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ARTICLE

Development of a Video Trawl Survey System for New England Groundfish

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Abstract

Using an iterative approach and extensive field testing we developed a new video trawl survey system that used a live-feed video camera mounted in the cod end of a demersal trawl to record, identify, and quantify fish as they pass through the net. The majority of tows are made with an open cod end, allowing the fish to escape the net after being recorded by the camera. Periodically, closed cod end tows are made to collect biological samples and validate the video data. Eight field trials were conducted on Georges Bank and in the Gulf of Maine, and 229 h of video were recorded. The in-trawl camera system performed reliably under harsh conditions in the field. Preliminary data analysis showed that the in-trawl camera system can be used to count and identify roundfishes, such as Atlantic Cod *Gadus morhua* and Haddock *Melanogrammus aeglefinus* with a high degree of accuracy (97%), and the video can be used to calculate absolute abundance estimates. However, identifying flatfishes to the species level in the video was challenging, although improvements in identification rates were realized by modifying our camera system and lighting. This approach provides an alternative methodology to acquire abundance and distribution data for groundfish stocks. We described the iterative approach used to develop the video trawl system and discussed the future direction of the video processing and analysis.

Fishery-independent surveys are used to investigate trends in the relative abundance of fish populations, and biological samples collected during these surveys are used to characterize the size and age structures of the resource. On Georges Bank and in the Gulf of Maine, large-scale, fishery-independent, trawl surveys are carried out by the Northeast Fisheries Science Center (NEFSC) and Fisheries and Oceans Canada (DFO). The NEFSC trawl survey is biannual; the autumn survey has been conducted since 1963, and the spring survey was initiated in 1968 (Grosslein 1969; Azarovitz 1981; Despres-Patanjo et al. 1988). The DFO survey typically occurs on Georges Bank in February and March and has been conducted since 1987 (Chadwick et al. 2007). These trawl surveys have been used to establish a time series of relative abundance indices that are critically important to the stock assessment of groundfish in the northwestern Atlantic Ocean. Data collected during these surveys has also been used to monitor long-term changes in the distribution of fish species (Nye et al. 2009).

Although a wealth of information is collected during trawl surveys, there are also challenges associated with this data collection approach. Resources to conduct trawl surveys are limited, both in terms of available time and funding, which

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limits the number of tows that can be completed in a given year. Trawl surveys are inherently time consuming; the time required to set and haul the trawl, sample the catch, and transit between sampling locations is substantial, which limits the number of stations that can be sampled per day at sea. Another disadvantage of trawl surveys is that the catch is mixed, and information about how each species was distributed along the tow path is lost (Rosen et al. 2013). Alternative data collection approaches such as underwater video and acoustics can serve as a valuable complement to the information that is routinely collected during trawl surveys.

Underwater video techniques have been developed over the last 60 years to investigate the abundance, distribution, behavior, and biodiversity of marine species (Mallet and Pelletier 2014). The recent development of high resolution digital cameras has led to vast improvements in image quality, enabling researchers to make quantitative observations about fish capture and behavior (Graham et al. 2004; Williams et al. 2010; Mallet and Pelletier 2014). In addition, software programs have been developed that can automatically detect, identify, and quantify fish in underwater video (e.g., Zion et al. 2007; Aguzzi et al. 2009; Spampinato et al. 2010; Shafait et al. 2016). However, despite the advancements in underwater cameras, obtaining consistent, high-quality, underwater video is challenging due to a myriad of factors including turbidity, light limitation, and sediment suspended by the passage of the trawl (Krag et al. 2009).

Optical approaches have been used to examine the behavior of fish in and around otter trawls and to estimate the efficiency of trawls (e.g., Godø et al. 1999; Albert et al. 2003; Piasente et al. 2004; Churnside et al. 2012; Bryan et al. 2014; Underwood et al. 2015). Recent studies have used cameras to identify, measure, and quantify fish passing through a trawl net. For example, the DeepVision stereo camera system developed by researchers at the Marine Research Institute and Scantrol AS in Norway was able to accurately identify and count fish as they passed through the extension of a pelagic trawl net (Rosen and Holst 2013; Rosen et al. 2013). In a similar experiment, Williams et al. (2010) and Sigler et al. (2015) placed two digital cameras into the extension of a midwater trawl and captured still images to investigate the behavior of Walleye Pollock *Gadus chalcogrammus* and other species in the net.

In-trawl camera systems are promising because they increase the spatial and temporal resolution of the data that can be collected during a trawl survey. Using the traditional trawl survey approach, the spatial distribution of the organisms in the catch is unknown, and the data are aggregated and analyzed at the scale of the entire tow (e.g., kilometers). However, using an in-trawl video camera allows researchers to investigate how the organisms are distributed along the path of the tow. With this approach, the sampling unit can be reduced from an entire tow to a segment of video (e.g., 1 min), and this high-resolution information can be used to model the spatial distribution of marine organisms at a much finer scale (e.g., meters) than is typically available from trawl surveys (Stoner et al. 2007). In addition the sampling units (i.e., video segments) can be rebinned post hoc, which provides greater flexibility and statistical power to test hypotheses (Rosen et al. 2013).

Since 2013, scientists at the University of Massachusetts Dartmouth, School for Marine Science and Technology (SMAST) have collaborated with regional fishermen to develop a video system that could be installed in the cod end of a demersal otter trawl and used to survey groundfish in the northwestern Atlantic Ocean. This approach has several potential advantages over a traditional trawl survey. First, by using the camera to record the fish as they pass through the net, the net can be towed with the cod end open, so that the net does not fill with fish, allowing long duration (e.g., 2–4 h) survey tows. With this approach samples could be collected over much longer distances, increasing the proportion of time spent actively trawling versus setting and hauling the net (Rosen et al. 2013). Secondly, during these open cod end tows the fish are not retained in the net, thereby substantially reducing the mortality associated with the survey, which may be an important consideration when sampling fishes that are critically depleted or endangered. Finally, the video can be used to gain information about the distribution of fish species along the path of the trawl, which increases the spatial and temporal resolution of the survey.

To date, approximately 229 h of video has been recorded during eight field trials completed on Georges Bank and in the Gulf of Maine. After much trial and error over the last 3 years, we have made significant progress in developing the hardware and components of the in-trawl camera system. However, substantial work remains to process and analyze the video that has been collected thus far. Here we described the iterative process used to develop the in-trawl camera system, highlighting the major challenges associated with this approach, the strengths and limitations of the system, and future refinements to the hardware.

METHODS

Development of the camera system.—The objective was to develop a video system that could be implemented in demersal trawl surveys throughout New England. The system evolved through an iterative process and extensive field testing. We sought to develop a trawl camera system that met the technical criteria of (1) robust hardware that could withstand continued deployment on a commercial fishing vessel, (2) sufficient image resolution and clarity to allow for the identification of organisms as they pass through the net, (3) a field of view that was large enough to record all organisms passing through the trawl, (4) real-time viewing capabilities, and (5) the ability to record high-definition video for data analysis.

For a prior industry-based survey, we had collaborated with Reidar's Manufacturing Inc., a net manufacturing company based out of New Bedford, Massachusetts, to construct a trawl net designed to catch Yellowtail Flounder *Limanda ferruginea* and other groundfishes on Georges Bank. We chose this net for the video trawl survey in order to reduce costs. The net is a two-seam, two-bridle net, which has a 76-mm diamond mesh in the cod end and is constructed of 3-mm twine throughout. During field trials on Georges Bank the net was fished with a footrope made of heavy chain, 18.3-m bottom bridles, and 54.9 m of ground cables. For the sixth field trial in the Gulf of Maine, the footrope was changed from a heavy chain to a 30.5-cm rockhoppper, and the ground cables were shortened to 27.4 m.

The camera and lights were mounted onto a rigid polyethylene cylinder (134 cm diameter × 86 cm depth), which was sown in to the extension of the trawl net, approximately 5 m ahead of the cod end (Figure 1). The exterior of the cylinder was wrapped in mesh, allowing it to be connected and disconnected from the net relatively quickly. Early field trials revealed that the cylinder was dragging on the bottom during trawling, which increased the amount of suspended sediment in the cylinder and occasionally led to poor image quality. Therefore, deepwater trawl floats (22 cm diameter) were added to the cylinder, which lifted it slightly off the bottom and reduced the amount of suspended sediment in the field of view. During the first field trial several different camera placements and angles were tested; mounting the camera in the extension facing towards the cod end provided a full field of view and provided the greatest ability to identify and enumerate fish as they passed through the net. This camera placement relied on the forward portion of the trawl to aggregate fish past the camera.

Three camera systems were field tested. During the first three field trials we used the Simrad FX80 camera system to record fish passing through the cod end extension of the survey trawl (specifications available at: www.simrad.com). The Simrad FX80 system is commercially available and includes a high-density, light-emitting-diode (LED) light and a monochrome underwater camera, both of which are

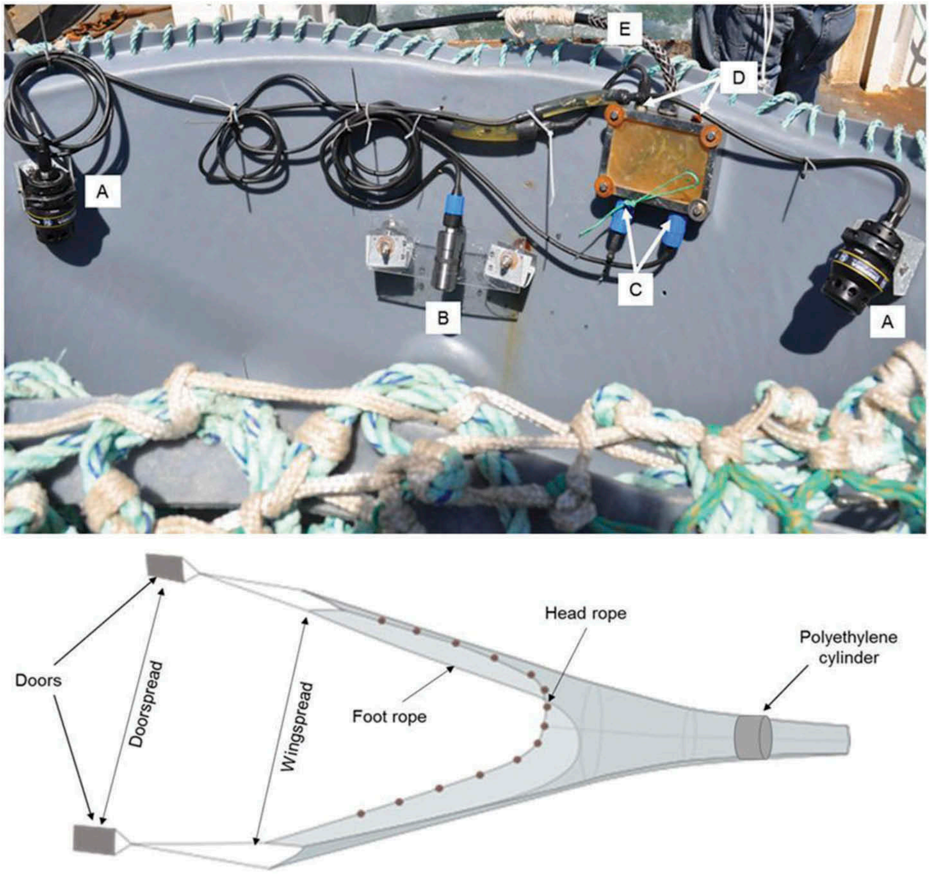

FIGURE 1. Upper panel: The wiring setup used for the DeepSea camera and lights inside of the polyethylene cylinder that is mounted to the trawl. Components labeled in the picture: (A) DeepSea LED light, (B) DeepSea camera, (C) camera ports, (D) lighting ports, and (E) third-wire cable. Lower panel: Diagram showing the location of the polyethylene cylinder (pictured in the upper panel) in the cod end extension. The camera and lights are mounted at the top of the polyethylene cylinder pointing away from the headrope, looking into the cod end.

produced by Kongsberg Maritime (Kongsberg, Norway). The video was recorded with a horizontal resolution of 560 television (TV) lines and transmitted from the camera to the FX80 communication hub, which was fastened to the top of the trawl behind the headline. The communication hub used a standard third-wire cable that used a digital data link to relay the video to a bridge control unit located in the wheelhouse. A dedicated monitor in the wheelhouse was used to view the real-time video from the cod end of the net.

Prior to the fourth field trial we developed a new camera system using cameras and lights produced by DeepSea Power & Light (San Diego, California). The camera is a Multi-SeaCam (MSC-2065) with green LED lights, a titanium housing, and SEACON (El Cajon, California) BH4 pluggable marine connectors. The video was recorded in a National Television System Committee video format with a resolution of 480 TV Lines, and the camera had an 80° field of view. Two SeaLite Sphere (SLS-5100) LED lights were mounted next to the video camera; the lights had a titanium housing, a light output of 6,000 lm, and SEACON MCBH3 pluggable marine connectors. For the fourth field trial, two white LED lights were used, but these lights were too bright, and it was often difficult to distinguish the coloration and markings on the fish. Following this field trial we consulted with a technician at DeepSea Power & Light, who recommended using one white LED and one green LED light, and this combination of lighting was used on subsequent field trials. A 200-V DC power supply (model XLN30052, B & K Precision, Yorba Linda, California) provided continuous power to lights, and a 31-V DC power supply (model 9130, B & K Precision) provided continuous power to the camera.

A 610-m-long, custom, third-wire cable was designed and built by Cortland Company (Cortland, New York), and a custom built winch was used to deploy and retrieve the third-wire cable during the setting and hauling of the trawl net. The core of the cable consisted of two 75-Ω coaxial cables, two 16-AWG (American wire gauge) conductors composed of stranded tinned copper wire and polyolefin insulation, and four 18-AWG conductors. An extruded polyurethane inner sheath covered the core and exterior of the wire, and a Vectran braided strength member was used between the polyurethane sheath layers. The termination of the third-wire cable was designed and built by Electromechanica (Mattapoisett, Massachusetts). A custom-designed, hard-coat, aluminum cable housing was mounted onto the polyethylene cylinder that was sown into the extension of the trawl net. SEACON bulkhead marine connectors were used for the four ports. A 3.3-m cable built by SEACON facilitated power, grounding, and a video feed to the camera and lights mounted in the cylinder in the extension of the trawl. A longer cable (23 m) was occasionally used to power a second camera and lights that were mounted to the headrope of the net to examine how well the footrope of the trawl was tending bottom. Only two ports are required for the camera and lights located in the cylinder, so the additional two ports can be used to deploy a camera and lights elsewhere on the net, and we designed a custom built, adjustable housing that was used to mount the camera to different locations on the net. These two ports also provide redundancy should the primary ports become damaged. Through repeated field testing we found that building redundancy into the hardware components was critical to building a robust system that could function reliably over an extended period of time.

High-definition (HD) color TV monitors are used to view the real-time video in the wheelhouse. The color video is saved using a high-resolution digital video recorder (Defeway H-264, China), and a unique audio–video interleaved (AVI) file is created for the footage collected during each tow. The date, time, and tow number is overlaid on the video using the digital video recorder.

During the seventh and eighth field trial a GoPro HERO3+ Black Edition camera was mounted in the polyethylene cylinder adjacent to the Multi-SeaCam on a subset of tows. The GoPro HERO3+ recorded video at a rate of 47 frames per second with a resolution of 1920 × 1080 pixels. The GoPro recorded HD video that was downloaded from the camera at the conclusion of each tow. The GoPro camera was placed in a waterproof Sartek Deep Housing that is rated to a depth of 229 m.

Field trials.—Approximately 229 h of video were collected during eight field trials completed on Georges Bank and in the Gulf of Maine (Figure 2; Table 1) on the FV *Justice*, a 27-m stern trawler from Fairhaven, Massachusetts. The study area on the southeastern part of Georges Bank included a portion of Closed Area II, which has been closed with some exceptions to groundfishing since 1994, and the depth in this region ranges from 60 to 90 m. Recent cooperative trawl and dredge surveys (DeCelles et al. 2014; Martin and Legault 2014) suggest that Yellowtail Flounder are relatively abundant in this region. A field trial was also completed on Stellwagen Bank in the southern Gulf of Maine, which is an important fishing ground for Atlantic Cod *G. morhua* and other species. Depth in this region ranged from approximately 30 to 100 m.

During each tow, the speed, heading, and position of the vessel were recorded every 28 s using a handheld GPS unit connected to a laptop computer with FLDRS, a fishery data collection software program developed by the Northeast Fisheries Science Center. The start of the tow was marked when the trawler's captain had paid out the specified amount of wire and the winches were locked, and the end of the tow was recorded when the winches were engaged to retrieve the net. The target tow speed was 5.6 km/h, although average tow speeds typically ranged from 5.0 to 5.9 km/h. The camera and lights were turned on while the net was being set out, and recording was continued until the net was hauled back on deck to ensure that video was recorded during the entire trawling process. The geometry of the trawl net was monitored and recorded continuously using net mensuration sensors (Notus Electronics, St.

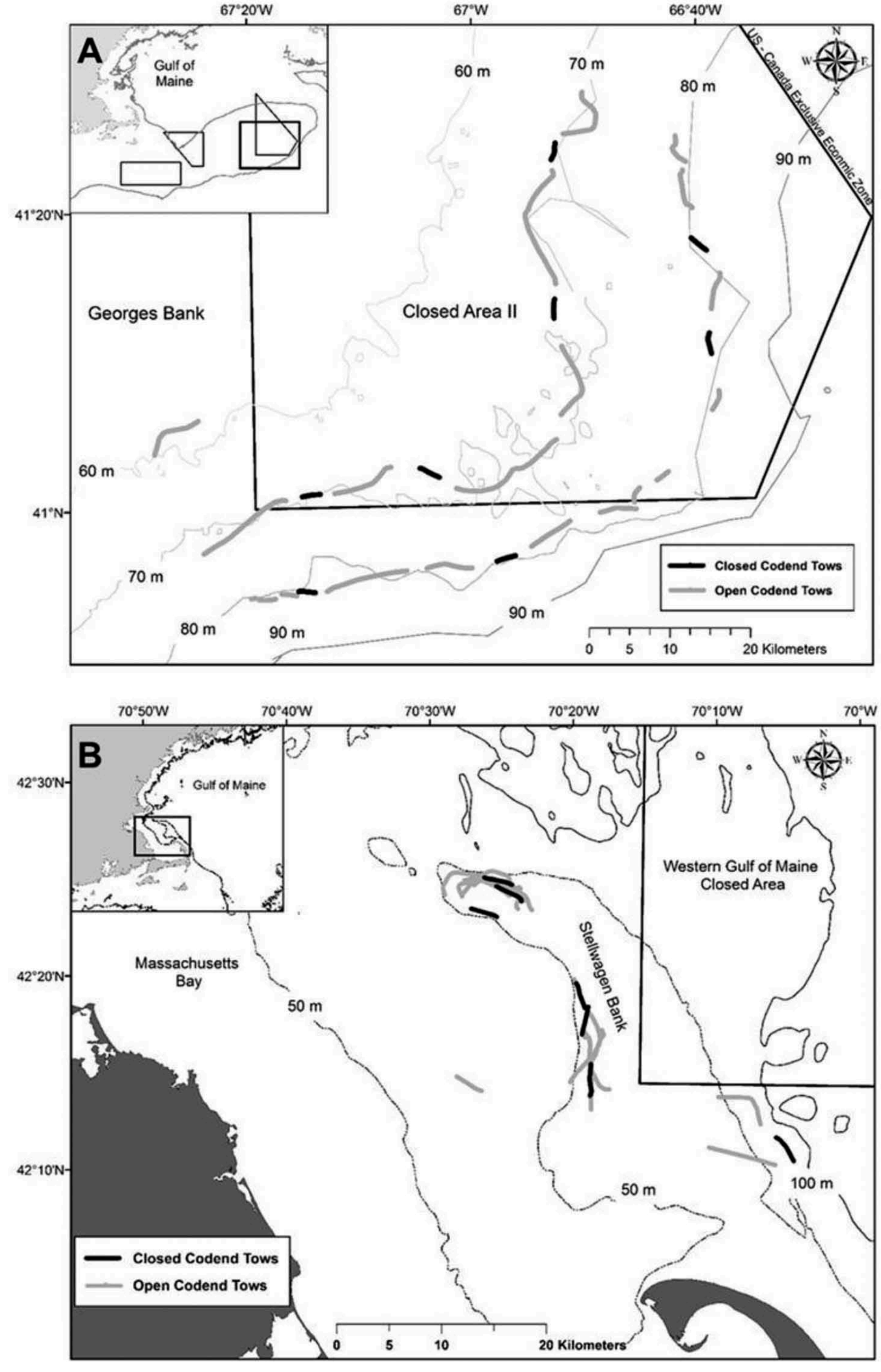

FIGURE 2. (**A**) The study area on Georges Bank where seven of the field trials were carried out. Locations of the open and closed cod end tows that were completed during the fifth field trial in the fall of 2015 are shown. (**B**) Study area for the sixth field trial that was completed on Stellwagen Bank in the Gulf of Maine in January 2016. The locations of the closed and open cod end tows are shown.

John's, Newfoundland and Labrador). Temperature and depth sensors (Vemco Minilog, Bedford, Nova Scotia) were attached to the trawl doors and also collected data continuously during trawling.

Field trials were performed by completing a combination of trawl tows with the cod end of the net open or closed. The target tow duration for the closed cod end tows was 30 min, while tows made with the cod end open generally ranged from 1 to 4 h. The

TABLE 1. The date, location, and sampling intensity of the eight field trials of the video trawl survey system completed to date, along with the camera components that were used on each cruise.

Field trial	Dates	Survey location	Number of open cod end tows	Number of closed cod end tows	Hours of video collected	Camera system
1	Oct 2013	Georges Bank	10	8	32	Simrad FX80
2	Apr 2014	Georges Bank	18	15	47	Simrad FX80
3	Oct 2014	Georges Bank	17	17	36	Simrad FX80
4	May 2015	Georges Bank	4	38	12	DeepSea cameras and lights
5	Oct 2015	Georges Bank	20	8	35	DeepSea cameras and lights
6	Jan 2016	Gulf of Maine	12	7	20	DeepSea cameras and lights
7	Apr 2016	Georges Bank	13	8	10	DeepSea cameras and lights and GoPro Hero3+
8	Oct 2016	Georges Bank	17	12	24	DeepSea cameras and lights and GoPro Hero3+

objective of the closed cod end tows was to collect biological samples and to compare the counts of each species observed in the catch to the counts observed in the video. At the conclusion of each closed cod end tow, the catch was unloaded onto the deck and sorted to the species level. For each species, the number of individuals in the catch wer counted. For most tows, actual weights were obtained for all flatfish species and for other commercially important species using a calibrated, motion-compensating marine scale with an accuracy of 50 g. For these species, the TL of each individual was measured to the nearest centimeter and recorded. The sex of each Yellowtail Flounder was determined, when possible, by holding the fish up to a bright light and examining the blind side of the flounder in order to identify the ovary extension that is characteristic of mature female flounders. Other species, such as skates, dogfish, searobins, and Longhorn Sculpin *Myoxocephalus octodecemspinosus* were counted and returned overboard as quickly as possible.

For the January 2016 field trial in the Gulf of Maine, area-swept abundance estimates of cod were calculated using the actual cod catch observed on deck for the seven closed cod end tows. Area-swept abundance estimates were also calculated for the open and closed cod end tows based on the counts of cod observed in the video. For each tow, the area swept by the trawl was calculated as follows:

$$\text{Area swept (km}^2\text{)} = \text{doorspread (km)} \times \text{tow speed (km/h)} \times \text{tow duration (h)}.$$

The density of cod in the study area was calculated for the closed cod end tows as

$$\text{Density (number/km}^2\text{)} = \text{catch (number)} / \text{area swept (km}^2\text{)},$$

and the density of cod observed in the video was calculated as

$$\text{Density (number/km}^2\text{)} = \text{cod count in the video} / \text{area swept (km}^2\text{)}.$$

The size of the study area (300 km^2) was estimated using the program ArcGIS by calculating the area of a polygon that encompassed the start and end locations of the survey tows. The abundance of cod in the study area was estimated as

$$\text{Cod abundance} = \text{density (number/km}^2\text{)} \times \text{size of survey area (km}^2\text{)}.$$

Video analysis.—We developed a customized graphic user interface (GUI) to facilitate the analysis of videos recorded during the survey (Figure 3). The GUI was created for this project using Qt software, and the program backend was coded in C++ using the open-source libraries and OpenCV and Boost. The GUI allows the analyst to review the video at full or reduced speed or to watch the video frame by frame. Before any fish were counted in the video, a trained reviewer watched the video in its entirety to characterize the image quality (high, medium, or low visibility) of the video. If there was little or no suspended sediment in the field of view, the video was considered to have high visibility (Figure 4). When suspended sediment periodically obscured the field of view, the video had medium visibility. For low-visibility video, the field of view was frequently obscured by suspended sediment, often for extended periods of time.

Trained reviewers watched the video at half-speed to count and identify the fish in the images. As the fish entered the frame of view, the reviewer marked that individual and classified it to a “type” (roundfish, flatfish, skate, or other). A dropdown menu in the GUI allowed the operator to further classify that individual to the species level, when possible. Each fish marked in the video was given a unique numerical identifier, and the location (frame), “type” (roundfish, flatfish, skate, or other), and species identification of each fish in the video was written to a comma-separated values (CSV) file, allowing the annotated video data to be uploaded quickly to a centralized database.

The GUI also includes a video annotation interface that allows the reviewer to track individual fish frame by frame

FIGURE 3. Screen shot of the graphic user interface (GUI) that was developed to analyze the video. Bounding boxes (shown in red) are used to track individual fish through the field of view.

through the field of view using a series of bounding boxes. Currently an extensive data set of annotated images for each species of interest is being compiled. We are working to develop an algorithm that can automatically recognize and track fish in the video, and the database of annotated images will be used to train the algorithm and validate the results.

We compared the ability of the three different camera systems to identify flatfishes and roundfishes to the species level. Video recorded using the Simrad FX80 camera during tow 18 of the spring 2014 field trial was examined at half-speed by a trained reviewer. All flatfish and roundfish individuals observed in the video were annotated, and the analyst attempted to identify each fish to the species level. Identical protocols were applied to video collected using both the DeepSea and GoPro cameras during tow 9 of the spring 2016 field trial on Georges Bank. These tows were chosen for comparison because they were conducted at similar locations and depths, had comparable levels of image quality, and the species composition was similar between the two tows. To examine the change in species composition as a function of trawling time, we analyzed video recorded using the GoPro camera during tow 9 of the spring 2016 field trial in 1-min increments and counted the number of Atlantic Cod, Haddock *Melanogrammus aeglefinus*, Silver Hake *Merluccius bilinearis*, and Red Hake *Urophycis chuss* that were observed in each minute.

We compared the ability of six different reviewers, who had varying levels of video analysis experience, to identify fish in the video. Five 1-min video clips that were recorded on Georges Bank using the DeepSea camera were examined independently by six reviewers, who were instructed to identify all fish to the species level, if possible. For each reviewer, we calculated the total number of individuals that were observed for each fish species in the five video clips, and these species counts were compared between the six observers. The same reviewers also watched five 1-min video clips that were recorded on Georges Bank using the GoPro camera, and the species counts were compared between reviewers.

RESULTS

After three field trials we determined that the Simrad FX80 system did not meet all of the technical requirements of the survey. Videos recorded with the Simrad FX80 system could be viewed in real time, and the camera had a sufficiently large field of view to observe all fish that passed through the cod end. However, we routinely had problems with the camera system, and troubleshooting hardware problems at sea proved to be time consuming and difficult. The digital data link used to transmit the video may have been more susceptible to transmission problems across the long trawl cable (610 m) than the analog data link that we used for the DeepSea camera. In addition, the Simrad FX80 system recorded the video in black and white and at relatively low resolution.

Videos from six closed cod end tows that were recorded using the Simrad FX80 system during the spring 2014 survey were analyzed. These six tows were chosen because they represented the range of image quality that was often encountered during the survey. The number of flatfish observed in the catch was compared with the number of flatfish observed in the video (Table 2). For videos with high visibility there was a high level of agreement between the flatfish counts in the video and in the catch, demonstrating that the camera

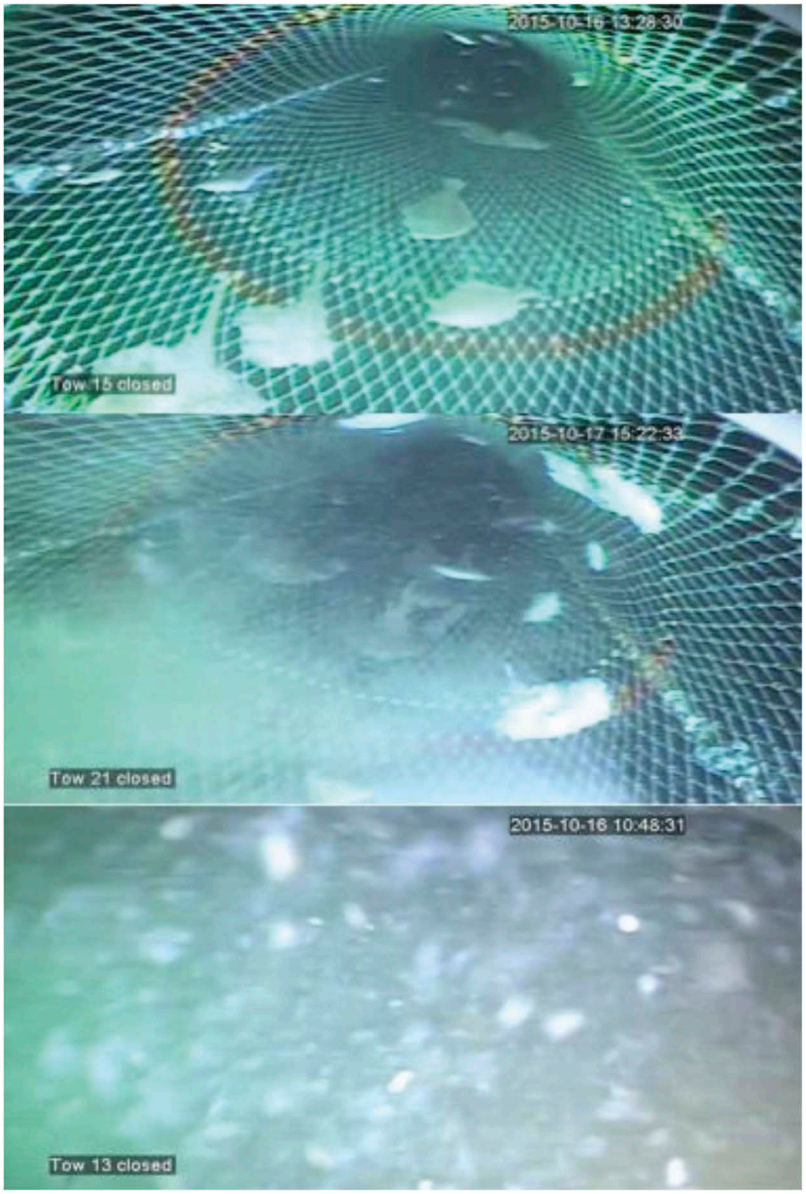

FIGURE 4. Screenshots of video recorded using the DeepSea cameras and lights. Video with high visibility is shown in the upper panel. The video shown in the middle panel was characterized as having medium visibility, while the image in the lower panel depicts video with low visibility.

potentially had sufficient resolution to identify and enumerate flatfish in the trawl. However, as the visibility decreased, the ability of the reviewer to identify and count flatfish in the video was substantially reduced, as flatfish were able to pass by the camera without being detected. In addition, only 17% of flatfish and 30% of roundfish that were recorded using the Simrad FX80 system during tow 18 of the spring 2014 survey could be identified to the species level due to the low resolution of the images.

Using an iterative approach, we designed a new, in-trawl, camera system that met the technical requirements of the survey. The field of view of the DeepSea camera was sufficiently large to record all organisms passing through the cod end of the trawl. The custom-built third wire allowed us to view the video in real time, and a digital video recorder was used to save the video in HD. Most importantly, the hardware proved to be robust, and the camera system operated reliably for extended periods of time during the field trials.

To examine how well we could identify flatfishes in the videos recorded using the DeepSea camera, a trained reviewer analyzed footage from all eight closed cod end tows from the fall 2015 survey on Georges Bank. The eight videos had high or medium visibility. The number of flatfish recorded in seven

TABLE 2. Comparison of flatfish counts observed in the video using the Simrad FX80 camera system, and the counts observed in the catch, from six closed cod end tows that were completed during the spring 2014 field trial.

Tow number	Visibility	Number of flatfish in catch	Number of flatfish observed in video	Video : catch ratio
6	High	534	534	1.00
21	High	137	132	0.96
18	Medium	454	403	0.89
16	Medium	229	169	0.74
29	Low	468	178	0.38
3	Low	265	138	0.52

TABLE 3. Comparison of flatfish counts observed in the video using the DeepSea camera and lighting, and the counts observed in the catch, from closed cod end tows that were completed during the fall 2015 field trial.

Tow number	Visibility	Number of flatfish in catch	Number of flatfish observed in video	Video : catch ratio
4	High	225	421	1.87
7	High	51	143	2.80
13	Medium	120	176	1.47
15	High	1,135	1,241	1.09
19	High	94	92	0.98
21	High	246	363	1.48
24	High	145	239	1.65
26	High	261	470	1.80

of the eight videos exceeded the number of flatfish that were observed in the catch (Table 3). The results suggest that the system we developed using the DeepSea cameras and lights had sufficient resolution to record and enumerate nearly all of the flatfish passing through the trawl and provided a higher count than the deck collections (Table 3). The results also suggest that the 76-mm diamond mesh in the cod end of the net did not retain all of the flatfish that were present in the trawl. Ten flatfish were observed escaping through the meshes in the cod end extension, and many more presumably escaped through the cod end. The mean number of flatfish observed in the video and in the catch were compared using a simple t-test. The difference between the mean flatfish counts observed in the catch and video was significant ($P < 0.05$) suggesting that the deck collections significantly underestimated the abundance of flatfish in the study area, due to the escapement of small flounder that were not fully selected by the 76-mm mesh in the cod end.

Videos from a closed cod end tow (tow 9) completed during the spring 2016 survey on Georges Bank were reviewed to examine how accurately fish could be identified to the species level. Both the DeepSea camera and GoPro Hero3+ camera were used on this tow and both videos were reviewed at half speed by a trained analyst. Four flatfish species were observed in the cod end catch (Table 4): Yellowtail Flounder, Windowpane Flounder *Scophthalmus aquosus*, American Plaice *Hippoglossoides pletessoides*, and Witch Flounder *Glyptocephalus cynoglossus*. More flatfish were observed by using the GoPro camera (n = 277) than the DeepSea camera (n = 262), although neither camera detected all of the flatfish that were ultimately counted in the catch (n = 292). Overall, 47% and 71% of flatfish observed in this tow could be identified to the species level by using the DeepSea and GoPro cameras, respectively.

Only 11% of the Yellowtail Flounder could be identified in the video recorded by the DeepSea camera, whereas 63% of Yellowtail Flounder were identified in the GoPro video. The GoPro camera provided a clearer image than the DeepSea camera, which allowed the identification of the distinct coloration and protruding mouth characteristic of Yellowtail Flounder (Underwood et al. 2011). The identification rate of Windowpane Flounder was slightly greater using the GoPro camera. Windowpane Flounder could be differentiated from other flatfishes by their deeper body, their distinct coloration pattern, and their quick swimming motion in the net. However, neither the American Plaice (n = 8) or Witch Flounder (n = 2) that were present in the catch were identified in the video collected by either camera. The difference in the mean count of the four flatfish species sampled, where n = 3 in each case, was significant ($F_{3,\ 8} = 13.324$, $P < 0.05$).

Four roundfish species were also observed in the catch on this tow (Table 4): Atlantic Cod, Haddock, Silver Hake, and Red Hake. For both cameras, the number of roundfish observed in the video exceeded the number observed in the catch, suggesting that the selectivity of the 76-mm-mesh cod end was <100% for these species. The number of cod recorded using the DeepSea camera (n = 14) was slightly greater than the number recorded using the GoPro camera (n = 11), although the count of cod from each camera exceeded the number observed in the cod end (n = 8). Atlantic Cod could easily be distinguished from other roundfishes by their lethargic swimming behavior, unique coloration (white lateral line and mottled green color), wide head, the shape of their caudal fin (not forked), and the rounded shape of their first dorsal fin. The number of Haddock observed by using the DeepSea camera (n = 717) and GoPro camera (n = 749) far exceeded the number observed in the cod end (n = 156). Haddock could be differentiated from the other roundfishes by their erratic swimming behavior, black lateral line, distinct coloration (grayish black spot above lateral line and silver body color), and the shape of their fins (Figure 5). Silver Hake were not captured in the net, although this species was observed by using both the GoPro (n = 9) and DeepSea (n = 12) camera systems. Silver Hake were identified based on their small and slender body shape, their relatively large

TABLE 4. Analysis of video recorded during one tow completed during the seventh field trial on Georges Bank. Both the DeepSea and GoPro cameras were deployed, and the ability of each camera to identify fish to the species level was examined.

Species	Number observed in catch	Number observed in video recorded with DeepSea camera	Video : catch ratio	Number observed in video recorded with GoPro camera	Video : catch ratio
Total, all flounder	292	262	0.90	277	0.95
Yellowtail Flounder	114	13	0.11	76	0.67
Windowpane Flounder	168	111	0.66	120	0.71
American Plaice	8	0	0.00	0	0.00
Witch Flounder	2	0	0.00	0	0.00
Unidentified flounder	0	138		81	
Total, all roundfish	171	775	4.53	793	4.64
Atlantic Cod	8	14	1.75	11	1.38
Haddock	156	717	4.60	749	4.80
Silver Hake	0	12		9	
Red Hake	7	11	1.57	12	1.71
Unidentified roundfish	0	21		12	

head, and the length of their second dorsal fin. Fewer Red Hake were present in the catch (n = 7) than were observed by using the DeepSea (n = 11) and GoPro (n = 12) camera systems. Their dark coloration and the filament on their first dorsal fin allowed Red Hake to be differentiated from the other roundfishes in the video. The difference in the mean count of the four roundfish species sampled, where n = 3 in each case, was significant ($F_{3,\ 8} = 7.610$, $P < 0.05$). Overall, 97% and 98% of roundfish observed in this tow could be identified to the species level by using the DeepSea and GoPro cameras, respectively. During tow 9, at least five Haddock were recorded every minute while the trawl was actively fishing, (Figure 6). Silver Hake and Red Hake were observed periodically throughout the tow, while the distribution of Atlantic Cod within the tow appeared to be more aggregated. Interestingly, the greatest numbers of Haddock were observed in the camera as the winches were engaged to retrieve the net. In fact, we commonly observed fish in the cod end camera while the net was being hauled back.

For the seven closed cod end tows completed during the January 2016 field trial in the Gulf of Maine, the area-swept abundance estimates of Atlantic Cod were similar whether the cod were counted by using the video camera or counted in the catch observed on deck (Table 5). The slightly higher abundance estimate calculated by using the video reflects the cod that were observed in the video but were not retained in the 76-mm cod end mesh. The average abundance of cod was lower in the 12 open cod end tows than the seven closed cod end tows, and the large variance associated with the abundance estimates are indicative of the aggregated distribution of cod within our small study area.

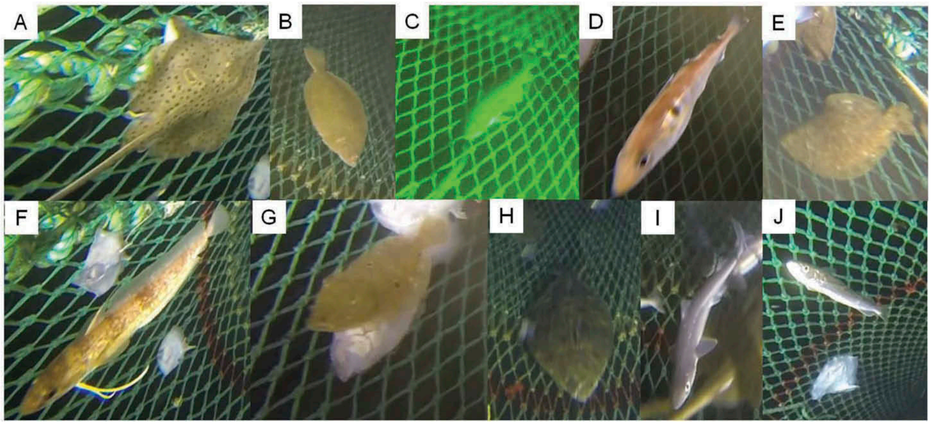

FIGURE 5. Screenshots of different species recorded using the GoPro camera and DeepSea lights. (**A**) Barndoor Skate, (**B**) Yellowtail Flounder, (**C**) Atlantic Cod, (**D**) Haddock, (**E**) Windowpane Flounder, (**F**) Red Hake, (**G**) Fourspot Flounder, (**H**) Summer Flounder, (**I**) Spiny Dogfish, and (**J**) Silver Hake.

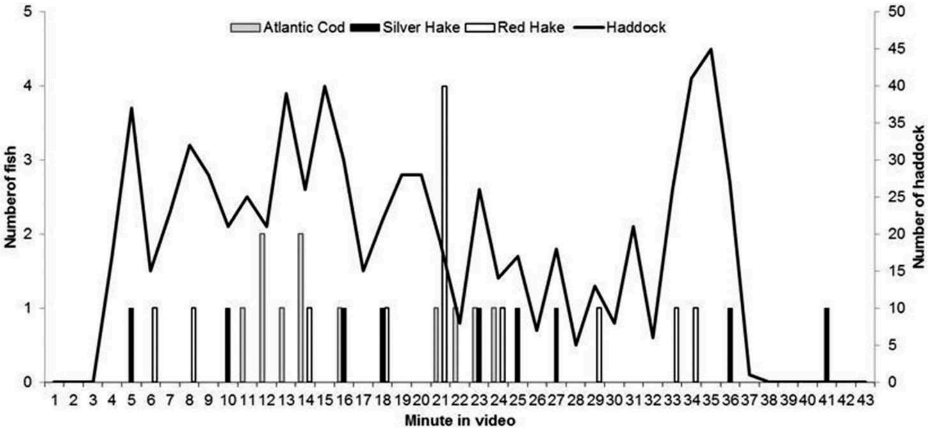

FIGURE 6. Abundance of Atlantic Cod, Haddock, Red Hake, and Silver Hake observed in each minute of video that was recorded during tow 9 of the January 2016 field trial in the Gulf of Maine. The net was fully deployed and the winches were locked during the third minute of the video, and the winches were engaged to retrieve the net during minute 33 of the video. Fish were recorded in the cod end camera while the trawl was being hauled back.

For six closed cod end tows completed during the spring 2016 field trial we quantified the amount of video in each tow with adequate image quality to count and identify fish in the image. Overall, the proportion of video with sufficient image quality was high, but the GoPro camera consistently recorded video with a higher proportion of usable footage than did the DeepSea camera (Table 6). When suspended sediment was present in the field of view it often obscured the images that were recorded by the DeepSea camera. However, the suspended sediment was less noticeable in the video recorded by the GoPro camera, and the analyst could often count and identify fish in the GoPro video even when suspended sediment was present in the field of view.

The duration of the open cod end tows was often determined by image quality; the image quality was often high at the start of the tow but would gradually decrease over time as benthic invertebrates (primarily sea scallops *Placopecten magellanicus*) accumulated in the belly of the net in front of the polyethylene cylinder that housed the camera and lights. These invertebrates would cause the belly of the net to drag on the sea floor, which increased the amount of suspended sediment in the video and often caused us to abort the tow after an hour or two of sampling.

There was close agreement between the total number of fish counted by the six reviewers in the five 1-min video clips recorded using the DeepSea camera (Table 7) and the GoPro camera (Table 8). However, the ability of the reviewers to identify fish to the species level varied considerably. For species with distinguishing morphological characteristics, such as Spiny Dogfish *Squalus acanthias*, skates, and scallops, the species counts were in close agreement among the six reviewers. However, for species with similar body shapes, there was greater variability in the counts between reviewers. For example, our most experienced reviewer (reviewer 2) was able to identify the majority of roundfish to the species level, while less experienced reviewers (e.g., reviewers 4 and 6) could not.

The camera system we developed performed reliably during field trials on Georges Bank and in the Gulf of Maine, in depths ranging from approximately 40 to 100 m. We typically conducted six or seven tows per day, and the camera system was deployed from 12 to 35 h per field trial (Table 1). The camera system performed consistently when we encountered relatively rough weather (waves of approximately 5 m in height), and cold weather (air temperatures near 0°C). On Georges Bank, we tested the camera system primarily in areas with sandy substrate and strong tidal currents. In the Gulf of Maine, tows were made across a variety of bottom

TABLE 5. Comparison of area-swept abundance estimates calculated for Atlantic Cod during the January 2016 field trial in the Gulf of Maine. Cod abundance was estimated using the actual catches observed on deck during the seven closed cod end tows and using the number of cod observed in the video during both the open and closed cod end tows.

Tow type	Method of counting	Number of tows	Total area swept (km^2)	Cod abundance	SD
Closed cod end	Catch sampling	7	0.8	417,871	401,926
Closed cod end	Video	7	0.8	492,647	500,398
Open cod end	Video	12	3.5	231,205	216,419
Open and closed cod end	Video	19	4.3	327,526	359,924

TABLE 6. Comparison of the image quality obtained using the DeepSea and GoPro camera systems during the spring 2016 survey trip on Georges Bank. For each tow, the amount of video with adequate visibility to count and identify fish was quantified.

Tow number Camera	12 DeepSea	12 GoPro	13 DeepSea	13 GoPro	15 DeepSea	15 GoPro	19 DeepSea	19 GoPro	24 DeepSea	24 GoPro	26 DeepSea	26 GoPro
Length of video (min)	37	37	42	42	40	40	40	40	38	38	42	42
Amount of video with adequate visibility (min)	35.4	36.5	40.3	41.2	39.3	39.7	19.0	25.7	21.0	24.2	35.0	38.7
% of video with adequate visibility	96%	99%	96%	98%	98%	99%	47%	64%	55%	64%	83%	92%

types, and the camera worked reliably while sampling in all substrates. On one occasion during the May 2015 field trial on Georges Bank the trawl net hung down on the bottom and the trawl door parted, which placed excessive strain on the coaxial cable and caused it to break. We could not repair the cable at sea, and the video feed was unavailable for the remainder of the trip.

DISCUSSION

Using an iterative approach we developed a reliable, high-definition, in-trawl camera system that was robust enough to withstand continued deployment in harsh conditions over an extended period of time. This data collection approach could serve as a valuable supplement to regional trawl surveys. For example, open cod end tows provide a nonextractive method for sampling fish abundance in areas that are closed to fishing. In addition, a series of transect samples could be collected using long-distance open cod end tows, and these transects could be used to delineate the size and distribution of spawning or feeding aggregations Open cod end tows can be combined with brief, closed cod end tows to obtain biological samples and validate the video observations. However, the in-trawl camera system is not a replacement for traditional trawl surveys, especially in instances where the visibility is poor or for fish that are difficult to identify in the video, such as flatfish. Although the open cod end tows reduce the mortality associated with the trawl survey, fish that encounter and

TABLE 7. Number of fish counted by six independent reviewers who watched five 1-min video clips that were recorded on Georges Bank using the DeepSea camera system (CV = SD/mean).

Species	Reviewer 1	Reviewer 2	Reviewer 3	Reviewer 4	Reviewer 5	Reviewer 6	Mean	CV
Atlantic Cod	55	62	44	36	60	56	52.2	0.2
Haddock	62	61	74	86	63	65	68.5	0.1
Red Hake	0	0	2	0	0	0	0.3	2.4
Unidentified roundfish	23	5	24	22	6	26	17.7	0.5
Windowpane Flounder	3	0	0	0	0	0	0.5	2.4
Winter Flounder	1	8	0	0	0	0	1.5	2.1
Yellowtail Flounder	9	10	3	1	4	3	5.0	0.7
Summer Flounder	0	0	0	0	0	1	0.2	2.4
Unidentified flatfish	52	40	57	69	61	64	57.2	0.2
Spiny Dogfish	1	1	1	1	2	1	1.2	0.3
Skate	4	1	4	4	4	4	3.5	0.3
Barndoor Skate *Dipturus laevis*	0	2	0	0	0	0	0.3	2.4
Monkfish[a]	2	5	1	0	1	3	2.0	0.9
Longhorn Sculpin	8	10	9	2	7	4	6.7	0.5
Northern Searobin *Prionotus carolinus*	1	0	0	0	0	0	0.2	2.4
All species combined	221	205	219	221	208	227	216.8	0.04

[a] Goosefish *Lophius americanus*, referred to commercially as monkfish.

TABLE 8. Number of fish counted by six independent reviewers who watched five 1-min video clips that were recorded on Georges Bank using the GoPro camera system.

Species	Reviewer 1	Reviewer 2	Reviewer 3	Reviewer 4	Reviewer 5	Reviewer 6	Mean	CV
Atlantic Cod	0	0	9	0	3	0	2.0	1.8
Haddock	38	82	90	60	75	50	65.8	0.3
Red Hake	16	74	23	14	68	50	40.8	0.7
Silver Hake	2	7	3	10	6	7	5.8	0.5
Unidentified roundfish	85	7	30	78	22	58	46.7	0.7
Summer Flounder	1	2	8	15	18	22	11.0	0.8
Windowpane Flounder	2	0	1	0	0	0	0.5	1.7
Winter Flounder	0	4	0	0	2	2	1.3	1.2
Yellowtail Flounder	8	31	10	4	24	3	13.3	0.9
Fourspot Flounder *Paralichthys oblongus*	18	11	29	2	26	13	16.5	0.6
Unidentified flatfish	71	59	57	86	41	68	63.7	0.2
Skate	107	136	135	129	133	129	128.2	0.1
Barndoor Skate	1	2	2	3	2	0	1.7	0.6
Spiny Dogfish	93	103	103	103	102	126	105.0	0.1
Butterfish *Peprilus triacanthus*	1	1	1	0	2	2	1.2	0.6
Scallop	34	33	35	35	39	38	35.7	0.1
Sculpin	0	1	6	0	2	1	1.7	1.4
Northern Searobin	9	14	5	10	11	12	10.2	0.3
All species combined	486	567	547	549	576	581	551	0.06

escape the trawl may exhibit stress and changes in behavior that could lead to subsequent mortality (Ryer 2004). In addition, the bottom disturbance associated with trawling, especially over long distances, may make this sampling approach inappropriate for areas with critical or sensitive habitats.

Our camera system offers a number of advantages, but further research and field testing are needed to optimize and refine the hardware components. Most of the trawl-mounted camera systems that have been developed to date are battery powered (e.g., Piasente et al. 2004; Williams et al. 2010; Rosen et al. 2013; Bryan et al. 2014), which limits the amount of video footage that can be collected or requires that the batteries are changed frequently. Our system uses direct power, which allows for the continuous operation of multiple lights and cameras. This enables us to make long-duration (e.g., 2–4 h) open cod end tows that can cover much greater distances than a traditional survey tow. Provided the image quality is sufficient throughout the tow, these long-distance open cod end tows can provide information on distribution and abundance across a relatively large spatial scale.

Another characteristic of our camera system is that the third-wire cable provides direct power to the camera and lights, and allows the vessel's captain and scientists to watch the video in real time. In contrast, many other trawl-mounted camera systems do not have a live video feed, so the footage cannot be viewed until the system is retrieved and the video has been downloaded. Although the third-wire cable does add complexity to the system and requires a specialized winch to set and retrieve the camera system, the benefits of the third-wire cable outweigh the costs. The live video feed ensures that the video footage has sufficient image resolution and clarity to allow for the identification of the organisms in the net. If the image quality becomes poor the tow can be terminated, and sampling can be resumed in a new location. This is particularly important during the long-duration open cod end tows, during which the image quality can be reduced over time due to invertebrates accumulating in the net ahead of the camera. The direct power source allows us to use high-powered LED lights in the cod end, which aids in fish detection and identification. Further, if the camera or lights malfunction during the tow these problems can be detected in real time.

While most in-trawl systems have utilized a pair of stereo-imaging cameras (e.g., Williams et al. 2010; Rosen et al. 2013), our system was developed using a single video camera mounted in the cod end. Therefore, we cannot accurately measure the length of the fish in the video. While this is a limitation of the system, biological samples and length frequency data can be collected by conducting a closed cod end tow, and these closed tow samples are used to make inferences about the biological characteristics of the organisms observed in the video recorded during open cod end tows.

We are still processing the video that has been collected to date, but the video analysis that has been conducted thus far is informative for assessing the capabilities of the in-trawl camera system. Using the video to identify flatfish to the species level has proven to be difficult, which is a limitation of our in-trawl camera system. The majority of our field trials have been completed on Georges Bank where there is a diverse assemblage of flatfishes, which have similar morphology and overlapping size distributions. Identifying flatfish to the species level has consistently been a problem for researchers that use underwater video. For example, both Krag et al. (2009) and Bryan et al. (2014) could differentiate between flatfish and roundfish, but could not identify flounder to the species level. Similarly, Albert et al. (2003) classified fish in front of a survey trawl as "certain Greenland halibut," "certain flatfish," or "uncertain flatfish." Underwood et al. (2011, 2015) classified flatfish in their video as either Yellowtail Flounder or "unidentified flatfish" and used the pointed snout of the Yellowtail Flounder as an identifying characteristic. Underwood et al. (2011) achieved 72% and 46% classification accuracy for Yellowtail Flounder using an HD and standard-definition (SD) camera, respectively. Preliminary results suggest that the GoPro camera greatly increased our ability to identify Yellowtail Flounder and Windowpane Flounder, although our identification rates were <100%. The images collected using the DeepSea camera were often obscured by suspended sediment, and Yellowtail Flounder could only be identified when their snout was in close proximity to the camera. The GoPro camera consistently provided a clearer image than the DeepSea camera, which made it easier to identify the protruding snout of Yellowtail Flounder and the distinct coloration of the Windowpane Flounder. At present, our inability to reliably identify flatfish to the species level precludes us from estimating the abundance of flatfish species from the open cod end tows. However, we hope to overcome this limitation with further refinements to the camera and lighting.

Both the DeepSea and GoPro camera systems may perform best for surveying roundfish such as Atlantic Cod and Haddock, as the vast majority (approximately 98%) of roundfish observed in the video collected during tow 9 of the spring 2016 survey could be identified to the species level (Table 4). The four species of roundfish that were present in the video exhibited diverse behaviors in the net and could be differentiated from one another based on their morphology and size. However, before the in-trawl video system can be implemented for cod and other roundfish in New England, further video analysis is needed to ensure that these high identification rates can be achieved consistently. In addition, the variability in fish counts observed between different reviewers (Tables 7, 8) needs to be investigated further, and a rigorous quality control protocol should be developed for training and auditing reviewer performance.

These results suggest improved detection and identification of all species using the GoPro video camera, which suggests this technology has promise as a cost-effective survey tool. While the DeepSea camera provides sufficient resolution and image clarity to count and identify roundfish species, the GoPro camera provides superior ability to identify and enumerate all species of fish when the visibility is reduced by suspended sediment. In the future, we will place two GoPro cameras in the cod end for all tows and test different lighting configurations to optimize the clarity and contrast obtained in the GoPro footage.

Lighting is a key component of the system, and the ability to provide high-powered, continuous, LED lighting vastly improves image quality. The lighting in the net now provides optimal illumination for the DeepSea camera system, but the early results suggested that the green LED light reduced our ability to identify flatfish in the GoPro footage because it obscured the markings on the back of the flatfish. In future, we are likely to continue using the DeepSea camera in order to maintain the live video feed while the net is deployed and will also pursue the development of a live video feed for the GoPro camera. Ideally, the final video trawl system will use a single type of camera, which will allow for the ideal lighting configuration to be established.

Our lights are placed in the cod end facing towards the end of the net, but there is still a possibility that the artificial lights may be visible to the fish in the mouth of the net, which could affect their behavior and the net's efficiency. Weinberg and Munro (1999) used a paired tow design to demonstrate that placing an artificial light on a trawl net significantly decreased the capture efficiency for Flathead Sole *H. elassodon*, but did not significantly change the capture efficiency for five other species. We could test for this effect in future field trials by completing closed cod end tows with and without the lights operating.

Obtaining consistent, high-quality images is a common challenge when using underwater video (Mallet and Pelletier 2014). We used a bottom-tending demersal trawl in areas with fine-grained sediments and strong tidal currents. This combination of factors occasionally resulted in periods when sediments that were resuspended by the net and doors scattered light in front of the camera and caused reduced image clarity and poor contrast. This problem was ameliorated to some extent by modifying the belly of the net to keep it from dragging on the bottom ahead of the camera. Image quality was also improved by switching to a HD camera and recording system that can capture and store images in color.

The time and cost required to process the data collected using an in-trawl camera can be expensive relative to a traditional trawl survey, and the time requirement for video analysis is typically viewed as a shortcoming of using underwater video (Mallet and Pelletier 2014). For example, Rosen et al. (2013) reported that the ratio of data analysis time to data collection time exceeded 10:1 in some instances (i.e., 10 h to analyze a 1-h video), which is similar to the data processing time we have experienced. We are attempting to expedite the video analysis through two approaches. First, we are developing an automated fish identification and classification algorithm, which should greatly reduce data processing times. Similar algorithms have been developed to identify and classify fish species for aquaculture applications (Zion et al. 2007) and marine ecology studies (Aguzzi et al. 2009; Spampinato et al. 2010). Initially, the purpose of the algorithm will be to automatically detect and track fish through the frame of view, after which an analyst will review the fish tracks identified by the algorithm and attempt to identify each fish to the species level. Over time, we hope that the algorithm can be programmed to automatically classify fish to the species level. Secondly, we are testing the accuracy and precision of different subsampling methods that could be used to analyze the video. Although the video analysis is time consuming, the video trawl technique does offer the ability to collect large amounts of information per day at sea. During our field trials we typically collected 6–8 h of sea floor observations per day. Although not all of the video we collect can be analyzed because of occasional instances of low visibility, we have made a number of modifications to the survey net and camera system that have increased the proportion of usable video collected per day. If low visibility was a persistent problem in a certain area during a field trial, abundance estimates and biological samples could still be obtained using closed cod end tows.

Previous studies have modified the design of their survey trawl net to increase the uniformity of the images, reduce the variability in the lighting, and improve species identification rates. For example, Rosen et al. (2013) used an image chamber in the trawl that each fish passes through where it is recorded by the camera. A similar image chamber would likely not be feasible in the present study, as we typically encountered a large volume of fish on each tow, which would likely overwhelm an image chamber in a relatively short period of time. During early field trials we also placed fabric in the cod end directly behind the camera to cover the meshes and increase the uniformity of the image background. However, we found that this material reduced the flow of water through the cod end and altered the behavior of fish in the trawl, so we removed this material from the cod end in subsequent field trials.

A unique advantage of the video trawl approach is that it provides researchers with the capability to examine how species are distributed along the path of the tow (Rosen et al. 2013). However, an understanding of this fine-scale distribution may be confounded to some extent by the behavioral reaction of the fish to the trawl. Species that do not swim in response to the trawl will quickly move from the mouth to the cod end of the trawl, while other species with higher swimming capabilities may swim in the mouth of the trawl for an extended period of time before falling back into the cod end of the net (Ryer 2008; Winger et al. 2010). Swimming endurance and behavior in front of a trawl net can also be affected by the size of the fish and by abiotic factors such as temperature and light levels (He 1991; Ryer and Barnett 2006). Therefore, the time and location at which a fish is observed by the camera in the cod end may not be representative of the time and location where the fish first encountered the trawl. Further research to understand the species-specific behavior of fish ahead of and inside the trawl would help to interpret the distribution data at finer spatial scales (Rosen et al. 2013).

Underwater video technology is constantly evolving, and improvements in system autonomy, camera resolution, and storage capacity are expected in the coming years (Mallet and Pelletier 2014). One planned upgrade to our system is to replace the current third-wire cable with a fiber optic cable that has multiple redundant video and power feeds, which will allow us to operate several lights and cameras simultaneously. The diameter of the third-wire cable is relatively large (1.9 cm), which limits the amount of wire that can be spooled onto the third-wire winch (currently 610 m) and precludes the survey from sampling in areas deeper than 150 m. The diameter of the fiber optic, trawl wire will be substantially smaller, enabling us to fit a longer third-wire cable onto the winch, which should allow us to use the system to survey in deep water habitats along the continental shelf. Another potential improvement to our study would be to supplement the in-trawl video system with a towed video camera (e.g., Stoner et al. 2007; Williams et al. 2010), which could be used to sample fish abundance and distribution in complex, high-relief habitats that are unavailable to the trawl.

As we continue to make improvements to the video trawl system, we hope to establish an alternative method for fisheries-independent data collection in New England and create a system that could be easily adopted for use in other parts of the world. This technique could be used to increase the spatial and temporal extent of our fisheries-independent data collection, and combining visual techniques with traditional fishery-independent trawl surveys should provide a more complete understanding of the abundance and distribution of fish stocks (Murphy and Jenkins 2010).

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