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FEATURE

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There is considerable controversy regarding abundance estimates of New England groundfish. Federal surveys sample randomly but are restricted to short tow lengths and minimal area covered at high daily expense. Working collaboratively with fishermen, we developed a video system that can be deployed in a commercial trawl net to improve the information on the abundance and distribution of groundfish stocks (focusing on Atlantic Cod *Gadus morhua* and Yellowtail Flounder *Limanda ferruginea*) by increasing the amount of sea floor sampled per sea day without killing more fish. Rather than being hauled to the surface for counting, fish are counted as they pass through the net. This results in continuous transect data that can be processed into sampling units, randomized, and used to estimate abundance. High-intensity sampling of important habitats can complement existing multispecies random and stratified random survey designs to reduce uncertainty, presenting a clearer picture of the resource.

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 km^2, 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).

Figure 1. Atlantic Cod and Yellowtail Flounder in a multispecies groundfish collection from a half-hour tow in the Gulf of Maine.

* 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.

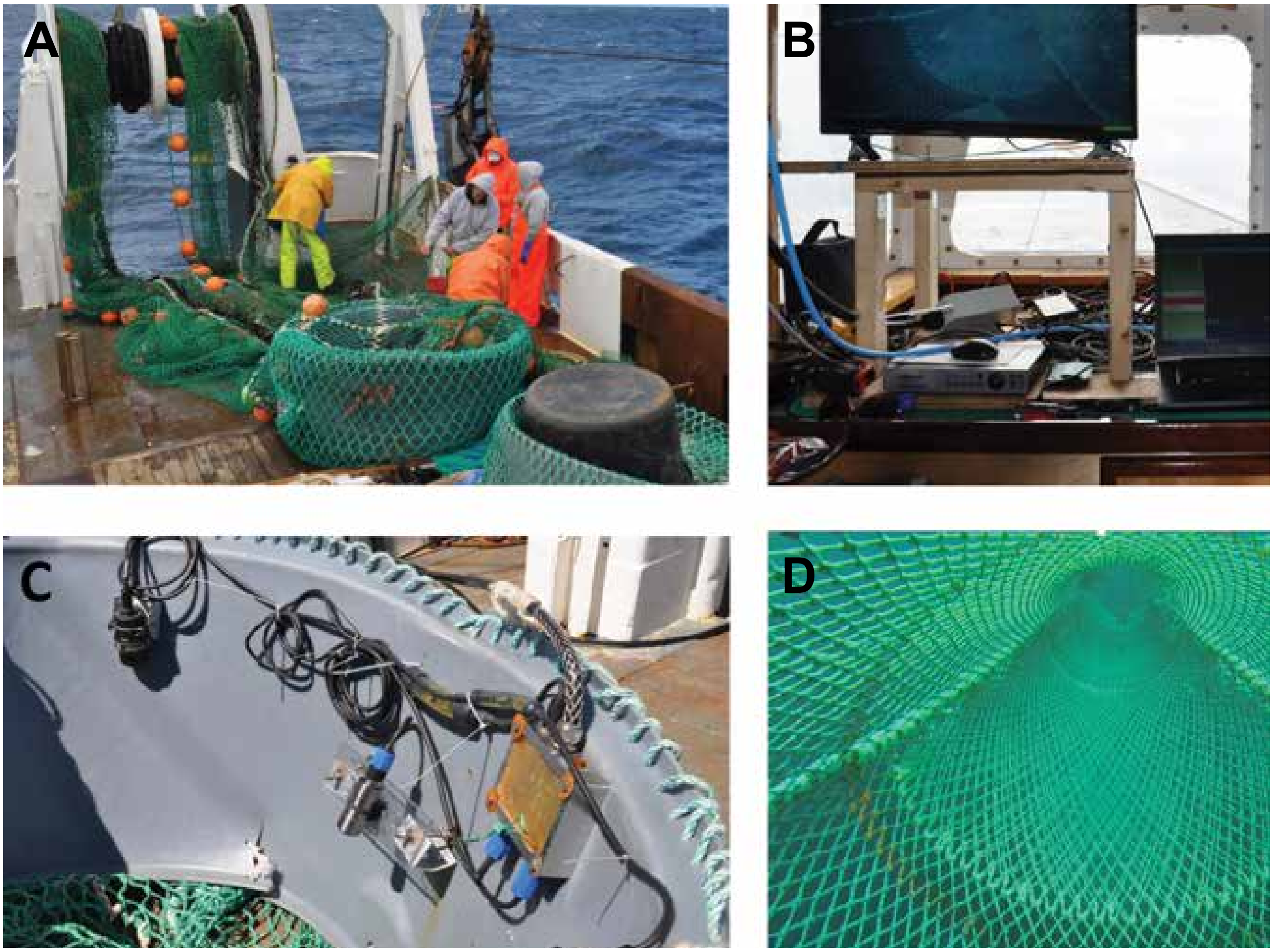

Figure 2. (A) The otter trawl with the housing for the video camera and lights sewn into the cod end on the *F/V Justice;* (B) the bridge setup, including high-definition recording equipment for the video footage, real-time monitor, Notus, and FLDRS data collection systems; (C) the DeepSea video camera and LED lights mounted in the camera housing; and (D) GoPro image of the otter trawl cod end as it is being set on an open tow (note that the opening where they fish pass through can be clearly seen).

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, wingspread, 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

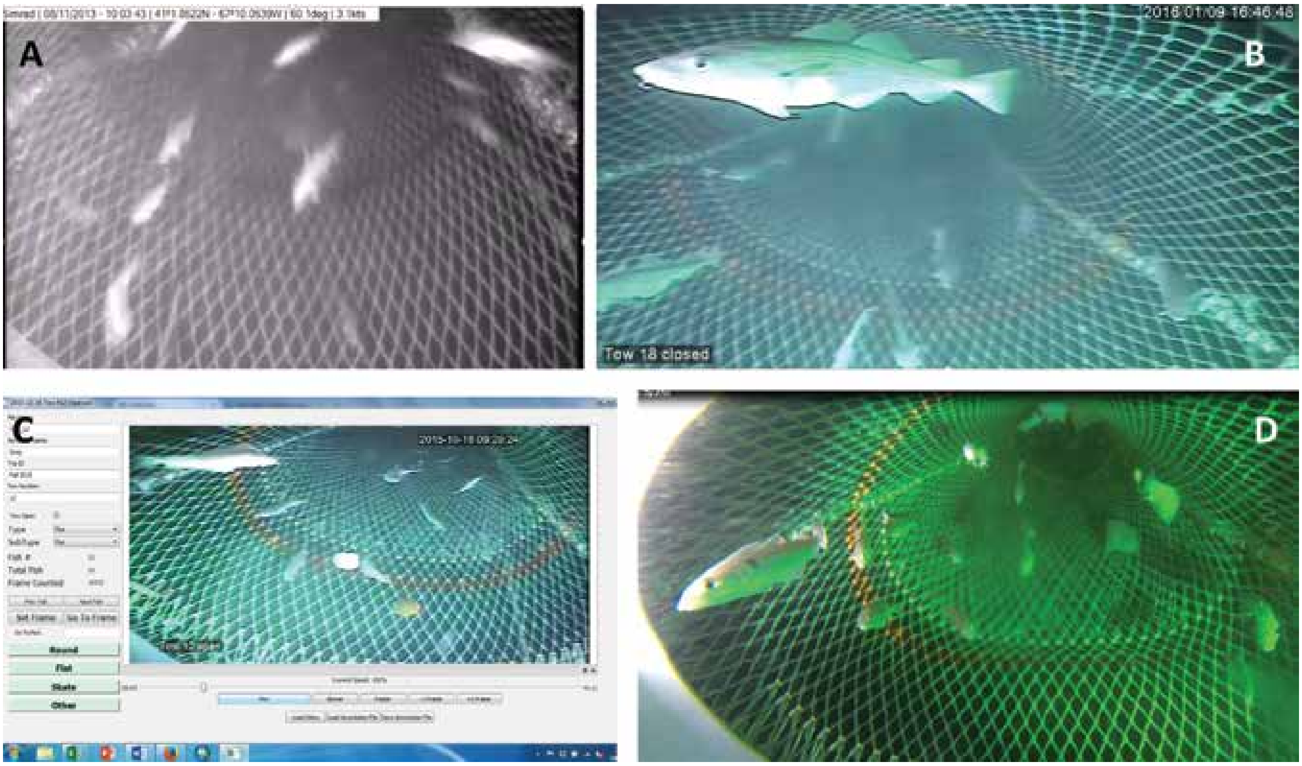

Figure 3. Where we began, where we are now, and how we will process the video data: screen grabs of (A) the FX80 SIMRAD used during the first cruises, (B) the DeepSea video camera system based on the SMAST sea scallop survey, (C) the graphical user interface, and (D) the supplemental GoPro camera attached during the most recent surveys.

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 (DeCelles 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 (km^2) 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 kilomter) 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 (km^2). The abundance was then estimated as the density of fish (numbers per square kilometer) multiplied by the sample area (km^2). The biomass for the closed tow estimate was also calculated by multiplying the weight of the animals (weight/km^2) by the sample area (km^2). 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

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 (km^2), the study area sampled by the transects (km^2), 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.

Year	2013	2014	2014	2015	2015	2016	2016
Season	Fall	Spring	Fall	Spring	Fall	Winter	Spring
Target species	Yellowtail Founder	Yellowtail Flounder	Yellowtail Flounder	Yellowtail Flounder	Yellowtail Flounder	Atlantic Cod	Yellowtail Flounder
Closed tows	8	15	17	38	8	8	8
Open tows	10	18	17	4	20	11	13
Hours of video	32	47	36	12	35	20	26
Net swept (km^2)	8.86	13.22	9.54	7.38	8.85	2.83	5.77
Study area (km^2)	1,483	1,908	2,709	2,900	2,396	300	2,365
% Surveyed of stock area	4.0	5.1	7.3	7.8	6.4	0.6	6.3
Target fish from closed tows (numbers)	1,993	1,370	3,315	1,195	1,030	1,096	653
Mean target fish in closed tows	249	91	195	31	129	157	82
SD	151.2	76.1	190.9	27.1	310.2	156.7	68.8
Target fish weight (kg) from closed tows	823	435	1,185	424	374	1,344	262
Mean target fish weight (kg) from closed tows	102.9	29.0	69.7	11.2	46.8	192	32.8
SD	67.5	24.8	66.7	9.6	110.7	167.9	26.9
Target fish biomass (metric tons) using closed tows	870.3	290.4	1,251.6	174.0	701.3	512.5	496.9
SD	638.2	212.1	1,396.1	150.0	1,614.5	433.9	395.1

Maine, collecting more than 200 h of video (Table 1). Using the closed cod end tows, the Yellowtail Flounder biomass estimates ranged from 174 to 1,252 mt and varied seasonally, with consistently lower values in the spring surveys (Table 1). There was no significant difference between the mean number or biomass of Yellowtail Flounder in the fall surveys of 2013, 2014, and 2015. In the spring closed-tow surveys, Yellowtail Flounder estimates were significantly lower in 2015 than 2014 and 2016, which did not differ (analysis of variance, mean number of fish $F = 9.591$, $P < 0.001$, Tukey's test $P = 0.001$ and 0.027; biomass $F = 8.287$, $P < 0.001$, Tukey's test $P = 0.006$ and 0.004, respectively). There may be several reasons for the lower estimate in 2015, including a higher number of tows and a delay due to weather, resulting in sampling later in the season with different water temperatures that may influence fish distribution. Although our study area was small, representing between 4% and 8% of the total stock area, the biomass estimates represented 9–43% of the 2016 Georges Bank stock varying by year and the assumption of 100% net efficiency (TRAC 2016; Table 1; Figure 4).

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

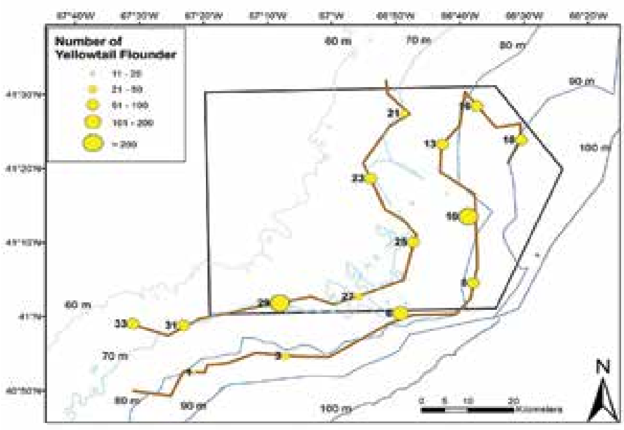

Figure 4. Study area for the Spring 2014 survey trip. Fifteen closed cod end tows (yellow dots; size of yellow dot indicates number of Yellowtail Flounder) and 18 open cod end tows (brown lines) were completed, which covered 290 km.

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 km^2, 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 average area swept by 1 min of sampling was 0.00366 km^2 (SD = 0.00034) for the open- and closed-tow video footage. The average number of Atlantic Cod observed in 375 randomly selected 1-min samples was 3.02 fish (SD = 5.362).

Several abundance estimates were produced from the Gulf of Maine data set. The first is a traditional swept area abundance estimate using only the closed cod end tow collections counted on the deck, which gave an estimate of 420,097 cod (n = 7, SD = 403,680.9); using the counts from the video footage of the closed tows increases this number slightly to 492,647 cod (n = 7, SD = 502,398.5). Using the cod counts from all of the tows (video and closed) gave an estimate of 327,526 cod (n = 19, SD = 359,924.8). Using the 1-min segments of the tow randomly selected produced a lower estimate of 247,650 cod (n = 375, SD = 22,697.1).

DISCUSSION

High-intensity sampling of important habitats where fish aggregate can complement the existing multispecies random survey designs. When fish stocks are depleted and the fish are highly aggregated, the observed distribution becomes one of many empty tows and a few extremely large tows. Creating a spatial mosaic where the densities are examined by subarea may be more insightful (Stokesbury et al. 2009).

The ideal variate for stratification is the value itself (i.e., the target population); in practice, this is not possible, but large gains in precision can be achieved if the population is composed of groups varying widely in size, the principal variables to be measured are closely related to the size of these groups, and a good measure of size is available for setting up the strata (Cochran 1977). If each stratum is homogeneous, in that the measurements vary little from one unit to another, a precise estimate of any stratum mean can be obtained from a small number of samples in that stratum (Cochran 1977). This reduces the cost of the survey compared to a simple random or systematic design. However, if fish are aggregated within the stratum, then the assumption of a normal distribution fails, resulting in (1) rare, large tows that are statistical outliers, making the stratum mean highly imprecise and the stratified variance large and (2) stock assessments

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.

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

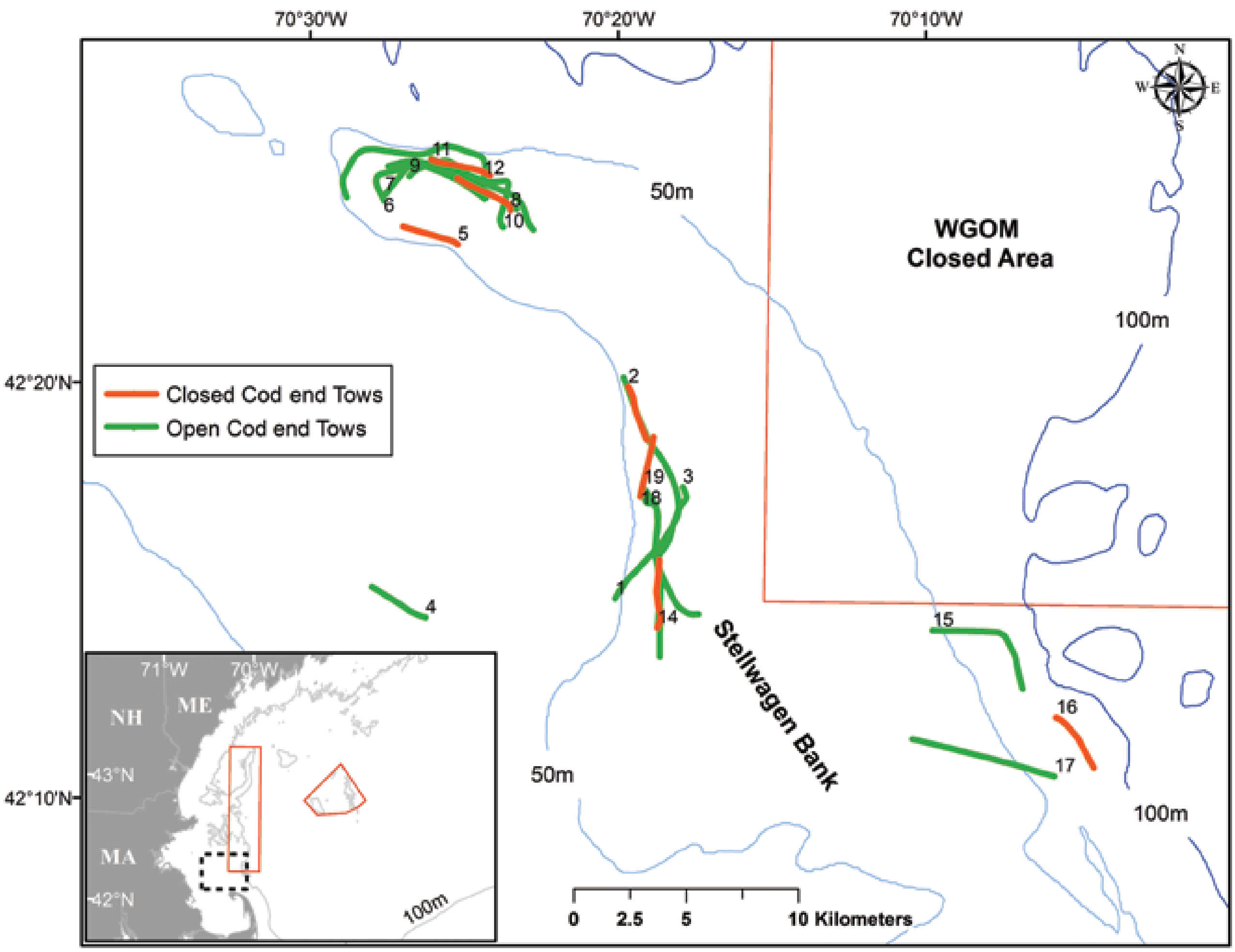

Figure 5. Study area covered during the Gulf of Maine Pilot Survey, January 6–10, 2016. More than 80 km of video was recorded.

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 km^2 of the 54,000 km^2 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-

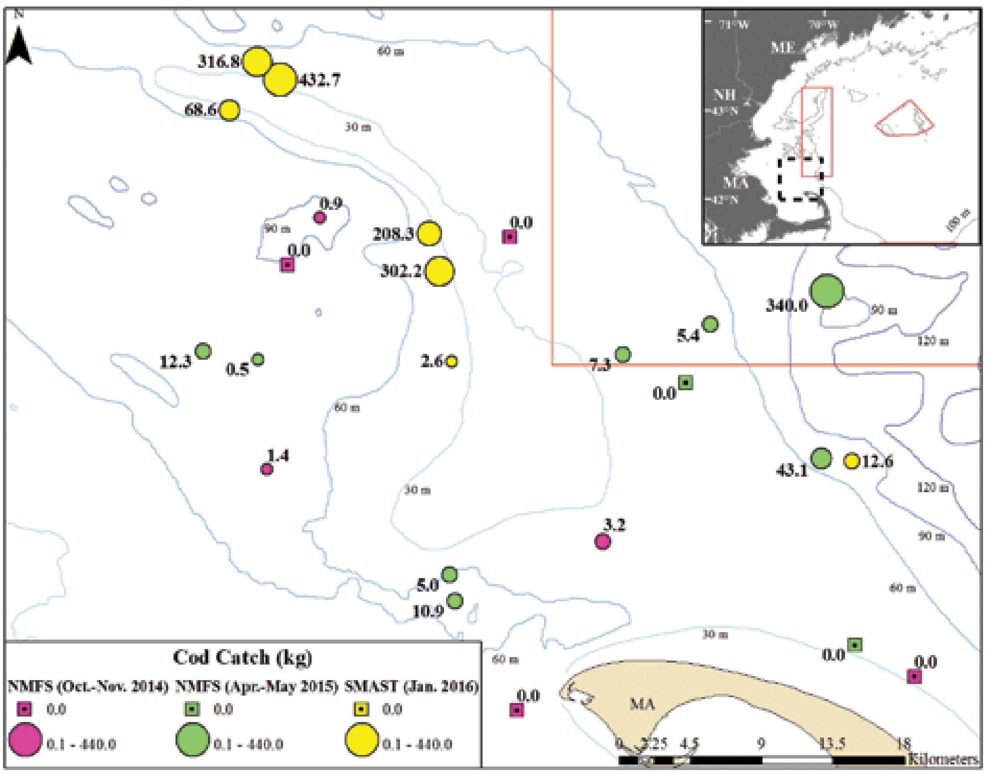

Figure 6. Atlantic Cod catches (kg) observed during the Fall 2014 and Spring 2015 Northeast Fisheries Science Center surveys compared to cod catches observed during closed cod end tows completed during the January 2016 SMAST pilot study.

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 entering 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 discrepancy between fishermen's observations and recent stock assessments by providing improved information on specific fish aggregations. 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 working 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 traditional swept area abundance estimates. The amount of sea floor sampled per day is greatly increased without killing greater numbers 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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REFERENCES

Ames, E. P. 2004. Atlantic Cod stock structure in the Gulf of Maine. Fisheries 29:10–28.

Cochran, W. G. 1977. Sampling techniques, 3rd edition. Wiley, New York.

Cuddy, D. 2017. NOAA science director steers a new course. New Bedford (Massachusetts) The Standard-Times (January 28). Available: www.southcoasttoday.com/news/20170128/noaa-science-director-steers-new-course. (July 2017).

DeCelles, G. R., E. F. Keiley, T. M. Lowery, N. M. Calabrese, and K. D. E. Stokesbury. 2017. Development of a video trawl survey system for New England groundfish. Transactions of the American Fisheries Society 146:462–477.

Gunderson, R. D. 1993. Surveys of fisheries resources. Wiley, New York.

Hoffman, A. A., and M. J. Hercus. 2000. Environmental stress as an evolutionary force. BioScience 50:217–226.

Interjurisdictional Fisheries Act of 1986. Title III of Public Law 99–659, Approved Nov. 14, 1986, 100 Stat. 3731, (Amended through P.L. 111–348, Enacted January 4, 2011).

Meng, K. C., K. Oremus, and S. Gaines. 2016. New England cod collapse and the climate. PLoS (Public Library of Science) ONE [online serial] 11(7) e0158487.

Murphy, T., A. Kitts, D. Records, C. Demarest, D. Caless, J. Walden, and S. Benjamin. 2014. 2012 Final report on the performance of the northeast multispecies (groundfish) fishery (May 2012–April 2013). National Marine Fisheries Service, Northeast Fisheries Science Center, Reference Document 14-01, Woods Hole, Massachusetts.

National Marine Fisheries Service. 2016. Magnuson-Stevens Fishery Conservation and Management Act provisions; fisheries of the northeastern United States; northeast groundfish fishery; framework adjustment 55. Federal Register 81:54(21 March 2016):15003–15033.

Northeast Fisheries Science Center. 2013. 55th Northeast regional stock assessment workshop (55th SAW) assessment report. National Marine Fisheries Service, Northeast Fisheries Science Center, Reference Document 13-11, Woods Hole, Massachusetts. Available: www.nefsc.noaa.gov/publications/crd/crd1311/. (June 2017).

———. 2015. Operational assessment of 20 northeast groundfish stocks, updated through 2014. National Marine Fisheries Service, Northeast Fisheries Science Center, Reference Document 15-24, Woods Hole, Massachusetts. Available: www.nefsc.noaa.gov/publications/crd/crd1524/. (June 2017).

O'Boyle, R., and M. Sinclair. 2012. Seal–Cod interaction on the Eastern Scotian Shelf: reconsideration of modelling assumptions. Fisheries Research 115–116:1–13.

O'Brien, L., and K. Clark. 2014. Proceedings of the diagnostic and empirical approach benchmark review for Georges Bank Yellowtail Flounder: report of meeting held 14–18 April 2014. Fisheries and Oceans Canada, Ottawa and National Marine Fisheries Service, TRAC Proceedings 2014/01, Woods Hole, Massachusetts.

O'Keefe, C. E., and G. R. DeCelles. 2013. Forming a partnership to avoid bycatch. Fisheries 38:434–444.

O'Sullivan, J. 2016. Are there more fish in the ocean than regulators say? The Boston Globe (December 31). Available: www.bostonglobe.com/metro/2016/12/30/high-tech-battle-for-future-fishing-industry/MSLQlz5ybod7pcV6XD5OQK/story.html.

Palmer, M. C., J. J. Deroba, C. M. Legault, and E. N. Brooks. 2016. Comment on "Slow Adaptation in the Face of Rapid Warming Leads to Collapse of the Gulf of Maine Cod Fishery." Science 352:423.

Pershing, A. J., M. A. Alexander, C. M. Hernandez, L. A. Kerr, A. L. Bris, K. E. Mills, J. A. Nye, N. R. Record, H. A. Scannell, J. D. Scott, G. D. Sherwood, and A. C. Thomas. 2015. Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. Science 350:809–812.

———. 2016. Response to comments on "Slow Adaptation in the Face of Rapid Warming Leads to Collapse of the Gulf of Maine Cod Fishery." Science 352:423.

Richardson, D. E., M. C. Palmer, and B. E. Smith. 2014. The influence of forage fish abundance on the aggregation or Gulf of Maine Atlantic Cod (*Gadus morhua*) and their catchability in the fishery. Canadian Journal of Fisheries and Aquatic Sciences 71:1349–1362.

Rothschild, B. J. 2007. Coherence of Atlantic Cod stock dynamics in the northwest Atlantic Ocean. Transactions of the American Fisheries Society 136:858–874.

Rothschild, B. J., E. F. Keiley, and Y. Jiao. 2013. Failure to eliminate overfishing and attain optimum yield in the New England groundfish fishery. ICES Journal of Marine Science 71:226–233.

Stokesbury, K. D. E., B. P. Harris, and M. C. Marino II. 2009. Astonishment, stupefaction, and a naturalist's approach to ecosystem-based fisheries studies. Pages 113–124 *in* B. J. Rothschild and R. Beamish, editors. The future of fisheries science. Springer, New York.

Swain, D. P., H. P. Benoit, S. P. Cox, and N. G. Cadigan. 2016. Comments on "Slow Adaptation in the Face of Rapid Warming Leads to Collapse of the Gulf of Maine Cod Fishery." Science 352:423.

TRAC (Transboundary Resource Assessment Committee). 2011. Georges Bank Yellowtail Flounder. Fisheries and Oceans Canada, Ottawa and National Marine Fisheries Service, Transboundary Resource Assessment Committee Status Report 2011/01, Woods Hole, Massachusetts.

———. 2014. Georges Bank Yellowtail Flounder. Fisheries and Oceans Canada, Transboundary Resource Assessment Committee Status Report 2014/03, Ottawa, and National Marine Fisheries Service, Woods Hole, Massachusetts.

———. 2016. Georges Bank Yellowtail Flounder. Fisheries and Oceans Canada, Transboundary Resource Assessment Committee Status Report 2016/03, Ottawa, and National Marine Fisheries Service, Woods Hole, Massachusetts.

Zemeckis, D. R., M. J. Dean, and S. X. Cadrin. 2014a. Spawning dynamics and associated management implications for Atlantic Cod. North American Journal of Fisheries Management 34:424–442.

Zemeckis, D. R., D. Marins, L. A. Kerr, and S. X. Cadrin. 2014b. Stock identification of Atlantic Cod (*Gadus morhua*) in U.S. waters: an interdisciplinary approach. ICES Journal of Marine Science 71:1490–1506. AFS