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An Evaluation of Closed Area Boundaries of the Sea Scallop Stock in the Middle Atlantic Bight

John David Lange
College of William and Mary - Virginia Institute of Marine Science

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AN EVALUATION OF CLOSED AREA BOUNDARIES ON THE SEA SCALLOP STOCK IN THE MIDDLE ATLANTIC BIGHT

A Thesis

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The Faculty of the School of Marine Science

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In Partial Fulfillment

Of the Requirements for the Degree of

Master of Science

by

John David Lange Jr.

2002

APPROVAL SHEET

This thesis is submitted in partial fulfillment of

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Master of Science

John D. Lange Jr.

John David Lange Jr.

Approved, January 2002

William D. DuPaul, Ph.D.
Committee Chairman / Major Advisor

David A. Evans, Ph.D.

Roger Mann

Roger L. Mann, Ph.D.

John A. Musick, Ph.D.

Dedication

to karen

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Acknowledgements

I would like to thank my wife and family, friends, committee members, and the captains and crews for their support. I would like to especially thank Todd Gedamke for helping me more than anyone will ever know.

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Abstract

The utilization of a rotational closed area system to supplement existing regulations is at the forefront of sea scallop fishery management. It has been recognized by the New England Fishery Management Council and other scientific investigators, that these areas require monitoring and evaluation to document the effectiveness. This study was conducted to determine how the closed area boundaries affected the abundance and spatial distribution of the scallop stock in the mid-Atlantic bight, and the efficacy of the current closed area management with modern commercial scallop harvesting.

Data collected from annual stock abundance surveys of the Hudson Canyon South and Virginia Beach Closed Areas were evaluated with kriging and regression analyses to determine the location of the "effective boundary" for each closed area. The effective boundary was described as the location at which the scallop population reflected the difference in fishing mortality due to protection from the closed areas.

The best estimate of the mean location of the effective boundary was at 0.13 nm outside of the Hudson Canyon South Closed Area, and at 1.3 nm inside of the Virginia Beach Closed Area boundaries. The total area effectively protected by the mid-Atlantic closed areas would be reduced by 0.7% after adjustment of the boundaries by the appropriate measures. Therefore, the total area being effectively protected was not substantially different from the original area, and did not produce significant bias in the area-based biomass calculations used by the fishery's managers.

An Evaluation of Closed Area Boundaries on the Sea Scallop Stock in the Middle Atlantic Bight

Introduction

Description of Target Species

Distribution and Range

The Atlantic sea scallop, *Placopecten magellanicus* (Gmelin, 1791), is an epibenthic bivalve mollusk that is distributed along the continental shelf waters of the northwest Atlantic from the northern Gulf of St. Lawrence to Cape Hatteras, North Carolina (Posgay, 1957; MacKenzie, 1979; Serchuk *et al.*, 1979). Water temperature is the primary factor that limits both the latitudinal and longitudinal distribution of scallops on the shelf (Bourne, 1964; MacKenzie, 1979; Brand, 1991). North of Cape Cod, scallops can be found from the subtidal zone to a depth of approximately 100 meters, while south of Cape Cod they are found in deeper, cooler offshore waters between 40 and 200 meters. Scallop beds of commercially sufficient size are usually located between 40 and 100 meters depth (MacKenzie, 1979). The three major commercial resource areas for the United States are the Gulf of Maine, Georges Bank, and the mid-Atlantic (Serchuk *et al.*, 1982).

Life History

P. magellanicus has been described as a long-lived, iteroparous species (Orensanz *et al.*, 1991), and its growth follows the von Bertalanffy (1938) growth model (MacDonald and Thompson, 1985). Scallop growth is very rapid in the first several years of life. Between the third and fifth years of life, shell height increases 50% to 80% and meat weight increases up to 400% (Mullen and Moring, 1986).

The earliest observed age at sexual maturity was one year old, with the initial spawning occurring after deposition of the first growth ring (age 1.5 or 2). Size at sexual maturity may vary from 23 mm to 75 mm shell height (Naidu, 1970; Posgay, 1979; Serchuk *et al.*, 1979). Fecundity is proportional to size and the younger age groups contribute little to the overall egg production. By age 5 or 6, female scallops may each produce about two million eggs annually (Posgay, 1979; Serchuck *et al.*, 1979). Scallop eggs are fertilized externally after mass broadcast-spawning events. The planktonic larvae remain in the water column for approximately four weeks after fertilization, and this protracted larval stage subjects them to the prevailing currents of the spawning area (Posgay, 1979).

The spawning season progresses latitudinally from south to north. DuPaul *et al.* (1989a) presented evidence of a gametogenic reproductive cycle for sea scallops in the mid-Atlantic region. They showed the dominant spring event occurring between April and May, and the weaker fall event occurring in late October. Spawning on Georges Bank has been reported in late September to early October (Posgay and Norman, 1958; MacKenzie *et al.*, 1978). Spawning in the Gulf of Maine at the Isles of Shoals has been reported in late September (Culliney, 1974), and in late August to early September in the Bay of Fundy (Dickie, 1955).

Recruitment of juvenile scallops to the spawning population, and subsequently to the fishery, are the least understood ecological and fishery parameters due to the inherent difficulty of direct measurement. Direct measurement of scallop recruitment is difficult because it is highly variable both temporally and spatially. Measures of relative recruitment have been obtained through resource surveys performed by the United States and Canada, and these measures are used in proxy of absolute abundance for management purposes.

Description of Commercial Fishery

The commercial sea scallop fishery traditionally constitutes the second most valuable fishery for the east coast of the United States, with an annual ex-vessel value slightly less than lobsters (Serchuk *et al.*, 1982; Murawski *et al.*, 2000; NEFSC, 2001). Commercial landings of scallops from U.S. northwest Atlantic waters have been recorded since 1887 (Lyles, 1969; Serchuk *et al.*, 1982). Prior to the 1920's most of the landings came from the territorial waters of the state of Maine, and the average commercial landings between 1887 and 1928 was 304 tons per year (Serchuk *et al.*, 1982). Between 1926 and 1935, 58% of the U.S. sea scallop landings originated from mid-Atlantic populations (Lyles, 1969; Serchuk *et al.*, 1982). The development of the Georges Bank fishery in the 1930's caused the commercial landings to exceed the 1,000-ton per year mark. From the 1940's through the 1990's the commercial fishing effort and subsequent landings have alternated back and forth between the mid-Atlantic and Georges Bank (Serchuk *et al.*, 1982).

In 1999, the total U.S. landings exceeded 10,000 metric tons, which was the highest total since 1992 and an 80% increase from 1998 (NEFSC, 2001). According to the 2000 NMFS survey, biomass in the Georges Bank and mid-Atlantic regions are at record high levels, due to effects of the closed areas, above average recruitment, and previous effort reduction (NEFSC, 2001). A more detailed review of the historical scallop fishery is presented in Serchuck *et al.* (1979,1982).

The two predominant types of harvesting gear used in the U.S. commercial sea scallop fishery are the New Bedford style dredge and the otter trawl (Rago *et al.*, 1997). There are other types of gear used, but they account for less than 1% of the annual landings. Between 1982 and 1993, dredge vessels accounted for an average of 91% of the effort in terms of annual days-at-sea (DAS) for the scallop fleet (Rago *et al.*, 1997). For the 1998 and 1999 commercial fishing years, dredges accounted for approximately 90% of the total fishery landings, and otter trawls the remaining 10% (SPDT, 1999; SPDT, 2000).

Magnitude and Distribution of Commercial Fishing Effort

Commercial fishing effort has varied greatly within and between the mid-Atlantic and northeast region over time. Through the middle to late 1980's, effort was distributed evenly between the regions (NEFSC, 1997). In 1994, approximately one half of the fishing grounds on Georges Bank were closed to all mobile fishing gear. This resulted in a large redirection of effort to the mid-Atlantic (NEFMC, 1999). The instantaneous fishing mortality rate (F) on Georges Bank decreased from 0.76 in 1993 to 0.19 in 1994, while the F in the mid-Atlantic increased from 0.65 to 0.75 (SPDT, 1999). During the 1998 fishing season, there was a total of 318 permitted vessels in the fishery with 215 of these fishing full-time (SPDT, 1999). Landings from the scallop fishery show interannual variability which is strongly correlated with the interannual variation in the levels of recruitment. A more detailed review of historical scallop fishery landings by gear type, vessel type, and time period is presented in Serchuck *et al.* (1982); Smolowitz and Serchuk (1989).

Description of the Scallop Fishery Management

The genesis of offshore sea scallop fishery management was under the International Commission for the Northwest Atlantic Fisheries (ICNAF) in 1972; however, the USA and Canada were the only participants and the measures were not adopted until 1976 (Serchuk *et al.*, 1982). The measures accepted were the prohibition of the retention and landings of scallops from Georges Bank that were less than 95mm shell height, and resulted in an average meat count of 40 meats per pound (Serchuk *et al.*, 1982). Prior to 1981, the United States had not imposed any regulations for the scallop fishery.

In 1982, the Atlantic Sea Scallop Fishery Management Plan (ASSFMP) was developed through the combined effort of the New England Fishery Management Council (NEFMC), the Mid-Atlantic Fishery Management Council (MAFMC), and the South Atlantic Fishery Management Council (SAFMC) (NEFMC, 1982). At present, the NEFMC is the decision making body for the fishery, and an itemized compilation of management measures since the inception of the ASSFMP is shown in Table 1. The current focus of management is the development of a rotational closed area strategy to be used in conjunction with existing regulations governing effort and gear.

Table 1. Management measures for the sea scallop fishery from 1982 to present.

Year	**Document**	**Regulation**	**Purpose of regulation**
1982	Atlantic Sea Scallop Fishery Management Plan (ASSFMP)	Established the maximum meats-per-pound (mpp) allowed to be landed at 30 or 33 for pre- and post-spawning seasons respectively.	* Control age at entry into the sea scallop fishery. To reduce the landings of undersized sea scallops. * Increase Yield Per Recruit (YPR)
1993	Amendment 4 to ASSFMP	* Effort control: established limited access fishery, days-at-sea, and crew size restrictions. * Gear control: ring size / mesh size	* Transition management from meat count control to effort controls. * Decrease fishing mortality rate (F) by 70% over 7 years.
1994	Framework Adjustment 9 to Northeast Multi-Species Fishery Management Plan	Area closures on Georges Bank to all mobile fishing gear.	To protect overexploited groundfish stocks.
1996	Reauthorization of Magnuson-Stevens Fishery Conservation Management Act and Sustainable Fisheries Act	Mandated the development and implementation of a recovery plan for commercially harvested stocks	To rebuild commercially harvested stocks to Maximum Sustainable Yield (MSY) within 10 years.
1998	Amendment 7 to ASSFMP	Development and implementation of the recovery plan for sea scallops	To be in accordance with FCMA-SFA law.
1998	Emergency action put in Amendment 7	Two area closures in mid-Atlantic	To increase Spawning Stock Biomass (SSB) and YPR
1999	Framework Adjustment 11 to ASSFMP	Experimental sea scallop fishery	Harvest yield gained within closed areas on Georges Bank
proposed	Amendment 10 To ASSFMP	Design and implement an area-based management scheme that incorporates rotating closed areas.	*Improve yield and rebuilding potential by reducing mortality on small scallops *Reduce reliance on day-at-sea allocations to control fishing mortality either by area-based management, by output controls (quotas), or in combination. *Change the fishing year.
2001	Amendment 7 to ASSFMP	Sunrise date for mid-Atlantic closed areas	To permanently re-open Mid-Atlantic closed areas to commercial fishing.

Project Background

Closed Areas as Fishery Management Tools

The novel idea of using an area closed to fishing as a regulatory measure formally came from R. J. H. Beverton and S. J. Holt. They developed a model that considered the yield per recruit for different sized closed areas as a function of fishing mortality on the harvested grounds, and they used data from the North Sea plaice fishery to evaluate the model (Beverton and Holt, 1957). The closed areas in their study included areas unsuitable for trawling (but probably contained plaice), some nursery grounds where there was not much fishing, and areas of extensive mine fields that remained from World War II that could not be fished until the mines were cleared.

After consideration of their model's results, Beverton and Holt were not convinced of the utility of closed areas as a management tool. They found that, despite a potential increase in yield, a detailed knowledge of the movements of the fish would be necessary and thus the benefits difficult to assess, and both very fast and slow interchanges between the fished and unfished areas would negate the increases in yield. Therefore, they suggested using more traditional management approaches such as effort or gear control by fleet and catch reduction respectively (Beverton and Holt, 1957).

Despite Beverton and Holt's concerns, closed areas have been used and currently an array of terms exists to describe a parcel of ocean water or bottom specifically protected for biological conservation purposes. Some of these are "marine reserve, closed area, marine protected area, marine sanctuary, marine refuge or no-take zone", and they each offer different degrees of protection. A marine reserve is generally referred to as an area permanently closed to all fishing, while a closed area is temporarily closed or closed to a particular type of fishing gear such as trawls or dredges. Marine protected areas have been in existence for several decades (Bjorklund, 1974), yet there has been little evaluation of whether they achieve the aims for which they were set up (Polunin and Roberts, 1993). If the operational mechanisms and rates of fishery recovery can be better understood, area closures may be a simple but effective device in fisheries management (Polunin and Roberts, 1993).

Distinctions need to be made regarding the efficacy of closed area management between sedentary and mobile or migratory species. The focus of this paper will be on the considerations of closed areas in respect to (semi) sedentary species, such as the sea scallop. In non-migratory species, the spawning stock biomass could increase with a reserve, because the lower transfer rates allow better survival in a part of the population. This improves the reproductive capacity because the age structure includes more mature individuals (Guenette *et al.*, 1998).

Reserve designs that consider ontogenetic requirements of the target species and strategic locations for larval production, import, export, and metapopulation dynamics may optimize fishery benefits for the many marine vertebrate and invertebrate species that possess pelagic larvae (Stoner and Ray, 1996; Bohnsack, 1996; Guenette *et al.*, 1998; Murawski *et al.*, 2000). Reserves are especially suited for long-lived demersal species with planktonic larval dispersal (Bohnsack, 1996). There is now a growing body of literature concerning the utilization and subsequent effects of these areas as tools in fisheries management and biological conservation.

Examples of Closed Area Studies in Fisheries

There are two aspects of fisheries research regarding closed areas: theoretical modeling and field experimentation. The results of studies working on each aspect indicate that under suitable conditions, the beneficial impacts of the closed areas are significant. Investigators have explored the effects of closed areas on different ecological and fishery parameters such as community composition, population age-structure, and stability, exploitation, and survival.

Since Beverton and Holt, many investigators have enhanced their yield per recruit model to address the impacts of closed areas, and the transfer of animals between the fished and unfished areas, on the yield and reproductive capacity of a stock. Changes in the spawning stock biomass, number of eggs produced, or number of recruits have been measured to quantify this relationship (Guenette *et al.*, 1998). Dynamic models have been developed to account for biological factors such as stock-recruitment and weight-fecundity relationships (Guenette and Pitcher, 1998), density dependent effects (Quinn *et al.*, 1993), and also spatial factors such as the proportion of protected versus unprotected habitat within a species range (Nowlis and Roberts, 1999).

Quinn *et al.* (1993) explored the effectiveness of using marine reserves as a conservation mechanism for marine metapopulations affected by density dependent processes. Their model results indicated how marine reserves could significantly affect the harvest and population stability of another (semi) sedentary species, the red urchin. Nowlis and Roberts's (1999) model of optimal reserve proportions showed benefits whenever the fisheries were overfished (defined as fished above the MSY mortality level). They used data from the Red Sea spiny lobster to evaluate their model.

Murawski *et al.* (2000) evaluated the areas on Georges Bank closed to all mobile fishing gear between 1994-1998 and found a fourteen-fold increase in sea scallop biomass inside of the closed areas compared to outside. Stoner and Ray (1996) compared the population structure of the commercially important gastropod, the queen conch, between a fished area and a marine reserve in the Exuma Cays. They found the mean adult density was always higher, by as much as 15 times, in the reserve than in the fished area for each depth interval.

There are numerous ecological studies exploring the effects of edges, or habitat transition interfaces, on community composition, population structure, and species richness and evenness, including biotic interactions such as competition, predation, and parasitism. The ecological effects of habitat fragmentation, which is the subdivision of a large continuous tract of habitat into smaller and maybe isolated patches, are becoming more prevalent (Temple and Wilcox, 1986). As natural habitats become more fragmented the effect of the ratio of edge area to total area becomes even more important for many ecological processes.

The relationship between the number of species for a given distance or area is the central tenet of the theory of island biogeography (MacArthur and Wilson, 1967). It considers the equilibrium number of species on islands of different sizes and distances from a mainland (source). Closed areas can be conceptualized as islands, and the number of species and the amount of biomass they can sustain are proportional to their size and location. From an ecological viewpoint, the NEFMC has created a scenario where the predators' (man) foraging grounds have been fragmented and "islands" have been isolated, and now the question is how will the prey (scallops) respond?

Advantages and Disadvantages of Closed Areas as Management Tools

There are several inherent advantages to using closed areas as management tools. These include but are not limited to: (1) increases in yield, especially when fishing mortality and exploitation are high; (2) increases in individual size, biomass, and density; (3) some protection against stochastic events; (4) decreased risk of management failure when uncertainty of stock assessment and actual harvest are present; (5) protection of essential fish habitat in conjunction with stock; (6) export of larvae and adults into surrounding fishing areas (Guenette *et al.*, 1998; Dugan and Davis, 1993; Bohnsack, 1996; Murawski *et al.*, 2000; McClanahan and Mangi, 2000).

There are some inherent disadvantages. The implementation of closed areas without any reduction in commercial fishing effort would subsequently result in concentrating all of the effort onto a smaller fraction of the total stock. The resulting increased fishing mortality in the open areas reduces the overall benefits of the closed area. Marine reserves would decrease yield at low fishing mortality, but may increase yields slightly at high fishing mortality, and the increase depends on the size and transfer rate from the closed area (Guenette *et al.*, 1998). This emphasizes the necessity to use marine reserves as complimentary to more traditional management techniques employing controlled effort and gear (Guenette and Pitcher, 1998).

Summary

Some scientific investigators believe that fisheries science itself cannot advance unless management is recognized as an experimental endeavor (Larkin, 1978; Walters and Holling, 1990). It was with these thoughts in mind that Dugan and Davis (1993) stated that marine closed areas should be experimentally tested as management tools. Further evaluation of existing closed areas and the investigation of experimental closed areas over appropriate time spans will help resolve questions of optimal sizes, shapes, and distribution.

The real world impacts of utilizing closed areas as management tools is still limited to only a few case studies and consequently not fully understood (Dugan and Davis, 1993). Even well designed reserve networks will require continued conservation efforts outside reserve boundaries to be effective. They will require social acceptance, adequate enforcement, and effective scientific evaluation to be successful (Murray *et al.*, 1999). Further, analysis of marine reserves should be spatially and temporally structured to take into account realistic migration and aggregation patterns and other aspects of the life history (Guenette and Pitcher, 1998). Empirical studies of how fish stocks may respond to local protection are urgently needed, yet there have been few studies addressing this issue (Polunin and Roberts, 1993).

There has been much work done on the biology, ecology, fishery, and management of scallops in the northwest Atlantic, and this work has been primarily the result of their very high economic value. There is; however, an apparent chasm between the theoretical modeling efforts and practical application of closed areas in the commercial scallop fishery management. The opportunities to study functioning closed areas and quantify their effects on commercial scallop stocks are rare.

This study was possible because of:

- The ability to perform spatially-intensive surveys
- Access to relatively undisturbed scallop populations in mid-Atlantic closed areas
- A time series of fishery-independent surveys from pre- and post-closure

There is a fundamental question to be addressed when utilizing closed areas as management tools in a commercial scallop fishery. Is the scallop stock on the bottom protected throughout the same area delineated by the closed area boundaries? This becomes an especially important question when the management uses area-based estimates to calculate abundance and biomass for setting annual quotas. If the "**effective boundary**" of protection on the bottom was significantly different from the closed area boundary, then how would that affect the estimates? The effective boundary was defined as the location where the effect of fishing mortality becomes negligible. The focus of this study was to evaluate and document changes in the abundance and spatial distribution of the scallop stock at and around the boundaries of the mid-Atlantic closed areas.

Objectives

1.) To compare the structure of the scallop stock across the mid-Atlantic closed area boundaries. This was accomplished by quantifying the size-frequency distribution, abundance, biomass, and density of the stock in the areas adjacent to the boundaries. These parameters were examined temporally and spatially to document the position of the effective boundary of the stock.

2.) To assess the impacts of the findings in context of management of the mid-Atlantic scallop resource.

Hypotheses

H_0: The effective boundary is located at the chart boundary

H_A: The effective boundary is not located at the chart boundary

Materials and Methods

Approach

Study Sites

The Hudson Canyon South Closed Area (HCSCA) and the Virginia Beach Closed Area (VBCA) are located in the mid-Atlantic region of the fishery (Figure 1). The mid-Atlantic region extends southwest from the New York bight south to the Virginia/North Carolina border and is 8,428 nm^2 in total area. The HCSCA has an area of 1,466 nm^2 and is 60 nm due east from Cape May, New Jersey. The VBCA has an area of 422 nm^2 and is 50 nm due east of Virginia Beach, Virginia. The combined area of both closures was 22% of the total region (SPDT, 2000).

Vessels and Sampling Gear

A survey trip was taken to each closed area during September 1999, one to Hudson Canyon in June 2000, and one to Virginia Beach in September 2000. The *F/V Courageous* from Cape May, New Jersey performed the 1999 survey, and the *F/V Alice Amanda* from Hampton, Virginia performed the 2000 survey.

The sampling gear consisted of two identically configured 15' New Bedford style commercial sea scallop dredges (Posgay, 1957; Bourne, 1964; Smolowitz and Serchuk 1989; DuPaul *et al.* 1989b). Vessels were equipped with identical electronic instrumentation arrays for consistent data collection. A portable computer outfitted with

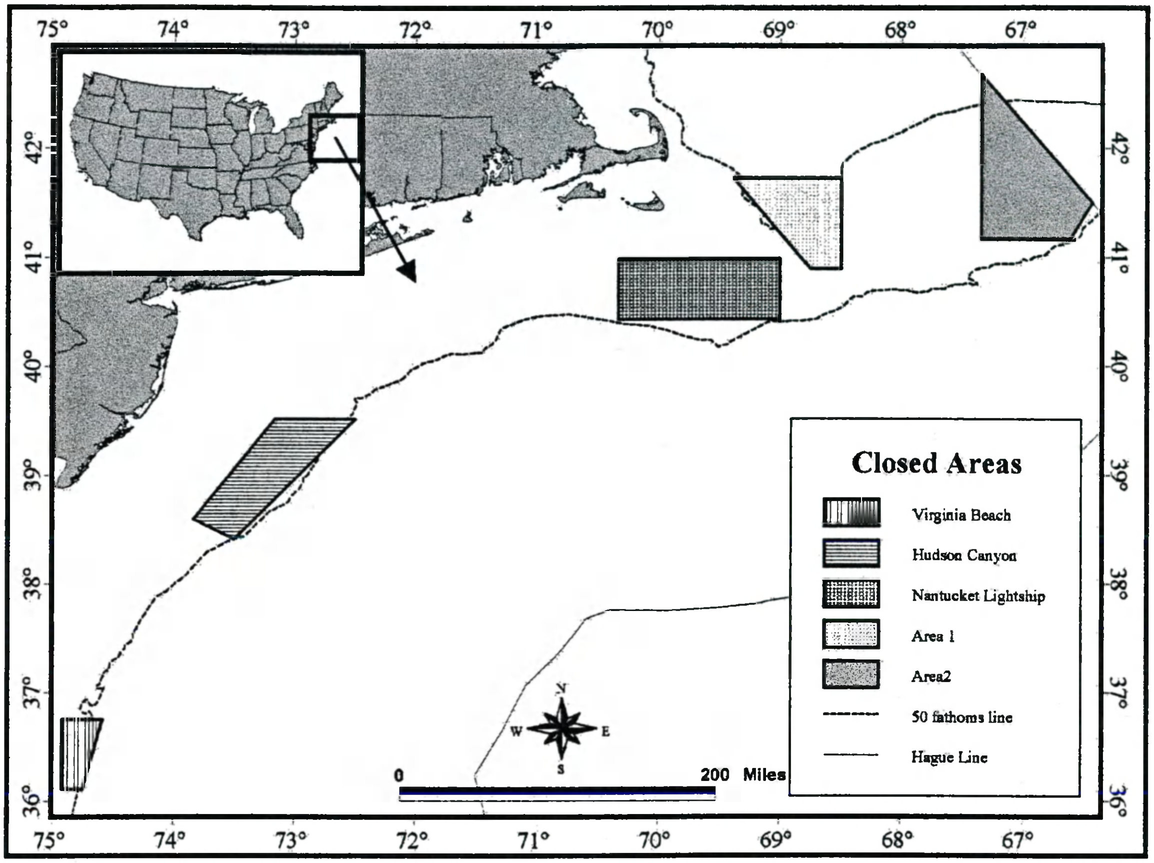


Figure 1. The five extant closed areas involved with sea scallop fishery management.

a differential geographic positioning system (DGPS) recorded real-time vessel position and operation data. A NMFS inclinometer sensor was fastened to one dredge on each vessel to record the angle of the dredge relative to the seabed to more accurately estimate the amount of time the dredge was in a fishing position.

Data Collection

All data were collected by fishery-independent surveys. The 1998 data were collected during the NMFS's annual scallop resource survey. The 1999 and 2000 data were collected during the Virginia Institute of Marine Science's (VIMS's) surveys.

Standardized tows (10 minute duration at 4.5 knots) were conducted at survey stations (Figure 2). Survey station positions were recorded directly from each vessel's DGPS. Tow logs were recorded by the captain and mate which included the tow number, station number, vessel position, tow duration, tow speed, depth, sea state, vessel heading, and wind speed and direction. Deck logs were recorded by the chief scientist to document the specifics on catches and samples. Tow quality, volume of scallops caught, volume of scallops sampled, and the size-frequency distribution of scallops were recorded. Tow quality consisted of evaluating the condition of the gear after hauling-back the tow. A good tow was when there were no abnormalities with the gear. A poor quality tow would occur if the twine top became hung on the frame, or the dredge had flipped during the tow etc.

Data Analysis

Overview

The abundance and distribution of scallops from the annual NMFS scallop survey performed in July 1998 were used as the benchmark reference for the condition of the resource at the time of the closures. These data were adjusted to account for the relative selectivity of the 8' dredge used on the *R/V Albatross IV*. Data from the 1999 and 2000 VIMS surveys provided the post-closure information of the scallop abundance and distribution. The 1999 and 2000 catch data were adjusted to account for the relative selectivity of a 15' dredge knit with 3.5" rings and 10" twine-top (DuPaul *et al.*, 1989b). All catch data were standardized to the common swept-area of one nominal commercial survey tow ($0.0037057\ \text{nm}^2$). Then relative sea scallop abundance and biomass indices

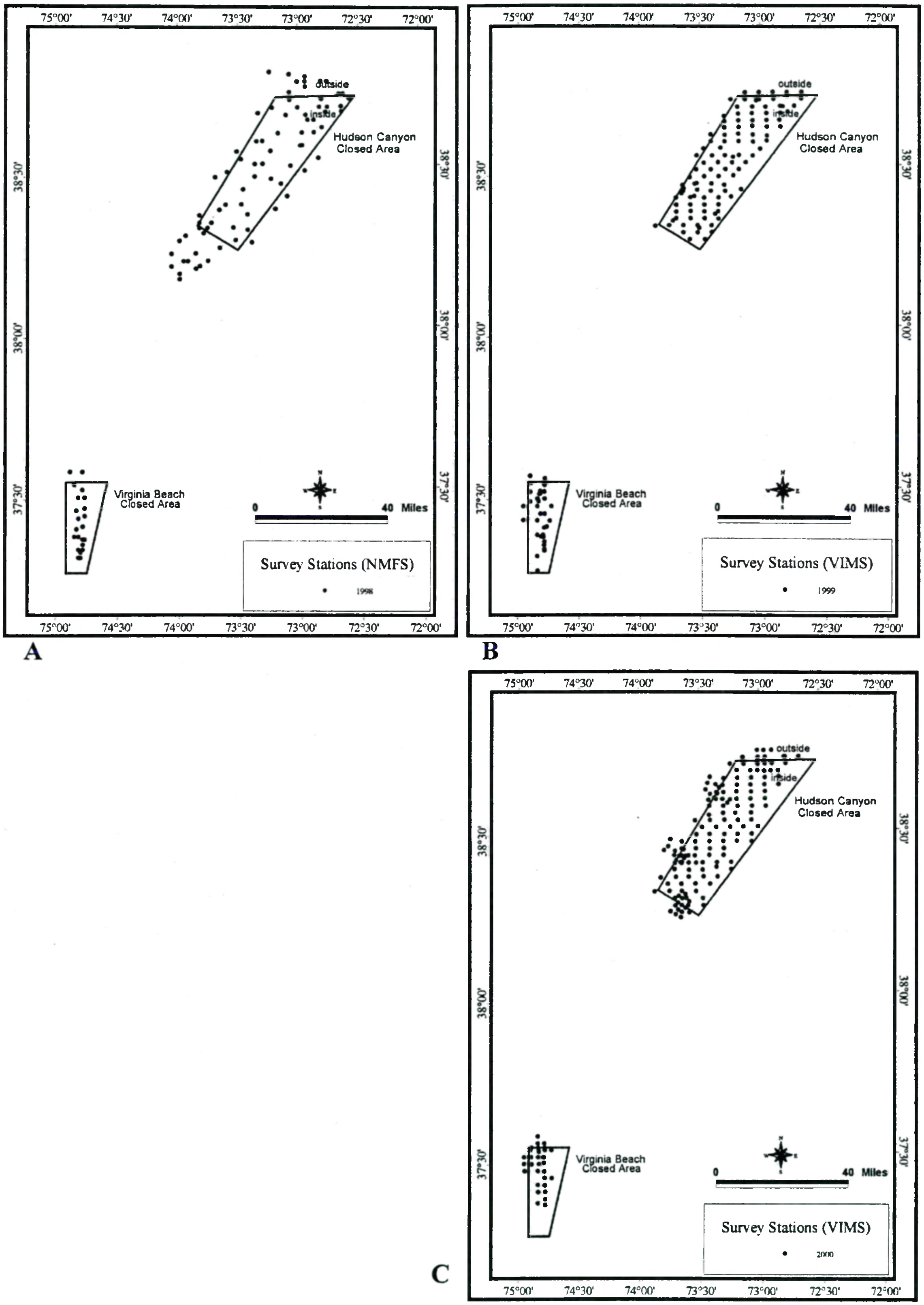


Figure 2. Survey station positions for each year evaluated.
(A) 1998 NMFS survey **(B)** 1999 VIMS survey **(C)** 2000 VIMS survey

were calculated for each station in each year. Since all of the survey stations were not in the same locations each year, kriging analysis was used to spatially compare catch data between years.

By creating a static grid over each study site and kriging the survey catch data, the abundance of scallops at each grid point was tracked through time. The same cohorts were examined in successive years, so the influence of recruitment was removed. This left immigration (I) as the only potential form of input. The removals could have been from emigration (E), natural mortality (M), and fishing mortality (F). Since there were no real physical boundaries or significant differences in environments out on the continental shelf, M was assumed to have had an equal effect between grid points. This left E and F as the only factors influencing the decline in abundance at a grid point over time.

The eastern boundary of each closed area was not included in analysis due to the low densities of scallops found in the deeper water (> 50 fathoms) of these regions. Review of the NMFS's vessel monitoring system (VMS) data from 1998 and 1999 revealed no record of fishing effort in water greater than 50 fathoms (Appendix I) (Rago, 1999). Additionally, the southern boundary of the VBCA was not evaluated due to the lack of survey stations from the 1998 NMFS survey. This was probably due to the historically low catches/abundance in that area. A glossary of key terms used in the data analysis has been provided for reference (Appendix II).

Data Manipulations

General

Post-closure survey data were entered into a Microsoft® Access 97 database that was custom-made for the VIMS sea scallop workgroup. Data auditing and conformation of NMFS (pre-closure) and VIMS (post-closure) data were accomplished using SAS® (version 8) in conjunction with the database. SAS was used to perform most of the analysis procedures, and also to manage and store survey catch and position data from multiple years. Size-frequency distributions were calculated as mean estimates of the total number of scallops in 5 mm size intervals, and the total number of scallops was estimated for each survey station in each year. Scallop cohorts were identified and growth was tracked between years at and around each closed area. Estimates of biomass were calculated by applying the shell height / meat weight relationship formula to the abundance data:

$$\ln(w) = -12.2484 + 3.2641 * \ln(h) \qquad (eq.\ 1)$$

where: w = meat weight in grams
h = shell height in millimeters (NEFSC, 2001).

These data were then brought into ARCVIEW GIS® (version 3.2) for contouring analysis and visualization.

Spatial Analysis

A static grid with points every two nautical miles was generated over each closed area, and its surrounding areas, out to a minimum of 10 nm from the relevant boundaries

(Figure 3). The variance structure of the stock was determined through experimental variography with the standard (semi)variogram model:

$$\gamma_z(h) = \frac{1}{|N(h)|} \sum_{N(h)} \frac{[Z_{(r_i)} - Z_{(r_j)}]^2}{2} \qquad (eq.2)$$

where: $\gamma_z(h)$ = half of the average squared difference between two values separated by vector h. $Z_{(ri)}$ denotes the observation made at location r_i (starting point), and $Z_{(rj)}$ is the observation at location r_j (ending point). N(h) denotes the set of sample location pairs such that the distance between locations is h and |Nh| is the number of pairs within the set (Warren, 1998) (SAS, 1999).

(Semi)variograms were produced to determine the neighborhood definition parameters of *sill*, *range*, *scale*, and *nugget* for kriging analysis (Figure 4). Ordinary kriging analysis was performed using the spherical form of the model and the neighborhood definition parameters with the SAS procedure PROCKRIG2D (SAS, 1999).

$$\begin{aligned} \gamma(h) &= c_0 + c_s[(3h/2a) - 1/2(h/a)^3],\ 0 < h \leq a \qquad (eq.3) \\ &= c_0 + c_s,\ h > a \end{aligned}$$

where: $\gamma(0) = 0$. As h increases from 0, $\gamma(h)$ increases until $h = a$, after which it remains constant, equal to $c_0 + c_s$, which is referred to as the *sill*. a is known as the *range*, which is the distance that catches cease to be correlated. c_0 is the *nugget*, which reflects microscale variation due to a discontinuity at the origin as $\gamma(h)$ approaches c_0. The *scale* is measured as the *sill* – *nugget* (Warren, 1998) (SAS, 1999).

The first step in the selection of suitable grid points was achieved by neighborhood definition constraints. A radius and a minimum number of stations requirement selected only the grid points that had estimates based on at least two stations within six nautical miles. As a result, only grid points with reasonable estimates due to relatively lower variances remained. For the second step, only those grid points that met

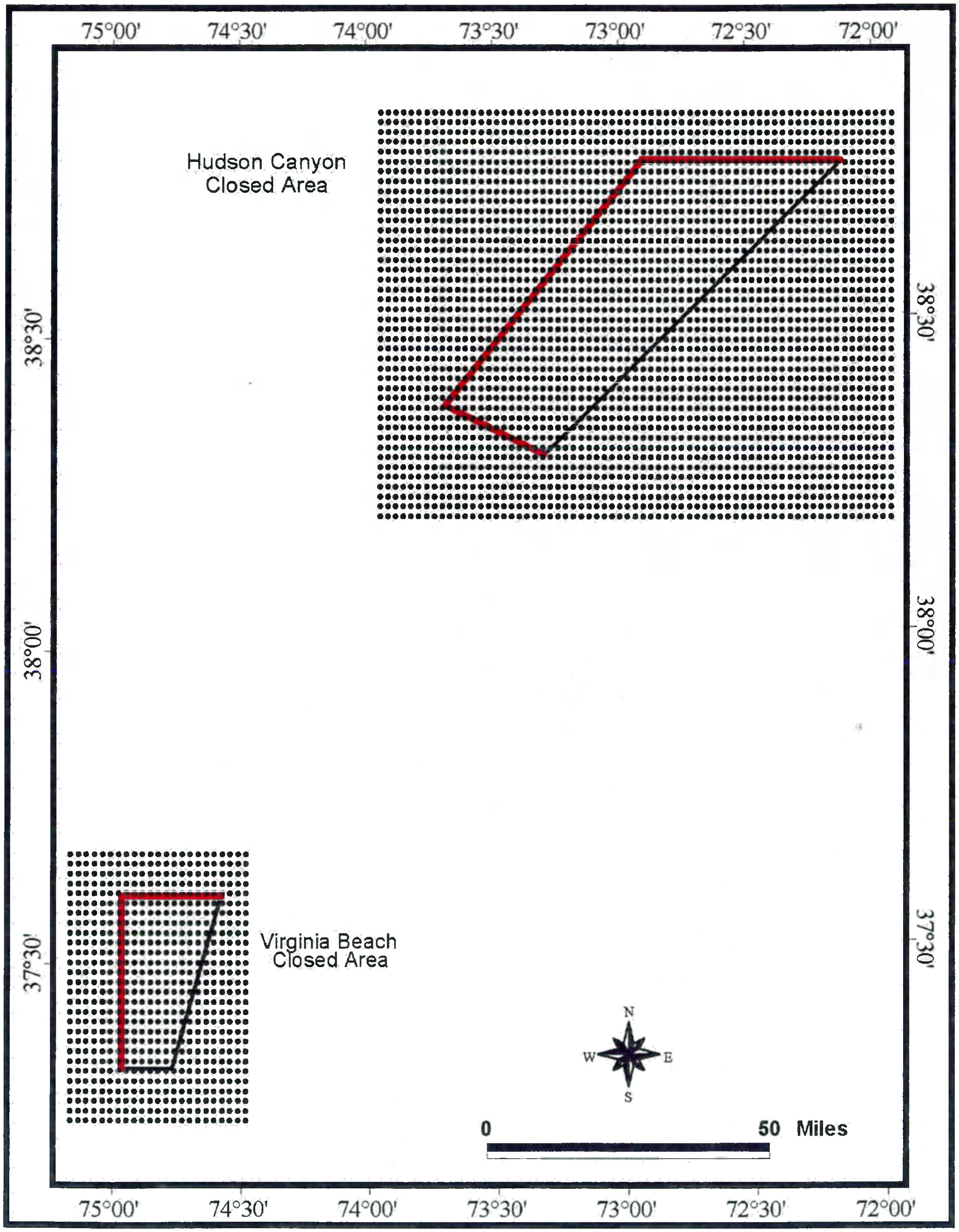
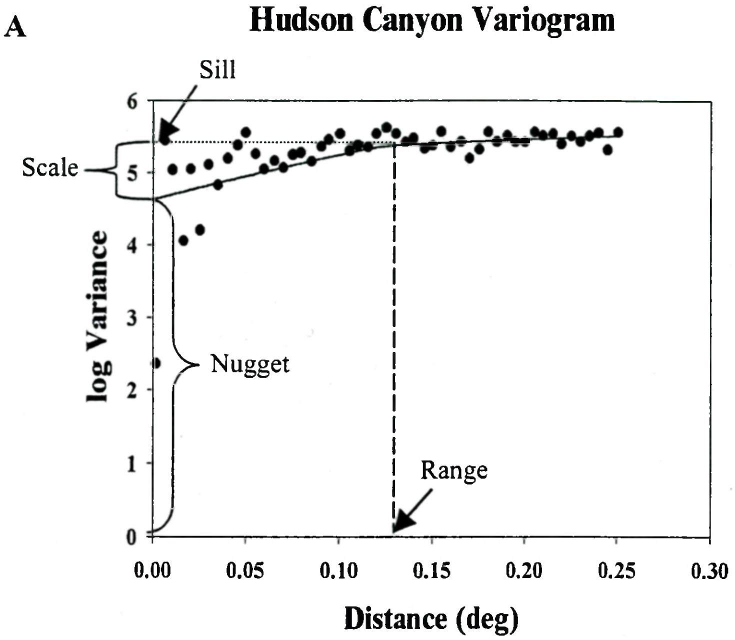


Figure 3. Static grids of points regularly spaced at 2 nm apart covering each of the closed areas, and extending a minimum of 10 nm outside of each relevant boundary (red).



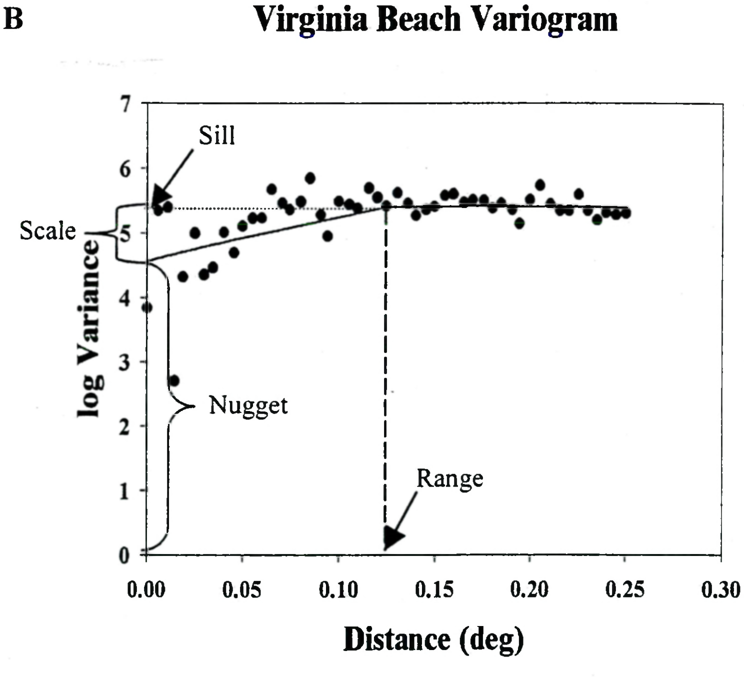


Figure 4. Experimental (semi)variogram developed from each closed area. The non-zero scallop catches were logarithmically transformed. **(A)** Hudson Canyon **(B)** Virginia Beach

the above criteria in all three years (1998-2000) were used in further analysis. These grid points are referred to as “common grid points” for the remainder of the paper (Figure 5). Finally, the common grid points were categorized into “outside, inside, and core” strata based on their location and distance to the boundary at each study site (Figure 6). The demarcation between the inside and core strata was determined by the distance of the outside strata adjacent to each relevant boundary.

Effective Boundary Calculations

Indices of mean abundance and biomass, measured as catch per unit effort (CPUE) (number or kg per tow respectively), were calculated from each strata in each year. Estimates of the total instantaneous rate of decline (D) were calculated for the outside and inside strata for each year post-closure using the formula:

$$D = -\ln\frac{N_t}{N_0} \qquad (eq.\ 4)$$

where: N_t = number of animals in a year
N_0 = number of animals in the previous year (Ricker, 1975).

The mean D-values were used as cutoff parameters required for transforming the kriging analysis results into binary form for probit regression analysis. Common grid points with estimates greater than the mean D value were assigned values of one, and those with less were assigned values of zero. The average value of D for both years post-closure was also calculated and used as the cutoff for the cumulative post-closure analysis. Minitab® (version 12.1) was used to perform probit regression analysis on the binary data to estimate the mean location of the effective boundary. In addition, a

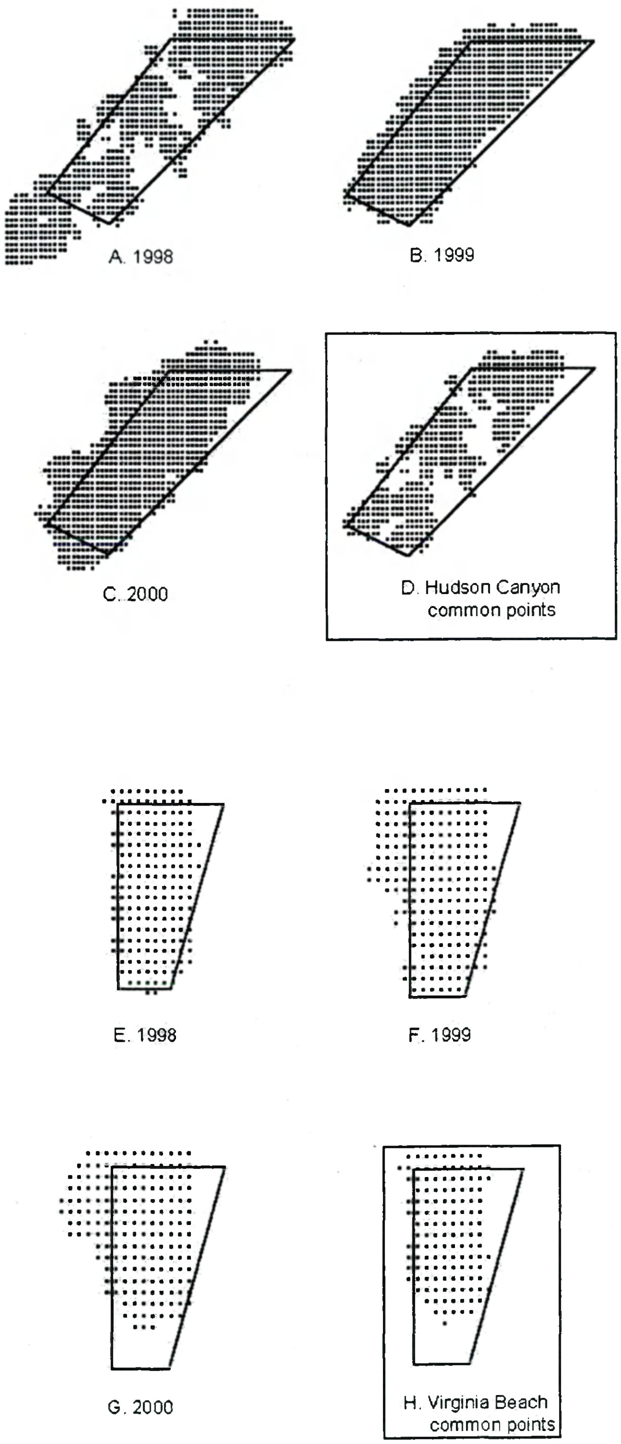


Figure 5. Determination of "common grid points" at each closed area.
Grid points that had kriged abundance estimates based on a minimum of 2 survey stations within 6 nm in each of the three years evaluated (1998-2000). These points were deemed "common points" because they possessed estimates with relatively lower variance in all three years.

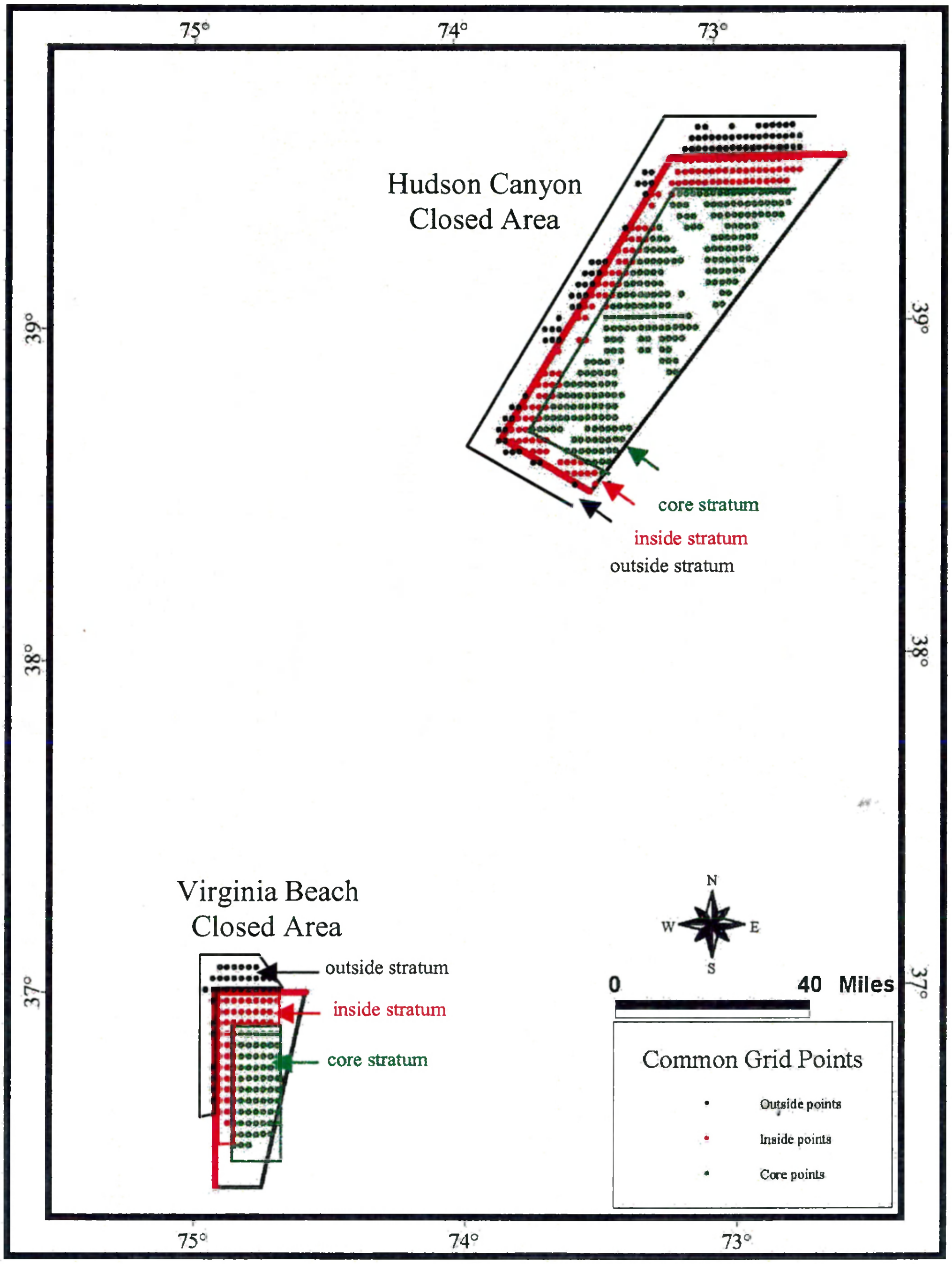


Figure 6. The three strata at each closed area were the "outside, inside, and core". The common grid points were classified into these based on their relative location (inside or outside), and distance from the relevant boundaries.

sensitivity analysis was performed on the probit analysis results to determine how the estimates of the mean effective boundary changed within a range of all reasonable D and size-cutoff inputs.

The mean effective boundary location was used to recalculate the total area effectively protected by the boundaries of each closed area. Finally, the mean CPUE of all common points inside each closed area in 1998 was used to estimate the biomass within the original and adjusted total areas. The difference between these estimates represented the difference between the expected and observed effective protection. The major steps in the analysis procedure assembled have been summarized in Figure 7, and the conceptual framework is described in Appendix III.

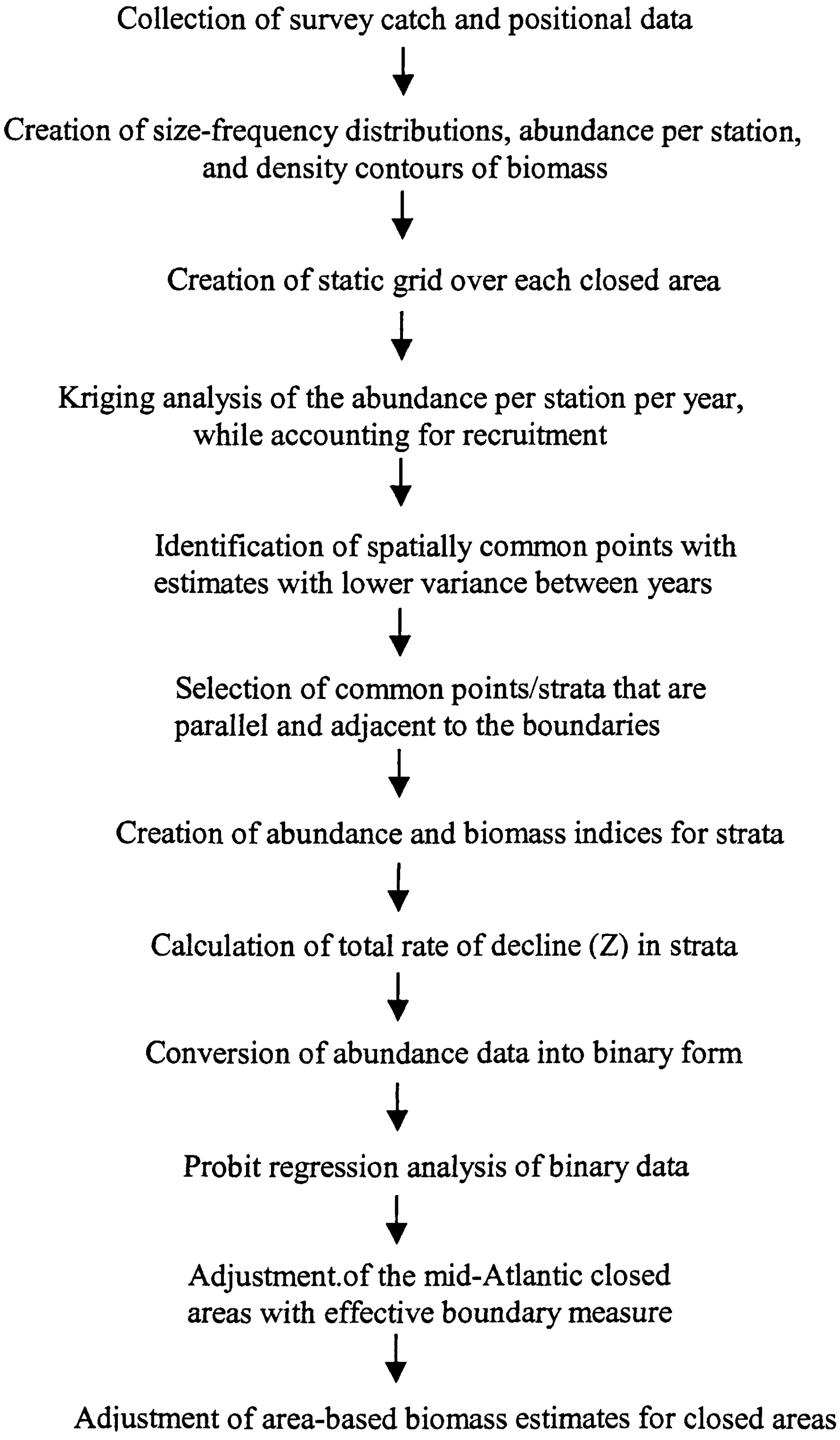


Figure 7. The major steps in the analysis procedure assembled for this study

Results

General Observations From Station Data

The regional size-frequency distributions (composed of data from the stations in and around each closed area) showed the recruitment and growth of scallop cohorts at each closed area in each year (Figures 8, 9). An increase in the spawning stock biomass was evident inside of each closed area between 1998 and 2000, because of the protection of more, larger animals. The size-frequency distribution from stations inside of each closed area was driving each regional distribution (Figures 8, 9).

The density contours, generated from the station biomass indices, provided an initial insight into the large-scale spatial distribution of the scallop stock. In 1998, there were two beds of higher density in the HCSCA, and one in the VBCA (Figure 10A). In 1999, after the first year post-closure, the northern bed in the HCSCA had diminished, while the southern bed had increased substantially in biomass. In addition, the northern bed in the VBCA had grown, and a relatively large bed of high-density had developed in the lower, central portion of the area (Figure 10B). In 2000, the southern bed in the HCSCA had increased substantially, and there was a re-development of a large northern bed. Both beds of higher density in the VBCA had been reduced from the previous year (Figure 10C).

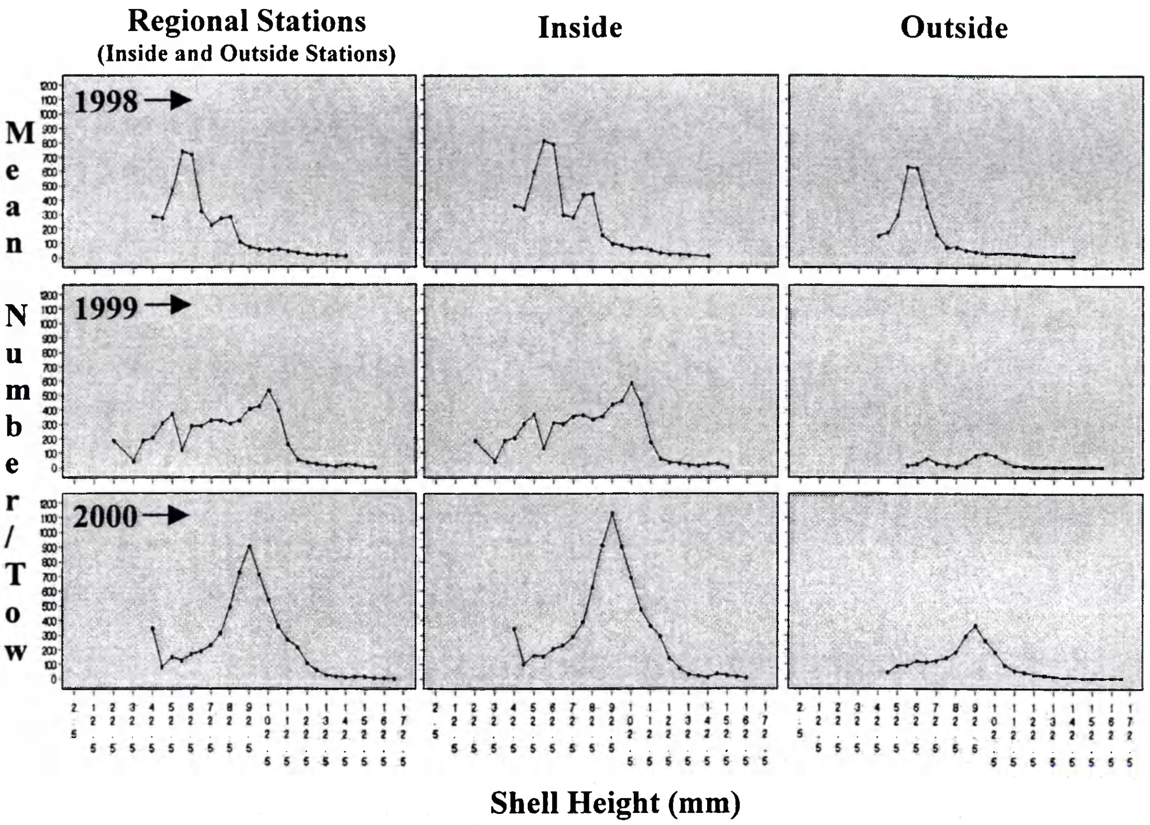


Figure 8. The size-frequency distributions for the Hudson Canyon region. A breakdown between inside and outside stations was included.

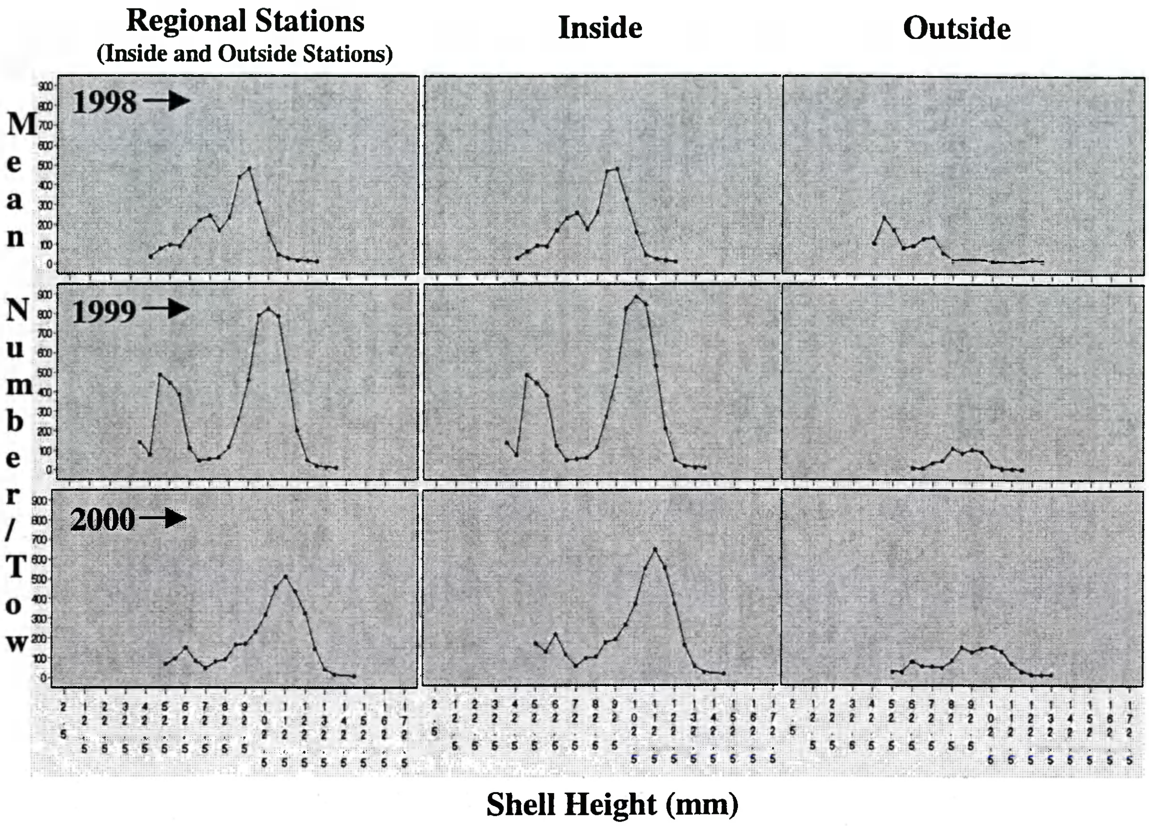


Figure 9. The size-frequency distributions for the Virginia Beach region. A breakdown between inside and outside stations was included.

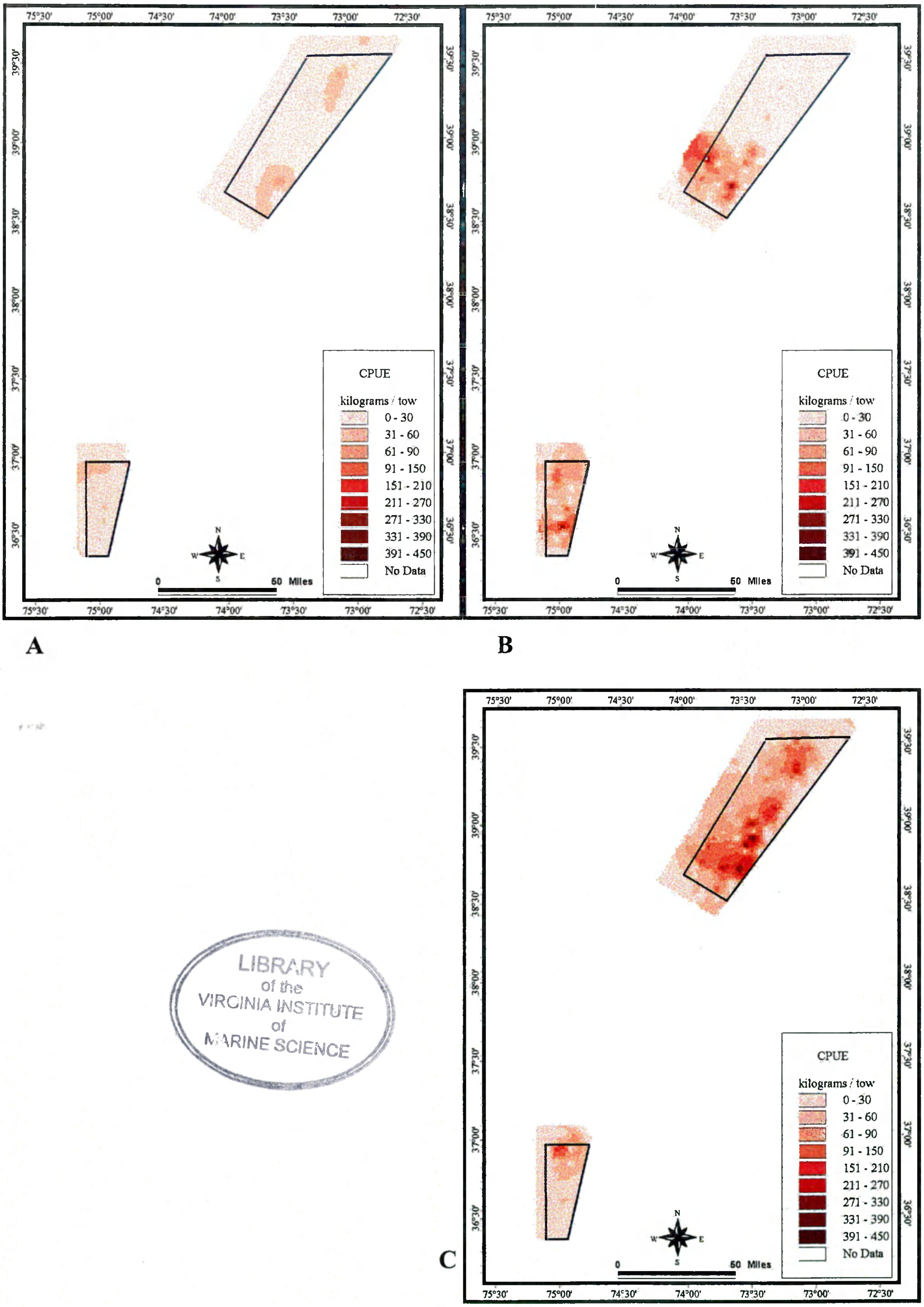


Figure 10. Density contours of biomass from survey station indices.
(A) 1998 (B) 1999 (C) 2000

Spatial Analysis / Kriging Results

Indices of Abundance

In 1998, the highest mean CPUE for the HCSCA region was in the core stratum and the lowest was in the outside stratum, while the opposite was true for the VBCA region (Figures 11A, 11B). In 1999, there was a decline in mean CPUE in all strata except for the Virginia Beach core which increased slightly, and both closed areas showed a gradient in mean CPUE from higher in the core strata to lower in the outside strata (Figures 11A, 11B) (Table 2). The *rates* of decline were highest in the outside strata at both closed areas, and lowest in the inside stratum at Hudson Canyon and the core stratum at Virginia Beach (Table 3). Additionally, the mean CPUE in each Hudson Canyon stratum was higher relative to the equivalent Virginia Beach stratum (Figures 11A, 11B).

In 2000, the mean CPUE for all strata had declined from the previous year (Figures 11A, 11B) (Tables 2, 3). The gradient of higher mean CPUE in the core stratum to lower in the outside stratum persisted at the HCSCA, but not at the VBCA (Figures 11A, 11B) (Tables 2, 3). The *rates* of decline were highest in the outside strata, and were lowest in the core stratum at the HCSCA and the inside stratum at the VBCA (Figures 11A, 11B) (Tables 2, 3). The cumulative percentage loss and rate of decline in mean CPUE at each closed area between 1998 and 2000 were highest in the outside stratum, and lowest in the inside stratum at the HCSCA and in the core stratum at the VBCA (Tables 2, 3).

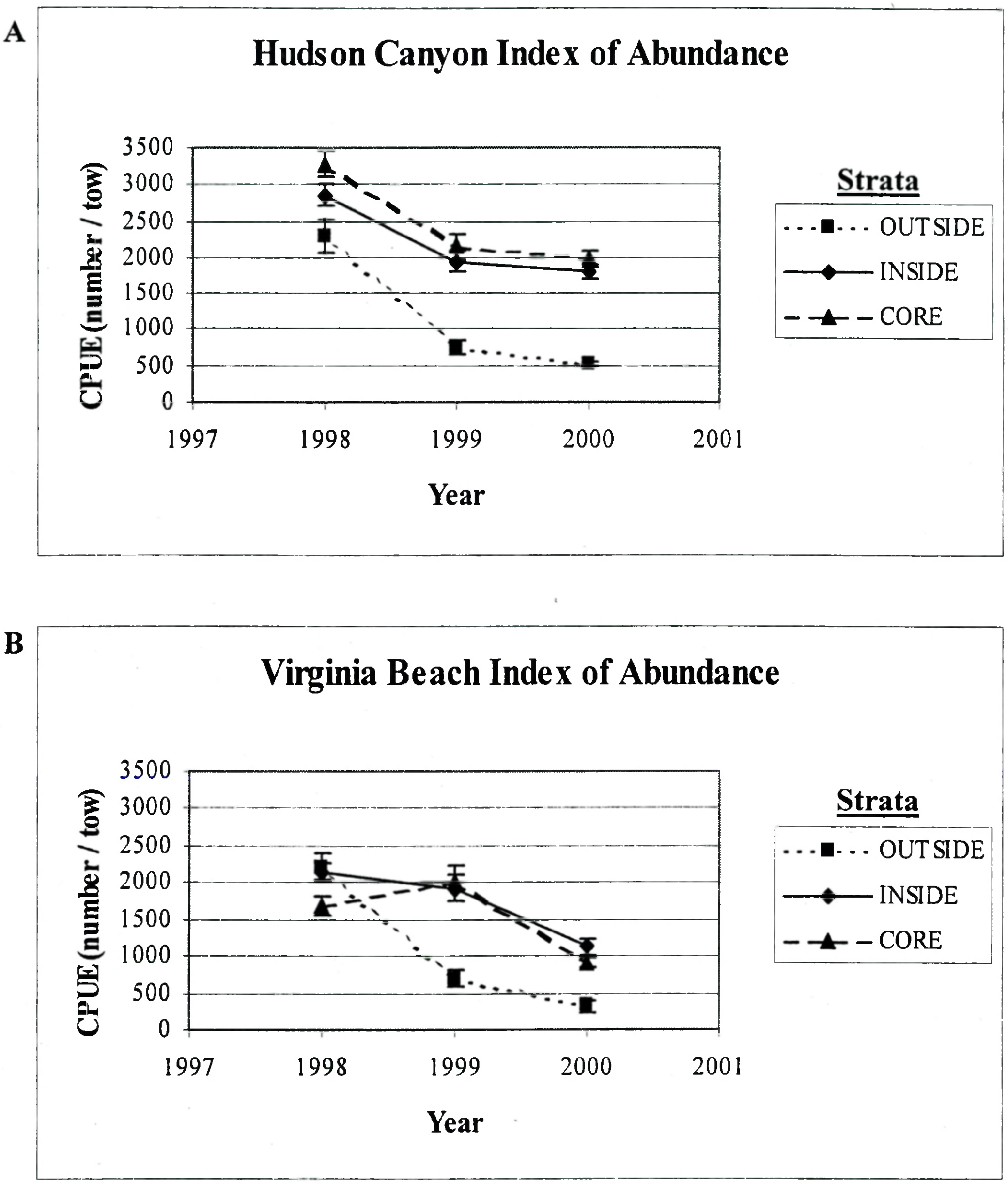


Figure 11. The mean CPUE (+/- 1SE) for each stratum in each year evaluated. (A) Hudson Canyon (B) Virginia Beach

Table 2. The percent change in the abundance index for each stratum in each year post-closure, and for the cumulative post-closure period.

Percent Change in Abundance Indices

Closed Area	Stratum	1st Year Post-Closure (1998 - 1999)	2nd Year Post-Closure (1999 - 2000)	Cumulative Post-Closure (1998 - 2000)
Hudson Canyon	Outside	-67.48	-29.39	-77.04
Hudson Canyon	Inside	-32.08	-7.81	-37.38
Hudson Canyon	Core	-34.58	-7.40	-39.42
Virginia Beach	Outside	-68.80	-54.88	-85.92
Virginia Beach	Inside	-10.22	-41.98	-47.91
Virginia Beach	Core	19.41	-53.90	-44.96

Table 3. The rates of decline in abundance for each stratum in each year post-closure, and for the cumulative post-closure period.

Total Rate of Decline in Abundance (D)

Closed Area	Stratum	1st Year Post-Closure (1998 - 1999)	2nd Year Post-Closure (1999 - 2000)	Cumulative Post-Closure (1998 - 2000)
Hudson Canyon	Outside	1.123	0.348	0.736
Hudson Canyon	Inside	0.387	0.081	0.234
Hudson Canyon	Core	0.424	0.077	0.251
Virginia Beach	Outside	1.165	0.796	0.980
Virginia Beach	Inside	0.108	0.544	0.326
Virginia Beach	Core	-0.177	0.774	0.299

Indices of Biomass

In 1998, there was no substantial difference in the mean CPUE of biomass between the inside and core strata at the HCSCA, and the inside and outside strata at the VBCA (Figures 12A, 12B). In 1999, the mean CPUE of biomass increased in all strata except for the Virginia Beach outside (Figures 12A, 12B) (Table 4). There was no substantial difference in the mean CPUE of biomass between the inside and core strata at each closed area (Figures 12A, 12B). These trends created a gradient in the CPUE at each closed area from higher in the core stratum to lower in the outside stratum (Figures 13A, 13B) (Table 4).

In 2000, there was no substantial difference in the mean CPUE of biomass in the inside and core strata at the HCSCA (Figures 12A, 12B). In addition, the gradient in the mean CPUE from higher in the core to lower in the outside persisted (Figures 12A, 12B). The mean CPUE of biomass declined in all strata at the VBCA from the previous year (Figures 12A, 12B). The highest measure was in the inside stratum and the lowest was in the outside (Figures 12A, 12B). The cumulative percentage change in the mean CPUE of biomass between 1998 and 2000 was negative in the outside stratum at each closed area (Figures 13A, 13B) (Table 4). The stratum with the most cumulative percentage change at the HCSCA and VBCA were the inside and outside respectively (Figures 12A, 12B) (Table 4).

Calculation of Total Rate of Decline (D)

The mean total instantaneous rate of decline (D) at the HCSCA was 0.76 and 0.21 for the first and second years post-closure respectively (Figure 13A). The mean value of

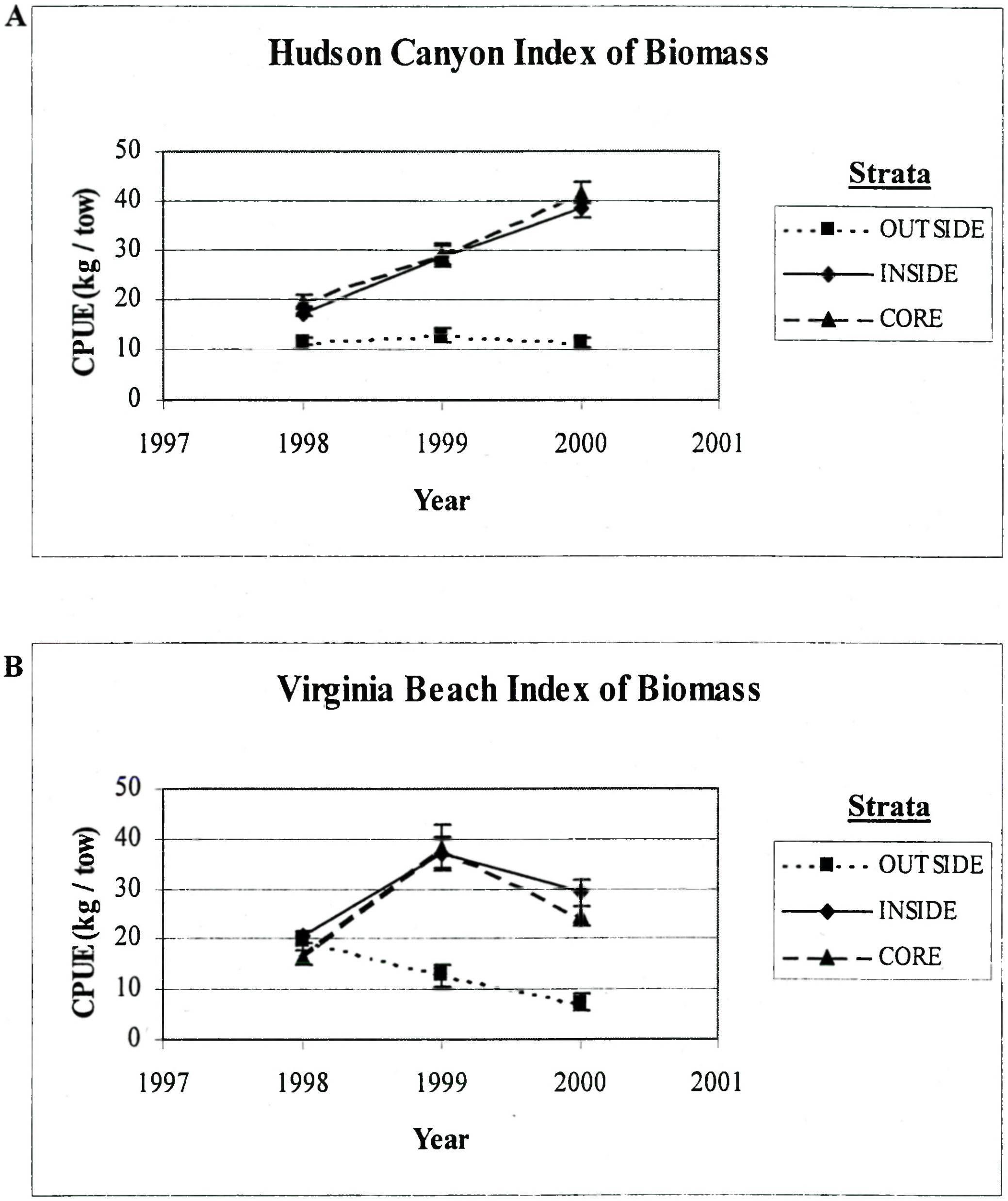
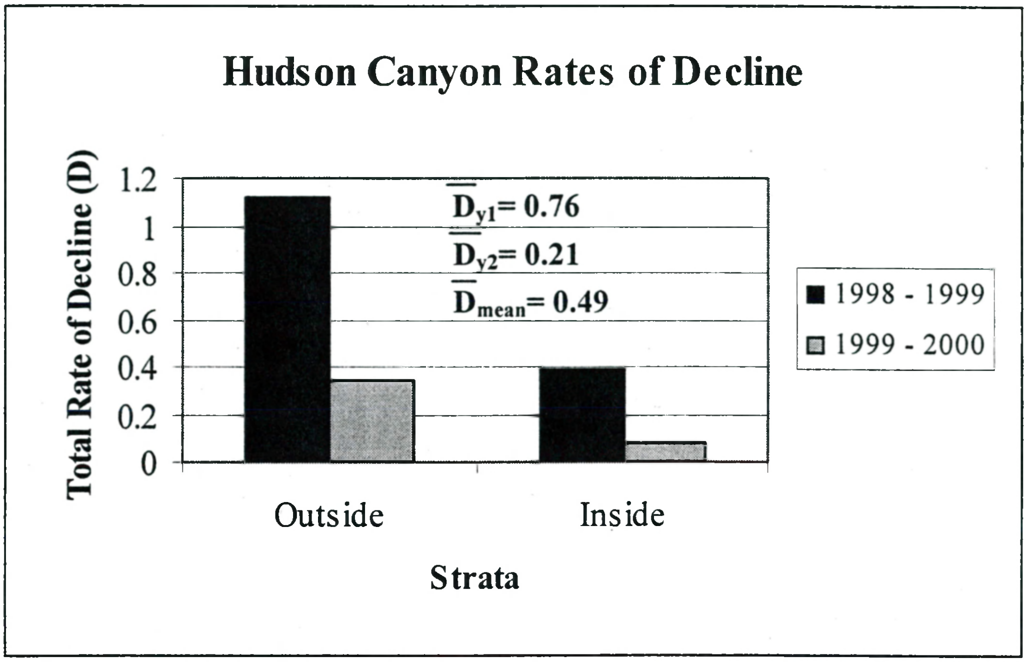


Figure 12. The mean CPUE (+/- 1SE) of biomass for each stratum in each year evaluated. **(A)** Hudson Canyon **(B)** Virginia Beach

Table 4. The percent change in the biomass index for each stratum in each year post-closure, and for the cumulative post-closure period.

Percent Change in Biomass Indices				
Closed Area	**Stratum**	**1st Year Post-Closure (1998 - 1999)**	**2nd Year Post-Closure (1999 - 2000)**	**Cumulative Post-Closure (1998 - 2000)**
Hudson Canyon	Outside	4.75	-5.28	-0.78
Hudson Canyon	Inside	92.38	-43.60	8.50
Hudson Canyon	Core	45.52	-54.71	-34.10
Virginia Beach	Outside	-18.71	-48.19	-57.88
Virginia Beach	Inside	42.07	-78.07	-68.85
Virginia Beach	Core	184.89	-79.03	-40.27

A



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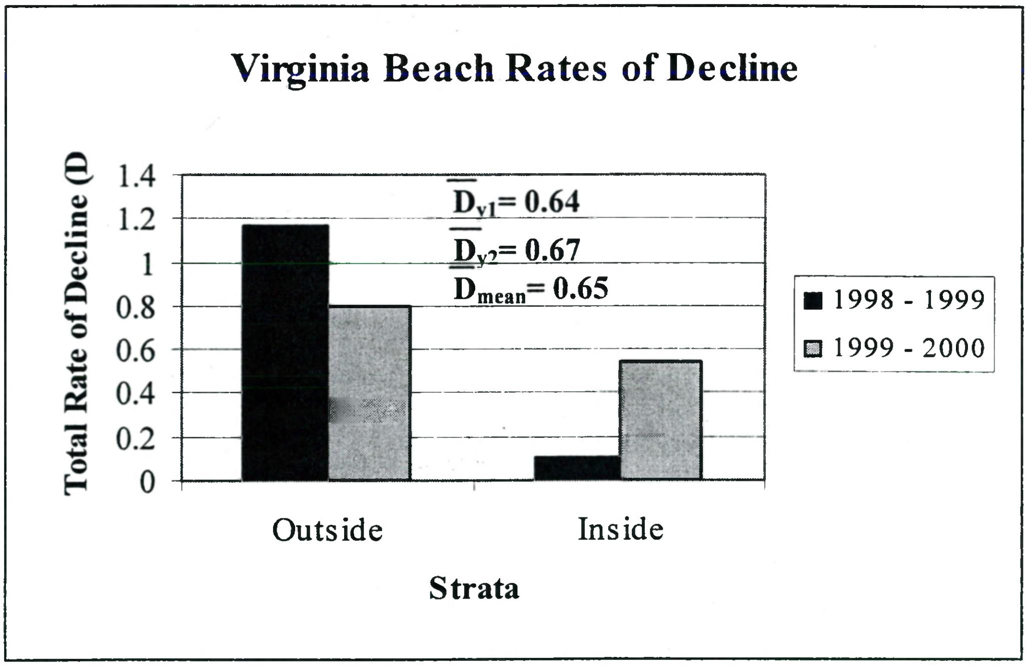

Figure 13. The rate of decline in abundance for the outside and inside strata at each closed area. Rates were calculated from the annual indices in each year post-closure. **(A)** Hudson Canyon **(B)** Virginia Beach

D for the first two years of the HCSCA was 0.49 (Figure 13A). The mean value of D at the VBCA was 0.64 and 0.67 for the first and second years post-closure respectively (Figure 13B). The mean value for the first two years of the VBCA was 0.65 (Figure 13B).

Probit Regression Analysis

Analysis of the first year post-closure binary data from the HCSCA calculated the mean effective boundary at 0.13 nm outside, with the lower and upper 95% confidence interval measures at 2 nm outside and 1.3 nm inside respectively (Figure 14A) (Appendix IV). Analysis of the second year post-closure binary data from the HCSCA calculated the mean effective boundary at 5.2 nm outside, with the lower and upper 95% confidence interval measures at 24.1 nm outside and 2.3 nm outside respectively (Figure 14B) (Appendix VI). Analysis of the cumulative post-closure binary data from the HCSCA calculated the mean effective boundary at 0.3 nm outside, with the lower and upper 95% confidence interval measures at 1.4 nm outside and .6 nm inside respectively (Figure 14C) (Appendix VI).

Analysis of the first year post-closure binary data from the VBCA calculated the mean effective boundary at 1.3 nm inside with the lower and upper 95% confidence interval measures at 0.2 nm inside and 2.8 nm inside respectively (Figure 15A) (Appendix IV). Analysis of the second year post-closure binary data from the VBCA calculated the mean effective boundary at 50.5 nm outside, with the lower and upper 95% confidence interval measures at 1,795 nm outside and 1694 nm inside respectively

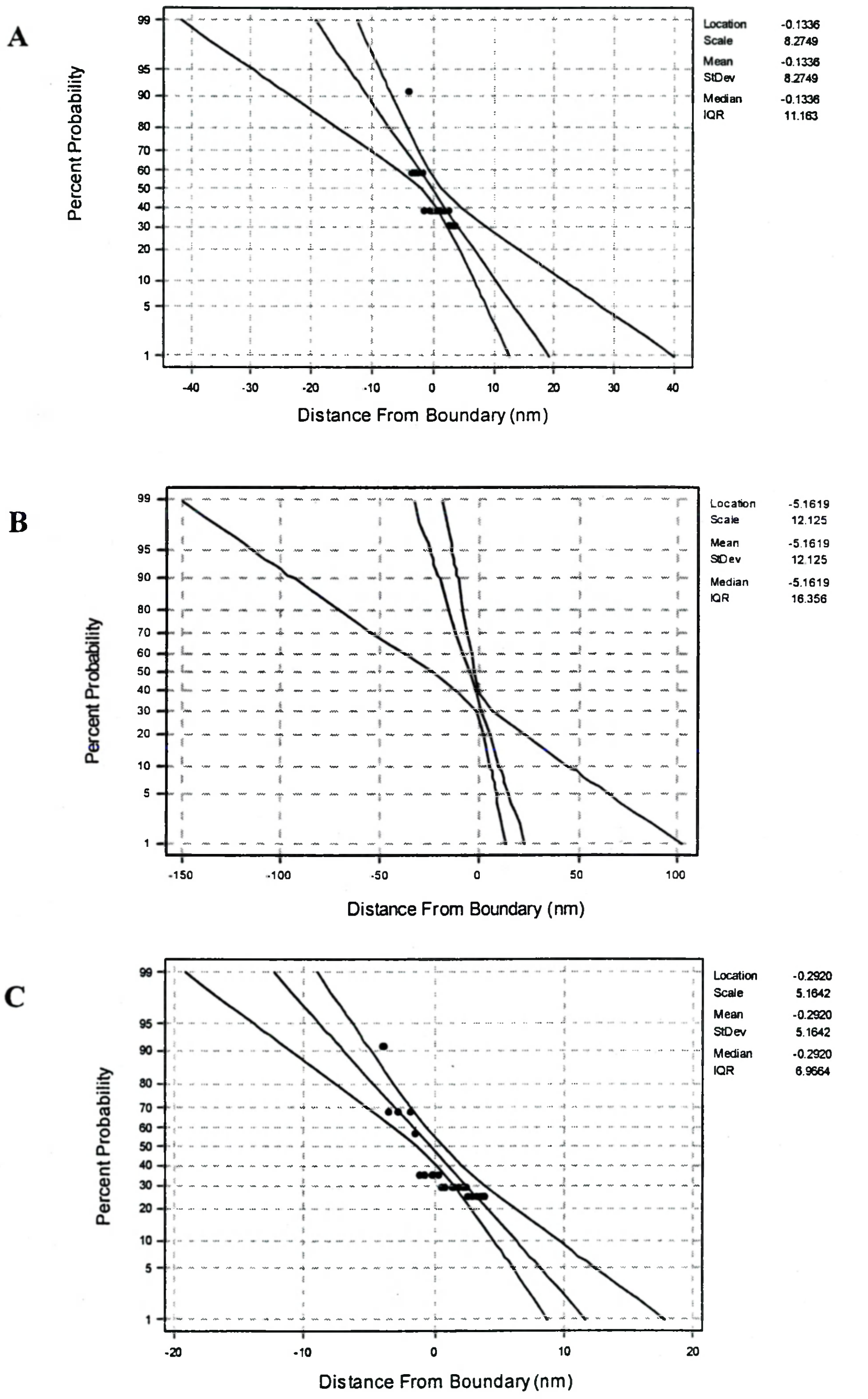

Figure 14. Probability plots from the Hudson Canyon probit regression analysis.
(A) First year post-closure (1998-1999)
(B) Second year post-closure (1999-2000)
(C) Cumulative post-closure (1998-2000)

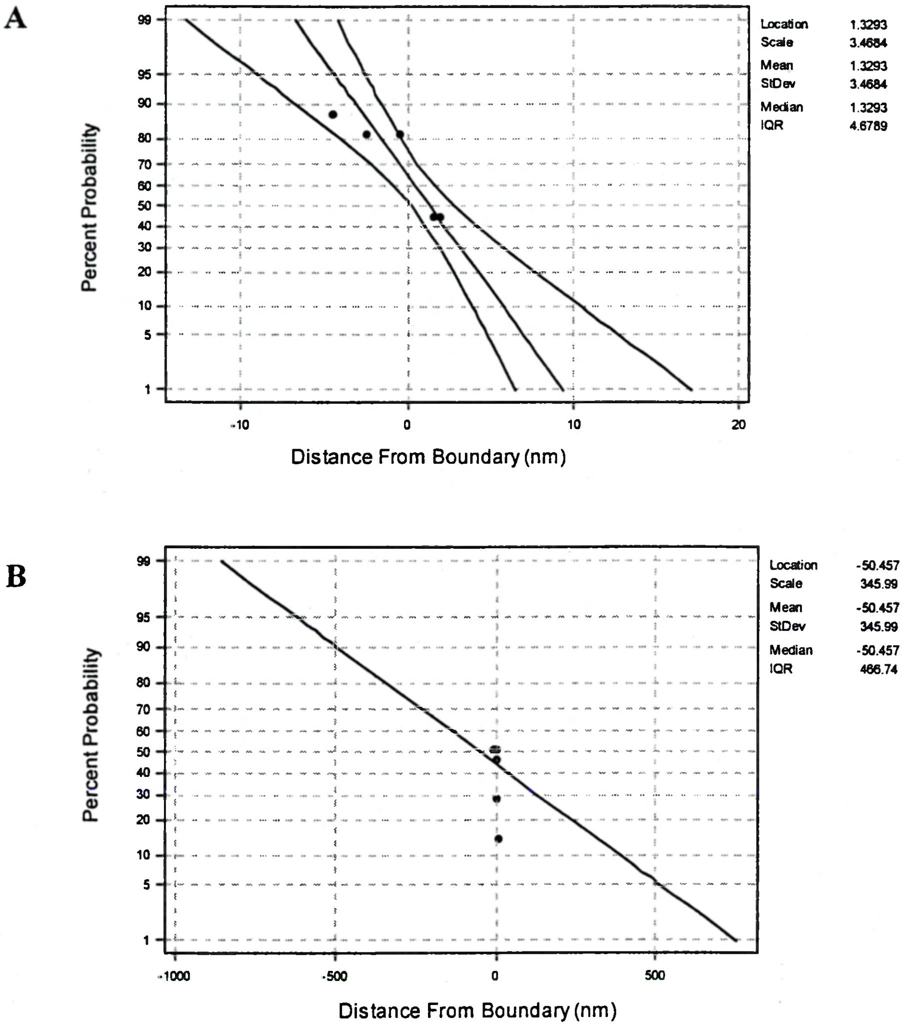

Figure 15. Probability plots from the Virginia Beach probit regression analysis.
(A) First year post-closure (1998-1999)
(B) Second year post-closure (1999-2000)

(Figure 15B) (Appendix IV). An analysis of the cumulative post-closure binary data was not performed due to all of the binary responses being 0.

Estimates of the mean effective boundary did not shift substantially within the range of reasonable variable inputs. For the HCSCA, the mean effective boundary estimate could possibly be shifted 2.5 nm toward the inside, 6.5 nm toward the inside, and 2 nm toward the outside based on the first, second, and cumulative years post-closure respectively (Figures 16A, 16B, 16C). For the VBCA, the mean effective boundary estimate could possibly be shifted 3 nm toward the outside based on the first year post-closure (Figure 17A). A sensitivity range for the mean effective boundary estimates from the second and cumulative years post-closure at the VBCA could not be accurately made, due to the contraction in the difference between the rates of decline between the outside stratum, and the inside and core strata (Figure 17B).

Closed Area and Biomass Estimate Adjustments

The total area being effectively protected by the HCSCA would be increased by 1% after adjusting for the calculated mean effective boundary of 0.13 nm outside. This would increase the original total area of 1,466 nm^2 to 1,480 nm^2 (Table 5). The total area being effectively protected by the VBCA would be decreased by 18.2 % after adjustment for the calculated mean effective boundary of 1.3 nm inside. This would decrease the original total area of 422 nm^2 to 345 nm^2 (Table 5). The total area effectively protected by both of the mid-Atlantic closed areas would be reduced by 0.7% after adjustment of the relevant boundaries by the appropriate mean effective boundary measure.

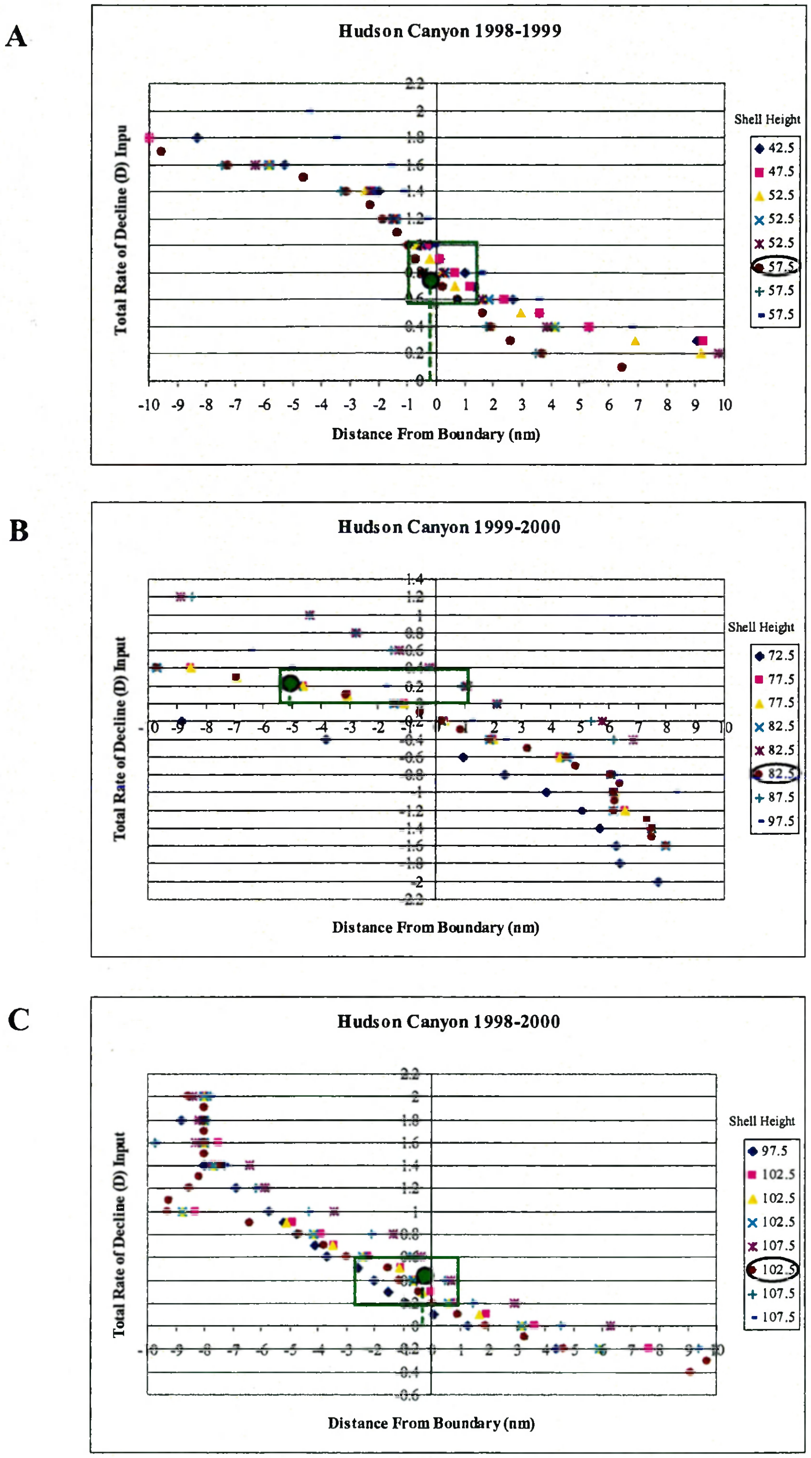

Figure 16. Sensitivity of Hudson Canyon's mean effective boundary estimates to the input variables, D and size-cutoff. The circled sizes were the cutoffs for 1998, 1999, and 2000 used in the analysis.
(A) 1998-1999 **(B)** 1999-2000 **(C)** 1998-2000

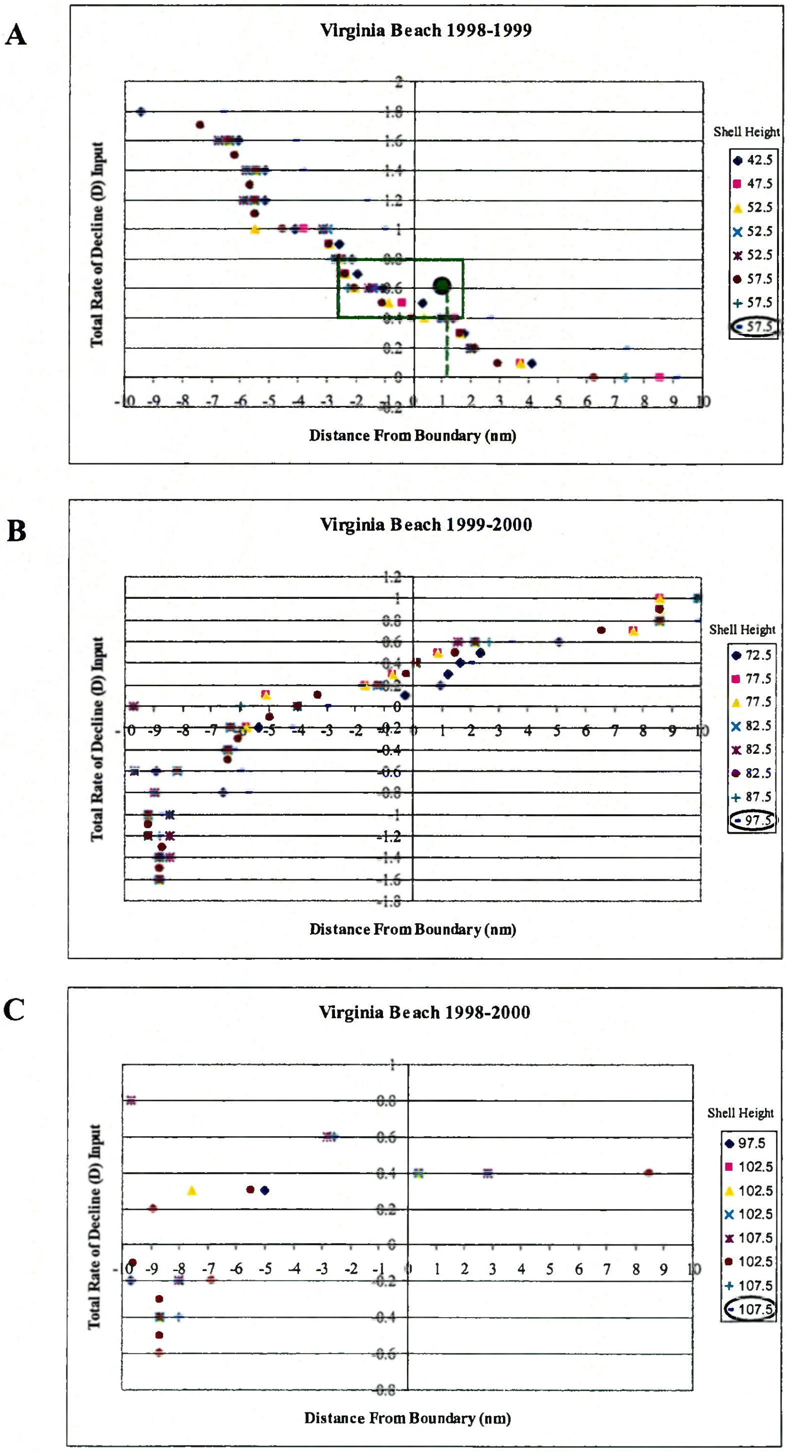

Figure 17. Sensitivity of Virginia Beach's mean effective boundary estimates to the input variables, D and size-cutoff. The circled sizes were the cutoffs for 1998, 1999, and 2000 used in the analysis.
(**A**) 1998-1999 (**B**) 1999-2000 (**C**) 1998-2000

Table 5. The original and adjusted values for the total area and biomass effectively protected by the mid-Atlantic closures in 1998.

Adjustments of Mid-Atlantic Closed Areas and Biomass Estimates

Closed Area	Swept Area (nm^2)	Original Area (nm^2)	Adjusted Area (nm^2)	Area Difference (nm^2)	Area Difference (percent)
Hudson Canyon	0.0037057	1,466	1,480	14	1.0
Virginia Beach	0.0037057	422	345	-77	-18.2
	1998 mean CPUE (kg/tow)	**Original Biomass Estimate (kg)**	**Adjusted Biomass Estimate (kg)**	**Biomass Difference (kg)**	**Biomass Difference (percent)**
Hudson Canyon	14.2	5,635,814	5,689,635	53,821	1.0
Virginia Beach	27.6	3,138,836	2,566,110	-572,726	-18.2

After substitution of the adjusted area into the area-based biomass calculation formula, the original estimate of 5,635,814 kg of biomass in the HCSCA would be increased to 5,689,635 kg for a difference of 53,821 kg (Table 5). The original estimate of 3,138,836 kg of biomass in the VBCA would be decreased to 2,566,110 kg, for a difference of -572,726 kg. The total amount of biomass effectively protected by the mid-Atlantic closed areas in 1998 would be decreased by 626,547 kg after adjustment of the relevant boundaries by the appropriate mean effective boundary measure.

Discussion

The utilization of a rotational closed area system is at the forefront of sea scallop fishery management. It has been recognized by the NEFMC and other scientific investigators that, although already in use, these areas require monitoring and evaluation to document their effectiveness (Murray *et al.*, 1999; Murawski *et al.*, 2000). This study was conducted to determine how actual closed area boundaries affected the abundance and spatial distribution of the scallop stock in the mid-Atlantic bight, and the efficacy of the current closed area management with modern commercial scallop harvesting.

Analysis Procedure

In fisheries science there is often the conflict between ideal experimental design and realistic logistical consideration. Data from offshore research surveys are relatively sparse due to the high cost and difficult logistics involved. Unfortunately, the number of stations sampled is limited by these concerns, although more accurate estimates could be achieved with finer-scale surveys (SPDT, 1999). Large-scale, random-stratified sampling schemes may not accurately assess resource abundance for species such as the sea scallop, which is found in relatively small, high-density contagions (Naidu, 1991). Data for this study were collected from both a standard NMFS stratified-random survey, and finer-scale VIMS grid surveys, so analysis design was crucial. A geostatistical approach provided a means to analyze data from both survey methods.

A growing number of fisheries studies have used geostatistical techniques, such as kriging analysis, as alternative methods to assess the abundance and spatial distribution of shellfish stock biomass and density (Conan, 1985; Warren, 1998). There are inherent advantages of geostatistics (model-based inference) over conventional (design-based inference) statistics in this regard. The largest advantage is the circumvention of random sampling in order to avoid the spatial autocorrelation between samples (Conan, 1985; Orensanz *et al.*, 1991). With the technological advancements of and accessibility to modern computational devices, modern statistical theory shows that through the exploitation of the spatial autocorrelation instead of its avoidance, an unbiased result can be obtained regardless of the sampling strategy (Conan, 1985). This approach results in more precise estimators than the design-based sampling schemes (Orensanz *et al.*, 1991).

Kriging analysis provided the best analytical method for the comparison of data from the fine-scale surveys conducted by VIMS, and the earlier larger scale survey conducted by NMFS. The resulting CPUE estimates were generated at common geographic points that could then be tracked through time. In addition, the utilization of only those grid points with lower variance excluded potential artifacts of the kriging analysis, and provided estimates for only adequately sampled areas. Mean rates of decline were calculated for the inside and outside strata for each year. The mean of these two measures (regional mean) was then used as a cutoff for comparason to the declines calculated at each grid point. A grid point was assigned a 0 or 1 depending on if the point estimate of decline was lower or higher compared to the regional mean, resulting in a binary data set.

Probit regression analysis was the best method for fitting the binary data. The analysis calculated the inflection point of the expected logistic-type function. The distance between the inflection point and zero on the x-axis was interpreted as the distance between the mean position of the "effective boundary", and the original boundary. Finally, these measures were used to estimate the total area and biomass being effectively protected by the closure.

The most satisfying accomplishment of this study was begininng with only a theory, and then assembling a number of different analytical steps in the proper order to produce a method of analysis that can detect and track the temporal and spatial shifts in differential (fishing) mortality as a function of distance from (across) a boundary.

Pre-Closure (1996-1997)

A preliminary analysis of each closed area's regional size-frequency distribution and fishing effort revealed several interesting aspects pertaining to the condition of the resource and operation of the fishery. In 1996, it was evident that the fishery was operating under conditions of growth overfishing as indicated by the relatively low overall abundance, and narrow peak in the size-frequency distribution at 82.5 mm shell height. Scallops are partially recruited to commercial dredges at 70 mm shell height, and fully recruited at ~90 mm shell height or at approximately four years of age. This evidence suggests that the majority of scallops were being captured as soon as they became fully vulnerable to the gear and the cull size of the crew.

Growth overfishing forces the success of the fishery in the next season to be almost completely dependent on the success of the next year's recruiting class. This minimized the yield per recruit and spawning stock biomass. These observations were consistent with the results of other studies on the population dynamics of the sea scallop (Serchuck *et al.*, 1979) and the performance of commercial scallop fishing gear (Rudders *et al.* 2000, Brust and DuPaul. in press). In 1997, there was evidence that the relatively larger scallops (> 70 mm shell height) had been fished down, but areas with high concentrations of smaller scallops remained. It was the protection of these groups of scallops that prompted the mid-Atlantic closures in April 1998.

First Year Post-Closure (1998-1999)

With the implementation of the mid-Atlantic closed areas and no corresponding reduction in fishing effort (i.e. reduction in days-at-sea or number of boats fishing), a redirection and concentration of effort into the open areas was observed. By July 1998 (four months post-closure), there was already evidence of protection of the larger scallops from the comparison between the size-frequency distributions from stations inside and outside of the closed areas. This protection facilitated the beginning of a build-up in the yield per recruit and spawning stock biomass. This trend was evident only inside of the closed areas, since the scallop stock outside had been fished down by sustained high levels of fishing effort.

As expected, a gradient developed in the measures of mean CPUE between the strata at each closed area between 1998 and 1999, from higher in the core to lower in the outside. Specifically, the outside stratum at the HCSCA had rate of decline that was approximately four-times higher compared to the inside stratum. The outside stratum at the VBCA had a rate of decline that was approximately 11 times faster compared to the inside stratum. The VBCA core stratum actually showed a slight increase in abundance during this year, which could have only come from animals immigrating into this area from adjacent surroundings.

Protection of the scallop stock was also evident in the density contours of biomass. Between 1998 and 1999, the growth of the scallops inside of the closures far exceeded the amount of loss. The indices of mean biomass from the strata inside of the VBCA doubled, and increased by 50% in the strata in the HCSCA. On the other hand, outside of the VBCA, the loss was enough to offset any new growth and actually removed some of the standing stock in the region. Outside of HCSCA, there was marginal net growth at the end of the year. The large differences in the rates of decline of mean CPUE between the outside and inside strata of each closed area helped facilitate clear results in both the probit regression and sensitivity analyses.

Evidence of an effect of the closed area boundaries was detected in the probit regression analysis of the 1998-1999 data, and the trends were mixed between the closed areas. The mean effective boundary was estimated at 0.13 nm outside the HCSCA, and at 1.3 nm inside the VBCA. This may have been due to differential access to each closed area by boats fishing for other target species.

Second Year Post-Closure (1999-2000)

There was a large difference in the magnitude of declines in abundance from 1999 to 2000 between the two closed areas. The declines at the HCSCA followed the trend that would be expected with natural mortality operating both inside and outside, and fishing mortality operating outside. The declines at the HCSCA were marginal compared to the declines at the VBCA. The abundance declined by 54% and 55% for the core and outside strata respectively at the VBCA.

The density contours of biomass revealed the expansion of the southern bed and the re-formation of the northern bed in the HCSCA, and the disappearance of the southern bed in the VBCA during this year. The trends of increasing biomass continued at the HCSCA at the same rates as the previous year; however, this was not true at the VBCA. Substantial declines in biomass were observed in all three strata at the VBCA between 1999 and 2000.

Evidence of an effect of the closed area boundaries was detected in the probit regression analysis of the 1999-2000 HCSCA data. The mean effective boundary was estimated at 5.2 nm outside at the HCSCA. The mean effective boundary measure of the VBCA data was considered suspect, since the decline in abundance inside was close to the decline outside due to unknown removals. This subsequently produced questionable results with estimates outside of the sampled area. The difference in the results between the first and second years post-closure at the VBCA provided evidence that the model works better when the difference in the declines between strata is greater.

Cumulative Post-Closure (1998-2000)

After the first two years of mid-Atlantic closures, the largest cumulative decline in abundance at each closed area was in the outside stratum. The smallest cumulative decline in abundance at each closed area was in the inside stratum at the HCSCA, and the core stratum at the VBCA. The only stratum without a net gain in biomass was the HCSCA outside. Although, the yield per recruit and spawning stock biomass increased as a result of protection by the mid-Atlantic closed area boundaries, the levels attained were short of expectations based on the levels of biomass attained within the closed areas on Georges Bank. Although there are some fundamental differences between the Georges Bank and mid-Atlantic regions, such as circulation patterns, substrate type, and temperature, these results were most likely due to the regulations surrounding the implementation of the respective closed areas.

The closed areas on Georges Bank specifically prohibited "any fishing gear capable of retaining groundfish", or essentially, all mobile fishing gear. The mid-Atlantic closures prohibited only "fishing directed at scallops", and boats targeting other species, such as squid or flounder, were allowed to fish in these areas. Although these vessels were not targeting scallops, additional removals would have resulted as retained bycatch. Undersized scallops not retained by the crew would have also been redistributed, potentially impacting the large-scale spatial distribution of the scallop stock. In addition to these types of "non-targeted incidental removals", the large decline in abundance observed between 1999 and 2000 in the VBCA could have resulted from: large scale migrations due to non-random swimming movement, or a rate of natural mortality that was above the long-term average of 0.1 ($M > 0.1$).

Although, scallop swimming-behavior/movement has been documented in the literature (Dickie, 1955; Posgay, 1963; Caddy, 1968; Posgay, 1981; Parsons *et al.*, 1992; Stokesbury and Himmelman, 1996), its subsequent effect on the large-scale spatial distribution of a stock has not been well documented. Studies have shown that during relatively short time scales (4 months) the mean swimming distance was only 3.3 meters (Parsons *et al.*, 1992). Tagging studies conducted over extended time periods (2.5 – 5 years) have reported movements as far as 10 miles (Posgay, 1963; 1981). This scale of movement could easily result in animals moving from a protected area to a non-protected area, and *vice verse*. Posgay (1981) believed that the distance and direction that any individual sea scallop may swim at any given time is random, and that any net movement over time was probably the result of the strength and direction of the tidal currents.

In the second year post-closure, this process may have been amplified by the above average hurricane season activity. Some transport of scallops with the mid-Atlantic's bottom currents from the northeast to southwest may have resulted. Although it is clear that movement of scallops occurs, it is difficult to believe that these processes could be solely responsible for the large losses observed in a large geographic region. Another mechanism was probably involved. Natural mortality could have also significantly contributed to the observed losses; however, there was no evidence of increased "clapper" concentration in the survey catches to indicate that natural mortality was heightened during this time period.

Although swimming movement and natural mortality may play a role in the large-scale spatial distribution of the scallop stock, their effects should be relatively small. Therefore the effective boundary calculated in this analysis most likely resulted from the interaction of fishing mortality and possible immigration in each of the relevant strata. Since neither of the estimates of the mean effective boundary was 0, the null hypothesis was rejected. Additional research from other closed areas being used as fishery management tools needs to be performed before any serious changes should be implemented.

Conclusions

1. Based on the evidence from the size-frequency distributions, abundance indices, and biomass indices, the HCSCA provided good protection during the first two years of closure. The VBCA provided ideal protection during the first year post-closure; however, this pattern was diminished during the second year post-closure.

2. The only stratum evaluated without a net gain in biomass during the first two years of the closures was the HCSCA outside.

3. Evidence of an effect of the closed area boundaries was detected, and the best estimate of the mean distance of the effective boundary was 0.13 nm outside at Hudson Canyon, and 1.3 nm inside at Virginia Beach. Estimates were based on the first year post-closure.

4. The total area effectively protected by the mid-Atlantic closed areas would be reduced by 0.7% after adjustment of the boundaries by the appropriate mean effective measure. Therefore, the total area being effectively protected was not substantially different from the original area, and did not produce significant bias in the area-based biomass calculations used by the fishery's managers.

Proposed Future Research / Refinements

- Re-sampling of the same systematic grid of survey stations after the re-opening of the mid-Atlantic closed areas, and analysis with this assembled technique.

- Analysis of NMFS's VMS data from boats fishing for other species (if applicable) in the closed areas, and their landing slips or logbooks of scallop bycatch.

- Prudent sampling of abundance within a systematic grid before and after large episodic weather events, such as hurricanes, tropical storms, and nor'easters could provide information about the extent of stock movement (redistribution) associated with these events.

- Investigation into how the size, shape, location, and duration of closed areas jives with depth preferences of scallops, spawning concentrations, larval production, nursery areas, and enforcement.

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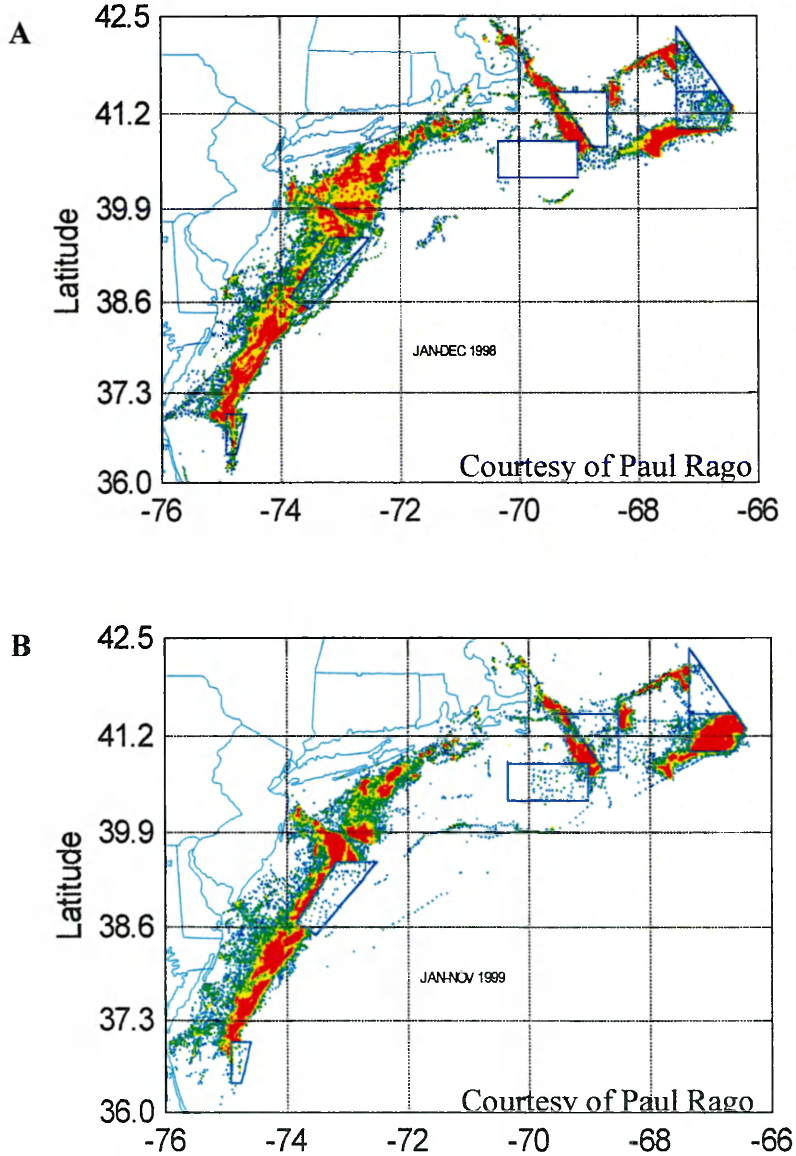
Appendix I



NMFS vessel monitoring system (VMS) records of commercial scallop boat positions. Coordinates were transmitted once per hour via satellite, and were partitioned into 1nm square grid cells. The number of hours per cell were summed over the time periods indicated, and represent the large-scale spatial distribution of fishing effort. The color gradient corresponds with high effort in red to low effort in green and transit in blue.

(**A**) Temporal composite of fishing effort from January-December 1998.

(**B**) Temporal composite of fishing effort from January-November 1999

Appendix II

Glossary of Key Terms

Abundance	number of scallops
Area	relative spatial scale description smaller than a region (e.g. a closed area is within a region)
Biomass	measure of shucked (processed) meat weight in units of kilograms
Common points	grid points with estimates with relatively low variance for each year evaluated
Cumulative	summation over time period of study (1998 – 2000)
Effective boundary	location where fishing mortality (F) ceases to have an effect on the abundance and distribution of scallops
First year post-closure	time period between 1998 - 1999
Region	relative spatial scale description larger than an area (e.g. the survey stations in and around the vicinity of the Hudson Canyon closed area are in the Hudson Canyon region)
Second year post-closure	time period between 1999 – 2000
Stratum / Strata	area designation based on aggregated common points

Appendix III

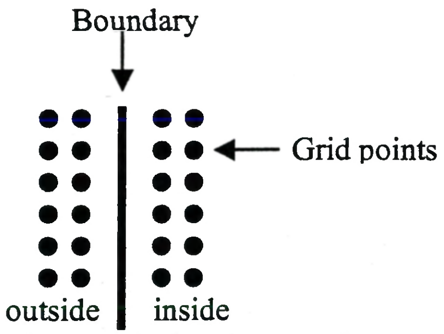
Conceptual Framework

Theory

If the closed area boundaries were solid walls extending from the ocean's surface down to the bottom, then a "hard-edge" effect would be expected in the response, because fishing boats could not enter the area and scallops could not leave; however, since no real physical boundaries exist, then a "soft-edge" effect would be expected. The question then becomes, how does one measure this?

Kriging Analysis

- create a static grid of sampling points on both sides of the closed area boundary



- use survey data and kriging analysis to track abundance at the same geographic points between years
- each grid point has a kriged abundance estimate and standard error for each year
- spatially analyze the changes in abundance at each grid point between years, relative to the boundaries
- the mechanisms governing the flux of scallops at each grid point must be considered
- if we grade the survey catch data by size between years, then we can eliminate recruitment as an input*

*graded survey catch data → then

N98 = Number of scallops in 1998 > 57.5 mm
N99 = Number of scallops in 1999 > 22.5 mm
N00 = Number of scallops in 2000 > 107.5 mm

Fluxes	Outside	Inside
Inputs	Immigration	Immigration
Removals	Emigration M F	Emigration M n/a

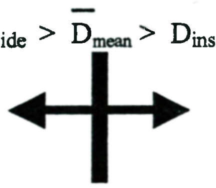
- after estimating the abundance at a point in successive years, the rate of decline

Total Rate of Decline (D) Model

$$D = -\ln (N_t / N_o)$$

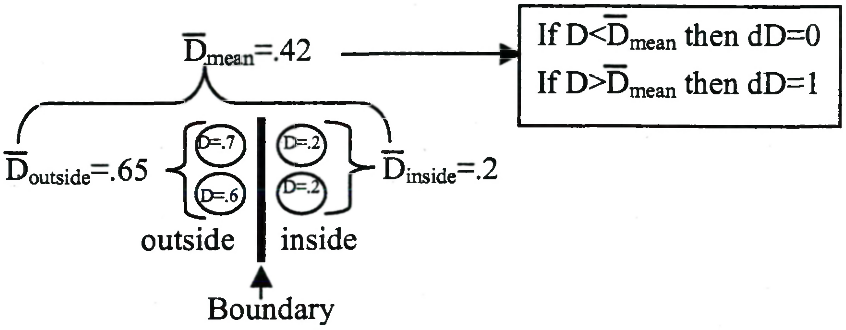
$$F + M = D_{outside} > \bar{D}_{mean} > D_{inside} = F + M$$

$F = ?$ $\qquad$ $F = 0$



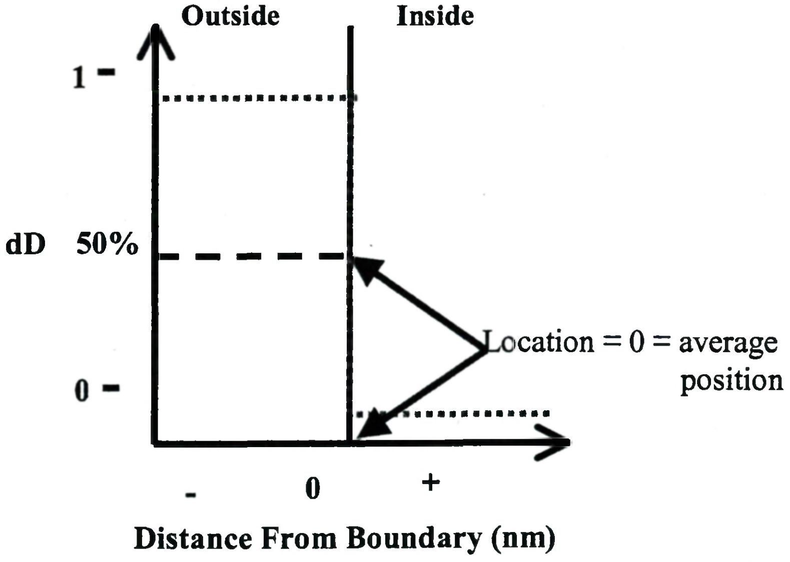
- a mean D is calculated for both the inside and outside groups of points, and then the mean of these two values is calculated and compared to the individual point estimates to convert the data into binary form

Convert data into binary form

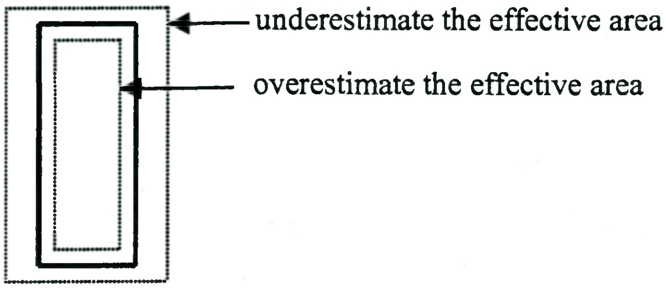


- the binary data is analyzed by probit regression analysis to find the inflection point of the expected logistic-type response. The x-coordinate of this point is the location of the mean effective boundary.

Probit Regression Analysis

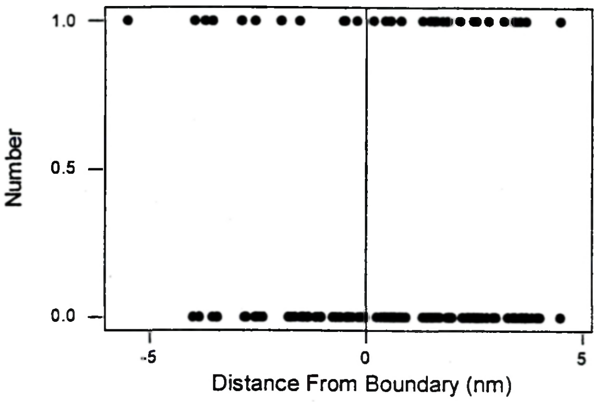


- take the measure of the mean effective boundary and adjust the original boundary by it. This will provide the total area effectively protected by the closure.



- the final step is to calculate the estimate of biomass contained in the adjusted total area.

Appendix IV



Probit Analysis

D=.755

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Distribution:  Normal

Response Information

Variable  Value       Count
NEWNUM98  1             107  (Event)
          0             119
          Total         226

Regression Table
                         Standard
Variable        Coef        Error         Z      P
Constant    -0.01615      0.08633     -0.19  0.852
DISTANCE    -0.12085      0.03252     -3.72  0.000
Natural
Response       0.000

Log-Likelihood = -149.157

Goodness-of-Fit Tests

Method                Chi-Square     DF       P
Pearson                  186.365    138   0.004
Deviance                 244.446    138   0.000

Tolerance Distribution

Parameter Estimates
                          Standard         95.0% Normal CI
Parameter    Estimate        Error       Lower        Upper
Location      -0.1336       0.7214     -1.5476       1.2804
Scale           8.275        2.226       4.884       14.021

Table of Percentiles
                          Standard         95.0% Fiducial CI
  Percent  Percentile        Error       Lower        Upper
        1     19.1166       5.0689     12.5787      40.0293
        2     16.8609       4.4686     11.0887      35.2699
        3     15.4297       4.0888     10.1413      32.2522
        4     14.3531       3.8038      9.4272      29.9835
        5     13.4773       3.5725      8.8453      28.1391
        6     12.7319       3.3761      8.3490      26.5703
        7     12.0783       3.2043      7.9131      25.1955
        8     11.4932       3.0509      7.5219      23.9654
        9     10.9609       2.9117      7.1654      22.8474
       10     10.4710       2.7840      6.8366      21.8190
       20      6.8307       1.8529      4.3562      14.2137
       30      4.2057       1.2291      2.4674       8.8301
       40      1.9628       0.8114      0.5824       4.5011
       50     -0.1336       0.7214     -2.0422       1.3175
       60     -2.2300       1.0094     -5.8150      -0.7177
       70     -4.4730       1.5022    -10.3256      -2.4211
       80     -7.0979       2.1518    -15.7645      -4.2548
       90    -10.7383       3.0941    -23.3925      -6.7124
       91    -11.2282       3.2226    -24.4224      -7.0397
       92    -11.7604       3.3625    -25.5419      -7.3947
       93    -12.3456       3.5166    -26.7735      -7.7844
       94    -12.9992       3.6891    -28.1496      -8.2190
       95    -13.7446       3.8862    -29.7198      -8.7139
       96    -14.6203       4.1181    -31.5654      -9.2945
       97    -15.6969       4.4038    -33.8355     -10.0073
       98    -17.1281       4.7844    -36.8546     -10.9533
       99    -19.3838       5.3855    -41.6156     -12.4417
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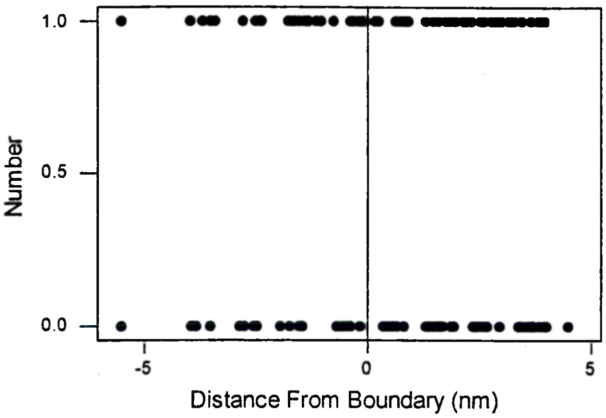

Probit Analysis

D = .215

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Distribution:  Normal

Response Information

Variable  Value        Count
NEWNUM99  1               74   (Event)
          0              152
          Total          226

Regression Table
                             Standard
Variable          Coef          Error         Z      P
Constant      -0.42573        0.08753     -4.86  0.000
DISTANCE      -0.08248        0.03262     -2.53  0.011
Natural
Response         0.000

Log-Likelihood = -139.684

Goodness-of-Fit Tests

Method                    Chi-Square     DF        P
Pearson                      183.104    138    0.006
Deviance                     221.923    138    0.000

Tolerance Distribution

Parameter Estimates
                              Standard         95.0% Normal CI
Parameter     Estimate           Error         Lower       Upper
Location        -5.162           2.367        -9.801      -0.523
Scale           12.125           4.795         5.585      26.320

Table of Percentiles
                              Standard         95.0% Fiducial CI
  Percent   Percentile           Error         Lower       Upper
        1      23.0444          9.0994       12.9442    101.9229
        2      19.7392          7.8027       11.0617     87.2479
        3      17.6422          6.9820        9.8634     77.9411
        4      16.0647          6.3660        8.9590     70.9428
        5      14.7815          5.8663        8.2209     65.2528
        6      13.6893          5.4420        7.5904     60.4119
        7      12.7316          5.0711        7.0354     56.1695
        8      11.8742          4.7400        6.5363     52.3732
        9      11.0944          4.4399        6.0803     48.9227
       10      10.3765          4.1648        5.6583     45.7487
       20       5.0425          2.1913        2.3681     22.3178
       30       1.1963          1.1308       -1.1109      6.5290
       40      -2.0901          1.3908      -11.0360   -0.009494
       50      -5.1619          2.3668      -24.1154     -2.3181
       60      -8.2337          3.4958      -37.5930     -4.2287
       70     -11.5201          4.7507      -52.1147     -6.1706
       80     -15.3663          6.2427      -69.1577     -8.3953
       90     -20.7004          8.3292      -92.8286    -11.4455
       91     -21.4182          8.6109      -96.0158    -11.8543
       92     -22.1980          8.9170      -99.4785    -12.2980
       93     -23.0554          9.2538     -103.2864    -12.7856
       94     -24.0131          9.6301     -107.5395    -13.3298
       95     -25.1053         10.0595     -112.3907    -13.9501
       96     -26.3885         10.5643     -118.0907    -14.6782
       97     -27.9660         11.1852     -125.0988    -15.5728
       98     -30.0630         12.0110     -134.4158    -16.7610
       99     -33.3682         13.3135     -149.1023    -18.6320
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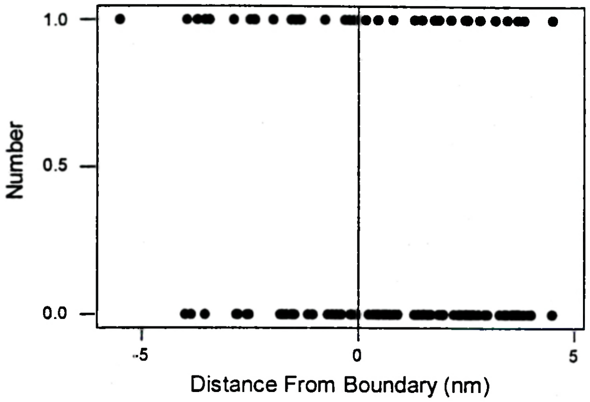

Probit Analysis

D = .485

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Distribution:  Normal

Response Information

Variable  Value        Count
NEWNUM98  1              101  (Event)
          0              125
          Total          226

Regression Table
                       Standard
Variable         Coef     Error         Z      P
Constant     -0.05655   0.08913     -0.63  0.526
DISTANCE     -0.19364   0.03439     -5.63  0.000
Natural
Response        0.000

Log-Likelihood = -138.101

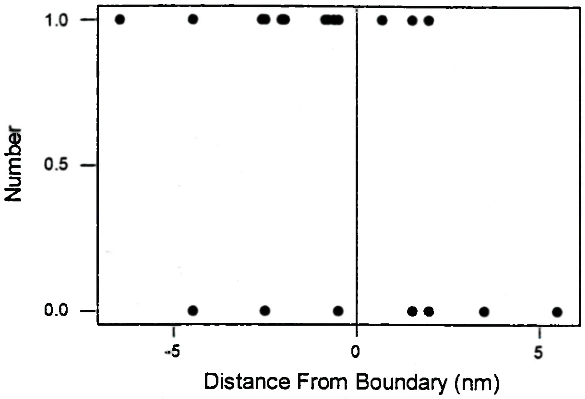
Goodness-of-Fit Tests

Method                 Chi-Square     DF       P
Pearson                   165.163    138   0.057
Deviance                  209.056    138   0.000

Tolerance Distribution

Parameter Estimates
                        Standard        95.0% Normal CI
Parameter   Estimate       Error        Lower       Upper
Location     -0.2920      0.4723      -1.2177      0.6336
Scale         5.1642      0.9172       3.6461      7.3146

Table of Percentiles
                        Standard        95.0% Fiducial CI
 Percent  Percentile       Error        Lower       Upper
       1     11.7218      2.0509       8.7143     17.8350
       2     10.3140      1.8079       7.6562     15.6893
       3      9.4208      1.6548       6.9828     14.3301
       4      8.7489      1.5403       6.4747     13.3091
       5      8.2024      1.4478       6.0602     12.4798
       6      7.7372      1.3696       5.7064     11.7748
       7      7.3293      1.3015       5.3954     11.1577
       8      6.9641      1.2408       5.1160     10.6059
       9      6.6319      1.1861       4.8612     10.1048
      10      6.3262      1.1361       4.6258      9.6444
      20      4.0543      0.7828       2.8399      6.2599
      30      2.4161      0.5709       1.4621      3.9095
      40      1.0163      0.4637       0.1206      2.0654
      50     -0.2920      0.4723      -1.3886      0.5971
      60     -1.6004      0.5823      -3.1347     -0.6343
      70     -3.0002      0.7635      -5.1433     -1.8113
      80     -4.6384      1.0125      -7.5719     -3.1108
      90     -6.9103      1.3852     -10.9958     -4.8573
      91     -7.2160      1.4366     -11.4591     -5.0898
      92     -7.5482      1.4927     -11.9629     -5.3419
      93     -7.9134      1.5547     -12.5173     -5.6186
      94     -8.3213      1.6241     -13.1371     -5.9271
      95     -8.7864      1.7036     -13.8445     -6.2784
      96     -9.3330      1.7974     -14.6764     -6.6903
      97    -10.0049      1.9131     -15.7000     -7.1958
      98    -10.8981      2.0675     -17.0619     -7.8666
      99    -12.3058      2.3121     -19.2107     -8.9215
```



Probit Analysis

D = .636

```
Distribution:  Normal

Response Information

Variable  Value       Count
NEWNUM98  1              45  (Event)
          0              32
          Total          77

Regression Table
                           Standard
Variable        Coef          Error           Z      P
Constant      0.3833         0.1660        2.31  0.021
DISTANCE    -0.28831        0.06855       -4.21  0.000
Natural
Response       0.000

Log-Likelihood = -40.765

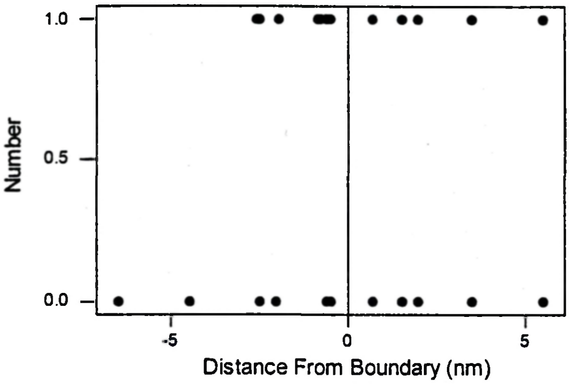
Goodness-of-Fit Tests

Method               Chi-Square     DF       P
Pearson                  27.147     14   0.018
Deviance                 33.938     14   0.002

Tolerance Distribution

Parameter Estimates
                           Standard        95.0% Normal CI
Parameter   Estimate          Error        Lower        Upper
Location      1.3293         0.5785       0.1956       2.4631
Scale         3.4684         0.8247       2.1764       5.5275

Table of Percentiles
                           Standard       95.0% Fiducial CI
 Percent  Percentile          Error        Lower        Upper
       1      9.3981         2.1545       6.4720      17.1824
       2      8.4526         1.9381       5.8103      15.4285
       3      7.8527         1.8019       5.3883      14.3178
       4      7.4015         1.7001       5.0694      13.4838
       5      7.0344         1.6179       4.8090      12.8064
       6      6.7220         1.5483       4.5864      12.2307
       7      6.4480         1.4877       4.3905      11.7267
       8      6.2027         1.4337       4.2144      11.2761
       9      5.9796         1.3850       4.0536      10.8669
      10      5.7743         1.3404       3.9050      10.4909
      20      4.2484         1.0212       2.7752       7.7223
      30      3.1482         0.8141       1.9104       5.7760
      40      2.2080         0.6682       1.0997       4.1848
      50      1.3293         0.5785       0.2243       2.8152
      60      0.4506         0.5568      -0.8375       1.6319
      70     -0.4895         0.6168      -2.2059       0.5984
      80     -1.5898         0.7680      -4.0199      -0.3987
      90     -3.1157         1.0520      -6.7116      -1.6054
      91     -3.3210         1.0938      -7.0817      -1.7599
      92     -3.5441         1.1398      -7.4852      -1.9264
      93     -3.7894         1.1911      -7.9302      -2.1081
      94     -4.0633         1.2491      -8.4287      -2.3094
      95     -4.3758         1.3161      -8.9991      -2.5373
      96     -4.7428         1.3957      -9.6711      -2.8032
      97     -5.1941         1.4948     -10.4996      -3.1275
      98     -5.7940         1.6281     -11.6044      -3.5554
      99     -6.7395         1.8410     -13.3515      -4.2240
```



Probit Analysis

D=.670

```
Distribution:  Normal

Response Information

Variable   Value       Count
NEWNUM99   1             34   (Event)
           0             43
           Total         77

Regression Table
                           Standard
Variable         Coef         Error         Z      P
Constant      -0.1458        0.1449     -1.01  0.314
DISTANCE     -0.00289       0.05050     -0.06  0.954
Natural
Response        0.000

Log-Likelihood = -52.844

Goodness-of-Fit Tests

Method               Chi-Square     DF        P
Pearson                  25.428     14    0.031
Deviance                 31.286     14    0.005

Tolerance Distribution

Parameter Estimates
                             Standard          95.0% Normal CI
Parameter    Estimate           Error         Lower         Upper
Location        -50.5           890.1       -1795.1        1694.2
Scale             346            6045             0    2.5819E+17

Table of Percentiles
                             Standard          95.0% Fiducial CI
 Percent   Percentile           Error         Lower         Upper
       1     754.4411        13175.17             *             *
       2     660.1240        11527.20             *             *
       3     600.2829        10481.61             *             *
       4     555.2667        9695.064             *             *
       5     518.6495        9055.268             *             *
       6     487.4825        8510.702             *             *
       7     460.1552        8033.225             *             *
       8     435.6868        7605.703             *             *
       9     413.4338        7216.889             *             *
      10     392.9499        6858.986             *             *
      20     240.7375        4199.522             *             *
      30     130.9817        2282.026             *             *
      40      37.1994        644.7578             *             *
      50     -50.4567        890.1352             *             *
      60    -138.1127        2420.858             *             *
      70    -231.8951        4059.293             *             *
      80    -341.6509        5976.938             *             *
      90    -493.8633        8636.452             *             *
      91    -514.3472        8994.359             *             *
      92    -536.6002        9383.175             *             *
      93    -561.0686        9810.701             *             *
      94    -588.3959        10288.18             *             *
      95    -619.5629        10832.75             *             *
      96    -656.1800        11472.55             *             *
      97    -701.1962        12259.10             *             *
      98    -761.0374        13304.68             *             *
      99    -855.3544        14952.66             *             *
```

Vita

John David Lange Jr. (a.k.a. wolf)

Born in Richmond, Virginia on February 26, 1971. Graduated from Kempsville High School in Virginia Beach, Virginia in June 1989. Graduated from the University of New Hampshire, *cum laude*, with a B.S. in Marine Biology in December 1997. Entered the M.S. program in Fisheries Science at the Virginia Institute of Marine Science, College of William and Mary in August 1998.