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Towards an Improved System for Sampling New England Groundfish Using Video Technology

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INTRODUCTION

Trying to avoid overfished stocks with low catch limits continues to constrain the New England fishery from achieving its allocations. Since the implementation of catch shares in 2010, the groundfish fishery has only caught, on average, 32% of their annual catch limit (Rothschild et al. 2013; Murphy et al. 2014). The groundfish fishery was declared a disaster* in the 2013 fishing year. The secretary of commerce cited the lack of stock rebuilding, due to “undetermined causes” (pp. 6, 142), as the reason for the significant loss of access to the resource and the social and economic impacts (Rothschild et al. 2013). The recent assessment for Gulf of Maine Atlantic Cod *Gadus morhua* estimated a spawning stock biomass of 2,225 metric tons (mt), which is a small proportion of the historic stock size (Northeast Fisheries Science Center 2015). In response to the poor status of the stock, the annual catch limit for 2016 was set at 473 mt (National Marine Fisheries Service 2016). The low catch limits of Atlantic Cod often constrain the ability of the fishery to effectively target healthy stocks in the Gulf of Maine, such as Haddock *Melanogrammus aeglefinus*, Pollock *Pollachius virens*, and redfish (Figure 1). Further confounding the situation, fishermen are reporting large catches of Atlantic Cod (O’Sullivan 2016; Cuddy 2017).

The Yellowtail Flounder *Limanda ferruginea* stock on Georges Bank is an important target and bycatch species for the New England groundfish and scallop fisheries and is managed as a transboundary resource by the United States and Canada. In 2014, the analytical stock assessment model was rejected as a basis for management advice and replaced by an empirical approach that uses area swept biomass estimates from trawl surveys (O’Brien and Clark 2014). The acceptable biological catch for Georges Bank Yellowtail Flounder is 354 mt, representing a small fraction of historical harvest levels, which peaked at 21,410 mt in 1970 (Transboundary Resource Assessment Committee [TRAC] 2014). The scallop fleet has occasionally exceeded their suballocation of Yellowtail Flounder, leading to costly in-season closures of scallop fishing grounds and changes in fishing behavior (O’Keefe and DeCelles 2013).

It is unclear what combination of environmental, biological, and fishing impact factors have caused Yellowtail Flounder and Atlantic Cod abundance and distribution to change (Rothschild 2007; O’Boyle and Sinclair 2012; Pershing et al. 2015, 2016; Meng et al. 2016; Palmer et al. 2016; Swain et al. 2016) because the catches for both species have not exceeded the annual catch limits in recent years.

A stressed population tends to continually restrict its distribution, aggregating tightly into discrete areas (Hoffman and Hercus 2000). In the Gulf of Maine, the management area is approximately 54,000 km², but Atlantic Cod aggregate and spawn in small discrete areas (Ames 2004; Zemeckis et al. 2014a, 2014b).

Similarly, Yellowtail Flounder aggregate in specific areas on Georges Bank; one of these is located in Closed Area II.

We present a sampling system for groundfish that improves the scientific information available, reduces the survey costs, and is conducted collaboratively with the fishing industry. Since 2013, we have been building an open cod end trawl system that increases the amount of sea floor sampled per sea day without killing more fish. Our test surveys are focused on aggregations of Atlantic Cod and Yellowtail Flounder with the idea that high-intensity sampling of important habitats could complement existing multispecies trawl surveys.

METHODS

We developed a video system that can be deployed in a commercial trawl net (see DeCelles et al. [2017] for more technical details). The new system must be physically robust so that it can withstand continued deployment under harsh conditions at sea. The system must be flexible so that it can be installed on different vessels and in different net configurations. It must also produce clear high-resolution images so that fish species can be identified as they pass through the net, viewed in real time, and recorded in high definition. The sampling design must be statistically flexible, enabling traditional and advanced approaches to spatially explicit data analysis.

Fishermen and local gear experts designed our otter trawl net specifically for catching Yellowtail Flounder. This net was modified by adding a different sweep for sampling Atlantic Cod in the Gulf of Maine. A polyethylene cylinder was mounted into the cod end of the net, serving as a frame to mount the cameras and lights. The net could be closed and fished normally or towed with the cod end open, allowing the fish to pass through the net, minimizing the harm that the animal experiences as much as possible (Figure 2).

* A fishery-resource disaster was declared under Section 308(b) of the Interjurisdictional Fisheries Act of 1986 and Section 312(a) of the Magnuson–Stevens Fishery Conservation and Management Act of 1976.

Figure 1. Atlantic Cod and Yellowtail Flounder in a multispecies groundfish collection from a half-hour tow in the Gulf of Maine.
Three camera systems were field-tested (Figure 3). DeCelles et al. (2017) describe the development of these systems in detail; briefly, the first system we tried was the commercially available Simrad FX80 system, which includes a high-density LED light and a monochrome underwater camera (Kongsberg Maritime AS, Kongsberg, Norway). It produced a high-quality black-and-white image, but the system was not flexible enough for our application. We then modified a video camera system based on equipment that has been used for the SMAST sea scallop survey (Stokesbury et al. 2009). A Multi-SeaCam (MSC-2065, DeepSea Power and Light San Diego, California) and two SeaLite Sphere (SLS-5100, DeepSea Power and Light San Diego, California) LED lights were mounted in the aft portion of the trawl, 5 m in front of the cod end. Color HDTV monitors were used to view the real-time video in the wheelhouse (Figure 2). The color video was saved using a high-resolution digital video recorder (Defeway H-264, China), and a unique audio video interleave file was created for the footage collected during each tow. The date, time, and tow number were overlaid on the video using the digital video recorder. We recently added a GoPro HERO 3 (Black Edition, GoPro Inc., San Mateo, California) camera in the polyethylene cylinder adjacent to the Multi-SeaCam (Figure 3).

Field trials were completed on the F/V Justice, a 27-m stern trawl vessel based out of Fairhaven, Massachusetts. Three systems collected simultaneous data during survey operations, the video system, the Notus (www.notus.ca), and the Fishery Logbook and Data Recording Software (FLDRS; Northeast Fisheries Science Center, Wood Hole, Massachusetts). The Notus net mensuration sensors were used to record the door spread, wing spread, temperature, and amount of ground cable set while fishing (Figure 2). The FLDRS is a fishery data collection software developed by the Northeast Fisheries Science Center and was used to record the Global Positioning System location (latitude, longitude), heading, and speed of the vessel. These systems are compact and easy to set up in the constrained space of a commercial fishing vessel bridge.

The survey design was based on acoustic sampling methods where data are collected along a continuous transect as density per unit, but biological samples are collected periodically to identify species, size, and weight of fish in the acoustic signal (Gunderson 1993; Stokesbury et al. 2009; Figure 4). Transects were positioned along isobaths and sampled during daylight hours, based on the assumption that the fish community is more constant at a similar depth and diurnal period (Gunderson 1993). The area sampled by the survey was assumed to be half the distance between the isobaths (i.e., samples collected on the 70-m transect would represent the area between the depths of 65 and 75 m).

The sampling procedure began with an open cod end tow; the
Fish freely passed through the net as the vessel moved along the transect at a targeted speed of 5.56 km/h (3 knots) for 1–3 h. After the open tow, the net was hauled on board, the cod end was closed, and the net was set for a 30-min tow. The net was retrieved, the cod end was emptied on deck, and fish were separated by species and counted. The catches of commercially important species were weighed (by basket), and individual fish were measured to the nearest centimeter; Atlantic Cod and Yellowtail Flounder were weighed individually (g) and the sex of Yellowtail Flounder was determined. While the biological samples were being processed, the net was set with the cod end open and the transect sample continued. Closed cod end tows were usually completed mid-morning, at noon, and mid-afternoon.

A key part of this research is the SMAST digitizing laboratory. Each year, five to 10 undergraduate and graduate students are trained in video processing and species identification. Since 1999, this laboratory has processed more than 429,000 video samples of the sea floor, primarily quadrat samples of the U.S. sea scallop resource where the substrate and more than 50 fish and macroinvertebrates are quantified (Stokesbury et al. 2009). Processing the groundfish video survey data is an extension of the quadrat survey, but the transect design presented new challenges. The volume of fish observed in the video was much greater than we had originally anticipated. During the first survey, 915 fish were counted in the first 5 min of video. To process the large volume of fish in the video, a graphical user interface (GUI) was developed (Figure 3), which streamlined and standardized the video analysis. Technicians watch the entire video at half speed and annotate each fish using the GUI, which counts the fish and records the exact frame in which the fish was first observed (De-Celles et al. 2017). The movements of the fish in the video are tracked to ensure that individuals are not double-counted. The GUI gives the analyst the flexibility to aggregate the data across temporal scales. For example, the analyst can calculate the number of fish observed in each minute of video or the total number of fish observed in the entire video tow.

Area swept abundance estimates for Atlantic Cod and Yellowtail Flounder were calculated using either the closed tow collections or the counts from the video footage of the tow collections (open and closed). The area swept (km²) was determined as the distance between the doors (km) multiplied by the speed of the tow (km/h) and the duration of the sample unit. We are surveying with a commercial trawl net designed to herd fish, so the door spread is the most appropriate measure of area swept. The density (numbers per square kilometer) of Atlantic Cod or Yellowtail Flounder was calculated as the number of fish in the closed cod end catch or video (numbers) divided by the area swept (km²). The abundance was then estimated as the density of fish (numbers per square kilometer) multiplied by the sample area (km²). The biomass for the closed tow estimate was also calculated by multiplying the weight of the animals (weight/km²) by the sample area (km²). A third abundance estimate of Atlantic Cod from the video data was generated by randomly selecting 1-min segments of video footage as the sample unit and using the counts of fish observed.

These estimates are conservative because they were calculated using the door spread and assumed that the net has 100% sampling efficiency. One-way analysis of variance and Tukey’s pairwise multiple comparison test were used to examine differences between years for Yellowtail Flounder collections.

**RESULTS**

Seven research cruises have been completed since 2013, six on the southern portion of Georges Bank and one in the Gulf of Maine.
Table 1. Summary table of SMAST groundfish video cruises on Georges Bank and in the Gulf of Maine by season, the number of closed and open tows, hours of video data collected, Atlantic Cod or Yellowtail Flounder, swept area of the net based on door spread (km²), the study area sampled by the transects (km²), and proportion of the total stock area it represents (%). The total number and weight of the target species sampled in the closed tows along with the mean and standard deviation and the area swept biomass from the closed tows, assuming 100% net efficient.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Season</td>
<td>Fall</td>
<td>Spring</td>
<td>Fall</td>
<td>Spring</td>
<td>Fall</td>
<td>Winter</td>
<td>Spring</td>
</tr>
<tr>
<td>Target species</td>
<td>Yellowtail Flounder</td>
<td>Yellowtail Flounder</td>
<td>Yellowtail Flounder</td>
<td>Yellowtail Flounder</td>
<td>Yellowtail Flounder</td>
<td>Atlantic Cod</td>
<td>Yellowtail Flounder</td>
</tr>
<tr>
<td>Closed tows</td>
<td>8</td>
<td>15</td>
<td>17</td>
<td>38</td>
<td>8</td>
<td>8</td>
<td>8</td>
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<tr>
<td>Open tows</td>
<td>10</td>
<td>18</td>
<td>17</td>
<td>4</td>
<td>20</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Hours of video</td>
<td>32</td>
<td>47</td>
<td>36</td>
<td>12</td>
<td>35</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td>Net swept (km²)</td>
<td>8.86</td>
<td>13.22</td>
<td>9.54</td>
<td>7.38</td>
<td>8.85</td>
<td>2.83</td>
<td>5.77</td>
</tr>
<tr>
<td>Study area (km²)</td>
<td>1,483</td>
<td>1,908</td>
<td>2,709</td>
<td>2,900</td>
<td>2,396</td>
<td>300</td>
<td>2,365</td>
</tr>
<tr>
<td>% Surveyed of stock area</td>
<td>4.0</td>
<td>5.1</td>
<td>7.3</td>
<td>7.8</td>
<td>6.4</td>
<td>0.6</td>
<td>6.3</td>
</tr>
<tr>
<td>Target fish from closed tows (numbers)</td>
<td>1,993</td>
<td>1,370</td>
<td>3,315</td>
<td>1,195</td>
<td>1,030</td>
<td>1,096</td>
<td>653</td>
</tr>
<tr>
<td>Mean target fish in closed tows</td>
<td>249</td>
<td>91</td>
<td>195</td>
<td>31</td>
<td>129</td>
<td>157</td>
<td>82</td>
</tr>
<tr>
<td>SD</td>
<td>151.2</td>
<td>76.1</td>
<td>190.9</td>
<td>27.1</td>
<td>310.2</td>
<td>157</td>
<td>82</td>
</tr>
<tr>
<td>Target fish weight (kg) from closed tows</td>
<td>823</td>
<td>435</td>
<td>1,185</td>
<td>424</td>
<td>374</td>
<td>1,344</td>
<td>262</td>
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<tr>
<td>Mean target fish weight (kg) from closed tows</td>
<td>102.9</td>
<td>29.0</td>
<td>69.7</td>
<td>11.2</td>
<td>46.8</td>
<td>192</td>
<td>32.8</td>
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<tr>
<td>SD</td>
<td>67.5</td>
<td>24.8</td>
<td>66.7</td>
<td>9.6</td>
<td>110.7</td>
<td>167.9</td>
<td>26.9</td>
</tr>
<tr>
<td>Target fish biomass (metric tons) using closed tows</td>
<td>870.3</td>
<td>290.4</td>
<td>1,251.6</td>
<td>174.0</td>
<td>701.3</td>
<td>512.5</td>
<td>496.9</td>
</tr>
<tr>
<td>SD</td>
<td>638.2</td>
<td>212.1</td>
<td>1,396.1</td>
<td>150.0</td>
<td>1,614.5</td>
<td>433.9</td>
<td>395.1</td>
</tr>
</tbody>
</table>

From January 6 to 10, 2016, we conducted a pilot survey to test the sampling design for Atlantic Cod on Stellwagen Bank in the Gulf of Maine. Eight closed and 11 open tows were completed, and roughly 80 km of video transects was collected (Table 1; Figure 5). In the closed tows, 6,423 fish were observed, representing 21 species. Haddock was the most common (2,062), followed by Yellowtail Flounder (1,444) and Atlantic Cod (1,096; Figure 1).

Atlantic Cod ranged in size from 20 to 80 cm fork length with an average of 47.3 cm (n = 1094, SD = 10.20) and an average weight of 1.23 kg (SD = 0.809), equaling about 2- to 6-year-old fish (Northeast Fisheries Science Center 2013). Although our study area on Stellwagen Bank was only 300 km², the seven closed tows produced an area swept biomass estimate of 513 mt.

Preliminary video analysis offers further improvement to the estimates of abundance and biomass. When all of the Atlantic Cod were counted in the video footage, there was 18% more cod than collected on deck during the closed tows (Table 2). The av-
Table 2. Counts of Atlantic Cod collected in the closed net tows compared to counts collected from observing video footage from the Stellwagen Bank, Gulf of Maine pilot study January 6–10, 2016.

<table>
<thead>
<tr>
<th>Tow</th>
<th>Video</th>
<th>Catch</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>138</td>
<td>131</td>
<td>5.3</td>
</tr>
<tr>
<td>5</td>
<td>67</td>
<td>50</td>
<td>34.0</td>
</tr>
<tr>
<td>8</td>
<td>292</td>
<td>267</td>
<td>9.4</td>
</tr>
<tr>
<td>11</td>
<td>214</td>
<td>194</td>
<td>10.3</td>
</tr>
<tr>
<td>14</td>
<td>6</td>
<td>5</td>
<td>20.0</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>13</td>
<td>23.1</td>
</tr>
<tr>
<td>18</td>
<td>562</td>
<td>436</td>
<td>28.9</td>
</tr>
<tr>
<td>Total</td>
<td>1,295</td>
<td>1,096</td>
<td>18.2</td>
</tr>
</tbody>
</table>

Figure 5. Study area covered during the Gulf of Maine Pilot Survey, January 6–10, 2016. More than 80 km of video was recorded.
downweighting survey estimates that have large variances, thereby decreasing the influence of surveys that have rare, large tows (and implicitly upweighting surveys that do not randomly hit an aggregation). Both of these ways of accounting for aggregations (outliers and downweighting) have been experienced for Georges Bank Yellowtail Flounder and Gulf of Maine Atlantic Cod.

For the two species examined here, Atlantic Cod and Yellowtail Flounder, the pattern of highly aggregated distribution is apparent from the federal trawl surveys because occasionally a station has a large catch, but most tows collect zero or few individuals (TRAC 2011, 2016, figure A70; Richardson et al. 2014). For example, the 2008 and 2009 Department of Fisheries and Oceans Canada trawl surveys encountered individual tows of Yellowtail Flounder that were much larger than any seen previously in the time series. These tows had a strong influence on the time series, resulting in biomass estimates greater than 60,000 mt compared to the other surveys estimates of about 10,000 mt (TRAC 2011). This also occurred with Gulf of Maine Atlantic Cod in the fall survey of in 2002 and the spring survey of 2007 (Northeast Fisheries Science Center 2013).

Our Stellwagen Bank survey area covered 300 km² of the 54,000 km² Gulf of Maine stock area, yet about 23% of the cod biomass occurred there based on our closed tow estimates. There is a high probability that this habitat will be missed with random style surveys; for example, the Northeast Fisheries Science Center Fall 2014 and Spring 2015 survey sampling locations are near Stellwagen Bank but missed this important habitat (Figure 6).

The video survey has great promise for roundfish such as Atlantic Cod because the video system has sufficient resolution to identify nearly all roundfish species. We observed comparable or greater numbers of Atlantic Cod in the video than we collected on deck. One possibility is that some fish are double-counted, but this is unlikely because our processing places a box around each fish image and tracks it as it moves through the net. A more likely explanation is that we are counting some small cod that pass through the mesh of the cod end. We will place a liner in our net during the next survey to test this hypothesis. Identifying flatfish to species is far more challenging, and we are debating whether the video data will be sufficient to improve survey estimates. We are developing two video processing techniques to help with fish detection. First, the video was subsampled based on target levels of precision. Second, we are working to develop an algorithm that can count and identify either group of fishes (e.g., roundfish or flatfish) and perhaps count fish by species. Both methods required processing some video tows completely and comparing video counts to the counts observed on deck. The latest high-resolution GoPro footage has very high quality and may allow identification to species.

Using the Gulf of Maine 2016 survey as a preliminary example of reducing uncertainty in an abundance estimate, the video trawl net sampled 19 h of sea floor in 4 days; the swept area abundance estimate (rounded to 1,000) from closed tows was 420,000 cod (95% confidence limit [CL] of 30,000–809,000) with a coefficient of variation (CV) of 0.39, and the video from closed tows gave 493,000 cod (95% CL = 44,000–942,000) also with a CV of 0.39. The video from all tows, using the tow as the sampling unit, gave an estimate of 328,000 (95% CL = 154,000–500,000) with a CV of 0.25. Randomly selected 1-min time intervals as the sampling unit produced lower estimates of 248,000 (95% CL = 203,000–292,000) with a CV of 0.09. The latter produced a smaller confidence interval and lower CV. The video system seems to meet the goal of increasing abundance information by reducing uncertainty, without killing more fish, by increasing the amount of sea floor sampled per time at sea and allowing different sampling unit sizes and selection.

Estimating gear efficiency is a difficult problem that we avoid.
ed by assuming that our net is 100% efficient (i.e., the net collects
every Atlantic Cod or Yellowtail Flounder within the sampled
area). On a recent survey to the Gulf of Maine, we mounted a
camera on the headrope, which provided continuous video of the
sweep interacting with the sea floor and the behavior of cod enter-
ing the net. This video will help us understand the efficiency of
the sweep and how it tends the bottom over a variety of habitats.

This video survey provides a mechanism to address the dis-
crepancy between fishermen’s observations and recent stock as-
sessments by providing improved information on specific fish ag-
gregations. It is a physically robust system and has successfully
operated on a commercial vessel under fall, winter, and spring
sampling conditions. It produces high-resolution video images
of groundfish that are simultaneously collected with location, depth,
time, and net configuration. It is possible to identify roundfish to
species and obtain a count of Atlantic Cod as they pass through
the net; flatfish can also be identified as a group and we are work-
ing toward species identification. The counts can be grouped by
time interval, and these can be randomly sampled to produce an
estimate of abundance that has tighter confidence limits than tra-
ditional swept area abundance estimates. The amount of sea floor
sampled per day is greatly increased without killing greater num-
bers of fish. The ability to work on commercial fishing vessels
and for fishermen to see what is being collected in the net in real
time is very powerful.

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