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AN ASSESSMENT OF JUVENILE AND ADULT SEA SCALLOP, *PLACOPECTEN MAGELLANICUS*, DISTRIBUTION IN THE NORTHWEST ATLANTIC USING HIGH-RESOLUTION STILL IMAGERY

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ABSTRACT Recent surveys using high-resolution imagery have enabled improved detection of Atlantic sea scallops, *Placopecten magellanicus*, between 10 mm and 65 mm in shell height, allowing the observation of juvenile scallops in the wild, which was previously difficult. Using these high-resolution images from 2008 and 2009 surveys of Georges Bank and the Mid-Atlantic Bight, the distribution and crowding levels of juvenile and adult scallops were examined. Mean crowding values revealed differences in small-scale distribution of scallops that were undetectable with density estimates. Juveniles on Georges Bank were 2.6–3.9 times more crowded than adults, and 2.9–7.4 times more crowded than juveniles and adults in the Mid-Atlantic Bight. The increased crowding of juvenile scallops on Georges Bank may be the result of differences in substrate, sea star interactions, and abundance of filamentous flora and fauna. The incorporation of high-resolution imagery into optical surveys represents an important development in the advancement of survey techniques because it has the potential (1) to quantify year class strength of 1-y-old scallops more accurately; (2) to improve growth, mortality, and biomass estimates in stock assessments; and (3) to advance our understanding of scallop ecology, including recruitment processes and population dynamics.

KEY WORDS: *Placopecten magellanicus*, juvenile, sea scallop, crowding, high-resolution optical survey, Georges Bank, Mid-Atlantic Bight

INTRODUCTION

Information regarding the ecology and distribution of juvenile sea scallops *Placopecten magellanicus* is lacking because observing them in the wild has been notoriously difficult (Olsen 1955, Brand 2006, Wong et al. 2006). Because they represent the future of the fishery, however, this information is important for successful management of the commercial resource (Minchin 1992). The U.S. commercial sea scallop fishery currently implements a rotational area management strategy (NEFMC 2003), and information on recruitment is a critical factor in the optimal timing of area openings and closures. Dredge surveys are commonly used to assess scallop populations and reveal trends in relative abundance, but collecting prerecruit juvenile scallops in representative abundance is difficult (Brand 2006). Furthermore, these surveys are conducted across large spatial scales and they provide no information on the spatial distribution of individuals on scales less than a kilometer (Caddy 1968, Caddy 1970).

Caddy (1989) suggests that time series of scallop fisheries should be classified as either "cyclical," with consistent alterations between periods of high catch and low catch, or "irregular," where transitions between high and low catch are inconsistent. This is likely a result of the high spatial and temporal variability in year class strength that sea scallops exhibit, caused by variations in total fertilized egg production, density-independent larval survival within the water column, density-dependent spatfall, and survival to age 2 (McGarvey et al. 1993). After they settle to the seafloor, scallops are exposed to a variety of factors that can affect survival. Physical and biological factors such as substrate type, predation, and presence of filamentous flora and fauna all affect mortality in young scallops and are critical factors in the formation of sea scallop beds (Stokesbury & Himmelman 1995).

There are two possible explanations for the limited appearance of juvenile scallops in surveys. Perhaps scallop spat are not present in the survey areas, as location of spat settlement does not always correspond with persistent adult aggregations (Stokesbury & Himmelman 1995, Arsenault et al. 2000). Bayne (1964) observed a disconnect between populations of juvenile and adult mussels, *Mytilus edulis*, and suggested that, as an adaptation to prevent competition with adults, juveniles settle in nursery areas that facilitate growth and eventually migrate or disperse into adult populations. Although some scallop populations may exhibit a similar behavior (Thouzeau et al. 1991, Minchin 1992, Arsenault et al. 2000), this is an unlikely cause of the absence of juvenile sea scallops in surveys, because resourcewide surveys cover tens of thousands of square kilometers. Several tagging studies indicate that sea scallops do not migrate at the scale of tens of kilometers or greater (Posgay 1981, Melvin et al. 1985, Stokesbury & Himmelman 1996).

A more likely explanation for the limited presence of juvenile scallops in surveys is that they are not detected by the survey design or equipment. Scallop larvae may be gregarious (Brand 2006), leading to high levels of aggregation in juvenile scallops. This could increase the chances that these individuals will be missed by randomly or systematically designed surveys, because a larger percentage of individuals would be located in a smaller area. In dredge surveys, small scallops may pass through the rings or liners, or pass under the frame. Because they are active swimmers, they may also avoid the gear or be pushed out of the dredge path by a pressure wave (Henry & Kenchington 2004). In optical surveys, although present, juvenile scallops may blend in with the substrate and go undetected as a result of their coloration and small size. If this is occurring, improving the resolution and image clarity of quadrat images in optical surveys should increase the percentage of juveniles detected.

The commercial sea scallop resources of Georges Bank and the Mid-Atlantic Bight were video surveyed in 2008 and 2009. A high-resolution digital still camera was added to the survey

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design in an effort to improve detection ability and to observe juvenile sea scallops in the wild. Distributions of juvenile and adult scallops were plotted across Georges Bank and the Mid-Atlantic Bight, and mean density and mean crowding were calculated for juveniles and adults in both areas and years. It was hypothesized that adding the high-resolution camera would improve the detection ability of small scallops, and that estimates of mean crowding would reveal differences in small-scale distribution of scallops that were undetectable with density estimates.

MATERIALS AND METHODS

Data Collection

In cooperation with the U.S. commercial sea scallop industry, the fishing grounds of Georges Bank and the Mid-Atlantic Bight were video surveyed between April 28, 2008, and June 30, 2008, and between April 27, 2009, and June 24, 2009. This video survey has been conducted annually since 2003, and used a centric systematic sampling design in which the first station location was chosen randomly and each subsequent station was placed on a 5.6 km^2 grid (Stokesbury et al. 2011) (Fig. 1). At each station, the survey pyramid was deployed to the seafloor from a commercial fishing vessel. As the vessel drifted, 4 video quadrat samples were collected, separated by approximately 25 m. Using a custom field application, technicians recorded station and quadrat number, date and time, latitude and longitude, depth, number of sea scallops observed, and other information regarding substrate and biota (Stokesbury 2002, Stokesbury et al. 2004).

The survey pyramid was equipped with 8 DeepSea Multi-SeaLites for illumination and 3 DeepSea MultiSeaCam-2060 live-feed underwater video cameras (DeepSea Power and Light, San Diego, CA) (Fig. 2). Two downward-facing video cameras were mounted 1.58 m and 0.70 m above the seafloor. The higher camera, or "large camera," provided a quadrat view area of 2.84 m^2 and easily detected scallops of commercially harvestable sizes. The lower camera, or "small camera," provided a smaller quadrat view area of 0.60 m^2, but was capable of detecting smaller scallops that were missed by the large camera. The third video camera was mounted parallel to the seafloor, providing a side profile for aid in species identification (Stokesbury 2002, Stokesbury et al. 2004).

In the laboratory, technicians used the "digitizer," a custom application, to digitize video footage and verify or update information collected in the field, including scallop counts. When identified, fully visible scallops that were completely within the image were measured from the umbo to the outer shell margin using ImagePro® image analysis software (Media Cybernetics, Inc., Bethesda, MD), with measurement calibrations for each camera (Stokesbury 2002, Stokesbury et al. 2004).

Although the small video camera was capable of detecting scallops as small as 30 mm in shell height (SH), sample sizes were low as a result of the small view area of each quadrat. To improve the detection ability of scallops less than 30 mm in SH and to identify other macroinvertebrates while sampling a larger area, an Ocean Imaging Systems DSC-10,000 high-resolution digital

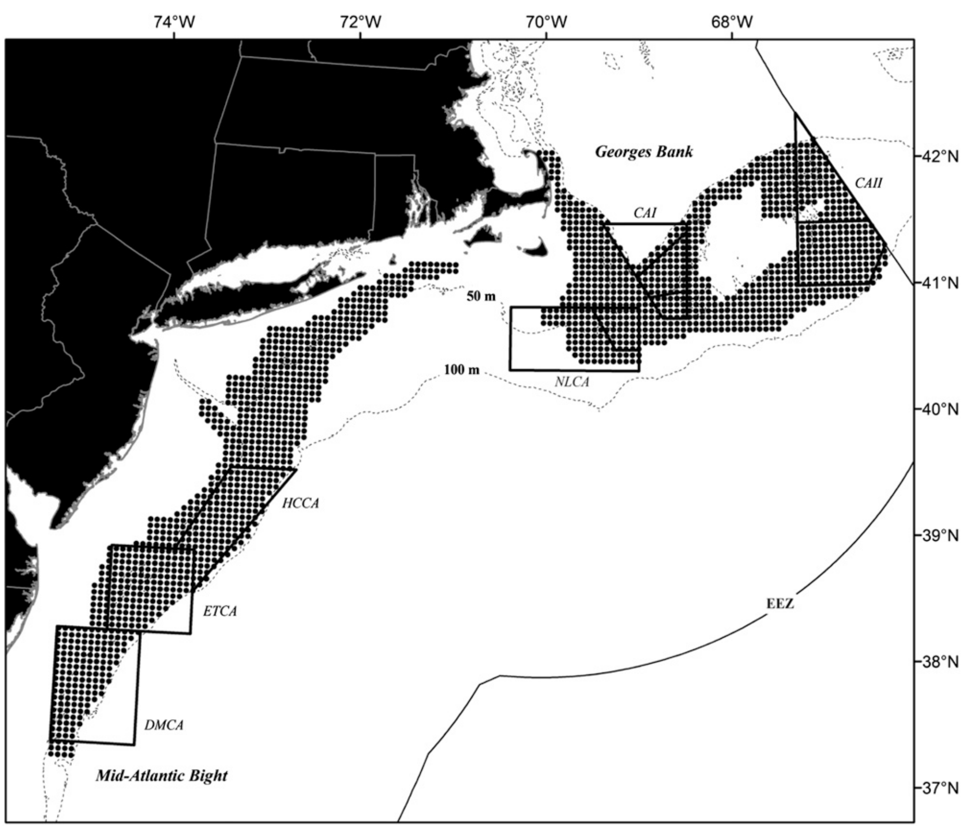

Figure 1. Video survey station locations on a 5.6 km grid. Georges Bank closed areas are the Nantucket Lightship Closed Area (NLCA), Closed Area I (CAI) and Closed Area II (CAII). Mid-Atlantic Bight closed areas are the Hudson Canyon Closed Area (HCCA), Elephant Trunk Closed Area (ETCA), and Delmarva Closed Area (DMCA).

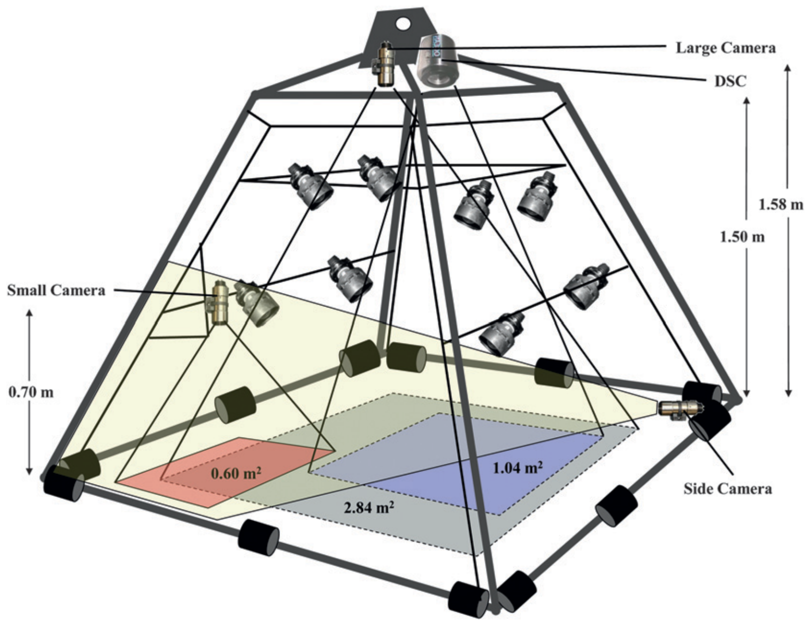

Figure 2. Sampling pyramid with 8 lights and 4 cameras: 2 downward-looking live-feed video cameras and a high-resolution digital still camera provide 2.84 m², 0.60 m², and 1.04 m² images, respectively, and a fourth video camera provides a view parallel to the seafloor.

still camera (DSC) was added to the survey pyramid, mounted 1.50 m above the seafloor (Ocean Imaging Systems, Falmouth, MA) (Fig. 2) (Stokesbury et al. 2010). Modifications were made to the unit, improving its durability and resulting in 89.1% coverage (7,641 quadrats captured of 8,572 total) of the 2008 survey and 94.6% coverage (10,879 quadrats captured out of 11,496 total) of the 2009 survey. To incorporate these data into the survey database, a calibration experiment was conducted to determine the view area and a measurement calibration.

The DSC was mounted to a calibration pyramid (full size, lightweight aluminum replica of the scallop survey pyramid) at a height of 1.50 m and deployed into a 4.53 m-deep test tank. The pyramid was lowered onto a grid of 3 cm squares, and images were captured. From these images the view area of the image was determined and the measurement calibration (millimeters per pixel) was calculated by dividing the horizontal and vertical dimensions of the image by the number of horizontal and vertical pixels.

Juvenile scallops were defined by SH frequency distributions measured with the DSC in both years. The SH that most effectively separated year classes and was consistent with life history characteristics was identified. Counts of juveniles and adults for each quadrat and station were determined using measurements and mapped with ArcGIS (Environmental Systems Research Institute, ESRI, Redlands, CA) to display broad-scale distributions across Georges Bank and the Mid-Atlantic Bight.

Data Analysis

Each camera's ability to detect scallops of varying sizes was compared. Measurements from Georges Bank and the Mid-Atlantic Bight were combined, but to ensure that the sample from each camera was comparable, only measurements from stations where images existed and were visible from all 4 quadrats for each camera were included. Density profiles were created by sorting the SH data for each camera into 10 mm bins and calculating the density of scallops per square meter for each bin (total number of scallops in the size bin divided by total area sampled).

Measurements were then used to determine counts of juvenile and adult scallops per quadrat, and densities of juveniles and adults were compared among cameras. Densities and SEs of juvenile and adult scallops were estimated using equations for a 2-stage sampling design, because each station contained 4 quadrats. The mean density of the sample was calculated as (Krebs 1999, Stokesbury et al. 2004)

$$\bar{\bar{x}} = \sum_{i=1}^{n} \left(\frac{\bar{x}_i}{n} \right) \tag{1}$$

where n is the number of stations and $\bar{x}_i$ is the mean of the 4 quadrats at station i. When the ratio of the sample area (n) to the survey area (N) is small, the SE of the 2-stage mean can be calculated as (Cochran 1977, Krebs 1999)

$$\mathrm{SE}\left(\bar{\bar{x}}\right) = \sqrt{\frac{1}{n}(s^2)} \tag{2}$$

where $s^2 = \sum\left(\bar{x} - \bar{\bar{x}}\right)^2/(n-1)$. This applies to these surveys, where thousands of square meters are sampled compared with tens of thousands of square kilometers in the survey area (Stokesbury et al. 2011).

Crowding is the number of organisms found within a given proximity of an individual of interest, and mean crowding is the average of crowding values for all individuals in the study area. In a population with defined parameters, mean crowding is calculated as

$$\dot{m} = m + \left(\frac{\sigma^2}{m} - 1 \right) \tag{3}$$

where m and σ^2 are the mean density and variance, respectively (Lloyd 1967).

Quadrat samples have been used to examine mean crowding values in scallop populations (MacDonald & Bajdik 1992). In a population with a patchy distribution, if the scale of patchiness is large compared with quadrat size, each quadrat can be used to represent the area surrounding an individual of interest (Lloyd

TABLE 1.

View area and measurement calibrations for the large camera, small camera, and DSC.

Camera	Vertical (mm)	Horizontal (mm)	View Area (m^2)	Vertical Pixels	Horizontal Pixels	Vertical (mm/pixel)	Horizontal (mm/pixel)
Large	1,430	1,986	2.84	480	640	2.979	3.103
Small	650	915	0.56	480	640	1.354	1.430
Digital	840	1240	1.04	2,592	3,872	0.324	0.320

1967). Therefore, the number of other scallops within a quadrat can represent the number of scallops that would be found in a circle (of the same area as the quadrat) centered on the individual of interest. For example, each scallop in a quadrat containing 3 scallops would be experiencing a crowding value of 2.

With quadrat samples, however, the spatial distribution of individuals is unknown, and calculating mean crowding with an estimation of error is necessary. Lloyd (1967) suggests that for species that exhibit a negative binomial distribution, a sample estimate for mean crowding is

$$\dot{x} = \bar{x} + \frac{\bar{x}}{\hat{k}} \tag{4}$$

where $\bar{x}$ is the sample mean and $\hat{k}$ is the maximum likelihood estimate of the negative binomial parameter k (Krebs 1999). The standard error for $\dot{x}$ is (Lloyd 1967)

$$\mathrm{SE}(\dot{x}) \approx \frac{\bar{x}}{\hat{k}^2}\sqrt{\left[\widehat{var(\hat{k})} + \frac{\hat{k}(\bar{x}+\hat{k})(1+\hat{k})^2}{qx}\right]} \tag{5}$$

where q is the number of quadrats and $\widehat{var(\hat{k})}$ is the sampling variance for $\hat{k}$ (Bliss & Fisher 1953).

Crowding can detect differences in distribution that density estimates cannot. It varies from density by assessing the number of organisms per individual rather than the number of organisms per unit area (Lloyd 1967). Because it is a mean averaged over individuals rather than quadrats, it is not affected by empty quadrats. Using Eq. (4) and (5), the mean crowding and associated errors were estimated for juvenile and adult scallops. To display the distribution of crowding values among the members of the populations, crowding profiles were created by plotting the percentage of the population experiencing a given crowding value (Orensanz et al. 1998).

RESULTS

The view area of each DSC image was 1.04 m^2, with 1.24-m horizontal and 0.84 m vertical edges (Table 1). These dimensions, along with the number of horizontal (h) and vertical (v) pixels (3,872 h × 2592 v) were used to calculate measurement calibrations in millimeters per pixel. Each horizontal and vertical pixel was equal to 0.320 mm and 0.324 mm, respectively (Table 1).

Juvenile scallops were defined as any scallop less than 70 mm in SH. An SH of 70 mm most effectively separated year classes

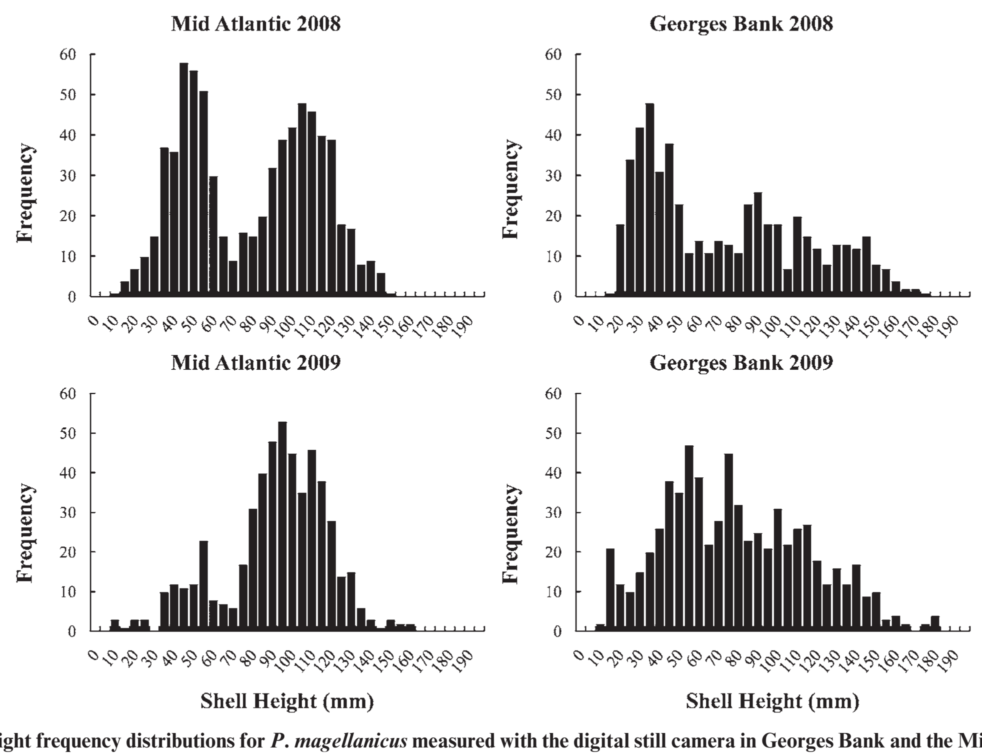

Figure 3. Shell height frequency distributions for *P. magellanicus* measured with the digital still camera in Georges Bank and the Mid-Atlantic Bight in 2008 and 2009.

in all 4 DSC data sets (Fig. 3). Seventy-millimeter scallops are just becoming sexually mature and are at the peak of mobility and hydrodynamic efficiency (Posgay 1982, Dadswell & Weihs 1990, National Marine Fisheries Service Northeast Fisheries Science Center 2010).

To compare cameras, images from 3,236 stations were examined, and 6,172 sea scallops were observed with the large camera, 1,621 scallops with the small camera, and 2,936 scallops with the DSC. Of the observed scallops 75%, 68%, and 79% were measured in the large camera, small camera, and DSC, respectively, as only fully visible scallops that were entirely in the image were measureable. The DSC had a larger view area and better clarity, resulting in a sample size of measured scallops more than twice that of the small camera.

The DSC detected smaller scallops than both the small and large video cameras. In the small and large camera images, the lower size detection limits were between 20–30 mm and 30–40 mm, respectively. Using DSC images, scallops as small as 10 mm were detected and measured (Fig. 4). Density profiles demonstrate that the smallest scallops observed in DSC images were as much as 20 mm below the detectable range of the large camera and 10 mm below the detectable range of the small camera (Fig. 5). For scallops less than 65 mm in SH, densities were higher in DSC images, suggesting that scallops were detected in DSC images that may have been missed in the large and small camera images, even within detectable size ranges. Adult densities were similar between all 3 cameras, whereas juvenile density estimated with the DSC was greater than when estimated with the with the large and small video cameras (Fig. 6).

In the Mid-Atlantic Bight in 2008, juveniles accounted for 44% of all measured scallops (320 juveniles and 405 adults). Densities of juveniles and adults were 0.085 (SE = 0.011) and 0.108 (SE = 0.015) scallops/m^2, respectively (Table 2). Areas of high juvenile density were further inshore and in shallower water than areas of high adult density (Fig. 7). In the Mid-Atlantic Bight in 2009 very few juveniles were observed, accounting for only 18% of all measured scallops (93 juveniles and 433 adults). Densities of juveniles and adults were 0.023 (SE = 0.004) and 0.112 (SE = 0.009) scallops/m^2, respectively (Table 2). We observed a large aggregation of adult scallops in the northeast portion of the Elephant Trunk Closed Area in 2008 (Fig. 7). By the time of our survey in 2009, however, the abundance of scallops in this area had decreased dramatically (Fig. 8).

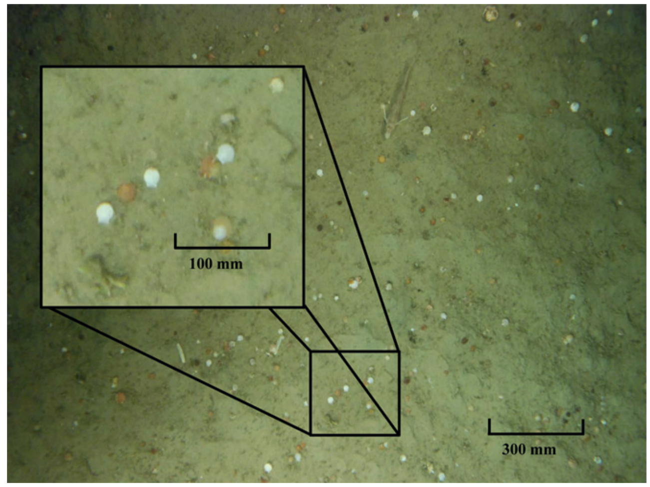

Figure 4. Digital still camera quadrat image containing 213 young-of-the-year *P. magellanicus* in the Elephant Trunk in 2007. These small scallops were not detected in corresponding large-camera images.

On Georges Bank in 2008, 51% of all measured scallops were juveniles (271 juveniles and 262 adults). Densities of juveniles and adults were 0.089 (SE = 0.019) and 0.084 (SE = 0.010) scallops/m^2, respectively (Table 2). Dense juvenile aggregations were found in three distinct locations: west of Closed Area I, in the northern corner of Closed Area II, and in

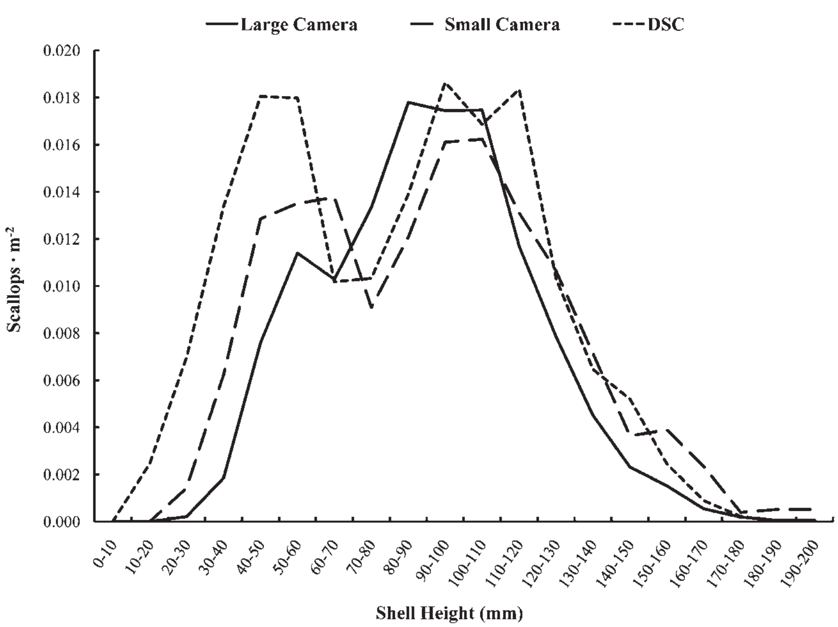

Figure 5. *P. magellanicus* density profiles by 10 mm shell height bin for the large camera, small camera, and digital still camera (DSC). Measurements were selected from all Georges Bank and Mid-Atlantic Bight stations in 2008 and 2009 where all 4 quadrat images were available from each camera.

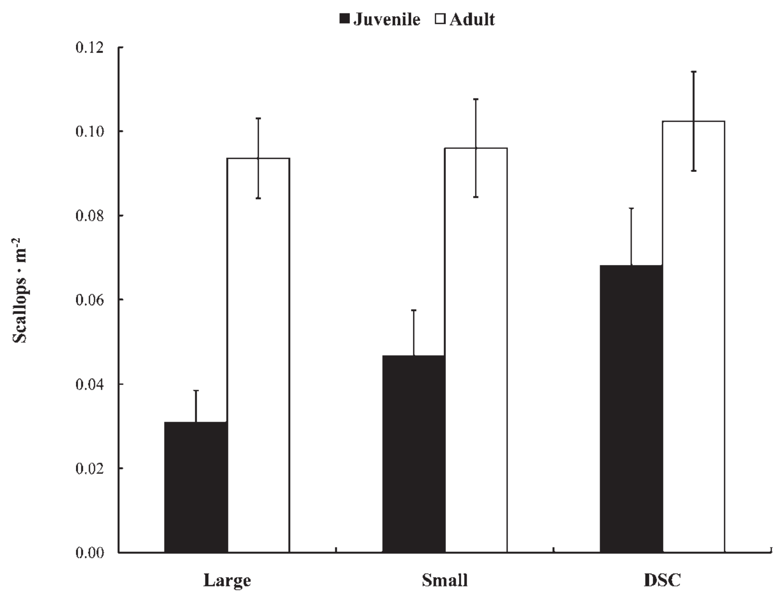

Figure 6. Densities of juvenile and adult *P. magellanicus* estimated with the large video camera, small video camera, and digital still camera (DSC) for Georges Bank and the Mid-Atlantic Bight in 2008 and 2009, combined. Error bars are 95% confidence intervals.

the southeast corner of Closed Area II (Fig. 9). Juvenile abundance and distribution on Georges Bank in 2009 was similar to 2008. Juveniles accounted for 43% of all measured scallops (287 juveniles and 385 adults) and were located in the same three areas observed in 2008 (Fig. 10). Densities of juveniles and adults were 0.079 (SE = 0.018) and 0.102 (SE = 0.012) scallops/m^2, respectively (Table 2).

Examining levels of scallop crowding identified differences in distribution that were undetectable in density estimates (Fig. 11). Adults were slightly more crowded on Georges Bank than in the Mid-Atlantic Bight. During both years, the average percentage of the adult population experiencing crowding values of two or more was 31% and 21% in Georges Bank and the Mid-Atlantic Bight, respectively (Figs. 12 and 13). Crowding trends of juvenile scallops were different on Georges Bank than in the Mid-Atlantic Bight. In the Mid-Atlantic Bight in 2008 and 2009, juveniles and adults both displayed similar, low mean crowding values. On Georges Bank, mean crowding values of juveniles were 2.5–4.0 times higher than adults, and 3.0–7.5 times higher than Mid-Atlantic Bight juveniles and adults (Table 2, Fig. 11). This trend is also apparent in crowding profiles. In the Mid-Atlantic Bight, crowding profiles were similar for juveniles and adults in both years. In 2008, only 27% of juveniles and 28% of adults experienced crowding values of two or more. In 2009, these values decreased to 5% for juveniles and 13% for adults (Fig. 12). On Georges Bank, juvenile scallops experienced higher crowding values than adults. In 2008, 58% of juvenile scallops experienced crowding values of two or more, whereas only 24% of adults were experiencing crowding values this high. In 2009 these values were 52% for juveniles and 37% for adults (Fig. 13).

TABLE 2.

Number of stations (n), mean density per square meter ($\bar{x}$), SE, negative binomial parameter k, mean crowding ($\dot{x}$), and estimated SE for juvenile (J) and adult (A) *P. magellanicus* in the Mid Atlantic (MA) and on Georges Bank (GB) in 2008 and 2009.

Area	Year	J/A	n	$\bar{x}$ (/m^2)	SE ($\bar{x}$)	k	$\dot{x}$	SE ($\dot{x}$)
MA	2008	J	875	0.085	0.011	0.029	1.13	0.165
MA	2008	A	875	0.108	0.015	0.118	1.05	0.134
MA	2009	J	859	0.023	0.004	0.027	0.41	0.126
MA	2009	A	859	0.112	0.009	0.102	0.53	0.070
GB	2008	J	709	0.089	0.019	0.084	3.31	0.604
GB	2008	A	709	0.084	0.010	0.119	0.84	0.113
GB	2009	J	870	0.079	0.018	0.067	3.00	0.518
GB	2009	A	870	0.102	0.012	0.290	1.17	0.154

DISCUSSION

Incorporating a high-resolution still image camera into the survey design improved our ability to detect and observe juvenile sea scallops in the wild. The lower size limit of detection for the DSC was 10 mm below that of the small video camera and 20 mm below that of the large video camera. In addition, more scallops per unit area were detected using DSC images, especially within the lower end of the selectivity range of both video cameras. Using data collected with the DSC allowed us to quantify incoming year class strength more accurately and at a younger age.

Significant recruitment events have occurred recently in the Mid-Atlantic Bight, leading to the implementation of the Hudson Canyon, Elephant Trunk, and Delmarva Closed Areas to protect the high concentrations of juvenile scallops (Hart 2003, Stokesbury et al. 2004, Hart & Rago 2006). In the case of the Elephant Trunk Closed Area, an enormous year class of sea scallops was observed in 2003, but a mass mortality of approximately 10 billion scallops occurred between 2003 and 2004, likely a result of incidental fishing mortality (Stokesbury et al. 2011). This may have been avoided by a timely management response and earlier survey detection. Adding high-resolution still cameras to surveys could help detect recruitment events earlier, allowing more time for management action to protect the

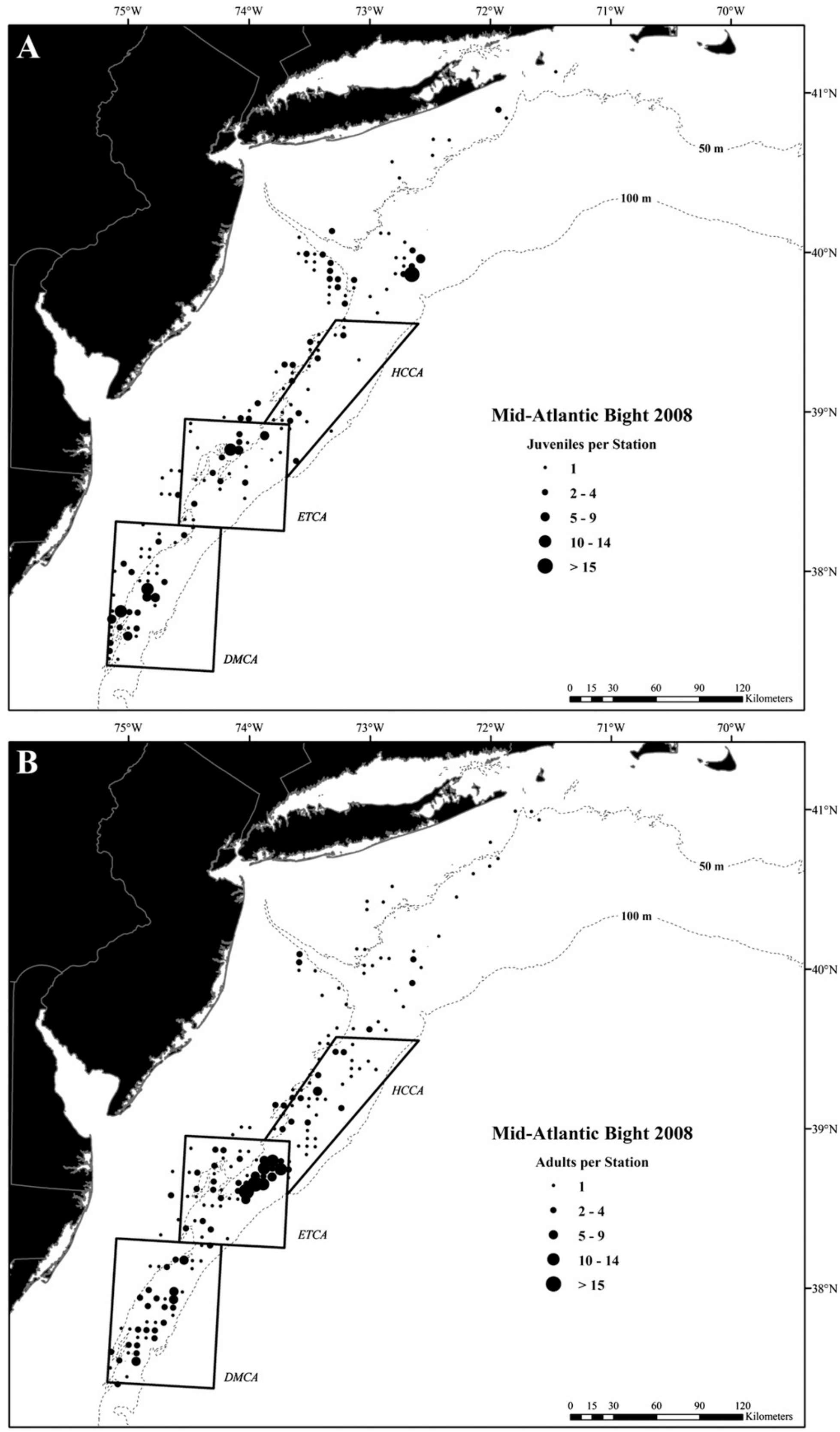

Figure 7. (A, B) Juvenile (A) and adult (B) *P. magellanicus* in the Mid-Atlantic Bight in 2008. The size of each dot represents the number of scallops observed at each station. The 3 boxes are the Delmarva (DMCA), Elephant Trunk (ETCA), and Hudson Canyon (HCCA) closed areas.

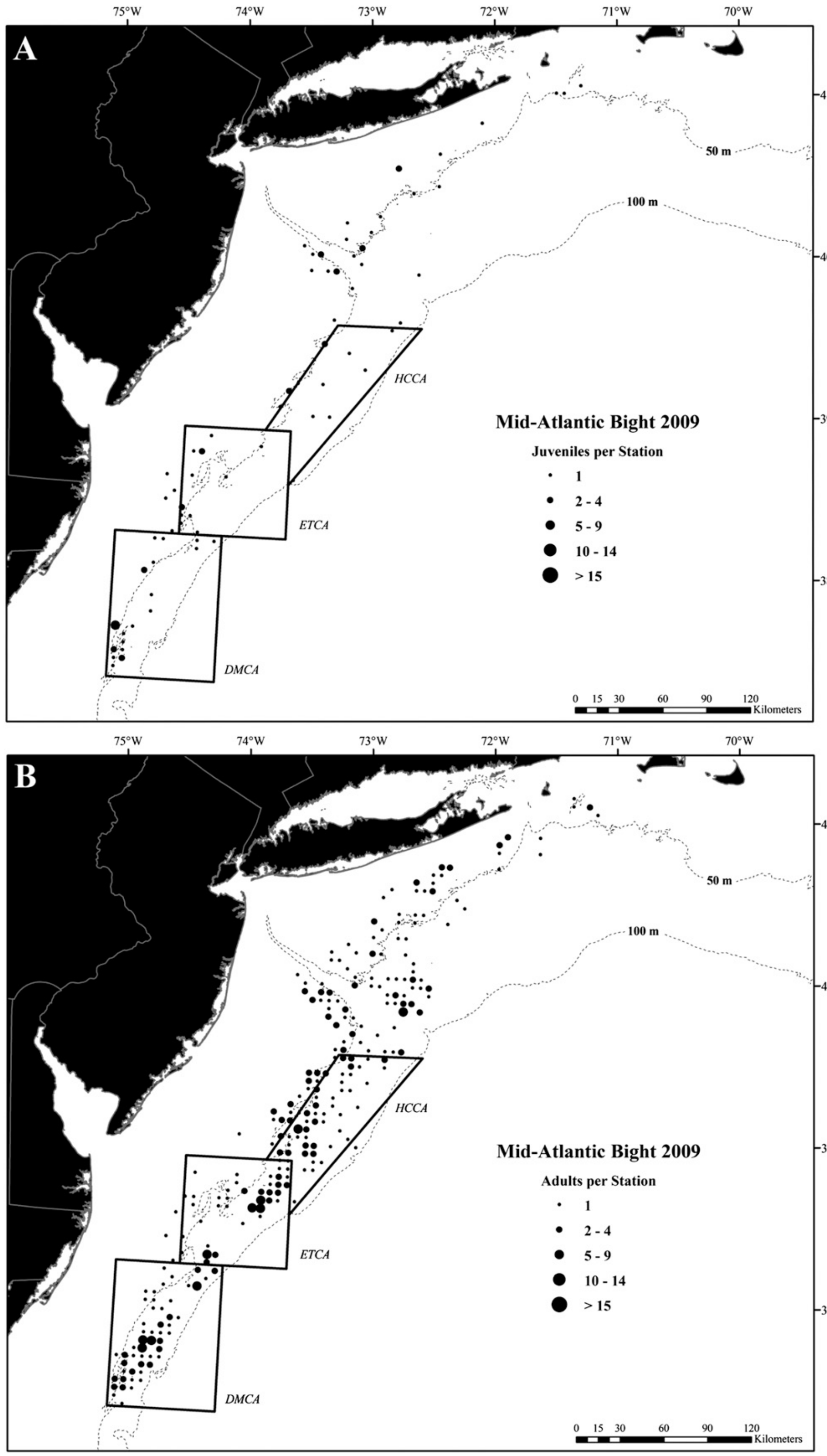

Figure 8. (A, B) Juvenile (A) and adult (B) *P. magellanicus* in the Mid-Atlantic Bight in 2009. The size of each dot represents the number of scallops observed at each station. The 3 boxes are the Delmarva (DMCA), Elephant Trunk (ETCA), and Hudson Canyon (HCCA) closed areas.

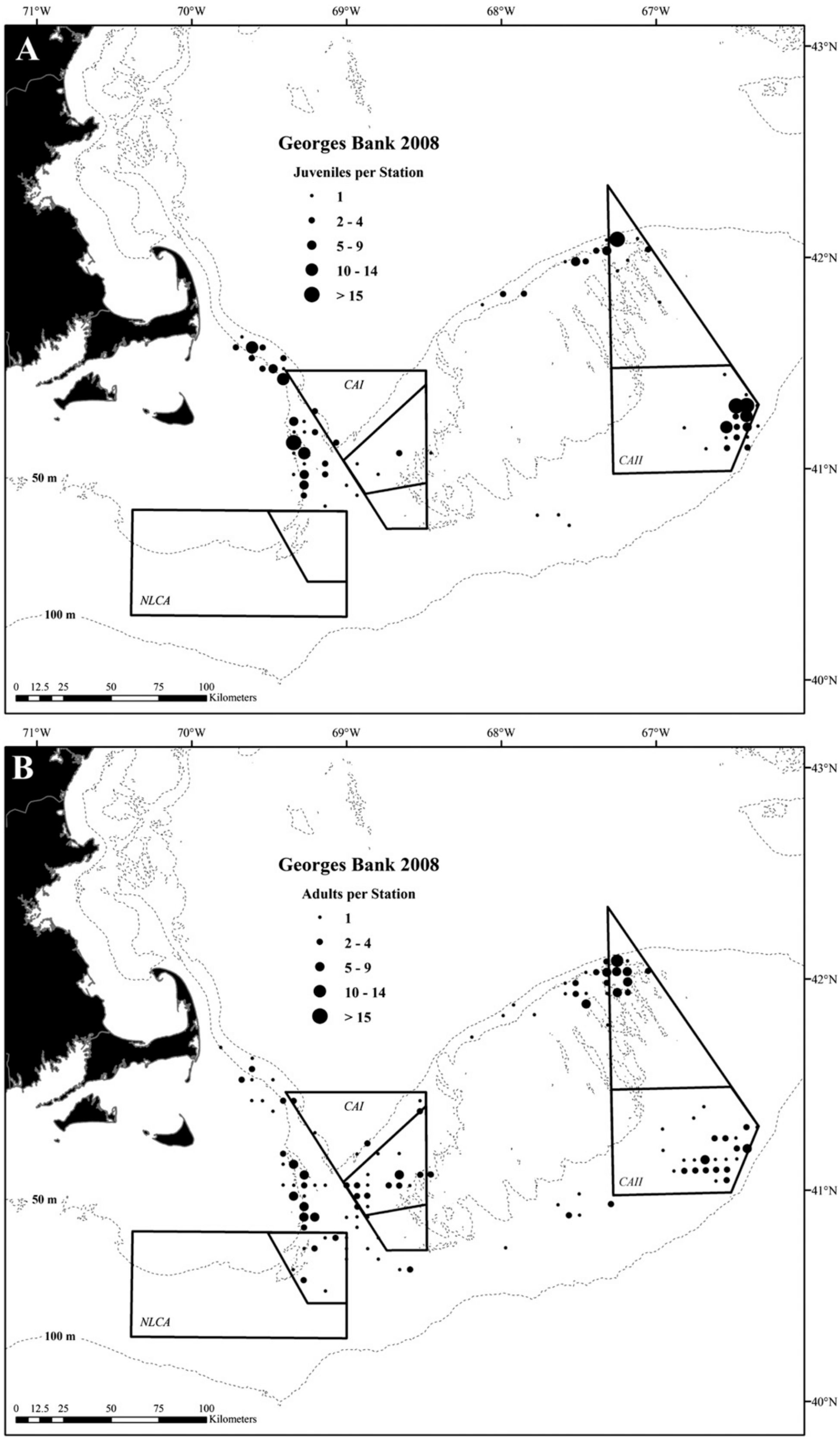

Figure 9. (A, B) Juvenile (A) and adult (B) *P. magellanicus* on Georges Bank in 2008. The size of the dot represents the number of scallops observed at each station. The 3 boxes are the Nantucket Lightship Closed Area (NLCA), Closed Area I (CAI), and Closed Area II (CAII).

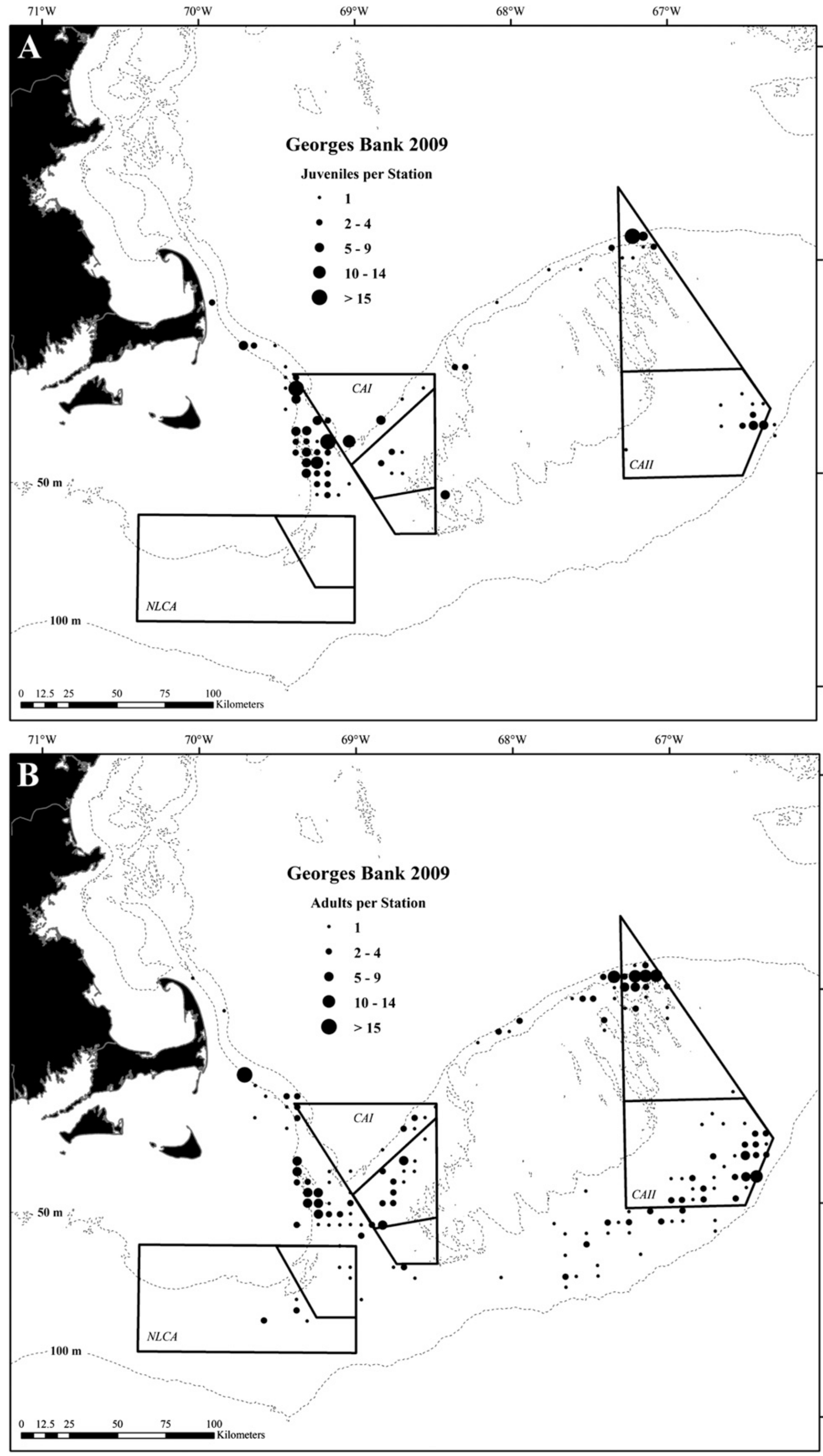

Figure 10. (A, B) Juvenile (A) and adult (B) *P. magellanicus* on Georges Bank in 2009. The size of the dot represents the number of scallops observed at each station. The 3 boxes are the Nantucket Lightship Closed Area (NLCA), Closed Area I (CAI), and Closed Area II (CAII).

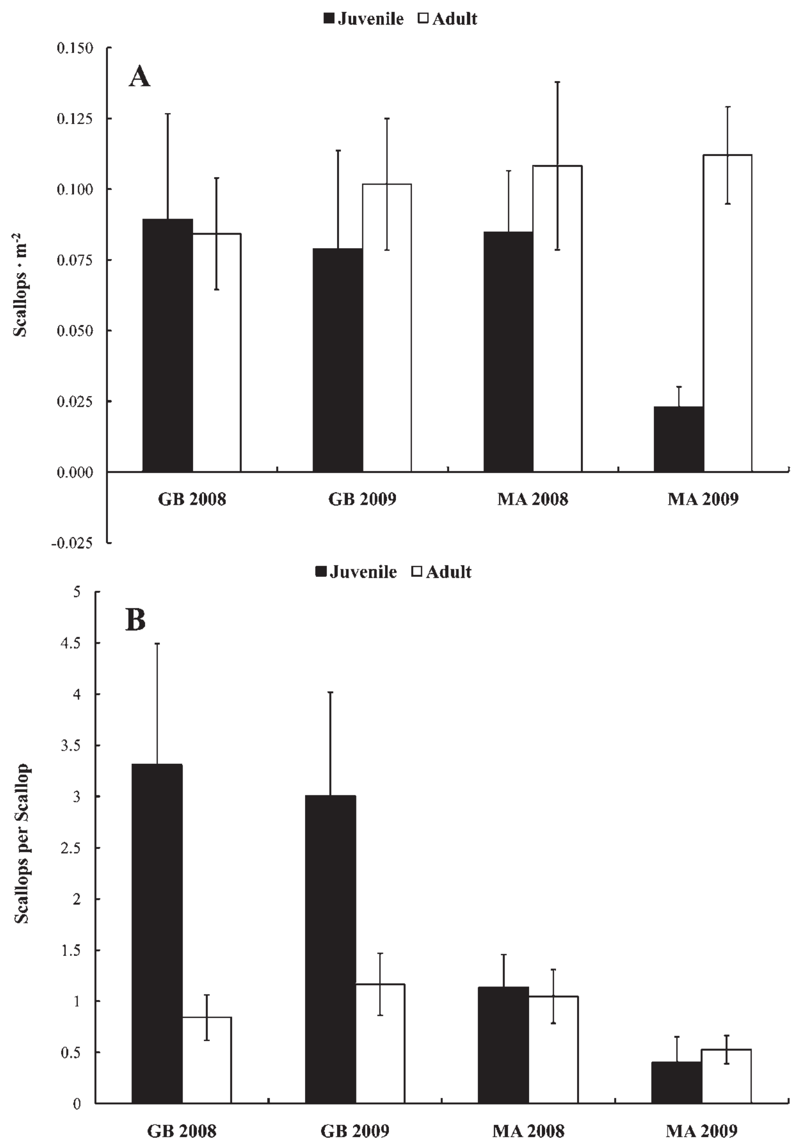

Figure 11. (A, B) Mean density (A) and mean crowding (B) for Georges Bank (GB) and Mid-Atlantic Bight (MA) juvenile and adult *P. magellanicus* in 2008 and 2009. Error bars are 95% confidence intervals.

resource. In this example, scallops as young as 1 y were detected, which will not recruit into the fishery until they reach 4 y old.

The DSC also provides SH measurements of greater precision. Each pixel in the large and small cameras is equal to 3.0 mm and 1.4 mm, respectively. With the DSC, this improved to 0.3 mm/pixel. Measurement error can impact growth, mortality, and biomass estimates in stock assessments. Furthermore, modes in SH frequency distributions are obscured by imprecision in size data, making it difficult to identify year classes or recruitment events (Jacobson et al. 2010). This trend is apparent when comparing SH frequency distributions between the DSC and the large and small cameras; year class modes were more prominent in DSC data.

Juveniles accounted for roughly half of all scallops on Georges Bank in both years, and in the Mid-Atlantic Bight in 2008, suggesting steady recruitment. In the Mid-Atlantic Bight in 2009, however, very few juvenile scallops were observed. Survey dates were similar in 2008 and 2009, so it is unlikely that this difference was the result of the size selectivity of the camera. A strong year class was present in the 40–60 mm SH range in the Mid-Atlantic Bight in 2008. By 2009, these animals had grown to sizes larger than 70 mm in SH and were no longer considered juveniles. The incoming 40–60 mm year class in 2009 was weak and did not sufficiently replace the previous year class, resulting in the limited number of juveniles. Tracking the size of incoming year classes can help to determine expectations of future stock biomass.

We observed a dramatic decrease in abundance of adult sea scallops in the northeast portion of the Elephant Trunk Closed Area. This was likely a result of high levels of fishing effort in this area between the 2008 and 2009 surveys. In 2008 and 2009 combined, all full-time limited-access commercial scallop vessels (approximately 350 vessels) were allocated 7 trips of 8,165 kg each (NEFMC 2007).

Adults were slightly more crowded on Georges Bank than in the Mid-Atlantic Bight, which can have implications on fertilization success. Because scallops are broadcast spawners, microscale distribution of spawning adults may be a critical

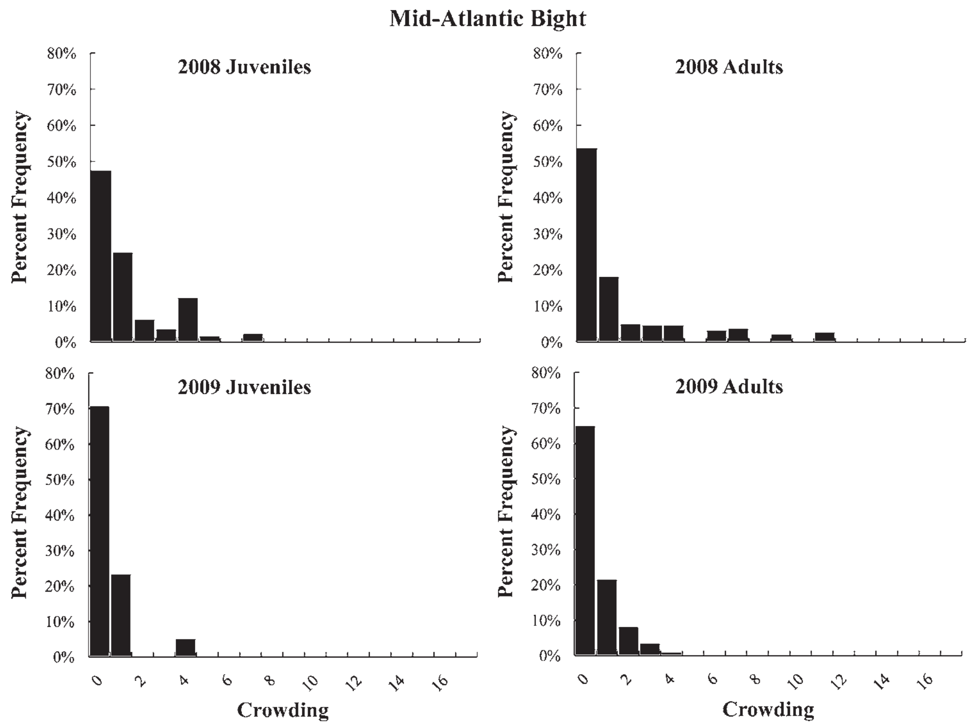

Figure 12. Crowding profiles for Mid-Atlantic Bight juvenile and adult *P. magellanicus* in 2008 and 2009.

factor in successful fertilization (Stokesbury & Himmelman 1993). Pennington (1985) demonstrated the effects of increasing distance on fertilization success in the broadcast-spawning sea urchin *Strongylocentrotus droebachiensis*. When spawning male and female sea urchins were within 20 cm of each other, fertilization success was between 60% and 95%. However, at distances beyond 20 cm, degree of fertilization success dropped rapidly to levels less than 15%. Claereboudt (1999) suggests that fertilization success is

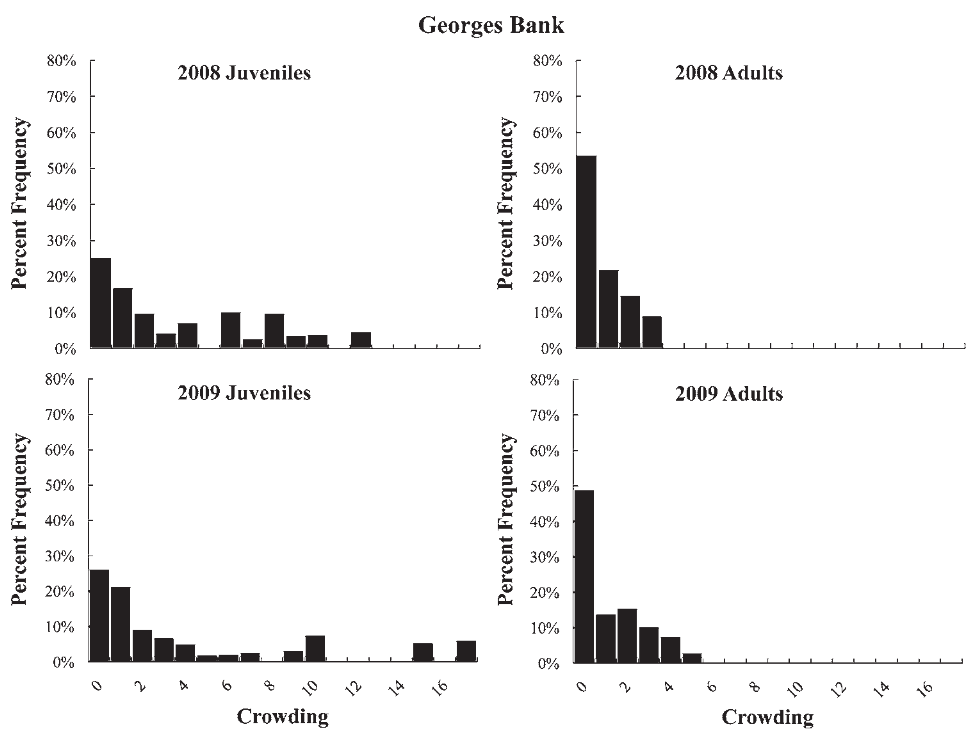

Figure 13. Crowding profiles for Georges Bank juvenile and adult *P. magellanicus* in 2008 and 2009.

low in populations with uniform and randomly distributed individuals, and increases rapidly as their distribution increases from random to aggregated. Based on higher crowding levels, populations of scallops on Georges Bank may have a higher reproductive potential than those in the Mid-Atlantic Bight.

Juvenile scallops on Georges Bank were significantly more crowded than adults. Scallops are aggregated at settlement (Brand 2006) and become motile around 30 mm in SH (Dadswell & Weihs 1990), indicating dispersal with age. Scallop dredging may also cause increased dispersal in adult scallops by targeting and removing older, larger individuals or by disturbing small-scale patches through displacement of individuals that are not captured (Brand 2006, Langton & Robinson 1990, Stokesbury & Himmelman 1993).

Mean crowding differed significantly between juvenile scallops on Georges Bank and in the Mid-Atlantic Bight. Georges Bank juveniles displayed mean crowding values that were 3.0 times and 7.5 times higher than Mid-Atlantic Bight juveniles in 2008 and 2009, respectively. Scallop dispersal may be higher in areas of high sea star density, because sea star encounters trigger an escape response in scallops (Barbeau & Scheibling 1994, Marino et al. 2007, Wong et al. 2006). Although sea star densities were high on both Georges Bank and in the Mid-Atlantic Bight, the location of aggregations overlapped with the distribution of scallops more in the Mid-Atlantic Bight, suggesting increased encounters and higher dispersal rates (Stokesbury et al. 2008).

Swimming frequencies are higher for scallops found on sand substrate (Bourgeois et al. 2006, Stokesbury & Himmelman 1996). For newly settled scallops, dispersal may be increased on sand substrate as a result of limited byssal thread attachment sites (Caddy 1972). Furthermore, sand substrate may become unstable with current and may bury scallops or cause sand particles to be deposited into the gape of the scallop, resulting in unsuitable conditions (Gould 1971, Stokesbury & Himmelman 1996, Stokesbury et al. 2007). After settlement on unsuitable substrata, juveniles can move, possibly in search of more favorable microhabitats (Arsenault et al. 2000, Brand 2006).

Sediment and substrate characteristics vary greatly between Georges Bank and the Mid-Atlantic Bight. Georges Bank substrate is heterogeneous, with abundant gravel substratum, whereas sand is the overwhelmingly predominant substrate type in the Mid-Atlantic Bight, with scarce patches of granule/pebble (Stokesbury et al. 2008, Harris & Stokesbury 2010). Based on previous studies, this suggests that rates of juvenile scallop movement and dispersal in the Mid-Atlantic Bight are comparatively high.

The aggregation of juvenile scallops in the southeast corner of Closed Area II occurs on sand substrate yet maintains a crowded distribution. In 2008, bryozoans and hydrozoans were found in very high densities in this area, compared with the Mid-Atlantic Bight where they were rarely observed (Stokesbury et al. 2008). Settling scallops display a strong association with filamentous flora and fauna such as bryozoans and hydrozoans (Caddy 1972, Larsen & Lee 1978, Brand et al. 1980, Minchin 1992, Harvey et al. 1993, Henry & Kenchington 2004). In the absence of granule/pebble substrate, the presence of these organisms in high density may act as a substitute attachment substrate. Juvenile scallops are gregarious at settlement (Brand 2006), and the availability of suitable substrate for byssal attachment on Georges Bank may allow these crowded areas to persist.

Incorporating high-resolution still cameras into optical surveys represents an important development in the advancement of survey techniques. They can improve the ability to detect juvenile scallops, resulting in earlier survey detection of significant recruitment events and allowing more time for managers to protect the resource. Furthermore, they can help to improve the accuracy and precision of survey data provided to managers for stock assessments. Lastly, they provide the opportunity to observe juvenile sea scallops in the wild, which was previously difficult. This can help to further our understanding of juvenile sea scallop ecology. We suggest that the distribution and crowding levels displayed by juvenile sea scallops is strongly related to substrate type, presence of filamentous flora and fauna, and predator abundance.

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