NOAA
National Marine Fisheries Service

Fishery Bulletin
established 1881

Spencer F. Baird
First U.S. Commissioner of Fisheries and founder of *Fishery Bulletin*

Abstract—The sea scallop (*Placopecten magellanicus*) fishery in the Atlantic is assessed during annual surveys by using both dredging and surface-deployed imaging techniques. In this pilot study in the Mid-Atlantic Bight, we used an autonomous underwater vehicle (AUV) to photograph the seafloor and to evaluate its use for determining scallop density and size. During 22 surveys in 2011, 257 km of seafloor were photographed, resulting in over 203,000 color images. Using trained annotators and photogrammetric software, we determined scallop density and shell heights for 15,252 scallops. The inshore scallop grounds near Long Island (at depths <40 m) had a density of 0.077 scallops per m^2, whereas the inshore grounds of the New York Bight had a density of 0.012 scallops per m^2. Shell heights derived from images were found to agree well with measurements from scallops collected with a commercial dredge. We show that images obtained with an AUV can be used to reliably estimate both density and shell height consistent with direct sampling from the same area. Moreover, side-scan sonar images obtained with an AUV can be used to detect dredge scars and, therefore, can provide a simultaneous, relative estimate of fishing effort in that area. AUVs provide a highly accurate suite of data for each survey site and therefore allow the design of experimental studies of fishing practices.

Manuscript submitted 9 April 2015.
Manuscript accepted 22 March 2016.
Fish. Bull. 114:261–273 (2016).
Online publication date: 26 April 2016.
doi: 10.7755/FB.114.3.1

Assessing the use of a camera system within an autonomous underwater vehicle for monitoring the distribution and density of sea scallops (*Placopecten magellanicus*) in the Mid-Atlantic Bight

Justin H. Walker[1]
Arthur C. Trembanis (contact author)[1,2]
Douglas C. Miller[2]

Email address for contact author: art@udel.edu

[1] Department of Geological Sciences
University of Delaware
109 Penny Hall
Newark, Delaware 19716

[2] School of Marine Science and Policy
University of Delaware
Lewes, Delaware 19958

The sea scallop (*Placopecten magellanicus*, Gmelin 1791) of the Mid-Atlantic Bight Atlantic fishery has been commercially active for over 100 years, and in recent years has consistently ranked in the top five most valuable domestic U.S. fisheries at around a half billion dollars (NMFS, 2009–2013). To promote the sustainability of the sea scallop fishery, the National Marine Fisheries Service (NMFS) monitors the fishery annually through a combination of survey approaches (Stokesbury et al., 2004; Kelly[1]; DuPaul and Rudders[2]; NEFSC[3]; Rudders and DuPaul[4]). The results of these monitoring efforts are used to determine annual catch limits that balance overfishing and sustainability against potentially unnecessary economic loss (Rosenberg, 2003; Naidu and Robert, 2006).

The sea scallop fishery stock is monitored by means of both dredge surveys (DuPaul and Rudders[2]; NEFSC[3]), and drop-camera surveys (Jacobson et al., 2010; Carey and Stokesbury 2011; Stokesbury, 2012; Hart et al., 2013). Dredging is performed by towing either a commercial or scientific survey dredge across the seafloor and has a direct impact on scallops, bycatch organisms, and

[1] Kelly, K. H. 2007. Results from the 2006 Maine sea scallop survey, 34 p. Maine Dep. Mar. Res., W. Boothbay Harbor, ME. [Available at website.]

[2] DuPaul, W. D., and D. B. Rudders. 2008. An assessment of sea scallop abundance and distribution in selected closed areas: Georges Bank area I and II, Nantucket Lightship and Elephant Trunk. VIMS Mar. Res. Rep. 2008-3, 47 p. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA. [Available at website.]

[3] NEFSC (Northeast Fisheries Science Center). 2010. 50th northeast regional stock assessment workshop (50th SAW) assessment report. Northeast Fish. Sci. Cent. Ref. Doc. 10-17, 844 p. [Available at website.]

[4] Rudders, D. B., and W. D. DuPaul. 2012. An assessment of sea scallop abundance and distribution in open access areas: New York Bight and the southern New England area. VIMS Mar. Res. Rep. 2012-8, 48 p. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA. [Available at website.]

the seafloor itself. Imagery-based surveys have fewer direct impacts on the seafloor and its inhabitants and have the advantage of covering large areas efficiently. Early studies were performed with cameras mounted on a rigid stationary pyramid-shaped platform that was lowered from a vessel to the seafloor (Stokesbury, 2002). More recently the HabCam system has been developed, which is a towed camera sled tethered to a ship, and it can photograph long stretches of the seafloor (Rosenkranz et al., 2008). In 2010, the National Marine Fisheries Service (NMFS) formally expressed the need to develop and apply new approaches to stock assessment of sea scallop in the Mid-Atlantic Bight (NMFS, 2010). A recent NOAA-sponsored workshop (NOAA[5]) gathered numerous researchers engaged in seabed imaging to highlight the development of a variety of imaging platforms, and among their findings, the potential value of autonomous imaging platforms was recognized for future survey efforts. The present study is a an application of those recommendations by extending previous smaller scale camera studies with the use of autonomous underwater vehicles (AUVs) in Iceland (Singh et al., 2013 and 2014) to a larger spatial scale study through surveys conducted within the Mid-Atlantic Bight.

AUVs have been shown to be an effective platform for mapping benthic habitat (Tolimieri et al., 2008; Forrest et al., 2012; Raineault et al., 2012; Seiler et al., 2012; Raineault et al., 2013) by coupling images obtained by underwater camera with highly accurate preprogrammed navigation. In this study, we used an AUV to assess sea scallop shell height and abundance, as well to estimate biomass in the shallow (< 40 m) open scallop fishing grounds within the Mid-Atlantic Bight. Because shallow grounds are not typically within the scope of the annual NMFS survey, this study offers unique findings of the sea scallop populations in such areas. Moreover, our results show that an AUV is a suitable platform for collecting images as part of the sea scallop stock assessment process. Our goal in this pilot study was to test and show the feasibility of the AUV platform by using synchronous commercial dredging samples to illustrate the efficacy of the underwater camera system for what could be scaled up to be a useful tool for a full stock assessment process.

Materials and methods

Field sampling

The Mid-Atlantic Bight is the shallow portion of the continental shelf that extends from Cape Hatteras, NC, to Cape Cod, MA. Our study area was selected to fulfill the needs of the Mid-Atlantic Fishery Management Council's Research Set-Aside (RSA) program to survey heavily fished inshore scallop grounds (<40 m depth) that are not regularly monitored. All of the AUV surveys reported here were conducted in the New York Bight (NYB) and Long Island (LI) regions during July 2011 (Fig. 1).

As part of their survey sampling design, the National Marine Fisheries Service uses a 30×30 minute latitude/longitude grid system. Our AUV surveys were executed at randomly selected sites within each block area of an 8-block grid. They involved photographically surveying at least 37,500 m^2 of seafloor at two or more sites within each grid. Sites were either chosen from recent NMFS survey sites for scallop stocks or were randomly chosen from within each grid to meet the predetermined total area. All of the surveys were conducted within 70 km of the coast of Delaware, New Jersey, or New York, and the water depths sampled ranged from 20 to 50 m (Table 1), which is within the normal habitable zone for the sea scallop (Merrill[6]; Hart and Chute, 2004). Extensive details of the sampling design were compiled in the master's thesis for the pilot study (Walker, 2013) and were reviewed and approved by both an internal and external panel of scientists selected by NMFS as part of the final project review process.

Survey design

At each site, we deployed the AUV on a preplanned path that ranged from 3 to 16 kilometers of contiguous survey trackline. Surveys lasted up to 3 hours, an operational limit imposed by the life of a single battery pack. The AUV was programmed in a terrain-following mode with a commanded altitude of 2.2 m. Postprocessing analysis of the survey logs showed that the AUV remained within a 16 cm standard deviation of the 2.2 m commanded altitude, a deviation that is consistent with previous studies in which the same vehicle system has been used (e.g., Forrest et al., 2012; Raineault et al., 2012). Precise navigation of the vehicle is accomplished by using a DVL-aided (Doppler Velocity Log) INS (Inertial Navigation System), which has been shown in the literature to provide a positional drift rate of 0.5 m/h (Patterson et al., 2008) or 0.1% of distance traveled (Rankey and Doolittle, 2012). Comparison of known targets (such as stationary man-made objects on the seafloor) in side-scan sonar imagery from repeated passes showed positional precision of within 2 m from one survey to the next—a level that is consistent with results from other published benthic habitat mapping studies conducted with this same vehicle system (e.g., Forrest et al., 2012; Raineault et al., 2013).

Because this was a pilot study, several trackline designs were tested to determine the most effective geometric design for image and acoustic sampling. The survey design that we used most often comprised a series of parallel boustrophedon lines, commonly known

[5] NOAA. 2014. Undersea Imaging Workshop: workshop report; Red Bank, N.J., 14–15 January, 34 p. New Jersey Sea Grant Consortium, NOAA, Fort Hancock, NJ. [Available at website.]

[6] Merrill, A. S. 1971. The sea scallop. *In* Annual report for 1970, p. 24–27. Am. Malacol. Union Inc.

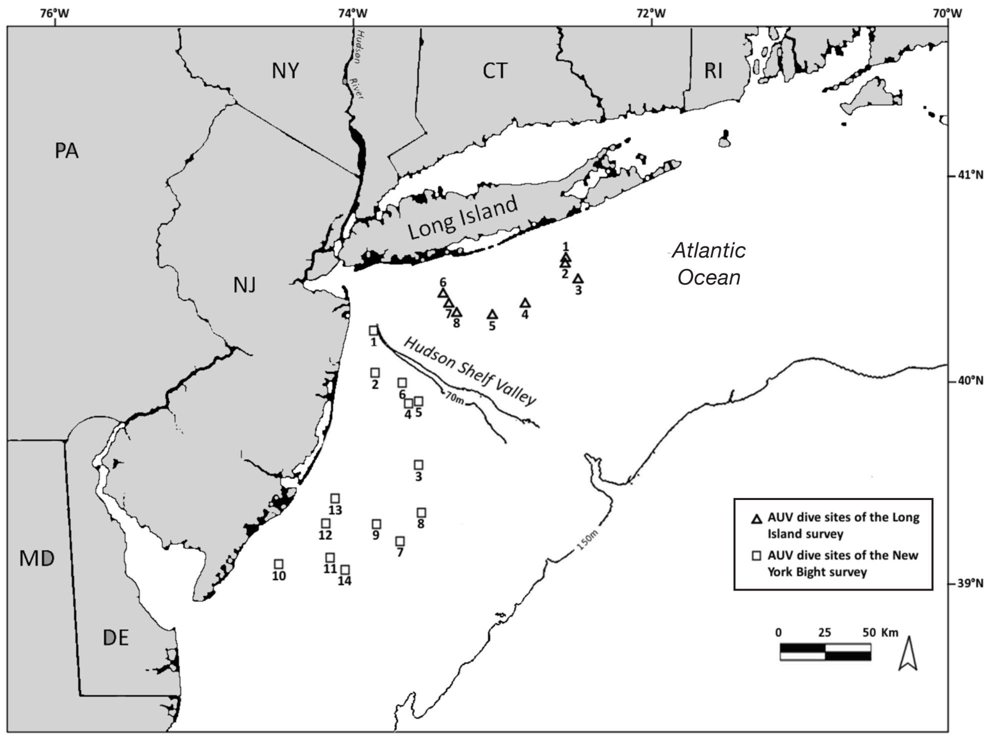

Figure 1

A map of the Mid-Atlantic Bight showing the sites where photographs of the sea bottom and sea scallops (*Placopecten magellanicus*) were taken with an underwater camera from an autonomous underwater vehicle (AUV) at 22 survey sites in 2011.

as a "lawn mower" pattern. Multiple equidistant transects were run parallel to each other at a commanded even spacing that ranged between 2 to 40 m laterally. This method had the advantage of allowing 100% imaging and side-scan sonar coverage depending on transect spacing. Less frequently, our survey design consisted of equidistant oblique transects that propagated along only one of the transect axes in a slalom path. This design would be most useful for sampling an elongated bed of scallops. The third most used survey design consisted of equidistant orthogonal transects that propagated along both transect axes (in the profile of a staircase). This design provided the largest extent of geographic coverage from a single battery charge.

Equipment

Our surface vessel was the FV *Christian and Alexa*, a 30-m eastern rig, commercial fishing ship with port and starboard New Bedford style 15-ft (4.57-m) scallop dredges. For comparison of the AUV imagery data, each survey site was dredged immediately after the AUV survey with the starboard scallop dredge by towing for 15 minutes at 4.5 to 5.0 knots at every site along the initial AUV transect line. The dredges were fitted with 4-inch (10.2-cm) interlocking rings to coincide with commercial fishing requirements, along with an 11-inch (27.9-cm) twine mesh top and turtle chains. Shell-height-frequency data were collected on the deck from the dredged contents by using standard survey methods for sizing a randomly selected bushel of scallops.

The photographic imaging platform used was a Teledyne Gavia AUV that has an operational depth limit of 500 m. The AUV was run in an imaging and sonar mapping configuration consisting (from front to back) of a nose cone camera, lithium ion battery module, GeoSwath phase measuring bathymetric sonar (500 kHz) module, Kearfott T-24 inertial navigation system (INS) and Doppler velocity log (DVL), command module (900/1800 kHz Marine Sonic side-scan sonar), and a propulsion module. During a survey, the AUV can simultaneously optically image the seafloor, map the seafloor with side-scan sonar and phase measuring bathymetric sonar, log depth and altitude of the vehicle, and measure water temperature, dissolved oxygen saturation, turbidity, and salinity.

The nose cone camera was a Point Grey Scorpion 20SO research camera, equipped with a Sony ICX274 Type 1/1.8" (8.923 mm diagonal) CCD camera, with a resolution of 800×600 pixels. This camera was configured to acquire images at a rate of 3.75 images per second. Illumination was provided by LED strobe array, positioned obliquely aft of the camera. The camera has a Fujinon DF6HA-1B 6-mm focal length lens and a horizontal viewing angle of 44.65° in salt water based on a salinity of 35 (PSU). Calibration results determined

Table 1

Summary of environmental data and measurements of sea scallops (*Placopecten magellanicus*) derived from photographs taken with an underwater camera within an autonomous underwater vehicle (AUV) during surveys within the Long Island (LI) and New York Bight (NYB) areas.

	AUV survey site	Latitude (°)	Longitude (°)	Water depth (m)	Bottom water temperature (°C)	Survey distance (m)	Survey area (m^2)	Number of bottom images	Number of scallops	Scallop density (scallops/m^2)	Mean shell height (mm)	Mean meat weight (g/scallop)
Long Island area	LI1	40.5529	-72.5899	41.9	8.8	15,904	26,834	14,742	2,172	0.081	121.1	37.0
	LI2	40.5503	-72.5872	43.5	8.8	3,015	5,280	2,387	894	0.169	119.6	35.2
	LI3	40.4712	-72.5294	45.4	8.5	10,337	18,135	8,065	3,706	0.204	103.7	23.7
	LI4	40.3449	-72.8817	45.8	8.6	12,280	21,689	9,992	1,365	0.063	101.4	21.8
	LI5	40.3111	-73.0825	42.1	8.9	10,773	19,085	8,338	1,850	0.097	102.8	23.6
	LI6	40.3961	-73.3818	31.7	11.9	14,211	23,473	11,329	422	0.018	100.0	25.3
	LI7	40.3551	-73.3483	33.7	10.8	12,271	20,384	10,163	227	0.011	112.6	33.5
	LI8	40.3213	-73.2749	35.3	9.8	12,154	21,328	9,780	1,403	0.066	104.2	26.5
				Mean	Mean	Total	Total	Total	Total	Mean	Mean	Mean
Summary				39.3	9.6	90,945	156,208	74,796	12,039	0.077	107.7	27.3
New York Bight area	NYB1	40.2368	-73.7828	35.5	11.0	10,398	17,684	9,141	82	0.005	106.4	28.4
	NYB2	40.0279	-73.8078	27.7	11.5	12,511	21,000	9,523	16	0.001	112.5	37.0
	NYB3	39.5942	-73.5386	41.5	8.4	11,691	19,079	9,544	508	0.027	116.4	35.5
	NYB4	39.8873	-73.6105	32.8	9.1	12,181	19,069	9,479	212	0.011	130.2	51.4
	NYB5	39.9019	-73.5318	36.9	9.2	11,752	20,440	9,425	801	0.039	117.2	36.7
	NYB6	39.9793	-73.6383	37.9	9.4	12,133	20,036	9,281	331	0.017	119.7	37.7
	NYB7	39.2332	-73.6423	46.6	8.0	12,196	18,228	12,068	506	0.028	121.0	35.9
	NYB8	39.3621	-73.5099	50.7	8.2	12,149	20,006	9,572	140	0.007	120.6	37.2
	NYB9	39.3266	-73.7925	40.0	9.5	13,086	21,704	10,950	523	0.024	128.9	45.8
	NYB10	39.1000	-74.4470	21.9	11.6	11,791	19,740	9,170	3	<0.001	92.2	23.3
	NYB11	39.1431	-74.0397	38.7	10.0	13,499	23,559	7,050	1	<0.001	86.8	14.0
	NYB12	39.1431	-74.0397	28.2	11.6	12,207	20,700	7,345	0	0	–	–
	NYB13	39.4200	-74.0267	20.1	12.7	8,292	13,494	6,285	0	0	–	–
	NYB14	39.0950	-73.984	42.0	9.2	12,331	21,334	9,437	90	0.004	126.7	43.6
				Mean	Mean	Total	Total	Total	Total	Mean	Mean	Mean
Summary				36.2	9.9	166,218	276,073	128,270	3,213	0.012	120.8	38.9

from a set of images taken within a test tank described below show that scale distortions in relation to the image center were less than 2 pixels over 65% of the full frame (Fig. 2). Each image had a metadata header that contained navigation (i.e. latitude, longitude, altitude, depth, etc.) and near seafloor environmental conditions corresponding to the capture time of the photo from the sensors of the AUV.

Calibration of the camera system was conducted with photos gathered with the AUV camera system in a saltwater tank. The calibration process entailed a sequence of images of a standard planar checkerboard pattern viewed from multiple angles and processed by using the Camera Calibration Toolbox for Matlab developed by Bouguet (2011) and based on the models of Zhang (2000) and Heikkila and Silven (1997). The analysis (Fig. 2) provided a direct quantitative measure of the camera field of view (FOV) and showed that minimal radial and tangential lens distortion affected the camera. These results agreed closely with previously published results from the same AUV and camera systems (Guðmundsson, 2012; Singh et al. 2013; Singh et al., 2014) and were further confirmed by independent analysis of the images (Rzhanov[7]).

The camera calibration (Fig. 2) showed the spatial pattern as that of the AUV camera, namely the impact of spherical and tangential lens distortion at each pixel point within the full image frame. Most of the area within each image (65%) exhibits distortion of less than 2 pixels (~5 mm in ground distance), except for the upper and lower left corners, which have 7 or more pixels of displacement (~16 mm in on the ground distance), representing a maximum error of <1% of total pixel width. These distortions will have generally less than 1% impact on the estimation of scallop shell height because the average distortion of 1–2 pixels translates to

[7] Rzhanov, Y. 2015. Personal commun. Center for Coastal and Ocean Mapping, Univ. New Hampshire, Durham, NH 03824.

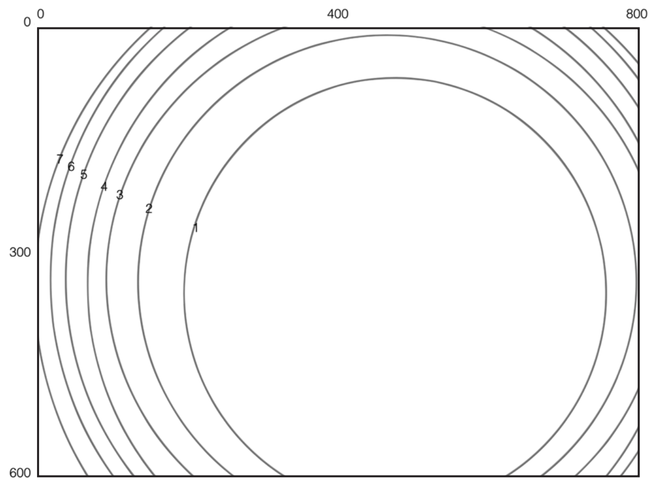

Figure 2

Distortion contours (measured from 1 to 7 pixels) in relation to the center of an image for the AUVs underwater camera used in a study of the distribution and abundance of the sea scallop (*Placopecten magellanicus*) during 2011.

between 0.23 and 0.46 cm in distance on the ground. This distortion uncertainty is approximately within <5% of the average shell height directly measured in the dredge tow samples, with which the image-based measurements were favorably compared. It is important to note, however, that camera distortions have no impact on the enumeration of scallops and the resulting analysis of scallop counts. In previously published studies of sea scallop shell height and abundance, this same combination of AUV camera was used and calibrated camera distortions along with both pitch and roll of the AUV were found to be negligible (Guðmundsson, 2012; Singh et al. 2013; Singh et al., 2014). Our study, therefore, is consistent with the findings of the previous research cited above, suggesting that the influence of roll bias (< 1%), camera distortions (< 1%), and manual digitization (< 1%) overall contributes less than 5% uncertainty for estimates of shell height. The width (W) of a single image was determined by using the image metadata collected by the AUV navigational system and sensors.

$$W = 2\tan\left(\frac{\alpha_h}{2}\right)[z - 1.3\sin(-\theta_p)], \qquad \text{(Eq. 1)}$$

where W = seafloor image width in meters;
α_h = horizontal viewing angle (degrees) of the camera in water;
z = height above the seafloor in meters; and
θ_p = pitch of the AUV in degrees.

Knowing the horizontal viewing angle of the camera in water (α_h=44,65°), and the height above the seafloor (z), we were able to calculate real world dimensions on the seafloor in each image. The pitch of the AUV (θ_p) and the arm length (1.3 m) from the camera to the AUV navigational reference point were known and used to correct the calculation, although in other studies (Guðmundsson, 2012; Singh et al., 2013, 2014) both pitch and roll were found to be negligible factors. Not accounting for pitch would have resulted in a potential 3% (mean) overestimation of image height for all of the photos. For Equation 1, the AUV is assumed to image a flat seafloor over the area of the full frame, and the equation also does not account for roll of the vehicle. The roll-induced error associated with image width is less than 1.0% (at 2 m altitude) if vehicle roll is less than 10° from horizontal, and log data showed that the AUV operated with roll characteristics of $\bar{x}$=4.01°C and σ=1.11° for all survey sites. Singh et al. (2013 and 2014) reported a similar ground distance error (<2%) due to both AUV pitch and roll for the same Scorpion 20SO camera when surveying at an altitude of 2 m. Similarly, Guðmundsson (2012) performed as detailed a calibration of the same AUV camera system as that used in our study and reported negligible effects of camera distortion, pitch, and roll.

Scallop counts and sizing

The 22 AUV surveys resulted in 203,066 images of the seafloor; see Figure 3 for a selection of representative images. In order to process all of the images, we engaged a team of graduate students and interns to count and size scallops using software written inhouse for this project. Each scallop annotator received training on identifying sea scallops in benthic images, and was required to successfully identify at least 95% of the scallops from a standardized image data set before being allowed to annotate the rest of the images. Repeated digital measurement of the same scallop by the same annotator (N=53, where N is the number of sea scallops) yielded a standard deviation of 5.0 mm in shell height measurement. This value of annotation repeatability for size determination is in agreement with the 5 mm annotator measurement error reported by Singh et al. (2014). Furthermore, it is worth noting that in comparison with manually sized scallops from dredge samples, manually sizing was itself segmented into 5-mm bin intervals and thus the discretization of image-based sizes was on par with the discretization from physical samples. The protocol used for image selection and sizing was the following:

1 All images that were taken at a height between 1.5 m and 2.5 m above the seafloor were counted (removing the starting descent and ending ascent portions of each survey).
2 Each sea scallop in an image was counted individually, unless it had already been counted from the previous image that overlapped the same section of seafloor. Annotators examined photos sequentially and were trained to recognize overlapped images, so that scallops were not counted more than once.
3 Each scallop shell height was sized on the basis of the distance from the shell umbo to the ventral margin by using a pixel-measuring tool. The projected

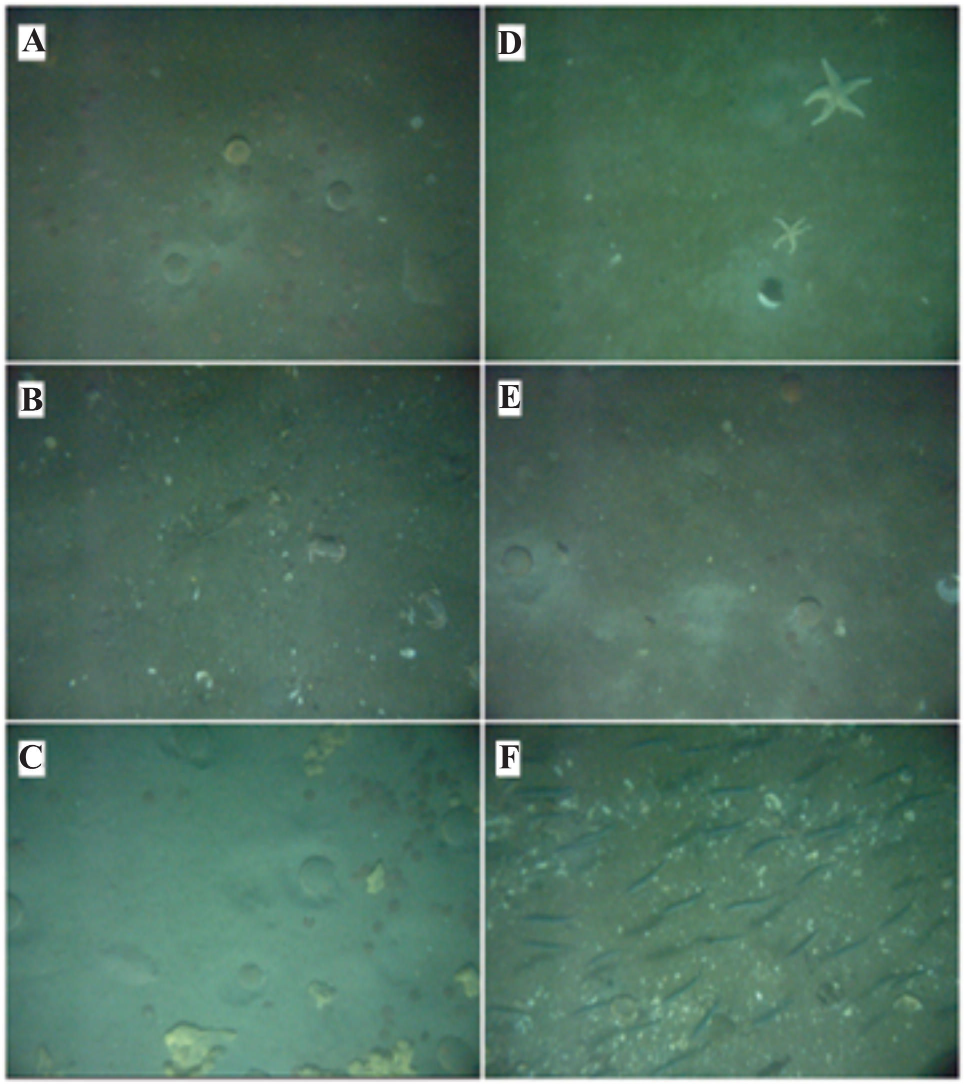

Figure 3

Representative examples of images from the database of photographs from the 2011 survey of sea scallops (*Placopecten magellanicus*) in the Long Island and New York Bight areas. The sea bottom was photographed with an underwater camera mounted inside the nose cone of an autonomous underwater vehicle. Images A, C, D, and E show sea scallops resting on the seafloor. Images B and F show other species incidentally photographed during the AUV surveys including crabs, fish, and skates.

on-the-ground length represented by the pixels was then calculated from the metadata of each image (e.g., altitude, pitch, and camera FOV) with Equation 1.

4 Shell height was not recorded if more than half of the entire scallop was not contained within the frame.

5 Scallops identified as disarticulated shells were neither counted nor sized.

6 The final count for a survey was the number of scallops that could be sized.

Scallop densities were calculated for each survey site. The number of scallops that were identified and sized for each survey were summed and divided by the area of the seafloor that had been photographed. In order to limit the effect of image overlap (as much as 5% in the current surveys), the AUV transect length was calculated from the global positioning system (GPS) start and end point of each survey line. The transect length was then multiplied by the mean image width for that transect, and the vehicle control kept the AUV to within 16 cm standard deviation of the 2.2 m altitude set point along the trackline. As part of the image analysis and review process, annotators classified the quality of each image on the basis of whether the image was out of focus, too dark, or the water was too turbid for scallops to be recognized. More than 95% of all the images were of sufficient quality for the annotators to recognize, count, and size the scallops. It is worth noting that many towed camera systems have only a fractional portion of the images annotated, whereas we were able to annotate all of our images. Additionally, the stability of the AUV platform ensured that fewer images (<5%) were removed with altitude or image quality filtering.

Biomass

Because our project methods were based on seabed images, we used an empirical relationship from the literature to estimate the meat weight of scallops for comparative purposes. This parameter has been shown to vary on the basis of a number of geographical and environmental factors and decreases with depth (Hennen and Hart, 2012). The equation chosen from Rothschild et al. (2009) is based on meat-weight measurements of sea scallops dredged from within the Mid-Atlantic Bight (the study area) and therefore was not further corrected for latitude and longitude. The meat-weight biomass was calculated for each scallop by using the photogrammetrically measured shell height of each scallop and the depth recorded for each image with the following equation:

$$W_m = e^{-8.94+2.94\ln H_S - 0.43\ln d} \quad \text{(Eq. 2)}$$

where W_m = meat-weight biomass of the sea scallop in grams;
H_S = shell height of the sea scallop in millimeters;
d = depth of the sea scallop in meters.

Fishing effort

Commercial fishing dredges create distinctive patterns of sediment disturbance on the seafloor, and these dredge scars are visible with side scan sonar (Dickson et al., 1978; NRC, 2002; Lucchetti and Sala, 2012; Krumholz and Brennan, 2015). For each survey, the dredge marks were determined from the side-scan data collected by the AUV at the same time that the photos were gathered. SonarWiz 5 (Chesapeake Technology Inc., Mountain View, CA) was used to process the acoustic data collected by the 900 kHz side-scan sonar and gridded at a 0.25×0.25 m horizontal resolution for inspection. Each dredge scar was then manually traced in each side-scan mosaic by using the SonarWiz digitizing tool. The track length was then multiplied by the measured width of the dredge scar (4.57 m) to determine the total area of the dredge scar. The area dredged was compared with the area acoustically surveyed (survey track length multiplied by a 20-m swath width) to give a ratio that represented a measure of recent fishing effort. For one site, we ran the AUV both before and after the dredge and verified that our dredge track was visible in the side-scan imagery. In most of the sonar mosaic images there were many dredge marks visible such that our sampling mark was only a small fraction of the total estimated dredge area.

Results

Over the 10-day cruise in July 2011, we completed 22 surveys with the AUV and covered 257 km of track line for a combined surveyed area of 490,000 m^2. In all, 203,000 images of the seafloor were produced, from which annotators identified and digitally sized 15,252 sea scallops.

Scallop density

The New York Bight (NYB) region was surveyed over 14 discrete sites and sea scallops were identified from images collected from 12 of those sites (i.e., 2 survey sites had no scallops). Overall, 276,000 m^2 of seafloor were surveyed (optically and acoustically) in the NYB, and densities for each survey ranged from 0 to 0.039 scallops per m^2 (Table 1). The area-weighted mean scallop density for the region was 0.012 scallops per m^2. The 6 sites that had scallop densities **<<**0.01 scallops per m^2 were the shallowest surveys (20.1–35.5 m) and also coincided with the warmest near bottom temperatures (10.0–12.7°C). We also observed that these sites typically had dense sand dollar populations.

The histogram in Figure 4A shows the shell-height frequency for all of the photogrammetrically sized sea scallops within the NYB. Taken together, 1.5% (48) of the 3,213 sized scallops fell into the recruit size class (<70 mm), and 13.8% were of a size larger than that of recruits but smaller than the 4″ dredge rings (>70 mm and <101.6 mm). The harvestable size class accounted for the remaining 84.7%, which results in an exploitable (harvestable) scallop density of 0.010 scallops per m^2 for NYB. The mean shell height for the NYB region was found to be 121 mm. These results indicate that the NYB had a size population dominated by large harvestable scallops.

The Long Island (LI) region was surveyed at 8 distinct sites, and an area of over 156,000 m^2 of seafloor was photographed in the region. The sea scallop density was 0.077 scallops per m^2, and there was a large variability in densities ranging from 0.01 to 0.20 scallops per m^2 (Table 1). As found in the NYB region, the denser scallop populations were found at near bed temperatures of 8–9°C, whereas the warmer (>10°C), shallower survey sites had the lowest population densities.

The distribution of shell heights in the LI region is shown in Figure 4B. Of the 12,039 scallops that were sized, 61.2% (7,368) were classified as harvestable and

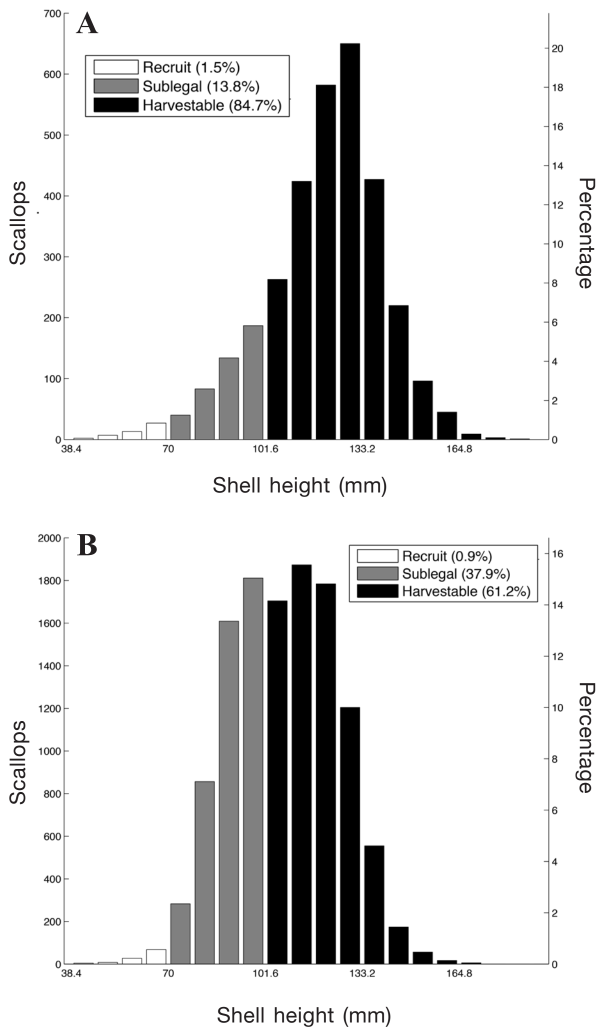

Figure 4

Frequency histograms of digitally sized shell heights (in millimeters) of sea scallops (*Placopecten magellanicus*) within (**A**) New York Bight (3213 sea scallops) and (**B**) Long Island areas (12,039 sea scallops).

37.9% (4,563) were classified as larger than the size of recruits but smaller than the 4″ rings. This distribution yields an exploitable scallop density (of harvestable size scallops) of 0.047 scallops per m^2. The remaining 0.9% (108) scallops were classified as recruits. The mean shell height for the region was 108 mm. As with the NYB sites, the scallop population was found to be dominated by scallops with a large shell height and only a small number of recruit-size scallops were observed (Fig. 5).

Comparisons of results from dredge tows with those from camera imagery were performed for a subset of the surveys from the NYB region (NYB4-8). The dredged scallops were manually sized into 5-mm bins. The dredged scallop sizes were compared with shell-height sizes obtained with the AUV from the same surveys by using size-class distribution plots (Fig. 6). The means of the manually measured scallop shell heights obtained with dredging (range of mean values 122–135 mm, N=54–22,) were found to be within 6% of the co-located AUV image-sized shell height means (range of mean values 117–130 mm, N=140–801, Fig. 6). The lower means of the AUV image-sized scallops are expected because recruit-size scallops are included within the distribution. By design, dredges do not accurately sample scallops under 101.6 mm (4″ diameter ring), thereby skewing the shell height distribution toward larger sizes (Yochum and DuPaul, 2008).

Biomass

Using a published equation (Eq. 2) we calculated the meat weight of each individual scallop from the shell height measurements derived from AUV images and the results are plotted in Figure 7. The majority of sea scallop biomass off LI is due to a high frequency of smaller meat weights (10–30 g each). The highest density sites in the LI region were typically coincident with smaller shell heights. The bulk of sea scallop biomass in the NYB region is due to a higher frequency of meat weights ranging from 30–50 g each.

Fishing effort

Digitized dredge scars in the side-scan mosaics revealed that over 174,000 m^2 or 35.5% of the total surveyed seafloor area showed signs of dredging. We found that higher dredging effort (>7% of the bottom area dredged) coincided with the highest scallop densities, whereas a low scallop density area typically showed little or no dredging. It was not uncommon for a site to have a single dredge scar from a commercial vessel— perhaps the mark of a test dredge tow that did not yield a large enough catch for continued fishing effort.

There was a noticeable difference between fishing efforts in LI and NYB. We found that the NYB had significantly less dredging (5% overall) than that found in the LI region. The scallop densities at all NYB sites were considerably less than those at LI counterparts. NYB8 had the most concentrated dredging in the region with 11.9% of the area dredged. In addition, the shell height distributions for the heavily fished sites were positively skewed because of the size selectivity of the commercial scallop dredge (Fig. 5).

The LI sites had an overall density 7 times that of the NYB region. As a result, the LI region had significant commercial dredging >18% of the total area dredged for 5 out of the 8 survey sites. Operationally, digitizing dredge scars did not add significant processing time of the data. After side-scan sonar mosaics had been produced for each site, it took a total of 8 man-hours to manually digitize and calculate the area dredged for all 22 survey sites.

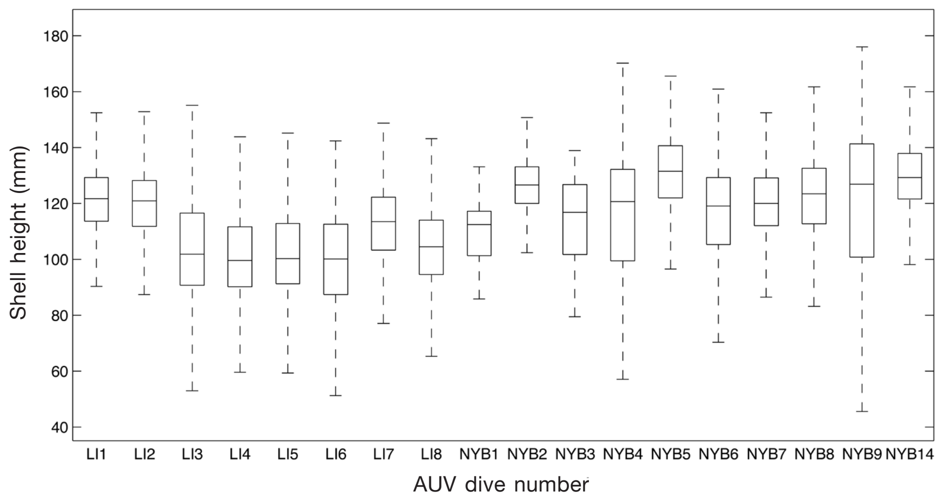

Figure 5

Boxplots of shell heights of sea scallops (*Placopecten magellanicus*) obtained from photographs taken with an underwater camera of an autonomous underwater vehicle with the Long Island (LI) and New York Bight (NYB) areas. Surveys where <16 sea scallops were collected were not plotted.

Discussion

Automated underwater vehicle as an image-producing survey platform

The AUV is an efficient platform that allows surveys from images (optical and acoustical simultaneously) over 15 km of seafloor on a single battery charge, and allows the noninvasive study of benthic organisms over any bed type, including rocky or uneven terrain that would be difficult or impossible for dredges. For sea scallops, we found that an altitude of 2.2 m allowed for the largest image area, while still maintaining visibility and resolution to size scallops. Particulate matter in the water column drastically decreased visibility of the seafloor for altitudes over 4 m. Continual logging of geographic and environmental conditions allowed accurate sizing and enumeration of scallops after processing. The highly accurate navigation—typically a 1-m drift over 1 km of trackline of the AUV—allowed precise repeatability of survey lines. Targets visible in overlapping side-scan sonar imagery exhibited horizontal offsets of less than 2 m—a finding that is consistent with numerous other AUV benthic and geomorphic survey studies (e.g. Patterson et al., 2008; Forrest et al., 2012; Rankey and Doolittle, 2012; Raineault et al., 2013). This navigational precision allowed for the reoccupation of survey lines.

A variety of survey designs were evaluated in our study. Although we believe designs that propagate in a continuous linear direction (e.g., in a stair-case pattern) have a use for surveying an extremely elongated bed of scallops, we did not find those designs suited this type of study or fully incorporated the strengths of the AUV. The boustrophedon survey design, or a more regular and approximately rectangular pattern design, was found to be most useful in simultaneously photographing the seafloor and acoustically mapping it. Surveys were designed to allow complete coverage of a rectangular survey site (~1.75 km×0.3 km) with side-scan sonar. The use of the geo-referenced data of each image also made it possible to plot the precise location of each scallop and to evaluate the distribution of individuals within the population (Trembanis et al., 2012; Walker, 2013).

Logistically, the AUV offers an effective and productive platform for the collection of sea scallop images as part of a larger stock assessment effort. The ability to quickly deploy and retrieve the AUV from a support vessel allows the rapid acquisition of photographic and acoustic data that can be analyzed at sea during transit time or after the completion of the cruise. Imaging the seafloor is a noninvasive way to survey the scallop population and gather data about the small-scale spatial structuring of the population, seafloor texture and morphological features, and water quality. Photogrammetric sizing of the scallops was rapid, requiring only a few seconds once a scallop had been located in an image. We found that the digital sizes agreed favorably with the measurements of dredged specimens from the survey sites.

One of the major advantages of the AUV is the high volume of data that can be collected in a few hours, but this high volume also results in a significant challenge for data processing. However, we showed that with the aid of sizing software, a team of trained scallop annota-

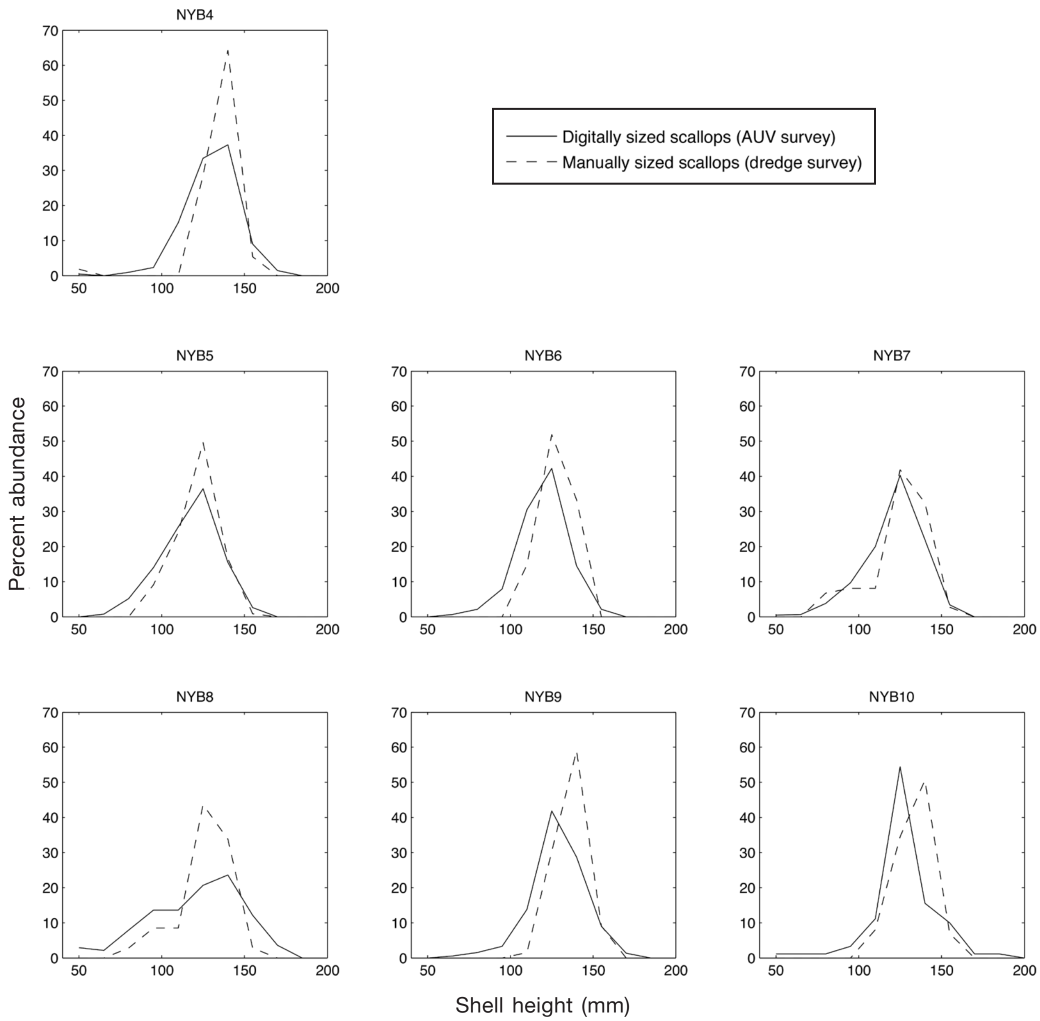

Figure 6

Histographs of shell height distribution for digitally sized sea scallops (*Placopecten magellanicus*) photographed with an underwater camera of an autonomous underwater vehicle (AUV) and for sea scallops collected with a commercial dredge in fishing operations undertaken at the same time and at the same locations in the New York Bight area.

tors could complete the observation of 203,000 images in 98 man-hours (a rate of 2,000 images per hour). Walker (2013) showed that the hours required to complete annotation of a set of images were directly related to the number of scallops and associated fauna.

Over 200,000 bottom photographs were obtained in this study, and all were examined by annotators trained to count scallops and measure their shell height. We found this manual step to require many hours of effort and some expense. We investigated statistical approaches by repeated random sampling simulations and text book formulae (Zar 1999, p. 109) that can be used to gauge the loss in precision by examining only a random subset of images. Overall, we found the mean density to be 0.075 scallops/image, with a standard deviation of 0.35. These values were sufficient to compute the standard error of the mean density from a smaller random subset of images with the formula for the standard error, $SE = s/\sqrt{n}$, where s is the standard deviation and n is the number of photos. For example, a random subset of 40,000 images would have a standard error of $0.35/\sqrt{40{,}000}=0.00175$, giving a 95% confidence interval (i.e., twice the standard error) of ±0.0035. This bound is at ±5% of the mean value (i.e., the relative error) obtained from all photographs and can be the expected precision when examining a random sample of only 20% of the images that we collected. Sampling half that number (20,000) increases the relative error to 6.6%, while doubling it to 80,000 decreases the relative error to 3.3%. Because imagery-based assessments typically generate large numbers of images,

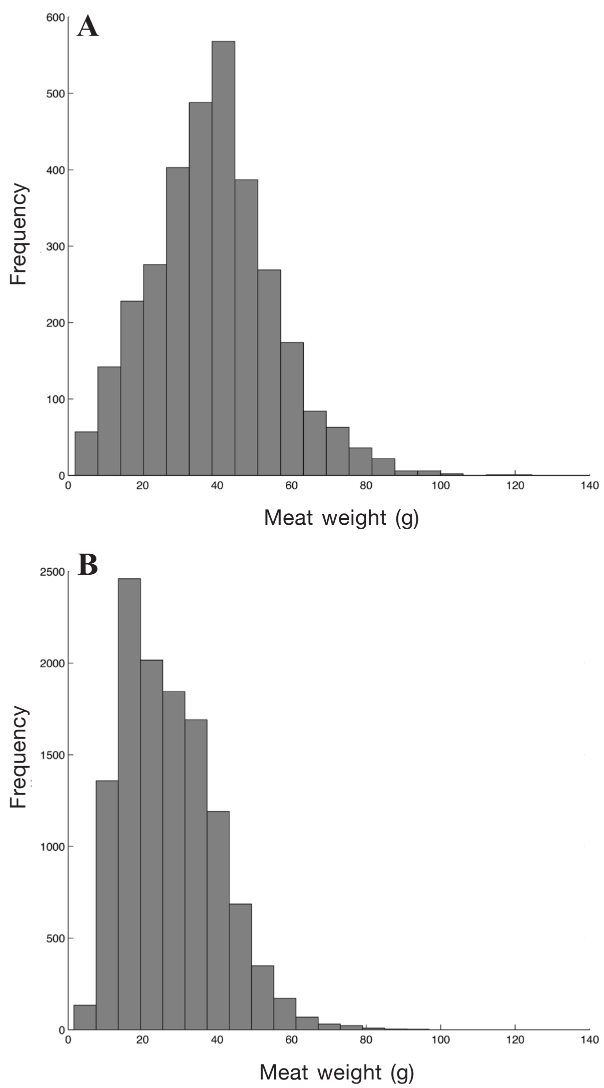

Figure 7

Histograms of calculated biomass based on meat weight (g) of sea scallops (*Placopecten magellanicus*) collected in 2011 from (**A**) the New York Bight (NYB) and (**B**) Long Island (LI) areas.

the examination of a much smaller random subset may yield sufficiently precise density values and substantial savings in time and effort.

Sea scallop stock assessment

The results of the inshore surveys showed that the LI region had an overall density of 0.077 scallops per m^2, which agrees with the density of 0.061 scallops per m^2 reported by Rudders and DuPaul[4] for dredge-based survey of the LI region in 2011. The NYB inshore sites were only slightly less populated (0.013 scallops per m^2) in comparison both with the density of 0.015 scallops per m^2 reported by Rudders and Dupaul[4] for the deeper NYB waters and with the population density in the LI region in general. The higher population level of the LI region has been hypothesized by Law (2007) to be due to seeding from the Georges Bank area. Conversely, the lower NYB region densities could be explained by the interruption of scallop larvae transport from the LI region caused by the influx of freshwater from the Hudson River (Law, 2007). Additionally, the Hudson Shelf Valley forms a natural bathymetric divide between the two regions. The two scallop populations were also different in their shell height distributions. The LI population was skewed toward smaller shell heights in contrast with the more symmetrical distribution of the NYB population. Both regions had very few recruit-size class scallops (<1.5%) and were found overall to possess large-size scallop populations. We also noted that the largest scallop populations occurred around the 9°C ocean water isotherm, which corresponds well with the optimal scallop growth temperature of 10°C reported by Posgay (1953).

Dredging effort and sea scallop density

The combined optical and acoustic AUV method used in this study was found to be an efficient way to further use commonly collected side-scan data to quantify dredging effort. This method could be used to assess the effects of dredging effort on other benthic organisms, particularly on common bycatch species in the scallop fishery. As would be expected, a direct comparison of dredging effort with scallop density revealed that fishermen concentrated dredging in only the most populated sites, and that size-selective dredges had a noticeable impact on the shell height distribution of the remaining scallop population (see Fig. 5).

The effects of dredging on the substrate of the seafloor have been investigated in multiple studies (Margetts and Bridger[8]; Caddy, 1973; Krost, 1990; Hall-Spencer and Moore, 2000; Jenkins et al. 2001; NRC, 2002; Lucchetti and Sala, 2012; Krumholz and Brennan, 2015). These studies have found that substrate texture and fishing effort are the leading variables in the preservation of trawl marks. Finer grained sediment (muddy sediment versus sandy bottom) allows the gear to penetrate further into the substrate due to lower mechanical resistance between the substrate and the gear (Krost, 1990). Researchers have reported dredge marks remaining for up to 1.5 years on continually fished substrate (Hall-Spencer and Moore, 2000). In the absence of dredging, disturbed bed contouring effects last for significantly longer periods of time; Hall-Spencer and Moore (2000) reported dredge scars can remain for up to 2.5 years without further fishing efforts and Bernhard (reported by Krost, 1990) reported a single trawl scar remaining for up to 5 years

[8] Margetts, A. R., and J. P. Bridger. 1971. The effect of a beam trawl on the sea bed. ICES Council Meeting (C.M.) Documents 1971/B:8, 9 p. [Available at website.]

in a bay setting devoid of fishing and strong near-bed tidal currents.

The fine-sand seabed of the study site allows for the formation of relatively shallow dredge scars. The limited seasonal time scale for discernibility of the dredge scars is due to ongoing fishing efforts that rework the surface sediment and the reworking of sediment from wave driven near-bed currents. As such, side-scan surveys at our study sites can be a useful tool for quantifying fishing effort but only for a current season.

Acknowledgments

This project was funded by the NOAA Research Set-Aside Program (award number: NA11NMF4540011). The authors are grateful to the crew of the FV *Christian and Alexa*: Co-Captain A. Ochse, Co-Captain K. Ochse, M. Newman, D. Crosson, and R. Adams; the late W. Phoel; D. Hart at NMFS; V. Schmidt; C. DuVal, A. Norton, AUV Team: J. Gutsche and B. Keller; and the Digital Image Scallop Annotator Team: V. Amrutia, B. Reed, M. Christie, T. Santangelo, and D. Wessell.

Literature cited

Bouguet, J.-Y.
2011. Camera Calibration Toolbox for Matlab. [Available at website, accessed October 2011.]

Caddy, J. F.
1973. Underwater observations on tracks of dredges and trawls and some effects of dredging on a scallop ground. J. Fish. Res. Board Can. 30:173–180. Article

Carey J. D., and K. D. E. Stokesbury.
2011. An assessment of juvenile and adult sea scallop, *Placopecten magellanicus*, distribution in the northwest Atlantic using high-resolution still imagery. J. Shellfish Res. 30:569–582. Article

Dickson, R. R., D. N. Langhorne, R. S. Millner, and E. G. Shreeve.
1978. An examination of a dredged channel using sector scanning sonar in side-scan mode. J. Cons. Int. Explor. Mer 38:41–47. Article

Forrest, A. L., M. E. Wittmann, V. Schmidt, N. A. Raineault, A. Hamilton, W. Pike, S. G. Schladow, J. E. Reuter, B. E. Laval, A. C. Trembanis.
2012. Quantitative assessment of invasive species in lacustrine environments through benthic imagery analysis. Limnol. Oceanogr. Methods 10:65–74. Article

Guðmundsson, E. O.
2012. Detecting scallops in images from an AUV. M.Sc. thesis, 82 p. Univ. Iceland, Reykjavik, Iceland. [Available at website.]

Hart, D. R., and A. S. Chute.
2004. Essential Fish Habitat Source Document: sea scallop, *Placopecten magellanicus*, life history and habitat characteristics, 2nd ed. NOAA Tech. Memo. NMFS-NE-189, 21 p

Hart, D. R., L. D. Jacobson, and J. Tang.
2013. To split or not to split: assessment of Georges Bank sea scallops in the presence of marine protected areas. Fish. Res. 144:74–83. Article.

Hall-Spencer, J. M., and P. G. Moore.
2000. Scallop dredging has profound, long-term impacts on maerl habitats. ICES J. Mar. Sci. 57:1407–1415. Article

Heikkilä, J. and O. Silvén.
1997. A four-step camera calibration procedure with implicit image correction. *In* Proceedings of the 1997 IEEE Computer Society Conference on Computer Vision and Pattern Recognition; San Juan, Puerto Rico, 17–19 June, p. 1106–1112. IEEE Computer Soc., Los Alamitos, CA.

Hennen, D. R., and D. R. Hart.
2012. Shell height-to-weight relationships for Atlantic sea scallops (*Placopecten magellanicus*) in offshore U.S. waters. J. Shellfish Res. 31:1133–1144. Article

Jacobson, L. D., K. D. E. Stokesbury, M. A. Allard, A. Cute, B. P. Harris, D. Hart, T. Jaffarian, M. C. Marino II, J. I. Nogueria, and P. Rago.
2010. Measurement errors in body size of sea scallops (*Placopecten magellanicus*) and their effect on stock assessment models. Fish. Bull. 108:233–247.

Jenkins, S. R., B. D. Beukers-Stewart, and A. R. Brand.
2001. Impact of scallop dredging on benthic megafauna: a comparison of damage levels in captured and non-captured organisms. Mar. Ecol. Prog. Ser. 215:297–301. Article

Krost, P.
1990. The impact of otter-trawl fishery on nutrient release from the sediment and macrofauna of Kieler Bucht (western Baltic). Ber. Inst. Meereskd. Christian-Albrechts-Univ. Kiel 200, 150 p. Article

Krumholz, J. S. and M. L. Brennan.
2015. Fishing for common ground: investigations of the impact of trawling on ancient shipwreck sites uncovers a potential for management synergy. Mar. Policy 61:127–133. Article

Law, C. G., III.
2007. The impacts of spatial and temporal variability of larval transport on the distribution and population dynamics of the sea scallop (*Placopecten magellancius*). Ph.D. dissertation, 120 p. Rutgers Univ., New Brunswick, NJ.

Lucchetti, A., and A. Sala.
2012. Impact and performance of Mediterranean fishing gear by side-scan sonar technology. Can. J. Fish. Aquat. Sci. 69:1806–1816. Article

NMFS (National Marine Fisheries Service).
2009. Fisheries of the United States 2008. Current Fishery Statistics No. 2008, 103 p. Natl. Mar. Fish. Serv., NOAA, Silver Spring, MD. [Available at website.]
2010. Fisheries of the United States 2009. Current Fishery Statistics No. 2009, 103 p. Natl. Mar. Fish. Serv., NOAA, Silver Spring, MD. [Available at website.]
2011. Fisheries of the United States 2010. Current Fishery Statistics No. 2010, 103 p. Natl. Mar. Fish. Serv., NOAA, Silver Spring, MD. [Available at website.]
2012. Fisheries of the United States 2011. Current Fishery Statistics No. 2011, 124 p. Natl. Mar. Fish. Serv., NOAA, Silver Spring, MD. [Available at website.]
2013. Fisheries of the United States 2012. Current Fishery Statistics No. 2012, 124 p. Natl. Mar. Fish. Serv., NOAA, Silver Spring, MD. [Available at website.]

Naidu, K. S., and G. Robert.
2006. Fisheries sea scallop, *Placopecten magellanicus*. Dev. Aquac. Fish. Sci. 35:869–905. Article

National Research Council (NRC).
2002. Effects of trawling and dredging on seafloor habitat, 136 p. National Academy Press, Washington, D.C.
Patterson, M., T. Hiller, and A. Trembanis.
2008. Exploring coral reef sustainability. HydroInternational Newsletter 12(7):10–15. [Available at website.]
Posgay, J. A.
1953. Sea scallop investigations. *In* Sixth report on investigations of methods of shellfisheries of Massachusetts, p. 9–24. Div. Mar. Fish., Mass. Dep. Conserv., Boston, MA.
Raineault, N. A., A. C. Trembanis, and D. C. Miller.
2012. Mapping benthic habitats in Delaware Bay and the coastal Atlantic: acoustic techniques provide greater coverage and high resolution in complex, shallow-water environments. Estuaries and Coasts 35:682–689. Article
Raineault, N. A., A. C. Trembanis, D. C. Miller, and V. Capone.
2013. Interannual changes in seafloor surficial geology at an artificial reef site on the inner continental shelf. Cont. Shelf Res. 58:67–78. Article
Rankey, E. C., and D. F. Doolittle.
2012. Geomorphology of carbonate platform-marginal uppermost slopes: insights from a Holocene analogue, Little Bahama Bank, Bahamas. Sedimentology 59:2146–2171. Article
Rosenberg, A. A.
2003. Managing to the margins: the overexploitation of fisheries. Front. Ecol. Environ. 1:102–106. Article
Rosenkranz, G. E., S. M. Gallager, R. W. Shepard, and M. Blakeslee.
2008. Development of a high-speed, megapixel benthic imaging system for coastal fisheries research in Alaska. Fish. Res. 92:340–344. Article
Rothschild, B. J., C. F. Adams, C. L. Sarro, and K. D. E. Stokesbury.
2009. Variability in the relationship between sea scallop shell height and meat weight. ICES J. Mar. Sci. 66:1972–1977. Article
Seiler, J., A. Williams, and N. Barrett.
2012. Assessing size, abundance and habitat preferences of the Ocean Perch *Helicolenus percoides* using a AUV-borne stereo camera system. Fish. Res. 129–130:64–72. Article
Singh W., E.B. Örnólfdóttir, and G. Stefansson.
2013. A camera-based autonomous underwater vehicle sampling approach to quantify scallop abundance. J. Shellfish Res. 32:725–732. Article
Singh W., E. B. Örnólfdóttir E.B., and G. Stefansson.
2014. A small-scale comparison of Iceland scallop size distributions obtained from a camera based autonomous underwater vehicle and dredge survey. PLoS ONE 9(10):e109369. Article
Stokesbury, K. D. E.
2002. Estimation of sea scallop abundance in closed areas of Georges Bank, USA. Trans. Am. Fish. Soc. 131:1081–1092. Article
2012. Stock definition and recruitment: implications for the U.S. sea scallop (*Placopecten magellanicus*) fishery from 2003 to 2011. Rev. Fish. Sci. 20:154–164. Article
Stokesbury, K. D. E., B. P. Harris, M. C. Marino II, and J. L. Nogueira.
2004. Estimation of sea scallop abundance using a video survey in off-shore US waters. J. Shellfish Res. 23:33–40.
Tolimieri, N., M. E. Clarke, H. Singh, and C. Goldfinger.
2008. Evaluating the SeaBED AUV for monitoring groundfish in untrawlable habitat. *In* Marine habitat mapping technology for Alaska (J. R. Reynolds and H. Gary Greene, eds.), p. 129–141. Univ. Alaska Fairbanks, Alaska Sea Grant College Program Rep. AK-SG-08-03.
Trembanis, A., J. Walker, D. Miller, B. Phoel.
2012. A high-density image analysis of sea scallop habitat in the Mid-Atlantic Bight [Abstract]. *In* Proceedings of the GeoHab 2012 Eleventh International Symposium; Orcas Island, WA, 1–4 May, p. 60. GeoHab, Eastsound, WA. [Available at website.]
Walker, J. H.
2013. Abundance and size of the sea scallop population in the Mid-Atlantic Bight. Master's thesis, 272 p. Univ. Delaware, Newark, DE.
Yochum, N., and W. D. DuPaul.
2008. Size-selectivity of the northwest Atlantic sea scallop (*Placopecten magellanicus*) dredge. J. Shellfish Res. 27:265–271. Article
Zhang, Z.
2000. A flexible new technique for camera calibration. IEEE Trans. Pattern Anal. Mach. Intell. 22:1330–1334. Article
Zar, J. H.
1999. Biostatistical analysis, 4th ed, 663 p. Prentice Hall, Upper Saddle River, NJ.