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Final Report for the time period 6/1/02 to 8/30/03

Sea Scallop Research

Hudson Canyon TAC

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Project Title: **Examination of the sea scallop, *Placopecten magellanicus*, recruitment in closed and open areas of Georges Bank.**

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1. Summary

Objectives: This research project examined sea scallop recruitment in the Nantucket Lightship Area and the open area of the Great South Channel. We 1) examined scallop abundance, size and spatial distribution and the associated macroinvertebrate benthic community and substrate in unsurveyed areas of the Great South Channel; 2) continued the video survey time series of the Nantucket Lightship Area; 3) examined growth and migration of scallops in the Great South Channel.

Methodology: There were two components to this research project. We conducted two video surveys, one in the Nantucket Lightship Area and the second in the adjacent open portion of the Great South Channel. The sampling procedure for these surveys was a multistage design with stations separated by 0.85 nautical miles, similar to the 1999/2000/2001 SMAST survey. These surveys produced a series of maps of the sea floor in open and closed areas of Georges Bank detailing the distribution of substrate, depth, live scallops, dead scallops, and macroinvertebrates (sponges, starfish, filamentous fauna). Secondly, we conducted a scallop tagging cruise in the open portion of the Great South Channel north of the Nantucket Lightship area. The tagging procedure was similar to the 2001 SMAST tagging study. Presently 1218 of the 18,186 tagged scallops have been returned from the 2002 study.

Rationale: This research project addresses the critical question "Where do the recruits for the Nantucket Lightship Area come from?" Our previous research indicates that although few small sea scallops are observed in the Nantucket lightship Area (NLSA) there is an increase in scallop abundance in the following year. Small scallops have been observed in the Great South Channel to the north of the NLSA. Could these small scallops be moving into the NLSA? To answer this question we conducted the research described above which provided information on scallop site-specific size and spatial distribution, growth and movement. Further, in collecting these data we mapped the habitat of presently unsurveyed portion of the Great South Channel. This research has direct implications for rotational fisheries management under consideration by the New England Fishery Management Council, on an appropriate spatial scale (km). We have presented the results of this research to the New England Fishery Management Council Planning and Development teams (Scallop and Habitat), the Oversight Committee and several scientific meetings. We have been invited to present this research to the upcoming NMFS 39th SARC.

Requested support: Each vessel participating in this research collected 17,900 lbs of scallops from the Hudson Canyon 1% TAC research set-aside in 1 harvest trip (14 days) exempt from DAS. In total $60,237 will be paid to SMAST to support the scientific research, primarily analysis. The harvest cruises also supported the 3 research cruises. Although we had to estimate the price as $4.5 per lb of scallop meat (as described in the Federal Register Vol. 66, No. 103, 29 May 2001), the actual price was much lower. To compensate for this difference in price several of the captain/owners gave up a portion of their share to pay for the research and crew.

2. Description of the issue/problem

Project goals and objectives: This research examined sea scallop recruitment, growth and movement in the Nantucket Lightship Area and the open area of the Great South Channel. We proposed to:

1) Examine scallop abundance, size and spatial distribution on several scales (cm, m, km) associated macroinvertebrate benthic community and substrate in unsurveyed areas of the Great South Channel.
2) Continue the video survey time series of the Nantucket Lightship Area.
3) Examine growth and migration of scallops in the Great South Channel.

Georges Bank (between 41 ° to 42° N, 66 ° to 69° W) contains the world's largest single natural scallop resource. In 1994 three large areas of the United States portion of Georges Bank were closed to fishing in an effort to protect depleted groundfish stocks (Figure 1). Today, these closed areas contain about 80% of the Georges Bank sea scallop resource (Murawski et al. 2000).

Estimates of sea scallop abundance on Georges Bank are made using dredge surveys (Murawski et al. 2000). These surveys estimate the relative abundance of scallops. Dredge surveys take the area swept by the gear and expand the catches by the proportion of the area surveyed (Hilborn and Walters 1992). However, absolute abundance estimates of scallops (the actual number of scallops covering an area of the sea floor) are required for analysis of harvest strategies and to calculate population dynamic statistics (Krebs 1989). To determine absolute estimates from dredge survey data, the proportion of scallops caught by the sampling dredge to the scallops in the area swept must be known (Hilborn and Walters 1992). Both the selectivity and efficiency of the sampling dredge determine this proportion. Selectivity and efficiency are influenced by physical variables such as heterogeneous substrate, biological variables such as the species ability to avoid capture, and experimental design such as the duration of the sampling tow and construction of the sampling dredge (Beverton and Holt 1957; Ricker 1975; Krebs 1989). Usually this proportion is inadequately estimated and the usefulness of these data is therefore limited.

The 1998 joint survey by Center for Marine Science and Technology (CMAST), National Marine Fisheries Service (NMFS Woods Hole) and Virginia Institute of Marine Science (VIMS) in association with the fishing industry suggested that high densities of mature scallops now occur in Closed Area II. However, there is a great deal of concern that the depleted fish stocks have not recovered sufficiently and that critical fish nursery habitat may be disturbed by scallop fishing. Further, the 1998 Closed Area II survey used commercial fishing gear to estimate relative density and spatial distributions of harvestable scallops (>75 mm). These relative densities were converted to absolute densities by applying trawl efficiency estimates calculated from depletion studies. Scallop trawl efficiency estimates vary greatly (from 15% to >40%) and this has a profound effect on the accuracy and precision of the absolute scallop density estimate. Correction factors and several models were created to improve these estimates of efficiency.

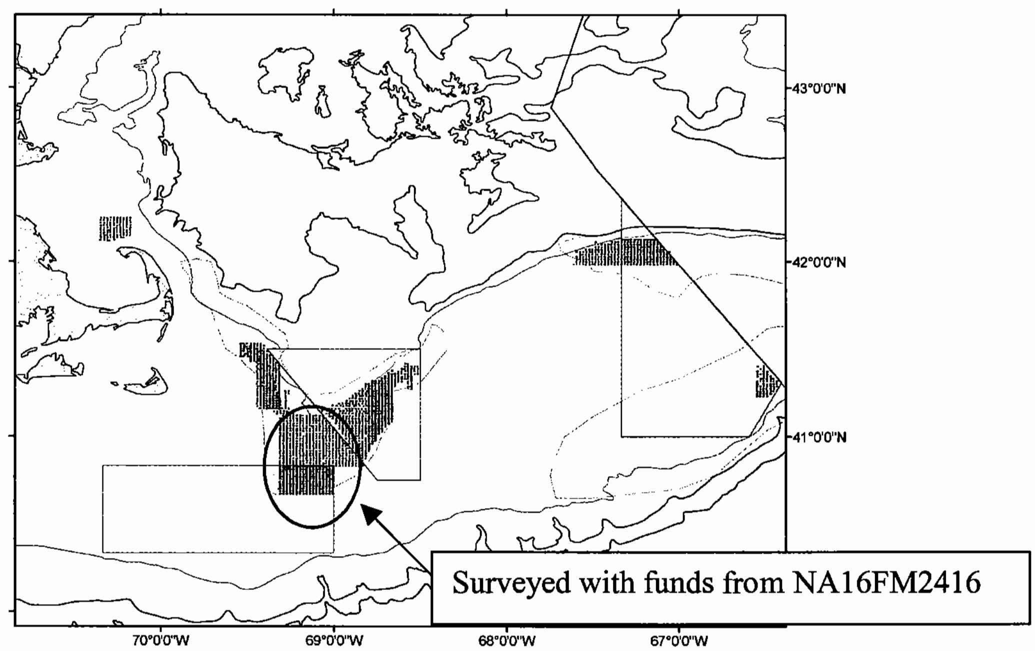
These models have not been verified by field observations. Further, substrate type, the small-scale distribution of scallops and their behavior have strong effects on these models and the resulting estimates of efficiency.

In 1999 we created a video sampling system to provide an independent estimate of absolute sea scallop density as well as information on the sea floor and marine benthic community (Stokesbury 2002); Figure 2). Since 1999 the University of Massachusetts Dartmouth School for Marine Science and Technology (SMAST), members of the commercial sea scallop industry, the Massachusetts Department of Marine Fisheries, with additional support from the sea scallop TAC-set-aside program (NOAA grants NA16FM1031, NA06FM1001 and NA16FM2416, this study) have completed 27 video and tagging cruises on Georges Bank, resulting in 700 hours of video footage and 17,000 digital images covering 7500 km^2 of sea floor at a 1.5 km resolution (Figure 1). This database provides assessments of scallop and other macroinvertebrate densities, and sediment and habitat distributions in closed and open areas of Georges Bank from 1999 onward.

The video survey technique has several advantages over dredge surveys. First, as sea scallops were readily identifiable on the sea floor the quadrats provide a direct measure of absolute abundance rather than a semiquatitative measure such as those provided by dredge samples (Caddy 1989). Further, the images are saved so they can be reexamined in the laboratory. Second, estimates of scallop density were precise with coefficients of variation estimates <11%. Coefficients of variation for many shellfish surveys roughly average about 40% (Krebs 1989). (Thouzeau et al. 1991a) video-monitored sled-dredge survey had coefficients of variation ranging from 19% to 34% for scallops >75 mm in the Canadian portion of Georges Bank. Coefficients of variation estimated from the National Marine Fisheries Service dredge surveys for the Nantucket Lightship Area, Closed Area 1 and the Northern portion of Closed Area II stratified to the same survey area as our video survey ranged from 21% to 43% (SAW 2001). Third, the video survey is a fast sampling procedure, 4 to 5 stations per hour in fair weather. Counts of scallops were entered into a laptop computer during the sampling of each station and preliminary estimates of total density were available directly after the survey was completed. Fourth, the video survey is a non-intrusive sampling procedure, no animals are collected and the sea floor is not disturbed, therefore no permits were required.

An example of the importance of the video surveys and the strength of coupling them to the NMFS scallop survey is the estimation of size distribution and density of scallops in the NLSA. The NMFS completed 20 stations in the NLSA during the summer of 2000 (Fishermen's Sea Scallop Report, 6 July – 18 August 2000, NMFS). Of these 20 tows, 5 were non-random, which means they had been selected by a researcher and placed in areas of high scallop concentrations, as the 15 randomly selected stations did not sample those areas. Of the 15 random tows only 4 collected more than 30 scallops. However, the placement of the non-random stations violates the sample design assumption of the survey and requires a special set of statistics. Further one of the 5 non-random tows contained an extremely high count of small scallops (Station 0265). This station was outside the major aggregation of scallops in the NLSA and also outside the SMAST video survey. If it is excluded the SMAST and NMFS size frequencies match closely. Only 7 tows are within the area surveyed by SMAST, which contains 90% of the scallops in the NLSA. To estimate the density within this aggregation using only the NMFS survey requires the use a very small sample size (7 tows) with catches ranging from 3 to 3824 scallops per tow and 3 of the tows were selected non-randomly. This is one of the reasons the SMAST video survey was included in the 32nd SAW (page 74) as it provides a precise estimate of size and abundance for the area it surveys. These difficulties are well documented in the 32nd SAW, which recommends examination of the current survey strata and comparisons of the video survey to the NMFS survey.

Figure 1. Georges Bank with the closed areas outlined. A) The historic scallop fishing grounds shaded in pink, the closed areas are outlined and shaded in green. The previous SMAST video stations are represented by black dots, each separated by 1.57 km.



Presently the New England Fisheries Management Council is developing Amendments 10 and 13 for sea scallop and groundfish management, respectively. Both of these management plans contain a series of management alternatives that include dividing the sea scallop resource into different sections based on sea scallop density and distribution and to protect essential fish habitat. In many cases the data used to predict the effects of these alternatives is sparse.

The relationship of the proposed project to management needs or priorities identified by the Council: This research project enhances the understanding of the scallop resource and contributes to the body of information on which management decisions are made. It addresses several critical regional and national issues described in the Federal Register Vol. 66, No. 103, 29 May 2001, by:

1. Improving information concerning scallop abundance estimates (considered high priority by the council).
2. Evaluating the distribution, size composition, and density of scallops in the closed areas (considered high priority by the council).

3. Conducting fishing industry-supported high-resolution surveys that include distribution, recruitment, mortality and growth rate information.
4. Identifying scallop habitat and ecological relationships that affect reproduction, recruitment, mortality, and growth including those enhanced/impeded by area closures.
5. Detailing sea scallop life-history information (especially on age-and area-specific natural mortality and growth) and to identify stock-recruitment relationships.

This study has direct implications for rotational fisheries management plans presently under consideration by the NEFMC.

This research also examines the critical question "Where do the recruits for the Nantucket Lightship Area come from?"

The three closed areas on Georges Bank present an opportunity to study what happens to a shellfish population in the absence of fishing. We know that the abundance of scallops in these areas has increased dramatically. We also know that the natural environment imposes a limit on the maximum size that a population can obtain (this is called the carrying capacity). What we do not know is what causes this carrying capacity limit. Is it predation or resource limitation? We are currently examining the effects of these very high densities on recruitment success, which is a measure of how many young scallops are coming into the fishery. It may be that high densities of scallops are limiting recruitment by utilizing resources, or by some other mechanism. It is important to understand recruitment processes because it is the future of the population and, hence, the fishery. With some standardization the video survey can be used as an alternative measure of recruitment.

In our video surveys few small scallops (<90 mm) were observed in the Nantucket Lightship Area. However, the density in this area is increasing each year (0.38 scallops m^{-2} in 1999, 0.40 scallops m^{-2} in 2000 and 0.58 scallops m^{-2} in 2001 from our video surveys). Using the von Bertalanffy growth equation we have estimated with Brad Harris's research (described below) and applying it to the shell height frequencies we observed in 1999, it appears that there was a 19% increase in recruiting scallops (50-90 mm) in 2000 that were not observed in 1999. Where have these recruits come from? Small scallops of this size range were observed 50 nautical miles to the North of the NLSA in the Great South Channel, which is open to fishing. In some scallop populations, juveniles are thought to settle in one area and then migrate into the adult bed. Previous tagging studies on Georges Bank show that scallops can move as much as 15 km in 5 years primarily as a result of the water current direction. The sea scallop is one of the strongest swimmers of all the scallop species. Could recruitment into the Nantucket Lightship Area be the result of migration from the Great South Channel? We are examining this question and also the relationship of adult densities to juvenile recruitment ratios using the video surveys and tagging studies.

The tagging study also provides information on sea scallop growth in the Great South Channel.

The sea scallop resource is presently managed using a yield per recruit model (how much harvestable meat a scallop can produce in it's life-time). The scallop resource on Georges Bank is considered a single stock and therefore has a single growth equation (32nd SAW, January

2001). The 2001 National Marine Fisheries Service (NMFS) Stock Assessment Review Committee stated that predicted scallop growth failed to describe observed shell height frequencies on Georges Bank. Following individuals through time provides the most precise measure of sea scallop growth. Therefore we tagged approximately 11,700 scallops and released them in the Great South Channel (GSC) just north of the Nantucket Lightship Closed Area (NLSA) during May-June 2001. To date 1288 tags have been returned from the 2001 experiment. We conducted a second experiment tagging 18,196 scallops in September 2002 and released them 50 nautical miles to the north of the 2001 tagging experiment (Figure 3). To date 1218 tags have been returned from the 2002 experiment. The preliminary information from these experiments suggest site specific growth occurs on Georges Bank with a variation in the yield per recruit equation of as much as 20%. This difference in growth rate for just the scallop in the NLSA could mean an increase in the biomass estimate of 4.16 million lbs equal to $20 million in harvest for one year.

2. Description of the methods of data collection and analyses

There were two components to this proposal to achieve the above stated objectives.

1. We conducted two video surveys, one in the Nantucket Lightship Area and the second in the adjacent open portion of the Great South Channel (Figure 1).
2. We conducted one scallop-tagging cruise in the open portion of the Great South Channel North of the Nantucket Lightship area.

We have completed the three research and six harvest cruises proposed in grant NOAA/NA16FM2416. Table 1 is a time-line listing the meetings and cruises.

Table 1. Milestones for the 2002 SMAST research cruises funded by NA16FM2416.

Date	Event
22-May-02	Meeting with participating Fishermen to discuss sampling and schedules
2-Jun-02	Memorandums of Agreement signed between the University and Fishermen
5 to 9 Jul-02	Video research cruise conducted aboard the *F/V Huntress,* 332 stations completed
1-Aug-02	NOAA/NA16FM2416 awarded and received
30-Aug-02	Harvest cruise completed by the *F/V Liberty*
5 to 9 Sep-02	South Channel scallop tagging research cruise conducted aboard the *F/V Liberty*
18 to 21 Sep-02	Video research cruise conducted aboard the *F/V Friendship,* 316 stations completed
10-Oct-02	Harvest cruise completed by the *F/V Friendship*
11-Oct-02	Harvest cruise completed by the *F/V Venture*
11-Nov-02	Harvest cruise completed by the *F/V Huntress*
10-Feb-03	Harvest cruise completed by the *F/V Edgartown*
26-Feb-03	Harvest cruise completed by the *F/V Mary Anne*

Before each cruise I contacted Mr. Pete Christopher of the NMFS who provided a letter of authorization for the research and harvest cruises. Mr. Christopher also notified the Coast Guard of our activities. Upon returning to port I contacted Mr. Christopher again and provided an account of the cruise. All cruises went very smoothly although we had some equipment failure during the *F/V Huntress* and *F/V Friendship* research cruise. However, we were able to continue with our back-up video system.

The SMAST Video Survey

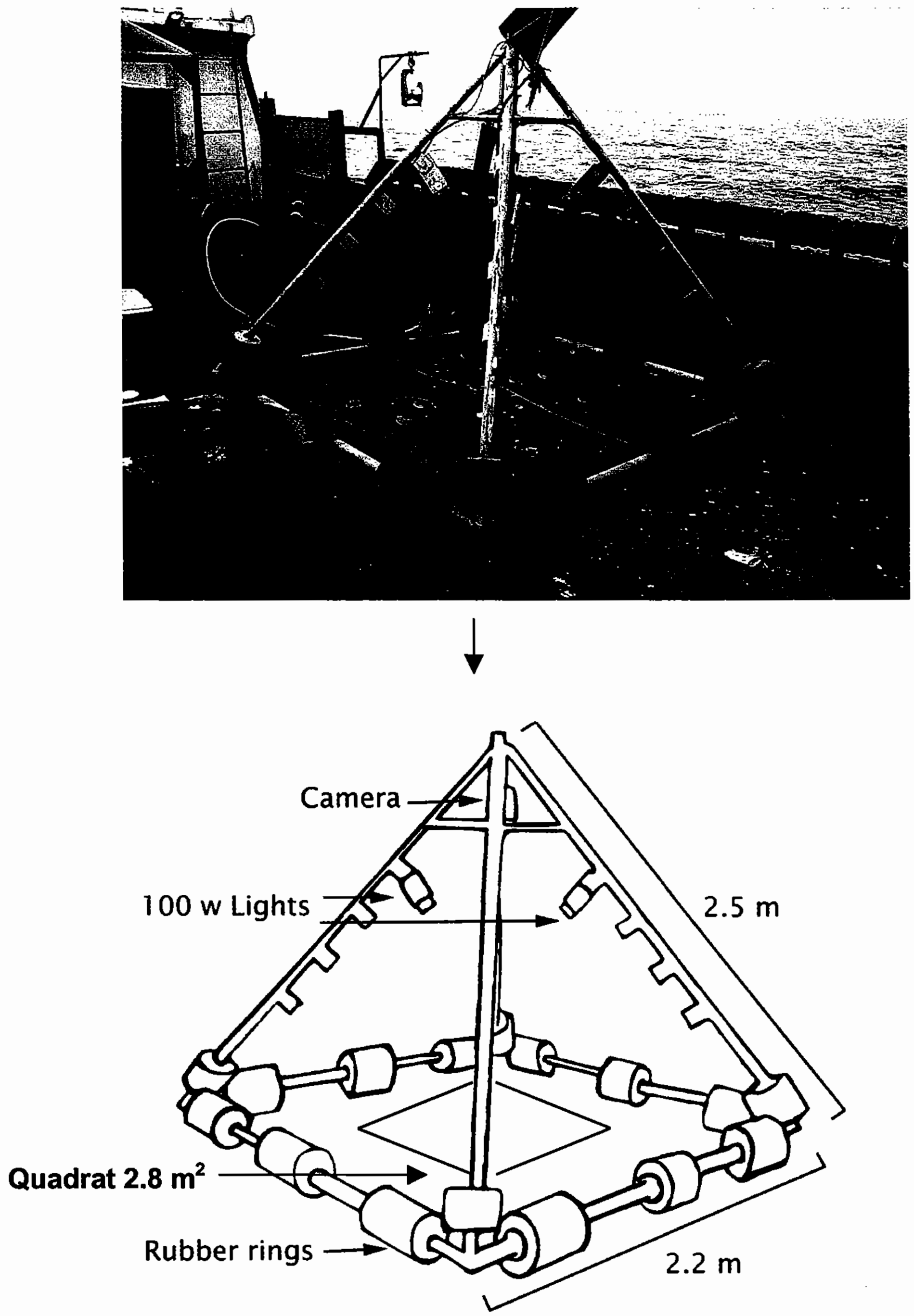
The sampling procedure for these surveys used a multistage design with stations separated by 0.85 nautical miles, similar to the 1999 and 2000 SMAST surveys (Stokesbury 2002). We used a centric systematic design for placing stations as it is simple, samples evenly across the entire survey area, and has been successfully used to survey scallops on Georges Bank (Thouzeau et al. 1991). The historic fishing ground within the Nantucket Lightship Area could be sampled with 204 stations on a grid with a 1.57 km between stations (0.85 nautical miles) (Figure 1). This station gird pattern was then used for all other closed areas that had supported historical scallop aggregations to maintain consistency throughout the surveys.

At each station a fishing vessel deployed the video camera mounted on the sampling pyramid providing a 3.235 m^2 quadrat image of the sea floor (increased from 2.8 m^2 due to edge effect; Figure 2). After the first quadrat the pyramid was raised so that the sea floor could no longer be viewed, the vessel drifted for approximately 50 m and then the pyramid was lowered again to obtain a second image. This procedure was repeated four times to provide four quadrat samples at each station. Images of the sea floor were recorded on a standard VHS tape. Along with each image, the time, depth, number of scallops observed, and latitude and longitude obtained from the vessel's differential global positioning system were recorded.

After each survey the videotapes were replayed in the laboratory and an image of each quadrat is digitized and saved (TIFF file format). Scallop counts from the video display taken aboard the fishing vessel were checked, and the substrate within each image was identified. The digitized images were loaded into Imagepro image analysis software and the shell heights of live scallops were measured (mm). Counts were standardized to individuals•m^{-2}.

Sediments were visually identified following the Wentworth particle grade scale from the video images, where the sediment particle size categories are based on a fixed reference point of 1 mm; sand = 0.0625 to 2.0 mm, gravel = 2.0 to 256.0 mm and boulders > 256.0 mm (Lincoln et al. 1992). Gravel is divided into three categories, granules = 2.0 to 4.0 mm, pebbles = 4.0 to 64.0 mm, and cobble = 64.0 to 256.0 mm. Shell debris is also identified although it is not included in the Wentworth scale. Quadrats are categorized by the presence of the largest type of particle. Therefore if one boulder (>256 mm) is observed, the quadrat is classified as "boulder". By contrast, a quadrat identified as sand had only sand in it, but a quadrat that had 60% sand, 30% shell debris and 10% granule/pebbles is classified as granule/pebbles.

Figure 2. The sampling pyramid, with a square base 2.2 m per side of 6 cm round iron, arms 2.5 m x 4.5 cm round iron, approximate weight 450 kg, was deployed with the large hydraulic winch used in the scallop fishing industry. Rubber rings (3 sets of 8 rings, each 20 cm diameter, 5 cm thickness, per side) were placed on the stand of this pyramid to prevent damage during deployment and provide gentle landings on the sea floor. An underwater camera (Deepsea Power & Light multi-Seacam) was attached to the center of the pyramid 157 cm above the pyramid base. Five 100 w lights (Deepsea Power & Light multi-Sealite) were attached 50 cm above the pyramid on opposite arms. This design provided a 2.8 m^2 field of view.



Scallop mean densities and standard errors were calculated using equations for a multistage sampling design (Cochran 1977 p. 277; Krebs 1989 p. 231):
The mean of the total sample is:

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

The standard error of this mean is:

(2) $$S.E.(\bar{x}) = \sqrt{\frac{1}{n}(s^2)}$$

n = primary sample units (stations)
$\bar{x}_i$ = mean value of the elements (quadrats) in primary unit i (stations)
$s^2 = \sum^{n} (\bar{x}_i - \bar{x})^2 / (n-1)$ = variance among primary unit (stations) means

As the sampling fractions were small, hundreds of scallops sampled compared to millions of scallops in the area, the finite population corrections were omitted simplifying the estimation of the standard error (Krebs 1989).

The number of scallops within a survey area was calculated by multiplying the mean number of scallops•m^{-2} by the total area surveyed. Distributions of scallops•m^{-2} were plotted using Arcview. Estimates of scallop meat weight were derived from shell height (SH) frequencies for each area and length/weight regressions for each area. These equations were calculated from live dissections of sea scallops collected during the last tow of fishing trips completed while the vessels were participating in the Sea Scallop Exemption Fishery in each of these areas (author's unpublished data).

The SMAST Tagging Study

The tagging study was conducted from the *F/V Liberty* in the northern portion of the Great South Channel from the 5th to the 9th September 2002 (Figure 3). This location was selected because in 2001 the SMAST video survey observed a high density of small scallops in that area. Before and after the scallop dredge was deployed the sample area was video taped. This allowed for a comparison between density and shell height frequency estimates between the commercial dredge and the video sampling gear (Figure 4).

Figure 3. Locations of the 2001 and 2002 SMAST scallop tagging experiments.

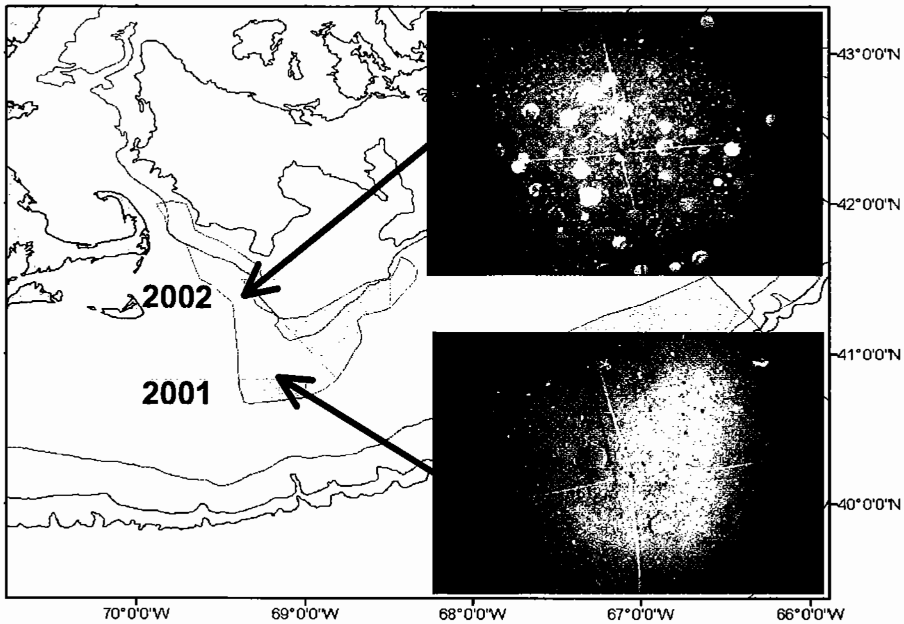
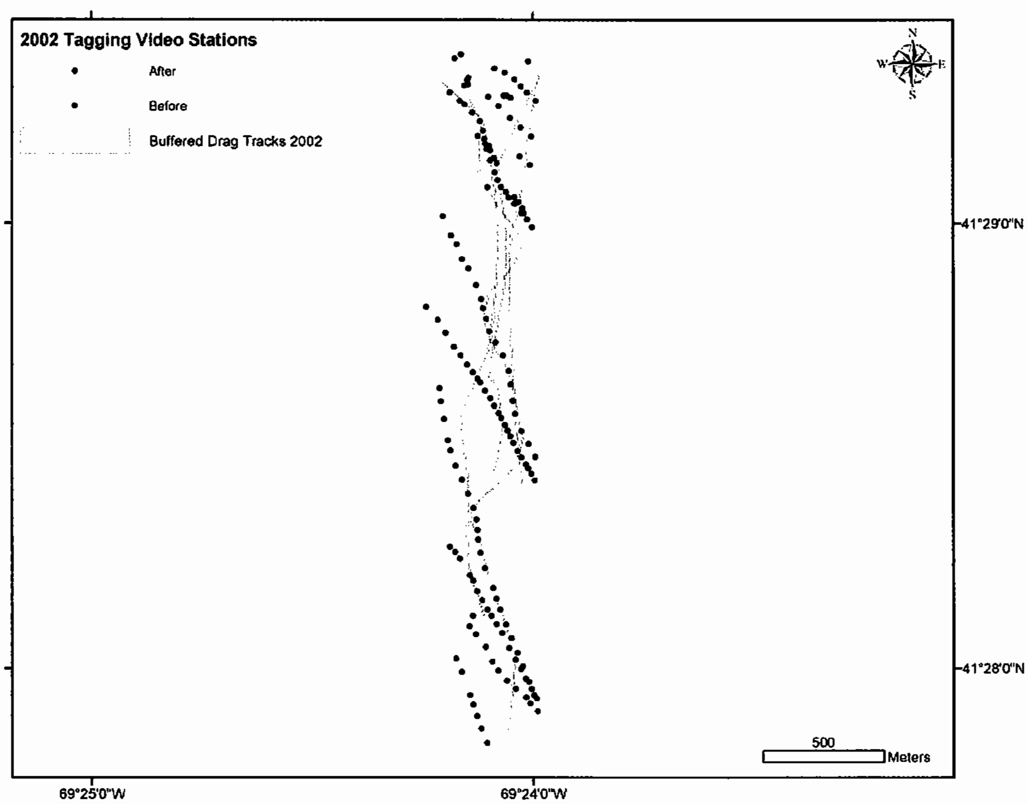


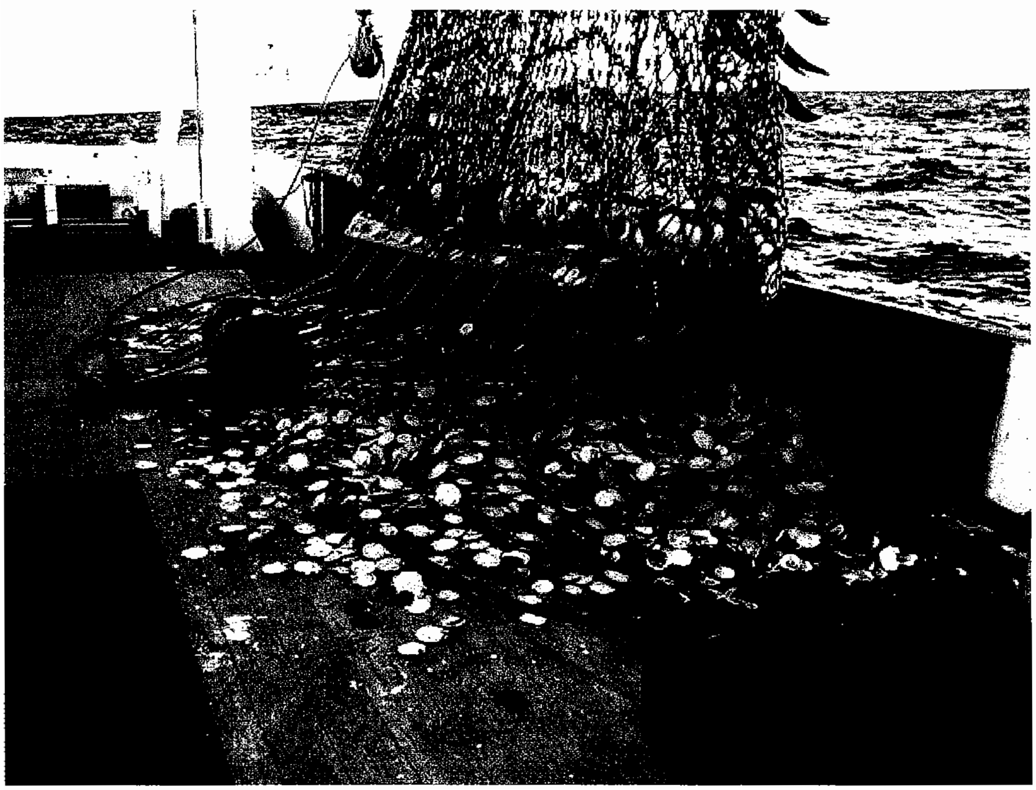
Figure 4. Locations of video quadrats and commercial scallop dredge paths sampled during the 2002 scallop tagging study.



Sea scallops were collected using a single commercial New Bedford scallop dredge. The dredge was deployed for a short period of time, about 5 minutes on average. The contents were emptied on the deck of the *Liberty* and the catch was sorted (Figure 5A). We digitally photographed all the rocks, cobble and shell debris collected. All fish and sea stars were identified and measured. All other macroinvertebrates were identified. Sea scallops were sorted and then held in tubs with flow-through seawater during the tagging procedure (Figure 5B). A 0.05mm hole was drilled in the upper shell of each scallop above the byssal notch using a Dremel tool with a tungsten-carbide cutting bit mounted on a drill press. A numbered Floy disc tag (2.5 mm diameter) was fixed to each shell with a 316-alloy stainless steel wire inserted through the hole in the shell (Figure 6). This wire was twisted using safety pliers. The shell height (mm) and tag number was recorded for each scallop (Figure 7). Scallops were out of flowing seawater for no more than 1 minute during the tagging procedure. The tagged scallops were released at a station adjacent to the tagging area.

Figure 5. Sea scallops collected for tagging aboard the F/V Liberty. A) This tow was only nine minutes on the 9th September 2002. B) Students, scientists and fishermen sorting scallops for tagging.

A).



B).

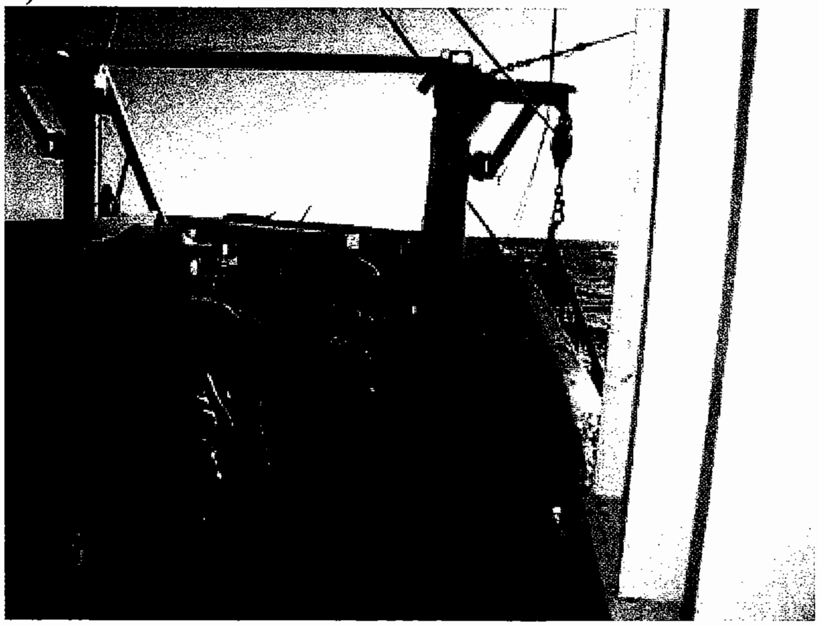


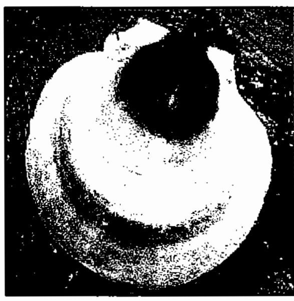
Figure 6. Tagging assemble line.

Commercial scallop fishermen, seafood processing plants and settlement houses were informed of the tagging study verbally and given flyers and posters in English and Portuguese (Figure 7). The fishermen were asked to retain the upper shell (with the tag attached) and to record the date and location of capture in exchange for a reward cap.

Figure 7. SMAST scallop project flyer providing information for the fishery about returning tagging procedures.

SMAST SCALLOP RESEARCH

Approx. 12,000 scallops have been tagged and released in the open area on Georges Bank



If you catch a tagged scallop call (508) 910-6373, 910-6359 **or**
e-mail kstokesbury@umassd.edu

Save

- **Shell with tag attached (Top)**

Record

- **Catch location (GPS/ LORAN)**
- **Catch Date**

SMAST
508-910-6373
09,687
Tag

Why return the tags and information?

We are conducting experiments to learn more about the life-cycle of the sea scallop and how it changes throughout the year and in different locations. The return of these scallops will tell us more about their growth rates, ability to move, and death rates.

These experiments are part of the research SMAST and Scallopers have been working on together since the 1998 survey of Closed Area II. We have completed 13 video surveys, and 4 tagging experiments. Additionally, 6 video cruises are planned for 2001. This research aids in better management of the scallop resource. The result is a healthier scallop fishery.

Plus you get a nice hat.

The tagging study supplies site-specific growth information for sea scallops in the Great South Channel. This is an important component of Mr. Bradley Harris's Masters of Science research. For further information on how this information in being analyzed and incorporated please refer to Mr. Harris's M.sc. proposal included as Appendix 1.

3. Discussion of results

We completed the two video cruises, all of the video tape footage has been digitized and the scallop and other macroinvertebrates have been counted. The substrate has been identified. We have measured all the scallops and macroinvertebrates. We also tagged and released 18,196 scallops in early September 2002 and to date we have 1218 tag returns from this experiment.

The scallop densities and biomass have continued to increase in the open and closed areas from 1999 to 2002 (Table 2).

Table 2. Densities of scallops per m^2, numbers of stations surveyed, estimates of variance, average meat weight based on size frequencies and shell height-meat weight relationships, area sampled in km^2, and biomass in millions of pounds for the open and closed areas of Georges Bank surveyed with the SMAST video system.

Area	Scallops per m^2	stations	SE	CV%	mwt (g)	km^2	Biomass in mill. lbs	Shell height meat weight equations
			1999					
CAI	0.25	454	0.021	8.6	22	1122	13.5	10^(-4.42541+2.737042*LOG(SH))
CAII	0.59	125	0.076	12.9	23	309	9.4	10^(-4.416+2.81888*LOG(SH))
NLSA	0.38	205	0.057	15.0	34	507	14.6	10^(-4.4448+2.861894*LOG(SH))
			2000					
CAI	0.42	183	0.056	13.2	27	452	11.3	10^(-4.42541+2.737042*LOG(SH))
North SC	0.36	157	0.080	22.2	7	388	2.1	10^(-4.4785+2.8401358*LOG(SH))
NLSA	0.40	204	0.033	8.2	38	504	16.8	10^(-4.4448+2.861894*LOG(SH))
NLSA (O)	0.44	174	0.058	13.2	39	430	16.3	10^(-4.4448+2.861894*LOG(SH))
Stellw	0.08	92	0.019	24.3	7	227	0.3	10^(-4.4785+2.8401358*LOG(SH))
			2001					
CAI	0.35	164	0.052	14.7	35	405	11.1	10^(-5.0855+3.1321*LOG(SH))
CAIIS	1.07	62	0.110	10.2	17	153	6.3	10^(-4.8186+3.0443*LOG(SH))
CAIIN	0.59	277	0.059	10.1	28	685	25.1	10^(-4.8186+3.0443*LOG(SH))
HC	0.17	188	0.014	8.3	18	465	3.2	10^(-4.7878+2.9485*LOG(SH))
NLSA	0.62	204	0.057	9.3	34	504	23.1	10^(-4.9168+3.1062*LOG(SH))
North SC	0.58	201	0.125	21.6	13	497	8.1	10^(-5.1647+3.1681*LOG(SH))
			2002					
NLSA	0.82	204	0.066	8.1	41	504	37.2	10^(-4.9168+3.1062*LOG(SH))
SC	0.27	444	0.045	16.6	16	1098	10.7	10^(-5.132+3.1559*LOG(SH))

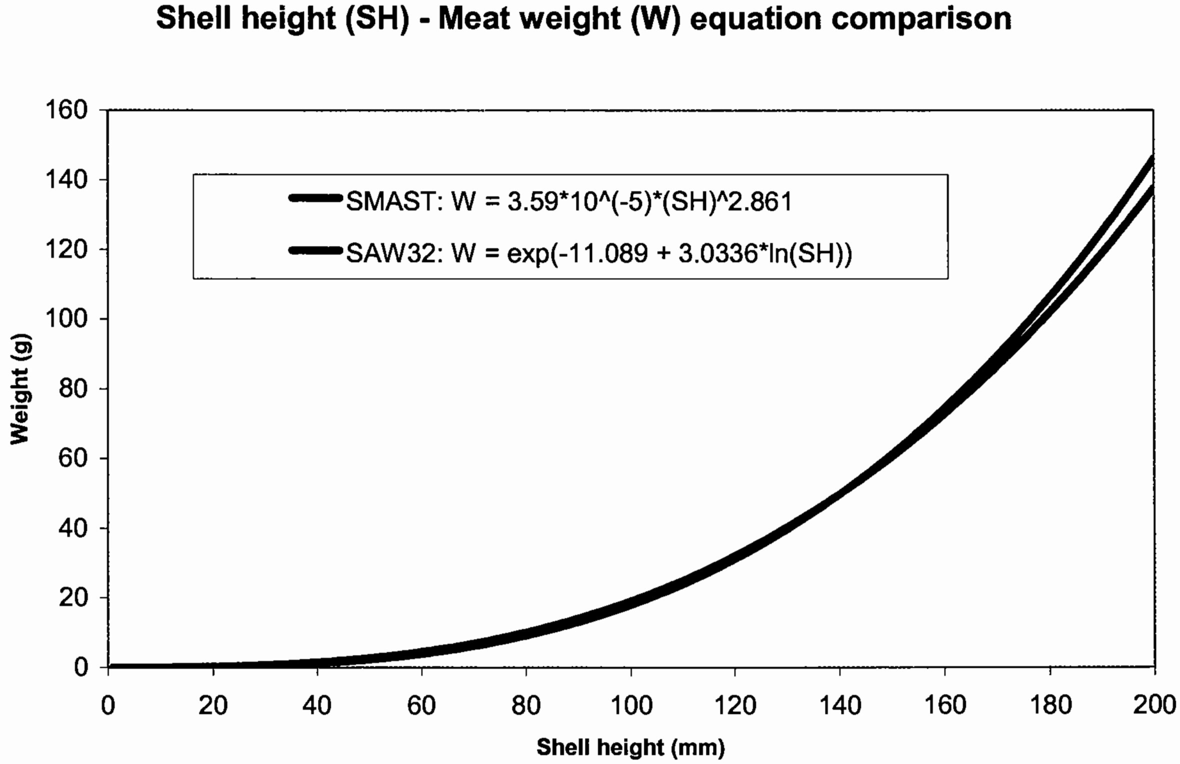
The information in the table above was presented to the New England Fisheries Management Council's Sea Scallop Planning and Development Team (PTD) at the 5th April 2003 meeting. The information and video system was further examined and compared to NMFS dredge sample estimates at the 2nd July 2003 meeting. At the request of the PDT chair we modified our total abundance estimates to exploitable scallop biomass based on the selectivity curve for a commercial scallop dredge and the shell height meat weight relationship approved by the NMFS SAW/SARC (Table 3). There was little difference between the SMAST and the NMFS shell height meat weight relationship (Figure 8).

Table 3. Exploitable sea scallop density and biomass estimates for the New England Fisheries Management Council's Sea Scallop Planning and Development Team. The first table is calculated with the SMAST shell height meat weight equation and scallops greater than 90 mm shell height. The second using the selectivity curve and the NMFS SAW/SARC shell height meat weight relationship.

Estimate using SMAST's Shell height-Meat weight equation for scallops > 90 mm shell height		
2002 - NLSA		
Total Density (scallops/m2)	0.82	
The number of observed scallops	1675	
The number of observed 90mm+scallops	1487	
90mm+ density	**0.73**	
Average weight of harvestable scallops (90mm+)	**41.04**	
NLSA area (m2)	**504,288,000**	**in millions lbs**
Total harvestable biomass (in tons)	**15,067**	**33.22**

Estimate using SAW32's Shell height-Meat weight equation and Commercial Dredge Selectivity		
2002 - NLSA		
Total Density (scallops/m2)	**0.82**	
Average weight of scallops weighted by selectivity	**36.56**	
NLSA area (m2)	**504,288,000**	**in millions lbs**
Total harvestable biomass (in tons)	**15,117**	**33.33**

Figure 8. Shell height meat weight relationship approved by the NMFS SWA/SARC compared to SMAST dissection estimates.



The shell height frequencies observed in 2002 indicated low proportions of recruiting scallops (Figure 9 and 10).

All the above data has been reviewed by the NEFMC Sea Scallop PDT and were submitted to the Scallop Oversight Committee in a Memorandum of 22nd July 03 as advice on the final Amendment 10 alternatives and revised projection and area access TAC/allocation estimates.

The density of sea scallops surveyed in 2002 was some of the highest recorded to date, however sea scallops are still aggregated within this area (Figure 11). One of the primary predators of sea scallops, the sea star also has an aggregated distribution in this area (Figure 12). The relationship between sea scallops and sea stars is the focus of Mr. Mike Marino's Master of Science research and is a CMER funded research program (Appendix 2). Mr. Marino has presented his preliminary results at the scientific meeting:

Marino, M., K.D.E. Stokesbury, and F. Juanes. Examination of sea scallop-sea star predator-prey interactions on Georges Bank. Southern New England Chapter of the American Fisheries Society, 14 January 2003.

Figure 9. Shell height Frequencies mm (counts) observed in the Nantucket Lightship area at the same stations from 1999 to 2002.

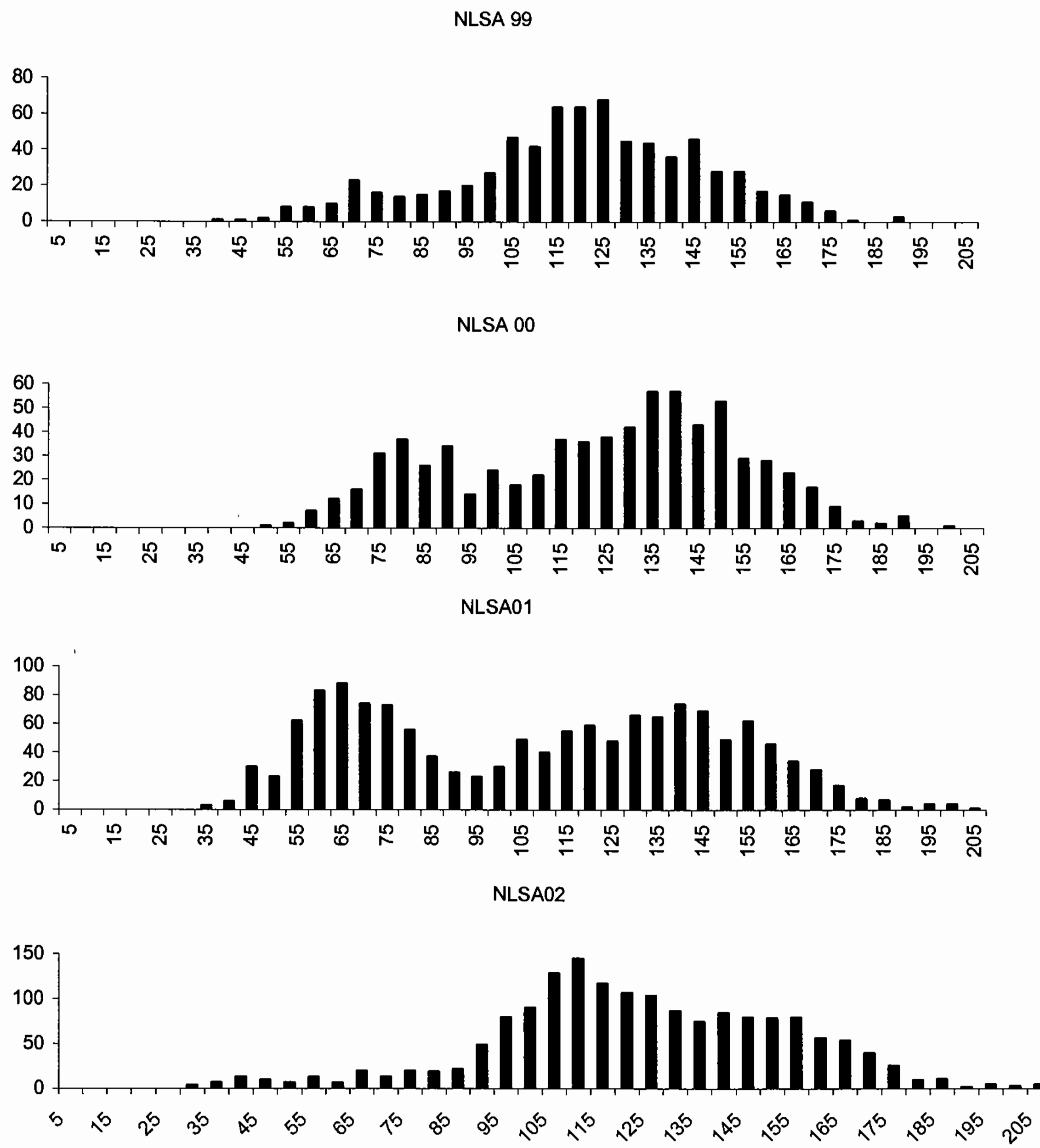
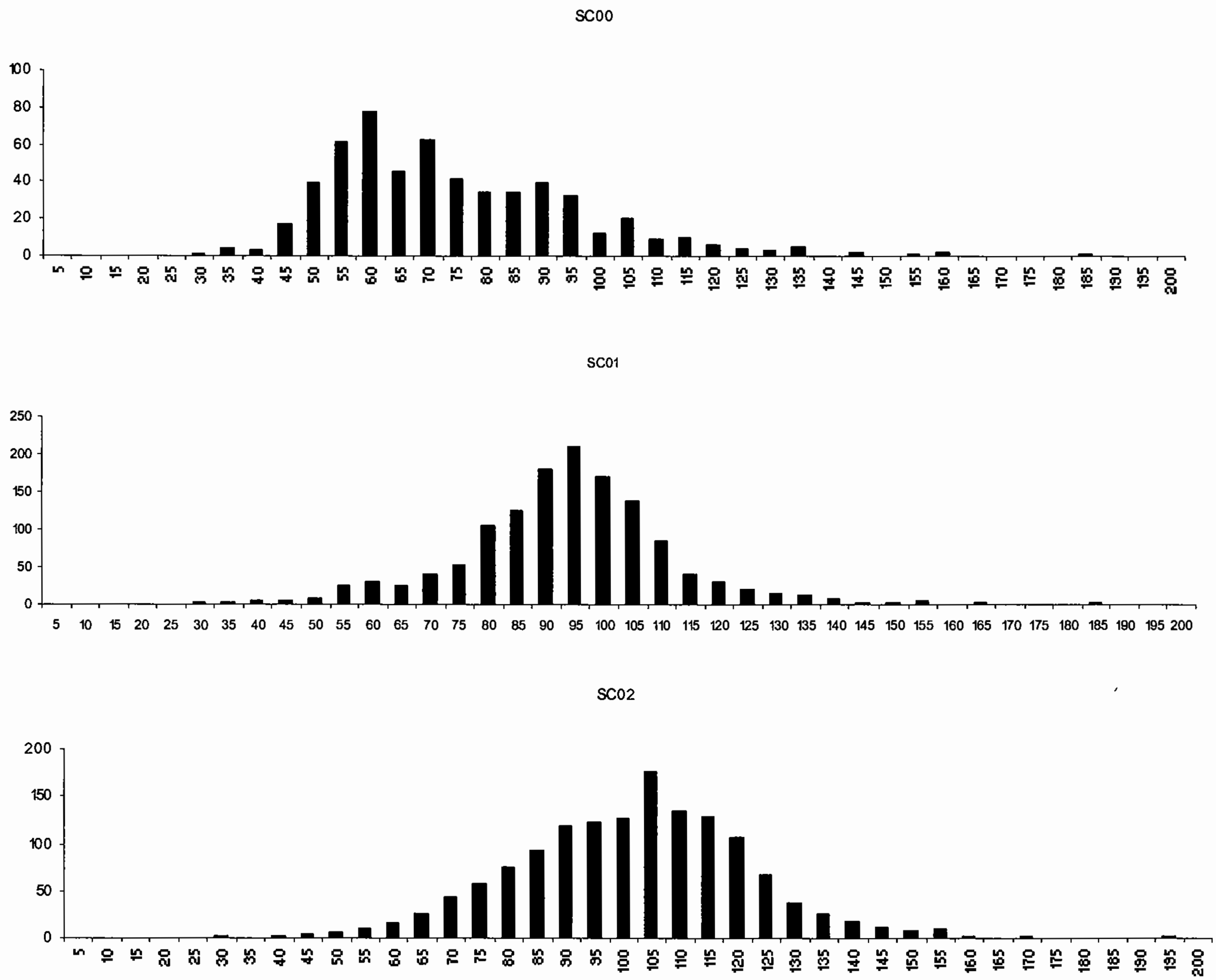


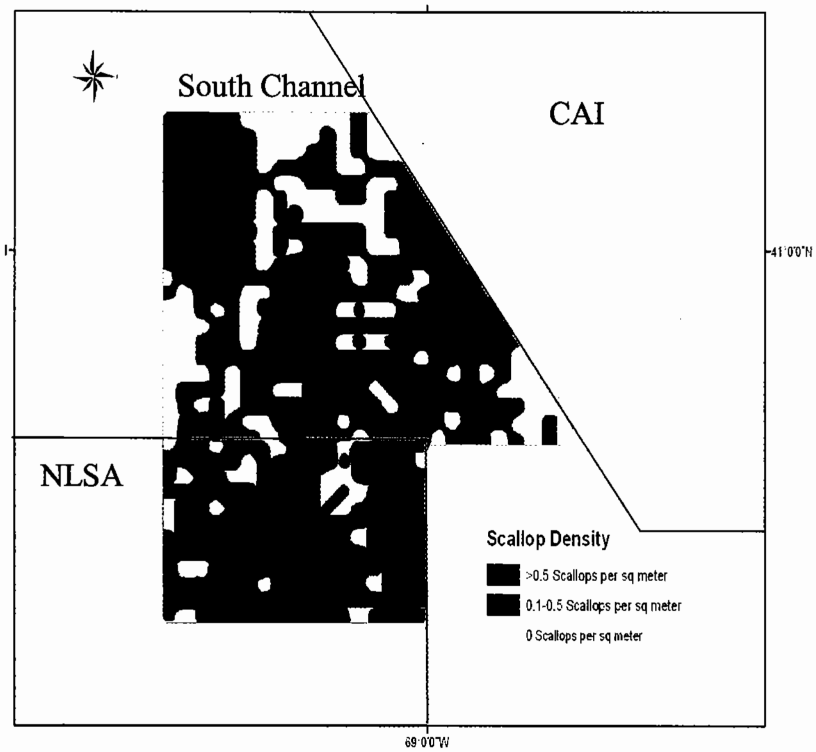
Figure 10. Shell height Frequencies mm (counts) observed in the Great South Channel at the same stations from 2000, 2001 (Northern portion) and 2002 (Southern portion, refer to Figure 13).



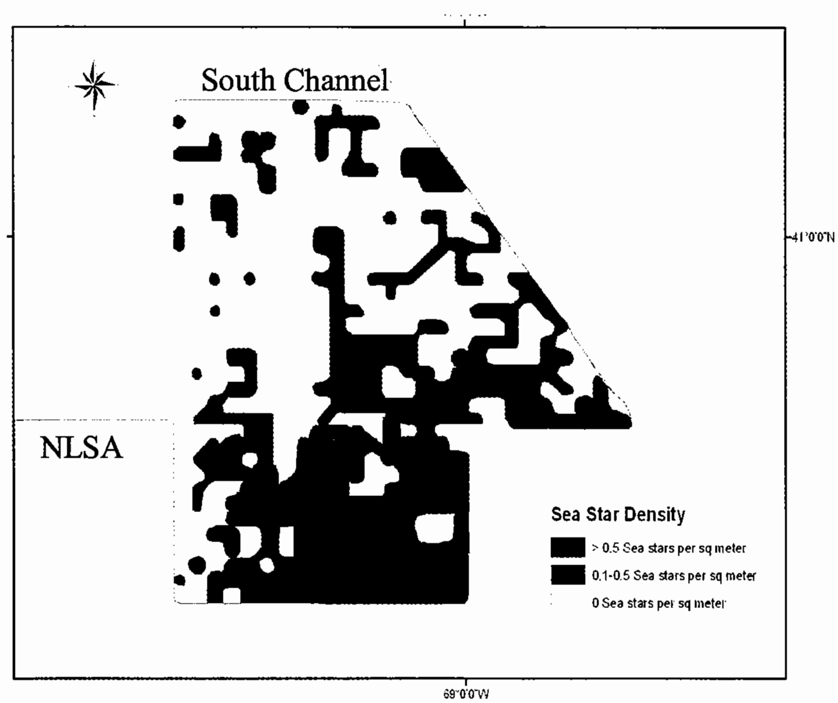
The relationship between adult sea scallops on the sea floor and recruiting juveniles is still unclear. This is the research topic of Mr. Jake Nogueria's Master of Science research project. He is continuing this analysis using the above information. His M.sc. proposal is included as Appendix 3.

Figure 11. Distribution and densities of, A) Sea Scallops, and B) sea stars, observed during the 2002 SMAST video survey.

A). Sea scallops.



B) Sea stars.



Sea Floor Mapping/Habitat Information.

Presently the New England Fisheries Management Council is developing Amendments 10 and 13 for sea scallop and groundfish management, respectively. Both of these management plans contain a series of habitat alternatives to protect essential fish habitat. In many cases the data used to predict the effects of these alternatives is sparse.

Identifying impacts of commercial fishing on fish habitat is often hampered by the lack of environmental-impact assessment, appropriate monitoring and adequate control sites (Thrush et al. 1998). Most studies examining marine environmental impact have been on a small temporal and spatial scale in sheltered locations that are not exposed and do not experiencing extreme natural disturbances, such as areas with frequent storm events or strong tidal currents (Thrush et al 1998).

A driving assumption for Habitat closed area Alternatives in Amendments 10 and 13 is that biologically complex habitat on the sea floor is essential fish habitat for juvenile groundfish, primarily cod and haddock, and that biologically complex habitat requires substrate that supports sessile and encrusting invertebrates.

We are making high-resolution maps of the sea floor within scallop fishing grounds (0.85 nm grid). Scallops have evolved to live on a dynamic sand-gravel substrate, which does not support sessile and encrusting invertebrates very well. Previous maps have been on a scale of one sample per 100 nm^2. By defining the gravel areas into their subgroups and showing where the substrates and sessile invertebrates do and do not exist some of the conflict over the effects of fishing on habitat may be removed. This can be demonstrated by comparing the map used to consider the different habitat alternatives in Amendments 10 and 13 (Figures 12 through 15).

Preliminary analyses suggest that the proportions of sediment within the surveyed area of the Nantucket Lightship area shift between years. Figure 16 is a histogram of the percentage of sediment types observed in the video quadrats. The proportion of granule/pebble substrates decreased from 36% in 1999 to 11% in 2000, before the fishing event. The proportion of sand increased from 53% in 1999 to 87% in 2000. These sediments have continued to shift and in 2002 the proportion of granule/pebble was similar to that observed in 1999. How dynamic these substrates are is a critical point as Amendment 10 uses the proportion of substrate effected by the footprint of the fishery to determine the preferred alternatives for scallop management from a habitat prospective. If sediments are shifting then this metric is both inaccurate and misleading. Refer to Table 207 and Figures 104 to 106 in Amendment 10 for examples of how estimates of scallop fishing effort effects substrate. These estimates are based on a single point sample substrate map (Figure 12; Poppe et al 1989, Map 33 in Amendment 10). There is no consideration for the dynamic nature of these different substrates and how they vary over time.

Figure 12. The sediment map presently used by the NEFMC to assess the different Habitat alternativies in Amendments 10 and 13, sampling frequency is approximately 1 grab sample every 100 nm^2. (Poppe et al 1989, Map 33 in Amendment 10)

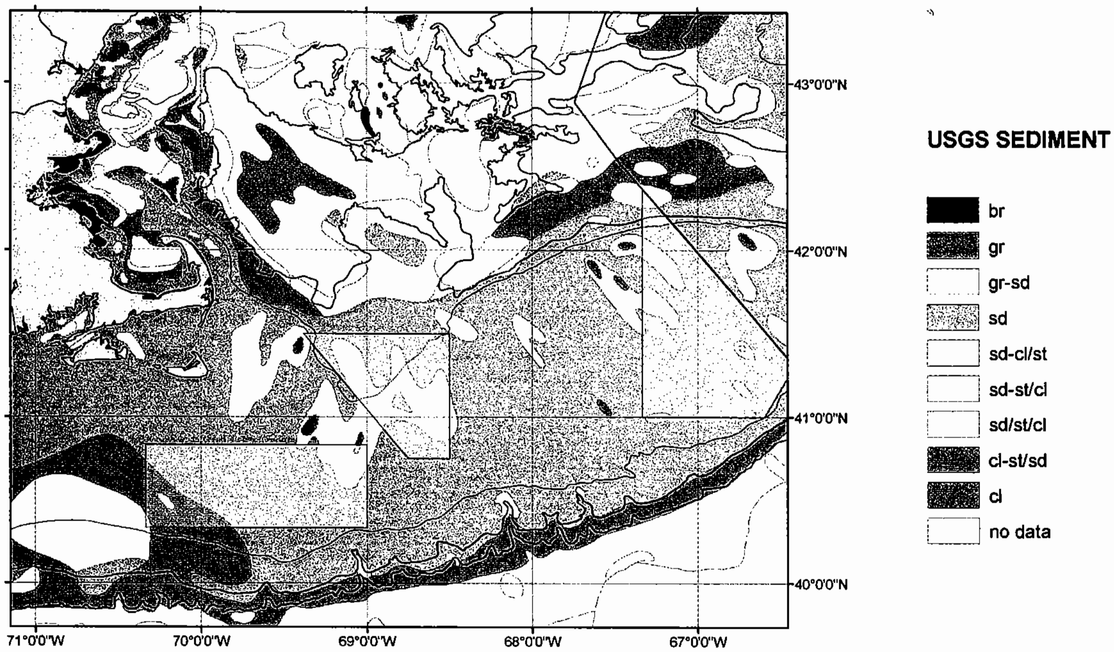


Figure 13. The SMAST video survey sediment map for Georges Bank with data collected between 1999 and 2002 creating using the procedure described above, refer to Figure 1 for the 0.85 nautical mile station grid.

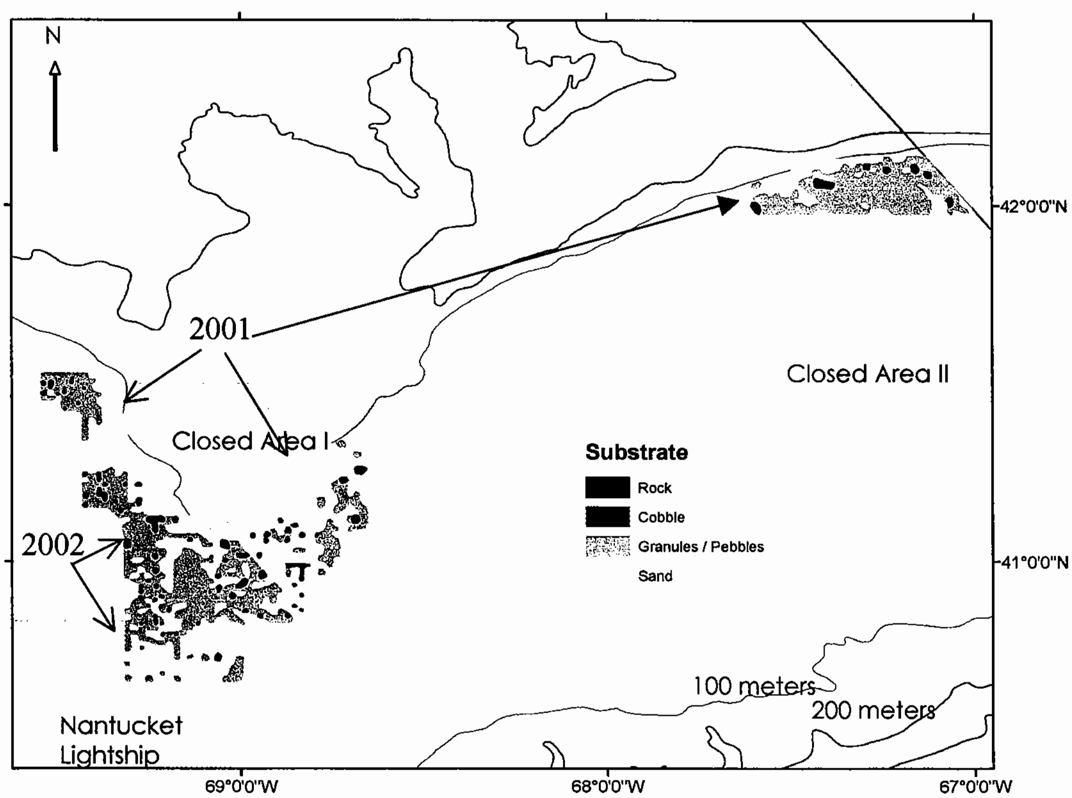


Figure 15. Overlay of SMAST sediment map on the (Poppe et al 1989, Map 33 in Amendment 10), SMAST color codes were converted to pink = sand, yellow = granule/pebbles, red = cobble, brown = rock/boulders.

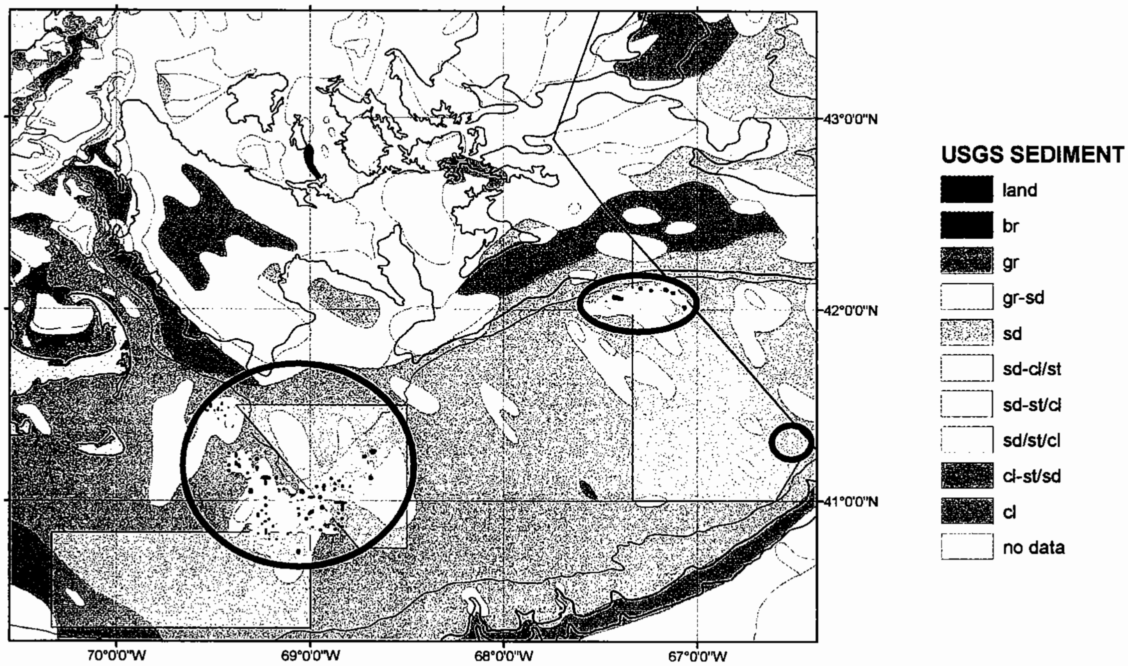


Figure 16. Overlay of the 2002 video survey data to the Poppe et al 1989, Map 33 in Amendment 10) SMAST color codes were converted to pink = sand, yellow = granule/pebbles, red = cobble, brown = rock/boulders.

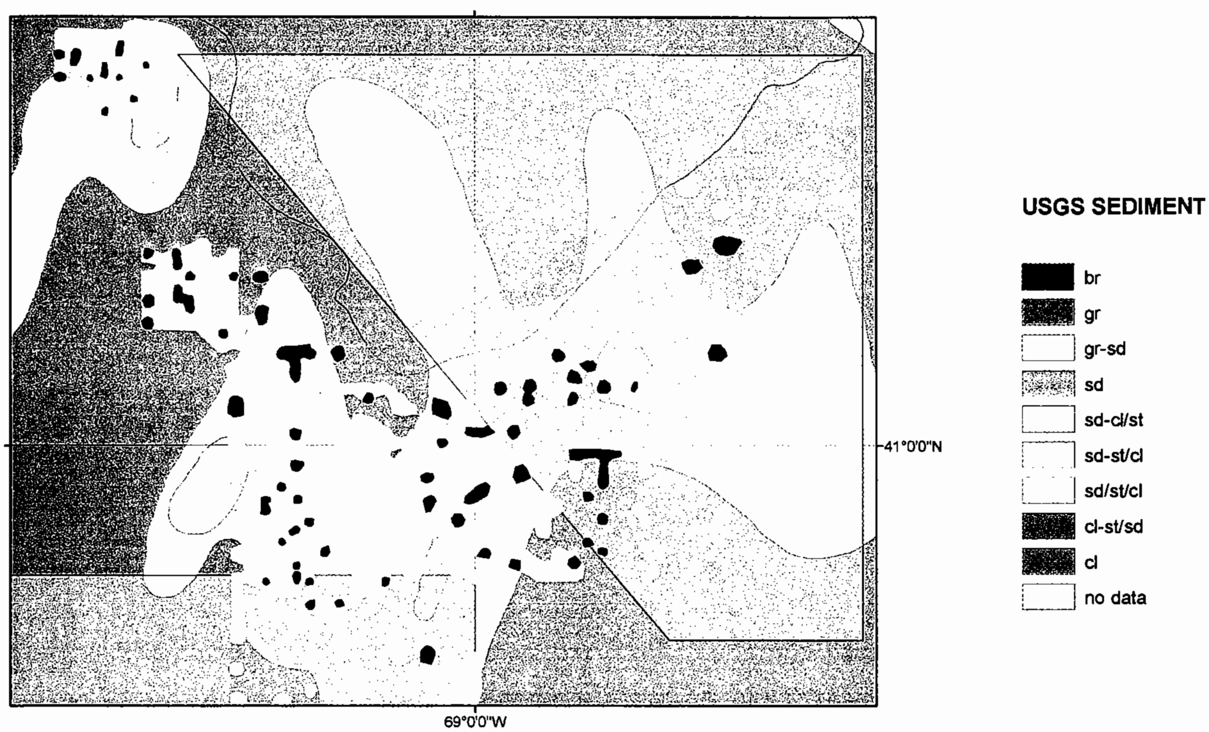
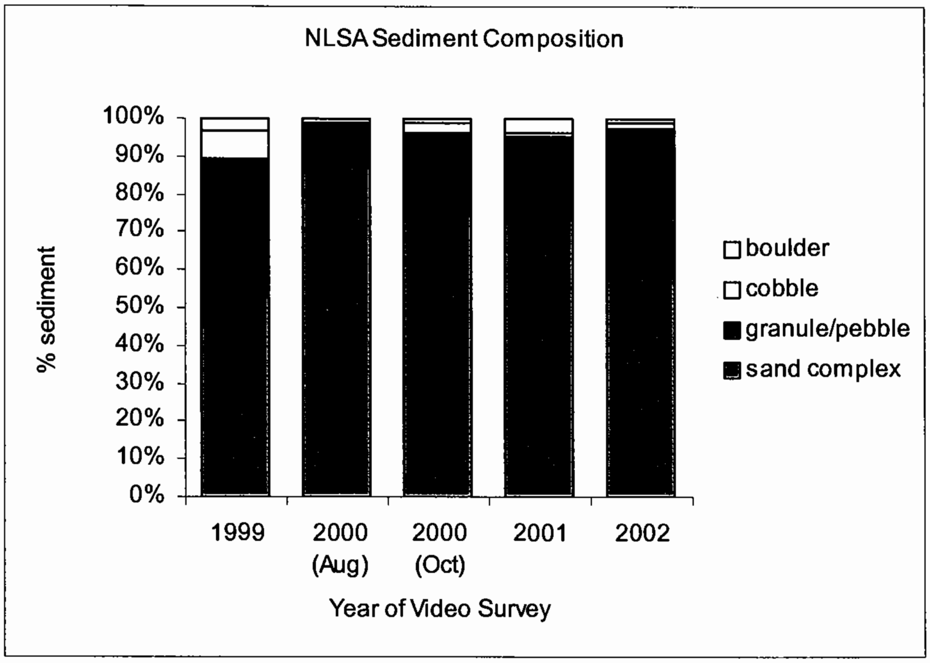


Figure 16. The percentage of sediment types observed in the video quadrats in the Nantucket Lightship Area.



Preliminary data have been presented to the NEFMC Habitat oversight committee (12 Sept 02), the Habitat Technician Team (25 Nov 02), and the Joint Advisor meetings on 6 February and 10 April 03. We have presented the preliminary results at several scientific meetings:

Stokesbury, K.D.E. and B.P. Harris. Fish and macroinvertebrates associated with sea scallop aggregations of Georges Bank and the impact of scallop harvesting. American Fisheries Society annual meeting, Quebec City, Quebec, 10-14 August 2003.

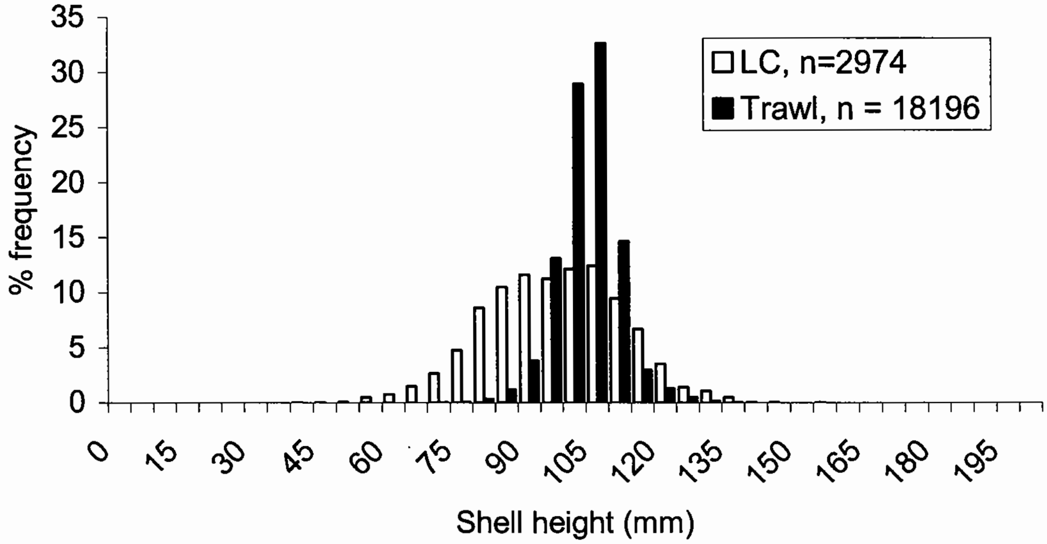
Stokesbury, K.D.E. and B. Harris. A Before-After-Control-Impact Study of the Sea Scallop Fishing Grounds of Georges Bank. Symposium on the Effects of Fishing activities on benthic habitats. USGS, NOAA, AFS, ESA. Tampa Florida, 12-14 November 2002. (Poster)

The SMAST Tagging Study

The SMAST tagging study supported by NOAA grant NA16FM2416 was divided into two experiments. The first is a comparison between the density estimates obtained by the video survey and the commercial dredge within a 4 nm^2 sampling area. The second was a movement/growth study that relies on recaptured tagged scallops returned by the commercial fishery.

The video survey estimated a shell height mean of 93.6 mm SD = 14.99 while the dredge estimated a mean of 100.9 mm with a SD of 6.74. A comparison of the shell height frequencies of sea scallops measured with the video survey and then collected by the commercial fishing dredge suggests that the video survey may see larger scallops as well as smaller ones (Figure 17).

Figure 17. A comparison of the shell height frequencies of sea scallops measured with the video survey and then collected by the commercial fishing dredge.



This discrepancy between size frequencies, particularly of large scallops, was also observed for the NMFS 8' scallop dredge and was a point of considerable debate during PTD meetings on the 5^{th} April and the 2^{nd} July 2003. We have completed 5 calibration experiments on the video system in both the laboratory and the field and the error between independent observers and the actual shell heights of test scallops was <5% with a precision of 1mm. We are continuing the analyses but the consequences of this research are large as it suggests that the selectivity for the commercial and experimental dredge differ as the shell height of the sea scallop increases. The video surveys suggest a dome-shaped recruitment pattern, which may affect the sea scallop assessments, reference points and even area rotation in general (Andy Applegate, Chair of the Scallop PDT, personal communication). This information was also presented to the Scallop Oversight Committee in a Memorandum of 22^{nd} July 03 from the sea scallop PDT chair.

The growth experiment is part of Mr. Brad Harris's Master of Science thesis research, (please refer to Appendix 1 for details on his analysis and progress). We tagged 18196 sea scallops in September 2002 (Figure 17). Although we presently have 1218 recaptures the critical part of the growth experiment are the scallops recaptured after one year in the wild. Mr. Harris has processed the 2001 scallops and that analysis is described in his thesis proposal (Appendix 1), and a similar analysis will be conducted on the 2002 tag returns this fall. Mr. Harris has presented his preliminary results at a number of public and scientific meetings including:

Harris, B.P., and K.D.E. Stokesbury. Growth for sea scallops in the Nantucket Lightship Closed Area of Georges Bank. American Fisheries Society annual meeting, Quebec City, Quebec, 10-14 August 2003.

Harris, B.P., and K.D.E. Stokesbury. Growth estimate for sea scallops in the Nantucket Lightship Closed Area of Georges Bank. Southern New England Chapter of the American Fisheries Society, 14 January, 2003. (received Best Student Paper Award).

Harris, B.P. Sea scallop research on Georges Bank: A Univeristy-Industry Collaboration. National Estuarine Research Reserve, Kachemak Bay seminar series. 3 January 2003.

Harris, B.P. Sea scallop research on Georges Bank: Collaborative Fisheries Research-the SMAST Video Survey of Georges Bank. The Alaska Department of Fish and Game. 3 January 2003.

Harris, B.P. and K.D.E. Stokesbury. Growth and movement of sea scallops in the southern part of the Great South Channel on Georges Bank: a tagging study. Annual Meeting of the National Shellfisheries Association, 16 April 2002, Mystic, Connecticut.

Harris, B. and K.D.E. Stokesbury. Growth estimate of sea scallops in the southern part of the Great South Channel on Georges Bank. American Fisheries Society annual meeting, Baltimore, Maryland 18-22 August 2002. (poster)

We will continue our analyses on the sea scallop. The research cruises funded by NOAA NA16FM2416 are being used in three Masters of Science theses, as well as providing key information to the New England Management Council and the National Marine Fisheries Service on sea scallop life-history, distribution and density and the benthic community of Georges Bank. We will supply the National Marine Fisheries Service with copies of all documents and published manuscripts as they are completed. Further we have been invited to present this research and contribute to the upcoming 39th SARC by Dr. T. P. Smith, Chairman of the Northeast SAW for the National Marine Fisheries Service (Letter to Dr. Rothschild 11 June 03). We are very excited about this opportunity to contribute and present our work.

List of Entities: Cooperative research with the fishing industry.

Since 1999 the University of Massachusetts Dartmouth School for Marine Science and Technology (SMAST), members of the commercial sea scallop industry, the Massachusetts Department of Marine Fisheries and with additional support from the sea scallop TAC-set-aside program (NOAA grants NA16FM1031, NA06FM1001 and NA16FM2416) have completed 26 video and tagging cruises to Georges Bank.

SMAST sea scallop research cruises.

Vessel	Date	Location	Research	Expenses
F/V *Huntress*	24-May-99	NLSA	Video survey	SMAST/INDUSTRY
F/V *Alpha & Omega II*	11-Jul-99	NLSA	video survey	SMAST/INDUSTRY
F/V *Alpha & Omega II*	26-Jul-99	CAI	video survey	SMAST/INDUSTRY
F/V *Liberty*	1-Aug-99	CAI	video survey	SMAST/INDUSTRY
F/V *Friendship*	16-Aug-99	CAI	video survey	SMAST/INDUSTRY
F/V *Edgartown*	26-Sep-99	CAII N	video survey	SMAST/INDUSTRY
F/V *Edgartown*	5-May-00	Cox ledge	video survey	SMAST/INDUSTRY
F/V *Frontier*	25-May-00	Stellwagon Bank	video survey	SMAST/INDUSTRY
F/V *Liberty*	31-May-00	Stellwagon Bank	video survey	SMAST/INDUSTRY
F/V *Friendship*	8-Aug-00	NLSA	video survey	SMAST/INDUSTRY
F/V *Liberty*	15-Aug-00	CA I	video survey	SMAST/INDUSTRY
F/V *Mary Anne*	29-Aug-00	South Channel	video survey	SMAST/INDUSTRY
F/V *Liberty*	21-Oct-00	NLSA	video survey	SMAST/INDUSTRY
F/V *Edgartown*	11-May-01	NLSA (open area)	tagging exp.	SMAST/INDUSTRY/DMF
F/V *Liberty*	18-May-01	NLSA (open area)	tagging exp.	SMAST/INDUSTRY/DMF
F/V *Tradition*	29-May-01	NLSA (open area)	tagging exp.	SMAST/INDUSTRY/DMF
F/V *Frontier*	4-Jun-01	NLSA (open area)	tagging exp.	SMAST/INDUSTRY/DMF
F/V *Huntress*	28-Jun-01	CA I	video survey	DMF/ NOAA GRANTS
F/V *Friendship*	10-Jul-01	CAII N	video survey	DMF/ NOAA GRANTS
F/V *Friendship*	15-Jul-01	NLSA, CAI	video survey	DMF/ NOAA GRANTS
F/V *Liberty*	17-Jul-01	Hudson Canyon	video survey	DMF/ NOAA GRANTS
F/V *Mary Anne*	15-Sep-01	S Channel	video survey	DMF/ NOAA GRANTS
F/V *Mary Anne*	23-Sep-01	CAII S	video survey	DMF/ NOAA GRANTS
F/V *Huntress*	5-Jul-02	NLSA	video survey	DMF/ NOAA GRANTS
F/V *Liberty*	5-Sep-02	S Channel	tagging exp.	DMF/ NOAA GRANTS
F/V *Friendship*	17-Sep-02	S Channel	video survey	DMF/ NOAA GRANTS

Whenever possible my students and I have presented this research to the public. For example: I was asked to be the keynote speaker for the 19th Annual High School Marine Science Symposium "Dynamic Marine Populations" (UMASS Dartmouth, 20 Mar. 2002) where I presented a talk entitled, "The population biology of sea scallops." Over 300 students from high schools across the commonwealth attended. Further we have presented our research to elementary, middle and high school students in the New Bedford area. These presentations include:

Stokesbury, K.D.E. The SMAST Sea Scallop Research Program. Marine Science program B, New Bedford VOKE, 5 May 03.
Stokesbury, K.D.E. The SMAST Sea Scallop Research Program. Marine Science program A, New Bedford VOKE, 30 Apr. 03.
Stokesbury, K.D.E. The SMAST Sea Scallop Research Program. Decas Elementary School, Wareham, 9 Apr 03.
Stokesbury, K.D.E. The SMAST Sea Scallop Research Program. 20th Annual High School Marine Science Symposium. University of Massachusetts Dartmouth, Feb. 03
Stokesbury, K.D.E. The SMAST Sea Scallop Research Program. Westport Elementary School 3rd Grade class. 16 January 2003.
Stokesbury, K.D.E. The SMAST Sea Scallop Research Program. Nativity Preparatory School of New Bedford. 11 January 2003.
Stokesbury, K.D.E. The SMAST Sea Scallop Research Program. An Industry-SMAST Scallop Research Presentation. New Bedford Whaling Museum 23 December 2002.

To continue our collaboration with the scallop fishing industry we have organized a steering committee made up of fishermen, owners and processors. This steering committee meets monthly to discuss management issues, the needs and concerns of industry, our present research and future goals. We have met ten times since this committee began in September 2002.

SMAST-Fishermen scallop steering committee planning the spring 2003 survey.

Table C.	Expenses for 6-day research cruises	per cruise	total 3 cruises
captain	$500 per day	$3,000	
3 crew	$300 per day per person	$5,400	
food		$2,679	
fuel		$9,000	
Total		**$20,079**	**$60,237**

Copies of the weight out sheets for each of the harvest cruises are provided in Appendix 4.

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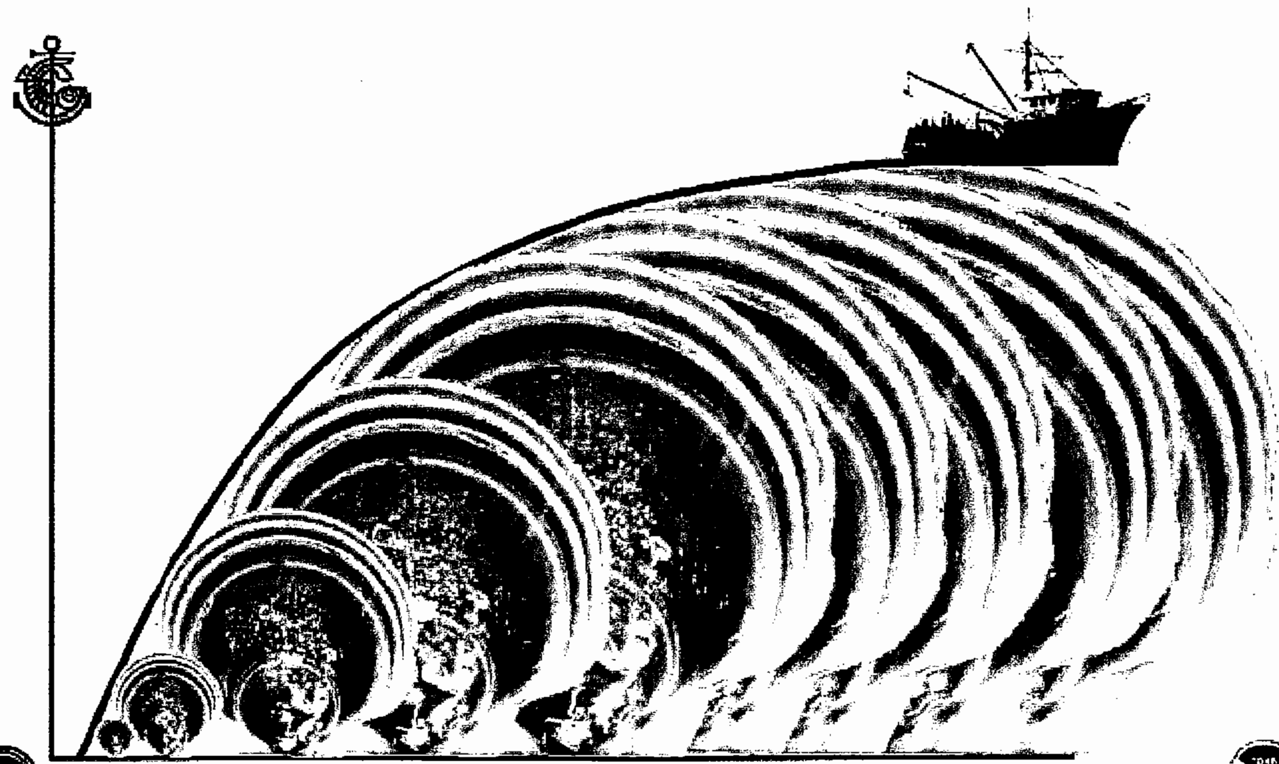
Thouzeau G, Robert G, Smith SJ (1991a) Spatial variability in distribution and growth of juvenile and adult sea scallops *Placopecten magellanicus* (Gmelin) on eastern Georges Bank (Northwest Atlantic). Mar. Ecol. Prog. Ser. 74: 205-218

Thrush SF, Hewitt JE, Cummings VJ, Dayton PK, Cryer M, Turner SJ, Funnell GA, Budd RG, Milburn CJ, Wilkinson MR (1998) Disturbance of the marine benthic habitat by commercial fishing: impacts at the scale of the fishery. Ecological Applications 8: 866-879

Appendix:

1) Harris, B. Shell growth estimate of the sea scallop *Placopecten magellanicus*, on Georges Bank. M.sc. Thesis proposal.
2) Marino, M. Examination of sea star-sea scallop predator-prey interactions on Georges Bank. M.sc. Thesis proposal.
3) Nogueira, J.I. Insight into the stock-recruitment relationship for the sea scallop *Placopecten magellanicus* M.sc. Thesis proposal.
4) Copies of the weight out sheets for each of the harvest cruises during NA16FM2416.

Shell growth estimate of the sea scallop, *Placopecten magellanicus*, on Georges Bank



Masters of Science Thesis Proposal Prepared by

Brad Harris

University of Massachusetts Graduate School of Marine Science and Technology

Advisor

Dr. Kevin D. E. Stokesbury

Committee

Dr. Jefferson Turner

Dr. Francis Juanes

Table of Contents

Abstract

The purpose of this study is to describe the shell growth of sea scallops, *Placopecten magellanicus*, on spatial and temporal scales on Georges Bank.

Sea scallops are found from Cape Hatteras, USA north along the continental shelf to the Straight of Belle Isle, Canada. Georges Bank contains the largest self-sustaining natural abundance of scallops in the world (Caddy 1989). In 2001 US commercial scallop landings totaled ≈47million lbs worth approximately $190 million. Landings from GB typically account for >50% of the US annual scallop landings.

Georges Bank scallops have been continually harvested since the end of WWII. Recently three large areas of Georges Bank were closed to scallop fishing to protect groundfish. Approximately 80% of the scallops on Georges Bank are now in areas inaccessible by the scallop fleet. No previous studies have assessed shell growth in scallop aggregations closed to commercial fishing. In 2001 the National Marine Fisheries Service (NMFS) reported the shell growth model being used for Georges Bank did not fit the observed scallop growth in the closed areas. Recent studies by the University of Massachusetts observe scallops as much as 31% larger than the maximum size presently estimated by the growth equation used by the NMFS.

Fisheries managers use scallop shell height to determine the annual harvestable biomass and the von Bertalanffy growth model to describe shell growth as a function of scallop age to predict subsequent annual scallop yield to the fishery. Scallop shells grow continually throughout life by depositing shell material on the outer edge of the shell. Environmental conditions such as water temperature, flow velocity, depth and food availability are known to impact shell growth rates. Several needs are evident in this field of research 1) an updated model for scallop shell growth is needed for Georges Bank, 2) A method for estimating scallop shell growth in areas closed to commercial fishing is needed, and 3) Spatially specific growth models are needed for the open and closed areas of Georges Bank.

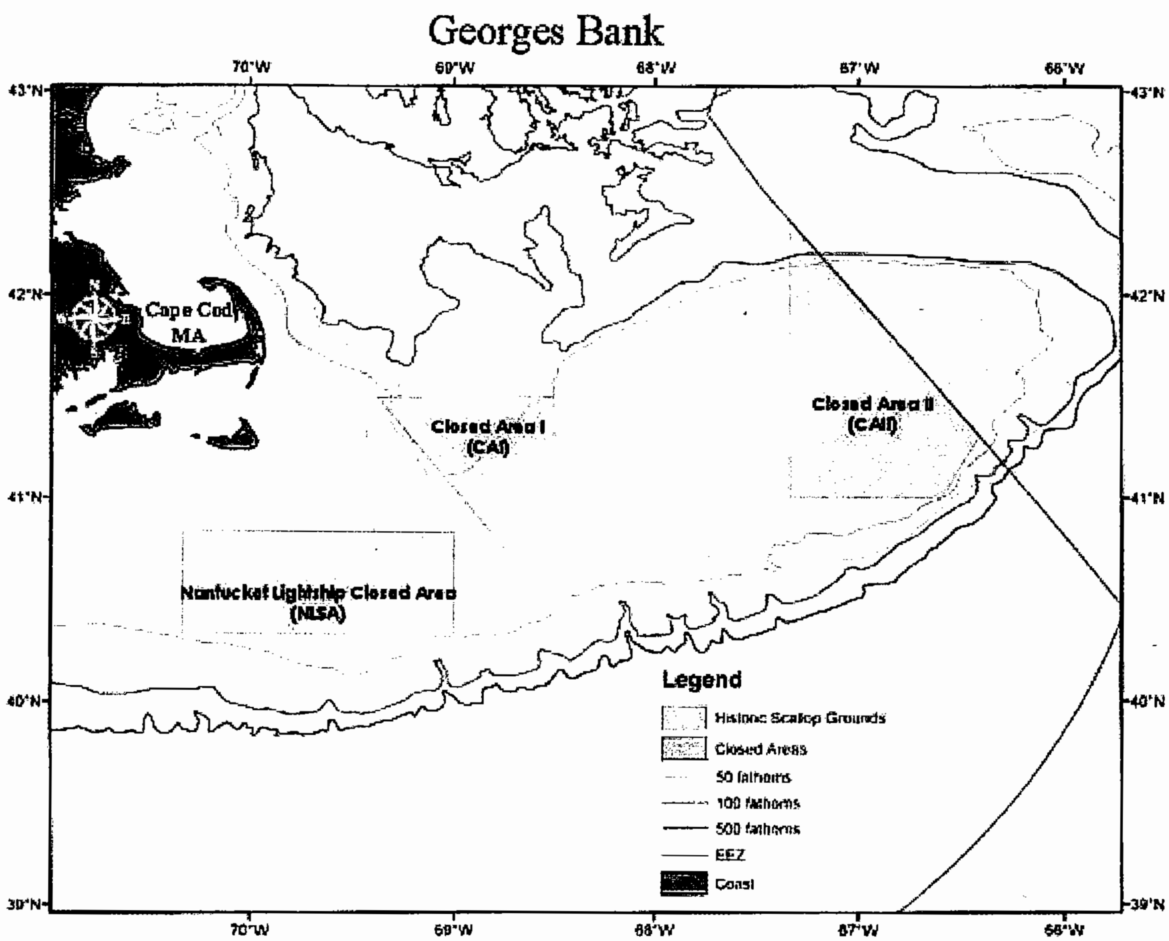
To address these needs we propose to test the following hypotheses: 1) *Sea scallop shell growth rates differ in the southern and northern portions of the Great South Channel.* 2) *Sea scallop shell growth rates differ in the southern GSC and the NLSA.* 3) *Sea scallop shell growth rates differ in the NLSA, CAI and the northern CAII.*

Scallops will be tagged to estimate growth in areas open to fishing and the University of Massachusetts School for Marine Science and Technology visual census method will be employed to estimate shell growth in closed areas.

Introduction

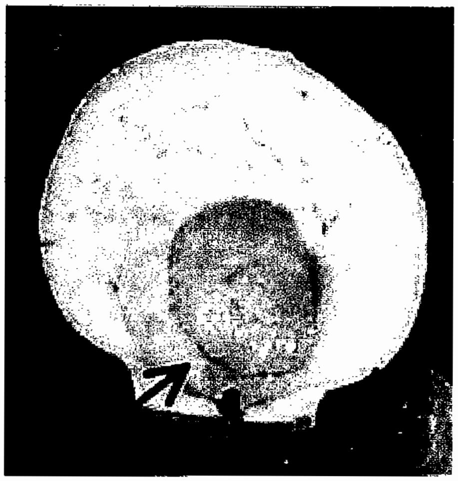
The sea scallop, *Placopecten magellanicus*, is a benthic bivalve mollusk inhabiting the northwest Atlantic Ocean along the continental shelf of North America from Cape Hatteras, USA to the Straight of Belle Isle, Canada. Sea scallops are found primarily on sand and gravel substrates in aggregated distributions on the scales of kilometers, meters and centimeters.(Caddy, 1989; Stokesbury, 1993)

Figure 1. Map of Georges Bank and Study Areas



Georges Bank (fig 1) contains the world's largest self-sustaining natural resource of sea scallops. (Posgay, 1979; Caddy 1989) This resource has been continually exploited since the end of WWII and presently supports the second largest fishery in the northeastern US. In 2001 US commercial scallop landings were worth approximately $190,000,000 ex vessel value. The US sea scallop commercial fishery is prosecuted with 1 or 2 large steel dredges (3-5 m wide) per commercial vessel. Scallops are processed or "shucked" at sea and only the adductor meats are landed (fig 2).

Figure 2. Scallop Adductor Meat



Scallop Adductor Meat

Figure 3. Scallop Shell height, tag and "shock marks"

The US commercially harvestable biomass (lbs of meat) of scallops is estimated by establishing a relationship between the shell size and the adductor meat weight. The equation $\mathbf{w = al^b}$, where w = adductor meat weight, a = constant, **b** = exponential factor, and ***l*** = shell height (fig 3) (measured from dorsal to ventral shell margins) is used to predict adductor meat weight. Total scallop biomass is calculated as $\mathbf{w * N}$, where **N** = number of scallops in the population. (SARC 2001) Thus, shell height information is required to determine scallop biomass. The change in scallop shell height over time (shell growth) is then used to predict the growth of scallop population biomass over time.

Shell growth rate is expressed as an increase in shell height per unit time. Curves are constructed to describe shell growth by establishing the relationship between shell height and scallop age using non-linear models like the von Bertalaffy growth function (VBGF) (Fig 4), which serve as predictive and comparative tools.

Ludwig von Bertalanffy (1938) suggested that the growth of an organism was like a reacting chemical system governed by the law of mass action. In living organisms, the physiological processes responsible for mass was either catabolic (breakdown) or anabolic (synthesis). Von Bertalanffy suggested that the rate of anabolism is proportional to the resorptive rate of nutritive material, and therefore proportional to the magnitude of the resorptive surfaces. Hence anabolism depends on the metabolic activity and dimensions of the scallop as well as the rate of food consumption. In contrast, catabolism was proportional to the total mass being broken down and therefore a constant percentage of body material is broken down per unit time. The rate of catabolism is only affected by the weight of the organism and the general level of metabolic activity. (Beverton and Holt, 1957)

The VBGF can be arranged to estimate the shell height (l_t) of a scallop of a given age where age is taken to be the time (t) after t_0. Where t_0 is the theoretical time at which the scallop has a shell height of zero if the postlarval growth trajectory is projected backwards. Actual age at the time the shell height is zero is very difficult to estimate as sea scallop larvae are pelagic and settled juveniles are small and difficult to capture. Therefore VBGF is not typically used to describe larval or early juvenile scallop shell growth, which follows a sinusoidal curve, but is used for post larval scallops within the size rage of the available shell height data. The maximum asymptotic shell height (L_∞) is the largest shell height attained by scallops in a given growth environment. The Brody growth coefficient (K) describes the rate at which shell height approaches L_∞. (Beverton and Holt 1957)

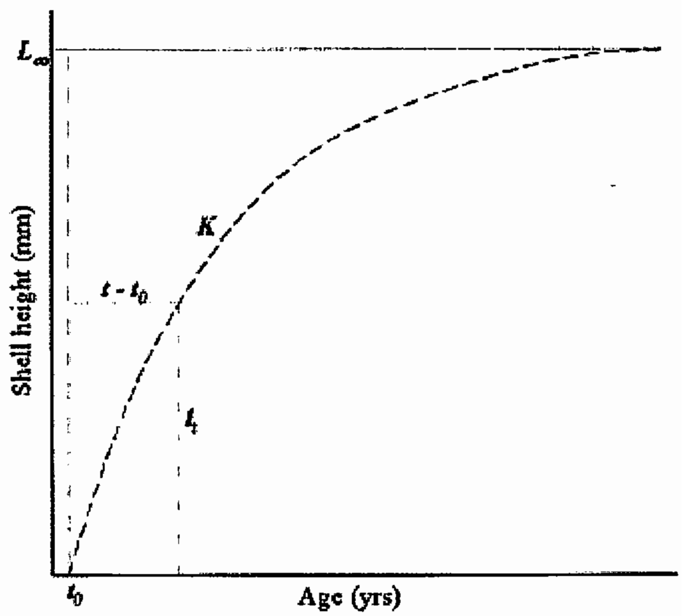
The VBGF is the most common model used to describe post larval scallop shell growth as a function of time. Polynomial equations may also be fit to scallop shell growth data but are used less frequently as their coefficients have no biological meaning.

Scallop shell growth is affected by water depth, temperature, flow velocity and food availability and as such varies spatially and temporally. (Wildish and Kristmanson, 1988; MacDonald and Thompson, 1985; Schick et. al, 1988) Scallop aggregations on Georges Bank cover thousands of km^2, and as such are subject to a variety of depth, temperature, flow and food availability conditions. The impact of growth condition variability over time and space are integrated into the scallops shell growth increment samples collected over growth study areas. The methods proposed in this study do not permit the explicit description of the effects of these environmental conditions on shell growth, but will suggest areas for further research to determine area specific causes of shell growth variability.

Figure 4. von Bertalanffy Growth Function (VBGF)

$$l_t = L_\infty\left[1 - e^{-K(t-t_0)}\right] + \varepsilon$$

Where
l_t = size of an individual at time t,
L_∞ = asymptotic size
K = Brody Growth Coefficient
t_0 = size at time = 0
ε = normal distribution of residuals



Previous research

Many studies have estimated scallop shell growth including (Stevenson, 1936; Cahisson, 1949; Welch, 1950; Stevenson and Dickie, 1954; Hayes, 1966; Merril *et al.*, 1969; Naidu, 1969, 1975; Jamieson, 1979; Posgay, 1979; Posgay and Merril, 1979; Ehinger, 1982; Serchuk *et al*., 1979; Serchuk *et al*., 1982; Serchuk and Rak, 1983; Choinard, 1984; Krantz *et al*., 1984; Mohn *et al*., 1984; MacDonald and Thompson, 1985; Roddick and Mohn, 1985, Schick and Shumway, 1988; Thourzeau et al., 1991; Dadswell and Parsons, 1992; Parsons *et al*., 1993). The majority of these studies estimated VBGF equations by counting rings on scallop shells or tagging and all sampled scallops with dredges or SCUBA. The ring-count method assumes the rings are annual; an assumption that is not valid throughout the range of the species (Dupaul 1978, SMAST unpublished data). In the scallop's northern range (Northern Gulf of Maine and Canadian waters) annual growth rings have been shown to be annual, and are more pronounced due to stronger seasonality in growing conditions. However, annual shell rings cannot be reliably identified on scallops in the central (Gulf of Maine and Georges Bank) and southern (Mid Atlantic) regions. Disturbance events, such as sever storms, and contact with commercial fishing gear can cause "shock" rings (fig 3) on scallop shells further confounding aging with shell rings. (Merril et. al, 1966) Posgay (1963) is the only previous study to use tagging to estimate scallop shell growth on Georges Bank. They used tagging to validate aging via shell rings and sampling was limited to dredges.

Closed Areas

In 1994 three large areas of Georges Bank were closed to all bottom-tending mobile fishing gear, including scallop dredges, in order to conserve groundfish stocks (fig 1). These areas contain approximately 80% of the Georges Bank scallop resource. Since 1994 the abundance of scallops in the closed areas has increased to record levels and fisheries managers report evidence of increased shell growth rates.

The Problems

1. *An updated VBGF for scallop shell growth is needed for Georges Bank.* The data used by Serchuk (1979) to estimate the VBGF presently employed National Marine Fisheries Service (NMFS) to manage the scallop fishery was collected forty-five years ago. The NMFS reports that this VBGF does not accurately describe the scallop growth they observe in the closed areas. (SAW 2001)

2. *A method for estimating scallop shell growth in areas closed to commercial fishing is needed.* Marine Protected Areas (MPA) are becoming a common tool used to protect marine habitat and control fishing mortality. No studies have estimated scallop growth in commercially viable scallop aggregations closed to fishing.

3. *Spatially specific VBGFs are needed for the open and closed areas of Georges Bank.* In spite of research indicating that scallop shell growth varies with water depth, temperature and food availability a single VBGF is presently used for the entire Georges Banks scallop resource. Fishery management are poised to implement a harvest area rotation strategy which requires shell growth information from harvest areas presently open and closed to commercial fishing.

2001 Budget.

DMF ISA Budget

Personnel	**Salary**	**Fringe at 30.75%**	**Fringe at 1.75%**	**Total**
Stokesbury (50% AY)	$28,000.00	$8,610.00		$36,610.00
Stokesbury (100% June, '01)	$6,222.22		$108.89	$6,331.11
Postdoctoral Associate (a)	$26,615.38	$8,184.23		$34,799.61
Two Technicians (b)	$60,000.00	$18,450.00		$78,450.00
secretary c)	$11,250.00	$3,459.38		$14,709.38
Subtotal				$170,900.10
Scallop Vessels (Four 5-day Cruises)				**Expense**
Three Crew @ $150/day				$9,000.00
Captain @ $200/day				$4,000.00
Fuel @ $5,000/Cruise				$20,000.00
Food @ $100/day				$2,000.00
Subtotal				$35,000.00
Non-Personnel				**Expense**
Winch for Deploying Video Equipment				$30,000.00
New Cables for Deploying Video Equipment				$5,000.00
2 TV Monitors with Built-in VCRs				$600.00
Computer Workstation and Measuring Software				$8,500.00
Subtotal				$44,100.00
Administrative Expenses				$0.00
Total Budget				$250,000.10

a) Starting Date 11/1/00 @ $40,000/year
b) Starting Date for both Technicians10/1/00 @ $40,000/year
c) half-time

2002 Budget.

	per vessel	Total 6 cruises
Requested TAC for harvest cruises (pounds)	**17900**	**107400**
Value ($4.5 per lb)	$80,550	$483,300
Expenses (EITHER a research cruise OR SMAST support)	**$20,079**	$120,474
Expenses deducted	$60,471	$362,826
Boat share (0.42)	$25,398	$152,387
Crew share (0.58)	$35,073	$210,439
Share per crew member (6)	$5,846	$17,537

Table B.			**SMAST Expenses**	per cruise	total 3 cruises
Salaries	1.	P. I.	Kevin Stokesbury (1 mo./yr.)		$6,533
	2.	Technician (Brad Harris 6 mon.)			$17,325
	3.	Graduate Student (6 mon.)			$10,000
Subtotal Salaries					$33,858
Benefits					
	1.		At 1.75%		$114
	2.		At 23.75%/ $9/week		$4,349
	3.		At 1.45% summer only		$75
Subtotal Benefits					$4,538
Total Salary and Benefits					$38,396
Other Direct Costs					
			Supplies and Equipment		$2,000
Indirect Costs					
	1.		At 58.6% of Salaries		$3,828
	2.		At 58.6% of Salaries		$10,152
	3.		At 58.6% of Salaries		$5,860
Total Indirect Costs					$19,841
Total Direct and Indirect Costs				**$20,079**	**$60,237**

Table C.	**Expenses for 6-day research cruises**	per cruise	total 3 cruises
captain $500 per day		$3,000	
3 crew $300 per day per person		$5,400	
food		$2,679	
fuel		$9,000	
Total		**$20,079**	**$60,237**

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Examination of Sea Star – Sea Scallop Predator – Prey Interactions on Georges Bank

Thesis Proposal

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15 May 2003

Summary

Goal / Hypotheses: To spatially examine the sea scallop-sea star predator-prey interaction for closed and open areas of Georges Bank. This examination will involve testing the following hypotheses: 1.) Sea stars are aggregating in the closed areas of Georges Bank; 2.) Sea star aggregations are moving from one scallop aggregation to another within the closed areas; 3.) Sea stars are larger in the closed areas than in the open areas of Georges Bank; 4.) Sea star predation on sea scallops is site-specific causing high levels of localized natural mortality.

Rationale: Predation strongly influences the structure of benthic marine communities (Menge 1982; Caddy 1988; Himmelman and Dutil 1991). Sea stars (*Asterias spp.*) are a primary predator in bivalve dominated benthic communities (Menge 1982). Georges Bank supports one of the world's largest sea scallop (*Placopecten magellanicus*) natural resources. Sea scallops are a bivalve that sustain both a constant mortality rate associated with sea stars and have experienced mass mortalities due to intense sea star predation (Dickie and Medcof 1963; Stokesbury and Himmelman 1995).

In 1994, three large areas of Georges Bank were closed to all mobile fishing gear. Effects of these closures on the marine environment, specifically natural mortality, are unclear. Video survey results indicate approximately 80% of the Georges Bank sea scallop resource are currently contained in these closed areas (Stokesbury 2002). The distributions of these sea scallops are highly aggregated, which may aggregate predators, including sea stars. Aggregating predators may result in increased site-specific natural mortality rates in these areas. Natural mortality is an important component of population simulation models used to estimate stocks over time in the management of this fishery. Estimates of site-specific natural mortality have direct implications for rotational fisheries management, currently under consideration by the New England Fishery Management Council for Georges Bank. A spatially specific examination of the sea scallop-sea star predator-prey interactions for closed and open areas of Georges Bank will provide insight into the ecosystem food-web structure and a key component of sea scallop natural mortality rates, which both have direct impacts on different management strategies.

Methods: To examine the sea star – sea scallop predator – prey interactions, I will use the video database that the School for Marine Science and Technology (SMAST) collected in the closed and open areas of Georges Bank from 1999-2002. This examination will involve: 1.) estimating and comparing the density of sea stars and the number and size of aggregations between open and closed areas of Georges Bank; 2.) determining shifts in sea star densities, to observe if the sea star population is moving from one scallop aggregation to another; 3.) measuring the length from the tip of an average size arm to the center of the disc (mouth) and comparing sea star arm length frequencies between open and closed areas; 4.) correlating the distributions of live scallops and clappers (dead scallops) to densities and distributions of sea stars to determine if predation is site-specific.

Introduction

The goal to spatially examine the sea scallop-sea star predator-prey interaction for closed and open areas of Georges Bank will enhance the understanding of the ecosystem food-web structure and sea scallop natural mortality rates.

Predation strongly influences the structure of benthic marine communities (Menge 1982; Caddy 1988; Himmelman and Dutil 1991). Sea stars (*Asterias spp.*) are a primary predator in bivalve dominated benthic communities, including economically significant commercial bivalve fisheries (Menge 1982). Sea scallops are bivalves that sustain both a constant mortality rate associated with sea stars, *Asterias vulgaris* [=*Asterias rubens* (Clark 1992)] and have experienced mass mortalities due to intense sea star predation (Dickie and Medcof 1963; Stokesbury and Himmelman 1995).

Georges Bank supports one of the world's largest sea scallop (*Placopecten magellanicus*) natural resources and is the second highest valued fishery in the Northeast United States (Posgay 1979; Caddy 1989). A single estimate of the natural mortality rate (M) is used in the management of the Georges Bank sea scallop fishery of $M = 0.1\ y^{-1}$ (Merrill and Posgay 1964; NEFSC 2001). This estimate is based on the relative number of clappers (dead scallops from natural mortality) to the total number of scallops observed. Fisheries models rely on accurate estimates of natural mortality in determining sustainable fishing levels, to avoid over exploitation. Causes of mortality in scallop stocks are an increasingly complex issue as changes, such as area closures, are made to manage this fishery (Medcof and Bourne 1964). Therefore, components of natural mortality, including predator – prey interactions, must be assessed and reassessed as changes in management are made.

In 1994, three large areas of Georges Bank were closed to all mobile fishing gear in an effort to protect declining groundfish stocks (Murawski et al. 2000). Effects of these closures on the marine environment are unclear. Video survey results indicate approximately 80% of the Georges Bank sea scallop resource are currently contained in these closed areas and have a highly aggregated distribution (Stokesbury 2002). Therefore, natural predators may be attracted to these highly aggregated scallop patches. Predator movement between these scallop aggregations can be associated with high levels of site-specific natural mortality. Research suggests natural mortality due to sea star predation is highly site-specific (Merril and Posgay 1964; Brun 1968; Dare 1982). Estimates of this site-specific natural mortality are required to implement a rotational management plan, which is currently being considered by Scallop Fisheries Management for Georges Bank (Hart 2003).

Although the importance of bivalve density on sea star predatory mortality has been documented in numerous studies (Menge 1979; Jost 1980; Sloan and Aldridge 1981; Dare 1982; Volkov 1983; Sloan 1984; Caddy 1989), most of the research is based on observations in tidal, subtidal, and aquaculture environments and in laboratory experiments. Direct studies of these interactions have not been conducted on Georges Bank. Furthermore, Barbeau and Scheibling (1994) recommended further research on natural conditions, specifically to see if scallop density has an effect on sea star predation.

This research examines the effects of sea scallop density on the sea star – sea scallop predator – prey interactions. This examination will involve testing the following hypotheses: 1.) Sea stars are aggregating in the closed areas of Georges Bank; 2.) Sea star aggregations are moving from one scallop aggregation to another within the closed areas; 3.) Sea stars are larger in the closed areas than in the open areas of Georges Bank; 4.) Sea star predation on sea scallops is site-specific causing high levels of localized natural mortality.

Hypothesis 1: Sea stars are aggregating in the closed areas of Georges Bank

Sloan (1984) suggests most predatory asteroid species will aggregate on superabundant food in keeping with their role as responsive opportunistic predators. Sea star aggregations and migrations are created by the summation of individual reactions to environmental stimuli (Sloan 1980). The most important stimulus is feeding, specifically super abundant food sources. Dare (1982) concluded that large dense aggregations of the sea star, *A. rubens,* are highly efficient predators, which can have catastrophic impacts on local bivalve fisheries. Dare (1982) observed *A. rubens* aggregations with densities up to 300-400 sea stars m^{-2} that traveled up to 300 m in 2 months and totally cleared 0.5-km^2 of seed mussels (equivalent to 3900-4900 tons) in Morecambe Bay. Additionally, sea star aggregations were observed feeding on beds of Icelandic scallops, *Chlamys islandica*, devouring all scallops in its path (Brun 1968).

As previously stated, approximately 80% of the Georges Bank sea scallop resource are contained in the closed areas (Stokebury 2002). Therefore, natural predators may be attracted to these scallop aggregations. I propose to test the hypothesis that sea stars are aggregating in the closed areas.

Hypothesis 2: Sea stars are moving from one scallop aggregation to another within the closed areas

Sea scallops, *Placopecten magellanicus,* are one of the strongest swimmers of the 400 species of scallops (Dadswell and Weihs 1990). Sea scallops frequently swim to escape sea star predation (Brand 1991; Stokesbury and Himmelman 1996). Menge (1982) suggests that this highly developed escape response triggered by the presence of sea stars, specifically *A. vulgaris*, suggests that sea star predation has been an intense and chronic selective force on sea scallops over evolutionary time. The ability to swim is another determinant in the vulnerability of sea scallops to predators. Sea scallop vulnerability to different predators changes as the sea scallop grows (Barbeau and Scheibling 1994; Barbeau and Scheibling 1994a). Larger scallops do not escape from sea stars as often by swimming than smaller scallops. This is important because the sea scallops observed in the closed areas were some of the largest sea scallops ever observed on Georges Bank (Stokesbury 2002). Thus these large sea scallops maybe more vulnerable to sea star predation compared to smaller sea scallops.

Additionally, observations were made on sea star aggregations following dispersing aggregations of seeded scallops (Volkov et al. 1983). Sea stars search for food using distance chemoreception and or by relying on chance encounters (Dickie and Medcof 1963; Sloan and Campbell 1982). The chemical sense of sea stars to detect food has been observed to be limited, with varying estimates (Smith 1940). Estimates vary depending on direction of water movement relative to the prey and predator and the intensity and concentration of the perceptible matter released by the prey (Smith 1940; Feder and Christensen 1976). However most movements have been described as random wandering, but modified when food is very close at hand (Feder and Christensen 1976).

The maximum distance traveled by a marked sea star was 200 m in four months (Smith 1940). As food sources become depleted within a scallop aggregation (clump), sea stars will move to another food source, possibly to another sea scallop aggregation. Therefore I hypothesize that sea star aggregations are moving from one scallop aggregation to another within the closed areas.

Hypothesis 3: Sea stars are larger in the closed areas than in the open areas of Georges Bank

Generally, prey size is regarded as an important factor affecting prey vulnerability (Juanes 1992; Barbeau and Scheibling 1994a). Sea stars have strict limitations on the size and shape of their prey and prey size increases with predator size (Birkeland 1974; Paine 1976; Anger et al. 1977; Hulbert 1980). Above this maximum size of prey, the muscle force is insufficient to open the shells or the feeding process, in terms of handling time, becomes so long that it leads to energy loss (Feder and Christensen 1967; Anger et al. 1977; O'Neil et al. 1983). Needler (1941) indicates that a sea star must be at least 1 ½ times the diameter of its prey to kill it. Therefore, juvenile bivalves are considered to be the most vulnerable (Juanes 1992). Sea stars also form groups on large bivalves to overcome these limitations (Anger et al. 1977; Hulbert 1980; Doering 1981; Sloan 1981; Stokesbury and Himmelman 1995; MacKenzie 1999). Further, sea stars feeding separately exhibit differences in size-selective feeding behavior compared to those feeding in aggregations of mixed size classes (Hulbert 1980; O'Neil et al. 1983). Larger prey is increasingly consumed when sea stars are feeding in these mixed size aggregations. As implied by the size limitation of sea stars, the magnitude of the predatory effect depends on the size distribution of the sea stars relative to that of sea scallops.

Additionally, sea star growth depends on the abundance of food available. Sea stars are capable of assimilating large quantities of food, if the food source is abundant (Feder and Christensen 1967). Smith (1940) showed that with an abundance of food, small sea stars (22.5-35mm in diameter) could increase their diameter by 40% in one month. The basic concept is that if there is a super abundant food source, sea stars will efficiently consume more prey and will thereby increase in individual size. However, Paine (1976) showed that sea stars in low densities relative to its resource are of larger size, while, at higher densities, the mean individual predator size is small. In order to determine the functional role of *A. vulgaris*, it is important to know what size classes are present (Hulbert 1980).

Consequently, I intend to test the hypothesis that sea stars are larger in the closed areas than in the open areas of Georges Bank, because of the relatively abundant sea scallop food source present. Analysis of this hypothesis will be conducted to determine the size structure and hence the functional role of *A. vulgaris*. This analysis will also attempt to observe if high densities of sea stars will have a smaller or larger mean individual predator size than those in low densities in the open areas.

Hypothesis 4: Predation of sea scallops is site-specific causing high levels of localized natural mortality

Sea stars have been shown to respond rapidly to short term changes in feeding conditions (Menge 1972; Anger et al. 1977; Barbeau and Scheibling 1994). Sea stars are capable of assimilating large quantities of food, if available (Feder and Christensen 1967). Additionally, sea stars, *Asterias rubens* has been shown to increase its feeding activity in the presence of enhanced food availability (Sloan 1984). Therefore, if chemoreceptive senses or random wandering leads a sea star aggregation into clumps of prey, sea stars can eliminate the entire clump. Brun (1968) observed such a phenomenon, where sea star aggregations were observed feeding on beds of Icelandic scallops, *Chlamys islandica*. The extreme densities of sea stars were observed in a band like formation (10 m wide by 100 m long) devouring all scallops in its path. Dare (1982) observed similar swarms of sea stars eliminating numerous scattered mounds of mussels in three months. These examples of high-localized natural mortality indicate the catastrophic impact that sea star aggregations can have on local prey populations. Merrill and Posgay's (1964) observation of high temporal and spatial variability of natural mortality also indicates site-specific, high levels of natural mortality. Furthermore, Stokesbury (2002) also suggested natural mortality is highly site specific and may be related to sea scallop density.

Accurate estimates of site-specific natural mortality are important for different management strategies, such as rotational management, which is currently being considered by Scallop Fisheries Management for Georges Bank (Hart 2003). Aimed to improve scallop yield, rotational management is a strategy of rotating harvesting between open and closed areas on a fixed schedule. This warrants analysis of the hypothesis that sea star predation on sea scallops is site-specific causing high levels of localized natural mortality. Through such analysis, the severity of sea star predation on sea scallop aggregations and the effects of closed areas, in terms of natural mortality, can be determined.

Hypotheses

In summary, I will test the hypotheses that: 1.) Sea stars are aggregating in the closed areas of Georges Bank; 2.) Sea star aggregations are moving from one scallop aggregation to another within the closed areas; 3.) Sea stars are larger in the closed areas than in the open areas of Georges Bank; 4.) Sea star predation on sea scallops is site-specific causing high levels of localized natural mortality.

By examining these four hypotheses we hope to better understand the sea scallop – sea star predator-prey relations on open and closed areas of Georges Bank. This understanding will provide insight into both ecosystem food-web structure and a key component of sea scallop natural mortality rates, which both have direct impacts on different management strategies, such as rotational management. This research will provide the first spatially specific examination of sea star - sea scallop predator – prey relations for open and closed areas of Georges Bank. A peer – reviewed scientific publication is anticipated from this research.

Methods and Data Analysis

To examine the sea star – sea scallop predator – prey interactions, I will use the SMAST and Industry based video survey conducted from 1999-2002. The survey is a centric systematic design placing stations evenly across the entire survey area on a grid with 1.57 km (0.85 nautical miles) between stations (Fig. 1). At each station a fishing vessel deployed the video camera mounted on the sampling pyramid providing 3.235-m^2 quadrat image of the sea floor (increased from 2.8-m^2 due to edge effect). A second camera was mounted on the pyramid providing a second image with a 0.6-m^2 area. After the first quadrat the pyramid was raised so that the sea floor could no longer be viewed, the vessel drifted for approximately 50 m and then the pyramid was lowered again to obtain a second image. This procedure was repeated four times to provide four quadrat samples at each station. This technique of sampling stations as the primary sampling unit and sampling four quadrats within each station is termed a two-stage sampling design. Images of the sea floor were recorded on a standard VHS tape. Along with each image, the time, depth, number of scallops observed, and latitude and longitude were recorded. After each survey, the videotapes were replayed in the laboratory and an image of each quadrat was digitized. Using the digitized images, scallop (live and dead) counts were verified, substrates and fish were identified, and invertebrates, including sea stars were counted and measured (mm) using ImagePro® image analysis software. (Stokesbury 2002).

In May – August 2003, SMAST in conjunction with the Scallop Industry will conduct a similar video survey, surveying all major scallop aggregations from the Hague line to Cape Hatteras on a grid with 5.56 km (3 nautical mile) in between stations. Data from this survey will be used to increase the amount of observations, specifically open area observations.

Hypothesis 1: Sea stars are aggregating in the closed areas of Georges Bank.

To test this hypothesis the density of sea stars and the number and size of aggregations will be compared between open and closed areas of Georges Bank. These aggregations will also be compared over time to determine shifts in these parameters. Sea star and sea scallop densities and standard errors will be calculated using equations for a two-stage sampling design (Krebs 1999; Stokesbury 2002):

The mean density of the total sample is:

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

where: n = Primary sample units (stations)

$\bar{\chi}_i$ = Mean value of the elements (quadrats) in primary unit I (stations)

The standard error of this mean density is:

$$\text{S.E.}(\bar{\chi}) = \sqrt{\frac{1}{n}\left(s^2\right)}$$

where: $s^2 = \sum^{n} (\bar{\chi}_i - \bar{\chi})^2 / (n-1)$ = Variance among primary unit density means

Aggregations will be determined by comparing observed distributions to the Poisson (Random) and Negative Binomial distributions using chi-square analysis. Aggregated distributions are described by the negative binomial distribution, when variance of the density is greater than the mean density (Elliot 1971).

Hypothesis 2: Sea stars are moving from one scallop aggregation to another within the closed areas

To test this hypothesis, distributions of sea stars will be compared between years for stations that were repeatedly sampled (Table 1). Circular statistics, such as Hotelling's one-sample T2-test have been used in predator-prey and spatial distribution theory. This examination will be used for bivariate analysis to determine shifts in sea star densities to observe if the population's center of 95% confidence ellipse deviates significantly from its origin (Batschelet 1981; Stokesbury and Himmelman 1996; Zar 1996). From this bivariate analysis, the direction and distance of a shift can be calculated.

Hypothesis 3: Sea stars are larger in the closed areas than in the open areas of Georges Bank

Sea star size is determined by measuring the length from the tip of an average size arm to the center of the disc (mouth) (Sloan and Aldridge 1981; Barbeau and Scheibling 1994). Sea stars will be measured using ImagePro® image analysis software. Sea star arm length frequencies will then be compared between open and closed areas. The Kruskal-Wallis test, which is a nonparametric analysis of variance used to detect differences among groups, will be used for arm length comparisons (Zar 1996). Figure 2 shows an example of preliminary data from the 2002 survey, indicating individual sea stars within the closed areas attained larger individual sizes compared to open areas.

Hypothesis 4: Predation on sea scallops is site-specific causing high levels of localized natural mortality

The distributions of live scallops and clappers (dead scallops) will be correlated to densities and distributions of sea stars, on the scale of centimeters, meters, and kilometers (Barbeau et al. 1996; Hatcher et al. 1996). Preliminary data from the 2002 video survey indicate the areas of highest sea star density overlap with areas where densities of sea scallops are highest (Fig. 3). Sea star densities will also be plotted against sea scallop densities to see if sea star densities increase with increasing sea scallop density (Barbeau et al. 1998). Furthermore, the severity of sea star predation pressure on sea scallop aggregations will be determined by examining the number of sea stars physically preying on sea scallops and other prey species. This analysis will incorporate predation rates and sea star movement estimates documented in the literature. Analysis will involve the use of spatial overlap indices, which will measure the overlap in resource use (space) between these two species, and nearest neighbor analysis, which will measure the distance from an individual to its nearest neighbor, to quantify how frequently these species co-occur (Krebs 1999).

Schedule of Work

1-Jun-02	Begin Project
1-Sep-02	Completion of 2002 video sampling season and basic data processing
20-Dec-02	Completion of semester (courses)
20-May-03	Completion of semester & thesis proposal, including literature review and hypotheses development
1-Sep-03	Completion of 2003 video sampling season, data processing, and testing of hypotheses 1 and 2
20-Dec-03	Completion of semester (courses) and testing of hypotheses 3 and 4
20-May-04	Write thesis and primary publications
1-Sep-04	Completion of thesis and primary publications

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Budget / Funding

This project has been peer reviewed by three anonymous reviewers and has been funded by the UMASS / NOAA Cooperative Marine Education Research Program. (Refer to table below).

Salaries	Student		$20,000
	Academic year	$12,000	
	Summer	$8,000	
	Kevin Stokesbury (1 wk summer)		$1,633
	Francis Juanes (1 wk summer)		$1,633
Benefits	At 1.45% Summer (Student)		$116
	At 1.45% Summer (Stokesbury)		$29
	At 1.45% Summer (Juanes)		$29
Travel			$1,000
Indirect Costs (20% of total direct costs minus equipment, CMER)			$4,888
Equipment (software upgrades, paper charges, phone)			$1,000
Yearly Total			$30,328
Total funding by CMER grant over two years			$60,655

Figures and Tables

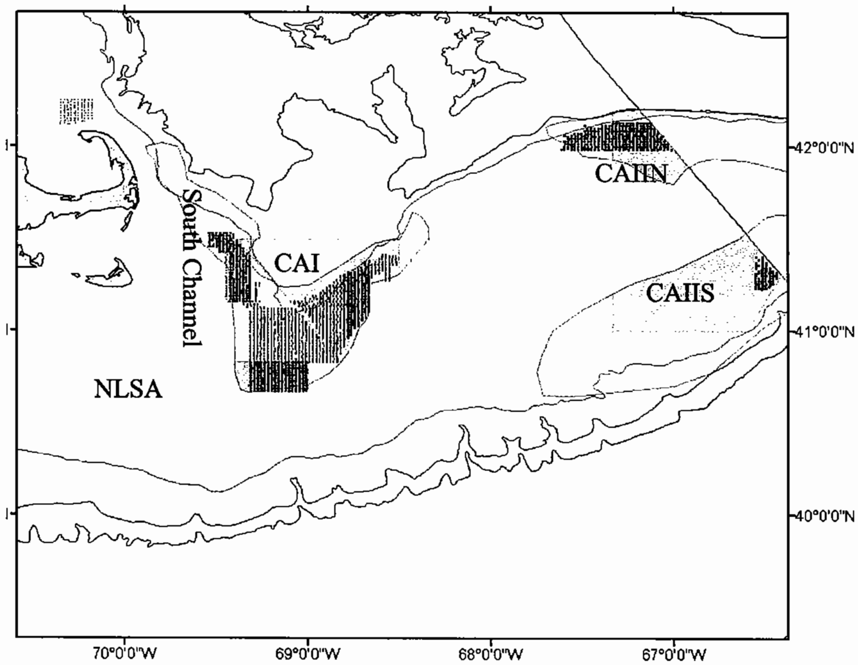

Figure 1. Georges Bank with the Nantucket Lightship Area (NLSA), Closed Area I (CAI), and Closed Area II (North (CAIIN); South (CAIIS)) outlined (gray), the historic scallop fishing beds (pink) and the video stations on a 1.57 km grid (black dots).

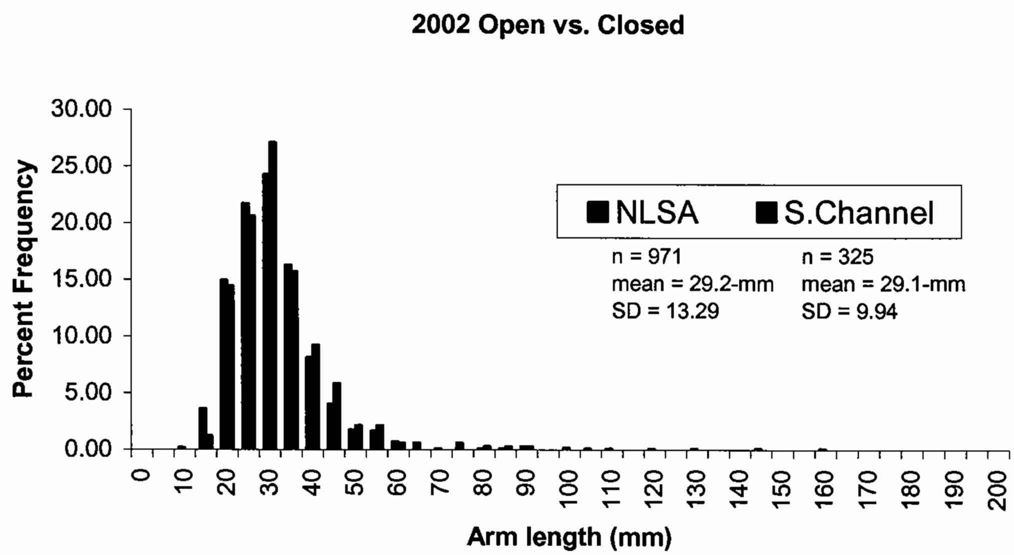

Figure 2. Sea star arm length frequencies observed in open and closed fishing areas from June to September 2002.

Insight into the stock- recruitment relationship of the sea scallop *Placopecten magellanicus*

Thesis Proposal- 5/15/03

Jacob I Nogueira

The relationship between the spawning stock biomass (SSB) of marine populations and recruitment success is a critcal biological question that has been studied for many years. It is the most critical piece of information to the management of fisheries yet it is the most poorly understood (Haddon 2001; Hilborn and Walters 1992). In many cases, we can merely speculate about the stock- recruitment relationship by applying limited data to theoretical models, such as the Ricker or Beverton- Holt stock-recruitment model.

Both models predict that recruitment initially increases with increasing spawning stock abundance. This is inherent in the fact that with zero spawners there is zero recruitment so there must be an initial increase. Recruitment success continues to increase as the number of spawners, and hence zygote production increases. However, the population eventually approaches the carrying capacity, or the maximum size it is able to achieve given the restraints of the environment. At this point the Beverton- Holt curve predicts that recruitment reaches an asymptote, and the Ricker curve predicts a decline in recruitment (figure 1). The Beverton- Holt model assumes that the carrying capacity only relates to the density of offspring while the Ricker curve assumes that it relates to all the cohorts in the population (Haddon 2001).

The decline is predicted because high densities of adults may limit recruitment via compensatory mortality (Ricker 1954). In other words, though the number of zygotes produced increases, the mortality of these offspring also increases as a result of the increase in adult density. Several mechanisms could explain this effect including competition for living space, cannibalism, and competition for food (Ricker 1954). Another compensatory mortality mechanism is the aggregation of predators on high densities of prey (Dare 1982; Sloan 1984; Volkov et al 1983). Data from various invertebrate populations suggest that these processes occur but it is not clear whether they occur in sea scallops *Placopecten magellanicus*.

Competition for living space.

Scallop spat settle and attach to the sea floor via byssal threads after a pelagic larval period of approximately 30-40 days (Tremblay and Sinclair 1994). They may settle on filamentous flora and fauna such as hydra and bryozoa in higher numbers than other substrates (Minchin 1992; Stokesbury and Himmelman 1995). If these settlement media are necessary for the survival of scallop spat, then they could be a limiting factor in recruitment. However adult scallops may *increase* the amount of hydra and bryozoa, as the shells of live scallops supports the growth of these animals (Stokesbury and Himmelman 1995). Thus, the number of adult scallops may increase the number of settlement sites available to spat, which would have a *compensatory* effect on recruitment (recruitment increases with increasing density. Scallops also settle on sand, pebbles, and shell fragments (Minchin 1992; Stokesbury and Himmelman 1995). It is not clear what settlement substrata are most conducive to the survival of juvenile scallops or if any particular feature of the sea floor is necessary for scallop recruitment.

It is difficult to imagine adult scallops exhausting the number of suitable settlement sites, however, space competition can be aggravated by territoriality (Ricker 1954). This could facilitate compensatory mortality, as the amount of available space would decrease with increasing density, leading to longer search times for juveniles. This could utilize resources, compromise growth, increase exposure time to predators, and displace settlement to unfavorable areas, all of which could lead to mortality. Territoriality has not been observed in the natural environment, however no directed studies have been conducted and the behavior may be subtle or infrequent, making it difficult to document.

Cannibalism.

Cockles, *Cardiem edule*, and mussels, *Mytilus edulis*, sometimes kill the recently settled larvae of their own species (Kristensen 1957; Bayne 1964; Davenport 2000). The larvae are sucked in through the siphon tube, and usually die even if they are not digested (Kristensen 1957; Bayne 1964). This behavior was used to partially explain the lack of young of the year (YOY) cockles in areas of high adult density (Kristensen 1957) and the fact that mussel larvae seldom settle on adult beds (Bayne 1964).

There is no evidence of adult scallops ingesting and killing juveniles, but it should be entertained as a possibility. Scallop larvae settle at a size of 240-300 μm (Tremblay and Sinclair 1994), and particles as large as 350 μm have been found in the guts of sea scallops in the Gulf of Maine (Shumway et al 1987). Most of the diet of scallops consists of algae, although Shumway et al (1987) found some zooplankton tests between 100 and 250 μm in scallop stomachs.

Considering that animals are rarely found in the stomachs of sea scallops and settling scallop larvae are near the limit of the size fraction of particles that scallops ingest, it is unlikely that adult scallops could inflict substantial mortality on the larvae of their own species. However the data are limited and a "cannibalistic" effect should not be dismissed. Stomach content analysis of adult scallops at the time of spat fall and laboratory feeding experiments are necessary to determine whether "cannibalism" occurs.

Aggregation of predators.

Sea stars are a major predator of scallops (Dickie and Medcof 1963; Stokesbury and Himmelman 1995) and display an aggregative response to prey (Dare 1982; Sloan 1984; Volkov et al 1983). The sea star, *Asterias rubens*, aggregated on prey in the laboratory (Sloan 1984). In the Sea of Japan shifts in the distribution of the scallop, *Patinopecten yassoensis*, and predatory sea stars coincided, and predation by the sea stars substantially reduced the density of the scallops (Volkov et al 1983). In aquaculture studies YOY sea stars that settle just prior to scallops inflict major mortality on the spat, so that it is necessary to deploy spat bags (to collect scallop spat) *after* the settlement of sea stars (Naidu and Scalpen 1976; Parsons and Dadswell 1990).

High densities of scallops on Georges Bank inducing aggregations of sea stars that have a significant negative effect on scallop recruitment is a mechanism for compensatory mortality. Most of the evidence to support this theory is based on relatively small- scale experiments in semi-controlled environments, as discussed above. It is unclear whether these interactions would be maintained in the large-scale, unpredictable environments of wild sea scallop populations.

Competition for food.

In order for food limitation to be a cause of compensatory mortality, it must be possible for scallops to deplete their food resource. Therefore, the population must not be predator controlled to the extent that food is not a limiting factor, and the food source must be fairly constant. The extent to which scallop populations are predator controlled is currently unclear, but there is evidence that at least one source of food is buffered.

Levinton (1972) categorized benthic invertebrates as either deposit feeders (food is mostly derived from the sediments) or suspension feeders (food is mostly derived from the water column). He argued that the food supply of suspension feeders constantly fluctuates due to physical processes so that competition for food is not possible, while deposit feeders face a relatively stable food supply leading to competetive exclusion. The relatively stable food supply is a result of the "fluff" layer- an accumulation of organic matter 2- 10 cm thick. This source of food is maintained by detritus and fecal matter, which is constantly decomposed by bacteria, making it available as food to deposit feeders (Levinton 1972).

Scallops are commonly labeled suspension feeders. This is misleading, because scallops are opportunistic feeders that consume both pelagic and benthic material (Shumway et al 1987; Caddy 1989). Scallops in deeper environments consume a higher proportion of benthic species than those in shallow environments (Shumway et al 1987). This is a reflection of the relative availability of pelagic vs. benthic food at different depths (Shumway et al 1987). The stable food supply from the "fluff" layer is available to scallops in the form of seston (re-suspended organic matter from the benthos). Further, "clapping" behavior, where scallops rapidly and forcefully open and close their shells, may be an evolutionary adaptation to exploit this resource, as it actively produces seston (Shumway et al 1987). Also, scallops sometimes form small craters in the sediment, which may be an adaptation to increase the amount of seston they are exposed to (Stokesbury pers comm). Thus, scallops utilize a relatively stable food resource, and at certain times of the year, when phytoplankton abundance is low (i.e. during the winter), it is possible that scallops rely on this.

Food derived from seston may be depleted by feeding activity. Newell et al (1982) found that the maximum available energy from seston in Long Island Sound corresponded with the lowest feeding rates of mussels. Scallop spat grown in suspended culture in their natural environment exhibit slower growth rates at higher stocking densities, suggesting that they are capable of depleting food resources more rapidly at higher densities (Parsons and Dadswell 1992).

Older individuals probably have a competitive advantage for food resources (Bayne 1964). Thus, it is advantageous for the young mussels to grow before entering into competition with older members of the population, which may explain why mussels tend not to settle among adults (Bayne 1964). This may also explain why the recruitment success of subsequent year classes of cockles are inversely correlated (Hancock 1973) and why subsequent year classes of the Lamellibranch, *Spisula subtruncata*, are not found in the same areas of the Dogger Bank (Davis 1923).

Based on the available data it is plausible that space competition, cannibalism, aggregation of predators, and food competition could be mechanisms for density limiting recruitment of sea scallops. Any of these could explain a situation where recruitment drops off at high levels of SSB, as is predicted by the Ricker model.

Currently density dependant recruitment is not accounted for in the management of the sea scallop fishery on Georges Bank, Southern New England, and the Mid Atlantic. Scallops in these areas are treated as a single stock. Recruitment is factored in merely as a random variable independent of density. If a stock-recruitment relationship was assumed to exist in sea scallops, managers could set the fishing mortality, F, and total allowable catch (TAC) at such a level to achieve a stock size that would maximize recruitment. Managers would strive to maintain a stock level high enough to produce a sufficient number of viable zygotes, yet low enough that recruitment would not be hampered by a density limiting effect. This would ensure the maximum return from the fishery in future years and protect the resource.

Stock- recruitment data is especially critical to managers contemplating a rotational management strategy. Under this type of management certain areas would be closed for periods of time to allow scallops in those areas to grow to a harvestable size. Stock- recrutiment data is important to ensuring that areas are not closed for so long that recruitment is compromised.

Scallop recruitment may follow the Ricker model (Caddy 1979), however there is little supporting data. Jamieson (1993) stated that this type of model is not very useful for the management of exploited invertebrate populations, because most data lie on the left side of the curve.

The scallop population in U.S. waters has been surveyed by the National Marine Fisheries Service (NMFS) on a yearly basis using a research dredge (SARC 2001). These data and data from the Canadian survey suggest a positive stock- recruitment relationship for scallops on Georges Bank (McGarvey et al 1993). However there are several limitations to this type of analysis. First, the relationship is driven by two very large year classes, without which, the relationship would have been negative. Second, since this is a year-by-year comparison, there is no way to control for variation in environmental conditions, which have a strong influence on recruitment success (Dickie 1955; Sutcliffe et al 1977; Caddy 1979; Cabilio et al 1987; Tremblay et al 1994). Therefore it is impossible to determine what caused the two large recruitment events driving the relationship. Third, the research dredge is towed over the bottom for approximately 1 nm so it does not provide information on a scale relevant to scallop recruitment. Fourth, the data came from areas that had been open to fishing so densities may not have been high enough to limit recruitment. And finally, there is a high degree of uncertainty associated with the efficiency of the scallop dredge (SARC 2001).

We have a unique opportunity to study the stock- recruitment relationship relationship on Georges Bank where three large areas have been closed to mobile fishing gear since 1994. Sections of the most productive scallop beds in the world lie within these closed areas, and these scallop beds have been surveyed with video equipment since 1999 (figure 2).

Methods:

The video survey is laid out on a grid using a centric systematic design, where the first station is chosen randomly and the other stations are placed every 0.85 nm. At each station several lights and two underwater video cameras attached to a large pyramid are deployed from a commercial scallop vessel and set on the sea floor. The pyramid is raised until the bottom is no longer visible, the vessel drifts for approximately 50 m, and the pyramid is lowered to the sea floor again. This procedure is repeated four times so that four quadrat images are obtained at each station. The video is recorded onto VHS tapes, which are re-played in the laboratory and digitized. The area under the camera has been calibrated three times so that accurate measurements can be made using the software ImagePro. Information about other invertebrates, fish, and substrate is also recorded (see Stokesbury (2002) for more detail). Over 17,000 digital images of the sea floor have been recorded and processed.

The data from these images have revealed some of the highest densities of scallops ever recorded on Georges Bank (Stokesbury 2002), so we have an opportunity to examine what happens to an invertebrate population in the absence of fishing. We know that the environment imposes a carrying capacity on the maximum size the scallop population can achieve, but we don't know what controls this- predation or intraspecific competition for limited resources. This is a fundamental biological question that has been studied for years. Insight into this question will not only provide basic information about the ecology of scallop populations but will enhance our understanding of the dynamics of benthic communities in general. Additionally, this information is critical to fisheries managers that are considering a rotational management system (Hart 2003). Based on this information managers could adjust the timing of openings and closures, accounting for recruitment, to maximize the yield from the fishery.

The average density of adult scallops in all stations that contain the smallest scallops was relatively low (figure 3). This suggests that scallop recruitment may be higher at stations with lower densities of adults, which could be a result of compensatory mortality mechanisms (mortality increases with increasing density) acting at these stations.

Scallop recruitment has increased in recent years but it is unclear whether this is a result of the high SSB in the closed areas or favorable environmental conditions (SARC 2001). However, very few pre- recruits were observed in the 2002 dredge survey (material presented to the PDT by D. Hart, 2003). Why did scallop recruitment drop off when the SSB was still increasing?

I would like to address this question in my research by determining whether high abundances of adult scallops can decrease recruitment success. I will perform a regression analysis on the abundance of pre- recruits observed in the video survey with the density of older scallops as the independent variable. This will be a quadrat-by-quadrat analysis so that the relationship can be analyzed on the scale of centimeters, which is relevant to the influence of biological and physical variables on scallop survival. To control for interannual variation in environmental conditions and to some degree, interspatial variation in physical characteristics, the analyses will be performed within the same year and area. This will provide a controlled, in depth analysis of the relationship between SSB and recruitment in the natural environment.

However other factors are likely to influence the distribution of juveniles. Robinson et al (1992) found that the highest scallop settlement consistently occurred at one site in Passamaquoddy Bay, New Brunswick in three consecutive years. They suggested that this was because the currents in the bay favored larval transport to this area and the chlorophyll-a concentration was highest at this site. Since the site did not contain a high abundance of adults they suggested that small scallops were using this site as a "nursery" area before entering into the adult population. "Nursery" areas may also increase the survival of young scallops by allowing them to grow before entering into direct competition with adults, which probably have a competitive advantage (Davis 1923; Thorson 1957; Bayne 1964; Hancock 1973).

Therefore I'd also like to investigate the presence of "nursery" areas on Georges Bank. To do this I will compare the spatial distribution of juveniles to that of adults by mapping the distributions using GIS software and applying circular statistics. I will also determine how variables affect the abundance of juveniles and compare that to how the same variables affect the abundance of adults. To do this I will apply multiple regression analysis on the abundance of juveniles with various independent variables such as adult density, depth, substrate, and flow characteristics. Multiple regression analysis also enables a comparison between the degree of significance of the effect of different independent variables on the dependent variable. Thus, I will be able to determine which variable has the strongest influence on juvenile abundance.

Finally, I would like to provide more information on the current status of scallop recruitment on Georges Bank. To do this it is necessary to determine the limitations of the video pyramid as a tool for quantifying recruitment, since we are only able to identify scallops down to a certain size.

The selectivity of the video pyramid can be estimated by back calculating the abundance of a cohort observed one year, to generate an expected abundance the previous year, factoring in growth, mortality, and migration (figure 4). Comparing the spatial distribution of juveniles to adults should provide a rough estimate of migration. Growth and mortality estimates already exist for sea scallops on Georges Bank, however current work by my colleagues, Brad Harris and Mike Marino, will provide improved estimates. The expected abundance can be compared to the observed abundance to provide an estimate of the selectivity of the gear.

Selectivity of the large camera can also be estimated by comparing data from the large and small cameras. The small camera is a blown up image of a section of the large camera and smaller scallops can be identified in the small camera. This is another way that expected abundances could be generated and compared to observed data.

We are also working to improve the quality of the images. We have purchased better cables, which should be more reliable and will enable us to add more lights and a third camera that will provide a more horizontal view of the sea floor. We have also purchased Super VHS VCRs that record at over double the resolution of standard VHS VCRs. These improvements will foster the identification of smaller scallops, which will enable us to forecast recruitment farther into the future.

Preliminary data from the video survey of the Nantucket Lightship Closed Area (NLSA) in 2002 confirms the low abundance of pre- recruits observed by the NMFS dredge survey (figure 5). Did the scallops exist, but were too small to be detected, did they exist outside of the survey area (i.e. in a "nursery" area), or was there actually a recruitment failure in 2002? If there was a recruitment failure, could this have been caused by the highest densities of scallops ever recorded in the NLSA?

I can answer the first question by determining the selectivity of the video pyramid. The second question will be answered a) by determining the presence of "nursery" areas and b) analyzing the size frequency data generated by the upcoming survey. Where surveys in the past have focused on areas of high adult abundance the upcoming survey encompasses a much broader area (figure 6). Therefore if "nursery" areas exist, they will likely be found in this survey. By answering these two questions I will be able to determine whether a recruitment failure actually occurred. A detailed analysis of what affects the abundance of pre- recruits will determine whether high densities could have contributed to a recruitment failure.

Data that has already been collected will support much of the analysis, however the identification of "nursery" areas will depend on data from the upcoming cruise. The cruise will start the end of May and will likely continue through July. During the cruise people will be processing the images as they come in, so that the data will be available by the end of Fall 2003.

The work involved in the master's thesis has been funded by a grant from the Massachusetts Department of Marine Fisheries and the NOAA. All of the necessary equipment for the upcoming cruise has already been purchased and exists at SMAST UMass Dartmouth. Food, fuel, several vessels, and money to pay the captain and crew has been donated by various members of the fishing community of the Atlantic states.

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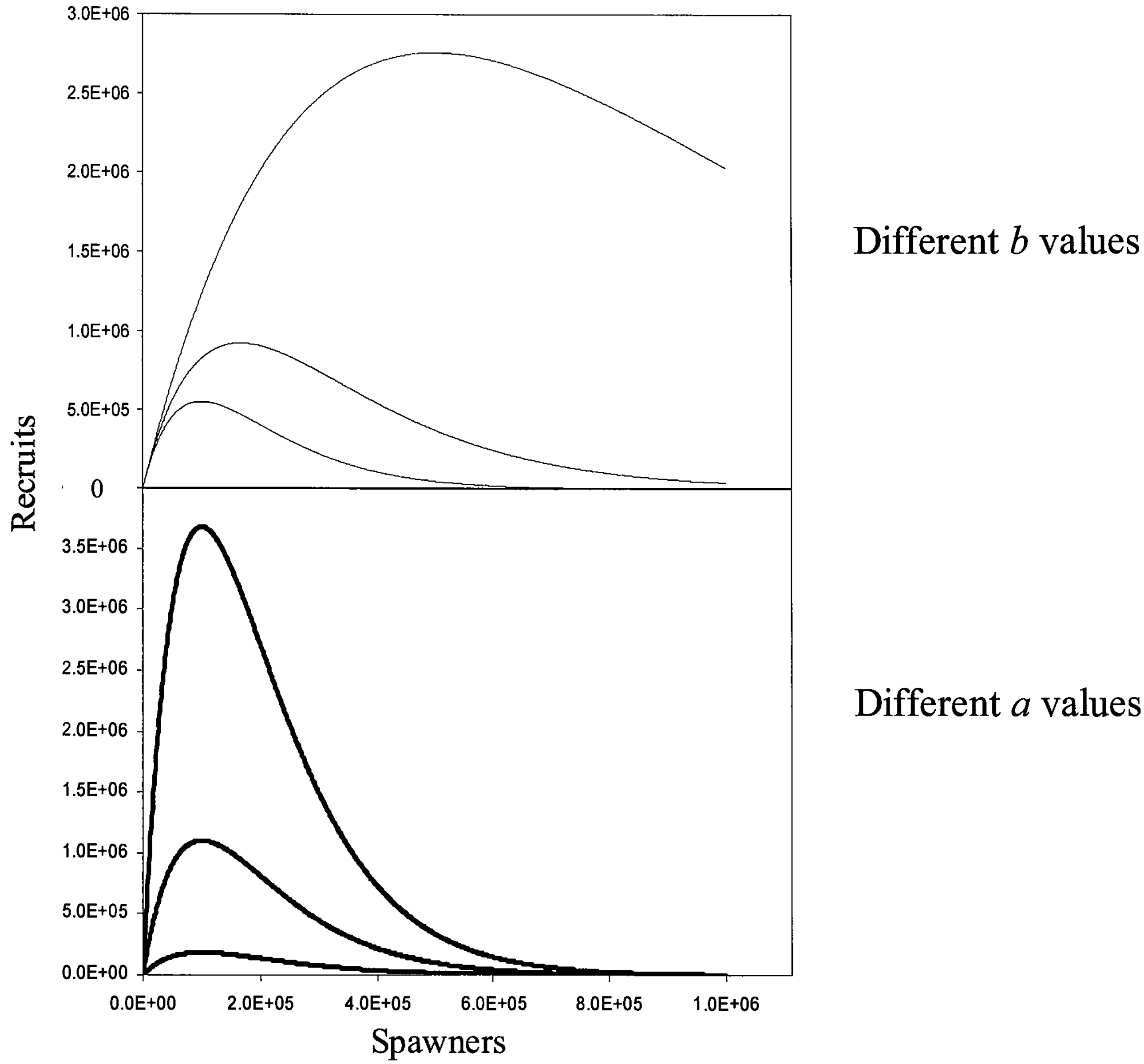

Figure 1. Ricker stock- recruitment curves with different *b* (top) and *a* (bottom) values. Note the decline in recruitment at both high and low abundance of spawners.

$$R = aSe^{-bS}e^{\varepsilon}$$

where R is the level of recruitment, S is proportional to the spawning stock size, *a* is the initial number of recruits per spawner, and *b* describes the rate at which the number of recruits per spawner decreases as S increases. e^{ε} indicates that the residual errors are lognormaly distributed about the curve.

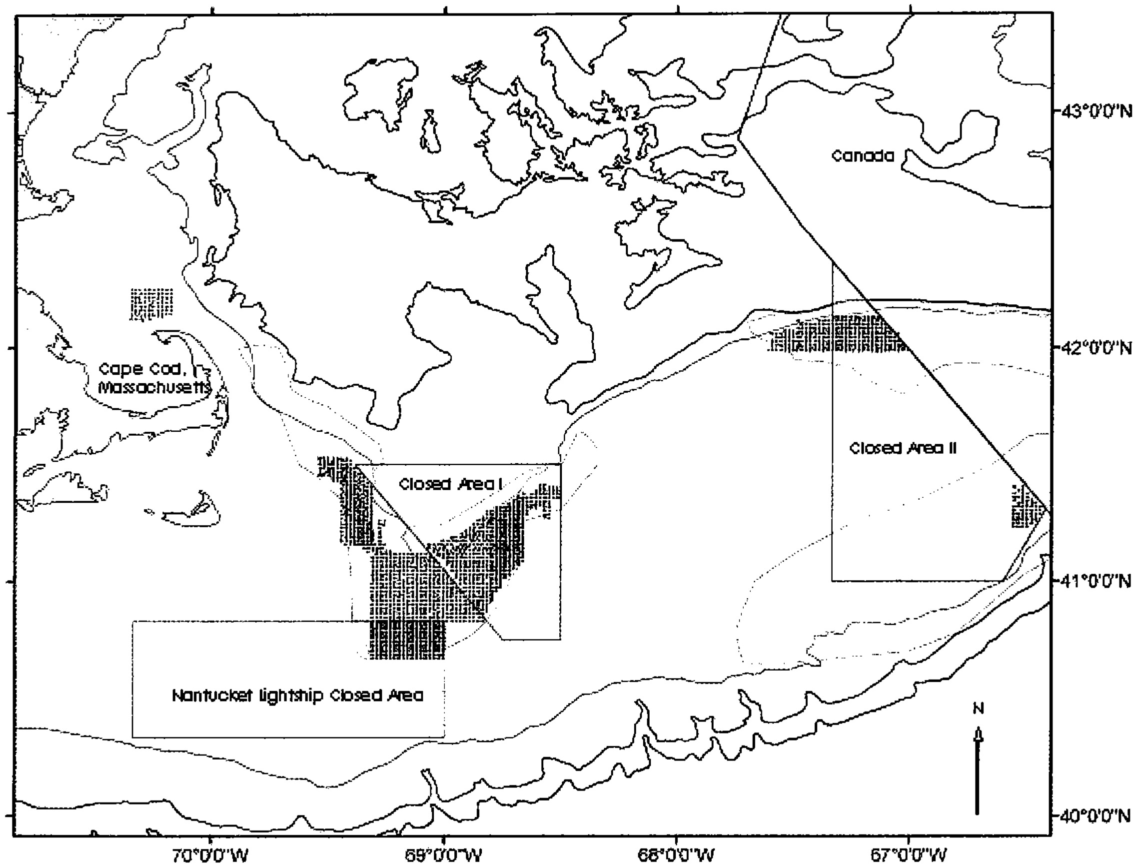

Figure 2. Map of Georges Bank showing areas closed to mobile gear since 1994 (polygons), historic scallop aggregations (pink), and SMAST video survey stations (black dots) from 1999-2002.

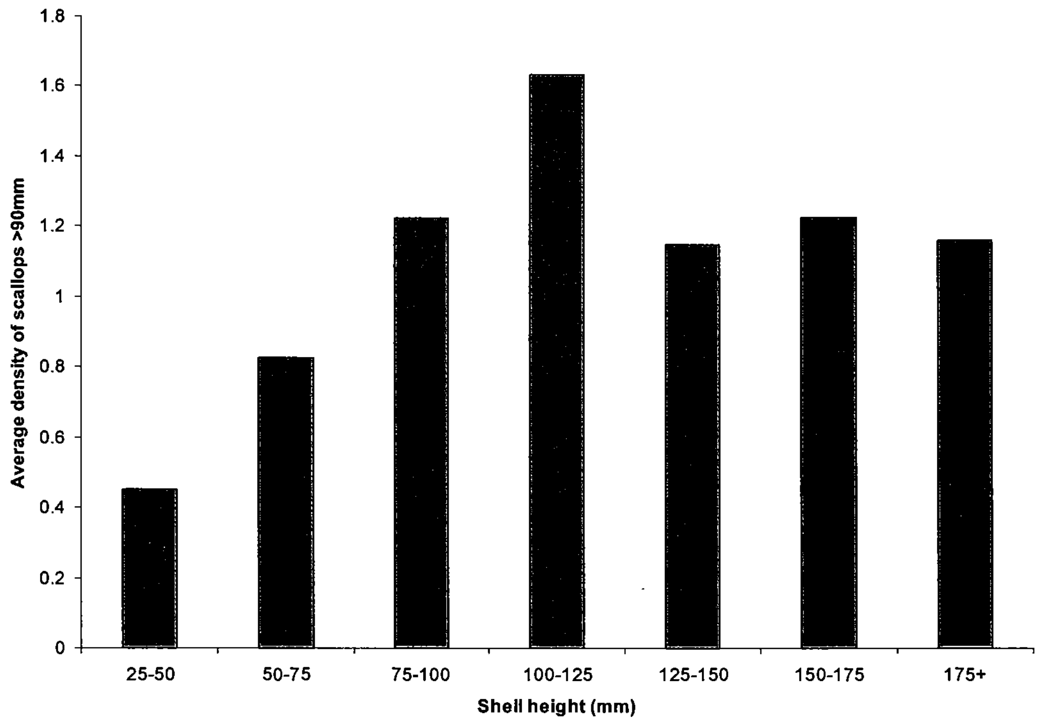

Figure 3. Average density of adult scallops (>90 mm) in all stations containing scallops within various size ranges.

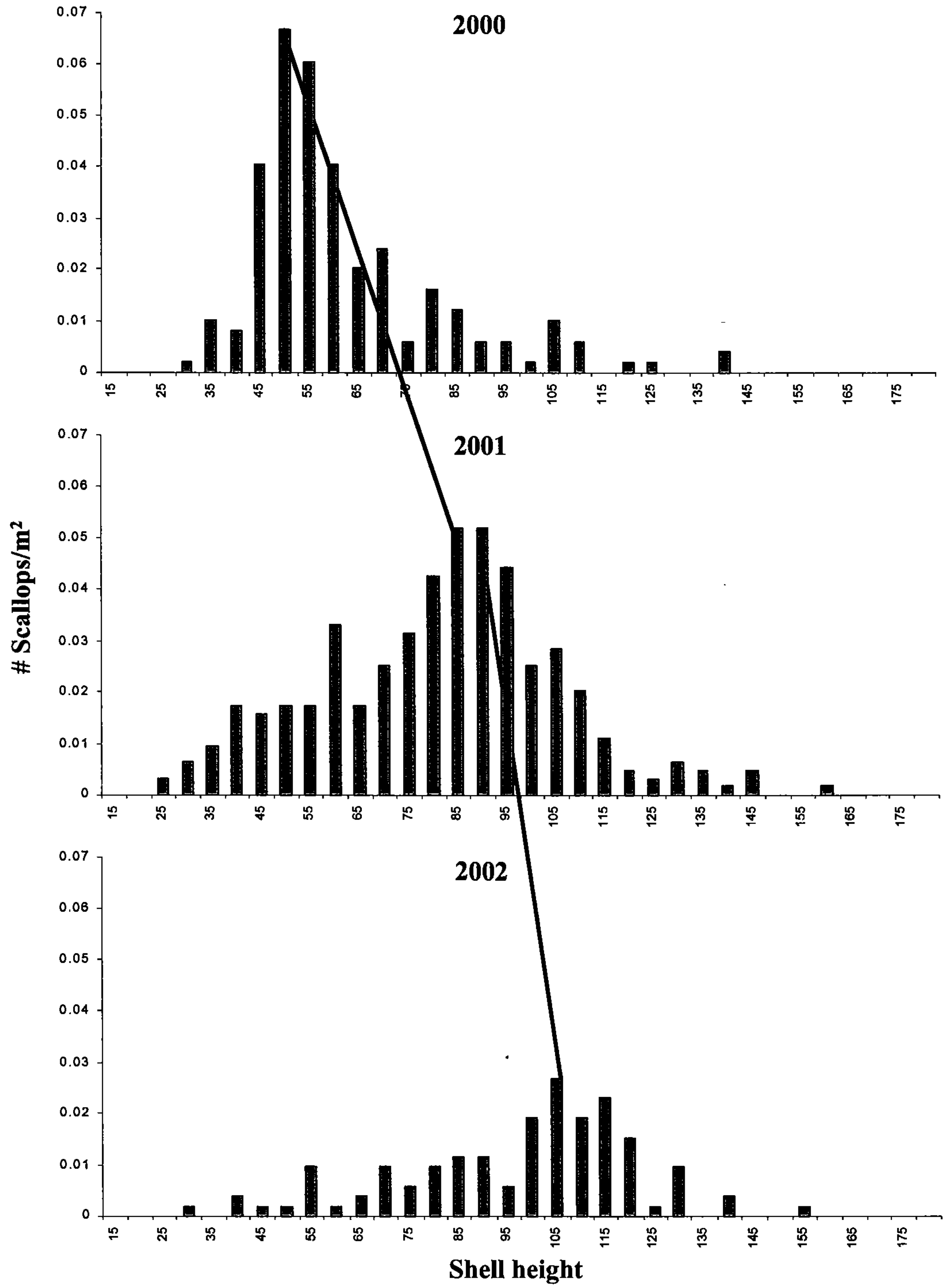

Figure 4. Shell height frequency histograms of scallops from the Great South Channel in 2000-2002.

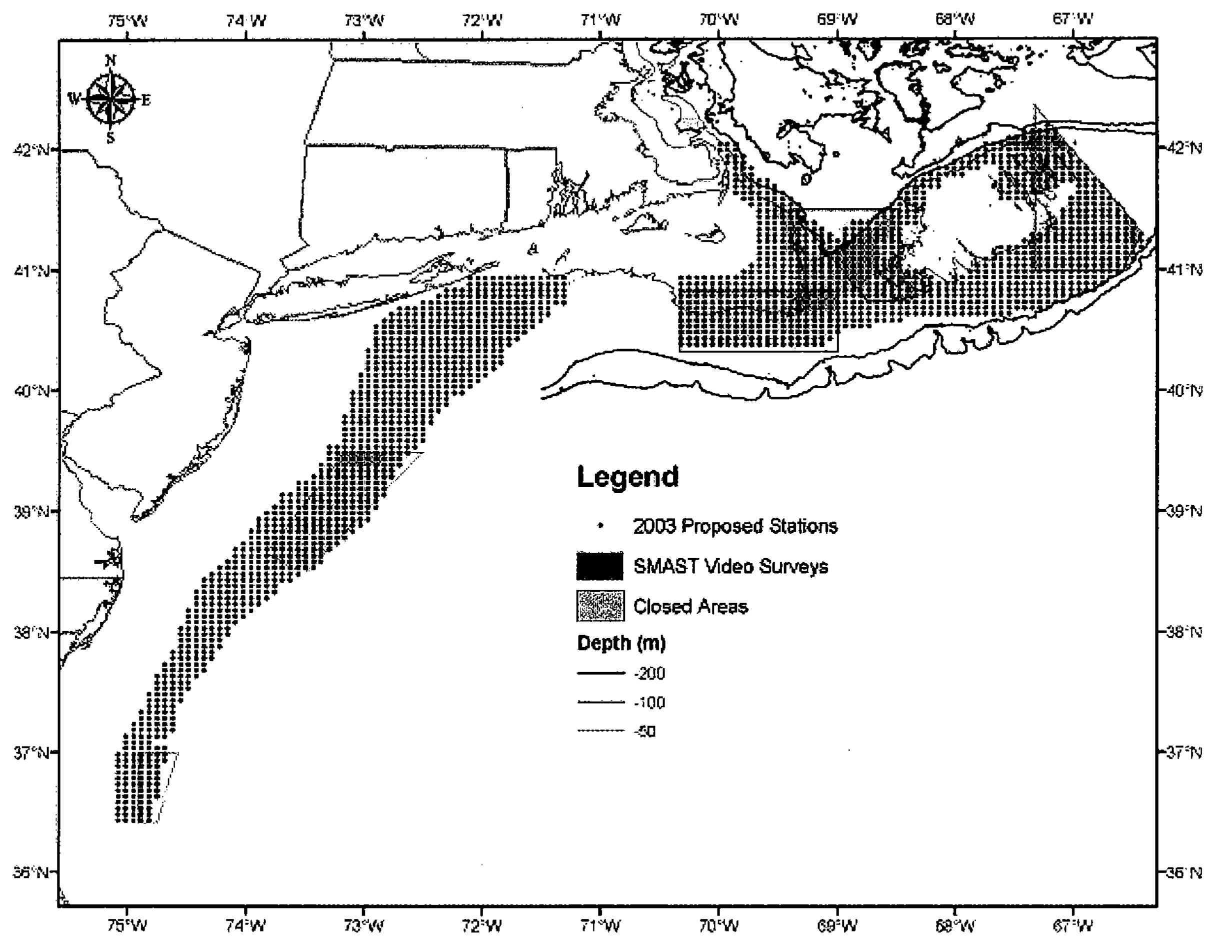

Figure 6. Map of Georges Bank and the Mid- Atlantic showing vdeo stations for the 2003 survey.