SFC
APPROVED
BY gMacuda
DATE 4/12/02

Final Report

Sea Scallop Research

Closed Area II TAC

Grant: NOAA/NA06FM1001

Award Date: 9/29/2000

Start Date: 10/01/2000

End Date: 9/30/2001

Project Title: **Examination of population biology and dynamics of the sea scallop, *Placopecten magellanicus*, in discrete areas of Georges Bank.**

Principal Investigator: Kevin D. E. Stokesbury, Ph.D.
Address: School for Marine Science and Technology (SMAST),
University of Massachusetts Dartmouth,
706 South Rodney French Blvd., New Bedford, MA, 02744-1221
Phone: (508) 910-6373
Fax: (508) 999-8197
Email: kstokesbury@umassd.edu

Kevin D.E. Stokesbury

Signature

Participants from the Fishing Industry

Marty Manley
F/V Marie-Ann
Harbor Development Commission
102 Pope's Island,
Route 6, New Bedford, MA
02740
(508) 961-3000

Danny Eilertsen
F/V Liberty, Justice, Venture
Solveigs
2 Middle Street
Fairhaven, MA
02719

Herman Bruce
F/V Zibet
Solveigs
2 Middle Street
Fairhaven, MA
02719

Roy and Ronnie Enoksen
F/V Friendship, Tradition, Expectation,
Foremost, Nordic Pride, Heritage,
Generation, Frontier
14 Hervey Tichon Ave.,
New Bedford, MA.
02740

Arnie Isaksen
F/V Huntress, Bountiful II, Diligence
Solveigs
2 Middle Street
Fairhaven, MA
02719

Project Summary

Objectives: To examine the scallop abundance, spatial distribution on several scales (cm, m, km), associated macroinvertebrate benthic community and substrate in open and closed areas of Georges Bank. To identify areas with high concentrations of small (<80 mm) scallops.

Methodology: Three research cruises were completed as proposed in grant: NOAA/NA06FM1001 . In Nantucket Lightship area 174 stations were sampled beginning on 10/21/2000. In the Northern portion of Closed Area II and the adjacent open area 277 stations were sampled beginning on 7/10/01. In the Southern portion of Closed Area II 62 stations were sampled beginning on 9/23/01. The later station number was low due to equipment failure and a threatening hurricane, which shortened the cruise. The sampling procedure was a multistage design with stations separated by 0.85 nautical miles with additional fine scale images to estimate scallop recruits. Mounted on the pyramid are two video cameras and several lights. Four quadrat images of the sea floor including counts and sizes of scallops, other macroinvertebrates and benthic fishes and sediment types, were relayed in real time to the surface. These images were video taped and the exact position (latitude and longitude from differential GPS) depth, time, and sea-state were recorded. Densities and size frequencies will be measured from digitized images processed with image analysis software. We are asking for a close-out period extension to complete these analysis as the data provide by these surveys will be critical in several stock assessment, scallop life history and environmental impact studies and scientific publications. We will supply the National Marine Fisheries Service with copies of all documents and published manuscripts as they are completed. Further this project will provide the data and support for several graduate students presently enrolled in the University of Massachusetts Intercampus Graduate School of Marine Sciences and Technology. Three harvest trips to Closed Area II were completed to fund this research.

Rationale: This project will provide the data to produce a series of maps of the sea floor in open and closed areas of Georges Banks containing high aggregations of sea scallops detailing the distribution of substrate, depth, live scallops, dead scallops, and macroinvertebrates (sponges, starfish, filamentous fauna). The video technique allows a precise, accurate measure of these variables and statistical comparisons between them. This research addresses the critical regional and national issue of the effects of mobile fishing gear on the marine benthic community. It has direct implications for rotational fisheries management, on an appropriate spatial scale (km), under consideration by the New England Fishery Management Council (NEFMC). It addresses the issues of understanding the linkage between fisheries and their habitats, and the restoration of that habitat. This survey has broad based industry support and information from these and previous surveys are used in the NEFMC SAFE and Framework documents and by the National Marine Fisheries Service (NMFS) regional office and Northeast Fisheries Science Center (stock assessment and habitat research).

Purpose of the Project:

Current state of knowledge: 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. Today, these closed areas contain about 80% of the Georges Bank sea scallop resource.

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.

Objectives: To examine the scallop abundance, spatial distribution on several scales (cm, m, km), associated macroinvertebrate benthic community and substrate in open and closed areas of Georges Bank. To identify areas with high concentrations of small (<80 mm) scallops.

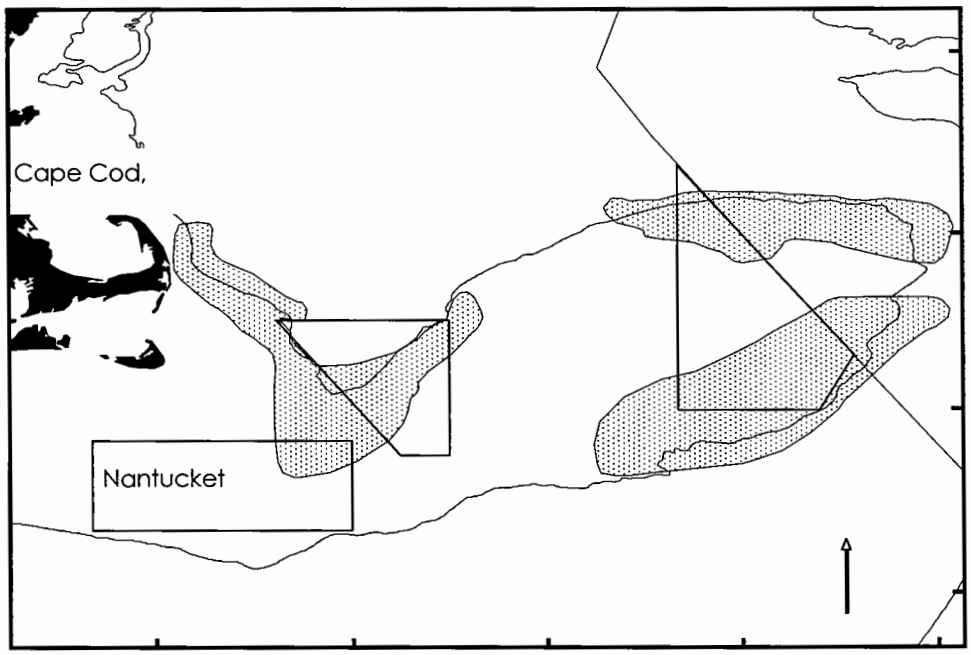
This study will provide:

a. an independent estimate of absolute scallop abundance and size structure;
b. determine areas with high concentrations of small (<80 mm) scallops;
c. scallop spatial distribution on three scales (cm, m, km);
d. information on the associated benthos community including species composition of flora and fauna and percent coverage in fished and unfished areas;
e. information on sediment composition; and
f. information on temporal shifts of the above variables compared to the 1999/2000 survey.

Description of research:

A meeting was held at SMAST on 21 March 2001 with the participating fishermen to organize the summers cruise schedule. 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. 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) (Map 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 (Map 2).

Map 1. Georges Bank with the Nantucket Lightship Area, Closed Area I, and Closed Area II outlined, the historic scallop fishing grounds shaded in gray speckle.



Map2. Stations of the video survey conducted on Georges Bank from May to September 2001.

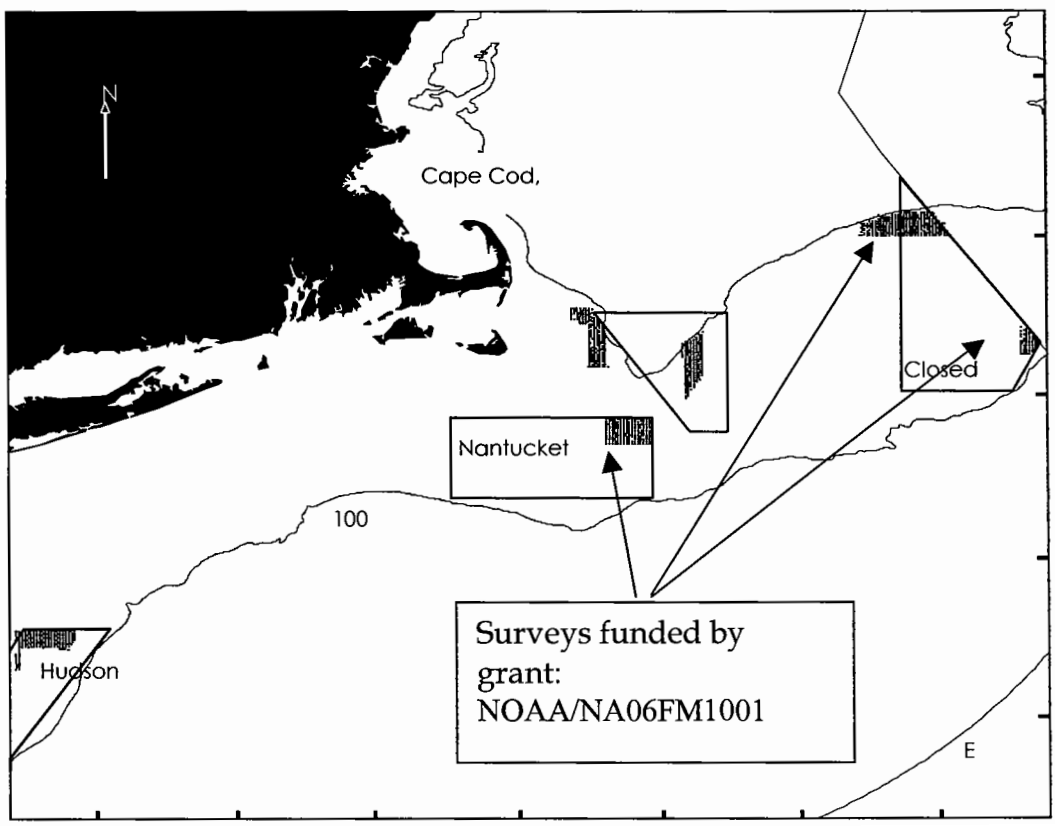
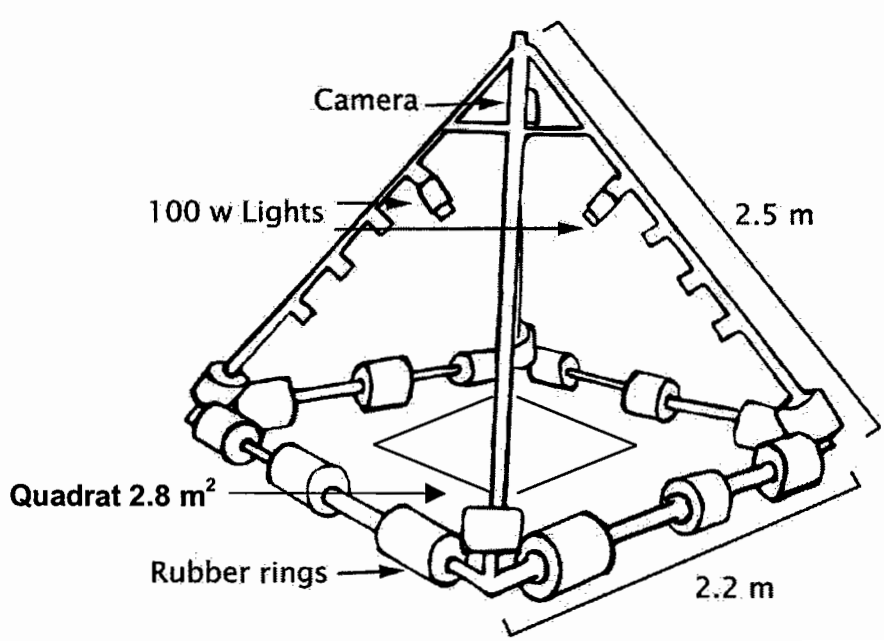


Figure 1. The sampling pyramid, with a square base 2.2 m per side of 6 cm round iron, arms 2.5 m x 4.5 cm round iron, approximate weight 450 kg, was deployed with the large hydraulic winch used in the scallop fishing industry. Rubber rings (3 sets of 8 rings, each 20 cm diameter, 5 cm thickness, per 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. Two 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.



The scallop aggregations within the three closed areas were surveyed from May to September 2001 (Map 2). 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 1). 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 are 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 are checked, and the substrate within each image is identified. The digitized images are loaded into Imagepro image analysis software and the shell heights of live scallops are measured (mm). Counts are standardized to individuals•m^{-2}.

Sediments are 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.

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 scallop 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 (n=83, $w = 3.59 \times 10^{-5} SH^{2.861894}$, r^2 =0.95 for the Nantucket Lightship Area; n=89, $w = 5.57 \times 10^{-5} SH^{2.737042}$, r^2 =0.68 for Closed Area I; n=123, $w = 3.837 \times 10^{-5} SH^{2.8189}$, r^2 =0.93 for Closed Area II). 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).

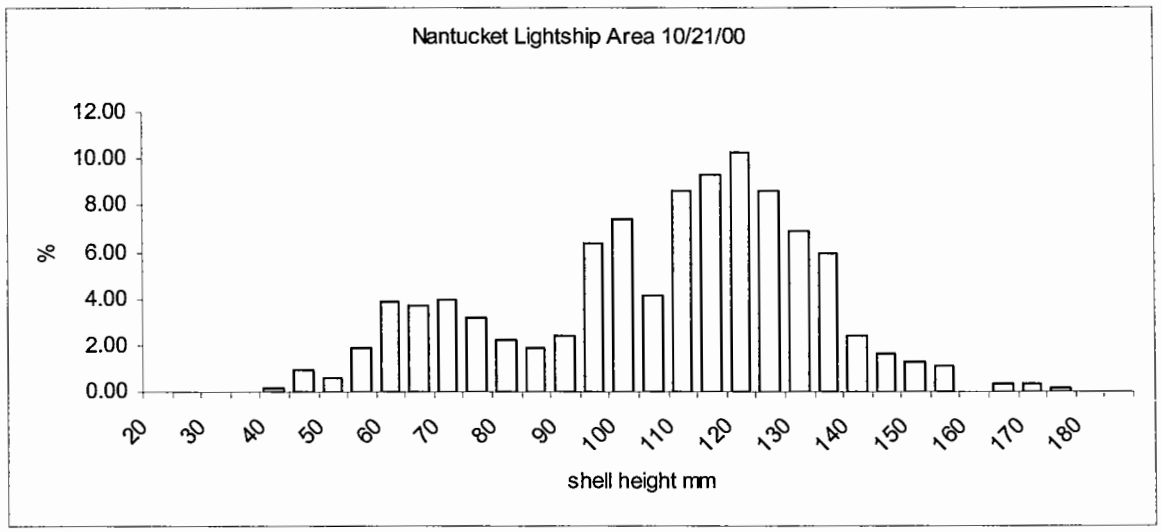
Results, Evaluation and Conclusions:

Three research cruises were completed as proposed in Grant: NOAA/NA06FM1001. In Nantucket Lightship Area (NLSA) 174 stations were sampled beginning on 10/21/2000. In the Northern portion of Closed Area II (CAIIN) and the adjacent open area 277 stations were sampled beginning on 7/10/01. In the Southern portion of Closed Area II (CAIIS) 62 stations were sampled beginning on 9/23/01. The later station number was low due to equipment failure and a threatening hurricane, which shortened the cruise.

Table 1. Sea scallop density and harvestable biomass estimates for the three areas surveyed during the NOAA/NA06FM1001 grant; mwt lf = meat weight from length frequencies; Sc. m^2 = number of scallops per meter squared.

Location	Sc. m^2	# Stations	SE	CV%	mwt lf (g)	km^2	millions of lbs
NLSA	**0.44**	174	0.058	13.17	39.0	430	16.3
CAIIS	**1.07**	62	0.110	10.24	26.9	153	9.8
CAIIN	**0.59**	277	0.059	10.05	26.9	685	33.5

The NLSA survey of 10/21/00 has been completely digitized, the scallop counts have been verified, the substrate, macroinvertebrates and scallop clappers (dead scallops) have been counted, and the scallops have been measured. The following histogram shows the observed shell height frequency during this cruise. The samples for CAII (North and South) are digitized but the scallop's shell heights have not been measured, therefore the meat weight of 26.9 grams is only a rough estimate. Our first manuscript describing the sampling procedure, abundance estimates and spatial analyses is in the final stages of review for the Transactions of The American Fishery Society journal. The procedures describe are the ones we will use to address all the proposed goals and the manuscript is included in this report as support document 1. We are asking for a close-out period extension to continue and complete these data analyses and publish the results in the primary scientific literature (some delay occurred due to the lose of personnel during this project). Further this project will provide the data and support for several graduate students presently enrolled in the University of Massachusetts Intercampus Graduate School of Marine Sciences and Technology.



Preliminary results of this research were presented to the sea scallop planning and development team of the New England Fisheries Management Council (PDT, NEFMC) on the 5th September 2001 and the 15th November 2001, to the American Scallop Association on 5 February 2002, and at the International Council for the Exploration of the Sea (ICES) Annual Meeting in Oslo, Norway (24 September 2001; support document 2). The sea scallop densities estimated during the cruises funded by Grant: NOAA/NA06FM1001 and NOAA/NA06FM1031 were presented to the New England Fisheries Management Council Sea Scallop Planning and Development team at the 11 Feb. 2002 meeting with documentation provided in an email of 19 Feb. 2002.

Scallop Research TAC Set Aside Research/Harvest Cruises

Three vessels participated in the research surveys funded by grant: NOAA/NA06FM1001, F/V's *Liberty, Friendship* and *Mary Anne*. Each vessel supported a 5-day research cruise, including the vessel, captain, 3 crew, food and fuel. Further, $7642 per cruise was paid to SMAST to support the scientific research. To pay for the research each vessel was allowed 15,000 lbs of scallops from the Closed Areas' 1% TAC research set-aside collected in 1 harvest trip exempt from DAS. Letters of Authorization for each research and harvest cruises were provided by the National Marine Fisheries Service. A complete summary of these expenses is presented in Table 2. The weight out slips for each of the harvest cruises and a copy of the check provided by each vessel to SMAST is presented in Appendix 1. For this research the TAC program worked very well. Before each cruise I contacted Dave Gouveia of the NMFS who provided a letter of authorization for the research and harvest cruises. Mr. Gouveia also notified the Coast Guard of our activities. Upon returning to port I contacted Mr. Gouveia again and provided an account of the cruise. This continuous contact with the National Marine Fisheries Service allowed all components of the project to run very smoothly and enabled us to successfully collect all the proposed data.

Table 2. Budget for a TAC set-aside cruise from Closed Area II.

			per vessel
Requested TAC conducting 1 5-day research cruise			**15000**
$ ($5 per lb)			$75,000
SMAST		$7,642	
SMAST deducted			$67,358
Boat share (0.42)		$28,290	
Crew share (0.58)		$39,068	
Expenses		$20,000	
Total			$19,068
per crew (6)			**$3,178**
Breakdown of Expenses			
Research cruise (5-days)			
		captain	$2,000
		3 crew	$3,000
		food	$1,000
		fuel	$6,500
Harvest cruise			
		food	$1,000
		fuel	$6,500
Total			**$20,000**
SMAST Expenses			
Salaries			
	1.	Principal Investigator	
		Kevin Stokesbury (1 mo./yr.)	$1,433
	2.	Research Assistant (Grad. Std.)	$1,875
Subtotal Salaries			$3,308
Benefits			
	1.	At 25.75%	$369
	2.	At 1.45% Summer Stipend ($6,000)	$27
Subtotal Benefits			$396
Total Salary and Benefits			**$3,704**
Other Direct Costs			
	1.	Expendable Supplies and Equipment	$667
	2.	Permanent Equipment	$1,333
Total Other Direct Costs			**$2,000**
Indirect Costs			
	1.	At 58.6% of Salaries	$839
	2.	At 58.6% of Salaries	$1,099
Total Indirect Costs			**$1,938**
Total Direct and Indirect Costs			**$7,642**

Products:

These video surveys provide a wealth of information on the Georges Bank sea scallop population and marine ecosystem. The surveys funded by grant: NOAA/NA06FM1001 are part of the SMAST sea scallop database presently being developed, which contains information from 24 cruises. This database provides assessment of scallop densities in closed and open areas of Georges Banks from 1999 onward. Table 3 lists the fishing vessels, locations and dates these cruises took place, and the type of data collected.

Table 3. SMAST sea scallop research cruises.

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

The data from these surveys have been presented to and used by the NEFMC (Framework 13 Atlantic Sea Scallop Fishery Management Plan 7 March 2000, and SAFE Report 8 September 2000) and the NMFS, SARC, 32nd Northeast Regional Stock Assessment Workshop (32nd SAW, January 2001). The 2001 video surveys will be used with the NMFS scallop survey to assess the abundance of sea scallop on Georges Bank and as a bases population dynamic models examining alternative rotational fishery management plans presently under review for the development of

Amendment 10. Further, we are using these data as the bases for developing a temporal-spatially specific fisheries management system. The three components of the system are: 1.) the collection of high-resolution information on the size and density of sea scallops in real-time, 2.) a standard model to estimate population trajectory and the effect of fishing, 3.) a procedure to determine the optimal harvest (preliminary results presented at International Council for the Exploration of the Sea (ICES) Annual meeting in Oslo, Norway (24 September 2001; ICES document CM 2001/N:17; support document 2)).

We have also successfully collected the information for one of the largest BACI studies ever conducted on a scallop resource (Table 4). The NEFMC in Framework 13 (presented 20 January 2000) allowed the scallop fishing fleet to make one fishing trip per vessel (10,000 lbs.) into the scallop aggregation in the NLSA from 15 August 2000 to 14 October 2000. The NEFMC also allowed the scallop fishing fleet to make three fishing trips per vessel (10,000 lbs.) into the Closed Area I scallop aggregation north of Loran line 43660 from 15 October 2000 to February 2000. Thus we have an excellent BACI experiment with a 1-year set of baseline observations, 2 experimental areas (NLSA and North of 43660 in CAI) that were exposed to intense fishing pressure, two control areas (the northern portion of CAII, and South of 43660 in CAI) with no fishing, and one control with constant fishing (South Channel), (Table 4). The NMFS monitored the fishing effort, including the location and amount of scallops collected. Changes in species composition, density and distribution of scallops, other macroinvertebrates and groundfish, and in sediment structure (for example sand ripple structure, which may be critical juvenile fish habitat) will be compared between open and closed areas. The BACI environmental experiment design will allow the determination of anthropogenic changes compared to the natural progression of the benthic community through time. Many of the management questions presently being addressed by the NEFMC require this type of data. Similar problems are being examined throughout the United States, for example in the Alaskan scallop fishery. We expect to publish at least two primary papers from this research. Further, as these data are key to fisheries management decisions we will present our results to the appropriate NEFMC PDTs (scallop, habitat, and multispecies) and the NEFSC of the NMFS.

Table 3. SMAST video database showing the surveys before and after fishing events on Georges Banks and the Gulf of Maine. Hashed areas represent periods of fishing, x = SMAST video surveys.

		Areas of Georges Banks							
Year	Month	NLSA	CAI N	CAI S	CAII N	N. edge	CAII S	SC	SW
1999	May	x							
	Jun.								
	Jul.	x	x	x					
	Aug.		x	x					
	Sep.				x				
	Oct.								
	Nov.								
	Dec.								
2000	Jan.								
	Feb.								
	Mar.								
	Apr.								
	May								x
	Jun.								x
	Jul.								
	Aug.	x	x	x				x	
	Sep.								
	Oct.	x							
	Nov.								
	Dec.								
2001	Jan.								
	Feb.								
	Mar.								
	Apr.								
	May								
	Jun.		x	x					
	Jul.				x	x			
	Aug.	x	x	x					
	Sep.						x	x	
		Test	Test	No Fishing Control	No Fishing Control			Fishing Control	

School for
Marine Science
and Technology

706 South Rodney French Blvd.
New Bedford
Massachusetts 02744-1221

Tel 508.999.8193
Fax 508.999.8197

University of
Massachusetts
Dartmouth

Dr. Dennis R. DeVries, Editor
Transactions of the American Fisheries Society
Department of Fisheries and Allied Aquacultures
Auburn University, Auburn,
Alabama, 36849 USA

14 Feb. 2002

Dear Dr. DeVries:

Enclosed are three copies of my revised manuscript entitled, "Estimation of sea scallop abundance in closed areas of Georges Bank, USA", (T01-62) for publication as an article in the *Transactions of the American Fisheries Society*.

I appreciate the thorough comments provided by you, the two reviewers, and the associate editor. I was pleased that the reviewers and the associate editor felt that my manuscript presented valuable information and was appropriate for publication. I have addressed all the comments and changed the manuscript accordingly. I have also provided a detailed list of my response to the reviewers, associate editor, and your comments plus the reviewer's copy of the manuscript.

To address these comments I contacted Dr. R. McGarvey (Reviewer 2, who had signed his name to his comments) and Dr. L. Jacobson. Dr. McGarvey provided so more details on his comments and some reference material. I discussed both the manuscript and the reviewers' comments with Dr. Jacobson. Dr. Jacobson is the chair of the Stock Assessment Review Committee of the National Marine Fisheries Service at the Northeast Fisheries Science Center, Woods Hole, Massachusetts, and my survey was reviewed by its' Invertebrate subcommittee (the survey has also been reviewed by the Science and Statistical Committee of the New England Fisheries Management Council). Following Dr. Jacobson's advice I have completed the statistical analysis using procedures that I hope addresses the reviewers, associate editor, and your comments in a satisfactory manor. I have included my correspondence with both Dr. McGarvey and Dr. Jacobson for your review.

All correspondence should be sent to me. My office phone number is (508) 910-6373, FAX (508) 999-8197 and my email address is kstokesbury@umassd.edu. I hope you find this manuscript satisfactory for publication.

sincerely,

Kevin D. E. Stokesbury

Estimation of sea scallop abundance in closed areas of Georges Bank, USA

Kevin D. E. Stokesbury

School for Marine Science and Technology, University of Massachusetts Dartmouth, 706 South Rodney French Boulevard, New Bedford, Massachusetts, 02744-1221

Phone: (508) 910-6373

Fax: (508) 999-8197

Email: kstokesbury@umassd.edu

Abstract

A high-resolution video survey conducted from May to September 1999 in historic scallop fishing grounds that have been closed to mobile fishing gear since 1994 reveled some of the highest densities and largest sea scallops ever observed on Georges Bank. Sea scallop densities ranging from 0.25 to 0.59 scallop•m^{-2} within the three surveyed areas and 0.58 to 1.06 scallops•m^{-2} at stations where at least one scallop was observed. Sea scallops were highly aggregated into patches (beds) on the scale of km^2 and this distribution was strongly associated with the distribution of coarse sand-granule-pebble substrate. The three areas surveyed (1938 km^2) contained approximately 650 million scallops representing 17 million kg of harvestable scallop meats. This is equivalent to 54% of the average harvestable scallop meat biomass from 1977 to 1988, which is now in 5% of the total scallop fishing grounds of Georges Bank. The video survey technique has several advantages over dredge surveys; it is fast, accurate, precise, and provides information on the biology of scallops and the associated habitat without disturbing the sea floor.

Introduction

Georges Bank supports the world's largest single natural sea scallop *Placopecten magellanicus* resource (Posgay 1979; Caddy 1989). Sea scallops have been fished continuously on Georges Bank, since the end of World War II, and are presently the second largest fishery in the northeastern United States with an average annual value of US$100 million (Posgay 1979; Caddy 1989; Murawski et al. 2000). To protect declining groundfish stocks large portions of Georges Bank were closed to all mobile fishing gear, including scallop dredges as this gear may collect groundfish and disturb groundfish habitat, in December 1994 (Auster and Langton 1999; Murawski et al. 2000).

Sea scallop densities and spatial distributions are influenced by physical and biological variables, including substratum type, current, and predator distributions (Brand 1991; Stokesbury and Himmelman 1993, 1995). On Georges Bank, sea scallops are aggregated into three large grounds, areas where the scallop is sufficiently abundant to support a commercial fishery, occurring where oceanographic currents facilitate larval retention (Brand 1991; Sinclair et al. 1985; Thouzeau et al. 1991), (Figure 1). Although sea scallops form smaller, denser, aggregations on several scales (cm, m, km) within these grounds their spatial distributions and densities have not been described, probably due to the limited biological information provide by dredge samples (Caddy 1989).

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 to analysis 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 objective of this study was to provide an absolute estimate of scallop abundance and size structure at a high degree of accuracy and precision. Portions of the closed areas believed to contain the highest abundances of sea scallops, based on discussions with New Bedford scallop fishermen and the literature (Sinclair et al. 1985), were surveyed using video equipment. These areas included the northeast corner of the Nantucket Lightship area (NLSA), the central portion of Closed Area I (CAI) and the northern edge of Closed Area II (CAII), (Figure 1). Scallop spatial distribution on the scale of kilometers, and substrate type were examined within these areas.

Methods

A sampling pyramid that supported a video camera and lights and could be deployed by commercial scallop fishing vessels was constructed (Figure 2). The camera was mounted on the pyramid at a fixed distance above the pyramid's base. The exact area sampled was determined by observing a checkered pattern and comparing the video image to the actual pattern. A calibration

equation defining the curvature of the lens and the proportional area sampled was calculated to correct all measurements that precisely estimated shell height (*t*-test: $t = 0.53$, df = 28, p = 0.60; actual shell height mean = 115.9 mm, SD = 20.4, estimated with calibration equation mean = 119.8 SD = 21.3).

A preliminary survey to test the video equipment and explore variability was conducted from 24 to 29 May 1999. This preliminary survey estimated scallop densities within a small area (55 km^2) of the Nantucket Lightship Area identified by fishermen as supporting very high densities of sea scallops. Eighteen randomly selected stations were sampled. A station in this study is a predetermined specific location. The fishing vessel was anchored on station and the video camera mounted on the sampling pyramid was lowered to the sea floor and then retrieved. Then ≈10 m of anchor line was released and the pyramid was deployed and retrieved until 10 quadrats of the sea floor had been collected. A quadrat in this study is an image of the sea floor collected at a station (Figure 2).

The preliminary survey indicated that the sampling technique was adaptable to fishing vessels, and provided precise estimates of scallop density (18 stations, 10 quadrats per station, mean number of scallops per 1.0 m^2 quadrat = 1.2, SE = 0.41). The resolution of the quadrat images indicated that the size could be increased to 2.8 m^2 providing more information on scallop distribution. The upper limit of quadrat size was restricted by visibility, 2.8 m^2 was the largest area that provided a clear image of the sea floor give the conditions on Georges Bank. Scallops within the viewing field and those along the edge were counted so the sample area was increased to 3.235 m^2 to correct for edge bias (Krebs 1989). This was determined by adding 75 mm to each edge of the quadrat image, based on the shell height of the scallops observed.

Sea scallops in other areas aggregate on the scale of centimeters and one scallop in 3.235 m^2 is a high density (0.31 scallops•m^{-2}) (Brand 1991; Stokesbury and Himmelman 1993). By increasing the number of quadrats to four per station the observed sample area increased to 12.94 m^2 thereby greatly increasing the chance of sampling a scallop if any are located at a station (0.08 scallops•m^{-2} is below sustainable commercial density) (Brand 1991). Further, the time required to sample four quadrats at each station is minimal compared to the deployment and retrieval of the sampling gear and moving the vessel to the next station.

The variance to mean ratio estimated from the preliminary study suggested that the sea scallops had a Poisson distribution within the sampled area (12.6 with 9 degrees of freedom). This ratio and the Poisson distribution indicated that the precision would be improved with fewer quadrats at each station and more stations, for example, 7 to 187 stations were required for 25% to 5% precision assuming an approximately normal distribution (Krebs 1989, p. 178):

(1) $$n = (200CV/r)^2$$

n = sample units (stations).
CV = coefficient of variation = standard error/observed mean.
200 = $t\alpha$ Student's t (1.96 multiplied by 100), for 95% confidence limits.
r = relative error (width of confidence interval as percentage).

However, sea scallops are usually aggregated rather than randomly distributed on the sea floor. If this is the case the number of stations increases greatly to obtain the same level of precision. The negative binomial distribution describes an aggregated distribution and has described scallop distributions in other locations (Stokesbury 1993). Using the mean and variance from the preliminary study provides a k value of 3.0 (k is the negative binomial exponent). Modifying equation 1 with a negative binomial distribution 75 to 1868 stations are

required for 25% to 5% precision (Krebs 1989). Based on these estimates approximately 200 stations in the northeastern corner of the Nantucket Lightship area would provide estimates of scallop density with 5% to 15% levels of precision for the normal and negative binomial distributions, respectively.

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 1a). This station gird pattern was then used for all other closed areas that had supported historical scallop aggregations to maintain consistency throughout the surveys (Figure 1).

The scallop aggregations within the three closed areas were surveyed from May to September 1999 (Figure 1). 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 (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 was digitized and saved (TIF 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 doubling or halving of the 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 was also identified although it is not included in the Wentworth scale. Quadrats were categorized by the presence of the largest type of particle. Therefore if one boulder (>256 mm) was observed, the quadrat was 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 was classified as granule/pebbles.

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:

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

The standard error of this mean is:

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

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 frequency distribution of sea scallops per station was compared to Poisson and negative binomial distributions using chi-squared analysis. Expected values were grouped according to Cochran's rule so that <20% of the expected frequencies have a value <5 (Elliott 1971; Sokal and Rohlf 1981; Zar 1996).

The number of scallop 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 (n=83, $w = 3.59 \times 10^{-5} \cdot SH^{2.861894}$, r^2 =0.95 for the Nantucket Lightship Area; n=89, $w = 5.57 \times 10^{-5} \cdot SH^{2.737042}$, r^2 =0.68 for Closed Area I; n=123, $w = 3.837 \times 10^{-5} \cdot SH^{2.8189}$, r^2 =0.93 for Closed Area II). 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).

Results

The sea scallop was the most abundant macroinvertebrate observed during the video surveys of the historic scallop fishing grounds within the Nantucket Lightship Area, Closed Area I, and Closed Area II. The three areas surveyed (1938 km^2) were estimated to contain approximately 650 million scallops representing approximately 17 million kg of harvestable

scallop meats (Table 1). The scallop aggregation in the northern portion of Closed Area II (15% of the total area surveyed) contained 26% of the total number of scallops.

Sea scallops were aggregated within the three survey areas on the scale of kilometers (Figure 3). In the Nantucket Lightship Area scallops were observed at 127 stations (62%) representing 260 km^2 and had a density of 0.62 scallops•m^{-2} (SE = 0.061). The majority of scallops (80%) were tightly aggregated in 22.4 % of the stations (114 km^2), in the central portion and in several smaller beds (Figure 3). In Closed Area I scallops were observed at 265 stations (58%) and had a density of 0.42 scallops•m^{-2} (SE = 0.032) with 65.5% of the sea scallops located at 13.7% of the stations (153 km^2) (Figure 3). In Closed Area II scallops were observed at 95 stations (76%) and had a density of 0.78 scallops•m^{-2} (SE = 0.059). In Closed Area II, scallops were distributed over a large portion of the area with the highest densities in the north and east boundaries. However, even within this area scallops were highly aggregated with 84.2% of the scallops located at 35.2% of the stations (109 km^2) (Figure 3).

The spatial distribution of scallops observed per station in Closed Area I and II was described by the negative binomial distribution (CAI k=0.3728, df = 17, χ^2 = 16.1, p=0.221; CAII k=0.5261, df = 14, χ^2 = 4.94, p=0.987). The observed distribution of scallops per station differed from the negative binomial distribution for the Nantucket Lightship area (k = 0.3380) due to the large number of stations (39) with 6 to 17 scallops (df = 16, χ^2 = 26.3, p=0.022).

The largest scallops on average occurred in the Nantucket Lightship Area although size frequency distributions were similar (Kolmogorov-Smirnov test; NLSA-CAI p = 0.99, NLSA - CAII p = 0.52, CAI - CAII p = 0.23), (Figure 4).

Scallops that had died from natural causes were identifiable on the video images as the two shells were still attached by the umbo ligament. Of the 3167 scallops observed 6% were

dead. The number of dead scallops was similar among the Nantucket Lightship Area (10%) and Closed Area II (7%) but lower in Closed Area I (1%; Table 1). In the Nantucket Lightship Area the majority of dead scallops were observed in the largest bed (64 km^2).

The distribution of substrates varied within the three closed areas (Figure 5). Shell debris (41%) and granule/pebbles (36%) dominated the Nantucket Lightship Area. Sand (61%) and shell debris (26%) covered most of Closed Area I, while granule/pebbles (56%) and cobble (22%) covered much of Closed Area II. Boulders were rare in the three closed areas, occurring in <3% of all quadrats (Figure 4). The distribution of scallops was strongly correlated with the distribution of granule/pebbles (NLSA df = 4, $\chi^2 = 93.0$, $p<0.0001$; CAI df = 4, $\chi^2 = 854.5$, $p<0.0001$; CAII df = 4, $\chi^2 = 84.2$, $p<0.0001$).

Station depths ranged from 37 to 104 m with an average of 71 m (SD = 14.1). Substrate was independent of depth in the Nantucket Lightship Area (Figure 5). Sand was associated with deeper water in Closed Area I and shell debris was associated with deeper water in Closed Area II (Figure 5). Scallop densities were independent of depth (Pearson's correlation: $r^2 = 0.002$, 0.098, and 0.257 for the Nantucket Lightship Area, Closed Area I, and Closed Area II, respectively).

Discussion

Densities of sea scallops within the three closed areas that had historically supported commercial scallop fishing were among the highest ever observed on Georges Bank. Sea scallop densities ranging from 0.25 to 0.59 scallop•m^{-2} within the three surveyed areas and 0.58 to 1.06 scallops•m^{-2} at stations where at least one scallop was observed. High densities of scallop spat occur on Georges Bank (123 scallops•m^{-2}; Larsen and Lee 1978). Thouzeau et al. (1991) surveyed the Northern portion of Georges Bank (Canadian waters) with a video-monitored sled-

dredge and estimated densities of 0.02 to 0.39 scallops·m^{-2} (shell height >75 mm) and 0.32 to 1.09 scallops·m^{-2} for all sizes. Lower estimates of 0.09 scallops·m^{-2} for the Northeast Peak (includes Closed Area II), were calculated using the commercial catches and relative estimates of abundance from the USA and Canadian federal dredge surveys (from 1977 to 1988) and applying a proportional scalar by the area (39,643 km^2), (McGarvey et al. 1992). However, these estimates were for a population exposed to high fishing mortality (F = 0.8).

The sea scallops observed within the three closed areas were also the largest ever observed on Georges Bank. Thouzeau et al. (1991) observed sea scallops ranging from 9 to 125 mm on Northern portion of Georges Bank. McGarvey et al. (1993) presented shell height frequencies ranging from 10 to 160 mm with modes ranging from 40 to 90 mm for all of Georges Bank from 1977 to 1987 (50,000 scallops sampled annually). The Nantucket Lightship Area had the largest scallops with the most individuals over 105 mm shell height and a maximum of 189 mm. In Closed Area I and II the majority of scallops were over 90 mm shell height with maximums of 195 and 173, respectively.

The combination of high densities and very large scallops has produced a large harvestable biomass in these three areas. The three areas surveyed (1938 km^2) contained approximately 650 million scallops representing 17 million kg of harvestable scallop meats. The average total biomass of scallops (>80 mm shell height) from 1977 to 1988 for all of Georges Bank (Canadian and United States portions) was 31.5 million kg (McGarvey et al. 1992). Thus 54% (17/31.5 million kgs x 100) of the average harvestable scallop biomass from 1977 to 1988 is now within 5% of the area (1938/39,643 km^2 x 100). The annual harvest was less than 3 million kg of scallop meat per year between 1994 and 1997 from the Georges Bank open areas (Murawski et al. 2000).

Natural mortality, deaths from all causes except fishing, for sea scallops on Georges Bank is estimated as M=0.1 (Merrill and Posgay 1964). This estimate (10%) assumes that dead paired shells (clappers) are caused by natural mortality only and are at equilibrium with the number being contributed to the population equal the number separating due to degeneration of the hinge ligament, which takes about 0.65 years (Dickie 1955, Merrill and Posgay 1964, Caddy 1989). Although there appears to be little evidence of density dependent natural mortality on Georges Bank (Caddy 1989) our estimates of dead scallop abundance and distribution suggest that natural mortality is highly site specific, for example very low in Closed Area I, and may be related to density as in the Nantucket Lightship Area.

Within the surveyed areas of Georges Bank, the sea floor was primarily composed of sand, shell debris, and granule/pebbles (90% of the Nantucket Lightship Area, 93% of Closed Area I, and 74% of Closed Area II). The Wentworth particle grade scale defines "gravel" as granules, pebbles and cobble. This has lead to confusion identifying the substrate of Georges Bank. Cobbles with a diameter of 64 to 256 mm are not commonly referred to as "gravel" (Sykes 1982). Small particles, such as granules and pebbles, can be frequently moved by natural disturbance, such as tidal currents and storm events occurring on Georges Bank (Butman 1987), and therefore do not to support large amounts of epifauna (such as sponges, hydra, and bryozoa). These substrates have a relatively low habitat complexity score, ranging between 1 and 5 (Auster and Langton 1999). Larger particles, such as cobbles and boulders, are less likely to be moved by natural disturbance and therefore may support epifauna. The term "gravel" includes both small particles (granules and pebbles, with little or no epifauna) and large particles (cobble that support epifauna). Sea scallops are most abundant on coarse sand-granule-pebble substrate (Langton and

Robinson 1990; Thouzeau et al. 1991; Stokesbury and Himmelman 1993, 1995; and the present study) that tends not to support epifauna and has a low habitat complexity score.

Sea scallops were highly aggregated into patches (beds) on the scale of km^2 and this distribution was strongly associated with the distribution of coarse sand-pebble-pebble substrate. Scallop beds in the Nantucket Lightship Area and Closed Area I were elongated in a north-south direction similar to the strong tidal currents in these areas (Brown and Moody 1987). This pattern was also observed on the northern edge of Georges Bank in 1970 and 1971 (Caddy 1989). In Closed Area II scallops were located along the northern edge where currents are strong (Tremblay et al. 1994). On Georges Bank tidally induced bottom currents and storm events can be strong and may surpass 11 to 37 $cm \cdot s^{-1}$ causing passive movement of scallops (Butman 1987; Grant et al. 1993). The sea scallops ability to swim and to form depressions in the sand-granule-pebble substrate may reduce the effects of these currents and allow it to persist in these areas (Baird 1954; Caddy 1968; Dadswell and Weihs 1990; Cheng and Demont 1996; Stokesbury and Himmelman 1996).

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. (1991) 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% (NMFS 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. Forth, 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.

The observed frequency distributions of scallops within all three surveyed areas were not normally distributed as larges areas did not contain scallops and therefore many of the quadrats had counts of zero. This presents a statistical problem with the data that sometimes may be solved by applying a different frequency distribution such as the negative binomial (Elliott 1971; Krebs 1989). However the scallop's spatial distribution was not described by the negative binomial distribution in all cases. Although a stratified random survey design may eliminate this problem, the spatial distributions of sea scallops on the scale of kilometers has never been determined on Georges Bank making stratification impractical as the strata boundaries cannot be determined (Krebs 1989). Further, how scallop distributions shift over time is unknown. Examining the dynamics of these scallop aggregations and different spatial analysis techniques, such as kriging, are required and will be the subject of ongoing research.

Rotational fisheries management strategies are being considered for the sea scallop resource of Georges Bank (Murawski et al. 2000; Myers et al. 2000). To implement such a management strategy will require precise, accurate estimates of scallop density and distribution by size class as well as information on the effects the fishery will have on the marine habitat. The video survey presented here provides that information.

Acknowledgements

I thank B.J. Rothschild for his support and guidance. A. Thibodeau, S. Buckley, C. Campbell, and B. Harris aided in data collection and processing. I thank R. Bruno, M. Manley, M. Orman and the owners, Captains, and crews of the F/V *Alpha and Omega II,* F/V *Edgartown,* F/V *Friendship,* F/V *Frontier,* F/V *Huntress,* F/V *Liberty* F/V *Tradition* and F/V *Mary Anne*. M Stokesbury, J. McLelland and P. Rago provided helpful comments. Reviews and recommendations by R. McGarvey, L Jacobson and an anonymous reviewer greatly improved the manuscript. Aid was provided by SMAST, the National Marine Fisheries Service, Woods Hole, the Massachusetts Department of Marine Fisheries, and the scallop fishery and supporting industries of New Bedford, Massachusetts.

References

Auster, P. J., and R. W. Langton. 1999. The effects of fishing on fish habitat. Pages 150-187 *in* L. Benaka, editor. Fish habitat: essential fish habitat and rehabilitation. American Fisheries Society, Bethesda, Maryland.

Baird, F. T. J. 1954. Migration of deep sea scallop (*Pecten magellanicus*). Fisheries circular. Department of sea and shore fisheries 14:1-8.

Brand, A.R. 1991. Scallop ecology: distributions and behaviour. Pages 517-584. *in* S. E. Shumway, editor. Scallops: biology, ecology and aquaculture. Elsevier, Amsterdam.

Beverton, R. J. H., and S. J. Holt. 1957. On the dynamics of exploited fish populations. Fisheries Investment Series 2. United Kingdom Ministry of Agriculture and Fisheries, London.

Brown, W. S., and J. A. Moody. 1987. Tides. Pages 100-107 *in* R. H. Backus, editor. Georges Bank. MIT press, Boston.

Butman, B. 1987. The effect of winter storms on the bottom. Pages 74-76 *in* R. H. Backus, editor. Georges Bank. MIT press, Boston.

Caddy, J. F. 1968. Underwater observations on scallop (*Placopecten magellanicus*) behaviour and drag efficiency. Journal of the Fisheries Research Board of Canada 25:2123-2141.

Caddy, J. F. 1989. A perspective on the population dynamics and assessment of scallop fisheries, with special reference to sea scallop, *Placopecten magellanicus* (Gmelin). Pages 559-589 *in* J. F. Caddy, editor. Marine invertebrate fisheries: their assessment and management. Wiley -interscience publication, John Wiley & sons, New-York.

Cheng, J.-Y., and M. E. Demont. 1996. Jet-propelled swimming in scallops: swimming mechanics and ontogenic scaling. Canadian Journal of Zoology 74:1734-1748.

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

Dadswell, M. J., and D. Weihs. 1990. Size-related hydrodynamic characteristics of giant scallop, *Placopecten magellanicus* (Bivalvia: Pectinidae). Canadian Journal of Zoology 68:778-785.

Dickie, L. M. 1955. Fluctuations on the Abundance of the giant scallop *Placopeten magellanicus* (Gmelin) in Digby area of the Bay of Fundy. Fisheries Research Board of Canada 12: 797-857.

Elliott, J. M. 1971. Statistical analysis of benthic invertebrates. Freshwater Biological Association Scientific Publication 25:1-142.

Grant, J., C. W. Emerson, and S. E. Shumway. 1993. Orientation, passive transport, and sediment erosion features of the sea scallop *Placopecten magellanicus* in the benthic boundary layer. Canadian Journal of Zoology 71:953-959.

Hilborn, R., and C. J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman & Hall, New York.

Krebs, C. J. 1989. Ecological Methodology. Harper & Row Publishers Inc., New York.

Langton, R. W., and W. E. Robinson. 1990. Faunal associations on scallop grounds in the western Gulf of Maine. Journal of Experimental Marine Biology and Ecology 144:157-171.

Larsen, P. F., and R. M. Lee. 1978. Observations of the abundance, distribution and growth of postlarval sea scallops, *Placopecten magellanicus*, on Georges Bank. Nautilus 92:112-116.

Lincoln, R. J., G. A. Boxshall, and P. F. Clark. 1992. A dictionary of ecology, evolution and systematics. Cambridge University Press, Cambridge.

McGarvey, R., F. M. Serchuk, and I. A. McLaren. 1992. Statistics of reproduction and early life history survivial of the Georges Bank sea scallop (*Placopecten magellanicus*) population. Journal of Northwest Atlantic Fishery Science 13:83-99.

McGarvey, R., F. M. Serchuk, and I. A. McLaren. 1993. Spatial and parent-age analysis of stock-recruitment in the Georges bank sea scallop (*Placopecten magellanicus*) population. Canadian Journal of Fisheries and Aquatic Sciences 50:564-574.

Merrill, A.S. and J.A. Posgay. 1964. Estimating the natural mortality rate of sea scallop (*Placopecten magellanicus*). Research Bulletin - International Communication for the Northwest Atlantic Fisheries. 1: 88-106.

Murawski, S. A., R. Brown, H.-L. Lai, P. J. Rago, and L. Hendrickson. 2000. Large-scale closed areas as a fishery-management tool in temperate marine ecosystems: the Georges Bank experience. Bulletin of Marine Science 66:775-798.

Myers, R. A., S. D. Fuller, and D. G. Kehler. 2000. A fisheries management strategy robust to ignorance: rotational harvest in the presence of indirect fishing mortality. Canadian Journal of Fisheries and Aquatic Sciences 57:2357-2362.

NMFS 2001. 32nd Northeast regional stock assessment workshop. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center, Woods Hole, MA

Posgay, J.A. 1979. Population assessment of the Georges bank sea scallop stocks. Rapports et Procès-Verbaux des Rèunions Conseil International pour l'Exploration de la Mer 175: 109-113

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada 191:1-382.

Sinclair, M., R. K. Mohn, G. Robert, and D. L. Roddick. 1985. Considerations for the effective management of atlantic scallops. Canadian Technical Report of Fisheries and Aquatic Sciences 1382: 1-99.

Sokal, R. R., and F. J. Rohlf. 1981. Biometry - the principles and practice of statistics in biological research. Freeman, San Francisco.

Stokesbury, K. D. E., and J. H. Himmelman. 1993. Spatial distribution of the giant scallop *Placopecten magellanicus* in unharvested beds in the Baie des Chaleurs, Québec. Marine Ecology Progress Series 96:159-168.

Stokesbury, K. D. E., and J. H. Himmelman. 1995. Biological and physical variables associated with aggregations of the giant scallop *Placopecten magellanicus*. Canadian Journal of Fisheries and Aquatic Sciences 52:743-753.

Table 1. The total number of sea scallops (*Placopecten magellanicus*) means (individuals•m^{-2}) and standard errors sampled in Nantucket Lightship Area (NLSA), Closed Area I (CAI) and Closed Area II (CAII) of Georges Bank from May to September 1999.

	NLSA	CAI	CAII
Area sampled km^2	507	1122	309
Number of stations	205	454	126
Quadrats per station	4	4	4
Mean number of live scallops•m^{-2}	0.38	0.25	0.59
Standard error of mean live scallops (SE)	0.039	0.021	0.043
Coefficient of variation (SE/mean*100)	10.2%	8.6%	7.3%
Mean number of dead scallops•m^{-2}	0.04	0.00	0.04
Standard error of mean dead scallops (SE)	0.010	0.001	0.007
Live scallops in surveyed area (millions)	194	276	182
Estimated scallop meat weight (g)	34.2	22.1	23.3
Total meat weight kg millions	6.6	6.1	4.2

List of Figures

Fig. 1. Georges Bank with the Nantucket Lightship Area, Closed Area I, and Closed Area II outlined, a) the historic scallop fishing grounds shaded in gray speckle, b) the video survey stations (black dots) sampled from May to September 1999.

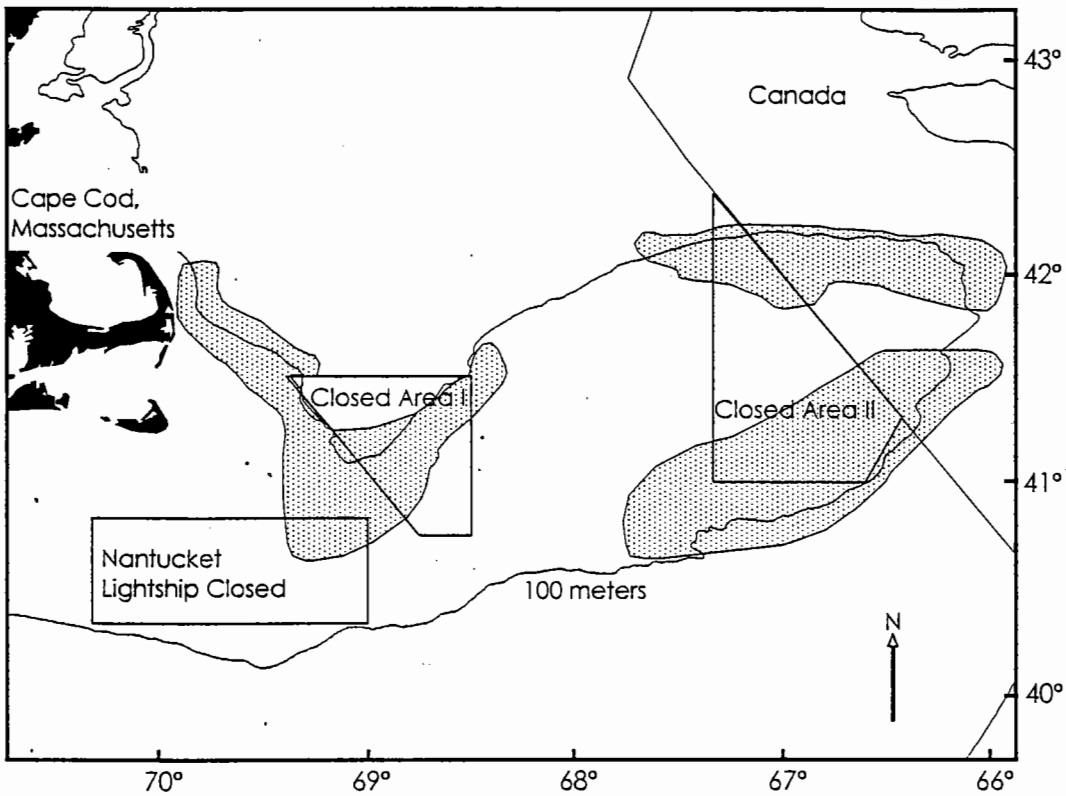
Fig. 2. The sampling pyramid, with a square base 2.2 m per side of 6 cm round iron, arms 2.5 m 4.5 cm round iron, approximate weight 450 kg, was deployed with the large hydraulic winch used in the scallop fishing industry. Rubber rings (3 sets 8 rings, each 20 cm diameter, 5 cm thickness, per side) were 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. Two 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. The camera and lights were attached to the vessel using 200 m cables and the tension of these cables was controlled by hand.

Fig. 3. Density contours of sea scallops, *Placopecten magellanicus*, in the Nantucket Lightship Area (NLSA), Closed Area I (CAI), and Closed Area II (CAII) of Georges Bank from May to September 1999. Lightly shaded area were sampled but no scallops were observed, medium shaded areas contained <0.5 scallop•m^{-2} and darkly shaded areas contained >0.5 scallop•m^{-2}.

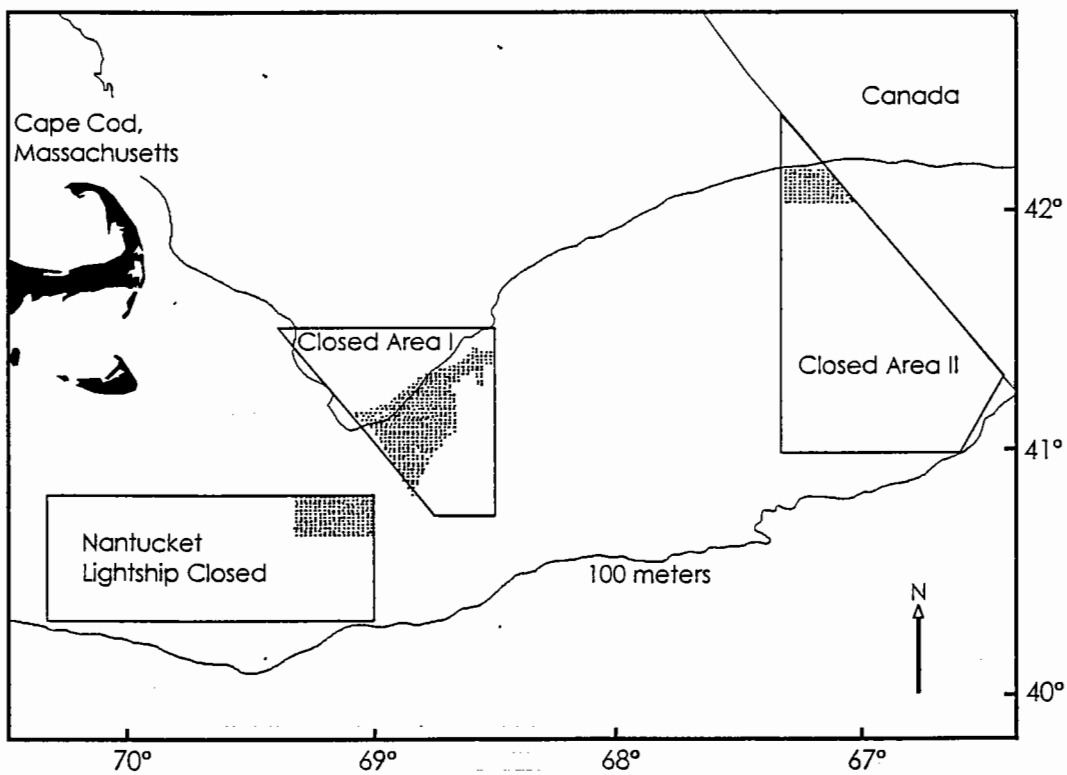
Fig. 4. Shell height frequencies of sea scallops, *Placopecten magellanicus*, in the Nantucket Lightship Area (NLSA), Closed Area I (CAI) and Closed Area II (CAII) of Georges Bank from May to September 1999.

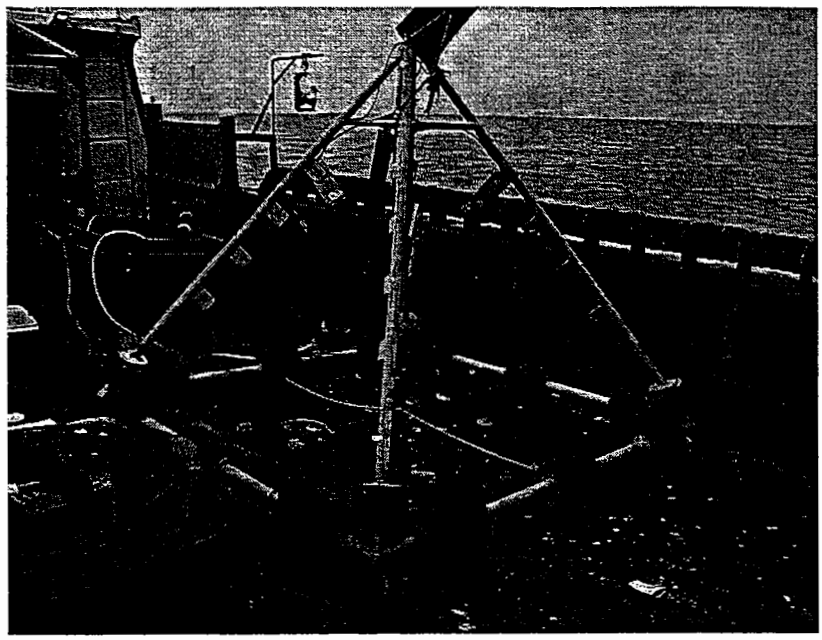
Fig. 5. Frequency distributions of sediment types observed per quadrat and average depth (m) with standard error bars in the Nantucket Lightship Area (NLSA), Closed Area I (CAI) and Closed Area II (CAII) of Georges Bank from May to September 1999; n = number of quadrats.

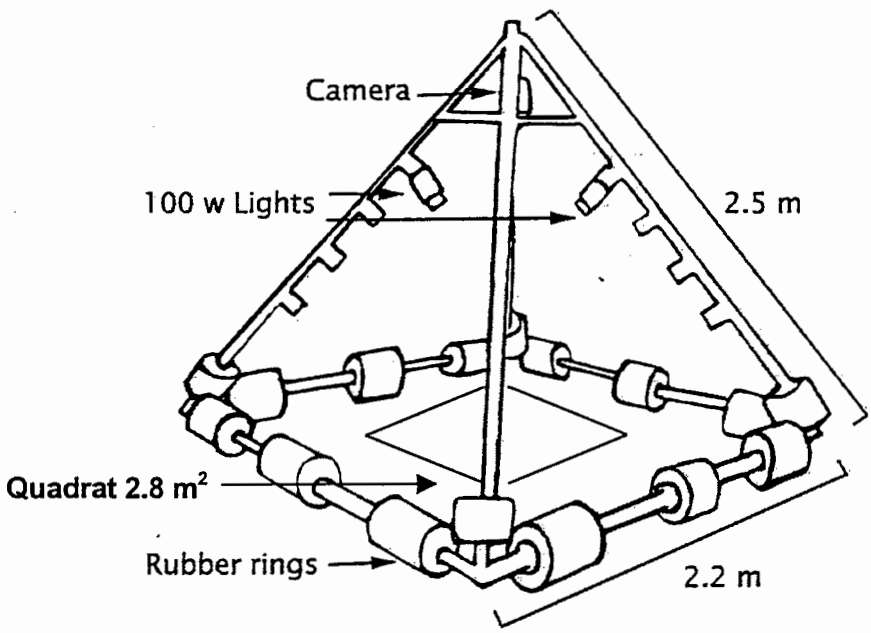
a)

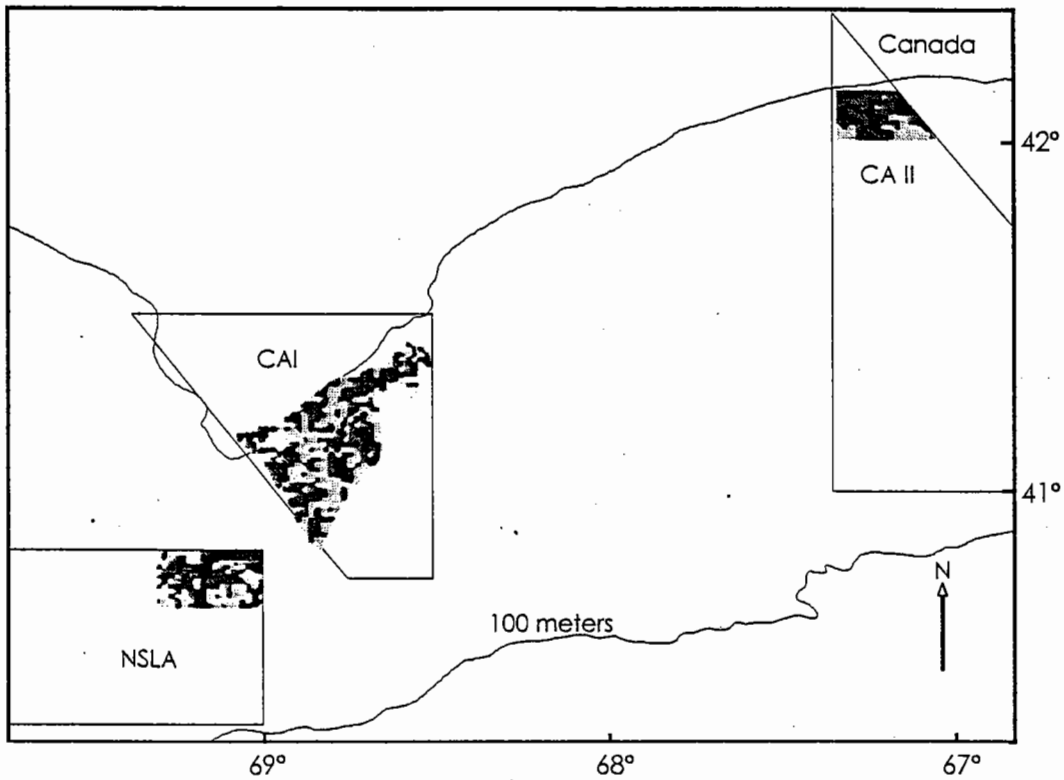

Canada
Cape Cod,
Massachusetts
Closed Area I
Closed Area II
Nantucket
Lightship Closed
100 meters
N
43°
42°
41°
40°
70°
69°
68°
67°
66°

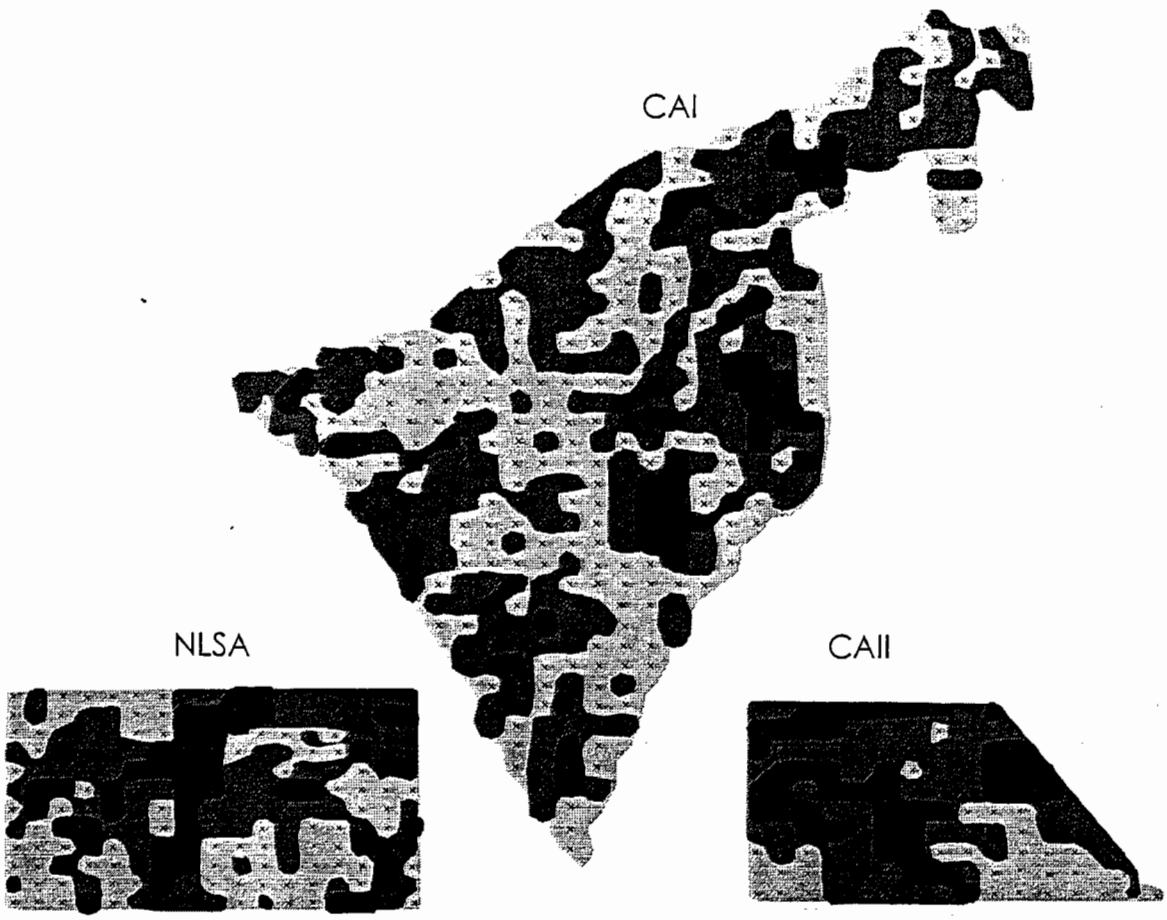
b)

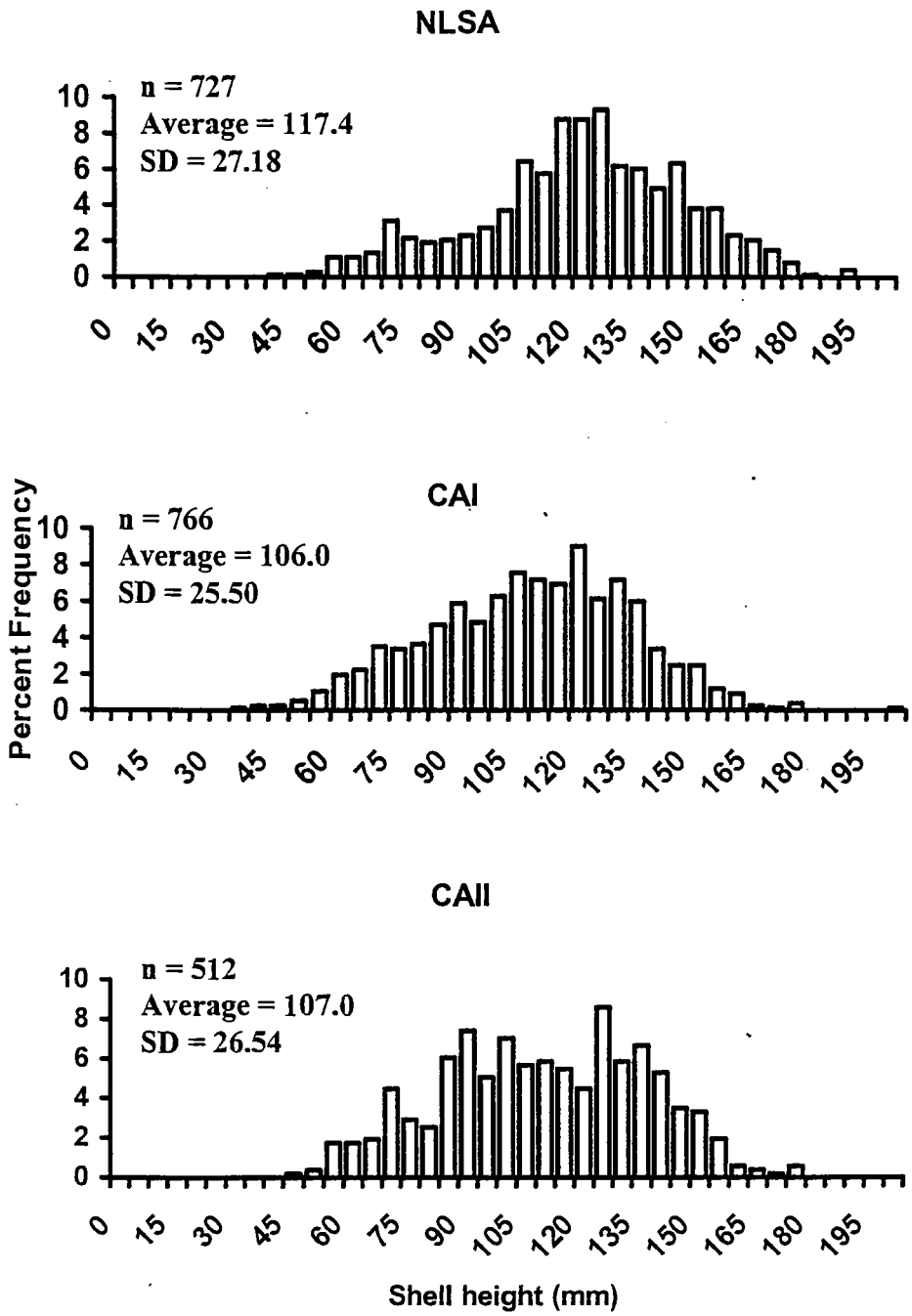

Canada
Cape Cod,
Massachusetts
Closed Area I
Closed Area II
Nantucket
Lightship Closed
100 meters
N
42°
41°
40°
70°
69°
68°
67°

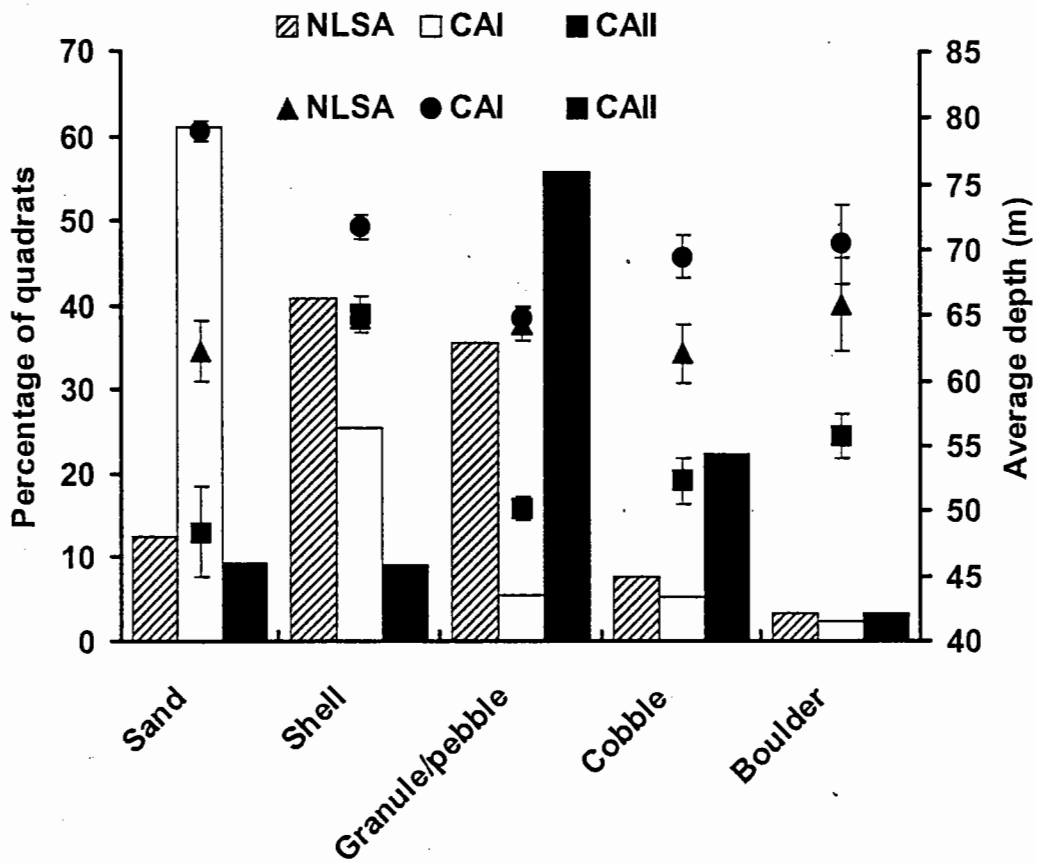



Camera
100 w Lights
2.5 m
Quadrat 2.8 m²
Rubber rings
2.2 m


Canada
42°
CA II
CAI
41°
N
100 meters
NSLA
69°
68°
67°


CAI
NLSA
CAII


NLSA
n = 727
Average = 117.4
SD = 27.18
CAI
n = 766
Average = 106.0
SD = 25.50
CAII
n = 512
Average = 107.0
SD = 26.54
Percent Frequency
Shell height (mm)
0
2
4
6
8
10
0
15
30
45
60
75
90
105
120
135
150
165
180
195


NLSA
CAI
CAII
NLSA
CAI
CAII
Percentage of quadrats
Average depth (m)
0
10
20
30
40
50
60
70
40
45
50
55
60
65
70
75
80
85
Sand
Shell
Granule/pebble
Cobble
Boulder

Not to be cited without prior reference to the authors

International Council for the Exploration of the Sea

CM 2001/N:17

Theme Session on Case Studies in The Systems Analysis of Fisheries Management (N)

A management system for the Atlantic Sea scallop using video surveys, a simulation model and an optimization method.

Kevin D. E. Stokesbury[1], Tu Truong[2], Farhad Azadivar[2], and Brian J. Rothschild[1]

[1] School for Marine Science and Technology, University of Massachusetts Dartmouth, 706 South Rodney French Blvd., New Bedford, MA 02744-1221 [Tel. (508) 999-8193; Fax. (508) 999-8197 email: first initialsurname@umassd.edu.

[2] College of Engineering University of Massachusetts Dartmouth 285 Old Westport Road, North Dartmouth, MA 02747-2300 [tel: (508) 999-8461 email: first initialsurname@umassd.edu.

Abstract:

The sea scallop resource of Georges Bank supports one of the largest commercial fisheries in the United States. Closures of large portions of the Bank in 1994 have produced extremely high concentrations of scallops in some areas while other areas remain heavily fished. Presently these closed areas contain about 80% of the Georges Bank scallop resource. This situation creates a unique opportunity to implement a rotational management strategy, however models are required to test alternative strategies given certain constraints. Simulation models are used in stock dynamics to estimate the effects of different variables, many of which are vague or unknown. Optimization methods are used to find the best fishing plan given specified quantitative objectives, a model of the stock dynamics, and specific management alternatives. The four components of the temporal-spatially specific fisheries management system for the Georges Bank scallop stock are: 1) the collection of high-resolution information on the biology and ecology of the sea scallop in real-time, 2) a simulation model to estimate stock dynamics, 3) a fisheries management plan using optimization methods, and 4) the communication of the fisheries management plan to the regulatory agencies. Constraints include unknown aspects of scallop biology and ecology, and the economics and logistics of the fishery.

Introduction:

Fisheries management plans are limited by incomplete information on the biology and state of the stock, the variables affecting fishing effort, and poor resolution of the temporal and spatial scales affecting biological and fishery processes. Many model driven management strategies estimate these factors on only a cursory level. Thus a critical problem facing management is the linkage of field biology to stock dynamic models on appropriate spatial and temporal scales.

Simulation models are used in stock dynamics to estimate the effects of different variables, many of which are vague or unknown (Law and Kelton 1991). Optimization methods are used to find the best fishing plan given specified quantitative objectives, a model of the stock dynamics and specific management alternatives (Hilborn and Walters 1992). The combination of a simulation model linked to optimization methods and drive by high-resolution field observations will provide the opportunity to manage fisheries with a new degree of accuracy.

The sea scallop, *Placopecten magellanicus*, ranges in United States waters from the Canadian/US boarder (the Hague Line) to the coast of Virginia. The sea scallop has been commercially fished since the 1800's. Sea scallops are spatially aggregated into grounds (100's of nautical miles) and within these grounds they form beds on the scale of km^2 (Brand 1991; Stokesbury and Himmelman 1993). Sea scallops lives to an approximate age of 16 years and enters the fishery between ages 3 and 4 on Georges Bank. Landings of the sea scallop fluctuate greatly from year to year and the fishery is primarily driven by year-class strength (Caddy 1989). Presently, there are approximately 250 vessels fishing for scallops in United States waters and the fishery is managed using three effort controls; Days-at-Sea (DAS), 8.89 cm (3.5') ring size in the dredge collection bag, and a maximum of seven people per vessel (Rago et al. 2000).

In 1994 three large areas of the United States portion of Georges Bank were closed to mobile fishing gear in an effort to protect depleted groundfish stocks (Murawski et al. 2000). These closed areas included portions of historic scallop fishing grounds. Presently, these areas contain about 80% of the Georges Bank sea scallop resource. In 1999 and 2000 portions of these areas were opened to limited fisheries for sea scallops. Extremely high catches were made with limited dredge contact time on the sea floor. This suggests that a temporal-spatially specific fishing management plan may produce better landings while greatly reducing dredge contact time with the bottom.

There are four key components to developing a temporal-spatially specific fisheries management system for the Georges Bank sea scallop resource (Fig. 1):

1. The collection of high-resolution information on the biology and ecology of the sea scallop.
2. The development of a simulation model to estimate the stock dynamics.
3. The development of a fisheries management plan using optimization methods.
4. The communication of the fisheries management plan to the regulatory agencies.

The constraints on our model were the von Bertalanffy growth equation parameters, the lack of recruitment or migration, a instantaneous natural mortality ($M = 0.1$) and a maximum instantaneous fishing mortality of ($F = 0.9$). Future modifications will develop these constraints.

METHODS:

1. The collection of high-resolution information on the biology and ecology of the sea scallop.

The scallop aggregations of Georges Banks were surveyed from May to September 1999 and 2000 (Fig. 2). Using a systematic design the scallop grounds were sampled on a 1.57 km grid (0.85 nautical miles), (Stokesbury 2001). At each station a fishing vessel deployed the video

camera mounted on the sampling pyramid providing a 2.8 m^2 image of the sea floor. After the first image the pyramid was raised so that the sea floor could no longer be viewed, the vessel drifted for several 10's of meters 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 video-tapes were replayed and an image of each quadrat was digitized and saved (TIF file format). Scallop counts taken aboard the fishing vessel were verified, the substrate within each image was identified, and visible macroinvertebrates were counted. Scallops within the viewing field and those along the edge were counted so the sample area was increased to 3.235 m^2 to correct for edge bias. All counts were standardized to individuals$\cdot m^{-2}$. These data provide the position and shell heights of each scallop observed.

Spatial interpretation of the video data

Kriging is a generalized linear regression technique used to calculate the spatial variation of an organisms mean density (MacLennan and Simmonds 1992). The premise of kriging is that every unsampled point can be estimated by the weighted sum of the sampled points. This method works well for populations that have a constant spatial-temporal structure (MacLennan and Simmonds 1992; Maravelias et al. 1996). We used the EasyKrig 2.1 program for Matlab that was developed by the Woods Hole Oceanographic Institute.

In kriging, the covariance between two points x and x+d is assumed to be independent of location x but depends on distance vector d. The semi-variogram measures the mean variability between the points x and x+d. The estimator $\gamma(d)$ of semi-variogram is defined by Matheron's equation (1971):

1) $$\tilde{\gamma}(d) = \frac{1}{2No(d)} \sum_{i=1}^{No(d)} [(AV(x_i) - AV(x_i + d)]^2$$

where

d = the distance between two known points, often referred to as the lag

$No(d)$ = the number of pairs of sampled points separated by a distance d

$AV(x)$ = the attribute value, scallop density in this case, at location x.

Based on the estimators of semi-variogram calculated from experimental data, we constructed a theoretical semi-variogram model $\gamma(d)$, which expresses the structure of the correlation between any pair of data points. In fisheries acoustics the most frequently used variogram models are the nugget model, the spherical model, the exponential model and the linear model (Maravelias et al 1996). We used the spherical model:

2) $$\gamma(d) = c_0 + c.[\frac{3}{2}\frac{d}{a} - \frac{1}{2}\frac{d^3}{a^3}] \quad \text{for } d \leq a$$
$$\gamma(d) = c_0 + c \quad \text{for } d > a$$

where:

c_o = the nugget representing unresolved, sub-grid scale variation or measurement error; the intercept of the semi-variogram.

a = the range which controls the degree of correlation between data points, usually represented as a distance.

c = the sill which is the value of the semi-variance as the lag (d) goes to infinity; representing the total variance of the data set.

c_0, a and c are determined by a least square errors regression so that the sum of errors between the estimators and the theoretical value is minimized (Fig. 3).

The data was plotted as a contour map using ordinary kriging (Matheron 1971). Ordinary kriging uses the above constructed semi-variogram model in spatial interpolation. The general equation for estimating the attribute value AV at a point is:

3) $$AV^*(x_0) = \sum_{i=1}^{S} AV(x_i).w_i$$

where

$AV^*(x_0)$ = the estimator of the interested attribute at an unsampled point x_0

$AV(x_i)$ = the values of the interested attribute at a sampled points x_i (i = 1..S)

w_i = the weight factor associated with the sampled point x_i

S = the number of sampled points

The kriging algorithm selects appropriate weight factors. Weight factors are calculated for each estimate. The weight factors must be constrained to add up to one to assure the unbiased property that the expected value of the error is equal to 0:

4) $$E[AV^*(x_0) - AV(x_0)] = 0$$

$$\sum_{i=1}^{S} w_i.[AV(x_i) - AV(x_0)] = 0$$

The estimation variance is:

5)
$$\sigma_E^2 = E\left\lfloor \{AV^*(x_0) - AV(x_0)\}^2 \right\rfloor$$
$$\sigma_E^2 = -\gamma(x_0 - x_0) - \sum_{i=1}^{S}\sum_{j=1}^{S} w_i . w_j . \gamma(x_i - x_j) + 2\sum_{i=1}^{S} w_i \gamma(x_i - x_0)$$

The weight factors are derived from solving a set of simultaneous equations. The ordinary kriging system is obtained by minimizing the estimation variance with the following constrain on the weight factors:

6)
$$\begin{bmatrix} \gamma(x_1 - x_1) & \dots & \gamma(x_1 - x_S) & 1 \\ \vdots & \dots & \vdots & \vdots \\ \gamma(x_S - x_1) & \dots & \gamma(x_S - x_S) & 1 \\ 1 & \dots & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ \vdots \\ w_S \\ \mu \end{bmatrix} = \begin{bmatrix} \gamma(x_1 - x_0) \\ \vdots \\ \gamma(x_S - x_0) \\ 1 \end{bmatrix}$$

Ordinary kriging is an exact interpolator so that at the point of the data the estimated value is equal to the data value.

2. The development of a simulation model to estimate the stock dynamics.

The high-resolution video survey data provided information on the density and size of sea scallops at specific locations on Georges Bank. Using these spatial density distributions and shell height frequencies a simulation model was developed that incorporated growth, natural, and fishing instantaneous mortalities, simultaneously. The survey area is divided into several smaller plots (I x J plots) in such a way that the assumption about homogeneousness within each plot would not lead to significant errors. Scallop abundance in each plot was then simulated independently.

A von Bertalanffy growth equation was derived from the video survey data as several locations were sampled over time. Scallop growth, measured as shell height (L) was described using the von Bertalanffy equation (Ricker 1975):

7) $$L_t = L_\infty.[1 - e^{-K(t-t_0)}]$$

where

L_t = scallop shell height at year t

L_∞ = asymptotic scallop shell height

K = the Brody growth coefficient

t_0 = the hypothetical age where the scallop has a shell height of zero

Scallops are grouped into N shell height categories. In the simulation model, up to 180 categories were used. In optimization models, 20 categories were used to keep the calculation burden minimal.

Let vector V_{ijt} denote the population of scallops in plot (i, j) at the beginning of year t so that $V_{ijt} = [n_{ijt1}\ n_{ijt2} \ldots n_{ijtN}]$ and n_{ijtr} is the number of scallops of r-th category. Scallops propagate forward from one category to the next. Thus the scallop population vector in the next year is:

8) $$V_{ij(t+1)} = [G].V_{ijt}$$

Where [G] represents an NxN matrix, presenting the growing process of scallops during one year:

$$g_{m,n} = \begin{cases} 1 & \textit{if} \quad \textit{scallop in n-th category will be in m-th category after one year} \\ & \quad \textit{according to above von Bertalanffy equation. } m, n = 1..N \\ 0 & \textit{otherwise} \end{cases}$$

Natural and fishing mortality are two continuous processes that occur in parallel fashion (Ricker 1975) and the number of scallops declines exponentially due to natural and fishing mortality:

9) $$N_t = N_1.e^{-(M+F).(t-1)} = N_1.e^{-Z.(t-1)}$$

or

10) $$N_{t+1} = N_t.e^{-(M+F)} = N_t.e^{-Z}$$

where:

N_1, N_t, N_{t+1} = the number of scallops at beginning of year 1, t and (t+1) respectively;

M = instantaneous natural mortality rate

F = instantaneous fishing mortality rate

Z = overall instantaneous mortality rate, $Z = M + F$.

A natural mortality of $M = 0.1$ was used based on previous research on Georges Bank scallops (Caddy 1989).

Fishing mortality varies over time, locations and scallop shell height. The above equations assume that instantaneous fishing mortality for each category of scallop in one plot is constant

within a year. Fishing mortality for each category depends on gear selection. Gear selection is discussed by Caddy (1975) as following:

$$p(h) = \begin{cases} 0 & for\ \ h \le 18mm \\ 0.2/37.(\mathrm{h}-18) & for\ \ 18mm < h \le 55mm \\ 0.8/64.(\mathrm{h}-55)+0.2 & for\ 55mm < h \le 119mm \\ 1 & for\ 119mm < h \end{cases}$$

where p(h) is gear selection corresponding to scallops with shell height (mm).

Let F_{ijt} be the overall instantaneous fishing mortality in plot (i,j) in year t. Since the shell height of the scallops is changing throughout the year, we use the shell height at the middle of the year as an average. Denote $h_{r+0.5}$ as the average shell height of scallops in r-th category at middle of the year, then, instantaneous fishing mortality for r-th category is calculated as follows (Caddy 1975):

11) $F_{ijtr} = p(h_{r+0.5}).F_{ijt}$ $\qquad$ r = 1..N

The scallop population after one year, considering natural mortality and fishing, is:

12) $$V_{ij(t+1)} = [G].\{(V_{ijt}.e^{-M})(.*)([e^{-F_{ijt1}}\ e^{-F_{ijt2}} \ldots e^{-F_{ijtN}}])\}$$

where (.*) operator is an *element-to-element multiplication* of two vectors of the same size.

The number of scallops caught in year t at plot (i, j) is presented by the vector C_{ijt}:

13) $$C_{ijt} = V_{ijt}(.*)\left[\frac{F_{ijt1}}{M+F_{ijt1}}(1-e^{-M-F_{ijt1}}),\ \frac{F_{ijt2}}{M+F_{ijt2}}(1-e^{-M-F_{ijt2}}),\ \ldots\ ,\frac{F_{ijtN}}{M+F_{ijtN}}(1-e^{-M-F_{ijtN}})\right]$$

Fishing yield in weight for year t for each plot is:

14) $Y_{ijt} = C_{ijt}.W$

where:

W = weight vector that represents average weight of each category; W = [w_1 w_2 ... w_N]

Estimates of scallop meat weight were derived from shell height (SH) frequency data and length/weight regressions (n=83, w = 3.59 x $10^{-5} \cdot SH^{2.861894}$, r^2 =0.95 for the Nantucket Lightship Area; n=123, w = 3.837 x $10^{-5} \cdot SH^{2.8189}$, r^2 =0.93 for the remaining locations).

Total fishing yield (Y_t) in year t for the whole area is:

15) $$Y_t = \sum_{i=1}^{I}\sum_{j=1}^{J} Y_{ijt}$$

As a new time period begins, the procedure is repeated with updated scallop populations.

3. The development of a fisheries management plan using optimization methods

After a dynamic simulation model was constructed a decision-making tool for scallop harvesting management was required. We developed an area-based approach in which the areas of George Bank surveyed with the high-resolution video were divided into blocks. Fishing factors for blocks were calculated for each year. Mathematically, the more blocks, the closer the output is to the optimal solution. We determined the optimal fishing factors within blocks for each year of a planning horizon so that the total fishing yield is maximized:

16) $$Max\ \ Y = \sum_{t=1}^{T} Y_t$$

where:

T = the number of years in the planning horizon.

The decision variables are the fishing factors within the blocks for each year of the planning horizon, denoted as F_{ijt} (i = 1..I, j = 1..J, t = 1..T). The constraints are the maximum value of the

fishing factor (set at 0.9) within the blocks. With each set of decision variable F_{ijt}, the objective function value Y is calculated by the simulation model described above.

The mathematical model is well structured but the order of objective function is high and prevented us from solving the optimization problem analytically. As an alternative we employed a heuristic search method, which guarantees a near optimal solution promptly. Among heuristics search methods Genetic Algorithms (GA) are widely used (Goldberg 1989; Chambers 2001). Genetic Algorithms are optimization techniques based on the concepts of natural selection and genetics. The significant feature of the Genetic Algorithm is that it requires only limited gradient information about the response surface, hence it can be employed for a wide variety of optimization problems. Furthermore, unlike other local search heuristics, the Genetic Algorithm is resistant to becoming trapped on local optima.

In the Genetic Algorithm a set of IxJxT fishing factors (rows, columns, years) is combined as one and converted into a binary string called a chromosome, such as 01010000101000111. A pre-specified number of chromosomes are maintained at a time and called a population. The initial population of chromosomes is created either randomly or by perturbing an input chromosome. In the second step, evaluation, the objective function values are computed. The third step is the exploitation or natural selection step. In this step, the chromosomes with the largest objective function values are placed one or more times into a mating subset in a semi-random fashion. Chromosomes with low objective function values are removed from the population. Solutions that violate constraints are assigned a very low value and, therefore, are removed from the population. The fourth step, exploration, consists of the crossover (recombination) and mutation operators. Two chromosomes (parents) from the mating subset are randomly selected to mate. The probability that these chromosomes are recombined

(mated) is a user-controlled option and is usually set to a high value (e.g., 0.95). If two chromosomes are allowed to mate, a recombination operator is employed to exchange genes between them to produce two children. If they are not allowed to mate, the chromosomes are placed into the next generation unchanged. We used a one-point recombination operator. In the one-point method, a crossover point is selected along the chromosome and the genes up to that point are swapped between the two parents. The children then replace the parents in the next generation. The second user-controlled option we employed was mutation. The probability that a mutation will occur was set to a low value (e.g., 0.01) so that good chromosomes were not destroyed. A mutation simply changes the value for a particular gene. After the exploration step, the population is full of newly created chromosomes (children) and steps two through four are repeated. This process continued for a fixed number of generations. Then the optimal pattern was run through the simulation model (described above) to demonstrate the optimal fishing stategy.

Results

The 1994 closure of three large areas of Georges Bank to mobile fishing gear gave the unprecedented opportunity to observe and measure sea scallops in an undisturbed state. The densities and sizes of sea scallops within these three closed areas were among the highest ever observed on Georges Bank. Sea scallop densities (>60 mm shell height) ranged from 0.25 to 0.59 scallop m^{-2} within the three areas surveyed (Table 1). The three areas surveyed contained approximately 650 million scallops representing 17 million kg of harvestable scallop meats (Table 1).

The video survey data were best described using a spherical semi-variogram model where the nugget = 0.739, sill = 1.37 and range = 0.95 (Fig 3). The spherical model ignores the high correlation of the quadrats that were extremely close to one another (four quadrats per station).

The contour maps resulting from kriging the video data indicated that scallops were highly aggregated on the scale of km^2, similar to estimates derived from smoothing techniques where scallop aggregations ranged from 19 to 151 km^2 (Fig. 4) (Stokesbury 2001). Kriging also provides contour maps of the variance of errors, which is the variance at each point compared to the average variance (Fig 5). Kriging estimates of scallop densities were similar to those calculated using the multistage sampling technique (Krebs 1989) (Table 2). However, the standard errors of the means were smaller for the kriging estimates suggesting that this is a better technique.

Two areas, the Nantucket Lightship Area and Closed Area I were surveyed several times during 1999 and 2000. Comparisons of the differences in densities by subtracting the earlier observed densities from the latter suggest that even when fishing does not occur there were shifts on the scale of km in scallop density within the Nantucket Lightship Area between 1999 and 2000. The positive shifts may be a result of immigration or recruitment while the negative shifts suggest site-specific high natural mortality, emigration or both. Shifts in scallop density distribution were also observed between August and October 2000 in the Nantucket Lightship Area (Fig 6). A pulse fishing event occurred during this time in the Nantucket Lightship Area harvesting 0.6 million kg (1.3 million lbs) of scallop meat. The negative shifts in density may have resulted from fishing, however, positive shifts were also observed and over such a short time period this suggests immigration rather than recruitment (Fig. 6). Positive and negative

shifts in scallop density were also observed in Closed Area I between August 1999 and August 2000 again suggesting site specific natural mortality, migration or both (Fig. 6).

The three video surveys of the Nantucket Lightship Area provide shell height frequencies over time, which enabled the estimation of the von Bertalanffy growth equation (Fig 7). Assuming that the peaks in these histograms represent the growth of a cohort of scallops over time (1999 = 120 mm; August 2000 = 134 mm; October 2000 = 137 mm) solving the von Bertalanffy growth equation resulted in the values L_∞ = 180 mm; K =0.288; t = 3.8 years with t_0 set at zero. The shell heights of sea scallops from these closed areas were much larger than scallops collected during previous studies conducted in heavily fished areas of Georges Bank (Fig. 8). These earlier studies estimated the parameters for the von Bertalanffy growth equation, with a low L_∞ of about 145 mm. The higher L_∞ reflects the shell heights observed in these closed areas and was used in the simulation model.

The biomass of sea scallops was simulated for an eight-year period using each video survey as the initial conditions (Fig. 9). For each simulation the fishing effort was set at zero as most of these areas are presently closed to fishing with model gear, the exception being the Great South Channel. The model assumed no migration or recruitment. The Nantucket Lightship Area model for the August 1999 data did not agree with the August 2000 data as the model predicted a biomass of 7800 tons and only 7300 tons was observed in 2000. However, scallop density increased between July 1999 and August 2000 in the Nantucket Lightship Area (Table 1). The opposite situation occurred in Closed Area I. When the 1999 survey of Closed Area I was partitioned to the same area as that sampled in 2000 a large increase in biomass was observed, the model predicted 3500 tons but 4500 tons were observed. This is due to a higher observed density per m^2 in 2000 (Fig. 4 and 6). The maximum for the curves in the closed areas all

indicated that 3 to 4 more years would increase the biomass but then the natural mortality would start to decrease the total biomass. The Great South Channel, which is open to fishing, requires six years of closure to reach its maximum (Fig. 9). The spatial distribution of these projections of biomass did not vary in spatial distribution over time (Fig. 10). This is due to the lack of recruitment in the model. Rather the curve is driven by the relationship between the initial scallop density and shell height, the von Bertalanffy growth equation and the natural mortality estimate.

The 1999 Nantucket Lightship Area video survey was used as the initial conditions for the optimization model. The model suggests that the optimal harvest could be achieved leaving the area for 2000 and then increasing the harvest sharply to a fishing effort of 0.9 in 2003 and keeping it high until the biomass is removed resulting in a total harvest of 9428 tons over five years. This is achieved by fishing certain areas when they reach their optimal breaking point (0 blocks in year 1, 6 blocks in year 2, and all blocks from year 3 onward). When a discount of 10% is added so that the increase in biomass has to be at least 10% to equal its value in the previous year, the optimal model suggests immediate harvest at a high fishing effort (Fig. 11). With the 10% discount the scallop harvest would be 9150 tons over five years. If the simulation model uses the average fishing effort of the first scenario (F = 0.5) the harvest is reduced to 8430 tons over five years. Using the present harvest strategy (F = 0.2) the scallop harvest would be 5903 tons over five years.

Discussion

The high-resolution video data collected in 1999 and 2000 provided accurate measures of sea scallop densities and site-specific shell height data. The kriging technique provided the best

estimates of surface densities and distribution as mean density estimates agreed with those derived from multistage sampling design techniques but with lower estimates of variance. Further the spatial distribution of the variance was also estimated by the kriging technique.

The spatial distribution of scallop aggregations appeared to shift over time. Comparisons between surveys in 1999 and 2000 in the Nantucket Lightship area and Closed Area I suggested that location specific natural mortality, migration or both were occurring on the scale of km. For many years fishermen have reported large-scale migrations of sea scallops. Although migration is not well demonstrated, researchers nevertheless consider that it may account for recruitment into beds because natural settlement in many beds appears to be low (Melvin et al. 1985; Stokesbury and Himmelman 1996). This could account for the density shifts, which were quite high (0.2 to 0.4 scallops per m^2) in both the Nantucket Lightship Area and Closed Area I. Further, locations with negative values were adjacent to areas with positive density values on a north/south axis similar to the prevailing currents which are dominated by sand/granule/pebble substrates (Stokesbury 2001). Scallop movement is greatly increased with current direction particularly over sand (Stokesbury and Himmelman 1996).

The von Bertalanffy growth equation estimated from the Nantucket Lightship survey series provided a larger asymptotic shell height than any previous estimates from Georges Bank. This suggests a faster growth rate primarily during the first year. Although the asymptotic shell height agreed with the observed maximum shell height from the video surveys, this may have resulting in the higher projected biomass from the 1999 Nantucket Lightship Area (7800 metric tons for 2000) than those observed during the 2000 survey (7300 metric tons). Perhaps the lower observed biomass in the Nantucket Lightship Area was the result for a higher natural mortality rate as the scallops. Although the observed density of scallops increased slightly (0.38 to 0.40

scallops m^{-2}) from July 1999 to August 2000 suggesting recruitment or immigration, these scallops would be small and if a higher natural mortality rate occurs on the very large scallops the results would be a lower biomass estimate. A greater number of dead scallops were observed in the Nantucket Lightship area in both 1999 and 2000 than any other location (Stokesbury 2001).

The instantaneous natural mortality estimate of M=0.1 is based on the assumption that dead scallops with their shells attached at the hinge by the ligament (clappers) are only caused by natural mortality. At equilibrium the number of scallops dying equals the number of clappers separating due to degeneration of the hinge ligament (Dickie 1955; Merrill and Posgay 1964; Caddy 1989). However, problems arise in establishing the rate at which the ligament decays and the sampling errors associated with dredge collections. There are few direct observations of scallop natural mortality (MacDonald and Thompson 1986; Stokesbury and Himmelman 1995; 1996).

The scallop densities in the closed areas of Geroges Bank were some of the highest ever observed suggesting that these areas maybe reaching their carrying capacity and that density-dependent growth and mortality may occur. Some authors suggest that density dependent growth and mortality occur in scallop aggregations. Shumway et al. (1987) suggested that the quality and quantity of food availability is a major limiting resource for suspension feeding organisms, particularly sea scallops. Caddy (1989) suggested that density dependent mortality could occur as predators (*Buccinum undatum*) were attracted to artificially high densities of scallops, this may also occur with starfish (Dickie and Medcof 1963). If density dependent mortality does occur in scallop aggregations it may be one of the few natural constraints restricting the maximum output of an area.

The constraints on our model were the von Bertalanffy growth equation parameters, the lack of recruitment or migration, and a constant natural mortality. These constraints combined to produce a knife-edge breaking point for harvesting in the optimization model. In this scenario the scallop aggregation grow until a critical size is obtained and then all the scallops are harvested at once with as high a fishing effort as the constraint on the model will allow. Variations in a discount rate will change the timing of the harvest but not the knife-edge pattern. However, the optimization model produced higher harvests by fishing specific areas within the grid, than the harvests achieved using a constant fishing effort over five years.

This is the first step in the development of a scallop fishery management system for Georges Bank. A great deal of information is still required including site specific growth, a natural mortality rate over the life of the scallop and how that rate interacts with predator densities, recruitment, migration and the marine environment. The model also has to be expanded to cover the whole Georges Bank scallop resource which will involve further video surveys or linking the video data with the National Marine Fisheries Service molluscan dredge survey. Finally, management parameters such as enforcement requirements and economics need to be considered. However, this first step clearly demonstrates the usefulness of such a model.

Acknowledgements: A. Thibodeau, S. Buckley, C. Campbell, and B. Harris aided in data collection and processing. We thank the owners, Captains, and crews of the *F/V Huntress, F/V Alpha and Omega II, F/V Liberty, F/V Friendship, F/V Mary Anne, F/V Frontier, F/V Tradition* and *F/V Edgartown*. Aid was provided by the National Marine Fisheries Service, Woods Hole, the Massachusetts Department of Marine Fisheries, and the scallop fishery and supporting industries of New Bedford, Massachusetts.

References

Brand, A. R. 1991. Scallop ecology: distributions and behavior. 517-584 *in* S. E. Shumway, editor. Scallops: biology, ecology and aquaculture. Elsevier, Amsterdam-Oxford-New York-Tokyo.

Caddy, J. F. 1975. Spatial model for an exploited shellfish population, and its application to the Georges Bank scallop fishery. Journal of the Fisheries Research Board of Canada 32: 1305-1328.

Caddy, J. F. 1989. A perspective on the population dynamics and assessment of scallop fisheries, with special reference to sea scallop, *Placopecten magellanicus* (Gmelin). 559-589 *in* J. F. Caddy, editor. Marine invertebrate fisheries: their assessment and management. Wiley -interscience publication, John Wiley & Sons, New-York.

Chambers, L. 2001. The practical handbook of genetic algorithms: applications. 2nd edition. Chapman and Hall, London.

Dickie, L. M. 1955. Fluctuations on the Abundance of the giant scallop *Placopeten magellanicus* (Gmelin) in Digby area of the Bay of Fundy. Journal of the Fisheries Research Board of Canada 12: 797-857.

Dickie, L. M., and J. C. Medcof. 1963. Cause of mass mortalities of scallops (*Placopecten magellanicus*) in the southwestern Gulf of St. Lawrence. Journal of the Fisheries Research Board of Canada 20(2): 451-482.

Goldberg, D. E. 1989. Genetic algorithms in search, optimization and machine learning. Addison Wesley , Reading MA.

Hilborn, R., and C. J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman & Hall, New York.

Krebs, C. J. 1989. Ecological Methodology. Harper & Row, Publishers, Inc., New York.

Law, A.M. and W. D. Kelton. 1991 Simulation modeling and Analysis, McGraw Hill, New York.

MacDonald, B. A., and R. J. Thompson. 1986. Production, dynamics and energy partitioning in two populations of the giant scallop *Placopecten magellanicus* (Gmelin). Experimental Marine Biology and Ecology 101: 285-299.

MacLennan, D. N., and E. J. Simmonds. 1992. Fisheries Acoustics. Chapman & Hall, London.

Maravelias, C. D., D. G. Reid, E. J. Simmonds , and J. Haralabous. 1996. Spatial analysis and mapping of acoustic survey data in the presence of high local variability: geostatistical application to North Sea herring (*Clupea harengus*). Canadian Journal of Fisheries and Aquatic Sciences 53: 1497-1505.

Matheron, G. 1971 The theory of regionalized variables and its applications. Les cahiers du CMM, 5 Ecole Natural Supplemental Mines Paris, Fontainebleau: 1-211.

Melvin, G. D., M. J. Dadswell , and R. A. Chandler. 1985. Movement of scallops *Placopecten magellanicus* (Gmelin, 1791) (Mollusca: Pectinidae) on Georges Bank. Canadian Atlantic Fisheries Scientific Advisory Committee, 85/30.

Merrill, A. S., and J. A. Posgay. 1964. Estimating the natural mortality rate of sea scallop (*Placopecten magellanicus*). Research Bulletin - International Commission for the Northwest Atlantic Fisheries. 1: 88-106.

Murawski, S. A., R. Brown, H.-L. Lai, P. J. Rago , and L. Hendrickson. 2000. Large-scale closed areas as a fishery-management tool in temperate marine ecosystems: the Georges Bank experience. Bulletin of Marine Science. 66: 775-798.

Rago, P., S. Murawski, K. Stokesbury, W. DuPaul, M. McSherry. 2000. Integrated management of the sea scallop fishery in the northeast USA: research and commercial vessels surveys, observers, and vessel monitoring systems. International council for the exploration of the sea CM2000/W:13.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada 191: 382 p.

Serchuk, F. M., P. W. Wood, J. A. Posgay , and B. E. Brown. 1979. Assessment and status of sea scallop (*Placopecten magellanicus*) populations off the Northeast coast of the United States. Proceedings of the National Shellfisheries Association. 69: 161-191.

Shumway, S. E., R. Selvin , and D. F. Schick. 1987. Food resources related to habitat in the scallop *Placopecten magellanicus* (Gmelin, 1791): A qualitative study. Journal of Shellfish Research 6: 89-95.

Stokesbury, K. D. E. 2001. Estimation of sea scallop abundance in closed areas of Georges Bank. Transactions of the American Fisheries Society submitted 15 May 2001.

Stokesbury, K. D. E. , and J. H. Himmelman. 1993. Spatial distribution of the giant scallop *Placopecten magellanicus* in unharvested beds in the Baie des Chaleurs, Québec. Marine Ecology Progress Series 96: 159-168.

Stokesbury, K. D. E. , and J. H. Himmelman. 1995. Biological and physical variables associated with aggregations of the giant scallop *Placopecten magellanicus*. Canadian Journal of Fisheries and Aquatic Sciences 52: 743-753.

Stokesbury, K. D. E. , and J. H. Himmelman. 1996. Experimental examination of movement of the giant scallop *Placopecten magellanicus*. Marine Biology 124: 651-660.

Thouzeau, G., G. Robert , and S. J. Smith. 1991. Spatial variability in distribution and growth of juvenile and adult sea scallops *Placopecten magellanicus* (Gmelin) on eastern Georges Bank (Northwest Atlantic). Marine Ecology Progress Series 74: 205-218.

Table 1. Summary of the SMAST video survey data for Closed Area I (CAI), Closed Area II (CAII), the Great South Channel (GSC), Stellwagon Bank and the Nantucket Lightship Area (NLSA).

Area	Date	Stations	Mean Scallop m^2	SE	CV%	Mean meat weight (g)	Area km^2	Scallops (mil)	Meat weight mil kg	Meat weight mil lbs
CAI	7/27/99	454	0.25	0.02	8.6	22	1122	276.2	6.1	13.5
CAI	8/15/00	183	0.42	0.06	13.2	27	452	190.5	5.1	11.3
CAII	9/28/99	125	0.59	0.04	7.3	23	309	182.2	4.2	9.4
SWC	8/29/00	157	0.36	0.07	20.6	7	388	139.3	0.9	2.1
NLSA	7/12/99	205	0.38	0.04	10.2	34	507	193.7	6.6	14.6
NLSA	8/8/00	204	0.40	0.03	8.7	38	504	201.1	7.6	16.8
NLSA	10/21/00	174	0.44	0.06	12.8	39	430	188.9	7.4	16.3
SW	5/25/00	92	0.08	0.03	37.4	7	227	17.5	0.1	0.3

Table 2. Comparison of mean scallop density (scallops m^{-2}) estimates derived from the multistage sampling technique (Krebs 1989) and the Kriging technique for Closed Area I (CAI), Closed Area II (CAII), the Great South Channel (GSC) and the Nantucket Lightship Area (NLSA).

			Multistage Sampling		Kriging			
			Mean		Mean			
Location	Date	Stations	Scallop m^2	SE	Scallop m^2	SE	t	
CAI	7/27/99	454	0.25	0.02	0.20	0.01	1.217	NS
CAI	8/15/00	183	0.42	0.06	0.35	0.03	0.875	NS
CAII	9/28/99	125	0.59	0.04	0.61	0.06	-0.215	NS
SWC	8/29/00	157	0.36	0.07	0.52	0.07	-1.482	NS
NLSA	7/12/99	205	0.38	0.04	0.38	0.03	0.032	NS
NLSA	8/8/00	204	0.40	0.03	0.38	0.02	0.294	NS
NLSA	10/21/00	174	0.44	0.06	0.40	0.03	0.480	NS

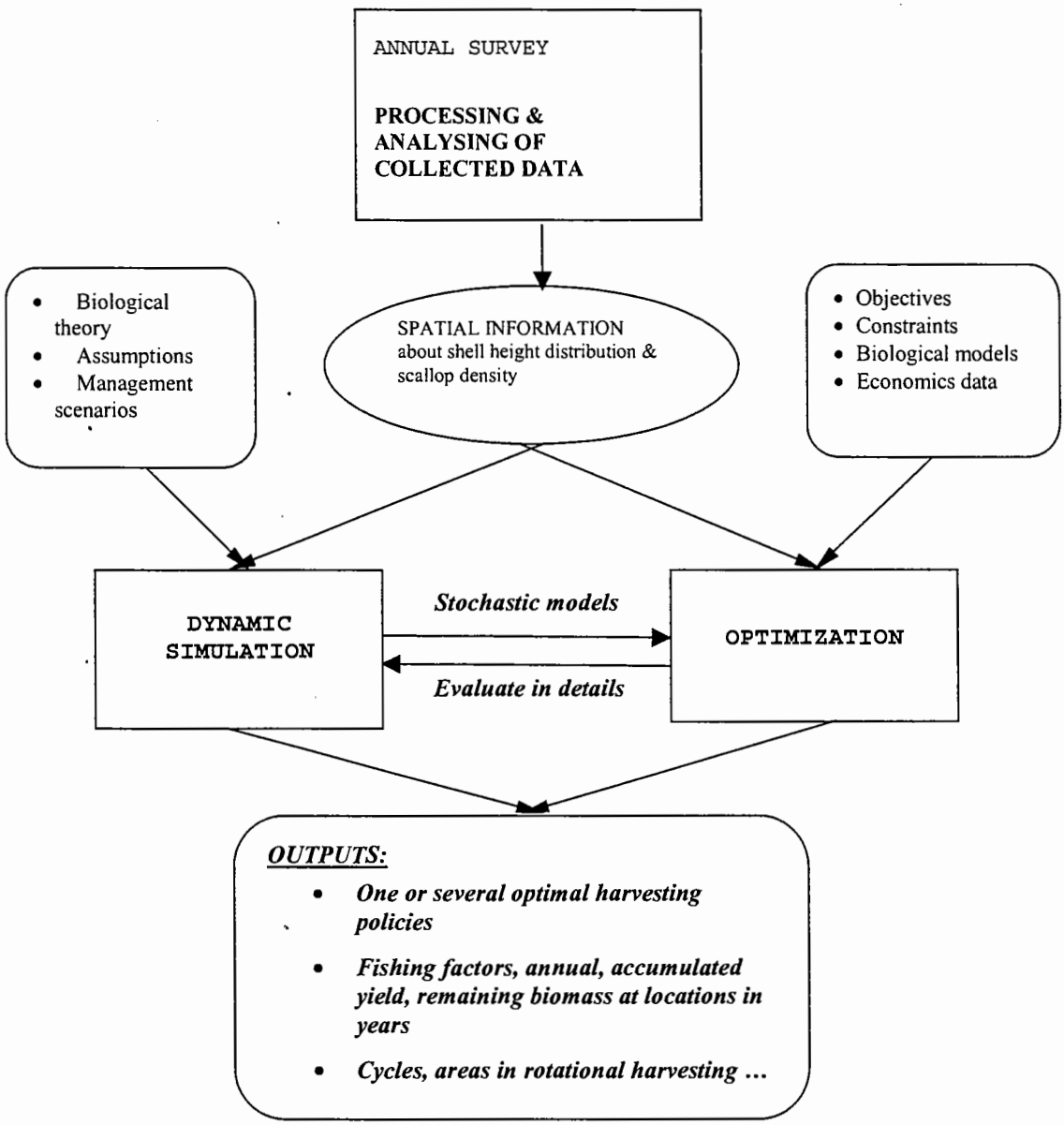


Figure 1. Structural diagram of the SMAST Atlantic sea scallop management system.

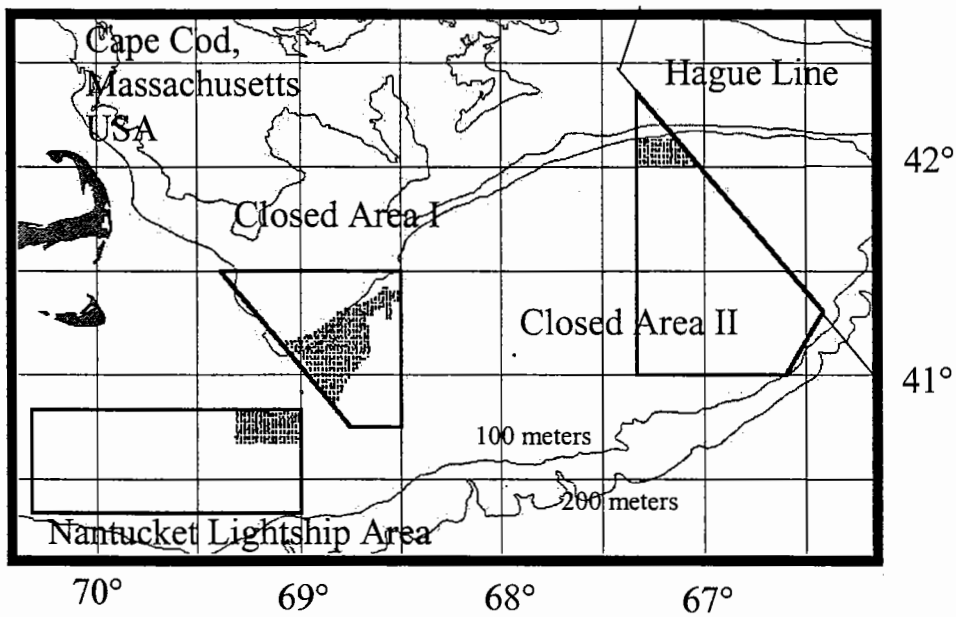


Figure 2. Map of Georges Bank detailing the 1994 groundfish closed areas and the 1999 to 2001 SMAST video survey stations.

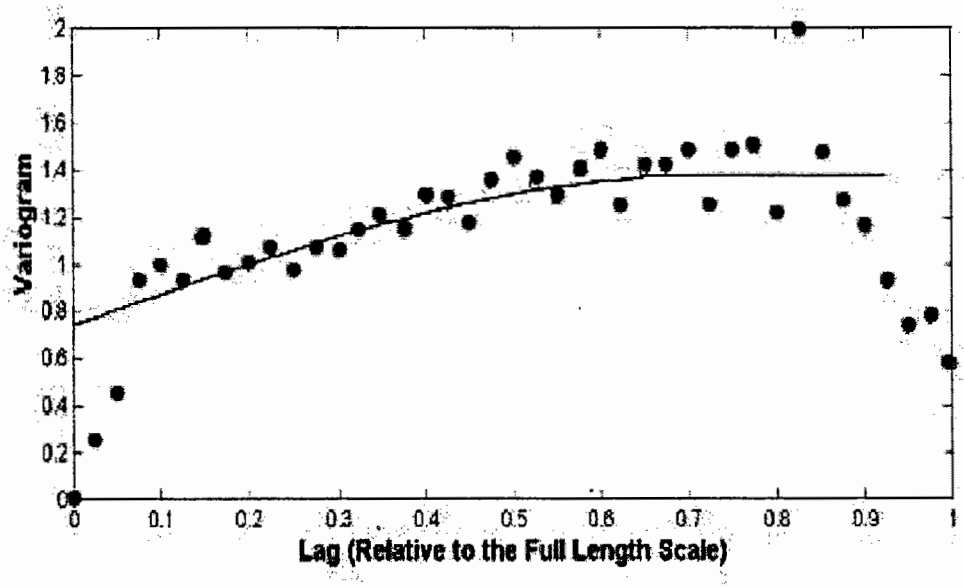
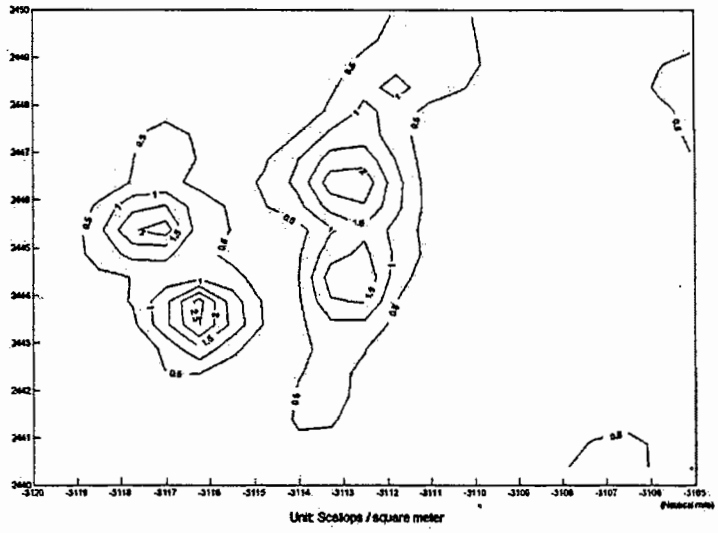
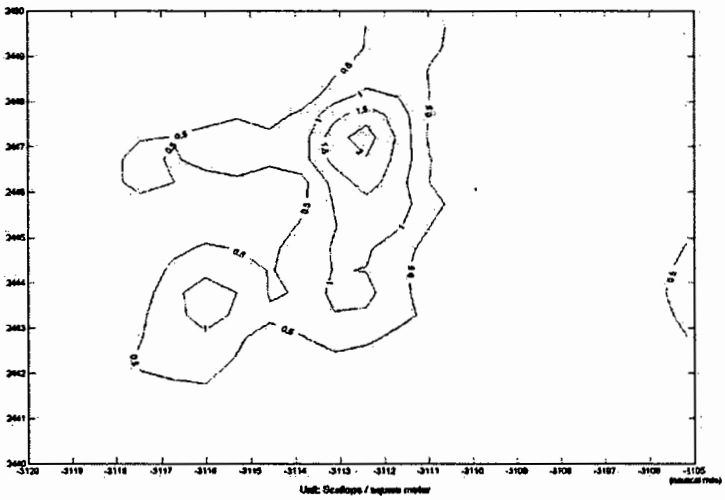


Figure 3. Estimator of semi-variogram compared to the theoretical spherical model.

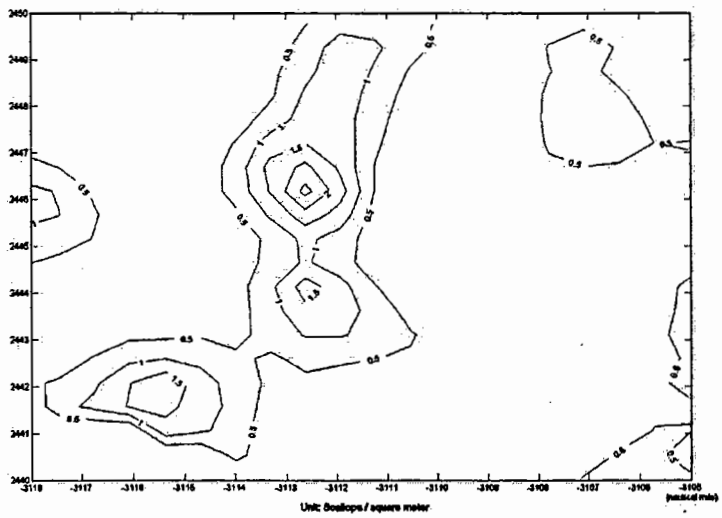
KRIGING RESULT: SCALLOP DENSITY IN NLSA - August 1999 data



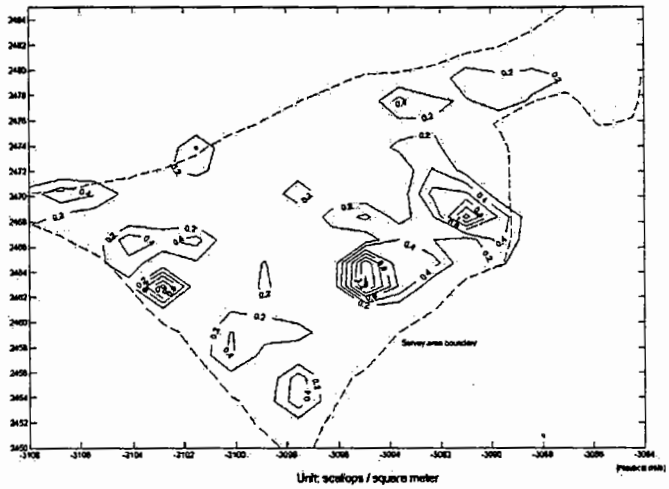
KRIGING RESULT: SCALLOP DENSITY IN NSLA - August 2000 data



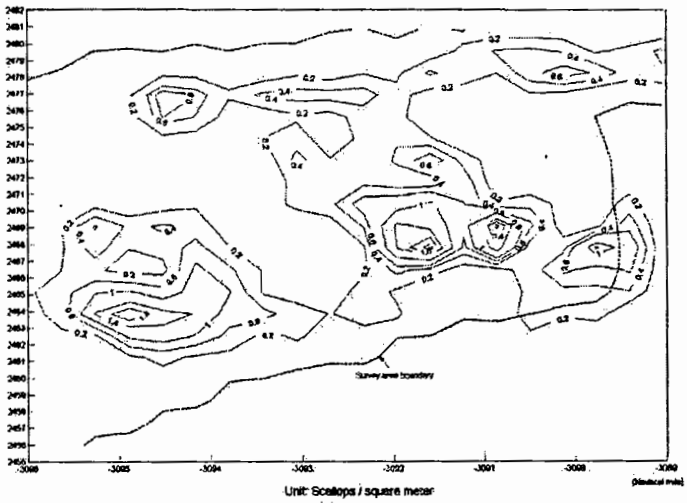
KRIGING RESULT: SCALLOP DENSITY IN NSLA - October 2000 data



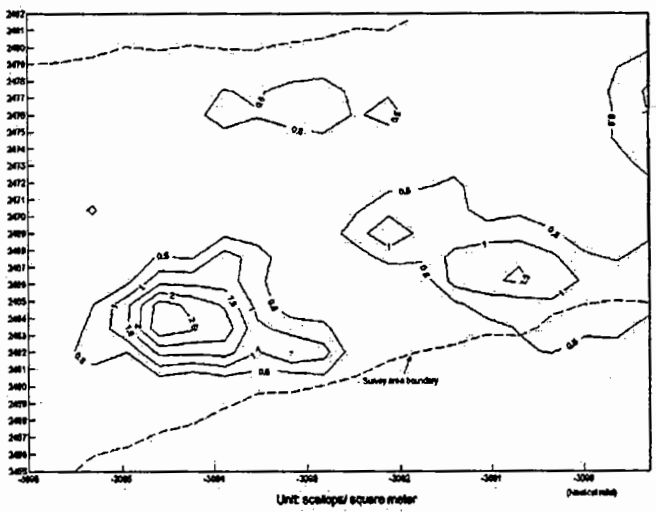
KRIGING RESULT: SCALLOP DENSITY IN CLOSED AREA 1 - August 1999 data



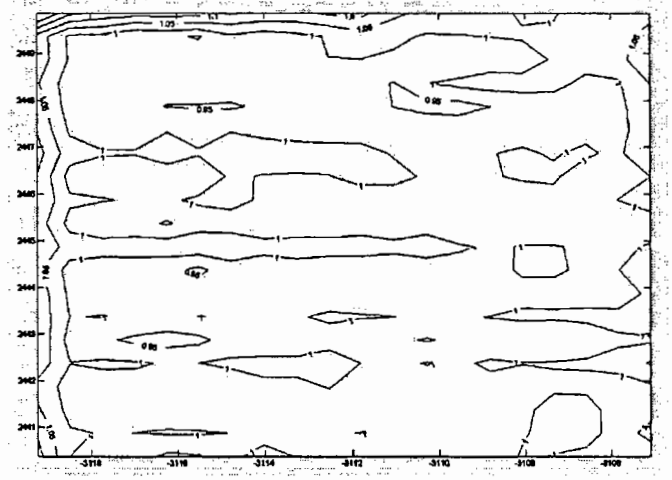
KRIGING RESULT: SCALOP DENSITY IN CLOSED AREA 1- part of Aug 1999 data



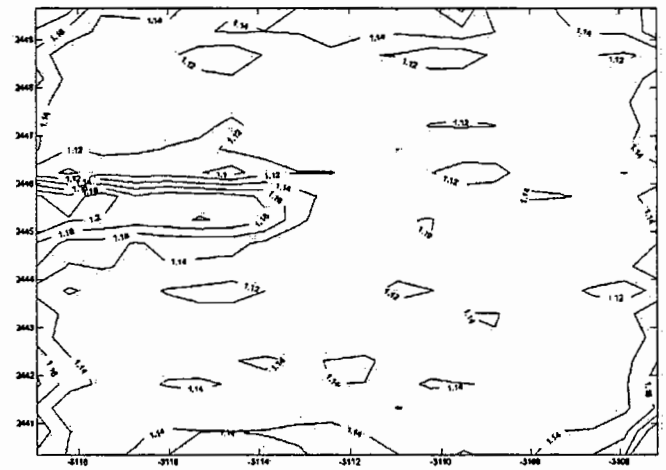
KRIGING RESULT: SCALLOP DENSITY IN CLOSED AREA 1 - August 2000 data



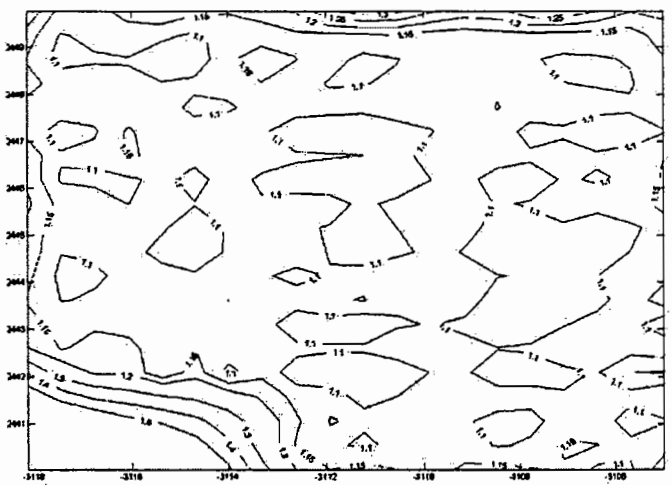
NORMALIZED KRIGING VARIANCE - NLSA Aug, 1999 data



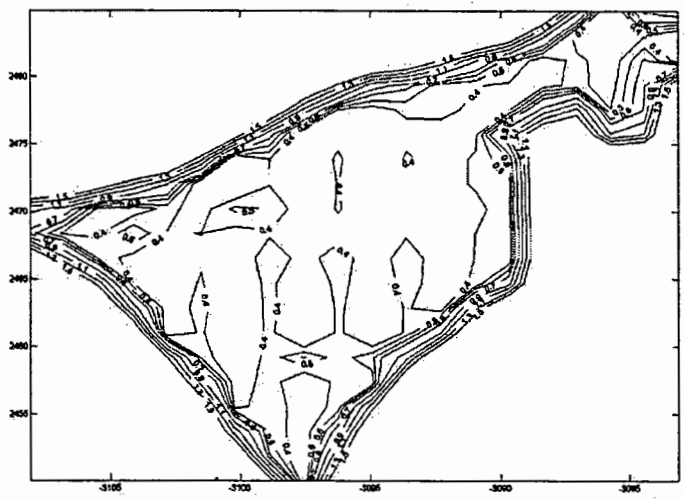
NORMALIZED KRIGING VARIANCE - NLSA Aug, 2000 data



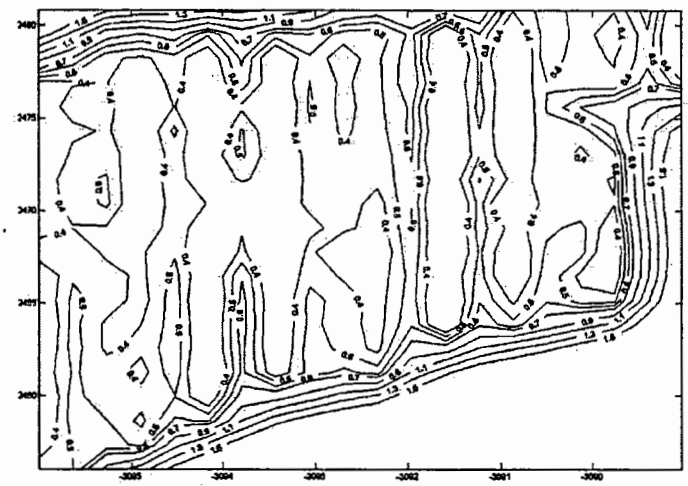
NORMALIZED KRIGING VARIANCE - NLSA Oct, 2000 data



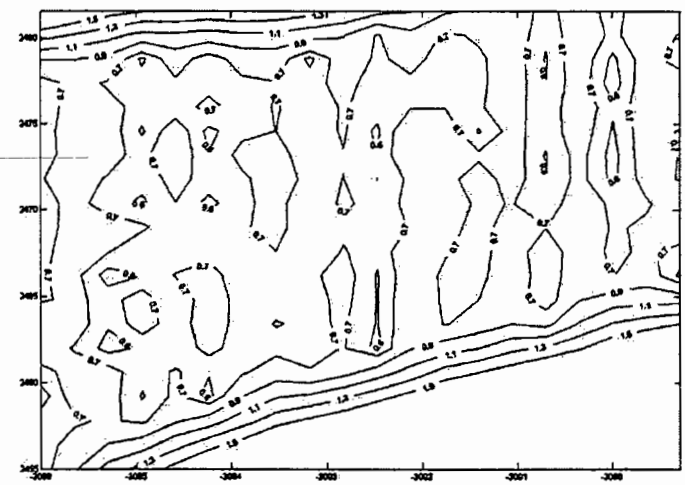
NORMALIZED KRIGING VARIANCE - CAI Aug, 1999 data



NORMALIZED KRIGING VARIANCE - part of CAI Aug, 1999 data



NORMALIZED KRIGING VARIANCE - CAI Aug, 2000 data



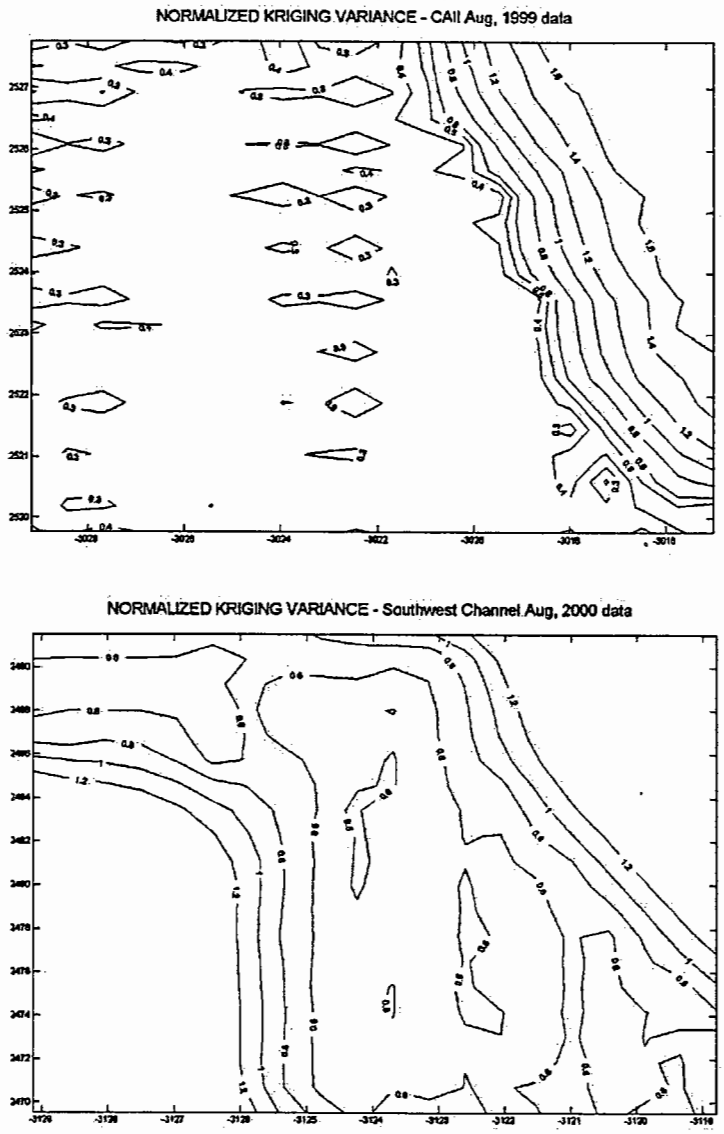


Figure 5. Kriging contour map of sea scallop density variance measures in the three closed areas and the greater south channel of Georges Bank.

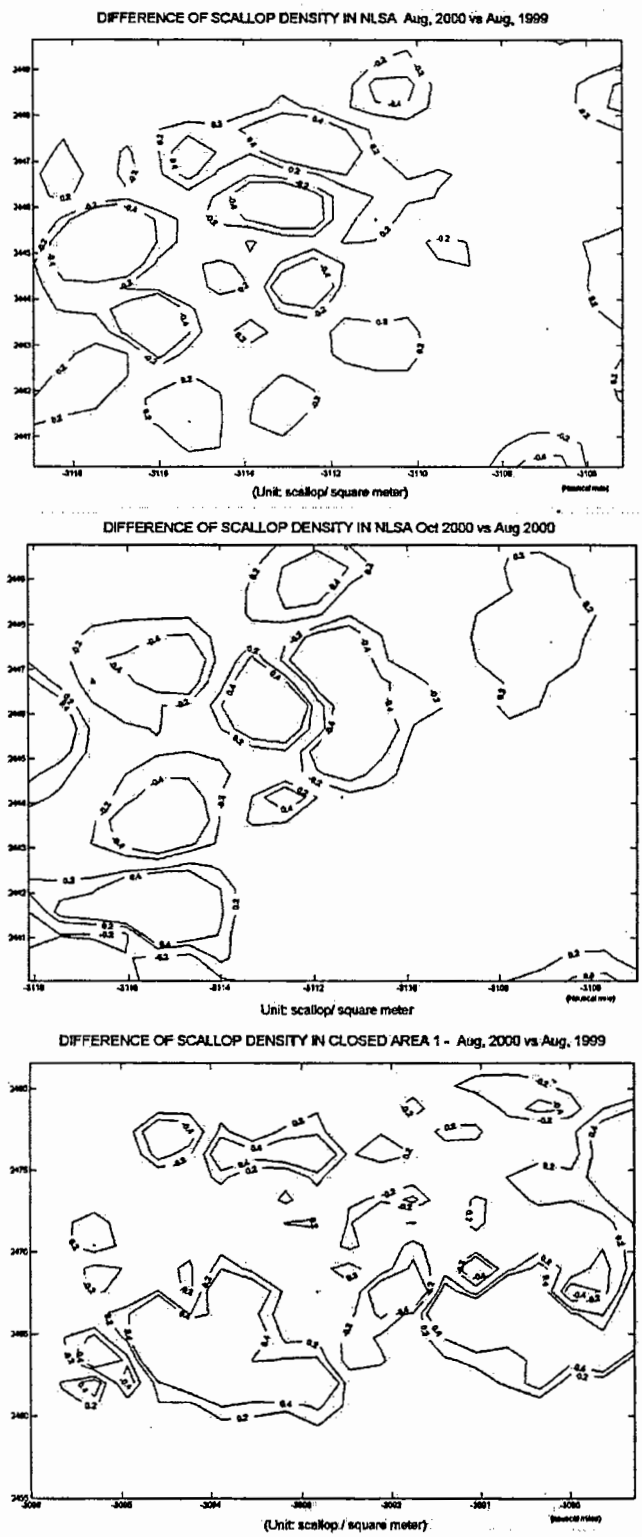


Figure 6. Kriging contour maps of sea scallop density (scallop m^{-2}) distribution differences between years (1999 and 2000) for the Nantucket Lightship Area and Closed Area I of Georges Bank.

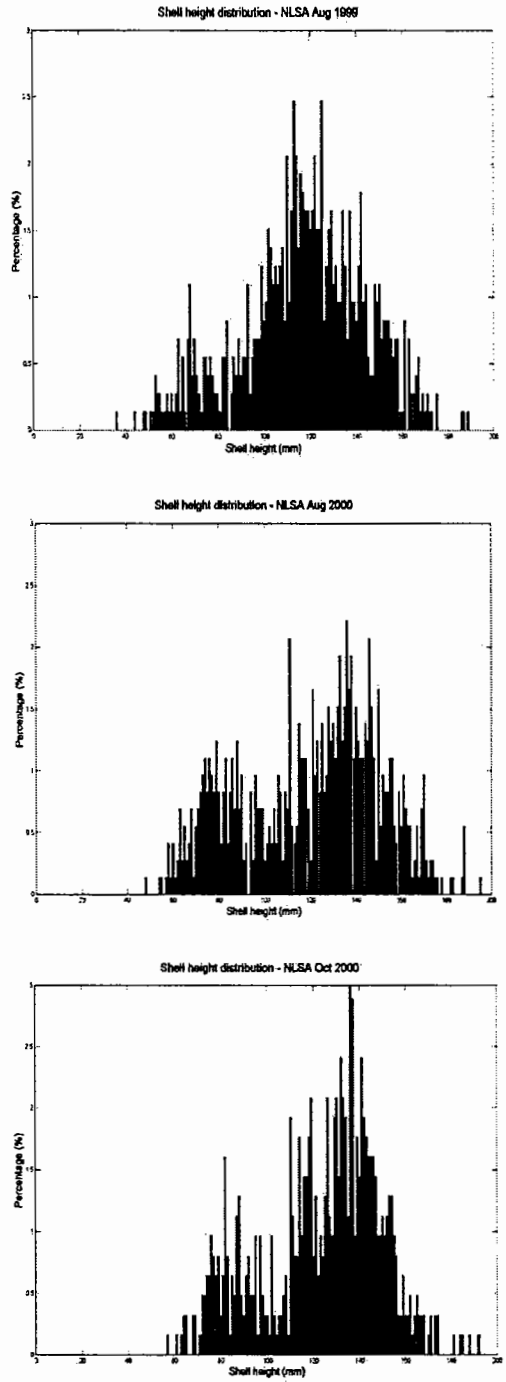


Figure 7. Sea scallop shell height frequencies from the Nantucket Lightship Area from July 1999 to October 2000.

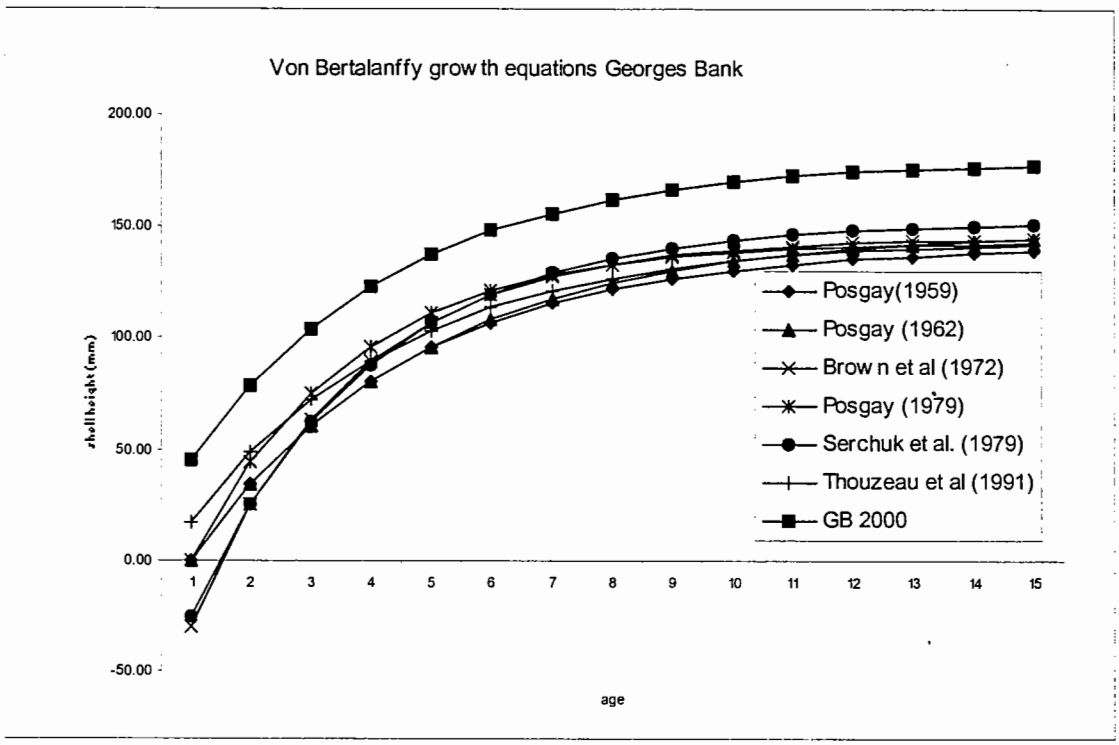


Figure 8. Comparison of the von Bertalanffy growth equation with the values L_∞ = 180 mm; K =0.288; t_0 = 0 (GB 2000) compared to values published in the literature (Serchuk et al. 1979; Thouzeau et al. 1991).

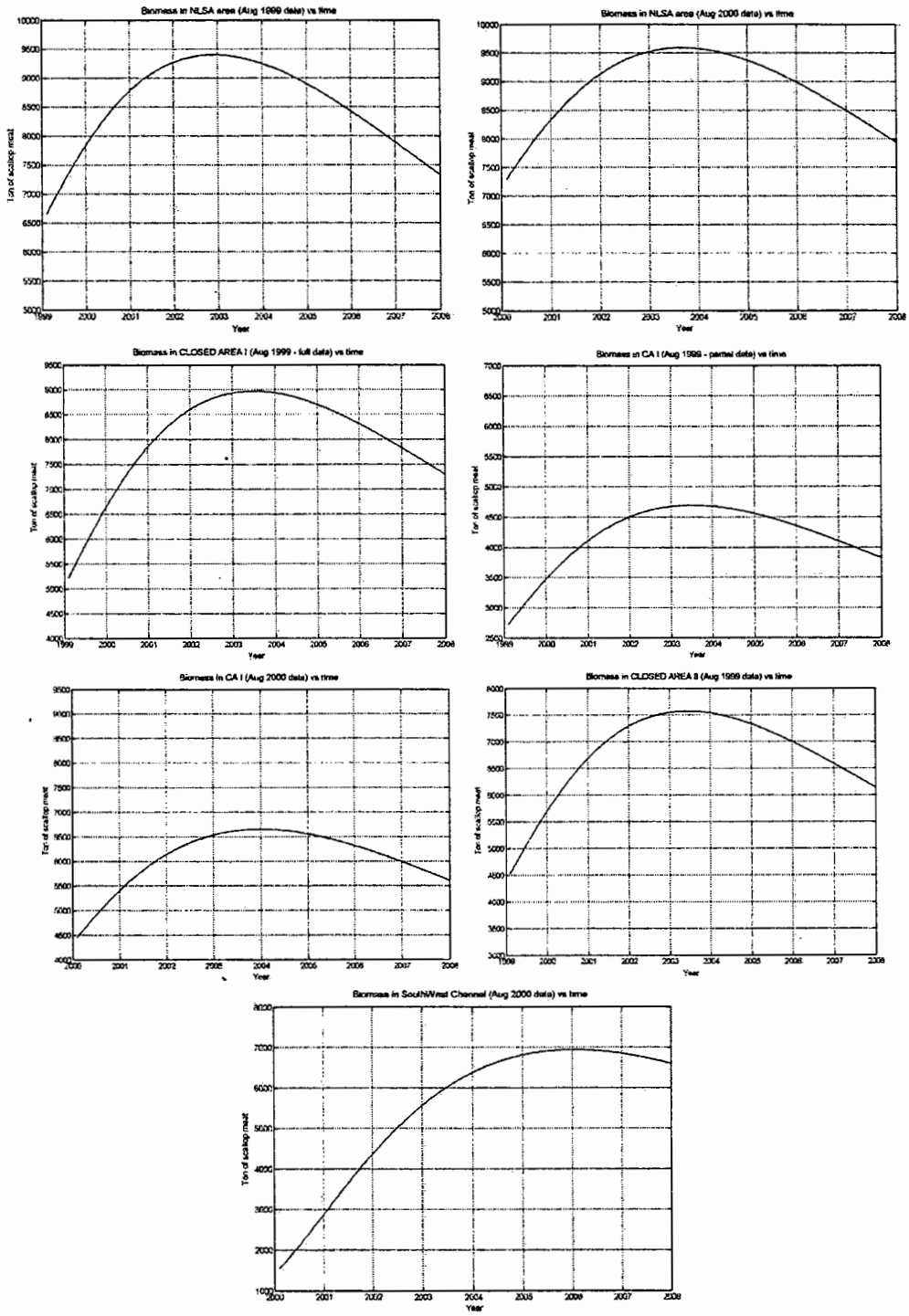


Figure 9. Projected biomass of sea scallops over eight years using the SMAST video survey data from 1999 and 2000 as the initial density and size to start the simulation models for the three closed areas and the greater south channel of Georges Bank.

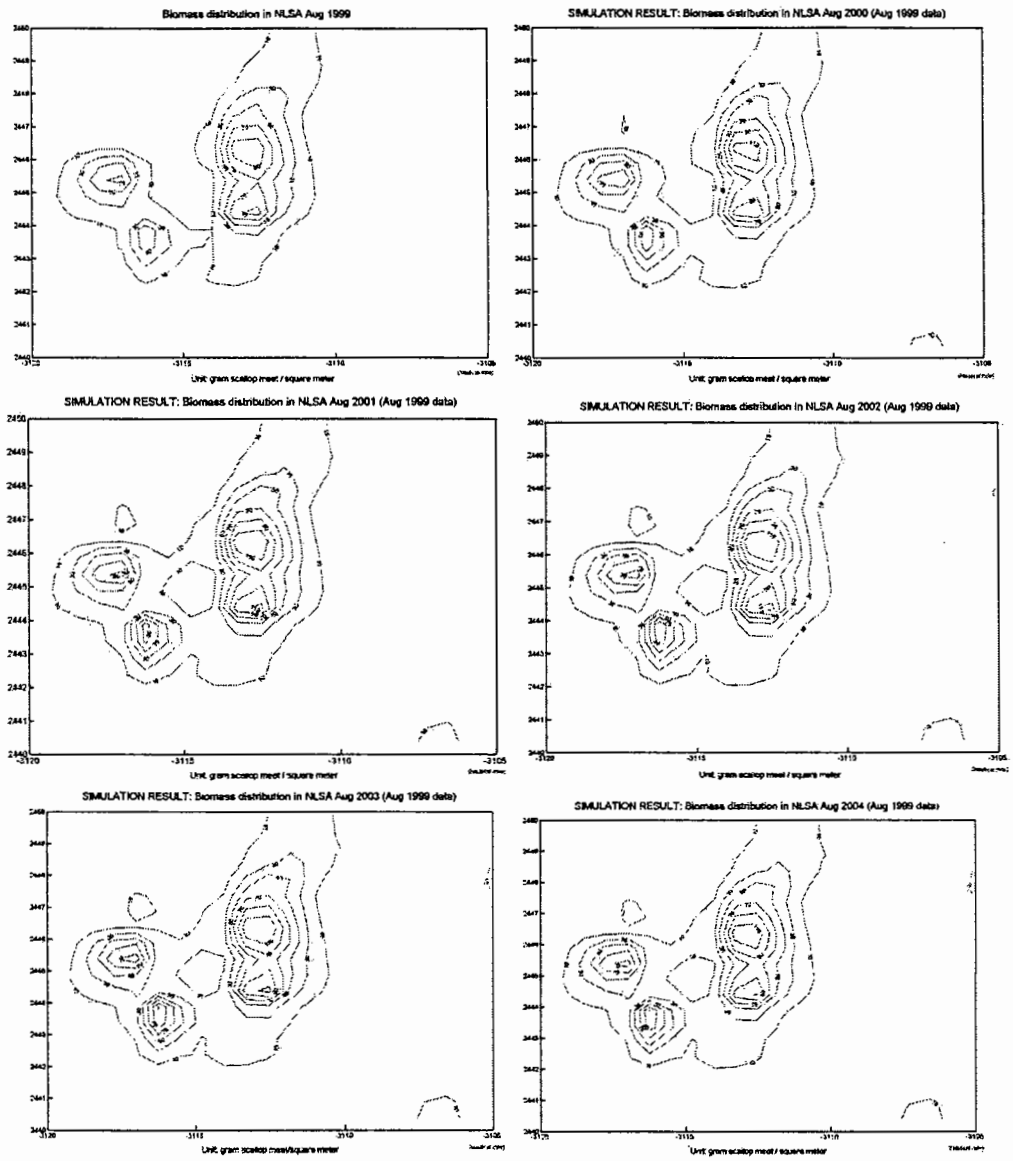
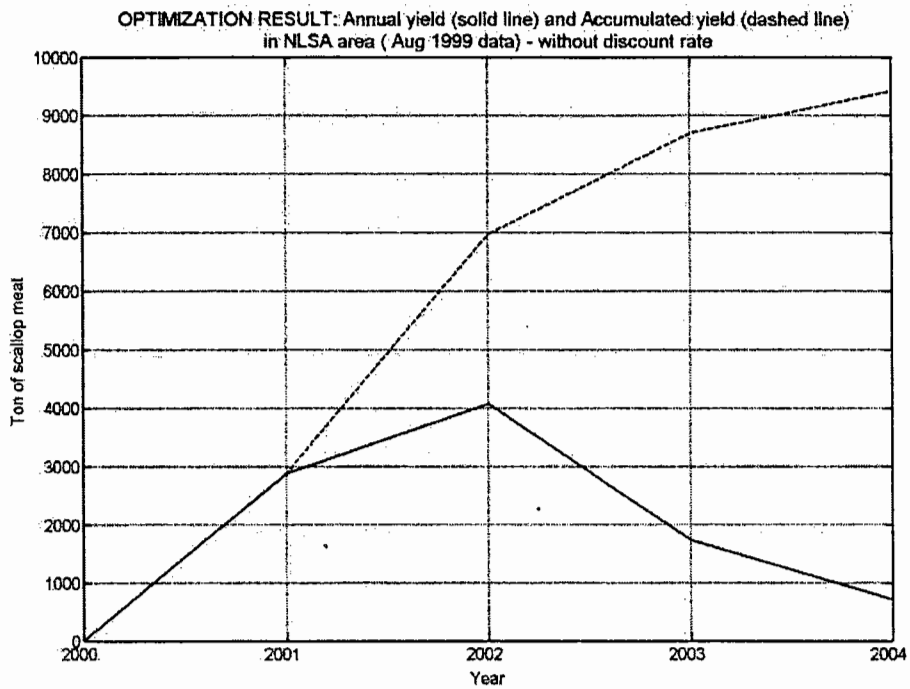
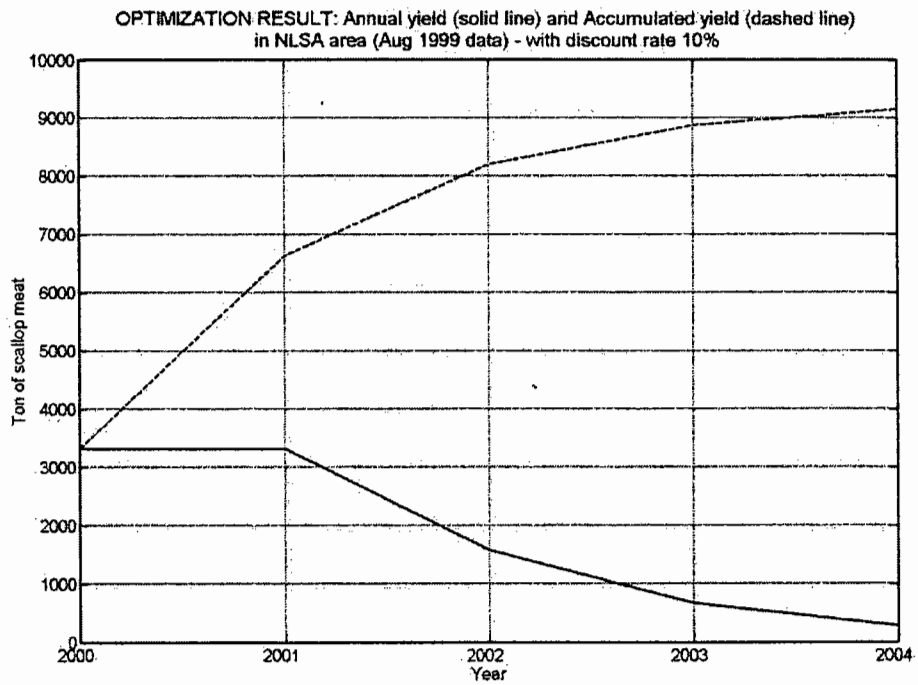


Figure 10. Contour map of the projected biomass of sea scallops over five years using the SMAST Nantucket Lightship Area video survey data from 1999 as the initial density and size to start the simulation model.


OPTIMIZATION RESULT: Annual yield (solid line) and Accumulated yield (dashed line)
in NLSA area (Aug 1999 data) - without discount rate
Ton of scallop meat
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
2000
2001
2002
2003
2004
Year


OPTIMIZATION RESULT: Annual yield (solid line) and Accumulated yield (dashed line)
in NLSA area (Aug 1999 data) - with discount rate 10%
Ton of scallop meat
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
2000
2001
2002
2003
2004
Year

OPTIMIZATION RESULT: Instantaneous Fishing mortality and Annual yield (in brace: ton/year) in NLSA, Aug 1999 data - without discount

	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[32.6] Year 4: 0.9[14.9] Year 5: 0.9[6.2]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[39.7] Year 4: 0.9[16.9] Year 5: 0.9[6.8]	Year 1: 0[0] Year 2: 0.9[360] Year 3: 0.9[166.5] Year 4: 0.9[69.2] Year 5: 0.9[27.9]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[185.4] Year 4: 0.9[77.9] Year 5: 0.9 [31.6]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[162.8] Year 4: 0.9[70.8] Year 5: 0.9[29.5]
2448.0	Year 1: 0[0] Year 2: 0.9[176.5] Year 3: 0.9[74.8] Year 4: 0.9[32.4] Year 5: 0.9[12.9]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[256.7] Year 4: 0.9[107] Year 5: 0.9[43.2]	Year 1: 0[0] Year 2: 0.9[696.6] Year 3: 0.9[293] Year 4: 0.9[121.6] Year 5: 0.9[48.4]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[54.1] Year 4: 0.9[23.3] Year 5: 0.9[9.5]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[211.9] Year 4: 0.9[91.2] Year 5: 0.9[37.2]
2446.1	Year 1: 0[0] Year 2: 0.9[538.5] Year 3: 0.9[232.2] Year 4: 0.9[97.7] Year 5: 0.9[39.2]	Year 1: 0[0] Year 2: 0.0[0] Year 3: 0.9[294.3] Year 4: 0.9[124] Year 5: 0.9[50.6]	Year 1: 0[0] Year 2: 0.9[733.2] Year 3: 0.9[318.4] Year 4: 0.9[129] Year 5: 0.9[50.7]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[156.1] Year 4: 0.9[69.8] Year 5: 0.9[28.6]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[52.4] Year 4: 0.9[23.3] Year 5: 0.9[9.9]
2444.2	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[208.6] Year 4: 0.9[91.2] Year 5: 0.9[37.7]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[502.2] Year 4: 0.9[212.5] Year 5: 0.9[84.9]	Year 1: 0[0] Year 2: 0.9[345.1] Year 3: 0.9[148.7] Year 4: 0.9[61.4] Year 5: 0.9[24.4]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[47.4] Year 4: 0.9[19.3] Year 5: 0.9[8.5]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[102.8] Year 4: 0.9[44.6] Year 5: 0.9[18.5]
2442.3	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[40.9] Year 4: 0.9[18.4] Year 5: 0.9[7.7]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[118.3] Year 4: 0.9[51.4] Year 5: 0.9[21.4]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[101.1] Year 4: 0.9[44.4] Year 5: 0.9[18.1]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[43.8] Year 4: 0.9[19.1] Year 5: 0.9[7.9]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[207.2] Year 4: 0.9[86.6] Year 5: 0.9[35]
2440.4	-3119.2	-3116.3	-3113.5	-3110.7	-3107.8 -3105.1

(Nautical mile)

OPTIMIZATION RESULTS: Instantaneous Fishing mortality & Annual yield (in brace: ton/year) in NLSA area, Aug 1999 data - discount rate = 10%

	Year 1: 0[0] Year 2: 0.9[28] Year 3: 0.9[14.7] Year 4: 0.9[6.7] Year 5: 0.9[2.8]	Year 1: 0[0] Year 2: 0.9[32] Year 3: 0.9[14.8] Year 4: 0.9[6.3] Year 5: 0.9[2.6]	Year 1: 0.9[326] Year 2: 0.9[158.8] Year 3: 0.9[71.4] Year 4: 0.9[29.8] Year 5: 0.9[12.3]	Year 1: 0[] Year 2: 0.9[162.6] Year 3: 0.9[72.4] Year 4: 0.9[30.2] Year 5: 0.9 [12.4]	Year 1: 0[0] Year 2: 0.9[142.8] Year 3: 0.9[69.7] Year 4: 0.9[30.2] Year 5: 0.9[12.5]
2448.0	Year 1: 0.9[160.7] Year 2: 0.9[74.3] Year 3: 0.9[31.7] Year 4: 0.9[12.9] Year 5: 0.9[5.2]	Year 1: 0.9[213.9] Year 2: 0.9[104.7] Year 3: 0.9[47.4] Year 4: 0.9[19.9] Year 5: 0.9[8]	Year 1: 0.9[640] Year 2: 0.9[290] Year 3: 0.9[123.2] Year 4: 0.9[50] Year 5: 0.9[19.6]	Year 1: 0[0] Year 2: 0.9[40.3] Year 3: 0.9[19.4] Year 4: 0.9[8.4] Year 5: 0.9[3.4]	Year 1: 0[0] Year 2: 0.9[194.6] Year 3: 0.9[88.9] Year 4: 0.9[37.2] Year 5: 0.9[15.9]
2446.1	Year 1: 0.9[485.9] Year 2: 0.9[231.5] Year 3: 0.9[102.6] Year 4: 0.9[42.6] Year 5: 0.9[17.5]	Year 1: 0.9[232.5] Year 2: 0.9[128.9] Year 3: 0.9[58.8] Year 4: 0.9[25.4] Year 5: 0.9[10.4]	Year 1: 0.9[695.6] Year 2: 0.9[310.1] Year 3: 0.9[130.8] Year 4: 0.9[52.4] Year 5: 0.9[21.4]	Year 1: 0[0] Year 2: 0.9[157.2] Year 3: 0.9[71.4] Year 4: 0.9[30.2] Year 5: 0.9[12.3]	Year 1: 0[0] Year 2: 0.9[45] Year 3: 0.9[22.6] Year 4: 0.9[9.7] Year 5: 0.9[4.2]
2444.2	Year 1: 0[0] Year 2: 0.9[187.5] Year 3: 0.9[86] Year 4: 0.9[38.3] Year 5: 0.9[15.6]	Year 1: 0[0] Year 2: 0.9[459.9] Year 3: 0.9[206.5] Year 4: 0.9[90] Year 5: 0.9[36.6]	Year 1: 0.9[325.9] Year 2: 0.9[144.8] Year 3: 0.9[59.9] Year 4: 0.9[23.7] Year 5: 0.9[10.7]	Year 1: 0[0] Year 2: 0.9[42.6] Year 3: 0.9[19.7] Year 4: 0.9[8.3] Year 5: 0.9[3.4]	Year 1: 0[0] Year 2: 0.9[88.8] Year 3: 0.9[42.4] Year 4: 0.9[19.1] Year 5: 0.9[7.9]
2442.3	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[40.6] Year 4: 0.9[17.9] Year 5: 0.9[8.2]	Year 1: 0[0] Year 2: 0.9[103.8] Year 3: 0.9[50.9] Year 4: 0.9[22.6] Year 5: 0.9[9.4]	Year 1: 0[0] Year 2: 0.9[96.4] Year 3: 0.9[44.8] Year 4: 0.9[19.4] Year 5: 0.9[8]	Year 1: 0[0] Year 2: 0[0] Year 3: 0.9[43.5] Year 4: 0.9[19] Year 5: 0.9[7.9]	Year 1: 0.9[188] Year 2: 0.9[91.5] Year 3: 0.9[40.2] Year 4: 0.9[16.6] Year 5: 0.9[6.8]
2440.4	-3119.2	-3116.3	-3113.5	-3110.7	-3107.8 -3105.1

(Nautical mile)

Figure 11. Two runs of the optimization model estimating potential harvest either without a discount rate or a 10% discount rate using the SMAST Nantucket Lightship Area video survey data from 1999 as the initial density and size to start the simulation model.