2002

Estimating Commercial Scallop Dredge Efficiency through Vessel Tracking, Catch Data, and Depletion Models

Todd Gedamke
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ESTIMATING COMMERCIAL SCALLOP DREDGE EFFICIENCY THROUGH VESSEL TRACKING, CATCH DATA, AND DEPLETION MODELS

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A Thesis
Presented to
The Faculty of the School of Marine Science
The College of William and Mary
In Partial Fulfillment
Of the Requirements for the Degree of
Master of Science

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by
Todd Gedamke
2002
APPROVAL SHEET

This thesis is submitted in partial fulfillment of
the requirements for the degree of
Master of Science

Todd Gedamke

Approved, January 2002

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# TABLE OF CONTENTS

ACKNOWLEDGEMENTS .............................................................................................................. v

LIST OF TABLES ........................................................................................................................ vi

LIST OF FIGURES ........................................................................................................................ vii

ABSTRACT ......................................................................................................................................... ix

INTRODUCTION ............................................................................................................................... 2

THE SCALLOP FISHERY ..................................................................................................................... 3

TARGET SPECIES/LIFE HISTORY ................................................................................................. 4

MANAGEMENT IN THE SCALLOP FISHERY ................................................................................ 4

CURRENT STOCK STATUS ............................................................................................................. 7

GEORGES BANK CLOSED AREA II EXPERIMENTAL FISHERY .................................................. 8

OBJECTIVES/HYPOTHESIS ES ........................................................................................................ 13

MATERIALS AND METHODS ........................................................................................................... 14

GENERAL OBSERVATIONS OF FLEET DYNAMICS ................................................................... 17

COMMERCIAL CPUE DECLINES ...................................................................................................... 20

THEORETICAL FRAMEWORK—DELURY MODEL ......................................................................... 20

DELURY MODEL ASSUMPTIONS ...................................................................................................... 25

BUILDING THE MODEL .................................................................................................................. 26

STANDARDIZING RAW DATA AND DEFINING UNITS OF EFFORT .............................................. 26

GRID ANALYSIS AND SATISFYING MODEL ASSUMPTIONS ....................................................... 27

PRODUCTION CONSTRAINT AND R² MODEL OPTIONS ............................................................... 28

PARAMETER ESTIMATION—MAXIMUM LIKELIHOOD ANALYSIS ............................................... 30

RESULTS ........................................................................................................................................ 33

SENSITIVITY ANALYSIS ................................................................................................................. 39

DISCUSSION .................................................................................................................................. 48

SATISFYING ASSUMPTIONS ........................................................................................................... 50

MODEL INPUTS AND SENSITIVITY .............................................................................................. 53

SURVEY CPUE DECLINES ................................................................................................................ 55

THEORETICAL FRAMEWORK—INDEX REMOVAL METHOD ....................................................... 55

METHODS ........................................................................................................................................ 60

RESULTS ......................................................................................................................................... 62

DISCUSSION .................................................................................................................................. 66

ASSUMPTIONS AND SENSITIVITY ................................................................................................. 70
ACKNOWLEDGEMENTS

Major Advisor—William DuPaul. For giving me the opportunity to attend VIMS, throwing me into the world of the commercial scallop fishery and paying my bills.

Committee Members—Andrew Applegate (NEFMC), John Hoenig, Jack Musick, Paul Rago (NMFS). I’m honored to have pulled together such a strong committee and must thank them all for their support and guidance throughout the process. A special mention is necessary to John Hoenig for teaching me that calculus can be my friend and to Paul and Andy for making the time to travel to VIMS for my qualifying exam and defense.

Sea Time, Sanity and Entertainment—Dave Rudders, Wolf Lange, Bob Carroll. One hurricane, six gales and some 140,000 scallops later they’re still my friends.

All the Advisory Services Staff—Special mention to Cheryl Teagle, Diane Roberts, and Barbara Kriete for getting me through the bureaucracy and generally making my life easier.

Statistics Lifeline—Rob Latour, Jim Kirkley, Rob Hicks. For explaining what John Hoenig was talking about and holding my hand and helping me through a world where math is the language of choice.

Computer Programming and Assistance—Chris Bonzek, Robert Hayhurst, Kevin Kiley, Pat Geer, Joe Cope. Chris showed me the power of SAS, Pat the power of Arcview, and everyone else helped bail me out of the trouble this created. Without their help my analysis wouldn’t have been nearly as comprehensive as it was.

Exam Moderators—Roger Mann, John Graves. For keeping the bloodletting to a minimum.

Vessel Captains and Crews—This project wouldn’t have been possible without the support of dozens of people we worked with at sea. They lived with us, fed us, some dressed up in diapers and drag for our entertainment and generally made brutal work bearable. A special mention is necessary to Charlie Quinn, the captain of the F/V Celtic for going above and beyond the call of duty to work with us, and for generally being a likeable guy. In addition, Dick Schaumberger volunteered to help out on one trip for the experience—I don’t think he planned on working a 28-hour shift.

Titleless Category—Mike Newman for listening to me. Mike McSherry (NMFS) for providing me with the VMS data. Kate Mansfield for being a good friend and writing coach. Research TAC set-aside for funding.

The Entire VIMS Community—Sometimes we take for granted how lucky we are to have an open academic environment that allows us to walk in to the offices of some of the best scientists in the field, to have a small supportive student body, and access to all the toys we need to do our work. To all that I’ve forgotten to specifically name that provided me with critical assistance along the way—Thanks!

My Family/My World—Rudy and Jason Gedamke. Everything! I’m lucky and I know it!
LIST OF TABLES

Table 1. Summary of sampled trips during the opening of GBCAI1I .........................15

Table 2. Initial least squares parameter estimates ...................................................38

Table 3. Linear least squares parameter estimates following production constraint correction. ........................................................................................................38

Table 4. Settings and results for a standard run of the model. .............................41
LIST OF FIGURES

Figure 1. Location of Georges Bank closed areas and study site. .........................10
Figure 2. Monthly distribution of fishing effort during the opening of GBCAII. .........................................................................................................................18
Figure 3. Kernel (95%) of reported VMS positions recorded during the entire opening of GBCAII. ..........................................................................................19
Figure 4. Standard form of the Leslie-Davis and DeLury models..........................23
Figure 5. Schematic of grid analysis ......................................................................27
Figure 6. Conceptual diagram of non-linear feedback relationship between CPUE and bottom time per hour of fishing ....................................................29
Figure 7. Conceptual diagram of model design for analysis of commercial CPUE declines ........................................................................................................32
Figure 8. Composite DeLury model for the entire re-opened area of GBCAII. .............................................................33
Figure 9. Grid analysis cells in GBCAII meeting criteria for effort (a.), sampled tows (b), and for both (c.). ..........................................................35
Figure 10. Location of cells that met grid analysis criteria, sampled tows used in the analysis, and cumulative effort for the opening.................36
Figure 11. CPUE declines in each cell analyzed. ..................................................37
Figure 12. CPUE declines in cells following production constraint correction ........40
Figure 13. Response of efficiency estimates to model radius settings .................42
Figure 14. Response of efficiency estimates to gear time on bottom per hour of fishing ........................................................................................................44
Figure 15. Response of efficiency estimates to R² and production constraint model options .................................................................46
Figure 16. Response of efficiency estimates to tow speed model input. ..........................47

Figure 17. Response of efficiency estimates to the combined effect of bottom
time and tow speed model inputs. .................................................................49

Figure 18. Location of survey and grid stations from the 1998 GBCAII
cooperative survey used in the kriging analysis. ...........................................57

Figure 19. Location of GBCAII 1998 cooperative survey stations re-
occupied at the end of the 1999 opening .....................................................58

Figure 20. Grid point used in kriging analysis of GBCAII survey stations ...............61

Figure 21. Semivariogram generated from the GBCAII 1998 cooperative
survey stations. .............................................................................................63

Figure 22. Results of 1998 cooperative survey kriging analysis. ..............................64

Figure 23. Results of kriging analysis from the 1998 cooperative survey
stations re-occupied at the end of the 1999 GBCAII opening. .......................65

Figure 24. Response of efficiency estimates to kriging settings and the
different grids used to generate CPUE means .............................................67

Figure 25. Response of efficiency estimates to total catch (or total removals)
input to model .................................................................................................68
ABSTRACT

As management in the U.S. commercial sea scallop fishery moves towards an area-based strategy, the ability to accurately convert dredge survey indices to absolute abundance becomes critical. Unfortunately, a wide range of dredge efficiency estimates exists, impeding managers’ ability to determine the appropriate quotas to maximize yield and net benefits. The opening of Georges Bank Closed Area II provided a unique opportunity to address this issue, to study a commercial fishing event and to estimate gear efficiency for the region.

During the five-month opening, nearly six million pounds of scallop meats were removed from the area and catch-per-unit effort data were collected from over 1,000 commercial tows. At the same time, the fine-scale distribution of fishing effort was recorded hourly by mandatory vessel monitoring systems. A spatial analysis of both catch and effort data was then performed to locate areas consistent with the DeLury model assumptions. Gear efficiency was estimated to be 45% utilizing a combined maximum likelihood analysis of CPUE declines in all suitable regions. Since estimates were derived from information from every vessel fishing in the area, a sensitivity analysis and review of fleet operations and model responses is presented. Estimates could range from 38% to 55% if fleet-wide vessel operations were significantly different than our results and at the extreme ends of possible values.

An additional independent estimate of efficiency was generated from survey stations that were re-occupied during the last few weeks of the opening. Kriging was used to determine mean catch rates from before and after the fishing event. The index-removal method was then applied comparing the change in catch rates to the total landings reported for the opening. Dredge efficiency was estimated to be 54% assuming that total removals from the area were equal to the reported landings. The possibility of additional losses to the area has been discussed, indicating that the results of this analysis also point toward an efficiency of near 50%.

The results of this study suggest that the 25% efficiency estimate used in calculations prior to the opening resulted in the overestimation of absolute biomass and the setting of a quota that clearly exceeded the target exploitation levels. In addition, the results of this study suggest that information from the vessel monitoring systems, now in use on many commercial fleets, can provide the fine scale spatial details necessary to successfully apply depletion models to open-ocean commercial fishing operations.
ESTIMATING COMMERCIAL SCALLOP DREDGE EFFICIENCY THROUGH VESSEL TRACKING, CATCH DATA, AND DEPLETION MODELS
INTRODUCTION

Commercial fishing on Georges Bank has evolved from the schooners and dory fleets of the past to the large-boat, high capital investment fisheries of the present. For decades fishermen have endured the harsh North Atlantic waters to work on one of the most productive fishing grounds in the world (Cohen et al., 1982; Sissenwine et al., 1984).

"There were some mighty adventures....in those days—deckloads of scallops, massive sets of fish in winter gales, huge 'rimracks' of the fishing gear...We repaired the gear, set it back into the heaving seas, basking in a momentary sense of pride, even heroism. And there was financial stability which the inshore man rarely sees" (Carey, 1999).

Unfortunately, stability was fleeting in the New England fisheries. Large distant-water fleets began to arrive from around the globe in the 1960's to harvest these highly productive waters. The days of "unlimited" resources were beginning to end. Stocks on Georges Bank began to decline and reflect the massive harvesting capabilities of a "new" technologically advanced fishing industry. In 1970, the International Commission for the Northwest Atlantic Fisheries recognized the potential impacts of overfishing on Georges Bank and through seasonal closures began an active area management strategy for northwest Atlantic groundfish (Murawski et al., 2000).
The science of fisheries management has evolved considerably since those first area closures, yet regulating the delicate balance between conservation, industry and the world's ever increasing demand for seafood has proven difficult. Over the past three decades additional management efforts, including year-round closures, have been implemented, but many stocks still remain at low levels in an overfished condition (Murawski et al., 2000). The Atlantic sea scallop (*Placopecten magellanicus*) fishery, however, has seen dramatic increases in biomass as a result of these year round closures and has generated cautious optimism for the use of a rotational area management strategy for the scallop fishery.

**THE SCALLOP FISHERY**

Georges Bank, including the areas closed to protect groundfish stocks, is the largest single scallop resource in the world (Caddy, 1989). The scallop fishery has been operating on these fishing grounds since the 1930’s and is currently the second most valuable fishery in the northeast U.S. (NEFSC, 2001) with an ex-vessel value of approximately $165 million in 2000 (NOAA, 2001). The commercial harvesting of scallops began fifty years earlier with the discovery of inshore scallop beds near Mt. Desert Island, Maine (Smith, 1891). Fishing efforts expanded to mid-Atlantic beds off Long Island in the 20's and then ten years later to the offshore beds of Georges Bank (Naidu, 1991).

Historical landings in the scallop fishery have exhibited the typical "boom and bust" pattern of many exploited stocks. Vessels have fished either the Mid-Atlantic or Georges Bank in response to the relative resource abundances in each region (Murawski et al.,
2000). Since 1953, an average of around 10,000 metric tons of meats have been landed with a peak occurring in 1990 when 17,500 metric tons (39 million pounds), worth $149 million was harvested (NEFMC, 1998; Serchuk et al., 1979; NMFS, 2000). Landings dropped to below 7,000 mt (15 million lbs.) in the early 90's, and only in the past few years have climbed back above the 10,000 mt (22 million lbs.) mark (NEFMC, 1999). In 1999 and 2000 the effects of the closed area openings were evident with landings exceeding 20 million pounds for the first time since 1992 (SPDT, 2000; NOAA, 2001).

In 1999, the commercial scallop fleet consisted of 290 permitted vessels with 213 full-time boats. Vessels today are generally large—sixty to one hundred feet—and fish primarily using a New Bedford style scallop dredge (NEFSC, 2001). Vessels will typically tow two dredges, each 15 feet in width, at speeds of approximately 4-5 knots. Otter trawls are also utilized, however, dredge vessels have made up approximately 85-90% of the overall effort in recent years (Rago et al., 1997; NEFSC, 2001).

**TARGET SPECIES/LIFE HISTORY**

The target of this fishery, the Atlantic sea scallop (*Placopecten magellanicus*), is confined to the western North Atlantic continental shelf and ranges from the waters off Cape Hatteras, N.C., to Newfoundland (Posgay, 1957). Sea scallops are generally found at depths of 40 to 200 meters (22 to 110 fathoms) but can be found in less than 20 meters (11 fathoms) in the inshore waters north of Cape Cod (Naidu, 1991). The major commercially exploitable sea scallop beds exist in the shallow inshore waters of the Gulf
of Maine, and at depths of 40 to 100 meters (22 to 55 fathoms) on Georges Bank and the Mid-Atlantic region (NEFMC, 1982; Naidu, 1991).

Scallops develop quickly during the first few years of life, reaching sexual maturity at age two. Shell height increases as much as 80% between the ages of three and five, and meat weights increase close to 400% (Mullen and Moring, 1986; MacKenzie, 1979). Spawning primarily occurs in late September or early October (Posgay and Norman, 1958) with evidence of a semi-annual spawning cycle in the Mid-Atlantic region (DuPaul et al., 1989a). The reproductive capacity of the stocks are driven by individuals older than age four (NEFSC, 1997; Serchuck et al., 1979) which may each produce up to 270 million eggs (Langton et al., 1987). Eggs and larvae are planktonic following the typical molluscan developmental stages and remain in the water column for four to six weeks before settling to the bottom (Culliney, 1974).

MANAGEMENT IN THE SCALLOP FISHERY

The life history traits of the sea scallop, specifically fast growth rates and quick maturation, should allow scallops to respond quickly to regulatory measures and recover quickly from population declines. The first federal attempts at managing the sea scallop fishery began in 1982 with the development of the Atlantic Sea Scallop Fishery Management Plan (FMP). This plan had four objectives (Federal Register, 1996):

- restore adult stock abundance and age distribution,
- increase yield-per-recruit for each stock,
- evaluate plans’ research, development, and enforcement costs,
- minimize adverse environmental impacts on sea scallops.
For the first 12 years of regulations, a minimum shell height and maximum average meat counts were implemented in an attempt to control the age at entry into the fishery and maximize yield per recruit. This measure proved to be difficult to enforce and ineffective due to commercial fishing practices (Kirkley and DuPaul, 1989) and compliance problems (DuPaul et al., 1989b; DuPaul, et al., 1990).

Despite these management efforts, landings remained highly variable. Periods of peak landings were followed by long declines indicating that the maximum sustainable yield (MSY) of scallop stocks was exceeded on at least three occasions (NEFMC, 1999). Historically, it appears that scallop stocks have been subject to severe growth overfishing. Previous management measures attempting to improve yield per recruit have been ineffective because of high exploitation rates and the problem of compliance (Murawski et al., 2000).

In 1994, Amendment 4 to the FMP created a limited access fishery controlled by gradually reducing days-at-sea (DAS) restrictions to address high levels of effort, chronic fishing mortality levels well above $F_{\text{max}}$ and the fisheries' reliance on a single year class (NEFMC, 1993). Gear restrictions including maximum overall width and minimum ring and mesh sizes were also established to reduce the harvest of small scallops. Additional restrictions of maximum crew size and allotted days-at-sea were intended to reduce overall effort and harvesting capabilities.
CURRENT STOCK STATUS

A recent analysis of the stock, conducted by the Stock Assessment Review Committee (SARC), however, indicates a reason for cautious optimism (NEFSC, 2001). Biomass indices for both the Mid-Atlantic and Georges Bank are at record highs since 1982 and above or near their target reference points. According to the biological benchmarks established following the Sustainable Fisheries Act (SFA), biomass on Georges Bank appears to be just above $B_{\text{msy}}$ and just below $B_{\text{msy}}$ in the Mid-Atlantic. Although there is uncertainty in the estimates, both regions are within 15% of $B_{\text{msy}}$ and well above the minimum 25% biomass threshold.

Reductions in fishing mortality mandated by the SFA are also occurring in both resource areas. The $F$ levels of over 1.0 seen on Georges Bank in 1993 were reduced to an estimated 0.14 for the 1999 season. Fishing mortality for the Mid-Atlantic stock was also reduced from 0.81 in 1996 to 0.43 in 1999. All estimates for the Mid-Atlantic, however were still above the $F_{\text{max}}$ of 0.24 indicating that some areas are still subject to overexploitation (NEFSC, 2001).

The rapid recovery of scallop stocks observed in the Georges Bank closed areas supports the evidence of historical growth overfishing and reinforces the validity of existing estimates of population parameters (rates of growth and natural mortality particularly) for the fishery (Murawski et al., 2000). In the closed areas, scallops were successfully protected from exploitation during their exponential growth phase and cohort yields were maximized more effectively than from other previous management efforts. The
information gathered from the Georges Bank closed areas, the observed biomass
recovery, and the appearance of abundant small scallops in parts of the Mid-Atlantic
prompted managers to close two additional areas off Virginia Beach and New Jersey in
April of 1998.

GEORGES BANK CLOSED AREA II EXPERIMENTAL FISHERY

As more grounds were closed and word spread through the industry of the "large piles of
scallops" in the Georges Bank closed areas, fishing groups began lobbying for access to
these areas. Managers were faced with the task of collecting enough information to
justify framework adjustments to both the groundfish and scallop FMP's before access to
the closed areas would be allowed. Specifically, three biological areas of concern were
identified (from Murawski et al., 2000):

- The rate and spatial/temporal variability of groundfish by-catch in scallop
dredges;
- Potential for habitat destruction by sea-scallop dredges, in areas deemed
essential for finfish and scallop recruitment;
- The overfished status of the sea-scallop resource and the need to reduce
fishing mortality of the resource as a whole.

An industry-government partnership was initiated to study the abundance and spatial
distribution of scallops, the by-catch rates of groundfish, and the potential impacts on
essential fish habitat. This cooperative survey involved participants from the Center for
Marine Science and Technology of the University of Massachusetts—Dartmouth, the
Virginia Institute of Marine Science (VIMS) of the College of William and Mary, the
Fisheries Survival Fund of New Bedford, Massachusetts and the National Marine
Fisheries Service (NMFS). During the summers of 1998 and 1999, as part of this cooperative program, an intensive fine-scale grid survey was conducted with commercial fishing vessels.

The results of this study provided managers with enough information to develop and approve Framework Adjustment 11 to the Scallop FMP and Framework Adjustment 29 to the Northeast Multi-species FMP. These framework adjustments allowed scallop fisherman access to Georges Bank Closed Area II (GBCAII) as part of an experimental fishery program on June 15, 1999 (Figure 1). A scallop total allowable catch (TAC) was set at near 10 million lbs. and a yellowtail flounder bycatch TAC was set at 850,000 lbs. In five months, almost 6 million lbs. of large scallop meats were harvested before the yellowtail TAC was reached on November 12, 1999. This experimental fishery was successful in providing an economic boost to the scallop industry and benefited management by redirecting significant amounts of effort from the overexploited open areas. Further benefits for reducing mortality in other areas were also achieved by charging ten days-at-sea for trips that averaged four to six days.

The potential management applications are clear, however, there is still doubt as to whether the models used in Framework Adjustment 11 calculated absolute biomass correctly and set TAC's appropriately for the opening. Even with accurate indices of biomass from the cooperative survey, the translation of this information into absolute values was difficult. Three different models estimated dredge efficiency between 16% and 40% and left managers with TAC estimates that ranged from 6 million to 15 million
FIGURE 1. Location of Georges Bank closed areas and study site (NLCA is Nantucket Lightship Closed Area, GBCAI is Georges Bank Closed Area 1, and GBCAII is Georges Bank Closed Area 2). The southern section of GBCAII which was reopened to fishing has been highlighted.
pounds. Agreeing on a suitable efficiency estimate proved difficult and an intermediate value of 25% was chosen and translated to the TAC for the opening (NEFMC, 1999). A preliminary look at CPUE declines from vessel monitoring systems (VMS) and landings data after the 1999 opening, however suggested that efficiency was underestimated and the resulting biomass estimates and TAC were too high (Rago et al., 2000; SPDT, 2000).

As the management of the commercial scallop industry increasingly uses area management strategies, the accuracy of and confidence of biomass estimates is critical. For a successful closed area opening, accurate biomass calculations must allow TAC’s and exploitation rates to be carefully controlled to maximize yield and net benefits. The success of an area-based strategy using TAC’s and local F targets hinges on these calculations, along with an understanding and quantification of the dynamics of the commercial scallop fleet and the ability to develop predictive models for long term planning.

The depletion of scallop stocks in GBCAII provided a unique opportunity to address these issues, to study a large-scale commercial opening and also to independently estimate operational, commercial dredge efficiency for this region. In most cases data from this type of open-ocean commercial fishing operation would not meet the assumptions of many depletion models and lack the spatial details on effort and resource distribution to provide reasonable results. In our case however, the opening of GBCAII
provides us with:

- A high density closed system—a sessile target species in an area with virtually no fishing mortality for 5 years;
- Spatial distribution of resource—*R/V Albatross* and cooperative survey provides fine-scale indices for the distribution and length-frequencies of scallops throughout the study area;
- Spatial distribution of effort—VMS systems, required beginning in May 1998 provide hourly positions of every vessel in the fleet;
- Catch data—vessels were constrained by a 10,000 lb. possession limit and landings for each trip were recorded.

We were presented with the rare opportunity to track the massive effort of the commercial scallop fleet depleting a high-density and well-documented closed population. Only a few published studies have had the opportunity to combine both commercial and research data in this fashion (Clausen et al., 1992), to study commercial fishing on a previously unexploited area (Clarke and Yoshimoto, 1990), to apply depletion models to large-scale events (Lasta and Iribarne, 1997; Currie and Parry, 1999) or in open-ocean conditions (Joll and Penn, 1990). The wealth of information surrounding the opening of GBCAI created an opportunity for one of the largest open-ocean depletion studies to date.
**OBJECTIVES**

The goals of the study were to:

1) Determine changes in commercial catch per unit effort (CPUE) and changes in the length frequency distribution of sea scallops over the course of the opening.

2) Estimate changes in sea scallop abundance (using information listed in goal 1), by re-occupying pre-opening survey stations and tracking effort from vessel monitoring systems.

3) Use information from goals 1 and 2 to calculate commercial catchability coefficients (q), fine-scale exploitation rates, and ultimately gear efficiency.

4) To compare results of this study to the projections that formed the basis of Framework Adjustment 11 to the sea scallop FMP.

**HYPOTHESES**

$H_1 =$ There will be no significant change in catch-per-unit effort during the course of the closed area II opening

$H_2 =$ There will be no significant difference between the results of this study and the projections in Framework Adjustment 11 to the sea scallop FMP.
MATERIALS AND METHODS

The study consisted of eight trips conducted between the opening day of GBCAII on June 15th, 1999 until the closure of the area on November 12th, 1999. During this time two scientists worked onboard seven different commercial vessels: F/V Celtic, F/V Tradition, F/V Mary Anne, F/V Alpha Omega II, F/V Endeavor, F/V Barbara Anne, and the F/V Heritage. Trip length ranged from 4.5 to 12.8 days, for a total of 72 days at sea or 144 scientist days at sea (Table 1). Vessels made an average of 140 tows per trip (ranging from 38 to 267 tows) and fished for an average of 8.9 days per trip (ranging from 2.8 to 11.1 days) to reach their possession limit of 13,000 pounds. Vessels participating in the research program were compensated with an exemption from the 10,000 lbs. possession limit and allowed to land a total of 13,000 lbs.

During the five-month opening, position, catch, and swept area information was obtained for 1,042 commercial tows on the eight research trips. Length-frequency distribution data from both scallops and bycatch species was collected from 558 of these tows. Vessels not participating in the research TAC set-aside project, submitted additional information from nearly 600 tows, providing us with information from a total of over 1,600 tows. During the last six weeks of the opening, 84 survey and grid stations from
Table 1. Summary of sampled trips during the opening of GBCAII.

<table>
<thead>
<tr>
<th>Trip</th>
<th>Vessel</th>
<th>Start Date</th>
<th>Trip Duration (Days)</th>
<th>Total Number of Tows</th>
<th>Mean Bottom Time (minutes)/Hour of Fishing</th>
<th>Mean Tow Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Alpha Omega</td>
<td>June 15</td>
<td>6</td>
<td>82</td>
<td>44.6</td>
<td>4.3</td>
</tr>
<tr>
<td>2</td>
<td>Endeavor</td>
<td>June 22</td>
<td>4.5</td>
<td>38</td>
<td>20.2</td>
<td>4.8</td>
</tr>
<tr>
<td>3</td>
<td>Mary Anne</td>
<td>July 13</td>
<td>9.9</td>
<td>132*</td>
<td>38.0</td>
<td>4.7</td>
</tr>
<tr>
<td>4</td>
<td>Barbara Ann</td>
<td>July 24</td>
<td>6.8</td>
<td>93</td>
<td>48.3</td>
<td>4.9</td>
</tr>
<tr>
<td>5</td>
<td>Heritage</td>
<td>Aug. 16</td>
<td>8.2</td>
<td>116</td>
<td>49.2</td>
<td>5.0</td>
</tr>
<tr>
<td>6</td>
<td>Celtic</td>
<td>Sept. 25</td>
<td>11.3</td>
<td>209</td>
<td>47.0</td>
<td>5.4</td>
</tr>
<tr>
<td>7</td>
<td>Celtic</td>
<td>Oct. 13</td>
<td>12.8</td>
<td>267</td>
<td>42.0</td>
<td>5.1</td>
</tr>
<tr>
<td>8</td>
<td>Tradition</td>
<td>Nov. 2</td>
<td>12.0</td>
<td>189</td>
<td>47.2</td>
<td>5.0</td>
</tr>
</tbody>
</table>

*The F/V Mary Anne lost a dredge and fished for 97 tows with only one 15 ft. dredge.
the 1998 industry survey were reoccupied. Sixty-four of these stations were sampled onboard the same vessel (F/V Celtic) that conducted the original industry survey providing a valuable endpoint to the GBCAII experimental fishery data set. All data were entered into a Microsoft Access® database, which was specifically designed for the VIMS scallop research program to be compatible with the NMFS survey database.

The spatial and temporal distribution of fishing effort during the opening was determined from satellite positioning data obtained from the NMFS. Vessel monitoring systems (VMS) have been in place since 1998 and provide a time stamped position and vessel identifying number for every vessel in the fleet. We were provided with a data set that contained a position, date, time, vessel speed and time elapsed since the last transmission. From this information, we were able to eliminate hits from vessels that were steaming in and out of the area (vessel speed of greater than 5.5 knots) and also potentially faulty information from vessels that had not reported a position for over 12 hours. A 95% kernel analysis was conducted on the cumulative VMS data in Arcview® (Animal movement extension) to determine the effective area fished (Hooge et al., 1999; Silverman, 1986).

All data were taken from the VIMS scallop database and analyzed using SAS® (SAS, 1999). Basic descriptive statistics on individual variables and regressions between correlated data were used as an auditing tool to insure the integrity of our data and to correct shipboard recording and data entry errors. Sampled commercial tows were then separated from the reoccupied survey stations into two different databases. Each was analyzed separately and will be presented in this paper individually.
GENERAL OBSERVATIONS OF FLEET DYNAMICS

Vessels first targeted those areas with the high-density patches of large scallops and over time exhibited a pattern of fishing consistent with Beverton and Holt's (1957) "limiting distribution of fishing effort". A month by month breakdown of the distribution of fishing effort is shown in Figure 2. Fishing began in two distinct high-density pockets—one in the northeast and one in the southwest—with vessels actively avoiding areas of high yellow tail flounder bycatch in the southeast. The distribution of effort expanded greatly after October 1, when each vessel was allowed three additional trips into the area and catch rates were becoming similar throughout the region.

Although scallop density played the primary role in the distribution of fishing effort, changes in dockside price and the size-frequency distribution of animals also influenced vessel operations. In July, massive landings of large scallop meats (<10 meats/pound) drove their usually high dockside price down to levels even below that of the smaller animals (NMFS, 2000). The distribution of fishing effort responded accordingly and vessels began fishing in the eastern section of the area (Figure 2) on a high-density patch of smaller scallops. By the end of the opening, a 95% kernel analysis of total effort (Hooge et al., 1999) showed that vessels had effectively fished 68% (2,670 km$^2$) of the total area reopened (3,944 km$^2$) (Figure 3).
Figure 2. Monthly distribution of fishing effort during the opening of GBCAII (June 15 through November 12, 1999). Each green dot represents a single report from the vessel monitoring system.
Figure 3. Kernel (95%) of reported VMS positions recorded during the entire opening of GBCAII. Each green dot represents a single report from the vessel monitoring systems.
COMMERCIAL CPUE DECLINES

THEORETICAL FRAMEWORK—DELURY MODEL

The fundamental building blocks for this analysis were laid down by Leslie and Davis in 1939. The concept behind their work is fairly intuitive and in its simplest form states that as more individuals are removed from a closed population it will take more effort to catch the same amount. Leslie and Davis were able to show that the relationship between CPUE decline and cumulative catch is linear and provides insights to the initial abundance of a population and to the characteristics of the gear used for capture. The basic derivation (Ricker, 1975) is as follows (a list of variable names and definitions are presented in Appendix A):

By definition, catch-per-unit effort is equal to:

\[
\frac{C}{f} = q \cdot N
\]

Eqn. 1

where:

\begin{align*}
C &= \text{catch} \\
N &= \text{true abundance} \\
f &= \text{unit effort} \\
q &= \text{catchability coefficient}
\end{align*}

The catchability coefficient (q) is a constant that is defined as the fraction of the population that is taken by one unit of fishing effort. It is based on the probability that an
individual in the population will be encountered by fishing gear and the probability of capture given encounter by gear (Ricker, 1975).

So:

\[ q = \frac{a}{A} \cdot E \]  

Eqn. 2

where:

\( E \) = efficiency  
\( a \) = area covered by gear  
\( A \) = total area of population or total area of study site

Substituting for \( q \) from Eqn. 2 into Eqn. 1 illustrates that CPUE is a function of gear efficiency, ratio of area fished to total area, and population abundance (\( N \)):

\[ \frac{C}{f} = E \cdot \frac{a}{A} \cdot N \]  

Eqn. 3

In practice, researchers use Braaten’s (1969) modification of the Leslie method and use mean values for both \( N \) and \( C \) over the time interval in question. The basic Leslie model is also generated as a function of time so that:

\[ CPUE_t = q(N_0-C_{cum,t}) \]  

Eqn. 4

Where:

\( N_0 \) = the population size prior to exploitation  
\( C_{cum,t} \) = the cumulative catch at time \( t \)
In other words, CPUE at time $t$ will be a function of the initial size of the population, the amount of total individuals removed from the population at time $t$, and the catchability coefficient.

To get this in a linear format we must first recognize that:

$$ N_t = N_0 - C_{\text{cum}, t} \quad \text{Eqn. 5} $$

From Eqn. 1 and Eqn. 5:

$$ \frac{C_t}{f_t} = qN_0 - qC_{\text{cum}, t} \quad \text{Eqn. 6} $$

Eqn. 6 indicates that CPUE during time interval, $t$, plotted against cumulative catch $C_{\text{cum}, t}$ should give a straight line whose slope is $q$. In addition, when CPUE is reduced to zero (x-axis intercept), the cumulative catch should represent the original population, $N_0$ (Figure 4).

Since 1939, the concepts behind Leslie and Davis' work have been expanded upon and both the assumptions and mathematical relationships have been modified for a wider range of applications. The general approach, now known as depletion estimators or Ricker's "fishing success methods" (Ricker, 1975), has been applied to both commercial and research data in terrestrial (Fletcher et al., 1990), marine (Currie and Parry, 1999; Lasta and Iribarne, 1997; Rago et al., 1999), and fresh water studies (Schnute, 1983; Havey et al., 1991).

One of the earlier modifications of the basic Leslie-Davis model and of most interest to this study was done by DeLury in 1947. The focus of his model shifted the basic
Figure 4. Standard form of the Leslie-Davis and DeLury models.
relationship from cumulative catch to cumulative effort. This allowed the application of this model to situations where catch statistics were unavailable, unreliable or difficult to interpret and data for effort was more accurate. In this case theoretical CPUE declines would exhibit a decay that is linearized by plotting the natural log of CPUE against cumulative effort.

DeLury rewrote Leslie Eqn. 1 so that (from both Ricker 1975 and DeLury 1947):

\[
\frac{C_t}{f_t} = q \cdot N_0 \left( \frac{N_t}{N_0} \right) 
\]  
Eqn. 7

or:

\[
\ln \left( \frac{C_t}{f_t} \right) = \ln (q \cdot N_0) - \ln \left( \frac{N_t}{N_0} \right) 
\]  
Eqn. 8

As long as the fraction of a stock removed by one unit of effort is small \((N_t/N_0<0.02)\), effort can then be used as an exponential index to show the fraction of stock remaining after \(f_{\text{cum},t}\) units of effort:

\[
\frac{N_t}{N_0} = e^{-q \cdot f_{\text{cum},t}} 
\]  
Eqn. 9

Substituting Eqn. 9 into Eqn. 8 we get DeLury's modifications in linear form:

\[
\ln \left( \frac{C_t}{f_t} \right) = \ln (q \cdot N_0) - q \cdot f_{\text{cum},t} 
\]  
Eqn. 10
DELURY MODEL ASSUMPTIONS

The application of the Leslie-DeLury type models are constrained by certain fundamental assumptions. Violations of model assumptions could result in biased estimates of catchability and biomass, and the false interpretation of results. The generalized form of Leslie-DeLury type depletion models assume that during the study (Ricker, 1975; Omand, 1951):

- the population in the study area must be closed, i.e., effects of immigration, emigration or recruitment are negligible;
- natural mortality must be negligible;
- the depletion must result in a significant reduction of the population size and all removals are known;
- catchability must be constant.

Implied assumptions or those necessary for application to the DeLury model include (Rago et al., 1999; Seber, 1973):

- sampling units of effort are independent and a Poisson process with respect to effort;
- both effort and the population are distributed randomly;
- units of effort do not compete with one another;
- the population redistributes itself randomly over the sample area after each removal event.

The challenge of any study using Leslie-Delury type depletion models is to avoid assumption violations in study design or to conduct an analysis that minimizes potential biases and provides a valid interpretation of the data. For our study, fishery dependent information was used so the analysis design was critical to avoid assumption violations.
BUILDING THE MODEL

Raw catch and effort data was standardized, filtered through a spatial analysis, evaluated through linear least squares regressions, corrected for production constraints and finally, a single efficiency estimate was generated through a maximum likelihood analysis. Each step of the analysis will be presented individually and then the model as a whole is summarized following this section in Figure 7.

STANDARDIZING RAW DATA AND DEFINING UNITS OF EFFORT

Catch rates were calculated from each dredge on each tow and only successful tows were included in the analysis (i.e. data from flipped or damaged dredges were removed). Length-frequency data from sub-sampled bushels was collected to calculate the average size and average number of individuals per bushel. An estimated total number of individuals caught and retained for each tow was then calculated by applying the average number of individuals per bushel to total bushel counts. All catch data were then standardized to number of individuals captured per minute of gear time on bottom.

The spatial and temporal distribution of fishing effort provided from the VMS systems representing total fishing time and needed to be scaled to represent actual minutes of gear time on bottom. A gear time on bottom per hour of total fishing time constant was calculated from seven of the eight trips during the opening. Under normal fishing operations raw VMS data was scaled by this bottom time constant, however, at extremely high catch rates vessels were constrained by production capabilities and a production constraint correction was applied later in the analysis.
GRID ANALYSIS AND SATISFYING MODEL ASSUMPTIONS

A one-mile by one-mile grid was generated covering the entire southern portion of GBCAII. Catch and effort data from within a certain radius of each grid point (Figure 5) was evaluated for consistency with the assumptions of a DeLury type model. The radius settings and resulting effective area (cell) to be analyzed could be changed on successive runs.

Figure 5. Schematic of grid analysis. A one-mile by one-mile grid was placed over GBCAII and data were analyzed from cells within a specified distance of each grid point. Quadrants (NW, NE, SW, SE) were used to evaluate the spatial distribution of effort in each half of the opening.
To get a more accurate picture of the spatial and temporal distribution of fishing effort, VMS data were evaluated for the first half (prior to Sept. 15th) and the second half of the opening (after Sept. 15th) separately. Each cell was divided into four quadrants (NE, NW, SW, SE) (Figure 5) and the percentage of effort in each was calculated. Cells were evaluated for each part of the season based on the distribution of effort in each of these quadrants and also by the total effort that occurred within that cell. Standard model settings required that for each half of the opening 15-35% of total effort occurred in each quadrant and there was a minimum of 10,000 minutes of effort. For the catch data, standard model settings required that at least 40 tows were sampled over at least 30,000 minutes of effort and spanned at least 70% of the total effort observed in each cell.

In grid cells that met both the criteria for effort and catch data, CPUE declines were then analyzed. For each cell, linear least squares regression was performed and parameter estimates and fit statistics were generated. If necessary, production constraint corrections were used to re-scale effort and re-estimate parameters.

PRODUCTION CONSTRAINT AND R² MODEL OPTIONS

A production constraint correction was necessary in areas where catch rates were extremely high and crews were unable to process the catch as quickly as it could be caught. In this situation, vessels ceased fishing to allow the catch on deck to be processed. As a result, the raw VMS data needed to be scaled differentially to reflect the reduced time on bottom. In cells where catch rates were initially greater than 50,000
individuals (approximately 5,000 lbs. in GBCAII) per day, a production constraint correction was necessary.

The relationship between the decline of catch rates and necessary effort scaling is a non-linear feedback loop (Figure 6), so a conservative estimate had to be made. Total fishing time for each area was initially scaled by 30 minutes of bottom time per hour. The point of scaled effort at which catch rates were predicted to be at 50,000 individuals a day was then calculated. Raw VMS data was then corrected for reduced time on bottom prior to this point, and then by the standard bottom time per hour constant being used for the current run of the model.

$$\text{Scaled Effort} = \frac{\text{Bottom time}}{\text{Hour of fishing}}$$

$$\text{CPUE} = f\left(\frac{\text{Initial CPUE}}{\text{Cumulative scaled effort}}\right)$$

$$\frac{\text{Bottom Time}}{\text{Hour of fishing}} = f(\text{CPUE})$$

**Figure 6.** Conceptual diagram of non-linear feedback relationship between CPUE and bottom time per hour of fishing.

Parameter estimates were then recalculated and as in Zhang et al. (1993), an $R^2$ cutoff could be used to remove cells with questionable fits ($R^2 < 0.5$) from the analysis.
PARAMETER ESTIMATION—MAXIMUM LIKELIHOOD ANALYSIS

Final parameter estimates were calculated with a maximum likelihood estimation analysis (MLE) as suggested in much of the recent literature (Seber, 1973; Gould and Pollock, 1997; Wang and Loneragan, 1997). All data from cells that met the screening criteria were used in the analysis. The derivation of the likelihood function, began with the probability density function of a normally distributed random variable:

\[ f(x | \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}(x - \mu)^2} \quad \text{Eqn. 11} \]

with \( x \) and \( \mu \) as predicted and observed values. The product likelihood function results by substitution with DeLury Eqn. 10;

\[ \Lambda = \prod_{i=1}^{n} \prod_{j=1}^{m_i} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\left[\ln(CPUE_{ij}) - \ln(q \cdot N_{0i}) - q \cdot f_{\text{cum},ij}\right]^2} \quad \text{Eqn. 12} \]

for each area (i), for each observation (j), and with \( f_{\text{cum}} \) representing cumulative effort. The simplified natural log of this function (log-likelihood function);

\[ \ln(\Lambda) \propto -\sum_{i=1}^{n} m_i (\ln \sigma) - \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{m_i} \left[\ln(CPUE_{ij}) - \ln(q \cdot N_{0i}) + q \cdot f_{\text{cum},ij}\right]^2 \quad \text{Eqn. 13} \]

was then maximized by the PROC NLP procedure in SAS version 8 using parameter estimates from the individual least squares fits of each cell as initial estimates for each MLE parameter (SAS, 1999). The catchability coefficient (q) was assumed to be
constant for all areas so for X number of grid cells, X+2 parameter estimates had to be made. For example, if 5 grid cells are being used in the analysis the initial populations in each (N1, N2, N3, N4, N5) and the variance had to be estimated in addition to q. For programming purposes, initial population values were scaled down by $1 \times 10^7$ and dummy variables were used to write the equation (Appendix B).

The catchability coefficient was then converted to an efficiency estimate from the following relationship:

$$q = \frac{Sampled\ Area}{Study\ Area} \cdot Gear\ Efficiency = \frac{a}{A} \cdot E$$  \hspace{1cm} \text{Eqn. 14}

Which is equivalent to:

$$E = q \cdot \frac{\pi \cdot (\text{Radius of grid cell})^2}{Tow\ speed \cdot Dredge\ width}$$  \hspace{1cm} \text{Eqn. 15}

Since the unit of effort has been standardized to one minute, tow time has not been included in the denominator of Eqn. 15 or in the definition of the area covered in one unit of effort (a). An overall summary of the model design is presented in Figure 7. Finally, a sensitivity analysis was performed to determine the effects of model options, variable inputs, and overall design on parameter estimates.
Effort data from VMS

Catch data from sampled tows

Effort scaled to gear on bottom time per hour of fishing

Catch standardized to individuals caught per minute of bottom time

- Radius setting determines size of study area (A)
- Criterion for % of total effort in each quadrant for each half of the opening
- Minimum effort requirements
- Minimum number of sampled tows
- Minimum range of sampled effort

Grid Analysis

Result: Suitable grid cells

Preliminary least squares regressions on each grid cell

Production constraint correction (if applicable)

Final least squares regressions
Result: parameter estimates for MLE initial guesses

R² cutoff (if applicable)

MLE analysis
Result: Single composite parameter estimate from all areas

Conversion of q to efficiency
Tow speed determines sampled

Efficiency estimate

Figure 7. Conceptual diagram of model design for analysis of commercial CPUE declines. All variable inputs and model options are highlighted in gray.
RESULTS

A composite of all recorded catch data plotted against cumulative effort showed CPUE declines of approximately 50% (Figure 8). The relatively high catch rates recorded in the beginning of the opening were from the high-density pocket of large scallops found in the northeast corner of the area. The relatively high catch rates recorded at the end of the opening were from higher density pockets of less valuable smaller scallops in the far east which were fished only as a last resort to reach their possession limit. Parameter estimates from this composite decline were generated using only effort from the 2,670 km$^2$ contained in the 95% kernel analysis assuming 45 minutes of bottom time per hour of fishing. Over the entire study area, gear efficiency was calculated to be 41.2% with an exploitation rate of 46%.

![Figure 8. Composite DeLury model for the entire re-opened area of GBCAII. All CPUE and VMS data collected for this study is included. Raw VMS data was scaled by 45 minutes of bottom time per hour of fishing. The dotted line represents the 95% confidence intervals for the linear regression (solid line).](image-url)
The validity of parameter estimates from the composite analysis of CPUE declines presented in Figure 8 is undermined by the spatial heterogeneity of the resource, effort and sampling. In addition, the weak assumption that our recorded catch rates were representative of the fleet as a whole would have to be made. Suitable sub-units of the area were necessary to avoid these common assumption violations and produce valid parameter estimates. The selection of these sub-units was the first step in the execution of our model.

Using standard model settings and a radius for analysis of 1.5 nautical miles (nm), the results of the grid analysis and selection of areas that are most likely consistent with the model assumptions are presented in Figure 9. The majority of the cells that met both the model criteria fall into two distinct areas in the northeast and southwest. This occurred in virtually all runs of the model regardless of screening criteria inputs. These two regions contained dense patches of scallops prior to the opening and received concentrated levels of effort early in the opening. The results of the grid analysis consistently selected these high-density, high-effort areas (Figure 10).

Linear least squares regressions of CPUE declines on each grid cell (Figure 11) produced parameter estimates that were somewhat variable. Using the standard model settings of 5.0 knots tow speed and 45 minutes of bottom time per hour of total fishing time, calculated efficiencies ranged from 25.4% to 59.6% (Table 2). A production constraint correction was then applied to the six northeastern most cells that had catch rates above
Figure 9. Grid analysis cells in GBCAIIL meeting criteria for effort (a.), sampled tows (b), and for both (c.). Cells in c. have been numbered for reference in Figures 10-12.
Figure 10. Location of cells that met grid analysis criteria, sampled tows used in the analysis, and cumulative effort for the opening.
Figure 11. CPUE declines in each cell analyzed. See Figure 9 for cell locations.
Table 2. Initial least squares parameter estimates.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Degrees of Freedom</th>
<th>Intercept Ln(q \cdot N_0)</th>
<th>Slope (q)</th>
<th>$R^2$ (%)</th>
<th>Efficiency (%)</th>
<th>Exploitation Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>117</td>
<td>3.14</td>
<td>-1.48 x 10^-2</td>
<td>37.2</td>
<td>25.4</td>
<td>57.5</td>
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<td>2</td>
<td>102</td>
<td>3.15</td>
<td>-1.57 x 10^-2</td>
<td>37.9</td>
<td>27.0</td>
<td>58.8</td>
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<tr>
<td>3</td>
<td>68</td>
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<td>-3.47 x 10^-3</td>
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<td>59.6</td>
<td>82.2</td>
</tr>
<tr>
<td>4</td>
<td>85</td>
<td>5.06</td>
<td>-2.37 x 10^-3</td>
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<td>40.8</td>
<td>92.4</td>
</tr>
<tr>
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<td>91</td>
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<td>37.3</td>
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<td>91.0</td>
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<td>108</td>
<td>4.57</td>
<td>-2.85 x 10^-3</td>
<td>70.5</td>
<td>48.9</td>
<td>89.3</td>
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</table>

Table 3. Linear least squares parameter estimates following production constraint correction.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Degrees of Freedom</th>
<th>Intercept</th>
<th>Slope (q)</th>
<th>$R^2$ (%)</th>
<th>Efficiency (%)</th>
<th>Exploitation Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>*</td>
<td>*</td>
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<td>68.8</td>
<td>49.9</td>
<td>89.7</td>
</tr>
</tbody>
</table>

*cells did not require production constraint corrections
the cutoff (50,000 scallops/day) which decreased cumulative fishing time and increased
the slope (q). Parameter estimates were then recalculated (Figure 12, Table 3).

Six of the eight fits on each cell had $R^2$ values greater than 0.5 and met the final criteria
for this run of the model. The results of the MLE analysis for these cells (3-8) estimated
dredge efficiency at 45.2%. A summary of model setting and results are presented in
Table 4 and the complete SAS output is presented in Appendix 3.

SENSITIVITY ANALYSIS
On all model runs, the 95% confidence intervals for efficiency estimates were never
greater than +/- 0.5%. Although this shows that these data fit the model well, the values
do not reflect the effects or sensitivity of the model to variable inputs and overall design.

One of the more critical variables to evaluate for a DeLury analysis and the first main
input to our model is the designation of study area (A). The effect of changing radius
settings between 1 and 3 nm (A=10.78 km$^2$ to 96.98 km$^2$) resulted in efficiency estimates
that ranged from 35.3% to 51.8% (Figure 13). Grid selection criteria had to be relaxed
below 1.4 nm to produce grid cells for analysis and estimates began to fluctuate
significantly. Above a radius of 1.6 nm, estimates began to gradually climb if limited by
$R^2$ criterion, and fall if not $R^2$ limited. A radius of 1.5 nm appeared to produce stable
results and was used for all successive runs of the model.
Figure 12. CPUE declines in cells following production constraint correction.
Table 4. Settings and results for a standard run of the model.

<table>
<thead>
<tr>
<th>GRID ANALYSIS</th>
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<tbody>
<tr>
<td>Radius</td>
</tr>
<tr>
<td>Percentage of total effort necessary in each quadrant for each half of the season</td>
</tr>
<tr>
<td>Minimum VMS effort in each half of the season</td>
</tr>
<tr>
<td>Minimum Number of Sampled Tows</td>
</tr>
<tr>
<td>Minimum amount of effort sampled</td>
</tr>
<tr>
<td>Minimum ratio of effort sampled to total effort</td>
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<tr>
<td>Result</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>EFFORT SCALING AND MODEL OPTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average bottom time per hour of total fishing</td>
</tr>
<tr>
<td>Use production constraints</td>
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<tr>
<td>Use R² cutoff</td>
</tr>
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</table>

<table>
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<tr>
<th>MLE ANALYSIS AND CONVERSION PARAMETERS</th>
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<td>Tow Speed</td>
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<tr>
<td>Final Results</td>
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<tr>
<td>Efficiency estimate</td>
</tr>
<tr>
<td>Upper 95% confidence interval</td>
</tr>
<tr>
<td>Lower 95% confidence interval</td>
</tr>
<tr>
<td>Exploitation Rate</td>
</tr>
</tbody>
</table>
Figure 13. Response of efficiency estimates to model radius settings.
With the radius of the study area set to 1.5 nm the effect of the grid selection criterion was evaluated. Standard selection criteria settings were changed to result in different numbers and locations of grid cells to analyze. Settings were changed as follows:

- the necessary effort found in each quadrant of the study area was set between 15-35% and 19-31%;
- the minimum effort found in each half of the opening was set at either 5000 or 10000 minutes;
- the minimum number of sampled tows between 10-40;
- the minimum range of sampled effort in relation to total cumulative effort between 50-70%;
- the minimum amount of total effort sampled between 5000 and 30000 minutes.

In 20 runs of the model between two and 23 grid cells met the criteria and were analyzed. Most of the areas selected were still located in the northeast and southwest pockets.

Efficiency estimates produced relatively stable results with a mean of 45.7% +/- 2.8% for cells with $R^2<0.5$ and 39.9% +/- 4.7% for cells not limited by the $R^2$ cutoff.

Once areas were selected, the scaling of total effort to bottom time becomes important. The model is fairly sensitive to these inputs and at standard settings begins to break down ($E>100\%$) at values below 20 minutes of bottom time per hour (Figure 14a). On the eight cruises conducted for this study, mean bottom time per hour of fishing was 44.8 min per hour. Based on our observed mean, additional bridge logs from other vessels and general observations during the opening, the fleet-wide mean is confidently estimated to be between 40-50 minutes per hour. With this range of input values and all other standard settings, the resulting efficiency estimates ranged from 41.6% to 49.5% (Figure 14b).
Figure 14. Response of efficiency estimates to gear time on bottom per hour of fishing.
Within this range of potential bottom times and with standard model settings, the effect of applying production constraint corrections and using the $R^2$ cutoff on efficiency estimates are shown in Figure 15. As expected, production constraint corrections have a greater impact at 50 minutes per hour (+ 2.6%) than at 40 (+ 0.7%). In this case, the $R^2$ cutoff shifted estimates by approximately 2.5% higher over the entire range. The combined effect of applying both the $R^2$ cutoff and production constraints raises estimates between 3.0% and 4.3% over the 40 to 50 minute range of bottom times.

Once the grid cells were selected and the total effort had been appropriately scaled to bottom time, a common catchability coefficient ($q$) and initial populations for each area ($N_1, N_2...N_n$) were generated through MLE. The conversion of the estimated $q$ to efficiency however, is determined by the ratio of sampled area ($a$) to the total study area ($A$) shown in Eqn. 14 and Eqn. 15. Since dredge width is fixed, tow speed is the only variable that will affect the area sampled by one unit of effort. As a result, the conversion of $q$ to efficiency is sensitive to this input. With all other standard settings, tow speeds just above 2 knots resulted in efficiency estimates of over 100% (Figure 16a). On the eight cruises conducted for this study, the mean tow speed was 4.9 knots (+/- 0.03). Based on our observed mean, bridge logs from additional vessels, and general observations during the opening, the fleet-wide mean is comfortably estimated to be between 4.5 and 5.5 knots. Using this range of inputs, efficiency estimates ranged from between 41.1% to 50.2% (Figure 16b).
Figure 15. Response of efficiency estimates to $R^2$ and production constraint model options.
Figure 16. Response of efficiency estimates to tow speed model input.
Since the model is sensitive to both tow speed and average time on bottom per hour of fishing inputs, the interaction between these two variables is presented. Within the range of reasonable estimates both variables shifted estimates by approximately +/- 4% and have a combined effect of +9.6% and −7.6% (Figure 17). At standard model settings, the mean efficiency estimate was 45.2% and could range from 37.9% to 55.1% if fleet-wide averages of bottom time and vessel speed are significantly different than our results and at the extreme ends of possible values.

**DISCUSSION**

Dredge efficiency was estimated to be 45.2% from a fine scale DeLury analysis of commercial CPUE declines in specific regions of GBCAI. Estimates from the composite fit of all recorded CPUE’s are surprisingly consistent with the fine scale results, although assumptions are clearly violated. One would expect an overestimation of efficiency to occur in this large-scale application, however the effects of the non-random spatial distribution of the resource and effort appear to be balanced by the spatial distribution of samples. For example, the high catch rates recorded from small high density patches of scallops were not sampled as frequently as tows in other regions because vessels needed fewer tows to reach their possession limit. As a result, sampling effort was somewhat spatially weighted and parameter estimates may not be as far off as one would expect.
Figure 17. Response of efficiency estimates to the combined effect of bottom time and tow speed model inputs.
SATISFYING ASSUMPTIONS

Results from the fine scale analysis are not suspect to the glaring assumption violations seen in the composite decline, however with fishery dependent data, a careful consideration of model assumptions and overall analysis design was critical. The first three main assumptions of the DeLury model—closed population, negligible natural mortality and significant reduction of population—were met due to the target species and magnitude of removals from the area. As a relatively sessile species large immigration, emigration or recruitment events are unlikely during the five-month opening, and the assumed annual natural mortality of 0.1 will be negligible in light of the massive fishing mortality and the short duration of fishing.

The failure of many studies to meet the fourth main assumption of a DeLury model, constant catchability, is the most commonly cited reason for biases or faulty interpretation of depletion studies (Ricker, 1975; Schnute, 1983; Clausen, 1992). Although a number of researchers including Winters and Wheeler (1985), Polovina (1986), Swain and Sinclair (1994), and Wang and Loneragan (1996) have suggested modifications to the original model, this issue still remains problematic. Changes in catchability over time often introduce systematic errors (Ricker, 1975) and can be caused by a number of density dependent behavioral processes including changes in feeding (Fletcher et al., 1990), contraction of home range (Winters and Wheeler, 1985; MacCall, 1976) and such things as the capture of the most vulnerable fish first (Hilborn and Walters, 1992; Clausen, 1992; Ricker, 1975). For this study, density dependent
behavioral processes are not a complicating factor due to the target species, however potential problem spots still exist and warrant further discussion.

One possibility for trends or variations in catchability could occur if gear efficiency itself were a function of density. Although the individual regressions of CPUE declines in the southwest section of GBCA II are suspect due to low $R^2$ values, the resulting estimates of efficiency were consistently lower than those from the higher density areas in the northeast. The relationship between efficiency and initial CPUE estimates from multiple areas was extremely noisy, but suggested that density dependence may play a role. A slight curvilinear trend was also observed in the residuals for some of the northeast plots supporting the possibility of density dependence. Previous studies that have noticed similar trends in their data have suggested modifying the basic relationship between CPUE$=qfN$ to CPUE$=qfN^b$ (Hutchings and Myers, 1994; Ulltang, 1976; Winters and Wheeler, 1985). Further analysis and the application of this model to other areas over a wide range of densities will allow this to be investigated further.

The most difficult and potentially the most confounding issue related to the assumption of constant catchability is the non-uniform spatial distribution of effort, target species and sampling. An implied requirement of the DeLury model is that the density of the resource is uniform and should also result in a random distribution of effort. Paloheimo and Dickie (1964) state that without "additional information on distribution of fish and the operations of fishing vessels" CPUE cannot provide a measure of abundance if fish are not randomly distributed. It appears that many of the sources of bias from non-random distribution will
result in the underestimation of abundance (Mohn and Elner, 1987; Miller and Mohn, 1993) and spatial homogeneity is critical for accurate results.

These issues had to be addressed for the GBCAII opening, as effort followed the pattern described by Beverton and Holt's (1957) "limiting distribution of fishing effort" theory and was focused on the denser patches first and then generally moved to areas of lower density. In addition, our sampling was conducted on commercial vessels following the general trend of the fleet resulting in a non-random sampling scheme. One of the most common ways to deal with this type of non-randomness and satisfy this fundamental assumption is to "group data over small statistical area and time units" which will hopefully be nearly random on a smaller scale (Sanders and Morgan, 1976; Caddy, 1975).

The grid analysis and the selection of specific cells to analyze was designed to meet this goal and reflect the commercial fleets ability to sense differences in resource abundance and change fishing behavior. Within suitable sub-units commercial CPUE's and effort should be uniform and generally higher than surrounding areas. During the first two weeks of the opening, effort focused on areas as small as 67.35 km² in the northeast. Multiple vessels, covering distances of 7.4 and 9.26 km on a single tow were essentially fishing randomly in these areas while at the same time the small scale contagious distribution of scallops would be expected to become random under this heavy fishing pressure (Langton and Robinson, 1990). The resolution of the grid analysis was fine enough to select 24.24 km² study areas within patches of effort. The use of VMS data
provided the fine scale detailed information on the spatial distribution of effort that is usually lacking for the successful application of a DeLury model to open-ocean commercial fishing events.

MODEL INPUTS AND SENSITIVITY

Although the VMS data provided the spatial information necessary to analyze regions most suitable to the DeLury model, the scaling of raw VMS data to our independent variable—actual gear time on bottom—was slightly more problematic. Quantifying this relationship, in addition to the appropriate tow speed and production constraint corrections, requires mean values from entire fleet operations. With precise data from only eight of the 644 trips taken during the opening, careful consideration of vessel operations as a whole needed to be taken into account and conservative estimates had to be made for these model inputs.

The appropriate scaling of VMS data required a mean bottom time per hour of fishing for all vessels that fished in each region. On trips sampled for this study vessels fished for a mean of 47 minutes an hour during optimal conditions, and for 45 minutes an hour when time lost to equipment failure or weather was included. It is unlikely that the true mean for the fleet will be greater than the 47 minutes observed under optimal conditions and the potential variability in model results should only be due to actual bottom times lower than this value. If we assume that the true mean is above 42 minutes an hour, the realistic range for efficiency estimates due to the variability of this input is reduced to 43.7% to 47.7%.
A conservative production constraints correction was calculated using a 50,000 individuals (~5,000 lbs.) per day cutoff, which is almost double the value (2,660 lbs.) used in the Framework 11 calculations (NEFMC, 1999). In addition, the initial scaling of effort by 30 minutes of bottom time per hour of fishing insured an underestimation of its effect on the overall catchability coefficient (q). The 1 to 2% positive shift in efficiency estimates that resulted from the use of production constraints would be expected to represent no more than half of the true effect. As better information is obtained on fleet operations a more accurate production constraint relationship can be developed that will include crew size, length of trip, and mean shell heights.

The final calculation, converting q into efficiency, should also result in conservative estimates. Data were collected from some of the larger vessels in the fleet and as a result observed tow speeds and dredge width model inputs should be slightly greater than the actual mean for the fleet. Some of the smaller lower horsepower vessels were using dredges less than 15 ft across and could not maintain the same fishing speeds as the larger vessels in high density or bad weather conditions. This resulted in a high estimate for the area fished by one unit of effort (a) and therefore a low estimate of gear efficiency. Although a power correction would be appropriate to adjust for these differences, specific information on the fishing behavior and gear used by individual vessels was not available for this study (Gulland, 1969; Sanders and Morgan, 1976).
SURVEY CPUE DECLINES

THEORETICAL FRAMEWORK—INDEX REMOVAL METHOD

In fisheries management, survey data are routinely used to calculate the absolute abundance of a population and in the determination of appropriate removals to insure the sustainability of a fishery. For mobile fishing gear, typically a mean CPUE and corresponding swept area will be calculated from survey data. Mean catch rates per survey tow are then expanded to a catch index for the total survey area and then absolute biomass by the following equation:

\[
\text{Total Biomass} = \left( \frac{\text{Survey Area}}{\text{Area Swept by Tow}} \right) \cdot \text{Catch} \cdot \frac{\text{Efficiency}}{} \tag{Eqn. 16}
\]

Unfortunately in many fisheries, accurate estimates of gear efficiency have been difficult to quantify. Incorrect estimates of efficiency can lead to false estimates of abundance and in turn removals or quotas which do not meet the target exploitation rate for a population.

Prior to the opening of GBCAII to scallop fisherman in 1999, two different resource surveys were conducted in 1998. A cooperative survey was conducted onboard commercial vessels utilizing commercial gear to sample a systematic grid of the area. The annual NMFS sea scallop survey on the \textit{R/V Albatross} also surveyed the area, but
used a stratified random design with survey gear. Very similar indices of abundance were generated from both surveys but with efficiency estimates that ranged from 16-40%, absolute biomass estimates ranged from 25 to 63 million lbs. (NEFMC, 1999). The calculation of an appropriate TAC was hampered by the inability to agree upon a suitable efficiency estimate.

The opening and consequent depletion of GBCAII, provided a unique opportunity to calibrate the conversion of sea scallop survey data into absolute biomass and an alternative way of estimating the efficiency of survey tows. The cooperative survey conducted in 1998 (Figure 18) resulted in an extremely fine scale description of resource abundance and distribution, as well as catch indices prior to the opening. Since the total catch was known and sample stations were reoccupied (Figure 19), gear efficiency can be estimated with the index-removal method (Eberhart, 1982; Hoenig and Pollock, 1998).

The index-removal method differs from the Leslie-DeLury type depletion models which use a continuum of commercial catch data for parameter estimates, in that only total catch and two catch indices (pre and post fishing event) are necessary. This method is similar to the change in ratio (CIR) method that uses indices from before and after a known removal to estimate initial populations and gear parameters (Eberhart, 1982). The CIR method utilizes the change in a given ratio, such as males and females or adults and juveniles, and requires a selective removal of one component of the ratio. For this study however, the total catch was known, so the relatively simple relationship between pre and post removal indices can be used without the need to classify or identify individuals.
Figure 18. Location of survey and grid stations from the 1998 GBCAII cooperative survey used in the kriging analysis (n=497).
Figure 19. Location of GBCAII 1998 cooperative survey stations re-occupied at the end of the 1999 opening (n=84).
The hypothetical framework for the index-removal method was introduced by Petrides (1949) and has been built upon by Seber (1973), Routledge (1989), Dawe et al. (1993), Chen et al. (1998) and others. A review of the methodology, assumptions, and relevant literature is presented in Hoenig and Pollock (1998). With the assumptions:

- the population is closed except for removals (i.e. immigration, emigration and natural mortality area negligible),
- that all animals have the same probability of capture in the surveys, and this probability does not vary from survey to survey,
- the fraction of the population taken in the surveys (compared to total removals) is negligible,

then it follows that:

\[
\text{Pre-Fishing Population} = N_1 = \frac{(I_1 \cdot A/a)}{E} \quad \text{Eqn. 17}
\]

\[
\text{Post-Fishing Population} = N_2 = \frac{(I_2 \cdot A/a)}{E} \quad \text{Eqn. 18}
\]

\[
\text{Catch} = N_1 - N_2 \quad \text{or equivalently} \quad N_2 = N_1 - C \quad \text{Eqn. 19}
\]

with: \( I_1 \) and \( I_2 \) are pre and post removal catch indices respectively, \( A \) is the total study area, \( a \) is the sample area, \( E \) is efficiency and \( C \) is total catch. By substitution, \( I_1 \) and \( I_2 \) are related to total catch by the following equation:

\[
\text{Catch} = C = \frac{(I_1 \cdot A/a)}{E} - \frac{(I_2 \cdot A/a)}{E} \quad \text{Eqn. 20}
\]
This is equivalent to:

\[
E = \frac{(A/a) \cdot (I_1 - I_2)}{C} \quad \text{Eqn. 21}
\]

Total catch for the opening of GBCAII was reported in terms of biomass and dictated the units used in our methodology.

**METHODS**

Catch data for both surveys were initially corrected for the selectivity of the gear using the selectivity curve from DuPaul et al. (1989b). Data from the cooperative 1998 survey were then corrected for growth and natural mortality using parameters from Serchuck et al. (1979) \( (k=0.3374, \ t_0=1.4544, \ L_\infty=152.46) \) and an assumed natural mortality of 0.1. This advanced the 1998 survey data by 10 months to expected values for the start of the opening of GBCAII on June 15th, 1999 and eliminates the potential for errors due to recruitment during the period prior to the opening. Only animals greater than 80 mm were included in the analysis. Finally, the size frequency composition of the catch was used to convert catch data to biomass using a shell height/meat weight relationship \( (K=-11.6038, \ R=3.1221) \) from the 2001 stock assessment workshop (NEFSC, 2001).

Spatial catch indices were then calculated from survey data using ordinary kriging. Random sampling is not a requirement of the kriging technique and will accommodate both the systematic grid conducted in the 1998 cooperative survey and the effort-based
selection of the resampled survey stations. An experimental semivariogram was generated from the 1998 survey stations to determine the appropriate range and scale for the model (Conan, 1985; Warren, 1998). Kriging estimates were then performed using the PROC KRIG2D procedure in SAS (SAS, 1999) for both one and two nautical mile grids on both the 95% effort kernel and the entire southern section of GBCAII reopened to fishing (Figure 20). As reported in Framework 11, a nominal tow length of 1 nautical mile per survey tow was used in these calculations (NEFMC, 1999). These results were then used to solve Eqn. 21 for efficiency, with a known catch of 5,996,110 pounds.

![Diagram](image)

**Figure 20.** Grid point used in kriging analysis of GBCAII survey stations. Grids were either one by one-mile (a,c) or two by two-miles (b, d). CPUE means were taken from either all points inside GBCAII (a,b) or from the 95% kernel of effort(c. d).
RESULTS

The experimental semivariogram (Figure 21) produced from the 1998 cooperative survey was best described by a spherical model as in Conan (1985) and Warren (1998). The model showed a variance sill beginning at approximately six nm and a variance scale of $3.5 \times 10^8$. With these settings, kriging estimates were generated on one and two-mile grids placed over the entire reopened area. Kriged estimates of advanced catch data from 1998 had means of 15.1 and 15.5 kg per tow from the one and two mile grids respectively. Estimates from the one and two mile 95% kernel analysis were 19.1 and 19.4 kg per tow respectively. A high-density region of large scallops ran from the southwest to the northeast section of the area with one extremely high-density pocket in the northeast corner (Figure 22). Two high-density pockets of smaller animals were also present in the southeastern corner of GBCAII.

A very different picture was generated from the survey stations re-sampled following the fishing event (Figure 23). Kriged estimates for the entire reopened area from the 1999 survey stations showed a significant reduction of catch means to 9.2 kg per tow from both the one and two mile grids. Estimates from both the one and two mile 95% kernel analysis were 9.9 kg per tow. Fishing effort had targeted the high-density areas first and spread out until catch rates had all but equalized throughout the region. The slightly higher catch rates that remained in the east were smaller, less valuable animals (>20 meats per pound) that vessels targeted as a last resort to reach their catch limit.
Figure 21. Semivariogram generated from the GBCAII 1998 cooperative survey stations.
Figure 22. Results of 1998 cooperative survey kriging analysis. The dark black line indicates the outline of GBCAII re-opened to fishing.
Figure 23. Results of kriging analysis from the 1998 cooperative survey stations re-occupied at the end of the 1999 GBCAI opening.
Using the mean catch indices estimates from both surveys for the entire reopened area, a total catch of 5,996,110 pounds and solving Eqn. 21, efficiency was estimated to be 50.5% from the one mile grid analysis and 54.5% from the two mile grid. Results from the 95% kernel analysis were similar with estimates of 53.2% and 55.4% efficiency from the one and two mile grids, respectively.

To verify the model’s sensitivity to the kriging range settings, data were reanalyzed using range settings of 4 to 6 nm (Figure 24). Efficiency estimates ranged from 50.2% to 57.8%, however in the 5 to 6 nm range estimates from one type of grid analysis (1 or 2 nm grids, entire area or kernel mean indices) showed variability of less than 0.6%. Efficiency estimates were also not very sensitive to kriging scale settings and remained unchanged in the range of reasonable inputs. Mean catch indices calculated from the two-mile kernel analysis were then used to test the model’s sensitivity to total catch estimates. Efficiency estimates ranged from 66.5% with a total catch of 5 million pounds and 47.5% if total catch was actually 7 million pounds (Figure 25).

DISCUSSION

Dredge efficiency was estimated to be between 50.5 and 55.4% by applying the index removal method to survey data collected before and after the opening of GBCAII. Although survey stations were re-sampled identically and Chen et al. (1998) found this to increase the precision of results in this type of analysis, a random selection of stations was not used, so a traditional design based analysis approach was not applicable. Kriging represents one approach that does not have the assumption of randomness and is suitable
Figure 24. Response of efficiency estimates to kriging settings and the different grids used to generate CPUE means.
Figure 25. Response of efficiency estimates to total catch (or total removals) input to model
for both the systematic grid conducted in 1998 and the effort-based selection of re-
sampled survey data collected at the end of the opening.

Interest in kriging arose from attempts to utilize the spatial patterns of populations and
the spatial correlation between samples in the analysis. Previous applications for the
assessment of marine species have been conducted primarily on relatively sedentary
animals (Conan et al., 1988; González-Gurriarán et al., 1993; Simard et al., 1992).
Advocates of kriging, suggest that results from this technique are more accurate due to a
smaller standard error, however due to fundamental differences in the techniques,
variance estimates from kriging and traditional design-based estimations cannot be
compared (Warren, 1998).

Although variance estimates have not been presented due to this conceptual problem, the
mean catch indices generated from our analysis are consistent with those generated from
the NMFS stratified random survey. Catch indices for the southern half of GBCAlI from
the 1998 survey, advanced to predicted values for the opening, were approximately 15.0
kg per survey tow for the NMFS calculations and 15.3 kg per survey tow from the
kriging technique (NEFMC, 1999). The kriging estimates would be expected to be
slightly higher than those calculated by NMFS since only the kriged estimates were
corrected for gear selectivity. Although fewer stations were sampled post-season, fishing
effort had significantly reduced the variability of the population, so the chance of errors
due to the spatial distribution of the resource was greatly reduced.
ASSUMPTIONS AND SENSITIVITY

The efficiency estimates, calculated from the index-removal method, were made assuming that the population was closed and all removals were known. As a primary assumption of this model, parameter estimates were sensitive to the total catch model inputs. Although the documented landings during the opening of GBCAII were 5,996,110 pounds, the actual total removals or losses from the area may differ from this value and deserve a closer look.

The first potential problem area is the conversion of size-frequency specific CPUE data to the same units as the reported catch. A shell-height/meat-weight relationship derived specifically on Georges Bank was used to convert CPUE data to biomass, however a number of factors including meat weight gains due to fresh water absorption and post spawning meat weight losses can skew this relationship. Previous studies have shown that changes in meat weights due to deck handling and storage on ice for a period of 10 days can increase meat weights approximately 13.6% (DuPaul et al., 1990). For the opening of GBCAII, however, trips lasted an average of only six days and the effect of this process would not be expected to be that great (NEFMC, 2000). Gains on the order of 4 to 5% were observed on both F/V Celtic trips where primitive attempts were made to weigh bags prior to storage.

The post-spawning decline of meat weights on the other hand, was observed beginning in September and vessels clearly had to catch more of the same size animals to reach their possession limits. Effort at this time had significantly increased due to the authorization
of three additional trips into the area. Calculations in Framework 11 suggest that these vessels would have to catch 31% more animals in the post-spawning condition to land the same amount (NEFMC, 1999). Although, significant errors in the model would not be expected due to either these processes, the magnitude of losses appear to be greater than the gains, and as a result efficiency estimates are likely to be slightly overestimated.

The second and more important consideration necessary to evaluate model results centers on removals or losses that are unaccounted for in the documented landings. Assuming that every landed scallop was reported, the actual total losses from the area are still likely to be greater than the 6 million lbs. reported. For example, minor removals of additional animals would have occurred on vessels processing catches and discarding animals while steaming home, while additional losses would result from natural and non-catch mortality. Although over the five month opening the effects of an assumed natural mortality of 0.1 should not be significant, recent studies suggests that the incidental mortality of scallops may be as high as 15% of the catch (Caddy, 1973; NEFSC, 2001). If this value was only 10%, an additional 600,000 lbs. would have been lost to this process and efficiency estimates would be reduced to 50.4%. Although difficult to accurately quantify all of these factors, the actual removals from the area are likely to be greater than the reported total catch and would cause lower efficiency estimates. If we assume that total non-harvest losses from all causes were no greater than one million pounds, the efficiency estimates would range from 47.5 to 55.4%.
INTEGRATED DISCUSSION

As the management of the sea scallop industry evolves toward an area-based strategy, accurately quantifying the relationship between survey data and absolute abundance becomes critical. The correct conversion of survey indices to precise abundance estimates allows managers to set appropriate TAC's to target specific exploitation levels, to maximize yield and net benefits, and allows for the long-term planning of closed area management. Although reasonably accurate indices of abundance can be generated, uncertain estimates of both commercial and survey gear efficiency undermine the completion of this process and result in questionable estimates of absolute biomass and difficulty in determining appropriate TAC's (Serchuck and Wigley, 1986; NEFMC, 1999).

The opening of GBCAIIF provided an ideal opportunity to address these issues and through a depletion analysis, independently estimate gear efficiency. Using a combination of commercial and survey data, two independent estimates of commercial dredge efficiency have been presented. The results of this study suggest that commercial scallop gear has an efficiency in the range of 45 to 55% and that the 25% estimate used by NEFMC for the opening of GBCAIIF resulted in the overestimation of absolute biomass and the setting of a TAC which was too high.
PREVIOUS ESTIMATES OF EFFICIENCY

The depletion models used in this study are just one technique that can be used to derive independent estimates of population parameters and gear efficiency. Previous studies of commercial dredge efficiency have been conducted both directly (i.e. photographs, video, divers) and indirectly (i.e. Leslie-DeLury methods, mark-recapture studies, or CIR) on both fishery dependent and fishery independent data. Unfortunately, results have remained variable and only a few studies have focused on the New Bedford style dredge used in this study.

Bourne (1966) conducted one of the first efficiency studies on this type of gear and found efficiencies of near 15%. Caddy's work (1968, 1971, 1973) on a New England style dredge, is the most comprehensive and was done primarily by direct observations. In his 1968 study, survey transects were made in an area that had been previously surveyed by divers and efficiency was estimated at 8.3% for scallops larger than 100 mm. This study was conducted in shallow water at dredge speeds of only 2 knots. His follow up study (1971) conducted on Georges Bank used cameras mounted to the front of the dredge. Density of the population was determined in the 1.29 m² areas photographed and compared to the actual catch. Efficiency was estimated at 16.9% for scallops larger than 100 mm. Rago et al. (1999) applied camera based methodology corrections presented in Mason et al. (1982) to these results and suggests that the true efficiency estimates from the 1971 Caddy study should be closer to 46.6%.
A depletion study conducted by Rago et al. (1999) during the 1998 NMFS survey on GBCAII is most comparable to our study (NEFMC, 1999). The Leslie-DeLury model was reparamaterized to incorporate the spatial aspect of the sampling and was applied to ten sets of depletion tows conducted during the survey. A negative binomial model was used to describe the distribution of catches and parameter estimates were generated from maximum likelihood methods. Since these studies were conducted in the same area and with the same basic tow methodology as our study, depth, tow speed, size of scallops and bottom type were virtually identical. Rago's efficiency estimates ranged from 25 to 57% with an overall average of 41% (Rago et al., 1999).

Other recent studies on comparable dredge equipment also suggest that gear efficiency may be higher than some earlier estimates. Hall-Spencer et al. (1999) suggested an efficiency of 44% for the Rapido trawl (3 m wide steel frame with 8 cm mesh weighing approximately 170 kg.) on Pecten jacobaeus for soft sandy bottom types, similar to that of the southern GBCAII. Currie and Parry (1999) found comparable estimates for the Peninsula dredge (3.1 m wide frame with 70 x 45 mm mesh towed at 5.5 to 6 knots) in southeastern Australia. Dredge efficiency estimates ranged from 51 to 56% in soft flat muddy bottoms and 38 to 44% in firm sandy sediments.

Although the results of our study are higher than those presented by Caddy and earlier research, they are consistent with these more recent studies on comparable gear. It is important to note, however that estimates from our study have been generated from a commercial operation and involve vessels of different sizes, slight variations of fishing
gear, different bottom types, and all weather and tide conditions. Many of the previous depletion studies used data only from only handpicked high horsepower vessels fishing in optimal conditions. It is possible that a careful fine-scale analysis of large amounts of commercial data may provide estimates that near "true" commercial dredge efficiencies.

SUMMARY

The challenge of any study using depletion estimators is to avoid assumption violations in the study design and to conduct an analysis that minimizes potential biases and provides an accurate interpretation of the data. Unfortunately, it is difficult to find data sets that will satisfy all assumptions unequivocally. Fishery-independent data are generally from designed surveys that are statistically sound, however financial and logistic considerations generally limit the amount of data available from these sources. Fishery dependent information, on the other hand, is usually readily accessible from a number of sources including landings tickets, observer data, call in weights, or dockside monitoring. In many cases, however the analysis and interpretation of this data is limited by a lack of a proper sampling design (Ricker, 1975), aggregated or cross sectional data (Dulvy et al., 2000), and lack of spatial details on catch and effort (Paloheimo and Dickie, 1964).

The success of our study and confidence in the resulting range of parameter estimates can be attributed to the careful consideration of the data sources, the use of VMS data for fine scale spatial analysis and the unique situation that evolved with the opening of GBCAII. The extremely high densities that resulted from the 5-year closure allowed exploitation
rates of over 90% in some areas. With depletions of this magnitude, the effects of sampling errors are reduced and the potential to produce valid estimates heightened (Gould and Pollock, 1997; Gould et al., 1997). In addition, the fine scale surveys conducted prior to the opening allowed the verification of initial catch data and an alternative means of independently estimating efficiency.

The opportunities to utilize both commercial and survey data as independent and corroborating analyses in this fashion are rare. While parameter estimates from both our analyses were similar and consistent with the results of recent studies on comparable gear, an overall difference of approximately 10% between estimates from each technique was observed. However, if we consider the clear biases built into each model very similar estimates would result. The best efficiency estimate from the DeLury model analysis of commercial data was 45.2% but is likely to be an underestimation due to conservative estimates of the commercial scallop fleet operations. The bias of the index-removal analysis of survey tows, on the other hand, suggests that a 55.4% efficiency would represent a high estimate. If we include these considerations in our interpretation of these data, an efficiency of near 50% seems appropriate.

Survey and commercial tows, however may not be completely comparable if efficiency of the New Bedford dredge is tow time dependent. Survey tows were 10 minutes in length while observed commercial tows averaged 49 minutes. Dredges may be more efficient in the earlier part of a tow when the bag is empty and water flow is not hampered. Previous studies have shown that efficiency can be greatly reduced by the
clogging of dredge openings (Baird, 1959; Mason et al., 1979). As a result, it is possible that survey tows may end up being more efficient than the longer commercial tows.

Although the difficulties in generating a precise estimate of efficiency are clear, the results of this study strongly suggest that the 25% efficiency used in the calculations prior to the opening of GBCAII highly overestimated absolute abundance in the region. This caused the overestimation of an appropriate TAC and resulted in exploitation rates that were higher than the targeted levels. In addition, it is important to note that both the biomass estimates and TAC calculations in Framework 11 were for GBCAII as a whole. Managers chose a target F level for the entire closed area although only south of 41° 30' N was being reopened. The overestimation of abundance and an appropriate TAC in this case, resulted in exceeding target exploitation levels for the entire area rather than just the southern section.

If an efficiency of 50% as suggested by this study were to have been used in the original calculations, an absolute biomass estimate of near 20 million pounds and a TAC of 4.8 million pounds would have resulted. These values are significantly different than the range used in the Framework 11 calculations that estimated absolute abundance between 25 and 63 million pounds and TAC’s of 6 to 15 million pounds.

The 4.8 million-pound TAC suggested by this study was landed by early October just following the authorization of additional trips into the area. Unfortunately, the decision to allow these additional trips had to be made with little new supporting scientific
information. With the widespread use of VMS systems, real time information is now available on the fine-scale distribution of fishing effort. The opportunity now exists to collect CPUE data from commercial vessels and successfully apply a depletion model to an open-ocean commercial fishing event. For future openings, the analysis developed in this study could act as one means to monitor the opening, to evaluate the original biomass estimates and to estimate gear efficiency for the different regions or closed areas.
LITERATURE CITED


Federal Register. March 5, 1996. Vol. 61, No. 44 Tuesday, March 5, 1996.


APPENDIX A

List of variable names and definitions.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
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<tbody>
<tr>
<td>C</td>
<td>Catch</td>
</tr>
<tr>
<td>$C_{\text{cum}, t}$</td>
<td>Cumulative catch at time $t$</td>
</tr>
<tr>
<td>N</td>
<td>Abundance</td>
</tr>
<tr>
<td>$N_0$</td>
<td>Initial abundance</td>
</tr>
<tr>
<td>f</td>
<td>Unit of effort</td>
</tr>
<tr>
<td>q</td>
<td>Catchability coefficient</td>
</tr>
<tr>
<td>E</td>
<td>Efficiency</td>
</tr>
<tr>
<td>a</td>
<td>Area covered by gear</td>
</tr>
<tr>
<td>A</td>
<td>Total area of study site, or area of population</td>
</tr>
<tr>
<td>$f_{\text{cum}, t}$</td>
<td>Cumulative effort at time $t$</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>Likelihood function</td>
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<tr>
<td>CPUE$_i$</td>
<td>CPUE in Area $i$</td>
</tr>
<tr>
<td>CPUE$_j$</td>
<td>CPUE for observation $j$</td>
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</tbody>
</table>
APPENDIX B

MLE formula as programmed in SAS for up to 25 different cells

(LNCATCH=ln(CPUE), TOWAREA=a, SAMPAREA=A, FINALEFF=fCUM, D1-25=dummy variables for each cell, N1-N25=initial populations in each cell, Q=Efficiency)

\[
F_1 = \text{LNCATCH} + Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times \text{FINALEFF} \\
- D_1 \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_1 \right) \\
- D_2 \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_2 \right) \\
- D_3 \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_3 \right) \\
- D_4 \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_4 \right) \\
- D_5 \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_5 \right) \\
- D_6 \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_6 \right) \\
- D_7 \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_7 \right) \\
- D_8 \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_8 \right) \\
- D_9 \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_9 \right) \\
- D_{10} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{10} \right) \\
- D_{11} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{11} \right) \\
- D_{12} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{12} \right) \\
- D_{13} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{13} \right) \\
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- D_{15} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{15} \right) \\
- D_{16} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{16} \right) \\
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- D_{19} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{19} \right) \\
- D_{20} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{20} \right) \\
- D_{21} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{21} \right) \\
- D_{22} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{22} \right) \\
- D_{23} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{23} \right) \\
- D_{24} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{24} \right) \\
- D_{25} \times \log \left( Q \times \left( \frac{\text{TOWAREA}}{\text{SAMPAREA}} \right) \times (1,000,000) \times N_{25} \right) ;
\]

\[
F_2 = F_1 \times 2; \\
\text{LOGLIKELIHOOD} = -\log(\text{var}) - 0.5 \times F_2 / \text{var} \times 2; \\
\text{run;}
\]
APPENDIX C

Complete SAS output for standard run of the model

**COMBINED MAXIMUM LIKELIHOOD ESTIMATOR**

**PROC NLP: Nonlinear Maximization**

Gradient is computed using analytic formulas. Hessian is computed using analytic formulas

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<tr>
<th>Optimization Start</th>
<th>Parameter Estimates</th>
<th>Gradient Objective Function</th>
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Value of Objective Function = -5773.627338

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Determinant = 1.0938492E37  Matrix has Only Negative Eigenvalues
### COMBINED MAXIMUM LIKELIHOOD ESTIMATOR

**PROC NLP: Nonlinear Maximization**

**Newton-Raphson Ridge Optimization**

**Without Parameter Scaling**

#### Optimization Start

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<th>Active Constraints</th>
<th>Objective Function</th>
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**GCONV convergence criterion satisfied.**
## COMBINED MAXIMUM LIKELIHOOD ESTIMATOR

**PROC NLP: Nonlinear Maximization**

### Optimization Results

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### Value of Objective Function = 168.59127738

#### Hessian Matrix

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<th>N3</th>
<th>N4</th>
<th>N5</th>
<th>N6</th>
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**Determinant = 8.4083842E28**

**Matrix has Only Negative Eigenvalues**
Covariance Matrix 2: \( H = \left( \frac{N O B S}{d} \right) \text{inv}(G) \)

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<th>N2</th>
<th>N3</th>
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Factor sigm = 1

Determinant = 1.189289E-29

Matrix has 8 Positive Eigenvalue(s)

Approximate Correlation Matrix of Parameter Estimates

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<tr>
<th></th>
<th>Q</th>
<th>VAR</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>N5</th>
<th>N6</th>
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<td>0.02911537</td>
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<td>0.02497915</td>
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<td>0.0180097</td>
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<td>0.00283179</td>
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<td>0.00132914</td>
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Determinant = 0.9337762243

Matrix has 8 Positive Eigenvalue(s)
**COMBINED MAXIMUM LIKELIHOOD ESTIMATOR**

**PROC NLP: Nonlinear Maximization**

<table>
<thead>
<tr>
<th>N</th>
<th>Parameter</th>
<th>Estimate</th>
<th>Alpha</th>
<th>Profile Likelihood Confidence Limits</th>
<th>Wald Confidence Limits</th>
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<td>0.95000</td>
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