Estimating Incidental Mortality in the Sea Scallop Fishery

Final Report
Prepared for the 2014
Sea Scallop Research Set-Aside

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Submitted by

Liese Siemann, Carl Huntsberger, Jasper Leavitt, Farrell Davis, and Christopher Parkins
Coonamessett Farm Foundation, Inc

and

Ronald Smolowitz
Coonamessett Farm, Inc.

Coonamessett Farm Foundation, Inc
277 Hatchville Road
East Falmouth, Massachusetts, USA 02536
508-356-3601 FAX 508-356-3603
contact@cfarm.org

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Project personnel

Project Coordinator (10/2014 - present) - Carl Huntsberger
Project Coordinator (3/2014 – 10/2014) – Katherine Thompson
Planning - Megan Winton, Farrell Davis, Chris Parkins, Liese Siemann
Sampling – Farrell Davis, Jasper Leavitt
Data Analysis - Liese Siemann, Jasper Leavitt, Carl Huntsberger
ROV Pilot - Bill Campbell
REMUS Coordinator- Amy Kukulya
Project Oversight - Ron Smolowitz

Trips for this project (NA14NMF4540082)

Vessel	Dates	Sampling
F/V Liberty	7/28/14-8/1/14	Towing, Dredge-mounted cameras, REMUS, ROV Surveys of individual tow paths
F/V Mister G.	8/7/14-8/8/14	Benthic sled test runs
F/V Atlantic	9/8/14-9/12/14	Towing, Dredge-mounted cameras, REMUS. Surveys of overlapping tow paths
F/V Mister G.	9/11/14-9/12/14	Benthic sled and ROV surveys of towed area
F/V Vanquish	5/15/15	Testing of benthic sled on large vessel with new lights
F/V Vanquish	6/16/15-6/20/15	Towing, Benthic sled, BACI sampling design Surveys of overlapping tow paths

Executive Summary

It has long been recognized that scalloping operations cause mortality to scallops and other species not only when they are caught, but also incidentally from gear contact when they are discarded or not selected by the dredge. Sea scallop stock assessments still use estimates of incidental mortality that are based on studies conducted over 25 years ago. Technology available for non-invasive optical surveys, using vehicles equipped with underwater cameras, has improved tremendously since then. The goal of this project was to more accurately estimate scallop incidental mortality using a variety of underwater survey vehicles.

All surveys were conducted in southern New England waters in areas with mainly sandy substrate using a standardized Coonamessett Farm Turtle Deflector Dredge (CFTDD) for all tows. Study locations were surveyed before and after dredge tows using the REMUS 100, an autonomous underwater vehicle (AUV) operated by the Woods Hole Oceanographic Institution, the CFF Benthos MiniRover remotely operated vehicle (ROV), and dredge-mounted cameras. CFF also designed a bottom-contacting benthic sled for the project to survey the tow paths. Scallop catch data was recorded for all tows, including the total number of scallops and shell height (SH) and damage condition of each scallop.

The first trip focused on getting video and images of single tow paths at four sites to examine the condition of scallops remaining in the tow path. We used the REMUS AUV to survey the tow paths, and we deployed the Benthos ROV for local examination of scallops or other areas of interest. Cameras were mounted on the dredge frame to detect scallops swimming away from the approaching dredge. Because we could not distinguish between towed and un-towed bottom during our single-tow surveys, we changed our survey design for later trips. During the second trip, we conducted a depletion study at three sites, with 8-10 repeated tows in the same area. The REMUS AUV was used as the main survey vehicle. The Benthos ROV was again used to stay on site and examine small areas of interest, and CFF benthic sled was tested as a survey vehicle. The final trip used the CFF benthic sled for before-and-after video surveys at the tow and control sites (a Before-After Control-Impact or BACI design). Depletion studies, with 12-15 tows each, were conducted at four sites. The benthic sled appeared to be a promising survey vehicle, and the cost to operate it is significantly less than other options.

REMUS images from the second trip were analyzed in a custom program written in R. The program allowed users to annotate the numbers and locations of scallops and scallop predators (crabs, sea stars, skates, and flatfish) in each image. Using REMUS altitude information included with each image and images including checkerboards of known sizes, the program also calculated the shell heights of scallops and categorized them based on size. Sled video from the third trip was analyzed using open-source event logging software that utilizes VLC media player. The numbers of scallops, damaged scallops, and scallop predators were annotated in these videos. ROV and dredge-mounted camera videos from the first two trips were viewed, but no analysis was done.

We identified five scallops that appeared to be damaged in after-tow surveys by the REMUS during our second project trip. Using the scallop abundance estimate from the same REMUS survey, we estimated that the incidental mortality due to scallop dredging during our survey was

approximately 1.0%. This estimate is an order of magnitude less than values currently used for sea scallop stock assessment (incidental mortality = 20% on Georges Bank and 10% in the Mid-Atlantic), but it is comparable to the incidental mortality estimates reported in the studies used to derive these values.

On-deck damage during the same depletion tow series was 2.9%. Furthermore, the number of damaged scallops counted on deck did not increase when tows went over a large percentage of area covered by previous tows. Both results suggest that the majority of scallop damage occurs on deck while maneuvering gear.

Data from this depletion tow series was also used to estimate for the efficiency of the CFTDD on sandy substrate (efficiency = 33%). This value is comparable to the NEFSC survey dredge efficiency estimate using the more comprehensive HabCam and NEFSC survey dredge data (efficiency = 36% for scallops > 70 mm SH), but it is much lower than a CFTDD efficiency estimate derived using a generalized linear mixed model of the relative efficiency of the CFTDD to the survey dredge during paired tows (efficiency = 63%).

Based on the amount of data we could collect and the subsequent analysis we could do with that data, the REMUS AUV was the best survey vehicle that we tested for assessing scallop and predator abundance and estimating incidental mortality and dredge efficiency. However, the REMUS was also the most expensive survey vehicle to use, limiting its value overall. The CFF benthic sled was not as useful for scallop surveys as we had hoped, but changes to our cameras and lights could address many of the issues.

Background

It has long been recognized that scalloping operations cause mortality to scallops and other species not only when they are caught, but also incidentally when they are not landed and not caught (Caddy 1973, Smolowitz 1983, Smolowitz and Serchuk 1988, Smolowitz 2006). This incidental mortality may result from mechanical processes (injury to individuals physically encountering the gear during fishing or shell breakage of individuals compressed within the dredge itself) or on-deck handling and culling procedures (dumping of catch from the dredge, prolonged air exposure on-deck during sorting and culling, or shoveling of undersized scallops overboard) (Medcof and Bourne 1964). Alterations to the sea bottom by the gear may weaken animals making them more susceptible to predation, kill them outright, or alter the suitability of the habitat for scallop survival (Jenkins and Brand 2001, Merrill and Posgay 1964).

Sea scallop stock assessment assumes that the rate of incidental mortality is 20% on Georges Bank and 10% in the Mid-Atlantic (NMFS 2010). These estimates were derived from published estimates of 15-20% on a range of bottom types in the Gulf of Saint Lawrence (Caddy 1973) and less than 5% on sandy bottom in the Mid-Atlantic (Murawski and Serchuk 1989). The difference in the incidental mortality estimates for the two areas may have been due to the different bottom types, resulting in different impacts on scallops left behind in the dredge path (Currie and Parry 1999, Murawski and Serchuk 1989). Incidental mortality is also influenced by dredge design. Caddy (1973) used a 2.44-m-wide dredge with 7.6-cm rings and a gang of three 0.8-m-wide Alberton dredges for his surveys, while Murawski and Serchuk (1989) used vintage 1980's New

Bedford-style dredges for their more recent work. It is important to estimate incidental mortality rates for contemporary gear on different bottom types since scallop dredge design has changed considerably since the current estimates were obtained.

Little reduction in incidental mortality has been documented during recent improvements in scallop gear design, and there is almost certainly scope for further development. For example, it is possible that if the belly of the dredge were raised slightly off the bottom, gear-induced mortality of scallops passing under the sweep chain or through the belly meshes would be reduced (Caddy 1971). In addition, underwater observations of dredges indicate that if the cutting bar of the dredge rides several centimeters above the substrate, the sweep chain passes over any scallops not taken in the dredge and inflicts little damage (Smolowitz and Serchuk 1988). Research has also been conducted to redesign the shape of the cutting bar to create sufficient hydrodynamic force to lift scallops from the bottom into the dredge, thereby reducing the number of scallops left behind in the dredge path (Smolowitz et al. 2012, Vaccaro and Blott 1987). This latter type of innovation is attractive because it would increase capture efficiency while reducing incidental mortality. Yet in order to determine if these or any other gear modifications reduce incidental mortality, an efficient and reliable method for estimating this loss must be developed.

Many techniques have been tested to examine the impact of dredges on the seafloor with the goal of examining incidental mortality and dredge efficiency. Smolowitz and Nulk (1982) successfully conducted detailed surveys of six clam dredge paths with SCUBA divers, with a focus on estimating dredge efficiency. They attempted the same experimental procedure with scallop dredges but had less success due to the low numbers and patchiness of scallops in diveable depths (Ronald Smolowitz, personal communication). Manned submersibles have been used to examine dredge paths and provide some estimates of incidental mortality due to scallop dredges in the northwest Atlantic (Caddy 1968, 1973, Murawski and Serchuk 1989), but these operations are extremely costly. Utilizing drop camera systems, towed cameras, remotely operated vehicles (ROVs), or autonomous underwater vehicles (AUVs) to evaluate the impact of fishing gear can be very effective and low cost relative to submersible surveys (Barker et al. 1999, Collie et al. 2000, Morrison and Carbines 2006). There are pros and cons to using each of these survey vehicles, based on the cost, the difficulty of using them in waters where commercial scallop harvesting typically occurs, and the amount and quality of image data collected during surveys. To highlight this, **Table 1** shows estimates for the daily cost of using an AUV, the CFF benthic sled, and an ROV for our research surveys, along with details about the imagery we could collect with each vehicle.

Project Objectives

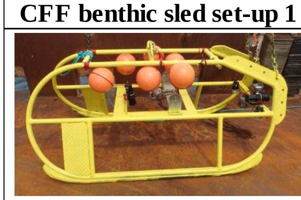
The main objectives of this project were:

1) Estimate the loss of scallop yield resulting from incidental mortality, with incidental mortality defined as the ratio of scallops damaged in the tow path to the number of scallops in the tow path prior to dredging.

2) Evaluate survey techniques for studying the impacts of scallop dredges. Surveys were conducted with the CFF benthic sled, an AUV, and an ROV. The CFF benthic sled was designed and built for this project.

3) Calculate the dredge efficiency for the Coonamessett Farm Turtle Deflector Dredge (CFTDD), a commercially rigged scallop dredge, in the surveyed areas (sandy bottom).

Table 1. Summary of survey vehicles

	Cost per day*	Output format	Resolution	Coverage area	Survey designs tested
 **REMUS 100 AUV**	$5,300	TIFF images	1360 x 1024	~3 m^2 at survey altitude	pre-programmed tracks perpendicular or parallel to the tow path
 **CFF benthic sled set-up 1**	$220	MPEG video 30 fps	720 x 480	~1.75 m^2 for bottom half of image, top half area much larger but difficult to estimate due to trapezoidal distortion	multiple tracks across the tow path
 **CFF benthic sled set-up 2**	$170	MP4 video 60 fps	1920 x 1080	~0.12 and 0.20 m^2 with rectilinear lenses, > 0.30 m^2 with fisheye lens	perpendicular tracks across the tow path and neighboring control area
 **Benthos MiniROVER ROV**	$1,300	MPEG video 30 fps	720 x 480	varies during survey	local searches over small areas

*** The cost per day was estimated based on the cost for contracting the vehicle (REMUS) or the cost to purchase the vehicle and use it for at least ten 6-day survey trips (sled and ROV). The sled cost varies based on the included camera equipment.**

Trip Summary

The first trip focused on getting video and images of single tow paths at four sites to examine the condition of scallops remaining in the tow path (red in **Figure 1**). We used the REMUS AUV to survey the tow paths, and we deployed the Benthos ROV for local examination of scallops or other areas of interest. Cameras were mounted on the dredge frame to detect scallops swimming away from the approaching dredge. We could not find the unique single tow paths during our surveys, so we abandoned this survey design.

During the second trip, we conducted a depletion study at three sites, with 8-10 repeated tows in the same area over a distance of 1500 meters (orange in **Figure 1**). The REMUS AUV was used as the main survey vehicle. The Benthos ROV was again used to stay on site and examine small areas of interest, and CFF benthic sled was tested as a survey vehicle.

The final trip used the CFF benthic sled for before-and-after video surveys at the tow and control sites (a BACI design) (green in **Figure 1**). Depletion studies, with 12-15 tows over 1800 m, were conducted at four sites. The benthic sled appeared to be a promising survey vehicle, and the cost to operate it is significantly less than other options.

Because the dredge survey and image and video survey designs varied for each project trip, the results for each trip are reported separately.

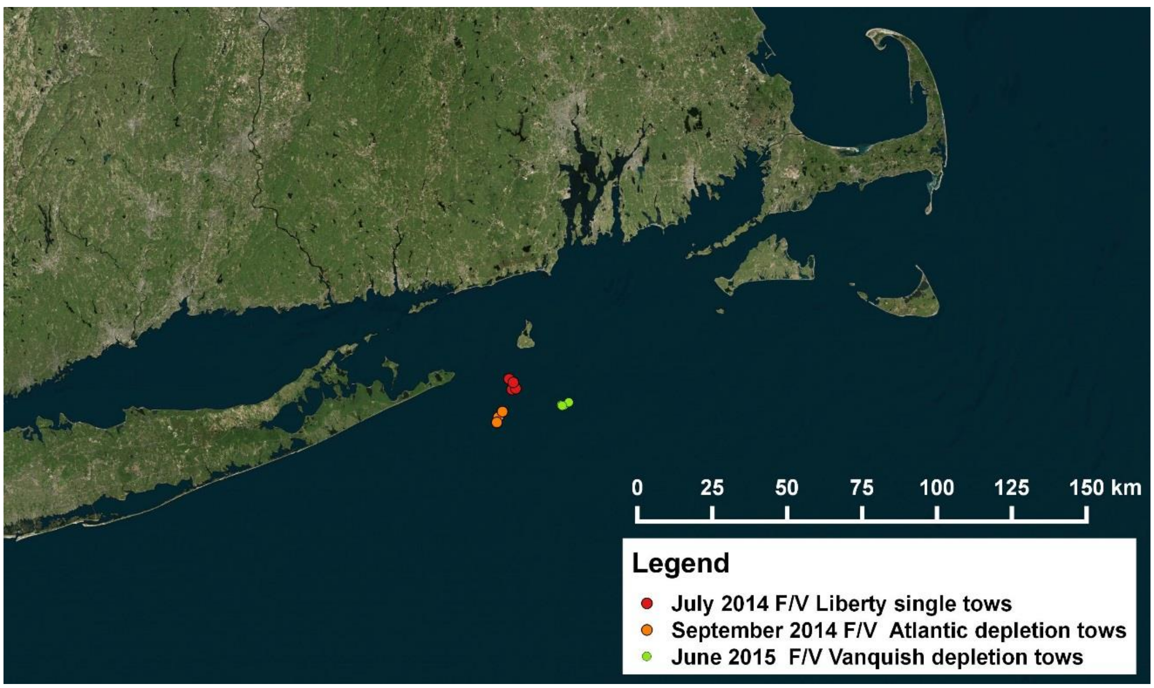


Figure 1. Map showing locations of incidental mortality trips.

First Survey Trip – July 2014

The trip conducted on F/V Liberty from July 29 to August 2, 2014 focused on getting video and images of single tow paths at four sites (**Figure 2**) to examine the condition of scallops remaining in the tow path. Sample locations were surveyed before and after dredge tows using the REMUS 100, an AUV operated by the Woods Hole Oceanographic Institution, as well as dredge-mounted cameras, and the CFF-owned Benthos MiniROVER ROV. Although we marked the beginning of the tow with a buoy marker system deployed from the dredge frame at the start of the tow, we had difficulty distinguishing the difference between the towed and un-towed bottom using the REMUS AUV. The ROV was deployed with the goal of examining scallops of interest in more detail, but the survey had limited value because it was difficult to steer the ROV in currents near the bottom or approach target scallops without disturbing the bottom sediment. The dredge-mounted cameras were included in the surveys to monitor swimming escapes by small scallops, but video quality was inadequate for this purpose due to low-light conditions and clouds of disturbed sediment. Because of these problems, images and video collected during the survey were reviewed but not analyzed. However, the trip allowed us to improve our survey methodology for future trips.

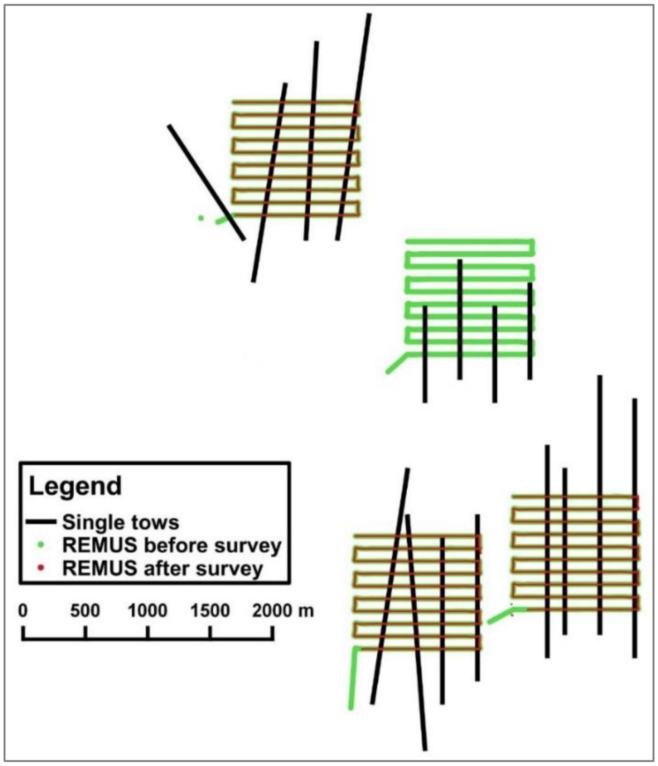


Figure 2. Schematic showing the paths of single dredge tows and the REMUS AUV survey tracks for the July 2014 trip. Overlapping before- and after- tow surveys ran perpendicular to tow paths.

Benthic Sled Design and Testing

CFF designed and built a bottom-contacting benthic sled for this project. The goal was to create a cost-effective and flexible platform for conducting benthic surveys. The sled was designed in Solid Works by CFF staff after reviewing benthic sled designs used by other research groups (**Figure 3**). The sled was constructed of welded steel round bar with attached steel runners (total length = 1.33 m, length of runner contact = 1.02 m, width = 1 m, weight = 123 kg). Crossbeams were added to support cameras and lights.

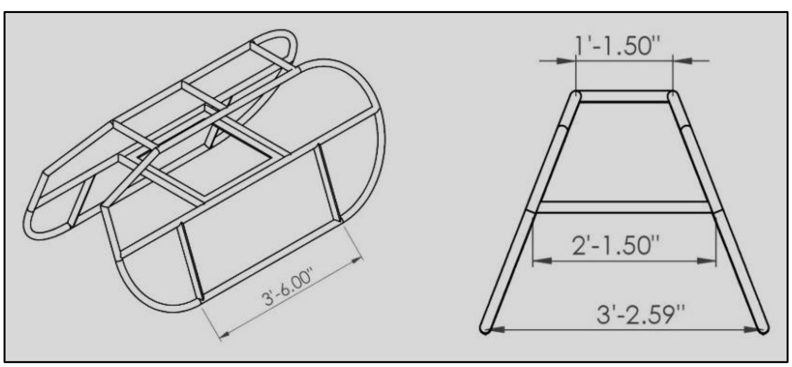


Figure 3. Benthic sled frame design from an oblique angle and from the front.

Fixed-focus underwater video cameras (Outland Technology UWC-325 and GoPro Hero 3 series cameras in underwater housings) can be mounted on the sled crossbeams. Underwater LED lights (Outland Technology UWL-401, Fix Neo 1200 DX, Nocturnal Lights SLX 800, and Fantasea Radiant 1600) can also be mounted on the sled. The Outland Technology camera and light can be turned off and on by the sled operator, but this requires additional cables that can get tangled during surveys. The GoPro cameras were fitted with different lenses (the original GoPro 2.97 mm fisheye lens, a 2.97 mm rectilinear lens, and a 4.14 mm rectilinear lens). Rectilinear lenses were purchased from Peau Productions (http://www.peauproductions.com/store/) and installed by CFF staff. These lenses allow more accurate estimation of the sizes of objects because there is no radial distortion of the image. However, the fisheye lens offers a wider angle view. Examples of different camera and light configurations that are possible on the benthic sled are shown in **Figure 4**.

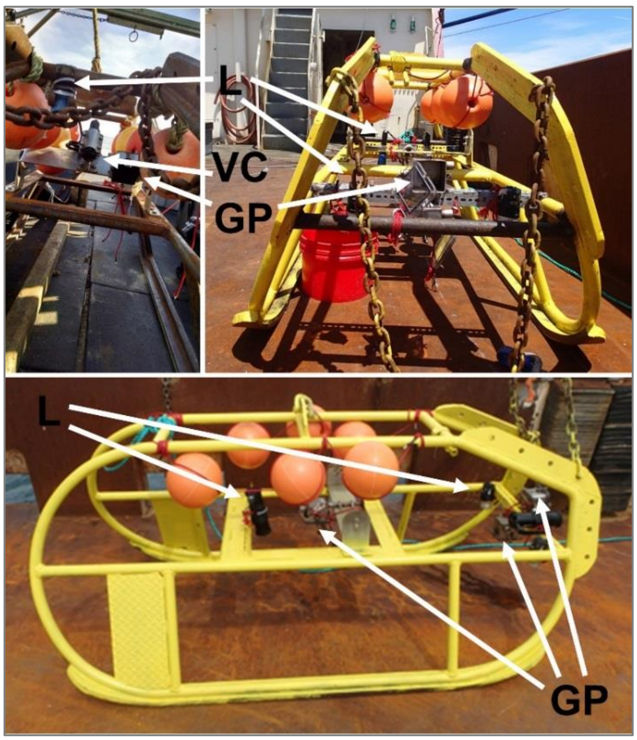


Figure 4. On-deck photos of the benthic sled with different camera (VC – Outland Technology underwater camera, GP – waterproof GoPro housings) and light configurations (L – different underwater LED lights).

The first benthic sled test runs were conducted on August 8-9, 2014, and the video footage indicated that the sled was a promising survey vehicle. We were able to identify and count scallops in our test videos.

Second Survey Trip – September 2014

Difficulty finding the tow paths with the REMUS AUV during the first trip resulted in a change of protocol for the trip aboard F/V Atlantic from September 8-12, 2014. During this trip, a depletion study was conducted at three sites, with 8 to 10 repeated tows in the same area over a distance of approximately 1500 meters (**Figure 5**). The REMUS AUV was used for before-tow surveys running perpendicular to the tow paths. After-tow surveys were planned to run parallel to and on top of the tow paths. The Benthos ROV was tested again during this trip, and the CFF benthic sled was used to survey tow tracks for the first time. Issues with REMUS operation resulted in the first after-tow survey being prematurely aborted and the second after-tow survey being conducted in the wrong location (**Figure 5**). Because of this, analysis was limited to the third depletion series.

Although we were able to approach a few scallops and obtain close-up footage (**Figure 6**), the ROV continued to be of limited use for surveying scallops and tow paths. Disturbed sediment that may have been caused by a dredge was seen by the ROV operator briefly, but attempts to get back to that spot were unsuccessful. In almost all cases, scallops approached by the ROV reacted to the vehicle and swam away.

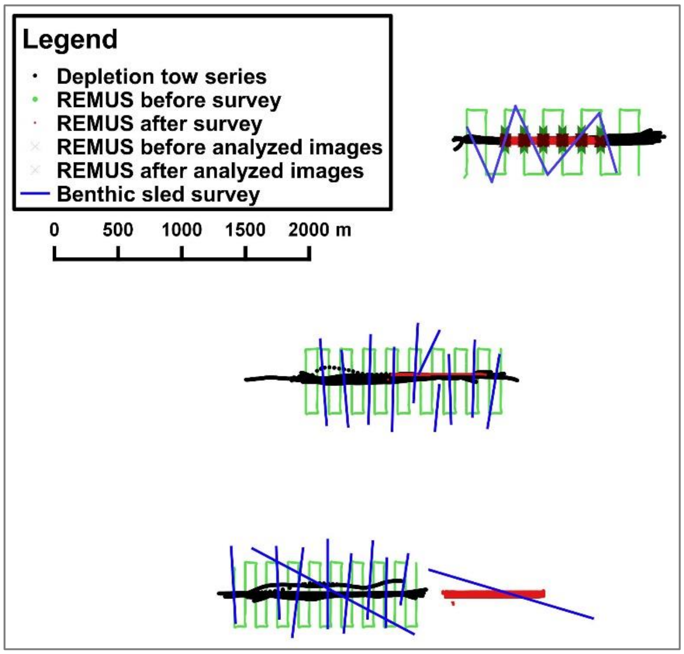


Figure 5. Schematic showing the paths of three depletion tow series and the REMUS AUV and benthic sled survey tracks for the September 2014 trip. Before-tow REMUS surveys ran perpendicular to the tow paths and after-tow REMUS surveys were planned to run parallel to and on top of the tow paths. Benthic sled survey tracks ran across the tow paths. Because of issues with the REMUS surveys for the first two depletion series (middle and bottom), analysis was limited to the third one (top).

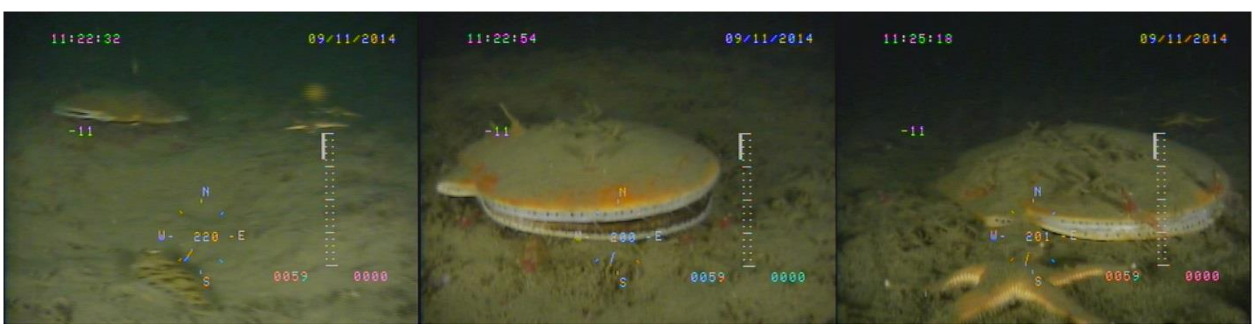


Figure 6. Screen shots from ROV footage showing scallops and nearby flounder, sea stars, and shrimp. All of these scallops were disturbed by the ROV and swam away shortly after these images were captured.

The benthic sled was towed across the tow paths after the depletion series were finished to determine if it could be used as the primary survey vehicle during the final project trip. We were able to clearly identify the tow path in one of 33 benthic sled videos. In addition, the footage from these surveys was used to analyze scallop behavior in response to artificial light, and we currently have a paper in press based on this work (Siemann et al. in press).

Analysis of REMUS images

Most of the image and data analysis from the second research trip focused on the third depletion tow series. This series included 8 tows with an average distance of 1531.5 meters (range 1425-1607 meters), with tow distances calculated in ArcGIS from GPS coordinates programmed to be recorded every second from the vessel navigation system. Tows overlapped with previous tows in the depletion series for 0-54% of their coverage area assuming dredge location could be estimated using vessel coordinates (**Table 2** and **Figure 7**).

Table 2. The percentage of tow area that overlapped with a previous tow.

	Proportion of tow path over previously towed area	Proportion overlapping one previous tow	Proportion overlapping two previous tows	Proportion overlapping three previous tows	Proportion overlapping four previous tows
tow 1	**0**	0	0	0	0
tow 2	**0**	0	0	0	0
tow 3	**13%**	13%	0	0	0
tow 4	**32%**	23%	9%	0	0
tow 5	**54%**	36%	9%	9%	0
tow 6	**43%**	26%	5%	4%	8%
tow 7	**15%**	15%	0	0	0
tow 8	**36%**	26%	9%	1%	0

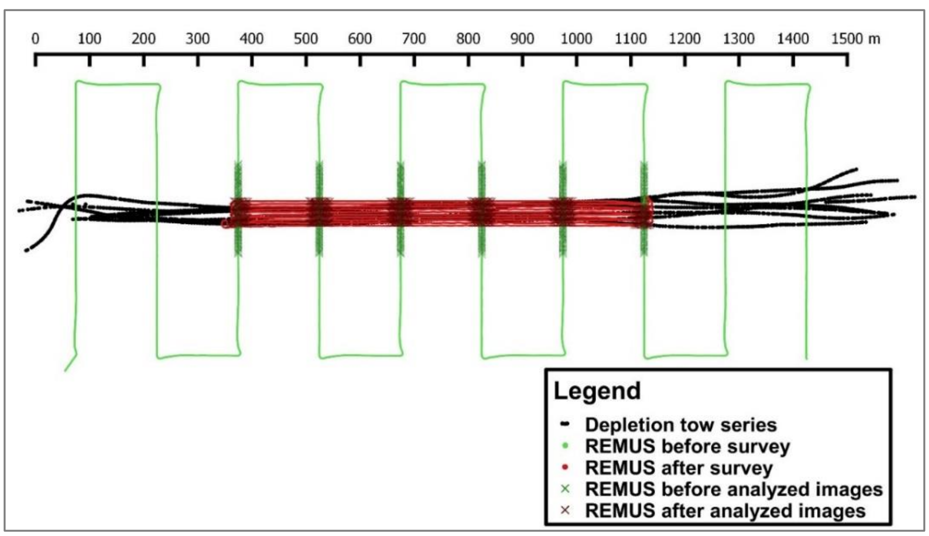


Figure 7. Tracks of depletion tows (black) and corresponding REMUS survey tracks. The REMUS pre-tows survey track is shown in light green, and the REMUS post-tows survey is shown in red. The locations for the subset of analyzed images are highlighted in maroon and dark green.

A subset of images from the REMUS before- and after-tows surveys were analyzed in a custom program written in R. Because each REMUS survey included thousands of images, a subset was chosen because it included areas covered in both the pre- and post-tows surveys. These areas are highlighted with crosshatches in **Figure 7**. Over 800 images were analyzed for each survey, covering 2500 square meters of sea floor each in the before- and after-tow surveys (before: 837 out of 5416 images taken, after: 823 out of 6663 images taken).

The R-program allows users to annotate the numbers and locations of scallops and scallop predators (crabs, sea stars, skates, and flatfish) in each image (examples in **Figure 8**). Using REMUS altitude information included with each image (distance from bottom in meters) and images including checkerboards of known sizes, the program also calculates the shell heights of scallops and categorizes them based on size. For this analysis, small scallops had shell heights of under 80 mm, medium scallops had shell heights between 80 and 120 mm, and large scallops had shell heights of over 120 mm. These cut-off values were chosen based on information available from NMFS on the selectivity of commercial scallop dredges with 4” rings (NMFS 2007a).

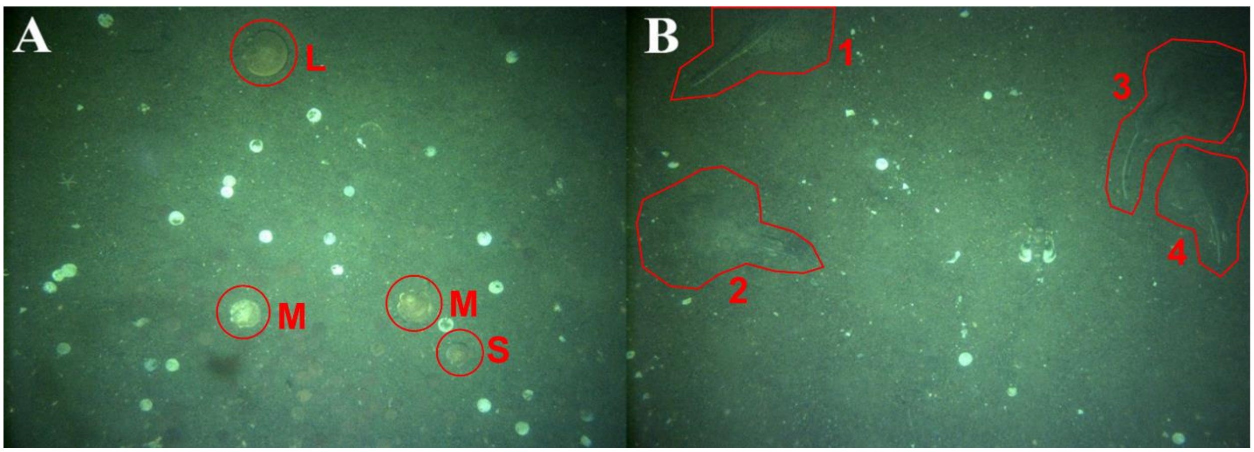


Figure 8. REMUS images with (A) one large (L), one small (S), and two medium (M) scallops (B) four skates.

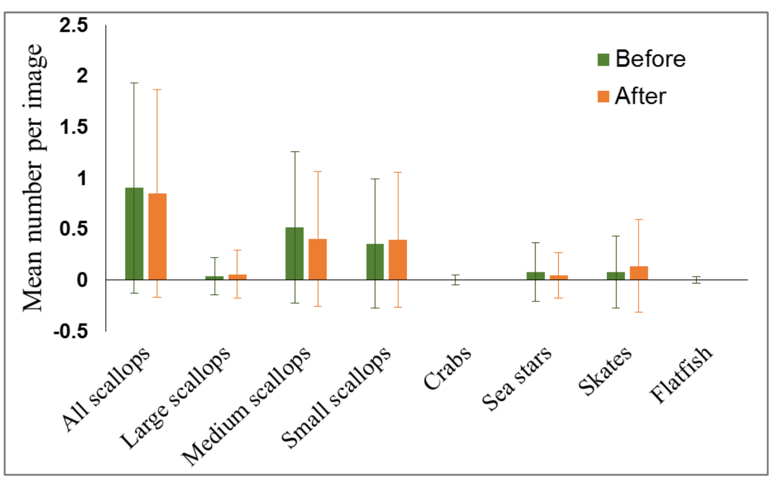


Figure 9. The mean number of animals per image. Error bars are standard deviation.

The mean number of animals per image before and after the tows are shown in **Figure 9**. Because many of the images did not include any scallops or predators, our count data set had a high proportion of zeroes (**Figures 10** and **11**). Because of this, we analyzed the count data using negative binomial regression modeling (McElduff et al. 2010). Although parametric *t*-tests and nonparametric Mann-Whitney U tests are known to often give invalid results when data are extremely skewed with an excess of zeroes, we also included those results in the tables for comparison (**Tables 3** and **4**).

The number of medium scallops significantly decreased after the depletion tows (negative binomial regression, p=0.001), while the number of large scallops significantly increased (negative binomial regression, p=0.044) and the number of small scallops was not significantly altered by the tows (**Table 2**). Though the number of skates significantly increased after the depletion tows (two-tailed paired t-test, p=0.003), the number of sea stars significantly decreased (two-tailed paired t-test, p=0.01) and the numbers of crabs and flatfish did not significantly change (**Table 3**).

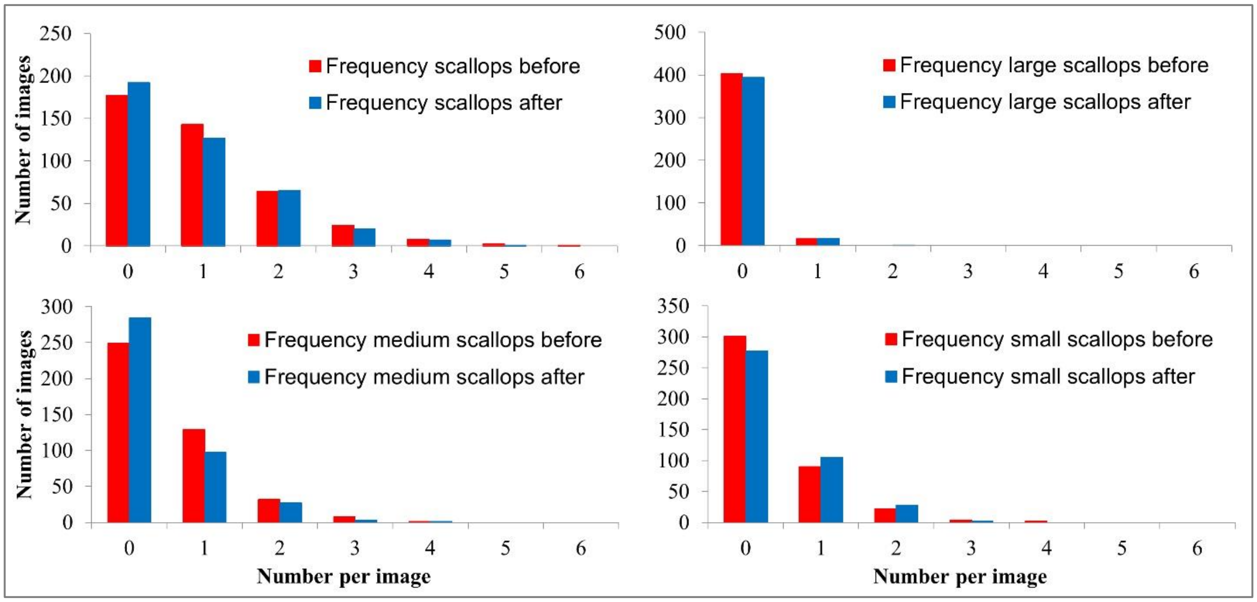


Figure 10. Histograms showing the numbers of images with zero through six scallops of each specified size class per image.

Table 3. Results of statistical tests comparing pre- and post-tows numbers of scallops per image. Categories with significant negative binomial regression results are highlighted.

	Pre-tows mean number per image (SD)	Post-tows mean number per image (SD)	Mann-Whitney U p-value	t-Test p-value	Negative binomial regression p-value
All scallops	0.904 (1.029)	0.847 (1.019)	0.165	0.253	0.254
Large scallops (>120mm SH)	0.035 (0.183)	0.056 (0.235)	0.061	0.040	0.044
Medium scallops (80-120mm SH)	0.515 (0.741)	0.399 (0.661)	0.001	0.001	0.001
Small scallops (<80mm SH)	0.355 (0.634)	0.392 (0.662)	0.209	0.237	0.234

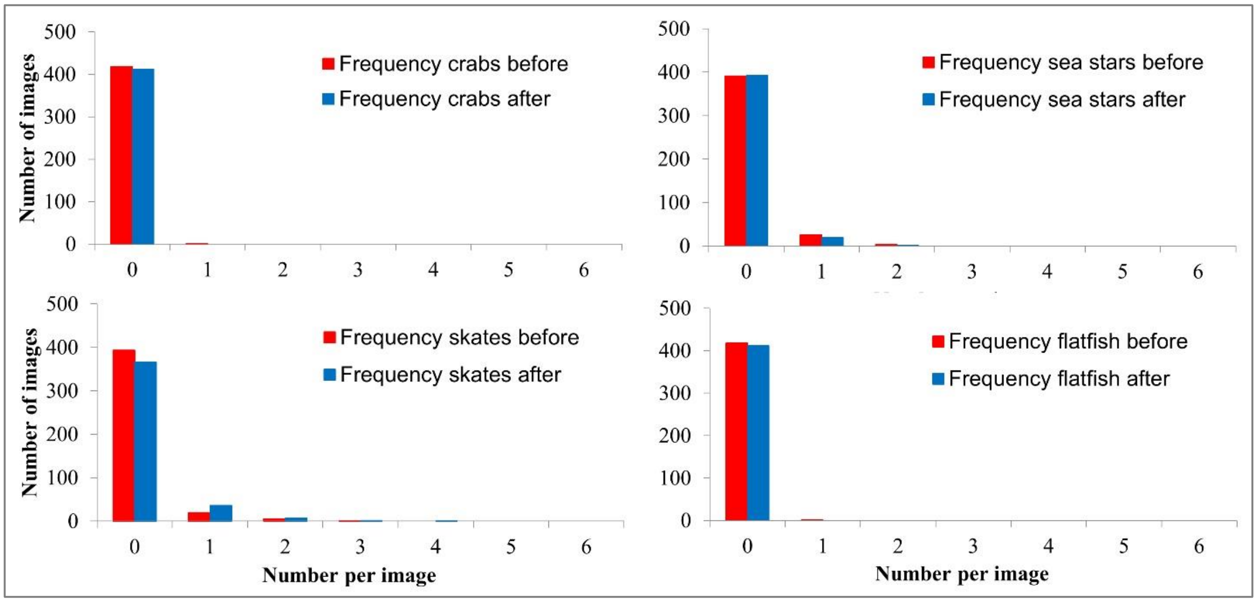


Figure 11. Histograms showing the numbers of images with zero through six predators of each specified animal type.

Table 4. Results of statistical tests comparing pre- and post-tows numbers of predators per image. Categories with significant negative binomial regression results are highlighted.

	Pre-tows mean number per image (SD)	Post-tows mean number per image (SD)	Mann-Whitney U p-value	t-Test p-value	Negative binomial regression p-value
Crabs	**0.002 (0.049)**	**0 (0)**	**0.161**	**0.157**	**0.996**
Sea stars	**0.079 (0.287)**	**0.046 (0.221)**	**0.009**	**0.010**	**0.010**
Skates	**0.079 (0.354)**	**0.137 (0.454)**	**0.001**	**0.003**	**0.003**
Flatfish	**0.001 (0.035)**	**0 (0)**	**0.321**	**0.318**	**0.998**

CFTDD selectivity and efficiency

The results of the REMUS image analysis were used to calculate expected densities of scallops available in the tow area, allowing a direct estimation of the percentage of scallops caught per size class and CFTDD efficiency (for scallops > 80 mm SH). To get an estimate of dredge efficiency, we used the density estimates of scallops in the REMUS before-tow images and catch data from tows that did not overlap with the previous tows. Confidence intervals were obtained by bootstrapping vectors of per image scallop densities 1000 times and using these vectors to calculate a range of dredge efficiency estimates. Our analysis of CFTDD catch indicated it has a dredge efficiency of 33% (95% confidence intervals: 29 – 38%) for scallops with shell heights over 80mm when towed on sandy bottom. This value is comparable to the sand-substrate efficiency estimates based on SMAST video surveys for the modified New Bedford dredge used by NMFS for scallop surveys on Georges Bank (36% for scallops > 70 mm SH, NMFS 2007; 40% overall, NMFS 2014), even though the survey dredge is not rigged as a commercial dredge. However, it is much lower than one derived estimate for the efficiency of the CFTDD.

Generalized linear mixed model estimates of the relative efficiency of the CFTDD to the NMFS survey dredge, based on paired tow surveys, suggested that the efficiency of the CFTDD is 63% (Rudders and DuPaul 2011).

Because this analysis was done with a very small sample size, we did not attempt to estimate a size selectivity curve for the CFTDD. Size selectivity analysis of commercial scallop dredges with 4” rings has shown that scallops with shell heights of under 80 mm have a less than 10% chance of being retained in the dredge, while scallops with shell heights over 120mm have a 90% retention probability (NMFS 2007a). When fishing on a sandy bottom, 1.2% of small scallops (< 80 mm SH) were retained in the CFF turtle-deflector dredge, which is consistent with published results.

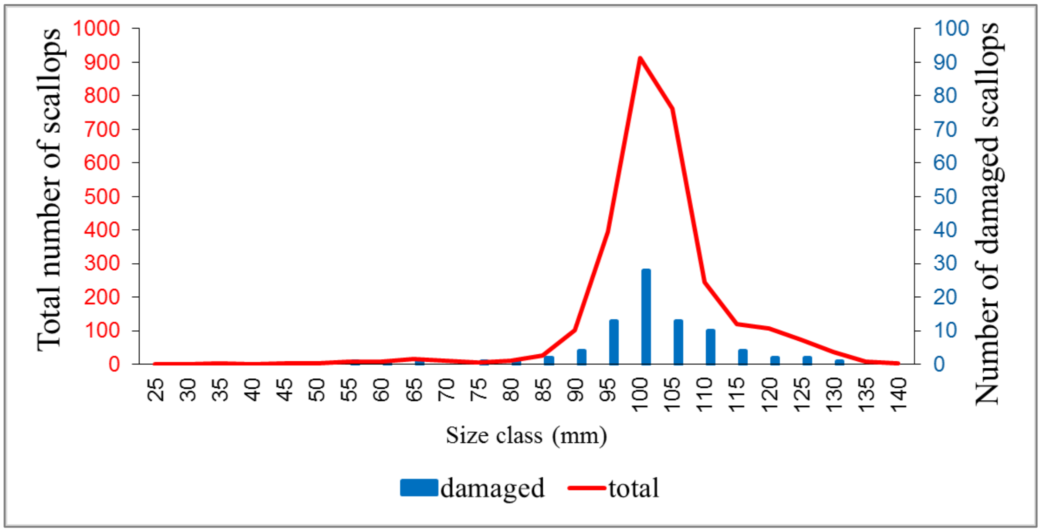


Figure 12. Size frequency histogram showing the total numbers of scallops landed (red) and the number of damaged scallops (blue) counted on deck during the third tow series.

Analysis of damaged scallops – second trip

Damaged scallops were identified and counted on deck at all three depletion study sites. During all three tow series, a total of 6,647 scallops were caught during 26 tows, and 295 of the scallops were classified as damaged (4.4% of the total). During just the third tow series, a total of 2,858 scallops were caught during 8 tows, and 84 of the scallops were classified as damaged (2.9% of the total). The highest proportion of scallops caught was in the 100-105 mm size class, with over 80% of the total scallops having shell heights between 95 and 115 mm (**Figure 12**). The highest proportion of damaged scallops was also in the 100-105 mm size class, with over 76% of the damaged scallops having shell heights between 95 and 115 mm (**Figure 12**). Because the survey tows were short relative to commercial tows, these damage percentages may be relatively high.

The location of scallops on the deck relative to the shoes of the dredge was recorded in order to attempt to quantify scallop damage resulting from the dredge contacting the deck (**Figure 13A**). We hypothesized that scallop damage was concentrated near the shoes where scallops were crushed (**Figure 13**). However, a comparison of the numbers of damaged scallops in the middle versus near the shoes showed no significant difference in scallop damage (paired t-test: middle mean = 5.4±3.6, shoe mean = 6.3±3.1, t (25) = -1.127).

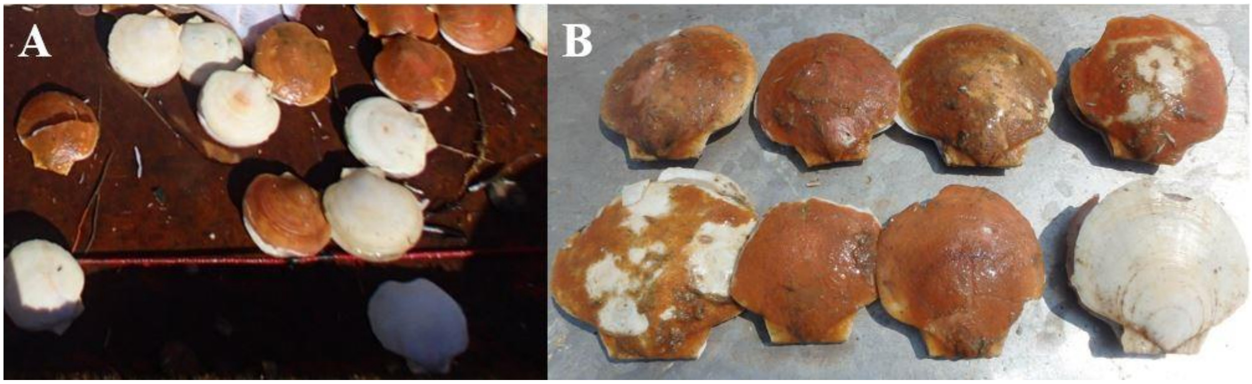


Figure 13. (A) Deck marking line to record the position of damaged scallops relative to where the shoes of the dredge were coming in contact with the deck. (B) Examples of damaged scallops counted on deck.

Estimating incidental mortality

We used two approaches to estimate incidental mortality. The first method examined the number of damaged scallops counted on deck to determine if that count increased when tow overlap increased. If a substantial number of scallops were being damaged during a tow, we would expect the number of damaged scallops counted on deck to increase when tows went over a large percentage of area covered by previous tows. Our analysis did not support this hypothesis, with no significant linear relationship between these statistics ($R^2 = 0.12$, $p = 0.401$), suggesting that the majority of scallop damage occurs on deck while maneuvering gear (**Figure 14**).

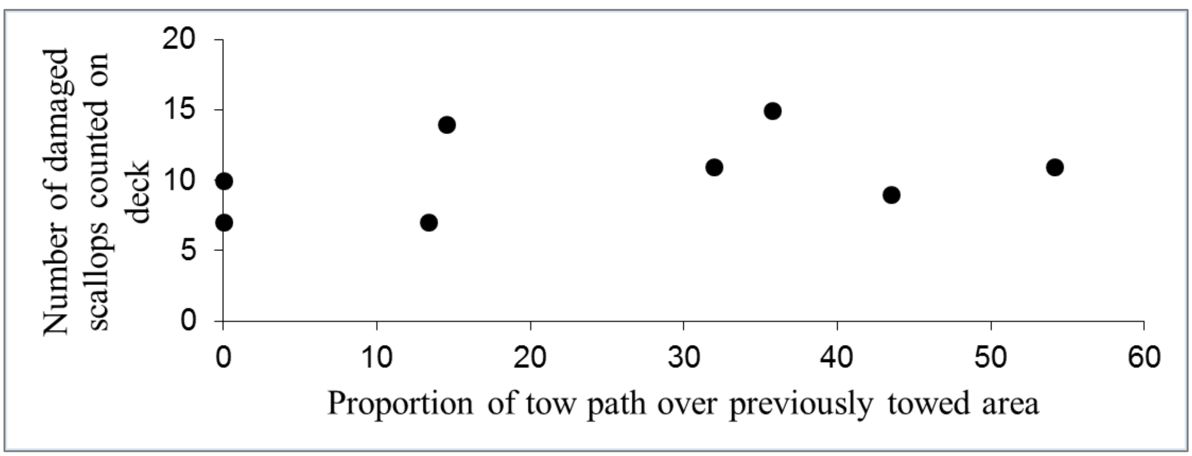


Figure 14. Proportion of tow over previously towed area versus the number of damaged scallops counted on deck.

For our second approach, the REMUS images from the after-tow surveys were examined for damaged scallops in the tow paths. Five apparently damaged scallops were identified, and after accounting for any image overlap, this analysis estimated incidental mortality to be 1.0% (if all injuries were lethal). The scallops ranged in size from 86 – 116 mm shell height, and sizes for each scallop are shown in **Figure 15**.

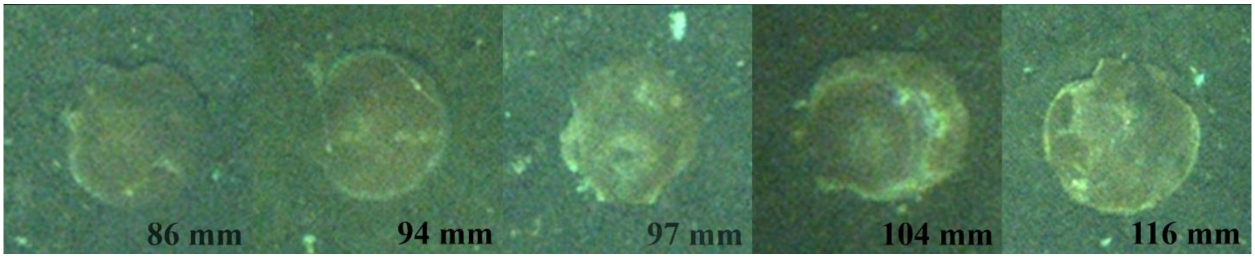


Figure 15. Examples of scallops identified as apparently damaged in REMUS post-tows images. The shell height for each scallop is shown in the bottom right corner of each image.

This estimate of incidental mortality is an order of magnitude less than the values currently used for the sea scallop stock assessment (20% on Georges Bank and 10% in the Mid-Atlantic, NMFS 2010). However, these values are based on two studies conducted over 25 years ago aboard submersibles, and when the data from these studies is examined, our result is comparable to what has been previously observed. Caddy (1973) dove along offshore dredge paths in the Gulf of Saint Lawrence on rocky and sand substrates and counted a total of 323 scallops. Overall, observed incidental mortality was 10.8%, with values ranging from 20.5% on rocky substrate (26/127 scallops with lethal damage) to zero on sandy substrate (0/59 scallops with lethal damage). He also documented a significant increase in scallop predators along tow paths shortly after dredging, interpreting this as a result of damaged scallops and scallop viscera being available after dredging. Murawski and Serchuk (1989) dove on four sites in the Mid-Atlantic region with mud and sand substrate. Their report does not include a data table, but they noted "the dearth of broken or mutilated scallops observed in the vicinity of the path" and estimated incidental mortality to be less than 5%. They did not observe increased numbers of predators along the tow paths after dredging, although feeding aggregations of predators were seen when scallop viscera was tossed overboard and along hydraulic clam dredge paths.

Third Survey Trip – June 2015

During this trip, the dredge surveys were once again conducted as depletion studies. Twelve to fifteen repeated tows were conducted in three areas over a distance of approximately 1800 meters (**Figure 16**). The dredge paths were kept within 100 meter wide areas. A series of ten tows was conducted in a fourth area (not shown), but because the vessel electronic monitoring system stopped functioning during the tow, video from this series was viewed but excluded from any video analysis. The CFF benthic sled was used to conduct before- and-after-tow video surveys at the towed and control sites (a Before-After Control-Impact or BACI design) (**Figure 16**). The ROV and dredge-mounted cameras were not used during this trip because they were of limited value during the first two trips. The REMUS AUV was not used because of the high cost.

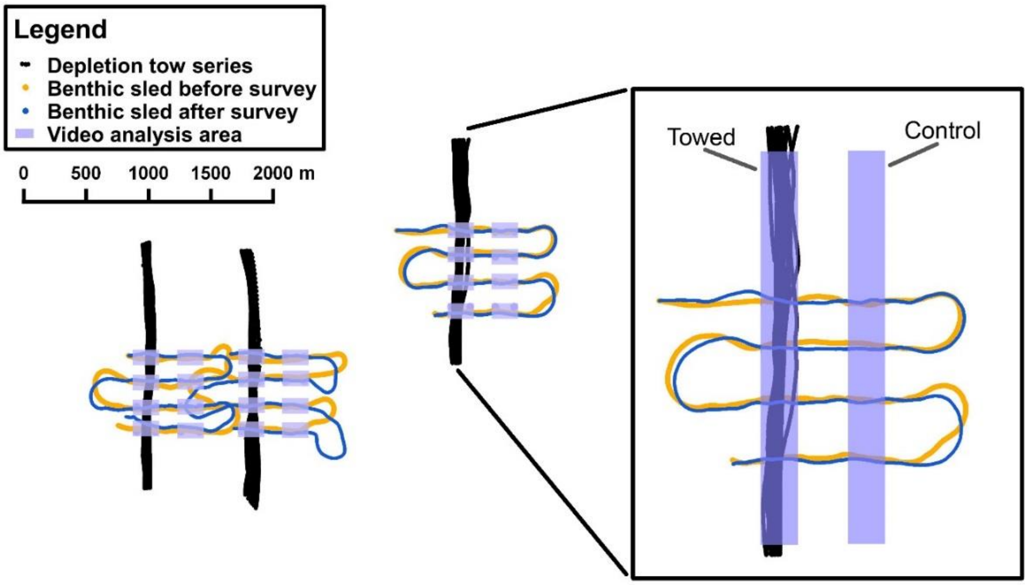


Figure 16. Schematic showing the paths of three depletion tow series and the benthic sled survey tracks for the June 2015 trip. Before-and after-tow surveys ran perpendicular to the tow paths. Though video was recorded during the entire sled survey, analysis was limited to the towed and control areas shaded in lavender. The inset shows one example of the GPS-defined towed and control areas used 1) to determine when the vessel towing the sled needed to change speed and coast across video analysis areas and 2) to select the video clips for analysis (see text for more details).

Video was analyzed using *Behavioral Observation Research Interactive Software (*BORIS), an open-source event logging software that utilizes VLC media player (http://penelope.unito.it/boris and http://www.videolan.org/vlc/index.html). The numbers of scallops, damaged scallops, and scallop predators were annotated in these videos. All videos were annotated by the same person, with videos watched at 1/10th speed for accuracy.

Our benthic sled test trips showed that in order for the GoPro cameras on the sled to take videos that can be used to examine scallop damage, the sled cannot move at a speed above 2 knots. Because a large scallop vessel cannot travel continuously and consistently at such a slow speed, we ended up conducting the surveys by having the vessel move at faster speeds approaching the designated video analysis areas (inset in **Figure 16**), coast through each area, and then pick up speed once again. Vessel GPS coordinates were used to determine when the vessel needed to slow down and speed up so that the sled was traveling slowly behind the coasting vessel through the video analysis areas. These coordinates were chosen to define areas that were approximately 150 meters wide and overlapped the 100 meter wide defined-dredging and control areas. Due to the nature of this survey method, the sled speed and image quality varied (**Figure 17**). Time stamps on the videos, coupled with bridge logs, were used to isolate the correct video segments for analysis.

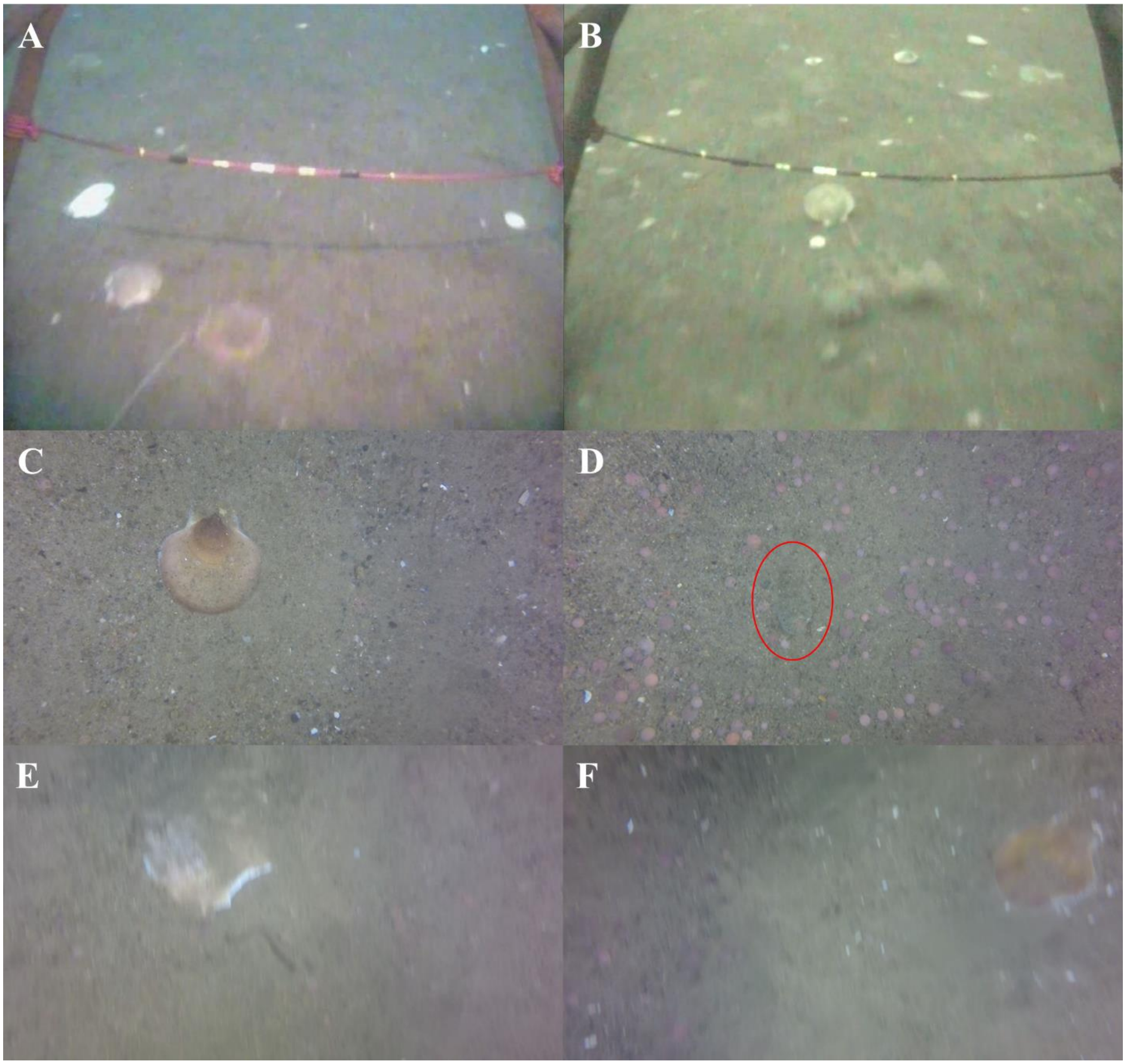


Figure 17. Sample images taken from video recorded by the CFF benthic sled. (TOP ROW) Screenshots from video taken by (A) the Outland Technology video camera with (A) and without (B) artificial light. (MIDDLE AND BOTTOM ROWS) Screenshots from video taken by GoPro Hero 3+ cameras with artificial light showing an 80 mm SH scallop (C), a small summer flounder circled in red (D), and two possibly damaged scallops (E-F). The middle row images were taken when the sled was almost stationary and image quality was very good compared to the images in the bottom row that were taken when the sled was moving.

Analysis of damaged scallops – third trip

Damaged scallops were identified and counted on deck at the four depletion study sites. A total of 4,640 scallops were caught during 52 tows, and 322 of the scallops were classified as damaged (7% of the total). The highest proportion of scallops caught was in the 117-122 mm size class, with the highest proportion of damaged scallops in the slightly smaller 112-117 mm size class (**Figure 18**). As during the second trip, the survey tows were short relative to commercial tows, and these damage percentages may again be high.

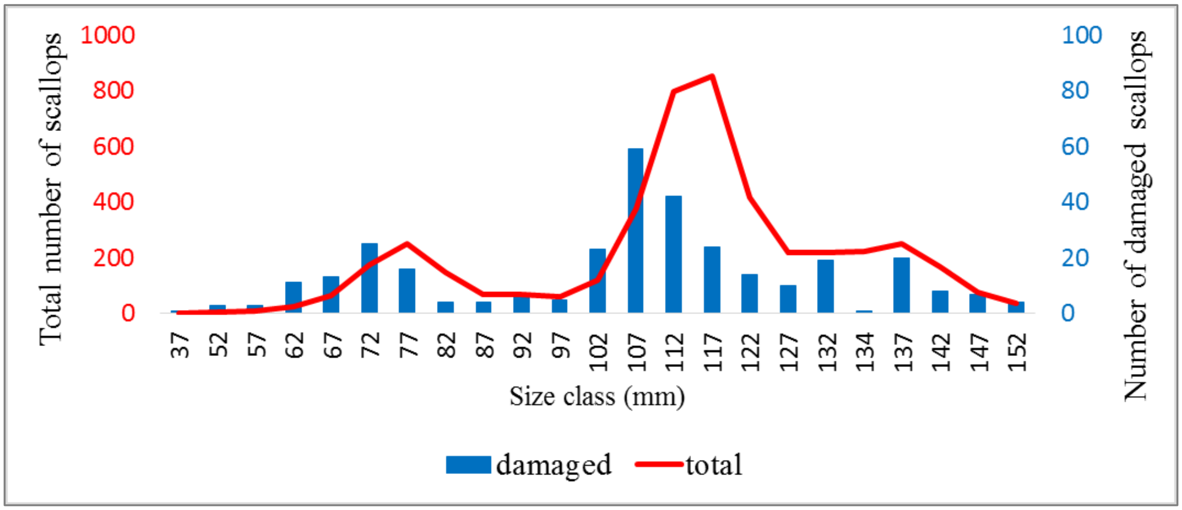


Figure 18. Size frequency histogram showing the total numbers of scallops landed (red) and the number of damaged scallops (blue) counted on deck.

Analysis of CFF benthic sled images

The video analysis from the third research trip focused on the first three depletion tow series. Two approximately 1500 meter long by 150 meter wide areas were defined at each site based on GPS coordinates (inset in **Figure 16**). One area included the tow paths, and the other area was located parallel to and 200 meters away from the tow paths. Video taken as the sled passed through these areas was used for analysis. Each survey track passed over the control and towed sites four times.

Three GoPro cameras were mounted on the sled, with two facing straight down and one facing forward. Camera and light malfunctions prevented us from getting footage from all three cameras during each survey. However, we were able to get complete camera coverage of each survey from at least one downward facing camera. All video analysis was limited to this main camera. Unfortunately, the main camera did not have the same lens for each survey, so the area covered per survey was not consistent. We estimated the total before and after survey coverage based on the size of the main GoPro camera field of view at each site, and these values are shown in **Table 5.** If the total area towed is estimated based on the length and width of the planned dredging area, an estimate that is reasonable based on GIS maps of the vessel tracks, the video surveys covered 0.2% of the towed area.

Table 5. The area covered the benthic sled during before and after surveys at the towed and control sites

		Lens	covered per video analysis area (m^2)	total before survey towed (m^2)	total after survey towed (m^2)	total before survey control (m^2)	total after survey control (m^2)
Site 1	before	2.97mm rectilinear	89.91	269.72		269.72	
	after	2.97mm rectilinear	89.91		269.72		269.72
Site 2	before	2.97mm fish eye	111.38	445.51		445.51	
	after	4.14mm rectilinear	68.03		204.10		272.14
Site 3	before	4.14mm rectilinear	68.03	272.14		272.14	
	after	4.14mm rectilinear	68.03		272.14		272.14
TOTAL AREA (m^2)				**987.36**	**745.95**	**987.36**	**813.99**

The data was analyzed as BACI design using a linear mixed model in the package "lme4" (linear mixed model function "lmer") in R (Schwarz 2012, R Core Team 2014). Changes to the densities of scallops, damaged scallops, and sea stars were modeled as functions of impact state (towed or control), time period (before or after towing event), and BACI effect (interaction between impact state and time period). Random effects for depletion series (Site 1 – Site 3) and individual sled crossings through video analysis areas were included to account for correlations between density observations at these levels. To assess the importance of including these random effects, caterpillar plots of the 95% prediction intervals for each depletion series-specific and sled crossing-specific random intercepts were examined for zero crossings relative to the global means over all depletion series and sled crossings, respectively. The initial model included all fixed and random effects, but this model was simplified to include only fixed effects for damaged scallop and sea star densities (**Table 6**). A random effect for sled crossing was retained in the total scallop density model (**Table 6**).

Table 6. Models used for BACI analysis

	BACI model (fixed effects retained even if non-significant)
Total scallops	Density ~ impact state + time period + BACI + sled crossing
Damaged scallops	Density ~ impact state + time period + BACI
Sea stars	Density ~ impact state + time period + BACI
	Final model (only significant effects)
Total scallops	Density ~ sled crossing
Damaged scallops	Tested variables do not predict density
Sea stars	Tested variables do not predict density

A summary of the results is presented in **Table 7** and **Figure 19**. Based on our analysis, the scallop dredge had no significant impact on damaged scallop or sea star densities (damaged scallop: BACI t = -0.922, p = 0.362; sea star: BACI t = 0.474, p = 0.638). However, because the analysis also showed that the scallop dredge had no significant impact on scallop densities (total scallop: BACI t = -0.023, p = 0.982), we have to assume the results are not meaningful. The variance in the mean densities before and after scallop dredge impact dwarfed any changes between the mean densities at the towed and control sites before and after dredging (**Figure 19**).

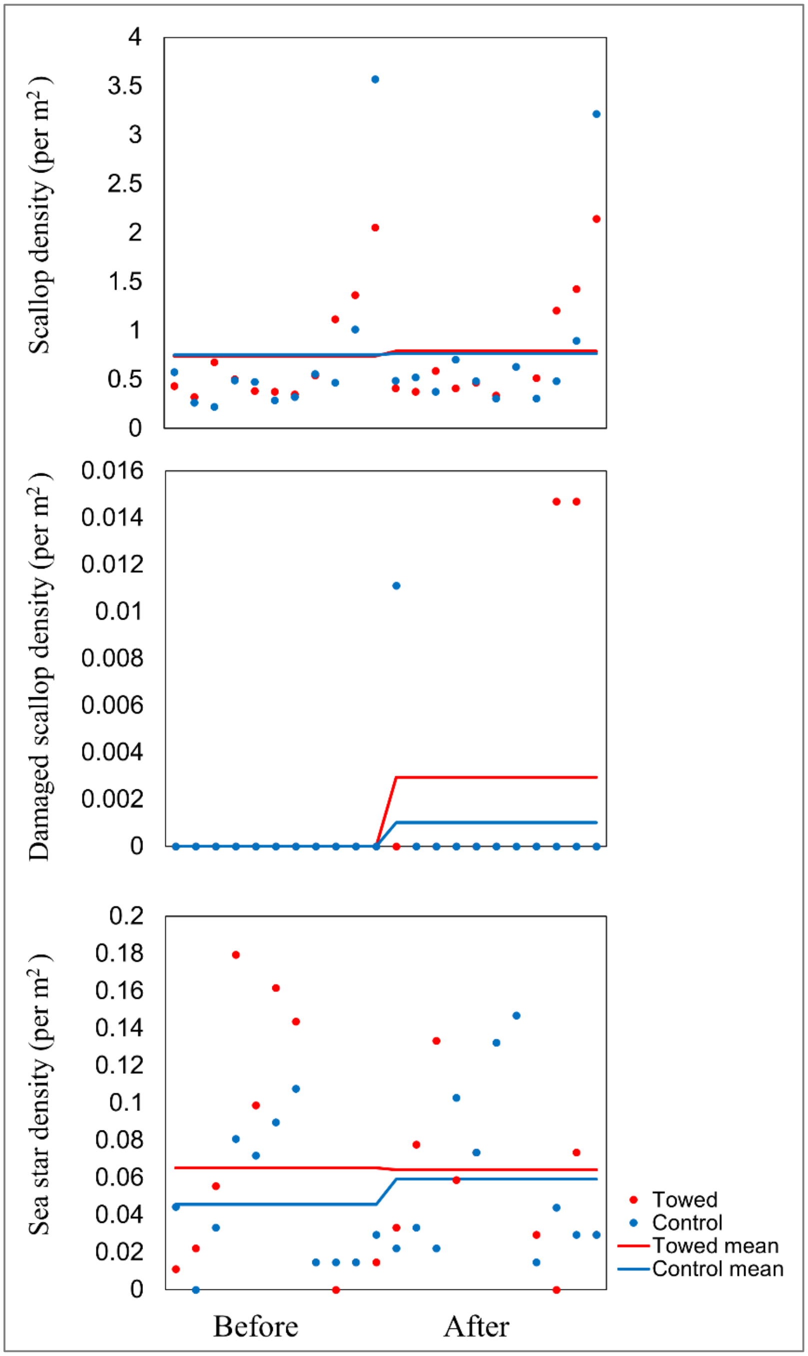


Figure 19. Summary of BACI results showing mean densities at each towed and control sled crossing as well as the overall means before and after dredging for total scallops, damaged scallops, and sea stars. Dredging had no significant impact on total scallop, damaged scallop, or sea star densities.

We identified three apparently damaged scallops in the sled videos used for the BACI analysis. Two were found in the towed area after dredging, and one was found in the control area after dredging. A fourth damaged scallop was seen in the video from the fourth tow site. All four scallops are shown in **Figure 20**. If we include only the two damaged scallops located in the towed areas and assume injuries were lethal, the observed incidental mortality was 0.3%. However, given that the observed density of scallops increased after dredging at towed and control sites and a damaged scallop was identified in the control site, this result must be interpreted with caution.

Table 7. Densities per meter squared (± standard deviations) of total scallops, damaged scallops, and sea stars before and after dredging at the towed and control sites

	Scallop density		Damaged scallop density		Sea star density	
	Before	**After**	**Before**	**After**	**Before**	**After**
Towed	**0.740** (± 0.552)	**0.789** (± 0.605)	**0.0** (± 0.0)	**0.003** (± 0.006)	**0.065** (± 0.068)	**0.064** (± 0.044)
Control	**0.751** (± 0.960)	**0.766** (± 0.832)	**0.0** (± 0.0)	**0.001** (± 0.003)	**0.046** (± 0.036)	**0.059** (± 0.047)

We assume we were unable to detect a change in scallop densities before versus after towing because our video survey covered a very small percentage of the tow paths (0.2%) and the images were not representative of the towed area overall. It is also possible that the video analysis areas that should have crossed over the tow paths did not actually do so. Our method for locating these areas depended on using vessel GPS coordinates combined with the bridge log and time stamps on the video recordings. In order for the CFF benthic sled to be a useful survey platform for similar projects, it will be necessary to expand the field of view of our survey cameras and choose a survey camera that can take clear images at faster sled speeds. With these changes, it would be possible to survey a larger area on the bottom. We are also considering adding a transponder to more accurately locate the sled relative to the boat and thereby get more accurate GPS locations for the sled during surveys.

Figure 20. Examples of scallops identified as apparently damaged in the benthic sled videos.

Manuscripts and presentations

1) Siemann, LA, Parkins, CJ, and Smolowitz, RJ. (in press) Scallops caught in the headlights: swimming escape behaviour of the Atlantic sea scallop (*Placopecten magellanicus*) is reduced by artificial light. ICES Journal of Marine Science

Abstract: Quantifying the distribution and abundance of the Atlantic sea scallop (*Placopecten magellanicus*) is a fisheries management priority, and stock assessments increasingly rely on video surveys. Interpreting the results of these surveys requires understanding the inherent biases introduced as a result of target animal behaviour. Our study investigated the effect of artificial lights on the behaviour of Atlantic sea scallops during a video survey using a towed benthic sled. Swimming and stationary scallops were counted in survey videos using event logging software. In addition, the locations, orientations, and swimming directions of the scallops were noted in a subset of the videos. The proportion of scallops that swam when an artificial light was turned on was significantly smaller than the proportion that swam when the light was off. Further analysis using a logistic model showed that just light state (off or on) predicted the likelihood of scallop swimming responses. Possible reasons for this unexpected behaviour are discussed, with a focus on the scallop visual system.

2) Estimating Incidental Mortality in the Sea Scallop Fishery: research update from Coonamessett Farm Foundation. Presented at the Joint Scallop Plan Development Team & Scallop Advisory Panel Meeting, 13 May 2015, Warwick Rhode Island.

Evaluation:

1) Estimate the loss of scallop yield resulting from incidental mortality, with incidental mortality defined as the ratio of scallops damaged in the tow path to the number of scallops in the tow path prior to dredging.

We had some success estimating incidental mortality. We identified five scallops that appeared to be damaged in after-tow surveys by the REMUS during our second project trip. Using the scallop abundance estimate from the same REMUS survey, we estimated that the incidental mortality due to scallop dredging during our survey was approximately 1.0%. This estimate is an order of magnitude less than values currently used for sea scallop stock assessment (incidental mortality = 0.2 on Georges Bank and 0.1 in the Mid-Atlantic). However, it is comparable to the incidental mortality estimates reported in the studies used to derive these values (0 to <5% on sandy substrates).

Possibly damaged scallops were also identified in the benthic sled videos. Using this date set, we estimated incidental mortality to be 0.3%. However, one of the damaged scallops was in a control site, the observed density of scallops decreased after towing, and our survey covered a very small percentage of the total towed area. Consequently, we believe this result must be interpreted with caution.

2) Evaluate survey techniques for studying the impacts of scallop dredges. Surveys were conducted with the CFF benthic sled, an AUV, and an ROV. The CFF benthic sled was designed and built for this project.

Based on the data we could collect and the subsequent analysis we could do with that data, the REMUS AUV was the best survey vehicle for assessing scallop and predator abundance and estimating incidental mortality and dredge efficiency. However, the REMUS was also the most expensive survey vehicle to use, limiting its value overall.

The CFF benthic sled was not as useful for scallop surveys as we had hoped. Image coverage during surveys and image quality as the sled moved were not adequate for this project. Furthermore, the sled often disturbed scallops, causing them to swim out of the camera field of view. Changes to our cameras and lights could address the former issues. Our study on the effect of artificial lights on scallop swimming behavior indicates that we may be able to minimize the latter problem.

The Benthos ROV and dredge-mounted cameras proved to be of little use during this project, and they were not used at all during the third trip. The ROV operation could not cover large areas so if incidental mortality was low, and resulting activity of predators was also low, it is highly unlikely that the ROV could have observed these impacts.

3) Calculate the dredge efficiency for the Coonamessett Farm Turtle Deflector Dredge (CFTDD), a commercially rigged scallop dredge, in the surveyed areas (sandy bottom).

Our estimate for the efficiency of the CFTDD (33% on sandy substrate) was based on data from one depletion tow series. This estimate is comparable to the NEFSC survey dredge efficiency estimate using the more comprehensive HabCam and NEFSC survey dredge data. However, it is much lower than a CFFTDD efficiency estimate derived using a generalized linear mixed model of the relative efficiency of the CFFTTD to the survey dredge during paired tows. The reason for this discrepancy is unclear, though we believe it may be related to the speed of the tows during the paired study. Our REMUS and dredge survey data sets could be used to improve our dredge efficiency estimate, but this would require devoting a significant amount of time and money to annotating many additional REMUS images.

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