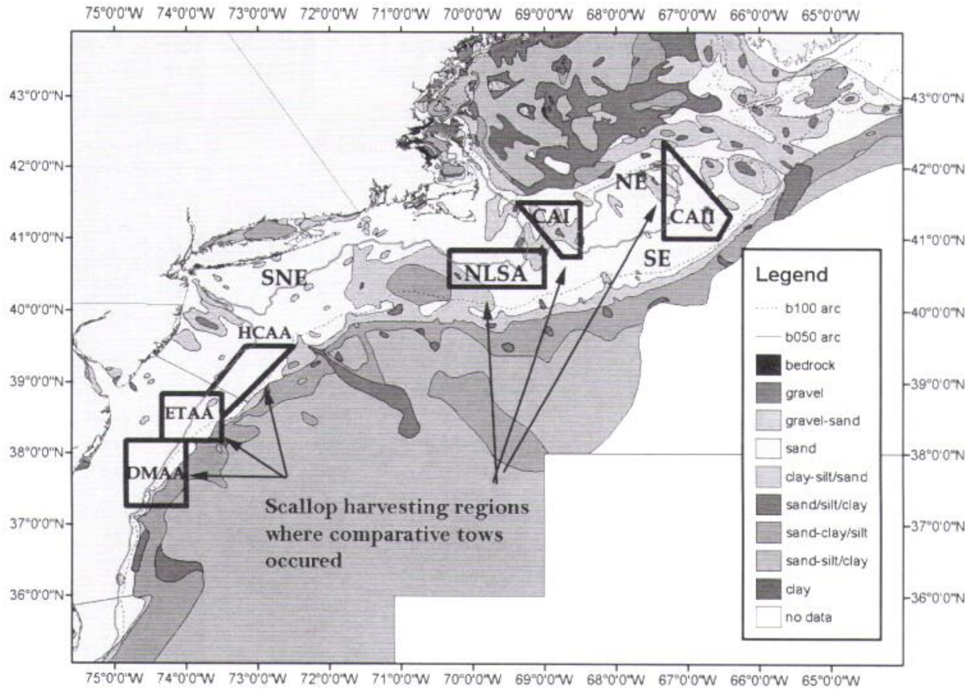


FIGURE 5. Map of sea scallop harvesting regions where comparative tows took place. U.S. Geological Survey sediment data are from http://pubs.usgs.gov/of/2000/of00-358/ (b100 arc = the 100 meter contour; b050 arc = the 50 meter contour). Closed Area I (CAI), Closed Area II (CAII), and the Nantucket Lightship Area (NLSA) are scallop access areas within areas closed to groundfish fishing. The Hudson Canyon Access Area (HCAA), Elephant Trunk Access Area (ETAA), and Delmarva Access Area (DMAA) are scallop rotational-access areas. Areas fished outside of the scallop access areas included the Northern Edge (NE), the Southeast (SE), and southern New England (SNE). [Figure available in color online.]

were recorded as bushels (bu; 1 bu = 35.2 L). A 1-bu subsample was picked at random from most tows, and those collected were measured in 5-mm incremental groups. Trained samplers recorded the tow times, tow parameters (vessel heading, speed, wire out, etc.), and identified and counted the species collected. When trained samplers were off watch, the vessel's crew was responsible for recording tow parameter data as well as the bushel counts of kept scallops, but they did not record fish bycatch.

Sea trials were distributed opportunistically across a variety of traditional sea scallop fishing grounds. Differences in seafloor characteristics make catch comparisons of the modified dredges difficult and potentially biased. Because of this, comparisons between modified dredges are not addressed in this paper. However, it is important to characterize the seafloor morphology and composition to understand the wide variability in commercial use of the New Bedford–style scallop dredge.

Nine different fishing grounds were sampled (Figure 5), six off the coast of New England and three off the coast of the mid-Atlantic region. The northern portion of Georges Bank Sea Scallop Access Area CAII consists primarily of a flat, poorly sorted sand substrate with patches of gravel (Valentine et al. 2005), high currents, and large concentrations of larger scallops and few yellowtail flounder *Limanda ferruginea*. The southern part of Access Area CAII has a similar but mostly sand substrate, lower currents, and high concentrations of both sea scallops and yellowtail flounder. The northern edge of Georges Bank (north of CAII) has mixed substrates of movable sand, gravel pavement, cobble, and boulders with high currents and patches of smaller scallops with few yellowtail flounder. The Nantucket Light Ship Access Area has undulating sand waves with some boulders, strong currents, and large populations of scallops and low levels of fish. Georges Bank Sea Scallop Access Area CAI has a complex substrate with dense patches of scallops and few yellowtail flounder but larger populations of winter flounder *Pseudopleuronectes americanus*. The fishing grounds in the mid-Atlantic region—the Hudson Canyon Access Area, the Elephant Trunk Access Area, and the Delmarva Access Area—have primarily flat sand bottoms with dense scallop concentrations, few fish, and dense patches of benthic organisms, such as common sand dollars *Echinarachnius parma*. Little skates *Raja erinacea* are common in all areas.

Data analysis.—We used paired t-tests to test for significant differences between the experimental and control dredges in terms of the catch of sea scallops and 10 other species. Significance was evaluated in terms of differences from zero using two-tailed tests. Towing two dredges simultaneously necessitated analyzing the data by paired t-tests Zar (1984). Catch ratios for each dredge were also calculated in order to compare the total counts of each bycatch species per sampled sea scallop bushel.

Flume tank tests.—Given the sunstantial design changes, we used flume tank tests to validate hydrodynamic flow with the

TABLE 2. Summary of flume tank testing of a model of the CFarm turtle deflector dredge. The cutting bar was angled either 45° or 90° to the direction of the water flow. The flume tank used during these tests had a moving belt representing the sea floor. During some tests, rubber disks were placed on the belt to represent sea scallops and were observed as they passed under the model dredge section. Two values are provided when the tests occurred at two different flume tank speeds.

Test	Cutting bar position	Pressure plate width (cm)	Flume tank speed (m/s)	Turtle chain plate
1	Forward 45°	22	0.44	Yes
2	Forward 90°	22	0.44/1.0	Yes
3	Forward 90°	22	1.0	None
4	Forward 45°	22	0.44/1.0	None
5	Forward round	22	0.44/1.0	None
6	Forward 45°	22	1.0	Yes
7	"Hat" design	22	0.5/1.0	None
8	Forward 45°	30	1.0	Yes
9	Forward 45°	10	1.0	Yes
10	Standard 90°	22	1.0	None

modified components and provide insights into sea trial performance. To do this, a 1-m-wide section of the modified dredge was tested at the flume tank at Memorial University in Newfoundland and Labrador. The design components were made of aluminum and mounted by bolts to facilitate quick changes and modifications during the testing process. The plate opposite the viewing side was fabricated out of aluminum, while the plate on the viewing side was made of rigid, transparent material (Lexan) to facilitate observations. Flow was observed by injecting a narrow stream of dye into the water path just ahead of the dredge components. Tank flow speeds were set between 0.4 and 1.0 m/s. Commercial dredge tow speeds can be much greater than those tested, but 1.0 m/s was the upper flow speed limit of the flume tank. Rubber disks (~75 mm in diameter), used to simulate sea scallops, were placed on the flume tank belt ahead of the dredge model during testing and observed during flow tests.

Ten separate tests were conducted in the flume tank (Table 2). Eight of the tests used a standard cutting bar that was moved forward and angled at either 45° or 90° to the direction of flow. One test used a round cutting bar, forward positioned and 7 cm in diameter (test 5). A second test employed a standard forward-positioned cutting bar with the addition of a hollow hemispheric "hat" to direct flow downward (test 7). Only test 10 was rigged as a conventional dredge with the cutting bar under the depressor plate. Turtle chain plates were affixed to the cutting bar on five of the tests (tests 1, 2, 6, 8, and 9).

RESULTS

Sea Trials

The results from the individual dredge tests are summarized in Table 3. Dredge 1 caught significantly more sea scallops than

TABLE 3. Dredge results by species. Dredge design cannot be directly compared because of the high degree of seasonal and spatial variability among tows. Number is the total number of the species caught in the experimental dredge (bushels for sea scallops), n is the number of comparisons, and P is the probability using the paired t-test (bold italics indicate significant values). The control is the New Bedford–style dredge. Blank cells indicate that the sample was too small for analysis.

	Dredge 1 (n = 114)			Dredge 2 (n = 404)			Dredge 3 (n = 385)			Dredge 4 (n = 43)			Dredge 5 (n = 872)		
Species	Number	P	% Difference from control	Number	P	% Difference from control	Number	P	% Difference from control	Number	P	% Difference from control	Number	P	% Difference from control
Sea scallop (bu)	1,330	***0.000***	10.65	3,945.25	***0.001***	−4.09	3,544	***0.000***	11.18	778.5	0.087	−6.71	8,972.41	***0.004***	2.03
Little skate	5,577	***0.000***	−11.77	20,177	***0.000***	−13.28	23,515	***0.000***	10.45	1861	***0.000***	−25.77	16,662	***0.000***	9.20
Goosefish	2,026	0.292	−2.13	2,966	0.414	−0.80	1,562	0.110	4.69	504	0.500	0.00	724	***0.026***	11.38
Summer flounder	53	0.216	−15.87	74	0.063	−22.11	516	0.433	−1.15	33	***0.007***	−42.11	567	***0.001***	−16.12
Yellowtail flounder	231	***0.002***	−28.48	3,107	***0.000***	−48.19	189	0.050	−15.25	965	***0.046***	−15.35	390	0.1937	7.14
Fourspot flounder	403	0.054	−13.33	596	***0.000***	−43.35	557	0.458	−0.71						
Windowpane	91	***0.006***	−38.10	464	***0.000***	−43.76	90	***0.005***	−31.82						
Winter flounder	8	***0.005***	−63.64	13	***0.000***	−71.74									
Barndoor skate	507	0.373	−2.12	272	***0.000***	−37.33									
Winter skate	145	0.335	5.84	451	***0.002***	−26.31									
Witch flounder	374	0.192	−6.50	15	***0.003***	−54.55	242	***0.003***	39.88						

TABLE 4. Catch summary for experimental dredges 1, 2, 3, and 5. The dredges were similar in that they all had the forward-positioned cutting bar, which is the most significant change from the standard dredge (control). Of particular interest is the significant decreases in the catch of key flounder species. The values are numbers of individuals except for sea scallops (bu). The number of combined paired tows was 1,632.

Variable or statistic	Sea scallop (bu)	Little skate	Goosefish	Summer flounder	Witch flounder	Yellowtail flounder	Winter flounder	Barndoor skate	Winter skate	Windowpane	American plaice	Fourspot flounder
Experimental catch	16,786	65,864	7,230	1,205	631	3,513	21	777	595	555	208	1,946
Control catch	16,345	66,074	7,148	1,347	606	6,521	67	948	744	1,062	97	2,436
% Difference from control	2.7%	-0.3%	1.1%	-10.5%	4.1%	-46.1%	-68.7%	-18.0%	-20.0%	-47.7%	114.4%	-20.1%
P	***0.000***	0.401	0.295	***0.004***	0.265	***0.000***	***0.000***	***0.000***	***0.006***	***0.000***	***0.000***	***0.000***

the control: 1,330 bu, compared with 1,202 bu for the standard New Bedford dredge (+ 10.7%). Dredge 1 also caught significantly fewer little skates (–11.8%), yellowtail flounder (–28.5%), windowpanes *Scophthalmus aquosus* (–38.1%), and winter flounder (–63.6%). Dredge 2 caught significantly fewer sea scallops, though not by as great a margin as dredge 4. It also decreased the bycatch of little skates (–13.3%), barndoor skates (–37.3%), winter skates (–26.3%), witch flounder *Glyptocephalus cynoglossus* (–54.6%), yellowtail flounder (–48.2%), winter flounder (–71.7%), fourspot flounder *Paralichthys oblongus* (–43.3%), and windowpanes (–43.8%). Dredge 3 caught 11.2% more scallops, but the catch of little skates was also significantly higher (+ 10.5%). Dredge 4 did not catch a significantly different number of sea scallops; however, it did significantly reduce the bycatch of little skates (–25.8%), summer flounder *Paralichthys dentatus* (–42.1%), and yellowtail flounder (–15.4%). It should be noted that throughout the final trip with dredge 4, a bend could be seen in the face of the bale and a twist appeared in the center towing structure; both seemed to worsen as the number of tows increased. Dredge 5 caught both more sea scallops and more little skates, while the bycatch of summer flounder was decreased by 16.1%. Bycatch was low because we were testing in areas of high sea turtle abundance. High quantities of most species of concern were not encountered during the tests of this dredge design. A preliminary analysis of the sea scallop length frequency data from a comparison of the plots for both shows no differences between the CFarm deflector dredges and the standard scallop dredge. Analyses of the finfish length frequencies have not been undertaken at this time.

We aggregated the data from dredges 1, 2, 3, and 5 to assess the overall ability of the experimental dredge design concept (cutting bar forward of the depressor plate, 45° cutting bar and strut, reduced number of bale bars) to increase the catch of sea scallops while decreasing the retention of important bycatch species. Dredge 4 was excluded from the compilation because its single-bail design differed significantly from the other versions of the excluder dredge. Of the 1,632 aggregated tows analyzed, the experimental dredges significantly increased sea scallop catch by 2.7% relative to the standard New Bedford dredge, while producing significant decreases in the bycatch of summer flounder (–10.5%), yellowtail flounder (–46.1%), winter flounder (–68.7%), barndoor skate (–18.0%), winter skate (–20.0%), windowpanes (–47.7%), and fourspot flounder (–20.1%) (Table 4). Interestingly, there were no significant differences in the catches of little skates (–0.3%) and goosefish *Lophius americanus* (+ 1.1%), but there was a significant increase in that of one species, the American plaice *Hippoglossoides platessoides* (+ 114.4%).

During the trials in the mid-Atlantic region, six loggerheads were taken, three in the experimental dredges and three in the control dredges (turtle chains were not used). Because Milliken et al. (2007) demonstrated that in interactions with dredges turtle carcasses go over the sea scallop dredge frame, it is probable that the encounters with the experimental dredges occurred while the dredges were in the water column and not on the substrate. We cannot speculate when the encounters with the traditional New Bedford scallop dredge occurred.

Hydrodynamic Testing in the Flume Tank

In the majority of the dye injection tests, the relocated cutting bar bifurcated the flow and the flow stalled behind the depressor plate (Figure 4B). This was evident at speeds of 1.0 m/s, at which the rubber disks placed on flume tank's belt were lifted up after encountering the cutting bar and many stalled behind it. The cutting bar and turtle chain plate formed a crude wing, and water flow was observed to accelerate over the top of the cutting bar. The turtle chain plate in effect acts as a splitter plate that reduces the drag coefficient. When the dye injector was located close to the tank floor, the dye stream showed some turbulence several centimeters beyond the cutting bar. It was not possible to determine whether the angle of the cutting bar had a significant impact on the flow patterns.

When the width of the depressor plate was increased from 22 to 30 cm, the space between the bottom of the depressor plate and the top of the cutting bar was decreased to 16.5 cm. Flow was observed to be directed downward after passing between the depressor plate and the cutting bar. The combined flow created increased turbulence. When the width of the depressor plate was decreased to 10 cm, the flow over the cutting bar was directed downward but at a point further aft. The narrow depressor plate was not observed to disturb flow relative to that with the wider plates.

In a configuration most like that of a standard dredge, the 7.6-cm cutting bar was placed under the depressor plate and perpendicular to the flow. The flow behind the cutting bar was very turbulent because of the influences from both the depressor plate and the cutting bar.

DISCUSSION

In the interactions between loggerhead carcasses and our dredges, the CFarm turtle deflector dredge demonstrated a high probability of significantly reducing injury and mortality. Of the nine sea turtle carcasses interacting with that dredge, all went over the dredge frame and none showed significant damage (Milliken et al. 2007; Smolowitz et al. 2010). While reducing loggerhead interactions is important, a new dredge design needs to maintain its catch efficiency with respect to the target species while reducing the bycatch of unwanted finfish.

The initial modifications to dredge design resulted in a raised cutting bar height. To address this in design 1, strut extensions were added every 30 cm and wrapped around the cutting bar. We hypothesized that this would help keep a sea turtle from being forced under the cutting bar and named the strut extensions "turtle guards." The cutting bar was turned 45° to form a ramp. This was implemented on all the experimental dredge designs tested to reduce the vertical flat surface, thus providing a smoother path of escape parallel to the assumed water flow over the top of the dredge.

With the cutting bar moved forward 38 cm, dredge 1 maintained the same depressor plate angle (45°) as the unmodified New Bedford dredge. Moving the cutting bar this distance nearly doubled the necessary shoe length to 80 cm. To maintain consistency within other elements of the dredge, the distance between the gooseneck (tow point) and the shoe (the lowest section of the frame, which contacts the substrate) was kept the same by shortening the bale. Because vessels are rigged to accommodate a set dredge length, increasing the length of the dredge frame would either require major changes to the vessel handling systems or shortening the bag to offset the increase, which would affect catch retention.

Three significant issues arose from these changes. First, the long shoe design increased the amount of sea scallops that were crushed by the dredge frame during the dumping of the catch. The extent to which this happened depended on a number of variables, including weather, crew experience, catch size, the presence of turtle and/or rock chains, and the dredge's position on deck on retrieval. During one trip, approximately 0.5 bu of scallops was crushed by dredge 1, compared with 0–0.25 bu by the New Bedford scallop dredge. Second, the relocation of the cutting bar also affected the space between it and the outer bale, thereby reducing egress space. Video data indicate this as an opening where sea turtles may escape (Milliken et al. 2007; Smolowitz et al. 2010). Finally, the shorter distance between the tow point and the cutting bar resulted in the cutting bar's being further off the sea floor. In this original dredge configuration, this may have increased the chance of a loggerhead's being run over by the dredge.

Dredge designs 1–3 had a common problem with the turtle guards being entangled with the chain bag and twine top. The entanglement often occurred during the beginning of the trip, when the crews were learning how to fish the experimental dredge under varying environmental conditions (e.g., tide and sea state). This malfunction occurred during 2% of all the paired tows. Since entanglement tended to happen at the start of the towing rather than during it, these unsuccessful tows were not included in the analysis. We felt that the lack of any catch in these entangled tows would unnecessarily bias the calculations of total catch. Similarly, in commercial fishing these entanglements represent lost time and money and, even if uncommon, are considered a major detriment by fishers.

Turtle guards were ultimately eliminated from the dredge design, not because of problems stemming from operator error but because of a design flaw noted during the testing. The turtle guards suffered unnecessary wear during towing and were reduced by roughly one-half of their initial thickness after approximately 100 tows. After 200 tows, the turtle guards broke off entirely, leaving jagged edges. Broken turtle guards were not replaced, resulting in both mutilated fish bycatch and an increase in gear hang-ups. When the turtle guards were broken, the catch results were not calculated and thus no longer included in the catch analysis.

By the time we incorporated modifications into dredge 3, it was very evident that the longer shoe design was not useful and had the negative consequence of crushing more sea scallops. The shoe design was modified so as to end at the dredge box frame; this placed the heel of the shoe in the same position relative to the cutting bar as in the standard dredge. The shorter shoe allowed the new bale to be extended 38 cm, at which point it bends toward the tow point. This widened the distance from the bale to the cutting bar, allowing for greater potential loggerhead escapement. Theoretically, this larger opening could even allow larger, more mature loggerheads to escape the dredge. Minor modifications to the chain bag were necessary to attach it to the new frame; however, the configuration and volume of the chain bag remained unchanged.

Dredge 4 benefited from the shortened shoe and was further modified to include a change in the bale bar from a V-shaped frame to a single tow bar attached to the centerline of the dredge. This single-point bar design reduced the number of bale bars from nine to one and reduced both weight and hydrodynamic drag. This simpler design, however, required heavy construction to resist bending when the dredge encountered large boulders. Although simple in concept, this design had poor performance. The single tow bar held up to fishing with no sign of bending; however, the dredge frame showed some twisting. The twisting is probably due to the loss of torsional stiffness supplied by the V-shaped bale. This mechanical problem coupled with poor fishing performance resulted in this design being discarded.

To strengthen the outer bale bar in dredges 3 and 5, a second bar of equal diameter was attached alongside it by a continuous weld in the horizontal axis. Adding a bar was more weight efficient than just increasing the diameter of the tow bar because the material was added in the direction of bending. The resulting strength was increased by approximately a factor of five in the x (towed) direction and by a factor of two in the y (vertical) direction compared with a single outer bale. Not only is this geometry provide greater strength, it also decreases hydrodynamic drag.

To further reduce the risk of sea turtles' snagging on the frame and to strengthen the frame, strut spacing was reduced from 46 to 23 cm. Because the depressor plate is supported by these struts, a reduction in spacing reduces the unsupported beam length. The added struts also eliminated the need for the reinforcing bar across the top of the depressor plate. While the impact on catch of the decreased strut spacing is not exactly known, we do know that the flow at this section of the dredge is high enough that a sea scallop should pass easily into the bag, even with the slightly increased strut surface area. This also reduces the possibility of a loggerhead's becoming lodged in the spaces between the struts.

It should be noted that all tows with dredge 5 were conducted during times and in areas of the mid-Atlantic region where sea turtle interactions with sea scallop gear have historically been observed. Unfortunately, these areas do not have the diversity

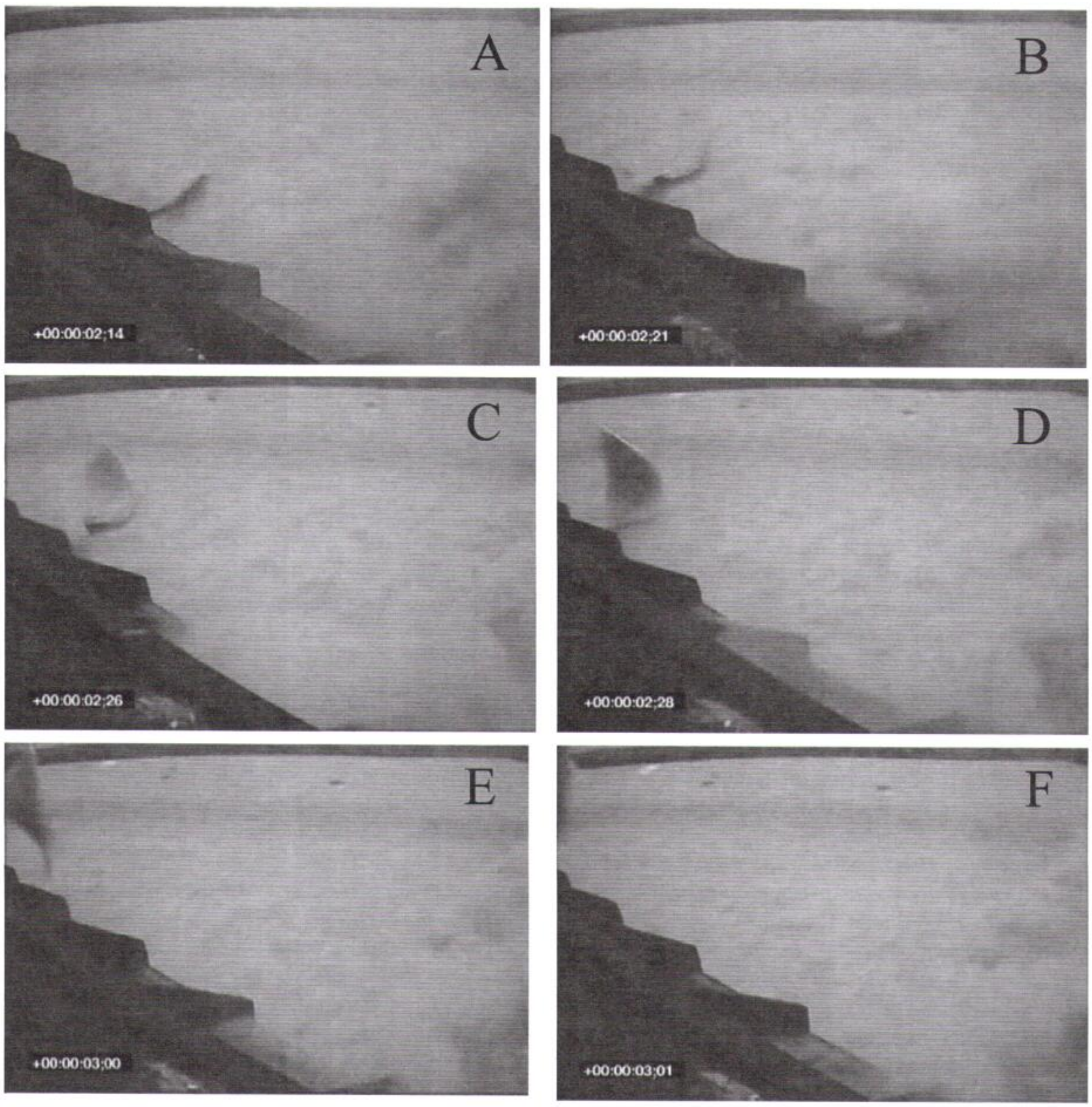


FIGURE 6. (A)–(F) Sequence of photographs showing a yellowtail flounder escaping from the turtle excluder dredge by swimming up and over the frame. In a standard dredge the depressor plate would have blocked this escape route. [Figure available in color online.]

or abundance of bycatch species found on Georges Bank, so the bycatch totals for dredge 5 may be slightly misleading relative to those of its predecessors (when viewed alone). We made a conscious effort to test dredge 5 in a "higher-turtle" area, knowing that dredge 5 was already benefiting from the positive results and design changes of dredges 1–3, which showed significant reductions in fish bycatch. Dredge 5, the CFarm turtle deflector dredge, underwent additional successful testing with sea turtle carcasses, proving the effectiveness of the design in minimizing injuries to loggerheads (Smolowitz et al. 2010).

As noted earlier, seasonal and spatial variations in the catch rates of bycaught species, combined with an extremely heterogeneous and mobile bottom type, make comparisons of dredge designs over different trips difficult. However, aggregating the results of the modified dredge designs highlights the importance of these design changes in reducing bycatch while increasing sea scallop harvesting efficiency. A 46% reduction in the bycatch of yellowtail flounder and a 69% reduction in that of winter flounder illustrate just how profoundly changes to gear designs can impact exclusion measures. We attribute the fish bycatch reduction of this dredge design to the forward cutting bar. Like a sea turtle, a fish encountering the cutting bar has an opportunity to escape upward that is not available when encountering a cutting bar located under the depressor plate (Figure 6). An increase in deflective surfaces, mostly achieved by rotating the key components from 90° to 45°, allows uninterrupted egress in the direction of the most likely route. The exclusion potential of the modified dredge is documented by video, where we observed a yellowtail flounder attempting to escape a towed dredge by swimming up rather than forward and away.

The goal of the design modifications ancillary to loggerhead interactions was to reduce finfish bycatch by achieving flow patterns in front of the dredge and lift behind the cutting bar to lift sea scallops into the dredge bag. Flume tank tests offered some insight into the slight increase in efficiency in scallop capture. In the standard dredge, the depressor plate overhangs the cutting bar and seems to mitigate some of the flow effects that help create lift behind the cutting bar. Moving the cutting bar ahead of the depressor plate places the cutting bar into an area of undisturbed flow. In this environment, more lift seems to occur behind the cutting bar, probably due to slightly higher flow disturbances behind the rotated cutting bar.

The rotated orientation of the cutting bar results in slightly higher drag, since more area is presented in the tow direction. This impact was moderated by welding the turtle chain attachment plate at the centerline of the cutting bar, which decreased turbulence and the associated drag. The flume tank tests also suggest an advantage to widening the depressor plate in the forward cutting bar design, in that increased lift is created behind the cutting bar.

All of these investigations can and should be taken further, especially design efforts focused on the relationship of the cutting bar to the depressor plate with respect to developing a strong lifting stream. There is also great room for other improvements in the hydrodynamic characteristics of the dredge frame. The depressor plate is of poor hydrodynamic design, with a lift-to-drag ratio of approximately 1. This ratio can easily be increased by changing the angle and lowering the vertical profile. For example, changing the 45° angle of attack to 22.5° increases the lift-to-drag ratio, which should save fuel. The resulting low-profile dredge may also reduce fish bycatch and have less impact on sea turtles.

In conclusion, the CFarm turtle deflector dredge has improved efficiency with respect to the target catch, significantly reduces fish bycatch, and minimizes the risk of injury to sea turtles. The indications are that additional improvements can be made to the basic design to improve catch, reduce bycatch, and minimize the carbon footprint of the sea scallop dredge fishery.

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