



Northeast Fisheries Science Center Reference Document 07-16

**45th Northeast Regional  
Stock Assessment Workshop (45th SAW)**

**45th SAW Assessment Report**

September 2007

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- 07-07 *Evaluation of a Modified Scallop Dredge's Ability to Reduce the Likelihood of Damage to Loggerhead Sea Turtle Carcasses*, by HO Milliken, L Belskis, W DuPaul, J Gearhart, H Haas, J Mitchell, R Smolowitz, and W Teas. April 2007.
- 07-08 *Estimates of Cetacean and Pinniped Bycatch in the 2005 Northeast Sink Gillnet and Mid-Atlantic Coastal Gillnet Fisheries*, by D Belden. May 2007.
- 07-09 *The Analytic Component to the Standardized Bycatch Reporting Methodology Omnibus Amendment: Sampling Design, and Estimation of Precision and Accuracy (2nd Edition)*, by SE Wigley, PJ Rago, KA Sosebee, and DL Palka. May 2007
- 07-10 *44th Northeast Regional Stock Assessment Workshop (44th SAW): 44th SAW assessment report*. May 2007.
- 07-11 *45th Northeast Regional Stock Assessment Workshop (45th SAW): 45th SAW Assessment Summary Report*. July 2007.
- 07-12 *Proposed Vessel Calibration Studies for NOAA Ship Henry B. Bigelow*, by NEFSC Vessel Calibration Working Group. August 2007.
- 07-13 *Monkfish Assessment Summary for 2007*, by Northeast Data Poor Stocks Working Group. August 2007.
- 07-14 *NEFSC Publications, Reports, Abstracts, and Web Pages/Documents for Calendar Year 2006*, compiled by LS Garner. August 2007.
- 07-15 *Characterization of the Northeast and Mid-Atlantic Bottom and Mid-water Trawl Fisheries Based on Vessel Trip Report (VTR) Data*, by CD Orphanides and GM Magnusson. September 2007.

*45th Northeast Regional Stock Assessment Workshop (45th SAW)*

## **45th SAW Assessment Report**

U.S. DEPARTMENT OF COMMERCE  
National Oceanic and Atmospheric Administration  
National Marine Fisheries Service  
Northeast Fisheries Science Center  
Woods Hole, Massachusetts

September 2007

## **Northeast Fisheries Science Center Reference Documents**

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**The stock assessments which are the subject of this document were peer reviewed by a panel of assessment experts known as the Stock Assessment Review Committee (SARC). Panelists were provided by the Center for Independent Experts (CIE), University of Miami. Reports from the SARC panelists and a summary report from the SARC Chairman can be found at <http://www.nefsc.noaa.gov/nefsc/saw>.**

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## INTRODUCTION TO SAW-45 ASSESSMENT REPORT

The Northeast Regional Stock Assessment Workshop (SAW) process has three parts: preparation of stock assessments by the SAW Working Groups and/or by ASMFC Technical Committees / Assessment Committees; peer review of the assessments by a panel of outside experts who judge the adequacy of the assessment as a basis for providing scientific advice to managers; and a presentation of the results and reports to the Region's fishery management bodies.

Starting with SAW-39 (June 2004), the process was revised in two fundamental ways. First, the Stock Assessment Review Committee (SARC) is now a smaller panel with panelists provided by the University of Miami's Independent System for Peer Review (Center of Independent Experts, CIE). Second, the SARC no longer provides management advice. Instead, Council and Commission teams (e.g., Plan Development Teams, Monitoring and Technical Committees) formulate management advice, after an assessment has been accepted by the SARC.

Reports that are produced following SAW/SARC meetings include: an *Assessment Summary Report* – a brief summary of the assessment results in a format useful to managers; this *Assessment Report* – a detailed account of the assessments for each stock; and the SARC panelist report – a summary of the reviewer's opinions and recommendations as well as appendices consisting of a report from each panelist. SAW/SARC assessment reports are available online at <http://www.nefsc.noaa.gov/nefsc/publications/series/crdlist.htm>. The CIE review reports and assessment reports can be found at <http://www.nefsc.noaa.gov/nefsc/saw/>.

The 45th SARC was convened in Woods Hole at the Northeast Fisheries Science

Center, June 4–9, 2007 to review two assessments (northern shrimp *Pandalus borealis*, and Atlantic sea scallop *Placopecten magellanicus*). CIE reviews for SARC45 were based on detailed reports produced by the ASMFC Northern Shrimp Technical Committee and the SAW Invertebrate Working Group.

This Introduction contains a brief summary of the SARC comments, a list of SARC panelists, the meeting agenda, a list of working group meetings and a list of attendees (Tables 1–4). Maps of the Atlantic coast of the USA and Canada are also provided (Figures 1–5).

### Outcome of Stock Assessment Review Meeting:

The northern shrimp assessment was accepted by the SARC. Although the reviewers were concerned about how to interpret the unprecedented high abundance index observed in the summer 2006 Gulf of Maine shrimp survey (particularly because the sampling intensity in that survey was lower than in preceding years), evidence of high abundance was also seen in commercial catch rates. The committee concluded that abundance in 2006 was high, but perhaps not as high as indicated by the survey and CSA assessment model. The large measure of agreement between the CSA and ASPIC models reinforced the credibility of the assessment results. Despite preference for reference points that take productivity into account, the reviewers concluded that, given the current low market demand and current high stock size, there is little risk to the stock of using the current reference points in the immediate future. Consumption estimates of northern shrimp by fish predators suggested that the rate of natural mortality ( $M$ ) is higher than the value assumed. The SARC felt that a higher value

for  $M$  should be used in future assessments. If  $M$  is changed, reference points will have to be recomputed.

The Atlantic sea scallop assessment was accepted by the SARC. The reviewers noted that much had been accomplished since the last assessment to improve data collection and interpretation. The SARC supported the approach of modeling the Mid-Atlantic and Georges Bank resources separately before combining the results. The committee noted that elimination of the retrospective patterns

when the CASA model results from the two areas were combined was fortuitous, and this does not imply that the patterns have similar causes or that the patterns will cancel out in future assessments. The SARC questioned using  $F_{\max}$  as a reference point because it does not explicitly ensure sufficient biomass to protect stock productivity. The SARC supported the projection model (SAMS) because it is based on fairly realistic inputs (e.g., includes spatial considerations).

Table 1. 45th Stock Assessment Review Committee Panel.

**45th Northeast Regional Stock Assessment Workshop (SAW 45)  
Stock Assessment Review Committee (SARC) Meeting**

June 4-9, 2007  
Woods Hole MA

**SARC Chairman:**

Dr. Michael Prager, chair  
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**SARC Panelists (CIE):**

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Table 2. Agenda, 45th Stock Assessment Review Committee Meeting.

**45th Northeast Regional Stock Assessment Workshop (SAW 45)  
Stock Assessment Review Committee (SARC) Meeting**

Stephen H. Clark Conference Room – Northeast Fisheries Science Center  
Woods Hole, Massachusetts

**June 4 – June 9, 2007**

Sessions are open to the public, except where indicated.

**AGENDA (5-24-07)**

TOPIC	PRESENTER	SARC LEADER	RAPPORTEUR
<b>Monday, 4 June (1:00 – 6:00 PM).....</b>			
Opening			
Welcome	<b>James Weinberg</b> , SAW Chairman		
Introduction	<b>Michael Prager</b> , SARC Chairman		
Agenda			
Conduct of Meeting			
Northern shrimp (A)	<b>Bob Glenn &amp; Jason Link</b>	<b>Jake Rice</b>	<b>Brad Spear</b>
SARC Discussion	<b>Michael Prager</b>		
<b>Tuesday, 5 June (9 AM – 6 PM)... (Lunch: Noon – 1:15 PM).....</b>			
Sea scallops (B)	<b>Dvora Hart</b>	<b>Nick Caputi &amp; JJ Maguire</b>	<b>Toni Chute</b>
SARC Discussion	<b>Michael Prager</b>		
<b>Wednesday, 6 June (9 AM – Noon) .....</b>			
Revisit Northern shrimp (A)	<b>Bob Glenn, Jason Link</b>	<b>Jake Rice</b>	<b>Brad Spear</b>
SARC Discussion	<b>Michael Prager</b>		

**Wednesday, 6 June (1:15 – 6 PM) .....**

Revisit Sea scallops (B)

**Dvora Hart**

**Nick Caputi & JJ Maguire**

**Toni Chute**

SARC Discussion

**Michael Prager**

**Thursday, 7 June (9 AM – 6:00 PM) .....**

Revisit Assessments (A – B) with presenters, if needed.

Followed by: SARC Report writing (closed).

**Friday, 8 June - Saturday, 9 June .....**

SARC Report writing (closed).

Table 3. 45th Stock Assessment Workshop, list of working groups and meetings.

<u>Assessment Group</u>	<u>Chair</u>	<u>Species</u>	<u>Meeting Date/Place</u>
ASMFC Northern Shrimp Technical Committee and NEFSC	Margaret Hunter, Maine Dept. Marine Resources		
		<b>Northern shrimp</b>	
			Sept. 28, 2006
			Oct. 10, 2006
			March 5, 2007
			April 19, 2007
			Durham, NH
Robert Glenn (Mass. Division Marine Fisheries)			
Josef Idoine (NEFSC)			
Clare McBane (NH Dept. Fish and Game)			
Braddock Spear (ASMFC)			
Jason Link (NEFSC)			
Invertebrate Working Group			
	Larry Jacobson, NMFS NEFSC		
		<b>Atlantic sea scallop</b>	
			March 3-9, April 9-11,
			April 30 – May 2, 2007.
			Woods Hole
Dvora Hart (Sea Scallop Assessment Lead Scientist, NEFSC, Woods Hole)			
Chuck Adams (School for Marine Science and Technology, UMASS Dartmouth)			
Andrew Applegate (New England Fishery Management Council)			
Deirdre Boelke (New England Fishery Management Council)			
Danielle Brezinski (University of Maine)			
Antonie Chute (Rapporteur, NEFSC, Woods Hole)			
Chad Demarest (Massachusetts Marine Fisheries Institute)			
Bill Du Paul (Virginia Institute of Marine Science)			
Demet Haksever (New England Fishery Management Council)			
Brad Harris (School for Marine Science and Technology, UMASS Dartmouth)			
Chad Keith (NEFSC, Woods Hole)			
Chris Legault (NEFSC, Woods Hole)			
Michael Marino (School for Marine Science and Technology, UMASS Dartmouth)			
Bob Mohn (Invited outside expert, Department of Fisheries and Oceans, Canada)			
Paul Nitschke (NEFSC, Woods Hole)			
Victor Nordahl (NEFSC, Woods Hole, MA)			
Cate O'Keefe (School for Marine Science and Technology, UMASS Dartmouth)			
Paul Rago (NEFSC, Woods Hole)			
Stacy Rowe (NEFSC, Woods Hole)			
David Rudders (Virginia Institute of Marine Science)			
Chris Sarro (School for Marine Science and Technology, UMASS Dartmouth)			
David Simpson (NEFMC and Connecticut Marine Fisheries Division)			
Stephen Smith (Invited outside expert, Department of Fisheries and Oceans, Canada)			
Ron Smolowitz (Fisheries Survival Fund)			
Kevin Stokesbury (School for Marine Science and Technology, UMASS Dartmouth)			
Jim Weinberg (NEFSC, Woods Hole)			
Noelle Yochum (Virginia Institute of Marine Science)			

Table 4. 45th SAW/SARC, List of Attendees

D. Cowan	NEFSC
R. Brown	NEFSC
H. Cook	NEFSC
M. Underwood	NEFSC
L. Brady	NEFSC
T. Lewandowski	NEFSC
L. Jacobson	NEFSC
J. Blaylock	NEFSC
N. Jacobson	SMAST, UMASS Dartmouth
P. Hughes	Atlantic Cape Fisheries, Inc.
D. Boelke	NEFMC
J. Fletcher	United National Fishermen's Assoc.
T. Bigelow	SMAST, UMASS Dartmouth
D. Hart	NEFSC
W. Gabriel	NEFSC
H. Moustahfid	NEFSC
K. Sosebee	NEFSC
M. Terceiro	NEFSC
W. Michaels	NEFSC
C. Keith	NEFSC
A. Hall	NEFSC
T. Chute	NEFSC
M. Taylor	NEFSC
J. Link	NEFSC
F. Almeida	NEFSC
K. Whitmore	MASS Division of Marine Fisheries
P. Chase	NEFSC
J. Idoine	NEFSC
B. Spear	ASMFC

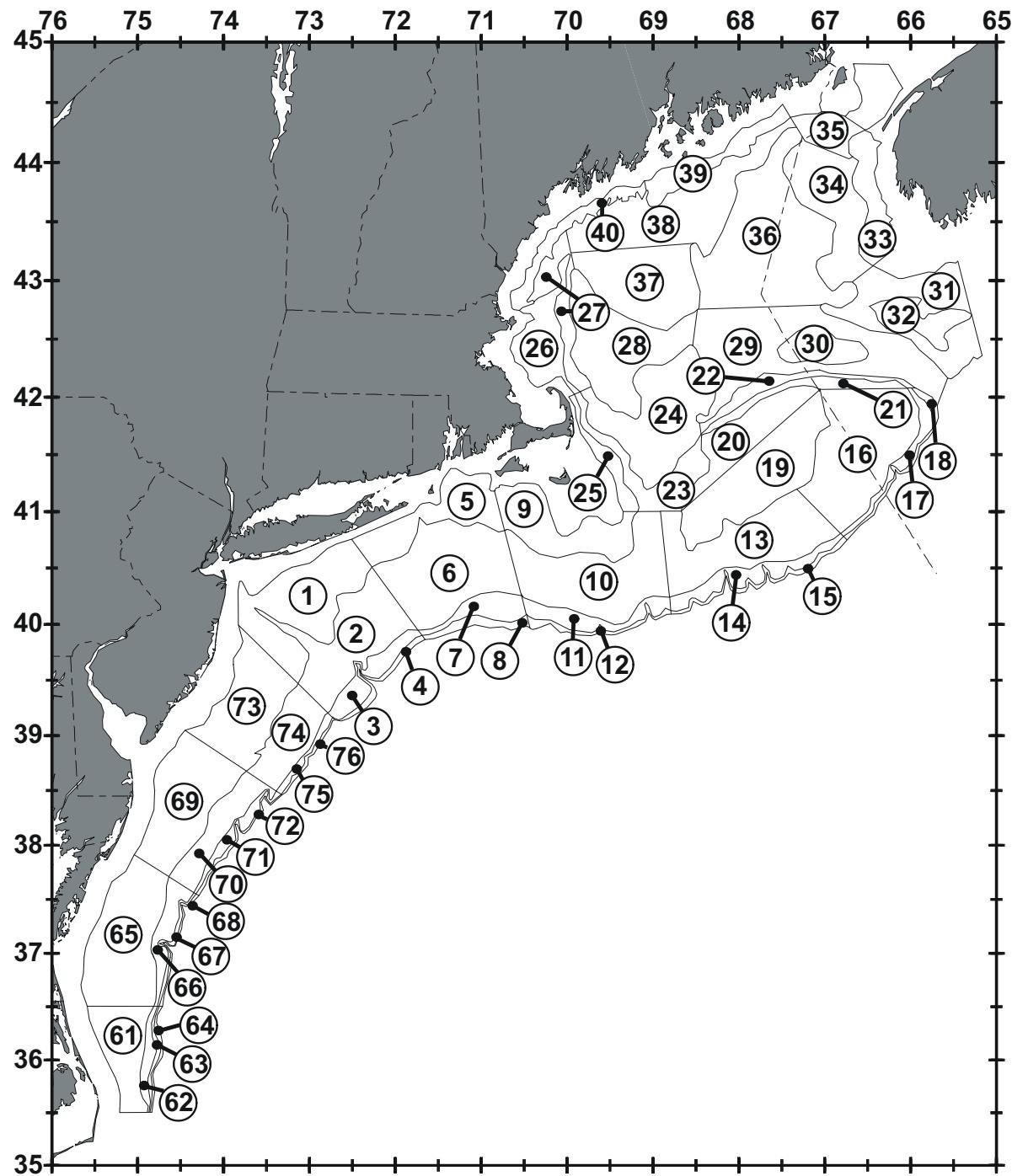


Figure 1. Offshore depth strata sampled during Northeast Fisheries Science Center bottom trawl research surveys.

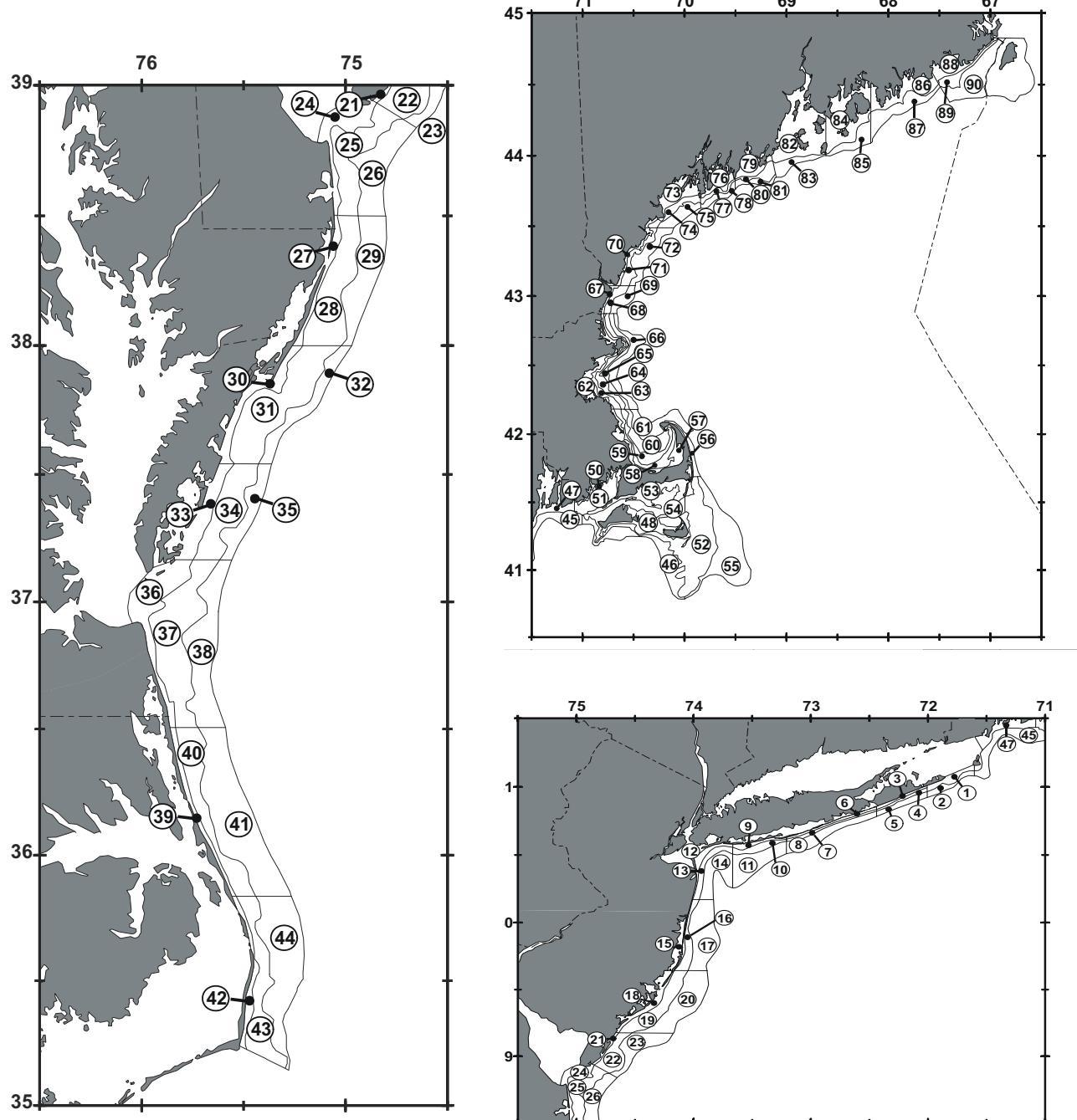


Figure 2. Inshore depth strata sampled during Northeast Fisheries Science Center bottom trawl research surveys.

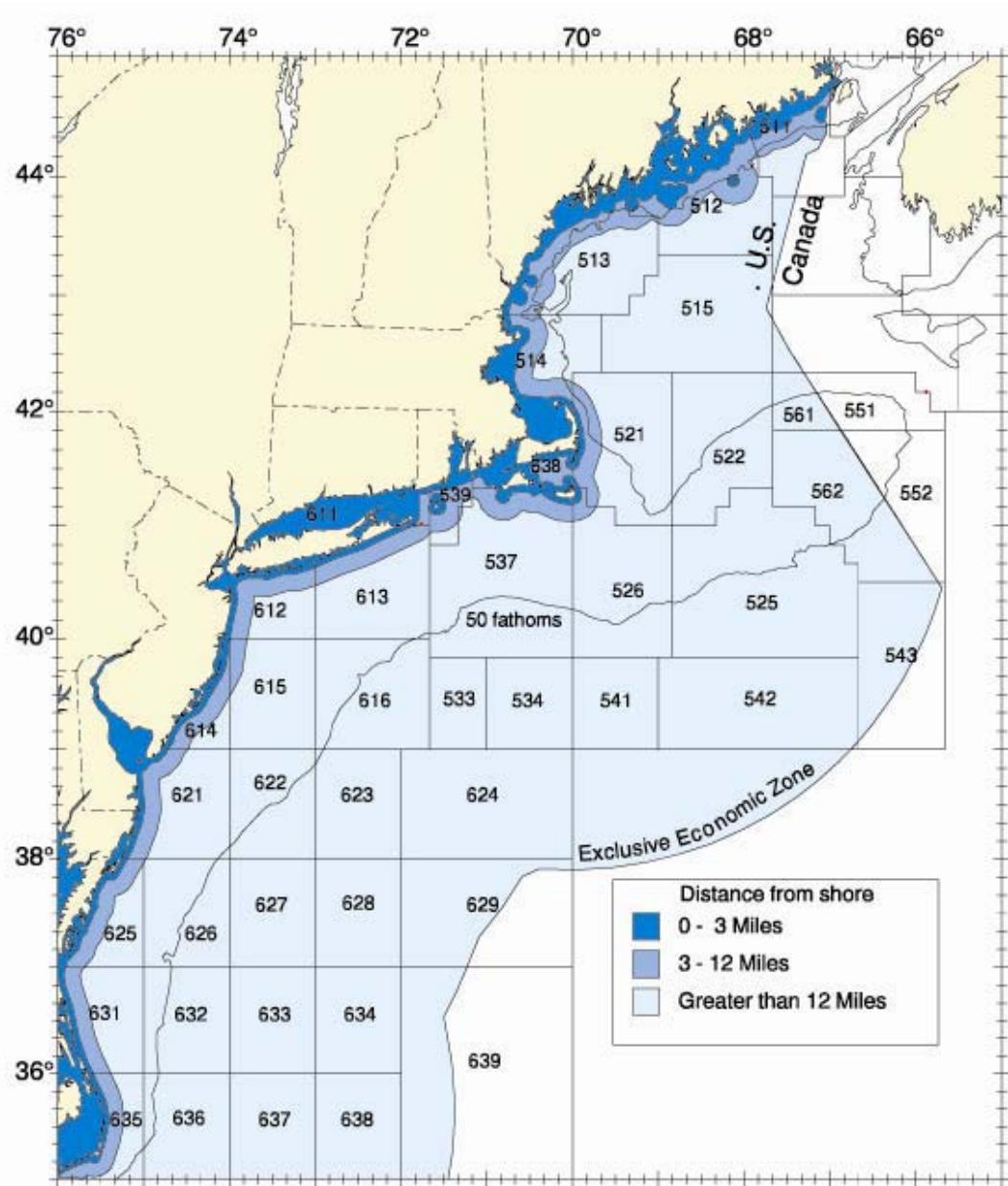


Figure 3. Statistical areas used for reporting commercial catches.

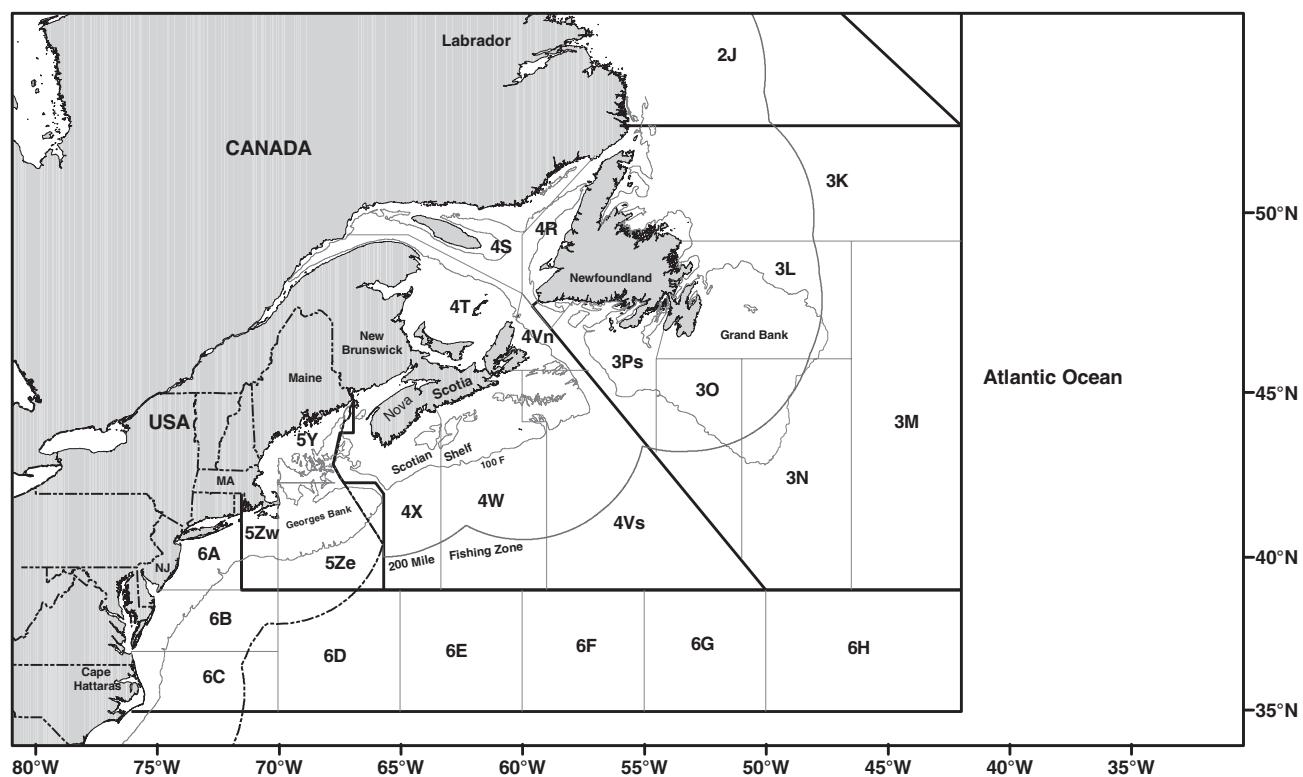


Figure 4. Catch reporting areas of the Northwest Atlantic Fisheries Organization (NAFO) for Subareas 3-6.

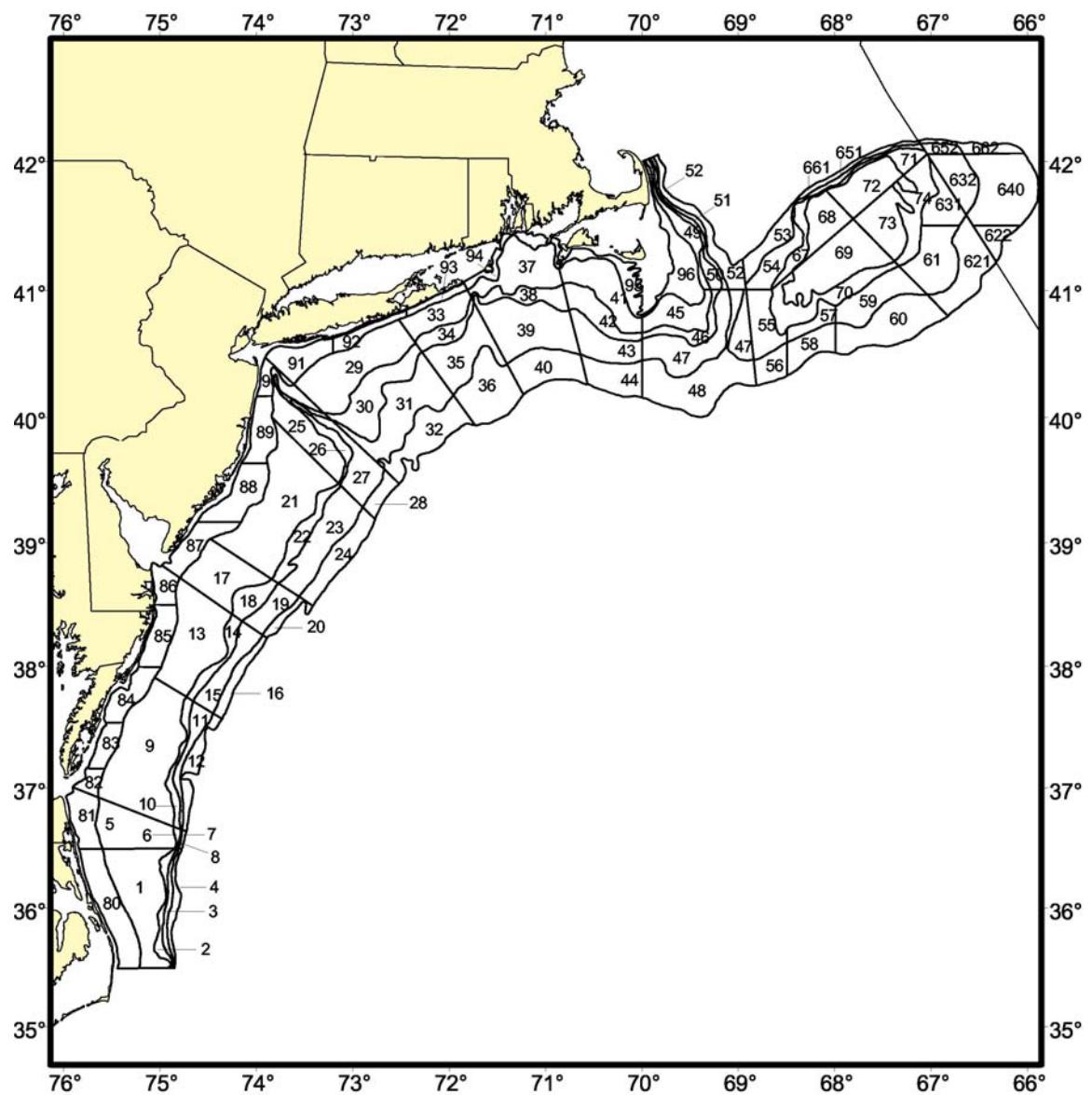


Figure 5. Shellfish strata for NEFSC resource surveys.

## A. ASSESSMENT OF NORTHERN SHRIMP

### A1.0 CONTRIBUTORS

ASMFC Northern Shrimp Technical Committee:  
Robert Glenn, Massachusetts Division of Marine Fisheries  
Margaret Hunter, Maine Department of Marine Resources, Chair  
Josef Idoine, Northeast Fisheries Science Center  
Dr. Clare McBane, New Hampshire Department of Fish and Game,

Braddock Spear, ASMFC coordinator

and

Dr. Jason Link, Northeast Fisheries Science Center

### A2.0 TERMS OF REFERENCE (TOR) FOR NORTHERN SHRIMP

1. Characterize the Gulf of Maine northern shrimp commercial catch, effort, and CPUE, including descriptions of landings and discards of that species.
2. Estimate fishing mortality and exploitable stock biomass in 2006 and characterize the uncertainty of those estimates. Also include estimates for earlier years.
3. Comment on the scientific adequacy of existing biological reference points (BRPs).
4. Evaluate current stock status with respect to the existing BRPs.
5. Perform sensitivity analyses to determine the impact of uncertainty in the data on the assessment results.
6. Analyze food habits data and existing estimates of finfish stock biomass to estimate annual biomass of northern shrimp consumed by cod and other major predators. Compare consumption estimates with removals implied by currently assumed measures of natural mortality for shrimp.
7. Review, evaluate and report on the status of the 2002 SARC/Working Group Research Recommendations.

## **A3.0 EXECUTIVE SUMMARY**

### **A3.1 Major findings for TOR 1 – Gulf of Maine northern shrimp commercial catch, effort, and CPUE, with descriptions of landings and discards**

Landings in the Gulf of Maine northern shrimp fishery declined since the mid 1990s (with 182-day seasons), from a high for the decade of 9,166 mt (20 million lbs) in 1996 to a low of 424 mt (0.9 million lbs) in 2002, the result of low abundances of shrimp and reductions in fishing effort. Since then, landings have increased to 2,553 mt (5.6 million lbs) in the 70-day 2005 season (preliminary) and 1,877 mt (4.1 million lbs) in the 140-day 2006 season (preliminary). The 2006 season was characterized by very high catch rates, low participation, and poor market demand. The numbers of fishing vessels and trawl trips have dropped from about 310 and 10,734 respectively in 1997 to 119 and 1,646 in 2006 (preliminary). Discard rates for northern shrimp have been low, except in the 1995 and 1996 whiting fisheries. See Section A5 for details.

### **A3.2 Major findings for TOR 2 – Estimate fishing mortality and exploitable stock biomass in 2006 and characterize the uncertainty of those estimates. Also include estimates for earlier years**

The estimate of fishing mortality from CSA modeling (preferred method) for 2006 was  $F=0.03$  (3% exploitation), based on preliminary 2006 landings data. Annual estimates for 1985 to 2005 range from 0.08 to 1.06. Exploitable stock biomass estimates vary from a low of 4,400 mt (9.7 million lbs) in 2001 to a high of 71,500 mt (158 million lbs) at the beginning of the 2007 fishing season. ASPIC modeling in general confirms the CSA trends, and provides fishing mortality and biomass estimates back to 1968. Bootstrap results suggest that estimates of abundance, biomass and fishing mortality were relatively precise, with the greatest uncertainty about the most recent biomass estimate. See Section A6 for details.

### **A3.3 Major findings for TOR 3 – Comment on the scientific adequacy of existing biological reference points (BRPs)**

The current biological reference points for Gulf of Maine northern shrimp are:

$$B_{\text{Threshold}} = 9,000 \text{ mt or } 19.8 \text{ million lbs}$$

$$B_{\text{Limit}} = 6,000 \text{ mt or } 13.2 \text{ million lbs}$$

$$F_{\text{Target/Threshold}} = 0.22$$

$$F_{\text{Limit}} = 0.60$$

(ASMFC 2004) and are based on historical abundance estimates and responses to fishing pressure, as shown in Figure A6-12. The BRPs provide adequate guidance to managers in a timely fashion. It is also noted that, unlike many managed species, the northern shrimp management process provides the ability for responses to changes in stock status in a short time period (annually). See Section A7 for details.

### **A3.4 Major findings for TOR 4 – Evaluate current stock status with respect to the existing BRPs**

The Gulf of Maine northern shrimp stock is in good condition; the stock is not overfished, nor is overfishing occurring. Recent fishing mortality rates were well below the BRPs, and biomass is well above. See section A8 for details.

### **A3.5 Major findings for TOR 5 – Perform sensitivity analyses to determine the impact of uncertainty in the data on the assessment results**

Sensitivity analyses on underreporting of landings in terminal years showed that CSA abundance and biomass estimates were not affected, but F values were sensitive. Starting biomass values from ASPIC runs were also affected. CSA abundance and biomass were sensitive to changes in the mean weight of a landed shrimp, while F was not. CSA abundance and biomass estimates were increased by a factor of 4 to 5 when values of M were increased from 0.25 to 0.60, while values of F were reduced. See section A9 for details.

### **A3.6 Major findings for TOR 6 – Analyze food habits data and existing estimates of finfish stock biomass to estimate annual biomass of northern shrimp consumed by cod and other major predators. Compare consumption estimates with removals implied by currently assumed measures of natural mortality for shrimp**

Food habits data (stomach contents) from NEFSC bottom trawl surveys conducted in the western Gulf of Maine were analyzed, and 18 major predators of pandalid shrimp were identified. Their annual rates of consuming pandalid shrimp were calculated, then multiplied by predator stock abundance estimates, and then summed over all the predator species to estimate the total pandalid abundance removed. The total amount of pandalid shrimp removed was finally multiplied by the ratio of *Pandalus borealis* to all pandalid shrimps, as estimated from the shrimp surveys and bottom trawl survey ratios, to estimate the total *P. borealis* removal. Consumptive removals of *P. borealis* were compared with survey abundance indices and model biomass estimates. Consumptive removals were generally the same order of magnitude, but usually higher, than model exploitable biomass estimates. Consumption exhibited some of the same trends as survey and model indices. The results suggest that there is more *P. borealis* biomass in the system than the models estimate, and that a value of M higher than 0.25 may be appropriate. See Section A10 for details.

### **A3.7 Major findings for TOR 7 – Status of the 2002 SARC Research Recommendations**

The stock assessment review committee (SARC), which met during the 36<sup>th</sup> Stock Assessment Workshop (SAW) in December 2002, made nine recommendations for further research (NEFSC 2003). Each recommendation was discussed and its status listed here. There has been significant progress made in improving estimates of natural mortality, M, based on predation data and sex-stage abundance ratios. Some other recommended items still await further work. See section A11 for details.

## **A4.0 INTRODUCTION**

### **A4.1 Management history**

The Gulf of Maine fishery for northern shrimp (*Pandalus borealis* Krøyer) is managed through interstate agreement between the states of Maine, New Hampshire and Massachusetts. The management framework evolved during 1972-1979 under the auspices of the State/Federal Fisheries Management Program. In 1980, this program was restructured as the Interstate Fisheries Management Program (ISFMP) of the Atlantic States Marine Fisheries Commission (ASMFC). The Fishery Management Plan (FMP) for Northern Shrimp was approved under the ISFMP in October 1986 (McInnes 1986). The full Commission in May 2004 approved Amendment 1 to the FMP (ASMFC 2004). Amendment 1, which entirely replaces the original FMP, establishes biological reference points (BRPs) for the first time in the shrimp fishery and expands the tools available to manage the fishery. Any new tools proposed to manage the shrimp fishery must be implemented through the ASMFC addendum process.

Within the ISFMP structure, the Northern Shrimp Technical Committee (NSTC) provides annual stock assessments and related information to the ASMFC Northern Shrimp Section. Annually, the Section decides on management regimes after thorough consideration of the NSTC stock assessment, input from the Northern Shrimp Advisory Panel, and comment from others knowledgeable about the shrimp fishing industry. In the first five years (1987 – 1991) after the passage of the 1986 FMP, the NSTC generally recommended full fishing seasons (182 days) and the Section followed the committee's recommendations (Table A4-1). Nearly every year from 1992 to 1999, the NSTC recommended restricted seasons. The managers set seasons that were less than the full 182 days but more than the seasons recommended by its scientific advisors. With the exception of 2001, the NSTC recommended no fishery from 2000 to 2004. The managers set limited fishing seasons during that time, with the shortest (25 days) in 2002. The NSTC has taken a new approach to its recommendation to the Section since 2005. It recommends a maximum landings amount for the fishing season. The Section used that number and recommendations from the Advisory Panel to establish recent seasons. In the past two years the Section has tentatively set both the upcoming and the following year's season length, provided triggers for number of fishing trips, landings, and fishing mortality in the first year are not exceeded.

### **A4.2 History of past assessments and approach taken in this one**

#### **A4.2.1 Past Assessments**

Stock assessments initially consisted of total landings estimates, indices of abundance from Northeast Fisheries Science Center (NEFSC) groundfish surveys, fishing mortality estimates from the application of cohort slicing of length frequencies from the State of Maine survey, and yield per recruit modeling (Clark and Anthony 1980; Clark 1981, 1982).

The NSTC unified individual state port sampling programs in the early 1980s to better characterize catch at length and developmental stage (sex and maturity), and established a dedicated research trawl survey for the species in the summer of 1983 to monitor relative abundance, biomass, size structure and demographics of the stock annually. Subsequent stock assessments provided more detailed description of landings, size composition of catch, patterns in fishing effort, catch per unit effort, relative year class strength and survey indices of total

abundance and biomass. Length distributions from the summer shrimp survey have been used for size composition analysis to estimate mortality rates, but did not fit length-based models well because of variable recruitment and growth (Terceiro and Idoine 1990, Fournier et al. 1991).

Beginning in 1997, the northern shrimp stock in the Gulf of Maine has been evaluated more quantitatively using three analytical models that incorporate much of the available data (Cadrin et al. 1999):

- Preferred: Collie-Sissenwine analysis (CSA) that tracks removals of shrimp using summer survey indices of recruits and fully-recruited shrimp scaled to total catch in numbers, and provides estimates of  $F$  (instantaneous fishing mortality rate) and  $B$  (exploitable biomass) – see Section A6.3;
- Supportive: A surplus production analysis (ASPIC) that models the biomass dynamics of the stock with a longer times series of total landings and three survey indices of stock abundance – see Section A6.3;
- A yield-per-recruit (YPR) model and an eggs-per-recruit (EPR) model that simulate the life history of northern shrimp (including growth rates, transition rates, natural mortality, and fecundity) and fishing mortality on recruited shrimp. It uses estimates of trawl selectivity to estimate yield and egg production at various levels of fishing mortality, providing guidance on the selection of biological reference points (Cadrin et al. 1999).

In 2004, Amendment 1 to the ASMFC Interstate Fishery Management Plan for Northern Shrimp was adopted. This was the first time formal biological reference points were defined for this fishery (see Section A7).

#### **A4.2.2 Current Assessment and Changes from Past Assessments**

Assessments are made annually in October, using the above methods, last reviewed by SARC 36 in 2002.

In 2002 the NSTC began using a new method of calculating the instantaneous rate of fishing mortality,  $F$ , based on CSA harvest rates instead of the log-ratio method (Collie and Kruse, 1998).

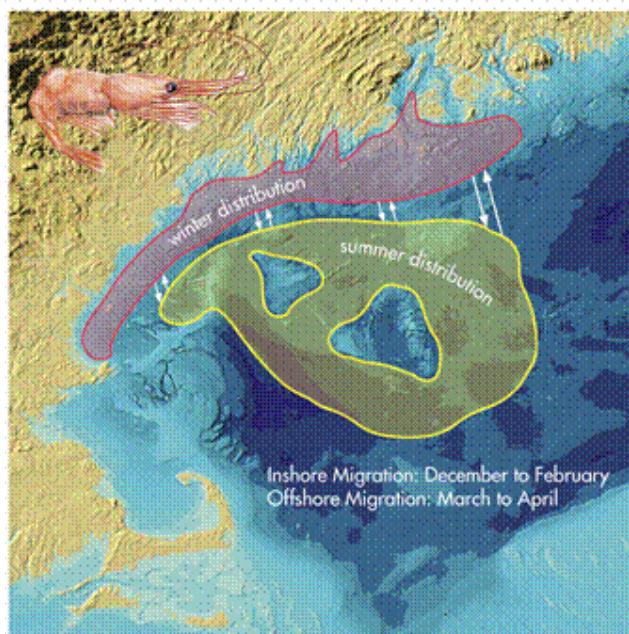
In the current assessment, results of using an instantaneous rate of natural mortality,  $M$ , of 0.25, which was used in past assessments, is compared with results using a value of 0.60. See Sections A6.3, A7, and A10 for discussion.

### **A4.3 Biology**

#### **A4.3.1 Life History**

Northern shrimp (*Pandalus borealis* Krøyer) are protandric hermaphrodites, usually maturing first as males at roughly 2½ years of age and then transforming to females at roughly 3½ years of age in the Gulf of Maine (Figure A4-1). Spawning takes place in offshore waters beginning in late July. By early fall, most adult females extrude their eggs onto the abdomen. Egg-bearing females move inshore in late autumn and winter, where the eggs hatch. The planktonic larvae pass through six larval stages and settle to the bottom in inshore waters after metamorphosing to a juvenile state (Berkeley 1930; Haynes and Wigley, 1969; Apollonio and Dunton 1969; Stickney and Perkins 1977; Stickney 1980). Juveniles remain in coastal waters for a year or more before migrating to deeper offshore waters, where they mature as males. The

males pass through a series of transitional stages before maturing as females. Some females may survive their first egg hatch to repeat the spawning process. Females that have never extruded eggs are referred to here as “female I”. Non-ovigerous females that have carried eggs in the past are “female II”. Female Is and IIs can be distinguished by the presence or absence of sternal spines (McCravy 1971). The females are the individuals targeted in the Gulf of Maine fishery. It is believed that most *P. borealis* in the Gulf of Maine do not live past age 5 (Haynes and Wigley 1969; Apollonio and Dunton 1969).



Distribution of adult female northern shrimp, from *Ecosystem Relationships in the Gulf of Maine-Combined Expert Knowledge of Fishermen and Scientists. NAMA collaborative report 1:1-16, 2006.*

was evidence of both very early- and late-maturing females appearing at assumed age 1½, but also males remaining as males at assumed age 3½ (Figure A6.7).

Growth, as in other crustaceans, is a discontinuous process associated with molting of the exoskeleton (Hartnoll 1982). Information on growth of Gulf of Maine northern shrimp has been reported by Haynes and Wigley 1969; Apollonio et al. 1986; Terceiro and Idoine 1990; and Fournier et al. 1991. Differences in size at age by area and season can be ascribed in part to temperature effects, with more rapid growth rates at higher temperatures (Apollonio et al. 1986).

Instantaneous natural mortality (M) for northern shrimp stocks has been estimated between 0.2 and 1.0 (Shumway et al. 1985). See sections A6.3 and A10 for further discussion of M.

#### 4.3.2 Habitat

*Pandalus borealis*, and its northeast Pacific relative *Pandalus eous*, have a discontinuous distribution throughout the North Atlantic, North Pacific, and Arctic Oceans. In the Gulf of Maine, northern shrimp populations comprise a single stock (Clark and Anthony 1981), which is concentrated in the southwestern region of the Gulf (Haynes and Wigley 1969; Clark et al. 1999). Water temperature, salinity, depth, and substrate type have all been cited as important factors governing shrimp distribution in the Gulf of Maine (Haynes and Wigley 1969; Apollonio et al. 1986; Shumway et al. 1985).

The extent, location, and timing of these transitions and migrations are variable. Several factors may influence the size and age at sex transition (see Bergström 2000 for review). Several year classes in recent decades show some percentage of 2½ year old shrimp maturing first as females instead of males (early-maturing females) (Figure A6.7). This presents both sexes in the same year class and may be a reaction to stress in the population as predicted by sex allocation theory (Charnov et al. 1978), or may be temperature (Apollonio et al. 1986; Hansen and Aschan 2000) or density dependent growth driven (Koeller et al. 2000), or may be the result of fishery removals of larger females selecting for smaller females

(Marliave et al. 1993; Bergström 2000). Other year classes have exhibited some late sex transition. In the 2001 year class, there

#### A4.3.2.1 Temperature

The most common temperature range for this species is 0-5 °C (Shumway et al. 1985). The Gulf of Maine marks the southern-most extent of this species' range in the Atlantic Ocean, and seasonal water temperatures in many areas regularly exceed the upper physiological limit for northern shrimp. This environmental limitation restricts the amount of available habitat occupied by this species to the western region of the Gulf (west of 68°W) where bottom topography and oceanographic conditions create submarine basins protected from seasonal warming by thermal stratification. The deep basins act as cold water refuges for adult shrimp populations (Apollonio et al. 1986). In the northeastern region of the Gulf, large shrimp populations do not persist because bottom waters are not protected from seasonal warming, due to continual mixing from intense tidal currents nearer to the Bay of Fundy (Apollonio et al. 1986).

Several studies have found a significant negative correlation between annual mean temperatures and recruitment of northern shrimp (Dow, 1977; Richards et al. 1996). While the manner by which temperature affects recruitment and abundance trends has not been precisely determined, record high sea surface temperatures during the early 1950s correlate with complete failure of the fishery from 1954-1957; and conversely, the cold temperature years of the early to mid-1960s appear to have been very favorable for recruitment, with rapid increases in abundance and record landings from 1969-1972. The collapse of the fishery during the 1970s was more problematic as it occurred during a period of warming temperatures, and high and increasing levels of F; overfishing has been strongly implicated for the collapse. During the last two decades, significant recruitment events have coincided with normal to below normal spring sea surface temperature anomalies (ASMFC 2004).

#### A4.3.2.2 Depth

In the Gulf of Maine, northern shrimp are most frequently found from about 10 m to over 300 m (30-1000 ft) (Haynes and Wigley 1969), with juveniles and immature males occupying shallower, inshore waters and mature males and females occupying cooler, deeper offshore waters for most of the year (Apollonio and Dunton 1969, Haynes and Wigley 1969, Apollonio et al. 1986). During the summer months, adult shrimp inhabit water from 93-183 m (300-600 ft) (Clark et al. 1999); ovigerous female shrimp are found in shallower near-shore waters during the late winter and spring (Apollonio and Dunton 1969, Clark et al. 1999) when their eggs are hatching.

#### A4.3.2.3 Substrate

Northern shrimp most commonly inhabit organic-rich, mud bottoms or near-bottom waters (Hjort and Ruud 1938; Bigelow and Schroeder 1939; Wigley 1960; Haynes and Wigley 1969), where they prey on benthic invertebrates; however, shrimp are not limited to this habitat and have been observed on rocky substrates (Schick 1991). Shrimp distribution in relation to substrate type determined by trawl surveys clearly show northern shrimp primarily occupy areas with fine sediments (sand, silt, and clay) (ASMFC 2004). Shrimp are often associated with biotic or abiotic structures such as cerianthid anemone (Langton and Uzmann 1989) and occasional boulders in these fine sediment habitats (Daniel Schick, Maine Department of Marine Resources, pers. comm.).

#### **A4.3.3 Predators and Prey**

Northern shrimp are an important component of marine food chains, preying on both plankton and benthic invertebrates, and being consumed by many commercially important fish species, such as cod, redfish and silver and white hake (ASMFC 2004). *P. borealis* diet was documented by Wienberg (1981) and Apollonio and Dunton (1969). Species that include *P. borealis* in their diet are documented by many authors (see Synopsis: Shumway et al. 1985.) See section 10.0 for further discussion of predation.

#### **A4.3.4 Migration**

The migrations of juvenile northern shrimp from inshore to offshore areas in the western Gulf of Maine, and the subsequent movement of ovigerous females from offshore to inshore, are discussed above.

##### **A4.3.4.1 Vertical migration**

Male and non-ovigerous female shrimp exhibit diurnal vertical migration, from bottom and near-bottom during the day, up into the water column to feed at night. Egg-bearing females are less likely to exhibit vertical diurnal migration, and are more likely to stay on the bottom (Apollonio and Dunton 1969; Apollonio et al. 1986).

#### **A4.3.5 Other Pandalid Species**

The striped shrimp, *Pandalus montagui*, and the bristled long-beak shrimp, *Dichelopandalus leptocerus*, both smaller and less abundant than *Pandalus borealis*, are also common in Gulf of Maine commercial and survey catches, but are not targeted by the fishery.

See ASMFC (2004) for more information on the biology of *Pandalus borealis*.

### **A4.4 Fishery Description**

Northern shrimp occur in boreal and sub-arctic waters throughout the North Atlantic and North Pacific, where they support important commercial fisheries. In the western North Atlantic, commercial concentrations occur off Greenland, Labrador, and Newfoundland, in the Gulf of St. Lawrence, and on the Scotian Shelf. The Gulf of Maine marks the southernmost extent of its Atlantic range (Parsons and Fréchette, 1989). In the Gulf of Maine, primary concentrations occur in the western Gulf where bottom temperatures are coldest. In summer, adults are most common at depths of 90-180 meters (Clark et al. 2000).

The fishery has been seasonal in nature, peaking in late winter when egg-bearing females move into inshore waters and terminating in spring under regulatory closure (ASMFC 2004). Northern shrimp have been an accessible and important resource to fishermen working inshore areas in smaller vessels who otherwise have few winter options due to seasonal changes in availability of groundfish, lobsters and other species (Clark et al. 2000).

A summer fishery, which existed in the 1970s, caught shrimp of all ages, including age 1 and 2. These immature and male shrimp made up 40-50% of the catch by numbers in April-June, increasing to 70-80% for July-September, during 1973-1974 (Clark et al. 2000). Since 1976, fishing has been restricted to months within a December to May timeframe. (Throughout

this document, references to a particular fishing year will include the previous December unless otherwise indicated – *e.g.* the 2006 season includes December 2005 but not December 2006, which will belong to the 2007 season.)

The fishery formally began in 1938, and during the 1940s and 1950s almost all of the landings were by Maine vessels from Portland and smaller Maine ports further east. This was an inshore winter trawl fishery, directed towards egg-bearing females (presumably age 4 and 5) in inshore waters (Scattergood 1952). New Hampshire vessels entered the fishery in 1966, but throughout the 1960s and 1970s New Hampshire landings were minor. In contrast to the historical wintertime Maine fishery, New Hampshire and Massachusetts vessels fished continually throughout the year and made significant catches during summer months in the 1970s. New Hampshire currently accounts for about 10% of the total catch for the Gulf of Maine.

Landings by Massachusetts vessels were insignificant until 1969, but in the early 1970s the fishery developed rapidly, with Massachusetts landings increasing from 14% of the Gulf of Maine total in 1969 to over 40% in 1974-1975. Massachusetts landings have declined to 1-6 % of total during the past 10 years, while Maine vessels have accounted for 80-90% (Tables A5-1 and A5-2).

A map of the areas fished in 2006 is shown in Figure A4-2 (preliminary data).

A wide variety of vessels have been used in the fishery (Bruce 1971; Wigley 1973). The predominant type during the 1960s and 1970s appears to have been side-rigged trawlers in the 14-23 m (45-75 ft) range. During the 1980s and 1990s, side trawlers either re-rigged to stern trawling, or retired from the fleet. Currently, the shrimp fleet is comprised of lobster vessels in the 9-14 m (30-45 ft) range that re-rig for shrimping, small to mid-sized stern trawlers in the 12-17 m (40-55 ft) range, and larger trawlers primarily in the 17-24 m (55-80 ft) range. The otter trawl remains the primary gear employed and is typically chain or roller rigged, depending on area and bottom fished. There has been a trend in recent years towards the use of heavier, larger roller and/or rockhopper gear. These innovations, in concert with substantial improvements in electronic equipment, have allowed for much more accurate positioning and towing in formerly unfishable grounds, thus greatly increasing the fishing power of the Gulf of Maine fleet. The number of vessels participating in the fishery in recent years varied from a high of 310 in 1997 to a low of 119 in 2006 (preliminary data).

A small pot fishery has also existed in mid-coastal Maine since the 1970s, where in many areas bottom topography provides favorable shrimp habitat that is too rough or restricted for trawling. The trapped product is of good quality, as the traps target only female shrimp once they have migrated inshore. According to vessel trip reports (VTRs), trappers accounted for 12% of Maine's landings in 2001-2006 (Table A5-3). There is some indication that trap fishing for shrimp has grown in a few areas such as South Bristol (mid-coast Maine) and would continue to grow if market conditions were more favorable. Since the trap fishery is dependent on the inshore availability of shrimp in a specific area, there is apparently a shorter season for traps than for draggers. Most shrimp trappers also trap lobsters at other times of the year.

Management measures currently in place include season length (varying from year to year within a December 1 through May 31 timeframe), gear restrictions, licensing, and mandatory reporting. Maine and New Hampshire have open-access shrimp fisheries. Legal restrictions on trawl gear require a minimum 44.5 mm (1.75 inch) stretch mesh net and the use of a finfish separator device known as the “Nordmore grate” with a maximum grate spacing of 25.4 mm (1 inch) (ASMFC 2004).

## A5.0 GULF OF MAINE NORTHERN SHRIMP COMMERCIAL CATCH, EFFORT, AND CPUE, WITH DESCRIPTIONS OF LANDINGS AND DISCARDS (TOR#1)

### A5.1 Data sources

Commercial landings by state and month have been compiled by NMFS port agents from dealer reports. It is likely that catches sold to the small “peddler” market were unreported, as well as some of those sold to those dealers (non-federally permitted) who are not required to report. These data were used for annual stock assessments until 2001, when vessel trip reports (VTRs) were found to be more complete. Small Maine vessels that did not have federal permits were not required to fill out VTRs until 2000. Landings (quantity kept, not discarded) and numbers of vessels and trips have been calculated from VTRs for use in assessments since 2001. However, the data for latter years (eg. 2005 and 2006 fishing seasons) are preliminary. Data used here for 2006 were compiled from VTRs received and entered as of September 2006. We expect final landings for 2006 to be as much as 20% higher than reported here.

Prior to 1994, effort (numbers of trips by state and month) was estimated from landings data collected from dealers, and landings per trip information (LPUE) from dockside interviews of vessel captains:

$$Effort = \frac{Landings}{LPUE}$$

Beginning in the spring of 1994, a vessel trip reporting system (VTR) supplemented the collection of effort information from interviews. From 1995 to 2000, landings per trip (LPUE) from these logbooks were expanded to total landings from the dealer weighouts to estimate the total trips:

$$Total.Trips = VTR.Trips \frac{Total.Landings}{VTR.Landings}$$

Since 2000, VTR landings have exceeded dealer weighout landings, and the above expansion is not necessary. The 1996 assessment report (Schick et al. 1996) provides a comparison of 1995 shrimp catch and effort data from both the NEFSC interview and logbook systems and addresses the differences between the systems at that time. It showed a slightly larger estimate from the logbook system than from the interview system. Thus effort statistics reported through 1994 are not directly comparable to those collected after 1994. However, patterns in effort can be examined if the difference between the systems is taken into account. An additional complication of the logbook system is that one portion of the shrimp fishery may not be adequately represented by the logbook system during 1994-1999. Smaller vessels fishing exclusively in Maine coastal waters are not required to have federal groundfish permits and were not required to submit shrimp vessel trip reports until 2000. In the 1994-2000 assessments, effort from unpermitted vessels was characterized by catch per unit effort of permitted vessels.

Beginning in 2001, landings, vessels, and trips are calculated from vessel trip reports (VTRs) only.

A port sampling program was established in the early 1980s to characterize catch at length and developmental stage, as well as to collect effort and fishing depth and location data. Samplers strive to achieve representative sampling by maintaining up-to-date lists of active buyers and visiting ports in proportion to their landings activity. Sampling consists of interviewing boat captains and collecting a 1 kg (2.2 lbs) sample of shrimp from each catch. The

samples are separated and weighed in the lab by species, sex and development stage. Measurements are made of all shrimp dorsal carapace lengths to the nearest 0.01 mm. The numbers of shrimp measured each season are shown in Table A5-6.

## A5.2 Commercial Landings

### A5.2.1 Total Landings

Small quantities of northern shrimp have been incidentally caught in New England otter trawl fisheries since 1905 (Scattergood 1952). A directed winter fishery in coastal waters developed in the late 1930s, which landed an annual average of 63 mt (139,000 lbs) from 1938 to 1953, but no shrimp were landed from 1954 to 1957 due to low inshore availability (Wigley 1973). The fishery resumed in 1958, and landings increased steadily to a peak of 12,824 mt (28,272,000 lbs) in 1969 as an offshore, year-round fishery expanded (Table A5-1). After 1972, landings declined rapidly, and the fishery was closed in 1978. The fishery reopened in 1979 and seasonal landings increased gradually to 5,253 mt (11,581,000 lbs) by 1987 and averaged 3,300 mt (7,275,000 lbs) from 1988 to 1994 (Tables A5-1 and A5-2). Seasonal landings increased to 6,466 mt (14,255,000 lbs) in 1995 and to 9,166 mt (20,208,000 lbs) in 1996, which was only exceeded by the five years of landings prior to the late 1970s stock collapse. Landings declined between 1996 and 1999 to 1,816 mt (4,004,000 lbs). This was followed by a slight increase to 2,390 mt (5,269,000 lbs) in the 2000 season. Landings dropped during 2001 to 1,329 mt (2,930,000 lbs) and in 2002 to a low of 424 mt (935,000 lbs) for the 25-day 2002 season. The 2002 landings were the lowest northern shrimp landings since the fishery was closed in 1978 (Table A5-1, Figure A5-1). Total landings increased in 2003 to 1,211 mt (2,670,000 lbs) and in 2004 to 1,949 mt (4,297,000 lbs). The 2005 northern shrimp landings increased to 2,553 mt (5,628,000 lbs) (preliminary), the highest since the 1998 season (Table A5-1). The fishing season for 2006 reached 1,877 mt (4,138,000 lbs) (preliminary) with poor market conditions.

### A5.2.2 Landings by State

Maine landings comprised 75% of season totals during 1984-1996. The proportional distribution of landings among the states has shifted gradually since the 1980's when Massachusetts accounted for about 30% of the catch. In 2005 and 2006, the proportional distribution of landings was still greatest for Maine, followed by NH with 12% (2005) and 5% (2006). Massachusetts landings made up 2% of the 2005 landings and 1% of the landings in 2006 (Tables A5-1 and A5-2, and Figure A5-1).

### A5.2.3 Landings by Time of Year

The distribution of landings throughout the season, during years which had full 6-month seasons (December to May, and some longer), is shown in Figure A5-2. The majority of landings generally occur in January and February (Table A5-2, Figure A5-2). See Clark et al. (2000) for a discussion of the distribution in the 1970s when fishing was allowed during summer months.

#### **A5.2.4 Landings Size and Sex Composition and Year Class Strength**

Size composition data, collected from catches since the early 1980s, indicate that trends in landings have been determined primarily by recruitment of strong (dominant) year classes (Figures A5-1 and A5-7). Landings more than tripled with recruitment of a strong 1982 year class in 1985 – 1987 and then declined sharply in 1988. A strong 1987 year class was a major contributor to the 1990-1992 fisheries. A strong 1992 year class, supplemented by a moderate 1993 year class, partially supported large annual landings in 1995 – 1998 (Figure A5-7). Low landings in 1999 – 2003 were due in part to poor 1994, 1995, 1997, 1998, and 2000 year classes with only moderate 1996 and 1999 year classes. The 2003 catches were composed primarily of assumed 4-year old females from the 1999 year class, and early-maturing two-year-old females and two-year-old juveniles, males and transitionals from the strong 2001 year class. Catches in 2004 were composed primarily of egg bearing, early maturing, presumed three-year-old females from the 2001 year class and a few larger females from the 1999 year-class. In 2005, catches were composed of egg bearing females and female II's from the presumed 2001 year class and males from the 2003 year class. 2006 catches were composed of egg bearing and female IIs, probably from the strong 2001 year class. Catches in March and April had significant numbers of smaller shrimp, presumably from the 2003 (transitionals and female I's) and 2004 (juveniles and males) year classes (Figures A5-5 and A5-6).

Maine trappers produced a smaller proportion of small shrimp in the landed catch than trawls, and generally were more apt to catch large females after egg hatch, as in previous years (Figure A5-5). See the table below for average counts per pound by month and gear.

<b>2006 commercial shrimp fishery average counts per pound, from port samples. 1 lb=0.45kg</b>										
	<i>Pandalus borealis</i> only					All shrimp species				
	<b>Dec.</b>	<b>Jan.</b>	<b>Feb.</b>	<b>Mar.</b>	<b>Apr.</b>	<b>Dec.</b>	<b>Jan.</b>	<b>Feb.</b>	<b>Mar.</b>	<b>Apr.</b>
Maine trawls	40	38	36	56	60	41	40	38	58	58
Maine traps	no samples	33	35	36	35	no samples	35	37	37	59
Maine total	40	37	36	48	57	41	39	37	50	58
<hr/>										
Massachusetts	no samples	48	50	50	44	no samples	48	50	49	43
New Hampshire	38	47	50	61	62	38	48	50	60	62

In the 2007 fishery it is expected (from the 2006 summer survey size distributions; see Figure A6-7) that the strong 2001 year class (assumed 6-year-old females) may still be present, the 2002 year class (assumed 5-year-old females) will be very weak, the strong 2003 year class (4-year-old females) will contribute most to landings, and the exceptionally strong 2004 year class and moderate 2005 year class will be transitionals, males and juveniles.

Landings from January to March consist primarily of mature female shrimp (presumably ages 3 and older) and December, April, and May landings have included higher proportions of males (assumed ages 1 and 2; Figure A5-4b, A5-5, and A5-6). These patterns reflect shifts in distribution of fishing effort in response to seasonal movements of mature females: inshore in mid-winter and offshore after their eggs hatch.

#### A5.2.5 Landings in Numbers

Catch in numbers for the CSA model (see section 6.0) was derived by dividing landed weight (Table A5-2) by mean individual weights from port samples by year, state and month -- see the example in the table below. Individual weights are calculated by dividing the total weight of a sample by the number of *P. borealis* in the sample. Mean weight for non-sampled landings was estimated (in past years) by a general linear model of mean weight incorporating year, month and state effects, or (in recent years) by using samples from a nearby state or month within the same year.

The general patterns in size composition of landings are reflected in mean weight of individual shrimp landed by year, state, and month: the size of landed shrimp generally increases from December to January, peaks in February, and decreases through the spring, and is often larger in Maine landings than in those of the other states, and larger in Maine trap catches than trawl catches.

Mean weights of individuals (and numbers of samples) of <i>P. borealis</i> in 2006 catches 1 g = 0.0022 lb				
		Maine	New Hampshire	Massachusetts
<b>December</b>	Trawls Traps	11.49g (14) No samples, use Jan.	11.97g ( 3)	No samples, use NH Dec.
<b>January</b>	Trawls Traps	12.36g (29) 13.69g ( 6)	9.68g ( 4)	10.01g ( 1)
<b>February</b>	Trawls Traps	12.97g (26) 13.76g (13)	9.41g ( 4)	9.28g ( 5)
<b>March</b>	Trawls Traps	8.63g (21) 12.90g (13)	7.62g ( 5)	9.45g ( 5)
<b>April</b>	Trawls Traps	7.99g ( 9) 29.71g*( 1)	7.45g ( 3)	10.58g ( 1)

\*From one sample that was more than half *P. montagui*.

#### A5.3 Commercial Discards

Sea sampling observations aboard trips using a shrimp trawl from 1989 to 1997 and 2001 to 2006 in the Gulf of Maine (NMFS statistical areas 511, 512, 513, and 514) indicate that the mean weight of shrimp discards is less than 1% of total catch for all years except 1997, when it was 1.36% (Table A5-7).

From examination of the observer database for 1989 to 2006, the only other fisheries which had trips with significant shrimp discards were the small-mesh herring and whiting fisheries. Industry representatives reported substantial discards of shrimp in the small-mesh whiting fishery east of Jeffreys Ledge in the mid 1990s. Sea sampling observations from finfish trawl fisheries in the Gulf of Maine suggest that bycatch of northern shrimp was inconsequential from 1984-1994. However, in 1995 and 1996 the amount of discarded shrimp per trip increased considerably, and the increase was from small-mesh (whiting) trips sampled in the area of Jeffreys Ledge. The mean shrimp discarded per observed whiting trip was 62 kg (137 lbs) in 1996. Unfortunately, no shrimp lengths were measured during sea sampling, and estimating the

total number discarded would be difficult. Shrimp discards in observed small-mesh trips have averaged less than 1 kg (2.2 lbs) since 1996 (Table A5-7).

Shrimp discards were considered, but not included in this assessment.

## A5.4 Commercial Catch Rates and Fishing Effort

### A5.4.1 Trips

Since the late 1970's, effort in the fishery (measured by numbers of trips in which shrimp gear is used) has increased and then declined on three occasions. The total number of trawl trips in the fishery peaked at 12,285 during the 1987 season (Table A5-4, Figure A5-8a). Increases in season length, shrimp abundance and record ex-vessel prices coupled with reduced abundance of groundfish all contributed to this increase. Effort subsequently fell to 5,990 trips in the 1994 season. Effort nearly doubled between 1994 and 1996 and then declined again from the 1996 level of 11,791 to 1,010 trips in 2002, a year with only a 25-day open season. The number of trips increased during 2003-2005 as the seasons were lengthened, to 3,091 trawl trips in 2005. Trips in 2006 dropped to 1,646 (preliminary), likely due to poor market conditions.

Maine trapping operations accounted for 18%, 25%, and 30% of Maine shrimp fishing trips in 2004, 2005, and 2006 respectively, but only 4%, 18%, and 11% of landings, according to 2004-2006 Vessel Trip Report (VTR) data (preliminary) (Table A5-3 and A5-5).

### A5.4.2 Vessels

The number of vessels participating in the fishery in recent years has varied from a high of 310 in 1997 to a low of 119 in 2006 (preliminary). In the 2006 fishery, there were 6 vessels from Massachusetts, 102 from Maine, and 11 from New Hampshire (preliminary data).

<b>Year</b>	<b>Vessels</b>	<b>Year</b>	<b>Vessels</b>
1997	310	2003	248
1998	260	2004	190
1999	238	*2005	197
2000	285	*2006	119
2001	288		*preliminary
2002	200		

### A5.4.3 Seasonal Spatial Distribution of Effort

Seasonal spatial trends in distribution of effort have been evaluated from port interview data. The relative magnitude of offshore fishing effort (deeper than 100 m (55 fathoms)) has varied, reflecting seasonal movements of mature females (inshore in early winter and offshore following larval hatching), but also reflecting harvesters' choices for fishing on concentrations of shrimp. During the 2005 season, 56% of the 25 sampled trips from Massachusetts and New Hampshire were inshore, while in Maine, most trips in December were offshore (90%) but increasingly inshore through the season, with 89% inshore in March. In the 2006 season, trips were generally offshore in December and April, inshore during January and February, and about 59% inshore in March, based on a total of 130 interviews. In years with a May fishing season, trips have been almost entirely offshore in that month.

#### **A5.4.4 Catch Rates**

Catch per unit effort (CPUE) indices have been developed from NMFS interview data (1983-1994) and logbook data (1995-2006) and are measures of resource abundance and availability (Figure A5-8b). They are typically measured in catch per hour or catch per trip. A trip is a less precise measure of effort, because trips from interviews and logbooks include both single day trips and multiple day trips (in the spring), and the proportion of such trips can vary from season to season.

Higher catch rates (per hour) may reflect increased biomass or denser aggregations of shrimp, which make them more available to the gear. For example, denser aggregations probably caused high catch rates during 2000, rather than high biomass. Another possible cause for an increase in catch rate is an increase in vessel fishing power. Higher catch rates per trip may also indicate a higher than average incidence of multiple-day trips.

In 2004 to 2006, only 0.24% of trips were multiple-day trips – and these were all two days – probably because shortened seasons limited the fishery to the times of year when shrimp are generally inshore and multiple-day trips are not necessary (from VTR data; 2005 and 2006 are preliminary).

Landings per trip increased from 383 kg (844 lbs) in 1983 to 602 kg (1,328 lbs) in 1985 when the strong 1982 year class entered the fishery. CPUE subsequently dropped to 328 kg (723 lbs/trip) in 1988 but increased to 478 kg (1,053 lbs) in 1990 with entry of the strong 1987 year class. This index averaged 445 kg (981 lbs) between 1991-1992, declined to 348 kg (767 lbs) in 1993, and increased in 1994 to 487 kg (1,073 lbs). The 1995-2000 CPUEs, from logbooks, averaged 632 kg (1,393 lbs). In 2001, the catch per trip dropped to 336 kg (740 lbs) per trip, the lowest since 1988, and remained low, at 377 kg (831 lbs), in 2002. In 2003, the catch per trip was 467 kg (1,029 lbs), and in 2004 it was 826 kg (1,821 lbs) per trip, one of the highest values in the past 30 years. In 2005 it was 699 kg (1,541 lbs) (preliminary) and in 2006 it was 1,022 kg (2,252 lbs) per trip (preliminary), the highest in the time series (Figure A5-8b and Table A5-8).

More precise CPUE indices (pounds landed per hour fished) have also been developed for both inshore (depth less than 100 m (55 fathoms)) and offshore (depth more than 100 m (55 fathoms)) areas using information collected by Maine's port sampling program, and agree well with the (less precise) catch per trip data from logbooks (see Table A5-8 and Figure A5-8b). Inshore CPUE for 2006 was 259 kg (572 lbs) per hour, offshore was 156 kg (345 lbs) per hour, and the season average was 226 kg (499 lbs) per hour, all time-series highs. Catch per trip, though high, did not increase as much as catch per hour, probably because trips were short. Port samplers report that shrimp trawlers sometimes came in after one good tow (usually about two hours), because of poor market demand.

#### **A5.5 Recreational Catch**

A very limited recreational fishery exists for northern shrimp. This fishery, using traps, has been for personal use and has not been licensed (ASMFC, 2004).

## **A6.0 FISHING MORTALITY AND EXPLOITABLE STOCK BIOMASS AND THE UNCERTAINTY OF THOSE ESTIMATES (TOR #2)**

### **A6.1 Data Sources**

#### *A6.1.1 Fishery data*

Landings data and numbers of shrimp caught by fishing season are compiled and calculated as described in Sections A5.1 and A5.2.5 above, and displayed in Table A5-1 and Figure A6-9.

#### *A6.1.2 Fishery-independent survey data*

##### **A6.1.2.1 Maine Shrimp Survey**

Maine conducted summer shrimp surveys in the Gulf of Maine from 1967 to 1983. Fixed stations were sampled with an otter trawl during daylight at locations where shrimp abundance was historically high (Schick et al. 1981; Figure A6-1). The Maine survey biomass index began declining in about 1970, and depicts the stock collapse in the late 1970s (Figure A6-5b, Table A6-3) (Clark 1981, 1982; Schick et al. 1981).

##### **A6.1.2.2 NEFSC Groundfish Surveys**

NEFSC autumn bottom trawl surveys have been conducted since 1963, and spring bottom trawl surveys have been conducted since 1968. Stations are sampled from Cape Hatteras to Nova Scotia according to a stratified random design (Figure A6-2; Despres et al. 1988). Although the groundfish surveys catch relatively few northern shrimp and have more measurement error, they represent a longer time series. Correspondence among research surveys and fishery indices of abundance suggests that the autumn survey tracks resource conditions more closely than the spring survey (Clark and Anthony 1980; Clark 1981, 1982). The autumn survey indicates a precipitous decline from peak biomass in the 1960's and early 1970's (averaging 3.2 kg/tow in 1967 - 1971) to a low of 0.2 kg/tow in 1976. The index subsequently increased, and fluctuated about a mean of 1.5 kg/tow from 1979 to 1999. It then dropped again to 0.2 kg/tow in 2001 but has increased to 2.8 kg/tow in 2005 (Figure A6-5a; Table A6-3).

##### **A6.1.2.3 NSTC Shrimp Survey**

The NSTC shrimp survey has been conducted offshore (depths > 50 m) each summer since 1983 aboard the R/V Gloria Michelle employing a stratified random sampling design and gear specifically designed for Gulf of Maine conditions (Blott et al. 1983, Clark 1989). The summer survey is considered to provide the most reliable information available on abundance, distribution, age and size structure and other biological parameters of the Gulf of Maine northern shrimp resource. Indices of abundance and biomass are based on catches in the strata that have been sampled most intensively and consistently over time (strata 1, 3, 5, 6, 7, and 8; Figure A6-3). Survey catches have been highest in strata 1, 3, 6, and 8 – the region from Jeffreys Ledge and Scantum Basin eastward to Penobscot Bay. The 1983 survey did not sample strata 6-8 and is not used in the assessment.

The statistical distribution of the summer survey catch per tow (in numbers) was investigated to determine the best estimator of relative abundance. Catches within strata were distributed with significant positive skew, and arithmetic stratum means were correlated to stratum variances. Log-transformed catches ( $\ln[n+1]$ ) were more normally distributed. Log transformation is a common practice for estimating relative abundance from trawl surveys, because stratum means and variances are seldom independent, and log transformation generally normalizes observations, renders the variance independent, and reduces anomalous fluctuations (Grosslein 1971). Geometric means were estimated with more precision (mean CV=2.4%) than arithmetic means (mean CV=13.5%). Therefore, stratified geometric mean catch per tow was used to estimate relative abundance (Cadrin et al. 1999).

Shrimp summer survey catches by length and developmental stage (Figure A6-7) reflect the predominance of the strong 1982, 1987, 1992, and 2001 cohorts in the stock. Although size at age-1.5 varies from year to year, discrete length modes indicate the relative abundance of age-1.5 shrimp (generally around 12-18 mm CL) and age-2.5 shrimp (generally 18.5-23 mm CL). Length modes for older cohorts overlap extensively. Age 1.5 shrimp are not fully recruited to the survey, probably because of variation in the timing of their migration from inshore to offshore, and also because they are not fully retained by the survey net.

#### A6.1.2.4 Fishery Selectivity

Relative abundance indices are estimated using NSTC shrimp survey stratified geometric mean catch per tow (Cadrin et al. 1999). Mean number per tow at length is classified as one of three components, based on growth and the selectivity to commercial gear (Schick and Brown 1997). The process is illustrated in Figure A6-4. Shrimp which are large enough to be caught by the fishery at the time of the survey are considered post-recruits. The sizes of the remaining shrimp by the end of one year (i.e., growth between surveys) are modeled using a von Bertalanffy growth curve:

$$CL_{t+1} = CL_t + (CL_{\infty} - CL_t)(1 - e^{-K})$$

where  $CL_{\infty}=35.2$  and  $K=0.36$  (McInnes 1986). The length frequency of those shrimp which were not fully recruited at the time of the survey are then multiplied by the same selectivity at length to obtain an index of recruits. The remaining shrimp are pre-recruits, and will not be selected by the fishery during the year following the survey. Using this selectivity method, age-classes recruit to the fishery over several years, and recruitment in each year is composed of several cohorts. Therefore, the definition of recruitment used in this assessment is not synonymous with year-class strength.

Mean weight of recruits and fully recruited shrimp are estimated according to length-weight equations for each developmental stage from Haynes and Wigley (1969), and 1990 northern shrimp survey observations.

## A6.2 Biomass Indices

### A6.2.1 NEFSC Fall Trawl Survey

There has generally been good agreement ( $r = 0.62$ ) between the NEFSC autumn survey index (Figure A6-5a and Table A6-3, stratified mean catch per tow, kg) and landings trends

(Figure A6-5a). This index was at all time highs at the beginning of the time series in the late 1960's and early 1970's when the Gulf of Maine Northern shrimp stock was at or near virgin levels. In the late 1970's the index declined precipitously as the fishery collapsed; this was followed by a substantial increase in the middle 1980's to early 1990's, with peaks in 1986, 1990 and 1994. This reflects recruitment and growth of the strong 1982, 1987 and 1992 year classes and the above average 1993 year class. After declining to 1.1 kg/tow in 1996, the index rose sharply in 1998 and 1999 to 2.30 and 2.54 kg per tow respectively, both well above the time series mean of 1.51 kg/tow. This is likely due to recruitment of the 1996 year class to the survey gear at age 2 in 1998 and age 3 in 1999. Beginning in 2000, the fall survey index declined precipitously for three consecutive years, reaching a time series low of 0.17 kg/tow in 2002, indicating very poor 1997, 1998, and 2000 year classes. Since 2002, the index has generally increased, reaching 2.77 kg/tow in 2005, the highest value observed since 1971. The improved fall survey indices observed since 2002 are indicative of robust 2001, 2003, and 2004 year classes.

#### **A6.2.2 NSTC State/Federal Summer Survey**

Abundance and biomass indices (stratified mean catch per tow in numbers and weight) for the state-federal summer survey for 1984-2006 are given in Table A6-1 and Figures A6-5 and A6-6, and length-frequencies by year are provided in Figure A6-7. The log<sub>e</sub>-transformed mean weight per tow averaged 15.8 kg/tow between 1984 and 1990. Beginning in 1991 this index began to decline and averaged 10.2 kg/tow between 1991 and 1996. The index then declined further, averaging 6.1 kg/tow from 1997 to 2001, and reaching a time series low of 4.3 kg/tow in 2001. In 2002 the index increased to 9.2 kg/tow, and then declined to the second lowest value in the time series (5.5 kg/tow) in 2003. Since 2003, the index has increased markedly, reaching new time series highs in both 2005 (23.3 kg/tow) and 2006 (66.0 kg/tow) respectively. The total mean number per tow demonstrated the same general trends over the time series.

The stratified mean catch per tow in numbers of 1.5-year old shrimp (Table A6-1; Figure A6-6, and graphically represented as the total number in the first size modes in Figure A6-7) represents a recruitment index. Although these shrimp are not fully recruited to the survey gear, this index appears sufficient as a preliminary estimate of year class strength. This survey index indicated strong year classes in 1987, 1992, 2001, and 2004, and moderately strong year classes in 1990, 1993, 1996, 1999, and 2003.

The strong 1992 year class observed at (assumed) age 1.5 in the 1993 summer survey (Figures A6-6 and A6-7) was smaller than the dominant 1982 and 1987 year classes, but was followed by the above-average 1993 year class. These two year classes supported the fishery in 1995-1998. The 1996 year class appeared comparable to the moderately strong 1993 year class (Table A6-1; Figures A6-6 and A6-7). The 1997 and 1998 age classes were very weak, both well below the time series mean of 410 individuals per tow. The above-average 1999 year class was comparable to the 1996 year class. In 2001 the age 1.5 recruitment index was at its lowest level since 1984, with a stratified mean of 18 individuals per tow on the transformed scale, representing recruitment failure of the 2000 year class. In 2002 the age 1.5 recruitment index increased dramatically to 1,164, which was the time series high and represents an extremely strong 2001 year class. It is interesting to note that, in the 2002 summer survey, more small, early-maturing females (< 19 mm CL, assumed 1.5 years old) were caught than at any other time in the history of the survey (Figure A6-7). The index subsequently dropped to 11 individuals per tow in 2003, indicating a very poor 2002 year class, the worst in the time series. The index

increased in 2004 to 286 individuals per tow, and reached a time series high in 2005 (1,753 individuals per tow). This is indicative of a moderate 2003 year class and a very strong 2004 year class. The 2006 index dropped to (423 individuals per tow) indicating a moderate 2005 year class.

The record 2001 year class appeared in a greatly diminished state in the 2003 survey, yet stabilized in the 2004 and 2005 surveys. The re-appearance of the 2001 year class, as indicated by the increased abundance of presumed 3.5 year old shrimp in the 2004 summer survey, is evidence that the distribution of shrimp in the summer of 2003 made them largely unavailable to the summer survey that year. This supports anecdotal reports that shrimp stayed “inshore” in 2003, in areas not visited by the survey. It is not so clear why the 2001 year class appeared to increase again in abundance between 2004 and 2005 (Figure A6-7, rightmost mode in 2004 and 2005 surveys). The virtually absent 2002 year class first observed in the 2003 survey remained very weak in the 2004 and 2005 surveys, however.

Individuals >22 mm will be fully recruited to the upcoming winter fishery (primarily age 3 and older) and thus survey catches of shrimp in this size category provide indices of harvestable numbers and biomass for the coming season. (Table A6-1 and Figure A6-6). The harvestable biomass index exhibited large peaks in 1985 and 1990, reflecting the very strong 1982 and 1987 year classes respectively. This index has varied from year to year but generally trended down until 2004. The 2001 index of 1.5 kg/tow represented a time series low, and is indicative of poor 1997 and 1998 year classes. In 2002 the index increased slightly to 2.9 kg/tow, reflecting recruitment of the moderate 1999 year class to the index. The index subsequently dropped to the second lowest value in the time series (1.7 kg/tow) in 2003. Since 2003, the fully recruited index has increased dramatically reaching a time series high in 2006 (28.8 kg/tow). This increase may be related to the continued dominance of the record 2001 year class, some of which may have survived into the summer of 2006, and to an unexplained increase in the number of female stage 1 shrimp (Figure A6-7), probably the 2003 year class.

Note that the 2006 summer survey indices (Table A6-1), which are almost all well above historical norms for this survey, are based on 29 tows, compared with about 40 tows in previous years.

## A6.3 Analytical Stock Assessment

### A6.3.1 CSA Model – Preferred

#### A6.3.1.1 Methods

Descriptive information for the Gulf of Maine shrimp fishery (total catch, port sampling, trawl selectivity, survey catches, and life history studies) were modeled to estimate fishing mortality, stock abundance, and candidate target fishing levels. The Collie-Sissenwine Analysis (CSA) (Collie and Sissenwine 1983; Collie and Kruse 1998) tracks the removals of shrimp using summer survey indices of recruits and fully-recruited shrimp scaled to total catch in numbers. The estimation of these indices is described above in Section A6.1.2.4.

This modified DeLury model was applied to the Gulf of Maine northern shrimp fishery:

$$N_{t+1} = (N_t + R_t - C_t) e^{-M} \quad (1)$$

where fully-recruited abundance at the end of the year ( $N_{t+1}$ ) equals fully-recruited abundance at the beginning of the year ( $N_t$ ), plus recruitment ( $R_t$ ), minus catch ( $C_t$ ), all reduced by one year of natural mortality ( $e^{-M}$ ).

Natural mortality ( $M$ ) was assumed to be 0.25 (but see Sections A9 and A10), as approximated from the intercept of a regression of total mortality on effort (Rinaldo 1973, Shumway et al. 1985). Estimates of  $Z$  for age-2+ shrimp from visual inspection of length modes from the Maine summer survey was 0.17 from 1977 to 1978, when the fishery was closed (Clark 1981, 1982), suggesting, for the population as a whole,  $M$  is low relative to estimates for other *Pandalus* stocks, which range from 0.2 to 1.0 (ICES 1977, Abramson 1980, Frechette and Labonte 1980, Shumway et al. 1985).

Catch was assumed to be taken at mid-year, whereby the summer survey marks the beginning of the “survey year” (August 1), and catch was taken on February 1 of the next calendar year (which was based on the time of 50% cumulative seasonal catch for 1985-1996 (Figure A5-2):

$$N_{t+1} = [(N_t + R_t)e^{-0.5M} - C_t] e^{-0.5M} \quad (2)$$

so that recruited shrimp ( $N_t + R_t$ ) experience a half-year of natural mortality ( $e^{-0.5M}$ ), catch is removed, then the survivors  $[(N_t + R_t)e^{-0.5M} - C_t]$  experience another half-year of natural mortality.

Abundance is related to survey indices of relative abundance:

$$n_t' = q_n N_t e^{\eta t} \quad (3)$$

and

$$r_t' = q_r R_t e^{\delta t} \quad (4)$$

where  $r_t'$  and  $n_t'$  are observed survey indices of recruits and fully-recruited shrimp,  $q$  is catchability of the survey gear, and  $e^{\eta t}$  and  $e^{\delta t}$  are lognormally distributed measurement errors. The process equation is derived by substituting survey indices into equation 3:

$$n_{t+1} = [(n_t + r_t/s_r)e^{-0.5M} - q_n C_t] e^{-0.5M} \quad (5)$$

where

$$s_r = q_r / q_n \quad (6)$$

is the relative selectivity of recruits to fully-recruited shrimp. Selectivity studies (Blott et al. 1983) and survey catch at length suggest that age-1.5 sized shrimp are sampled less efficiently than age-2+ shrimp, because total catch per tow is greater at age-2.5 than at age-1.5 for some cohorts (Figure A6-7). For the shrimp survey, there are two components to  $s_r$ : selectivity and availability of age-1.5 shrimp. The 32mm codend mesh in the survey trawl may not retain some small shrimp, and in some years, age-1.5 males may not completely migrate from inshore areas to the survey strata (Figure A6-3). Precise estimation of survey selectivity at size was not possible due to high variability in catch at size and few comparative experimental tows (Blott et al. 1983). For the present analysis,  $s_r$  was approximated from the relative sampling efficiency of <19mm CL shrimp to that of larger shrimp, and the relative proportions of those sizes comprising total recruits and fully recruited indices.

The parameters  $n_t$ ,  $r_t$ , and  $q_n$  were estimated by iteratively minimizing the sum of measurement errors for the entire time series.

In assessments from 2003 to 2006, fishing mortality was based on the CSA harvest rates (Collie and Kruse 1998). The harvest rate is defined as:

$$U_i = \frac{L_i + D_i}{(R_i + N_i) * e^{-M_i * (T_f - T_s)}} \quad (7)$$

where:

$U_i$  = Harvest Rate

$L_i$  = Landings

$D_i$  = Discards (For northern shrimp, discards are assumed to be zero)

$R_i$  = Recruiting Stock

$N_i$  = Fully Recruited Stock

$M_i$  = Natural Mortality

$T_s$  = Time of Survey during year

$T_f$  = Time of Catch during year

$i$  = year

Since this expresses exploitation,  $F$  may be iteratively solved based on:

$$U_i = \frac{F * (1 - e^{-Z})}{Z} \quad (8)$$

where  $Z = F + M$ .

The northern shrimp fishery occurs primarily in January-February (Figure A5-2), so an estimate of  $T_f - T_s = 0.5$  is reasonable.

The current analysis differs from that presented during SAW 36 (NEFSC 2003) in two aspects. The first is in the way fishing mortality is calculated. The problems associated with the log/ratio estimation of  $F$  and the formulation on the CSA software used was resolved by the use of the harvest rate approach described above. Since that time, the CSA software has been modified to calculate mortality using “exact” exponential mortality calculations. The harvest rate and “exact” approach provide the same estimates. Additionally, it has been determined to be appropriate to set the process error term to zero (0) that formerly appeared in equation 5. See the 2006 American lobster assessment (ASMFC 2006a) for the rationale for both of these changes in the most recent northern shrimp assessment.

#### A6.3.1.2 Results

CSA results are summarized in Table A6-2 and Figures A6-8 and A6-9. Abundance and catchability were relatively well estimated, and the model fit the data well. Total exploitable stock biomass estimates averaged about 14,000 mt (31 million lbs), with a peak at 16,000 mt (35 million lbs) before the 1991 season, and decreased to a time series low of 4,400 mt (9.7 million lbs) in 2001. Total stock biomass has increased over recent years to its current value of 71,500 mt (158 million lbs) (32,100 mt or 71 million lbs in 2006) mt (Table A6-2 and Figure A6-8).

The recent two years of high abundance and low  $F$  are due, in part, to the same years of observed very high survey catches and very low reported landings that have leveraged those

estimates to account for those observations. Since 2002, both fall and summer survey indices have been increasing, and the reported landings have declined steadily since the mid-1990s.

Annual estimates of fishing mortality (F) averaged 0.25 (19% exploitation) for the 1985 to 1994 fishing seasons, peaked at 1.06 (57% exploitation) in the 1997 season and decreased to 0.30 (22% exploitation) in the 2001 season (Table A6-2 and Figures A6-8 and A6-9). In 2002 F dropped to 0.08 (7% exploitation), due in part to a short season and poor stock conditions. Continued poor stock conditions (in terms of exploitable shrimp) along with an exceptional recruitment pulse resulted in F rising to 0.23 (18% exploitation) in 2004. The 2006 estimate of F is 0.03 (3% exploitation) (Table A6-2 and Figure A6-8). Recent patterns in F reflect the pattern in nominal fishing effort (Figure A5-8a).

Precision of CSA estimates was assessed by “bootstrap” analysis, in which survey measurement errors were randomly shuffled 2000 times to provide simulated replications of the model (Figure A6-8). Bootstrap results suggest that estimates of abundance, biomass and mortality were relatively precise.

Because of a lack of detailed information about discards (see Section A5.3), there were no analyses of discarding for this assessment.

#### A6.3.1.3 Retrospective Analyses

Comparison of results from 5 retrospective CSA runs to the results reported above was investigated to assess the stability of estimates in the last year of the analysis and the possibility that terminal mortality estimates are systematically inconsistent. The analysis was performed by sequentially deleting the last year of survey and catch data (for five years) to create a retrospective series of CSA estimates of abundance, biomass and fishing mortality. In the most recent assessment (ASMFC 2006b) the scale of terminal and previous year estimates of abundance, biomass and fishing mortality had larger than average confidence intervals. This, however, had little effect on terminal year estimates, and the pattern shows minimal retrospective differences and no pattern in terms of F (Figure A6-13). Similar stability was seen in estimates of abundance and biomass (Figure A6-13). The NLSS estimate of q was also very stable for the series of retrospective analyses.

#### A6.3.2 ASPIC Model – Confirmatory Analysis

##### A6.3.2.1 Methods

An alternative method of estimating stock size and F was explored to corroborate results from CSA. A nonequilibrium surplus production model (Prager 1994, 1995) was fit to seasonal catch and survey biomass indices from 1968 to 2006 (summarized in Table A6-3). The model assumes logistic population growth, in which the change in stock biomass over time ( $dB_t/dt$ ) is a quadratic function of biomass ( $B_t$ ):

$$dB_t/dt = rB_t - (r/K)B_t^2$$

where  $r$  is intrinsic rate of population growth, and  $K$  is carrying capacity. For a fished stock, the rate of change is also a function of F:

$$dB_t/dt = (r-F_t)B_t - (r/K)B_t^2$$

For discrete time increments, such as annual fishing seasons, the difference equation is:

$$B_{t+1} = B_t + (r - F_t)B_t - (r/K)B_t^2$$

Initial biomass ( $B_1$ ),  $r$ , and  $K$  were estimated using nonlinear least squares. The fall groundfish survey catch per unit effort (CPUE) contributed to the total sum of squares as a series of observed effort ( $E=CPUE/C$ ); the Maine summer survey and the NSTC shrimp surveys contributed as independent indices of biomass at the start of the fishing season. Note that no assumption about  $M$  is needed for the biomass dynamics analysis.

#### 6.3.2.2 Results

Two observations from the NMFS fall survey (1982 and 2002) and one observation from the summer shrimp survey (2006) appear to be outliers. The pattern of residuals from the Maine and NSTC surveys suggest autocorrelation (Figure A6-10). A fair portion of the variance in the fall and Maine surveys was explained by the model ( $R^2=0.49$  and  $0.63$ , respectively); however the majority of the variation in the NSTC summer survey was not resolved ( $R^2=0.15$ ). The model did not account for peaks in biomass from strong recruitment that occurred in 2005 and 2006.

Estimates of  $F$  and  $B$  from the biomass dynamics model generally confirm the pattern and magnitude of estimates from the CSA model (Figure A6-11). Recruitment of the strong 1982, 1987, 1992, 2001, and 2005 cohorts is not as pronounced in the biomass trajectory from the production model, because dynamic recruitment is not explicitly estimated, as it is in the CSA. The biomass dynamics model suggests that a maximum sustainable yield (MSY) of 5,395 mt can be produced when stock biomass is approximately 30,110 mt ( $B_{MSY}$ ) and  $F$  is approximately 0.18 ( $F_{MSY}$ ). However, estimated biomass was only above  $B_{MSY}$  during the first three years in the analysis, which are not reliable (Prager 1994, 1995).

Survey residuals were randomly resampled 1000 times to estimate precision and model bias. Bootstrap results suggest that  $B_1/B_{MSY}$ ,  $K$ ,  $r$ , MSY,  $B_{MSY}$  and  $F_{MSY}$  were relatively well estimated (relative interquartile ranges were  $<14\%$ , and bias was  $\leq 1\%$ ). Estimates of the survey  $q$ 's were moderately precise (relative IQs were 21-26%, bias was  $<1\%$ ). The ratio of  $F/F_{MSY}$  in 2006 was estimated with moderate precision (relative IQ = 26%, bias = 2.29%). Similarly,  $B/B_{MSY}$  in 2006 was estimated with moderate precision (relative IQ = 25%, bias = 1.18%).

#### A6.3.2.3 Retrospective Analysis

A total of 5 retrospective ASPIC runs were completed and examined to assess the stability of model estimates of biomass and fishing mortality in the terminal year, and to assess the sensitivity of time series trends of biomass and fishing mortality to terminal values of survey and catch time series. The analysis was performed by sequentially removing the last year of survey and catch data (for five years) to create retrospective time series of surplus production fishing mortality and biomass estimates.

Terminal fishing mortality estimates were very stable in most years with minimal retrospective differences in  $F$  observed (Figure A6-14a). Biomass estimates exhibited slightly more retrospective bias than  $F$  estimates, especially between 1982 and 1993 (Figure A6-14b). Despite the retrospective bias observed in the surplus production biomass estimate, stock status determination would not be affected because of the relative nature of the biomass threshold used for Northern shrimp.

## A7.0 SCIENTIFIC ADEQUACY OF EXISTING BIOLOGICAL REFERENCE POINTS (BRPs) (TOR #3)

Biological reference points for US Gulf of Maine northern shrimp were developed for and adopted by the ASMFC Northern Shrimp Section for Amendment 1 (ASMFC 2004) to the ASMFC Northern Shrimp FMP. The Section chose a fishing mortality target and limit based on Spawning Potential Ratio (SPR). The fishing mortality target of  $F_{50\%}=0.22$  was based on a level of the fishing mortality rate in the mid-1980s through mid-1990s when biomass and landings were “stable”. The fishing mortality limit of  $F_{20\%} = 0.6$  is based on the limit that was exceed in the early to mid-1970s when the stock collapsed (see Table A6-3).

The Section chose a stock biomass threshold and limit based on historical patterns. Amendment 1 does not employ a biomass target because the Section did not want to set unlikely goals for a species whose biomass can easily be affected by environmental conditions. The stock biomass threshold of  $B_{Threshold} = 9,000$  mt (19.8 million lbs) and limit of  $B_{Limit} = 6,000$  mt (13.2 million lbs) are based on historical abundance estimates and response to fishing pressure. The limit was set 2,000 metric tons higher than the lowest observed biomass – 4,000 mt in 1976 from ASPIC analysis (ASMFC 2001).

The absolute values of the other reference points are based on CSA estimates of stock status (ASMFC 2003) and on Egg per Recruit analyses (Cadrin et al. 1999). Although these reference points were not adopted in a formal manner until 2004, management decisions have tended to react to stock conditions that were between the now established thresholds and limits. Figure A6-12b shows the pattern of biomass and fishing mortality from 1985 to present. A similar pattern is seen when viewing the reference points scaled to estimates from a surplus production (ASPIC) analysis (Figure A6-12a). Although the CSA is used for absolute values for stock status and providing advice to management, the ASPIC runs have been used to corroborate that information, and in this case, provide a longer time period, including the late 1970s.

Observing these patterns, it appears that the BRPs provide adequate information to managers in a timely fashion. It is also noted that, unlike many managed species, the northern shrimp management process provides the ability for response to changes in stock status in a short time period. This is based, in part, on management review of northern shrimp assessments on an annual basis.

## A8.0 CURRENT STOCK STATUS WITH RESPECT TO EXISTING BRPs (TOR #4)

The existing biological reference points (BRPs) for northern shrimp, as defined in the FMP (ASMFC 2004) are:

$$\begin{aligned}B_{Threshold} &= 9,000 \text{ mt or } 19.8 \text{ million lbs} \\B_{Limit} &= 6,000 \text{ mt or } 13.2 \text{ million lbs}\end{aligned}$$

$$\begin{aligned}F_{Target/Threshold} &= 0.22 \\F_{Limit} &= 0.60\end{aligned}$$

[From the FMP wording,  $F=0.22$  is both a target (as defined on page 23 of the FMP) and a threshold (as implied on page 24 of the FMP, ASMFC 2004). A target Biomass is not defined in the FMP.]

For the purposes of determining the stock status of northern shrimp relative to the BRPs, fishing mortality and biomass estimates derived from the CSA model (using M=0.25) are used (ASMFC 2004).

In 2006 the CSA fishing mortality rate (2006 F = 0.03) was well below the target/threshold fishing mortality (F = 0.22) and has been so since 2005 (Table A6-2).

The 2006 CSA biomass estimate of 32,100 mt (70.9 million lbs) (Table A6-2) is well above the biomass threshold ( $B_{Threshold} = 9,000$  mt or 19.8 million lbs), and was the highest value observed in the time series. The Gulf of Maine stock of northern shrimp is in good condition; the stock is not overfished, nor is overfishing occurring.

Although results of biomass dynamics modeling are not used for management purposes, estimates of fishing mortality and biomass from the ASPIC model confirm the stock status determination from the CSA model. The 2006 fishing mortality estimate from ASPIC was F = 0.09, which is well below the 1985 to 1994 stable period average fishing mortality of F = 0.24. Similarly, the 2006 biomass estimate from ASPIC was B = 19,620 mt (43.3 million lbs), which is well above the 1985 to 1994 stable period average biomass of B = 15,453 mt (34.1 million lbs) (Table A6-3).

Size composition data from both the fishery and summer surveys indicate that good landings have followed the recruitment of strong (dominant) year classes. Poor landings from 1998 to 2004, as well as low biomass estimates, can be attributed in part to the below-average recruitment of the 1994, 1995, 1997, 1998, 2000, and 2002 year classes.

During the 2007 fishing season, the strong 2001 year class (assumed 6-year-old females) may still be present in part, the 2002 year class (assumed 5-year-old females) will be very weak, the strong 2003 year class (4-year-old females) will contribute most to landings, and the exceptionally strong 2004 year class and moderate 2005 year class will consist of males and transitionals, and immature males respectively.

## A9.0 SENSITIVITY ANALYSIS TO DETERMINE THE IMPACT OF UNCERTAINTY IN THE DATA ON ASSESSMENT RESULTS (TOR #5)

### A9.1 CSA Model

Sources of uncertainty in CSA estimates of stock status identified and tested involve the estimation of the mean weight of a landed shrimp, and underreported landings in the most recent years of the assessment. Additional analyses were performed to examine different natural mortality rates.

#### *A9.1.1 Mean weight of a landed shrimp*

The estimation of the mean weight of a landed shrimp (see description of this process in Section A5.2.5) would result in an inverse estimation of the CSA inputs: numbers landed, as well as the mean weight. To examine this, the mean weights used in the baseline CSA (the values used in the most recent assessment) were adjusted by +/- 10 and 20%. The total landings in weight remained constant. Predictably, the effect on the CSA estimates of abundance (N) and biomass (B) were essentially the same as the % changes in the indices (Figure A9-1.1). Also predictably, there was no change in the estimates of F, since that is derived from survey indices.

### **A9.1.2 Underreported landings in terminal years**

It has been noted that the reporting process for northern shrimp landings lags well behind the assessment cycle time constraints. Analysis of the last six years of data indicates that in the terminal year of an assessment, between 70 and 88% of landings for that year will be available. Landings for the previous year are 98 – 99% complete. Two CSA runs were done looking at a case where landings for the last year (2006) were 70% of the total, and where they were at 88%. In both cases, year t-1 (2005) landings were presumed to be 98% complete. The results of these runs (Figure A9-1.2) show no substantial changes in N or B estimates for any years including the terminal years. Estimates of F did show an increase equivalent to the magnitude of the change in landings, however an increase of 30% in an  $F = 0.03$  is small.

### **A9.1.3 Natural Mortality**

As noted above (Section A6.3.1.1) the natural mortality rate ( $M = 0.25$ ) used in US Gulf of Maine northern shrimp assessments may be underestimated. Several higher values were examined in further CSA runs. The choice of  $M = 0.6$  (an average of the range noted above) is presented here. The results are shown in Figure A9-1.5. In general, the results are relatively logical. The abundance and biomass estimates when  $M$  is increased from 0.25 to 0.6 also increase on average by a factor of 4 to 5 (compare Figure A9-1.5 with A6-8). Since landings remained constant, the catchability ( $q$ ) decreased for the higher value of  $M$  and the abundance and biomass had to increase in order to provide the same level of catch. The retrospective patterns (Figure A9-1.3 and A9-1.4) are similar to those for  $M = 0.25$  (Figure A6-13). The estimates of N, B and F were basically different only in scale. As a result, the use of a higher  $M$  should have little effect on management advice based on stock status. It is possible that a change in scale will be confusing (at best), but the overall process of maintaining biomass at a sustainable level through controlling F is the same. As mentioned before, it really is only a matter similar to using Fahrenheit vs Celsius scales to describe temperature.

These analyses are certainly far from exhaustive, but they point to the need for further examination of the values of rates of natural mortality used in the assessment. The US portion of the Gulf of Maine is marginal, in terms of environment, for *P. borealis*. It is clear that  $M = 0.25$  is an underestimate for a species that has a life span of 5 to 6 years. The use of a higher  $M$ , as presented here, is supported by the following section (A10) on the effects of predation. It seems probable that the higher value used includes the M2 component of  $M$ .

## **A9.2 ASPIC Model**

Estimates of fishing mortality and biomass derived from the biomass dynamics model (ASPIC) were examined for sensitivity to potential uncertainty and biases in reported shrimp landings. Three different sensitivity runs were completed; 1) Landings overestimated by 20%, 2) Landings underestimated by 20%, and 3) Landings underreported by 10% and 20% in the sub-terminal and terminal year respectively. The first two runs set an upper and lower bound on the impact of potential uncertainty in the landings data. The third run mimics an observed retrospective bias in Northern shrimp landings data related to late catch reporting that occurs after the assessment is completed on an annual basis.

Estimates of fishing mortality from ASPIC were not very sensitive to potential uncertainty in landings data (Figure A9-2.1). The average annual percent difference between fishing

mortality estimates using the “true” landings and runs 1, 2, and 3 were 11%, 5% and 4% respectively.

Estimates of starting biomass from ASPIC were fairly sensitive to potential uncertainty in landings data (Figure A9-2.2). The average annual percent difference between starting biomass estimates using the “true” landings and runs 1, 2, and 3, were -9%, 23% and 2% respectively. In general landings “underreporting” would cause starting biomass estimates to be biased high, and landings “over-reporting” would cause starting biomass estimates to be biased low. Systematic bias in the terminal years of landings had little impact on starting biomass estimates.

**A10.0 ANALYZE FOOD HABITS DATA AND EXISTING ESTIMATES OF FINFISH STOCK BIOMASS TO ESTIMATE ANNUAL BIOMASS OF NORTHERN SHRIMP CONSUMED BY COD AND OTHER MAJOR PREDATORS. COMPARE CONSUMPTION ESTIMATES WITH REMOVALS IMPLIED BY CURRENTLY ASSUMED MEASURES OF NATURAL MORTALITY FOR SHRIMP (TOR 6)**

**A10.1 Introduction**

Food habits data from NEFSC bottom trawl surveys were evaluated for a wide range of pandalid shrimp predators. The total amount of food eaten and the type of food eaten were the primary food habits data examined. From these basic food habits data, diet composition of pandalids, per capita consumption, total consumption, and the amount of shrimp removed by these shrimp predators were calculated. Combined with abundance estimates of these predators, when summed the total amount of shrimp consumed was calculated. Contrasts to other estimates of biomass (see above) were conducted to place this source of mortality into context and to fully address the Term of Reference.

**A10.2 Methods**

Every predator that contained pandalid shrimps was identified. From that original list, a subset of predators was analyzed to elucidate which predators ate pandalids with a diet composition of >1% for any five year block. The predators were examined in typical size classes and were limited to the bottom trawl survey strata 01240-01400 (Azarovitz 1981, NEFC 1988), a geographic area largely coincident with the shrimp survey (see above). These size classes correspond to notable changes in diet and life history and also minimized low data density (i.e., number of stomachs sampled) for each size class. From this secondary list, predators that had <10 stomachs per three year block, had a period of non-zero pandalid diet percentages for more than five years in a row, and were not routinely sampled across the time period were excluded as non-consistent pandalid predators. The remaining 18 consistent pandalid predators (size-species combinations) were analyzed as described below (Table A10-1).

Estimates were calculated on a seasonal basis (two 6 month periods) for each species, summed for each annum. Although the food habits data collections started quantitatively in 1973, not all species of shrimp predators were sampled during the full extent of this sampling program. In such instances as long as the sampling was routine for that predator by 1985 we included them as 1985 was the initial year in the shrimp assessment based on the summer shrimp survey. For more details on the food habits sampling protocols and approaches, see Link and

Almeida (2000). This sampling program was a part of the NEFSC bottom trawl survey program; for background and context, further details of the survey program can be found in Azarovitz (1981) and NEFC (1988).

#### **A10.2.1 Basic Food Habits**

To estimate mean stomach contents ( $S_{it}$ ), each shrimp predator had the total amount of food eaten (as observed from food habits sampling) calculated for each size class, temporal ( $t$ , fall or spring; year) and spatial (the selected strata) scheme. The denominator in the mean stomach contents (i.e., the number of stomachs sampled) was inclusive of empty stomachs. These means were weighted by the number of tows in a temporal and spatial scheme as part of a two-stage cluster design. Further particulars of these estimators can be found in Link and Almeida (2000). Units for this estimate are in grams (g).

To estimate diet composition ( $D_{ij}$ ) that was pandalids, where  $j$  is the specific prey type (here pandalids) and the amount that was summed across for each predator set of stomachs. These estimates were then divided by the total amount of food eaten in a size class, temporal and spatial scheme, totaling 100%. These estimates are the proportions of the data comprised by pandalids for each size class, temporal and spatial scheme. Further particulars of these estimators can be found in Link and Almeida (2000).

#### **A10.2.2 Consumption Rates**

To estimate per capita consumption, the gastric evacuation rate method was used (Eggers 1977, Elliott and Persson 1978). There are several approaches used for estimating consumption, but this approach was chosen as it was not overly simplistic (as compared to % body weight; Bajkov 1935) or overly complex (as compared to highly parameterized bioenergetics models; Kitchell et al. 1977). Additionally, there has been copious experience in this region using these models (e.g., Durbin et al. 1983, Ursin et al. 1985, Pennington 1985, Overholtz et al. 1991, 1999, 2000, Tsou & Collie 2001a, 2001b, Link & Garrison 2002, Link et al. 2002, Overholtz & Link 2007). Units are in g year<sup>-1</sup>.

Using the evacuation rate model to calculate consumption requires two variables and two parameters. The per capita consumption rate,  $C_{it}$  is calculated as:

$$C_{it} = 24 \cdot E_{it} \cdot \overline{S_{it}}^{\gamma},$$

where 24 is the number of hours in a day and the evacuation rate  $E_{it}$  is:

$$E_{it} = \alpha e^{\beta T};$$

and is formulated such that estimates of mean stomach contents ( $S_{it}$ ) and ambient temperature ( $T$ ; here used as bottom temperature from the NEFSC bottom trawl surveys for either season (Taylor & Bascuñán 2000, Taylor et al. 2005)) are the only data required. This was done for each predator  $i$  (size and species) for each time period  $t$  (season and year). The parameters  $\alpha$  and  $\beta$  are set as values chosen from the literature (Tsou and Collie 2001a, 2001b, Overholtz 1999, 2000). The parameter  $\gamma$  is a shape function is almost always set to 1 (Gerking 1994).

To evaluate the performance of the evacuation rate method for calculating consumption, a simple sensitivity analysis had been previously executed (NEFSC 2007). The results of that sensitivity analysis indicate singly the most sensitive factor when well within normal ranges is the mean stomach contents of a predator. The ranges of  $\alpha$  and  $\beta$  within those reported for the literature do not appreciably impact consumption estimates (< half an order of magnitude), nor do ranges of  $T$  which were well within observed values (<< quarter an order of magnitude). An order of magnitude change in the amount of food eaten linearly results in an order of magnitude change in per capita consumption. Variance about any particular species of predator stomach contents has a CV of ~50%. Thus, within any given species for each size class, temporal and spatial scheme, the variability of  $S_{it}$  is likely to only influence per capita consumption by half an order of magnitude or less. Estimates of abundance, and changes in estimates thereof, are likely going to dominate the scaling of total consumption by a broader range of magnitudes than the parameters and variables requisite for an evacuation method of estimating consumption. The parameters  $\alpha$  and  $\beta$  were set as 0.04 and 0.11 respectively.

#### *A10.2.3 Scaling Consumption*

Once per capita consumption rates were estimated for each shrimp predator in a size class, temporal ( $t$ ) and spatial scheme (these strata), those estimates were then scaled up to a seasonal estimate ( $C'_{it} = C_{fall}$  or  $C_{spr}$ ) by multiplying the number days in each half year:

$$C'_{it} = C_{it} \cdot 182.5 .$$

These were then multiplied by the diet composition  $D_{ijt}$  that was pandalids, to estimate the seasonal per capita consumption of pandalids  $C_{ijt}$ :

$$C_{ijt} = C'_{it} \cdot D_{ijt} .$$

These were then summed to provide an annual estimate,  $C'_{ij}$ :

$$C'_{ij} = C_{ij,fall} + C_{ij,spring} ,$$

and were then scaled by the total stock abundance to estimate a total amount of shrimp ( $j$ ) removed by any predator  $i$ ,  $C_{ij}$ :

$$C_{ij} = C'_{ij} \cdot N_i ,$$

where  $N_i$  is the swept area estimate of abundance for each predator (species-size class) for each year and spatial scheme.

These  $C_{ij}$  were then summed across all  $i$  predators to estimate a total amount of pandalid shrimp removed by all consistent pandalid predators,  $C_j$ :

$$C_j = \sum_i C_{ij} .$$

The total amount of pandalid shrimp removed was finally multiplied by the ratio of *Pandalus borealis* to all pandalid shrimps, as estimated from the shrimp surveys and bottom trawl survey ratios (see above). In practice, as this ratio exhibited a wide range of variability, we set this ratio to equal 0.5. The total consumption of shrimp per predator, total amount of pandalid shrimp removed by all predators, and total amount of *Pandalus borealis* removed by all predators are presented as metric tons year<sup>-1</sup>.

To evaluate the consumptive removals of *P. borealis* shrimp as a biomass index relative to total shrimp biomass, one contrast was executed. Comparisons of consumptive removals of *P. borealis* shrimp relative to survey indices of shrimp abundance and the assessment model were executed. These track three items: first whether trends and major changes in shrimp biomass were consistent across multiple indices, second whether the predatory index of shrimp biomass consumed was consistent in magnitude with other indices and estimates, and third if parameters in the shrimp assessment model were consistent with these trends and magnitude.

Results from just one representative species is presented, namely as an example of major, consistent pandalid predators. For the full suite of consistent pandalid predator graphics, see Appendix A1.

### A10.3 Results

The mean stomach contents for medium silver hake had a relatively stable amount of food eaten (Figure A10-1), averaging 3-4 g for the time series for both the fall (Figure A10-1a) and spring (Figure A10-1b). The per capita consumption for medium hake average 1-1.5 kg in the fall (Figure A10-2a) and 700g to 1 kg in the spring (Figure A10-2b), largely due to warmer fall temperatures. The per capita consumption of this shrimp predator generally tracks the amount of food eaten.

The diet composition of pandalid shrimps in medium silver hake averages approximately between 5-10% in both the fall (Figure A10-3a) and spring (Figure A10-3b), with both showing an increase in the late 1990s. The per capita consumption of pandalid shrimp by medium silver hake exhibits a notable increase in the mid 1990s, in both the fall (Figure A10-4a) and spring (Figure A10-4b) seasons.

The average per capita pandalid shrimp consumption by medium silver hake has averaged approximately 200 g yr<sup>-1</sup> since the mid 1980s, with lower values prior to that time period (Figure A10-5). The minimum swept area abundance of medium silver hake for these strata has exhibited a consistent increase through the early 2000s, with an average of about 125 million individuals (Figure A10-6). Scaling these two estimates, medium silver hake have eaten an increasing amount of pandalid shrimp through the early 2000s, averaging on the order of 10-20,000 mt yr<sup>-1</sup> (Figure A10-7).

Total consumptive removals by all 18 pandalid predators exhibits two increasing trends, one in the mid 1990s and another more recently (Figure A10.8a). These estimates have averaged around 50 mt yr<sup>-1</sup> since 1985, with a lower value prior that time period. When examining only the amount of consumptive removals of solely *Pandalus borealis*, the same trends and patterns follow, averaging approximately 40 mt yr<sup>-1</sup> since 1985 (Figure A10.8b).

When comparing the total amount of *Pandalus borealis* consumed by all predators to CSA runs using different levels of mortality (Figure A10.9a), some of the same patterns in the mid 1980s were coincident in both estimates. The mid 1990s show some departure of this trend, with the consumption estimates slightly higher than the model outputs, yet with both relatively stable during this period. Finally, the same increase in the early 2000s is tracked in both estimates.

The key observation is that those model runs with a higher mortality seem to be of a more consistent order of magnitude with the consumption estimates than runs with a lower mortality. When comparing the consumption estimates of *Pandalus borealis* to the shrimp survey, although different in magnitude and units, the same general trends and patterns are exhibited in both indices (Figure A10-9b).

#### A10.4 Summary

1. Total consumption of shrimp is on the same order of magnitude of independent estimates of stock biomass, but can be a bit higher.
2. Total consumption of shrimp exhibits similar trends as other biomass estimates.
3. The results suggests there is more shrimp biomass in the ecosystem than previously thought.
4. Total consumption of shrimp is suggestive of a higher M than the 0.25 previously used.

#### A10.5 Recommendations

1. At least, the consumption estimates of shrimp biomass should be able to be used as a qualitative index in the shrimp assessment, providing context.
2. More so, they serve as further justification, among other factors, for modifying (increasing) M in the assessment model.
3. Ultimately these estimates may prove to be useful as a scaling index in future efforts.

#### A10.6 Sources of Uncertainty

##### A10.6.1 Underestimating Consumption Index of Biomass relative to other estimates

1. Minimum swept area estimates of predator abundance; does not account for q
2. Dropped some predators that did not consistently eat Pandalids
3. 24 hour stomach sampling compared to shrimp survey sampling (just during day)
4. Spatial considerations

##### A10.6.2 Overestimating Consumption Index of Biomass relative to other estimates

1. *P borealis*/Pandalid ratio is hard to estimate; consumption of all shrimp is not just this species
2. Is the  $\alpha$  too high compared to the literature?
3. Prey misidentification: e.g. assigning Pandalid to euphasiid, mysid or similar prey while processing stomachs
5. Spatial considerations

## **A11.0 STATUS OF THE 2002 SARC RESEARCH RECOMMENDATIONS (TOR 7)**

The stock assessment review committee (SARC), which met during the 36<sup>th</sup> Stock Assessment Workshop (SAW) in December 2002, made the following nine recommendations for further research (NEFSC 2003). The NSTC agrees with the recommendations that it has yet to act on.

### **A11.1 Further exploration of natural mortality assumption**

The SARC felt that a value for M of 0.25 seemed very low for such a short-lived species. M has been estimated between 0.2 and 1.0 for other northern shrimp stocks (Shumway et al. 1985 and others; see Section A6.3.1.1).

Scientists at NEFSC have recently looked at using predation rates and stock sizes of finfish to estimate the consumption of northern shrimp and to compare with natural mortality assumptions made in past shrimp assessments. See Section A10.6 for details.

The NSTC has also looked at ratios of assumed age class abundances for further insight. Although they are still preliminary, these analyses also suggest a higher value of M.

### **A11.2 Investigation of growth for improved calculation of YPR and SPR**

Yield and eggs per recruit modeling for Gulf of Maine northern shrimp were reported by Cadrin et al., 1999. No new research on Gulf of Maine northern shrimp growth has been done since then.

### **A11.3 Consider alternative estimators of F**

The NSTC and SARC (2002) concluded that "...determining F from the CSA harvest rate....is a more precise approximation than the log ratio method." (NEFSC 2003) The NSTC has adopted the harvest rate method since 2002, and no further work has been done on this issue.

### **A11.4 Consider a two- rather than a one-stage control rule**

The SARC (2002) noted that "management advice based on the results of biomass dynamics models may not provide sufficient detail relative to the unique life history characteristics of the species. The SARC questioned the usefulness of a single reference point estimate..." (NEFSC 2003).

The NSTC has struggled to formulate appropriate management advice in certain situations: when the full recruit abundance (>22 mm) is moderate or high but the abundance of pre-recruits (age 1.5) is low (e.g., 1990 and 2004 in Table A6-1 and Figure A6-6), or conversely, when pre-recruits are high but full recruit abundance is low (e.g., 1993 and 2002 in Table A6-1 and Figure A6-6). In a stock with so few year classes, either situation can be reason for concern, even when total stock biomass is above the management threshold. Although the NSTC discusses these situations in its management advice, it has not proposed any two-stage BRPs or control rules.

### **A11.5 Investigate survey selectivity**

Several factors influence the selectivity of both the NEFSC fall trawl survey and the NSTC state/federal summer survey – the size-selectivity of the survey gears for northern shrimp, the timing and location of the surveys relative to shrimp inshore-offshore migration and distribution, diurnal vertical migration, distribution relative to towable/untowable bottom, and net avoidance behavior could all effect the ability of surveys to adequately represent the stock.

There has been no new work looking specifically at these issues.

There is concern that the 2003 summer survey may have underestimated the stock because a portion of the stock may have stayed inshore (not in the survey strata) that summer. There is also concern that the 2006 survey may have overestimated the stock because of small sample size.

In 2002, an industry-based survey was conducted using similar gear, timeframe, locations (survey strata), and stratified random design as the NSTC state/federal summer survey. Size distributions and spatial trends in abundance were similar to the NSTC survey, although the abundance indices were not directly comparable (Schick et al. 2007).

### **A11.6 Explore alternative assessment models, especially statistical catch-at-length methods**

Length distributions from the summer shrimp survey have been used for size composition analysis to estimate mortality rates, but did not fit length-based models well because of variable recruitment and growth (Terceiro and Idoine 1990, Fournier et al. 1991). No further work has been done on this issue.

### **A11.7 Consider the potential for using length-frequency distributions for developing management advice.**

The NSTC always includes a discussion of relative year class strengths, derived from visual inspections of commercial catch and summer survey length-frequency distributions, in its annual assessments (e.g., end of Section A8 and ASMFC 2006a), and in its oral presentation during annual management public hearings. This discussion is usually an important component of the NSTC's management advice. No recommendations for BRPs or control rules based on size distributions have been made however.

### **A11.8 Explore utilizing the ratio of stage 2 to stage 1 females for estimating total mortality**

The NSTC has recently explored this approach for estimating total mortality. Although they are still preliminary, these analyses suggest higher values of Z than those currently estimated by CSA using M=0.25.

### **A11.9 Investigate the appropriate weighting of port sample data for estimates of mean weight**

The NSTC currently does not weight port samples by catch weight, that is, each sample is weighted equally in the calculation for the mean weight of a shrimp for that state and month. An alternative would be to weight samples from large catches more heavily than samples from small catches (by raising, or expanding the sample by the ratio of the sampled catch weight divided by

the sample weight). This weighting would be appropriate if the mean size of individual shrimp tended to be larger or smaller in large vs. small catches.

No further work has been done on this issue.

## A12.0 ACKNOWLEDGMENTS

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## NORTHERN SHRIMP TABLES

Table A4-1. NSTC recommendations made and actions taken by the ASMFC Northern Shrimp Section for management of the Gulf of Maine northern shrimp fishery, 1987–2007 (adapted from Clark et al. 2000)

Fishing Season	Recommendations	Actions Taken
1987	<ul style="list-style-type: none"> <li>• Extension of season to maximum allowed</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (182 days)</li> <li>• Continuation of mesh regulations</li> </ul>
1988	<ul style="list-style-type: none"> <li>• Restriction of season to winter and spring</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (183 days)</li> <li>• Continuation of mesh regulations, except 0.25 inch tolerance in codend eliminated</li> </ul>
1989	<ul style="list-style-type: none"> <li>• Extension of season to maximum allowed</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (182 days)</li> <li>• Continuation of mesh regulations</li> <li>• Shrimp separator trawls required in April and May</li> </ul>
1990	<ul style="list-style-type: none"> <li>• Extension of season to maximum allowed</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (182 days)</li> <li>• Continuation of mesh regulations</li> <li>• Shrimp separator trawls required in December, April, and May</li> </ul>
1991	<ul style="list-style-type: none"> <li>• Extension of season to maximum allowed</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (182 days)</li> <li>• Continuation of mesh regulations</li> <li>• Shrimp separator trawls required throughout season</li> </ul>
1992	<ul style="list-style-type: none"> <li>• Restriction of season from January – March</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (153 days). December 16, 1991 – May 15, 1992.</li> <li>• No fishing on Sundays</li> <li>• Continuation of mesh regulations</li> <li>• Shrimp separator trawls required throughout season</li> <li>• Finfish excluder devices required April 1 – May 15</li> </ul>
1993	<ul style="list-style-type: none"> <li>• Restriction of season from January – March</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (138 days). December 14, 1992 – April 30, 1993</li> <li>• No fishing on Sundays</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices and separator panels required</li> </ul>
1994	<ul style="list-style-type: none"> <li>• Restriction of season from January – March</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (122 days) December 15, 1993 – April 15, 1994.</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices</li> </ul>
1995	<ul style="list-style-type: none"> <li>• Restriction of season from January – March</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (128 days). December 1, 1994 – April 30, 1995.</li> <li>• No fishing Fridays or Sundays (state choice)</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> </ul>
1996	<ul style="list-style-type: none"> <li>• Extension of season to maximum allowed</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (152 days). December 1, 1995 – May 31, 1996 for mobile gear; no fishing one day per week.</li> <li>• Open season (121 days). January 1 – May 31, 1996 for fixed gear (traps)</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> </ul>

Table A4-1 continued.

1997	<ul style="list-style-type: none"> <li>• Restriction of effort in December, April, and May</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (156 days). December 1, 1996 – May 31. Two 5-day and four 4-day blocks of no fishing. Trap gear may be left untended.</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> </ul>
1998	<ul style="list-style-type: none"> <li>• Restriction of effort in February – March</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (105 days). December 1, 1997 – May 22, 1998 for mobile gear; no fishing weekends except March 14 – 15 and December 25-31 and March 16 – 31.</li> <li>• Open season (65 days). January 1 – March 15 for trap gear. No fishing on Sundays except March 15.</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> </ul>
1999	<ul style="list-style-type: none"> <li>• Restriction of season to 40 days during February – March</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (90 days). December 15, 1998 – May 25, 1999 for mobile gear. No fishing on weekends plus December 24-25, December 28 – January 1, January 27-29, February 24-26, March 17-31, and April 29-30.</li> <li>• Open season (61 days). January 10 – March 10 for trap gear.</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> </ul>
2000	<ul style="list-style-type: none"> <li>• No fishing; closed season</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (51 days). January 15 – March 15. No fishing on Sundays.</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> </ul>
2001	<ul style="list-style-type: none"> <li>• Restriction of season to 61 days</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (83 days). January 9 – April 30. March 18-April 15 no fishing. Experimental offshore fishery in May.</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> </ul>
2002	<ul style="list-style-type: none"> <li>• No fishing; closed season</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (25 days). February 15 – March 11.</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> </ul>
2003	<ul style="list-style-type: none"> <li>• No fishing; closed season</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (38 days). January 15 – February 27. No fishing on Fridays.</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> </ul>
2004	<ul style="list-style-type: none"> <li>• No fishing; closed season</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (40 days). January 19 – March 12. No fishing on weekends.</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> <li>• No mechanical shaking of net on vessel</li> </ul>
2005	<ul style="list-style-type: none"> <li>• Landings should not exceed 2,500 metric tons</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (70 days). December 19 – 30, no fishing on Friday and Saturday; January 3 – March 25, no fishing on weekends.</li> <li>• Continuation of mesh regulations</li> <li>• Finfish excluder devices required</li> <li>• No mechanical shaking of net on vessel</li> </ul>
2006	<ul style="list-style-type: none"> <li>• Landings should not exceed 5,200 metric tons</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (140 days). December 12 – April 30.</li> <li>• 2007 fishing season tentatively set at 140 days.</li> <li>• Continuation of mesh regulations</li> <li>• No mechanical shakers allowed on vessel</li> </ul>
2007	<ul style="list-style-type: none"> <li>• No recommendation against 140-day season</li> <li>• Continuation of mesh regulations</li> </ul>	<ul style="list-style-type: none"> <li>• Open season (151 days). December 1 – April 30.</li> <li>• 2008 fishing season tentatively set at 151 days.</li> <li>• Continuation of mesh regulations</li> <li>• No mechanical shakers allowed on vessel</li> </ul>

Table A5-1. Commercial landings (mt) of northern shrimp in the western Gulf of Maine.  
1 mt = 2,205 lbs.

<b>Year</b>	<b>Maine</b>	<b>Massachusetts</b>	<b>New Hampshire</b>	<b>Total mt</b>	<b>Total lbs</b>	<b>\$/Lb</b>			
1958	2.3	0.0	0.0	2.3	5,072	0.32			
1959	5.4	2.3	0.0	7.7	16,979	0.29			
1960	40.4	0.5	0.0	40.9	90,185	0.23			
1961	30.4	0.5	0.0	30.9	68,135	0.20			
1962	159.7	16.3	0.0	176.0	388,080	0.15			
1963	244.0	10.4	0.0	254.4	560,952	0.12			
1964	419.4	3.1	0.0	422.5	931,613	0.12			
1965	947.0	8.0	0.0	955.0	2,105,775	0.12			
1966	1,737.8	10.5	18.1	1,766.4	3,894,912	0.14			
1967	3,141.1	10.0	20.0	3,171.1	6,992,276	0.12			
1968	6,515.0	51.9	43.1	6,610.0	14,575,050	0.11			
1969	10,992.9	1,772.9	58.1	12,823.9	28,276,700	0.12			
1970	7,712.8	2,902.1	54.4	10,669.3	23,525,807	0.20			
1971	8,354.7	2,723.8	50.8	11,129.3	24,540,107	0.19			
1972	7,515.6	3,504.5	74.8	11,094.9	24,464,255	0.19			
1973	5,476.7	3,868.2	59.9	9,404.8	20,737,584	0.27			
1974	4,430.7	3,477.3	36.7	7,944.7	17,518,064	0.32			
1975	3,177.0	2,080.2	29.5	5,286.7	11,657,174	0.26			
1976	617.2	397.8	7.3	1,022.3	2,254,172	0.34			
1977	148.0	236.9	2.3	387.2	853,776	0.55			
1978	0.0	0.0	0.0	0.0	0	0.24			
1979	32.9	451.3	2.3	486.5	1,072,733	0.33			
1980	71.4	260.3	7.4	339.1	747,716	0.65			
1981	528.6	538.1	4.5	1,071.2	2,361,996	0.64			
1982	883.2	*853.3	658.5	*655.3	32.8 *21.6	1,574.5 *1,530.2	3,471,773 *3,374,091	0.60	
1983	1,022.0	892.5	508.0	458.4	36.5 46.2	1,566.5 1,397.1	3,454,133 3,080,606	0.67	
1984	2,564.7	2,394.9	565.3	525.1	96.8 30.7	3,226.8 2,950.7	7,115,094 6,506,294	0.49	
1985	2,956.9	2,946.4	1,030.6	968.0	207.4 216.5	4,194.9 4,130.9	9,249,755 9,108,635	0.44	
1986	3,407.3	3,268.2	1,085.6	1,136.3	191.1 230.5	4,684.0 4,635.0	10,328,220 10,220,175	0.63	
1987	3,534.2	3,673.2	1,338.7	1,422.2	152.5 157.8	5,025.4 5,253.2	11,081,007 11,583,306	1.10	
1988	2,272.4	2,257.2	631.5	619.6	173.1 154.5	3,077.0 3,031.3	6,784,785 6,684,017	1.10	
1989	2,542.6	2,384.0	749.6	699.9	314.3 231.5	3,606.5 3,315.4	7,952,333 7,310,457	0.98	
1990	2,961.5	3,236.1	993.2	974.3	447.3 451.2	4,402.0 4,661.6	9,706,410 10,278,828	0.72	
1991	2,431.1	2,488.1	727.6	801.1	208.2 282.2	3,366.9 3,571.4	7,424,015 7,874,937	0.93	
1992	2,973.9	3,054.1	291.6	289.1	100.1 100.0	3,365.6 3,443.6	7,421,148 7,593,138	0.99	
1993	1,562.8	1,492.2	300.3	292.8	441.1 357.4	2,304.7 2,142.9	5,081,864 4,725,095	1.03	
1994	2,815.5	2,239.3	374.4	247.5	520.9 428.0	3,710.8 2,914.8	8,182,314 6,427,134	0.79	
1995	5,022.7		678.8		764.9	6,466.4		14,258,412	0.88
1996	7,737.0		658.0		771.0	9,166.1		20,211,251	0.72
1997	6,050.0		362.8		666.3	7,079.1		15,609,416	0.82
1998	3,482.0		247.2		445.2	4,174.4		9,204,552	0.94
1999	1,523.4		75.7		217.0	1,816.1		4,004,501	0.93
2000	2,067.3		109.9		212.3	2,389.5		5,268,848	0.79
2001	1,073.4		49.2		206.4	1,329.1		2,930,666	0.86
2002**	364.8		7.7		51.2	423.7		934,259	1.07
2003**	1,081.20		23.1		106.7	1,211.00		2,670,255	0.87
2004**	1,756.00		17.5		175.2	1,948.70		4,296,884	0.46
2005**	2,214.60		48.6		289.9	2,553.20		5,629,806	0.56
2006**	1,762.50		25.2		88.9	1,876.60		4,137,903	

\*Computed on a seasonal basis (includes December of the previous year).

\*\*Includes removals by experimental studies

2005 and 2006 are preliminary.

Table A5-2. Landings (metric tons) in the Gulf of Maine northern shrimp fishery by state and month. 1 mt =2,205 lbs.

	<u>Dec</u>	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>Other</u>	<b>Season Total</b>	<u>Dec</u>	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>Other</u>	<b>Season Total</b>
<b>1987 Season, 182 days, Dec 1 - May 31</b>									<b>1995 Season, 128 days, Dec 1 - Apr 30, 1 day per week off</b>							
Maine	485.9	906.2	1,192.7	672.9	287.6	127.9	7.0	3,680.2	Maine	747.6	1,397.7	1,338.2	912.0	627.2		5,022.7
Mass.	103.5	260.0	384.9	310.2	180.8	182.8	5.7	1,427.9	Mass.	210.7	154.0	104.1	111.0	99.0		678.8
N.H.	18.4	53.6	62.8	15.7	7.3	0.0	0.1	157.9	N.H.	160.6	186.8	118.3	158.5	140.7		764.9
Total	607.8	1,219.8	1,640.4	998.8	475.7	310.7	12.8	5,266.0	Total	1,118.9	1,738.5	1,560.6	1,181.5	866.9		6,466.4
<b>1988 Season, 183 days, Dec 1 - May 31</b>									<b>1996 Season, 152 days, Dec 1 - May 31, 1 day per week off</b>							
Maine	339.7	793.9	788.1	243.6	24.6	67.3	1.2	2,258.4	Maine	1,124.1	1,678.3	3,004.6	785.2	350.4		7,737.1
Mass.	14.4	225.8	255.0	104.9	8.6	10.9	0.0	619.6	Mass.	167.9	106.7	188.7	67.8	66.5		657.9
N.H.	13.0	72.6	53.7	14.9	0.3	0.0	3.1	157.6	N.H.	189.8	169.5	234.0	81.9	78.8		771.1
Total	367.1	1,092.3	1,096.8	363.4	33.5	78.2	4.3	3,035.6	Total	1,481.8	1,954.5	3,427.3	934.9	495.7		9,166.1
<b>1989 Season, 182 days, Dec 1 - May 31</b>									<b>1997 Season, 156 days, Dec 1 - May 27, two 5-day and four 4-day blocks off</b>							
Maine	353.6	770.5	700.6	246.4	218.7	94.2	0.1	2,384.0	Maine	1,178.5	1,114.9	1,713.1	758.4	754.8		530.3
Mass.	26.2	197.5	154.9	104.8	160.9	55.6	0.0	699.9	Mass.	90.2	110.4	111.4	49.0	1.2		6,050.0
N.H.	28.5	106.9	77.0	15.4	3.7	0.0	0.0	231.5	N.H.	185.6	104.1	140.1	108.6	85.8		362.7
Total	408.3	1,074.9	932.5	366.6	383.3	149.8	0.4	3,315.4	Total	1,454.3	1,329.4	1,964.6	916.0	841.8		666.4
<b>1990 Season, 182 days, Dec 1 - May 31</b>									<b>1998 Season, 105 days, Dec 8-May 22, weekends off except Mar 14-15, Dec 25-31 and Mar 16-31 off</b>							
Maine	512.4	778.2	509.7	638.5	514.0	282.8	0.1	3,235.7	Maine	511.1	926.8	1,211.1	401.7	228.7		3,482.0
Mass.	75.6	344.4	184.8	100.2	158.9	110.0	4.3	978.2	Mass.	49.1	78.0	90.5	14.3	15.3		247.8
N.H.	111.3	191.7	116.1	30.7	1.4	0.0	0.0	451.2	N.H.	89.4	106.9	143.5	54.3	49.0		445.2
Total	699.3	1,314.3	810.6	769.4	674.3	392.8	4.4	4,665.1	Total	649.6	1,111.7	1,445.1	470.3	293.0		4,174.4
<b>1991 Season, 182 days, Dec 1 - May 31</b>									<b>1999 Season, 90 days, Dec 15 - May 25, weekends, Dec 24 - Jan 3, Jan 27-31, Feb 24-28, Mar 16-31, and Apr 29 - May 2 off</b>							
Maine	238.2	509.1	884.0	454.9	251.7	148.2	2.0	2,488.1	Maine	79.9	192.7	590.8	240.6	204.5		214.9
Mass.	90.5	174.7	175.9	131.2	93.3	133.8	1.6	801.0	Mass.	25.0	23.8	16.0	2.5	8.4		1,523.4
N.H.	107.3	104.4	33.8	27.8	7.8	1.0	0.0	282.1	N.H.	46.5	63.2	52.2	10.0	36.5		75.7
Total	436.0	788.2	1,093.7	613.9	352.8	283.0	3.6	3,571.2	Total	151.4	279.7	659.0	253.1	249.4		217.0
<b>1992 Season, 153 days, Dec 15 - May 15</b>									<b>2000 Season, 51 days, Jan 17 - Mar 15, Sundays off</b>							
Maine	181.1	880.9	1,278.9	462.5	163.6	87.2	0.1	3,054.2	Maine	607.4	1,271.4	183.5				2,067.3
Mass.	17.1	148.2	73.3	47.5	2.9	0.1	0.0	289.1	Mass.	17.4	17.4	13.8				109.9
N.H.	33.4	47.0	11.9	6.8	1.0	0.0	0.0	100.1	N.H.	39.6	131.1	41.6				212.3
Total	231.6	1,076.1	1,364.1	516.8	167.5	87.2	0.4	3,443.7	Total	664.4	1,481.2	243.9				2,389.5
<b>1993 Season, 138 days, Dec 14 - April 30</b>									<b>2001 Season, 83 days, Jan 9 - Apr 16 off, experimental offshore fishery in May</b>							
Maine	100.9	369.0	597.0	297.5	127.8	0.1	0.0	1,492.2	Maine	576.0	433.5	37.1	26.5	0.3		1,073.4
Mass.	19.6	82.0	81.9	62.3	42.0	5.0	0.0	292.8	Mass.	38.5	8.9	1.9	0.0	0.0		49.2
N.H.	33.5	85.4	101.7	77.0	59.8	0.4	0.0	357.4	N.H.	127.9	37.4	12.1	29.0	0.0		206.4
Total	154.0	536.4	780.6	436.8	229.6	5.0	0.4	2,142.8	Total	742.4	479.8	51.1	55.5	0.3		1,329.1
<b>1994 Season, 122 days, Dec 15 - Apr 15</b>									<b>2002 Season, 25 days, Feb 15 - Mar 11</b>							
Maine	171.5	647.7	971.9	399.5	48.7	0.1	0.0	2,239.3	Maine	285.5	76.7					2.5
Mass.	27.1	68.0	100.8	38.8	12.8	0.0	0.0	247.5	Mass.	5.3	2.3					364.8
N.H.	117.2	124.3	128.7	49.6	8.2	0.0	0.0	428.0	N.H.	38.0	13.3					7.7
Total	315.8	840.0	1,201.4	487.9	69.7	0.4	0.0	2,914.8	Total	92.4	92.4					51.2
																423.7

Table A5-2 continued.

	<u>Dec</u>	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>Other</u>	<b>Season Total</b>
<b>2003 Season, 38 days, Jan 15 - Feb 27, Fridays off</b>								
Maine	477.5	602.4	1.2				0.02	1,081.2
Mass.	10.5	12.6						23.1
N.H.	28.2	78.5						106.7
Total	516.2	693.5					0.02	1,211.0
<b>2004 Season, 40 days, Jan 19 - Mar 12, Saturdays and Sundays off</b>								
Maine	1.8	522.3	846.5	378.0	4.7	2.7	0.02	1,756.0
Mass.		5.2	10.1	2.1				17.5
N.H.		27.3	87.4	60.5				175.2
Total	1.8	554.8	944.0	440.7	4.7	2.7	0.02	1,948.7
<b>*2005 Season, 70 days, Dec 19 - 30, Fri-Sat off, Jan 3 - Mar 25, Sat-Sun off</b>								
Maine	75.0	377.8	871.2	890.6				2,214.6
Mass.	5.9	8.1	25.7	8.9				48.6
N.H.	17.3	53.5	175.4	43.7				289.9
Total	98.2	439.4	1,072.3	943.3				2,553.2
<b>*2006 Season, 140 days, Dec 12 - Apr 30</b>								
Maine	132.6	553.7	723.1	276.3	76.9			1,762.5
Mass.	4.5	8.0	6.4	6.3	0.0			25.2
N.H.	3.4	27.9	7.6	43.6	6.5			89.0
Total	140.4	589.6	737.1	326.2	83.3			1,876.6

\* Preliminary data

Table A5-3. Landings (mt) in the Maine northern shrimp fishery by gear type and month, 2001 - 2006. 1 mt =2,205 lbs.

	<u>Dec</u>	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>Other</u>	<u>Season Total</u>	<u>% of season total</u>
<b>2001 Season, 83 days, Jan 9 - Apr 30, Mar 18 - Apr 16 off, experimental offshore fishery in May</b>									
Trawl	532.8	360.6	31.4	26.4	0.3	951.5	89%		
Trap	43.2	72.9	5.7	0.1	0	121.9	11%		
Total	576.0	433.5	37.1	26.5	0.3	1,073.4			
<b>2002 Season, 25 days, Feb 15 - Mar 11</b>									
Trawl		245.3	70.1			2.5	318.0	87%	
Trap		40.2	6.6			0	46.8	13%	
Total		285.5	76.7			2.5	364.8		
<b>2003 Season, 38 days, Jan 15 - Feb 27, Fridays off</b>									
Trawl	411.3	465.6	1.2			0.02	878.1	81%	
Trap	66.2	136.9	0			0	203.1	19%	
Total	477.5	602.4	1.2			0.02	1,081.2		
<b>2004 Season, 40 days, Jan 19 - Mar 12, Saturdays and Sundays off</b>									
Trawl	1.8	510.5	807.2	361.587	4.7	2.7	0.02	1,688.4	96%
Trap		11.8	39.3	16.4	0	0	0	67.6	4%
Total	1.8	522.3	846.5	378.0	4.7	2.7	0.0	1,756.0	
<b>*2005 Season, 70 days, Dec 19 - 30, Fri-Sat off, Jan 3 - Mar 25, Sat-Sun off</b>									
Trawl	75.0	369.2	743.4	633.793				1,821.4	82%
Trap	0	8.6	127.8	256.8				393.2	18%
Total	75.0	377.8	871.2	890.6				2,214.6	
<b>*2006 Season, 140 days, Dec 12 - Apr 30</b>									
Trawl	132.4	540.4	607.2	211.4	76.1		1,567.5	89%	
Trap	0.1	13.3	115.9	64.9	0.7		194.9	11%	
Total	132.6	553.7	723.1	276.3	76.9		1,762.5		

\* Preliminary data

Table A5-4. Distribution of fishing effort (number of trawl trips) in the Gulf of Maine northern shrimp fishery.

	<u>Dec</u>	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>Other</u>	<u>Season Total</u>	<u>Season Total</u>
<b>1987 Season, 182 days, Dec 1 - May 31</b>									
Maine	983	2,373	3,073	2,241	617	340	16	9,653	1995 Season, 128 days, Dec 1 - Apr 30, 1 day per week off
Mass.	325	354	414	426	283	317	164	2,283	Maine 879 2,341 2,641 1,337 694
N.H.	67	164	175	95	28	32	32	561	Mass. 145 385 275 157 109
Total	1,385	2,891	3,662	2,762	928	657		12,285	N.H. 189 331 279 359 344
									Total 1,213 3,057 3,195 1,853 1,147
<b>1988 Season, 183 days, Dec 1 - May 31</b>									
Maine	972	2,183	2,720	1,231	193	122		7,421	<b>1996 Season, 152 days, Dec 1 - May 31, 1 day per week off</b>
Mass.	28	326	426	315	26	57		1,178	Maine 1,341 2,050 3,190 1,461 444
N.H.	72	231	236	99	3			641	Mass. 299 248 325 106 126
Total	1,072	2,740	3,382	1,645	222	179		9,240	N.H. 331 311 389 248 155
									Total 1,971 2,589 3,904 1,978 705
<b>1989 Season, 182 days, Dec 1 - May 31</b>									
Maine	958	2,479	2,332	936	249	84		7,038	<b>1997 Season, 156 days, Dec 1 - May 31, two 5-day and four 4-day blocks off</b>
Mass.	103	479	402	254	297	102		1,637	Maine 1,674 1,753 2,37 1,178 793
N.H.	120	369	312	69	16			886	Mass. 184 226 245 114 7
Total	1,181	3,327	3,046	1,259	562	186		9,561	N.H. 277 301 218 62 1
									Total 2,135 2,224 3,283 1,510 989
<b>1990 Season, 182 days, Dec 1 - May 31</b>									
Maine	1,036	1,710	1,529	1,986	897	238		7,396	<b>1998 Season, 105 days, Dec 8-May 22, weekends off except Mar 14-15, Dec 25-31 and Mar 16-31 off.</b>
Mass.	147	459	273	202	175	118		1,637	Maine 852 1,568 725 1,653 530
N.H.	178	363	284	157	82	6		988	Mass. 94 200 148 70 1
Total	1,361	2,532	2,086	2,345	1,078	356		9,758	N.H. 141 216 182 134 83
									Total 1,086 1,964 1,983 929 593
<b>1991 Season, 182 days, Dec 15 - May 15</b>									
Maine	568	1,286	2,070	1,050	438	139		5,551	<b>1999 Season, 90 days, Dec 15 - May 25, weekends, Dec 24 - Jan 3, Jan 27-31, Feb 24-28, Mar 16-31, and Apr 29 - May 2 off.</b>
Mass.	264	416	401	231	154	147		1,613	Maine 556 1,125 553 324 172
N.H.	279	285	135	82	22	1		804	Mass. 39 57 71 9 40
Total	1,111	1,987	2,606	1,363	614	287		7,968	N.H. 82 192 213 44 123
									Total 311 805 1,409 606 487
<b>1992 Season, 153 days, Dec 15 - May 15</b>									
Maine	411	1,966	2,700	1,222	318	141		6,758	<b>2000 Season, 51 days, Jan 17 - Mar 15, Sundays off</b>
Mass.	59	337	145	101	41			683	Maine 633 1,838 401
N.H.	96	153	76	29	3			357	Mass. 23 100 27 78
Total	566	2,456	2,921	1,352	362	141		7,798	N.H. 36 179 78
									Total 712 2,117 506
<b>1993 Season, 138 days, Dec 14 - April 30</b>									
Maine	249	1,102	1,777	1,032	227			4,387	<b>2001 Season, 83 days, Jan 9 - Apr 30, Mar 18 - Apr 15 off experimental offshore fishery in May</b>
Mass.	60	200	250	185	72			767	Maine 1,531 1,230 116 39 6
N.H.	76	246	275	256	151			1,004	Mass. 111 47 11 1 2,922
Total	385	1,548	2,302	1,473	450			6,158	N.H. 305 145 27 30 170
									Total 1,947 1,422 154 70 6
<b>1994 Season, 122 days, Dec 15 - Apr 15</b>									
Maine	265	1,340	1,889	1,065	122			4,681	<b>2002 Season, 25 days, Feb 15 - Mar 11</b>
Mass.	58	152	147	83	15			455	Maine 573 221
N.H.	169	228	266	173	18			854	Mass. 13 9
Total	492	1,720	2,302	1,321	155			5,990	N.H. 126 53
									Total 712 283 15 1,010

Table A5-4 continued.

	<u>Dec</u>	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>Other</u>	<b>Season Total</b>
<b>2003 Season, 38 days, Jan 15 - Feb 27, Fridays off</b>								
Maine	773	1,020					49	1,842
Mass.	35	39					74	
N.H.	82	159					241	
Total	890	1,218					49	2,157
<b>2004 Season, 40 days, Jan 19 - Mar 12, Saturdays and Sundays off</b>								
Maine	7	601	949	373	21	14	2	1,967
Mass.	9	32	8				49	
N.H.	49	143	69				261	
Total	7	659	1,124	450	21	14	2	2,277
<b>*2005 Season, 70 days, Dec 19 - 30, Fri-Sat off, Jan 3 - Mar 25, Sat-Sun off</b>								
Maine	147	665	945	801				2,558
Mass.	13	20	62	26				121
N.H.	26	86	224	76				412
Total	186	771	1,231	903				3,091
<b>*2006 Season, 140 days, Dec 12 - Apr 30</b>								
Maine	137	487	551	231	66			1,472
Mass.	8	13	15	13	0			49
N.H.	8	28	22	57	10			125
Total	153	528	588	301	76			1,646

\* Preliminary data

Table A5-5. Distribution of fishing trips in the Maine northern shrimp fishery by gear type and month, 2001 – 2006.

	<u>Dec</u>	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>Other</u>	<b>Season Total</b>	<b>% of total</b>
<b>2001</b>									
Trawl	1,531	1,230	116	39	6			2,922	83%
Trap	191	347	68	1				607	17%
Total	1,722	1,577	184	40	6			3,529	
<b>2002</b>									
Trawl	573	221				14		808	77%
Trap	193	55						248	23%
Total	766	276				14		1,056	
<b>2003</b>									
Trawl	773	1,020						1,842	72%
Trap	253	466						719	28%
Total	1,026	1,486						2,561	
<b>2004</b>									
Trawl	7	601	949	373	21	14	2	1,967	82%
Trap		77	244	106	0	0		427	18%
Total	7	678	1,193	479	21	14	2	2,394	
<b>2005</b>									
Trawl	147	665	945	801				2,558	75%
Trap	0	20	362	476				858	25%
Total	147	685	1,307	1,277				3,416	
* <b>2006</b>									
Trawl	137	487	551	231	66			1,472	70%
Trap	3	82	325	210	10			630	30%
Total	140	569	876	441	76			2,102	

\* preliminary data

Table A5-6. Sample size (number of shrimp lengths measured) for Gulf of Maine northern shrimp port samples. (Samples were taken in 1997–2000 but data were not available for analysis here.)

Month	State	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	2001	2002	2003	2004	2005	2006
Dec	Maine	212	67	318	497	502	820	417	278	394	1149	904					912	1115	
	Mass.	92	441	287	101	446	205	310	269	1611	1528					0	0		
	NH	602	884	370	639	761	760	306	331	541	560	389				504	557		
Jan	Maine	326	519	849	825	1204	460	2191	2327	2136	1717	1498	2718	5188	4418	2,670	3384	3091	
	Mass.	1108	426	354	741	1137	819	642	789	903	1342	1231	741		748	0	0	100	
	NH	283	876	672	674	631	990	953	551	427	418	499	450	794		735	358	1363	
Feb	Maine	642	283	187	667	898	190	2816	2058	1915	2722	1420	4862	3518	2618	3355	3,557	6504	
	Mass.	776	195	161	512	900	515	726	198	714	277	835	1709	854	573	1,643	821	0	
	NH	585	788	459	517	551	513	336	480	422	439	370	355	648	455	697	629	872	
Mar	Maine	368	205	127	506	571	1407	1419	1570	1502	1572	944	3378	1147	927		1,891	4596	
	Mass.	830	388	414	149	232	358	652	1133	607	633		283	138		212	932	531	
	NH	91	298	499	75	639	508	97	375	550	598	392		205	532		294	472	
Apr	Maine	38	58	81	303	313	103	1076	526	108	563	2789	2882		1203			1115	
	Mass.	647	236	245				377		107	104			362	186	0		95	
	NH													648	510			461	
May	Maine																		
	Mass.	429	75	751	1218	226	1031	287											
	NH				1382	127	216												
Jun	Maine																		
	Mass.																		
	NH																		
Total		5,998	6,259	5,603	6,079	9,351	8,248	14,611	10,111	11,556	11,076	13,977	27,903	15,091	5,243	11,596	10,432	19,539	16,314

Table A5-7. Observed northern shrimp discards from the shrimp trawl fishery and other small-mesh fisheries in the Gulf of Maine. (1 lb = 0.45 kg.)

### Shrimp Trawl Fishery

<u>Year</u>	<u>observed no. of trips</u>	<u>total lbs shrimp discarded</u>	<u>total lbs shrimp landed</u>	<u>% Discarded</u>
1989	40	24.0	44,519	0.05%
1990	31	30.0	44,350	0.07%
1991	49	135.0	54,011	0.25%
1992	77	24.0	71,602	0.03%
1993	78	30.0	65,651	0.05%
1994	77	795.0	85,118	0.93%
1995	62	488.0	80,455	0.61%
1996	29	0.0	38,089	0.00%
1997	15	220.0	16,192	1.36%
2001	2	0.0	1,250	0.00%
2003	7	0.0	3,478	0.00%
2004	11	100.6	16,510	0.61%
2005	10	0.0	10,945	0.00%
2006	12	0.0	9,850	0.00%

### Herring Fishery

<u>Year</u>	<u>observed no. of trips</u>	<u>total lbs shrimp discarded</u>	<u>lbs shrimp discarded per trip</u>	<u>kg shrimp discarded per trip</u>
1995	13	1.0	0.1	0.03
1997	1	0.0	0.0	0.00
1998	1	0.0	0.0	0.00
1999	2	0.0	0.0	0.00
2000	3	0	0.0	0.00
2003	8	0	0.0	0.00
2004	88	1.1	0.0	0.01
2005	130	203.0	1.6	0.71
2006	14	16.0	1.1	0.52

### Whiting (silver hake) Fishery

<u>Year</u>	<u>observed no. of trips</u>	<u>total lbs shrimp discarded</u>	<u>lbs shrimp discarded per trip</u>	<u>kg shrimp discarded per trip</u>
1995	23	2,273	98.8	44.83
1996	44	6,044	137.4	62.31
1999	14	0	0.0	0.00
2000	7	3	0.4	0.19
2001	2	0	0.0	0.00
2002	16	0	0.0	0.00
2003	3	3	1.0	0.45
2004	31	0	0.0	0.00
2005	7	0	0.0	0.00
2006	4	0	0.0	0.00

Table A5-8. CPUE in lbs/hour towing from Maine port sampling, and catch/trip from NMFS weighout and logbook data for all three states. (1 lb = 0.45 kg)

Year	Maine pounds per hour towing			lb/trip	kg/trip	
	Inshore	Offshore	Combined			
	(<55 Fa)	(>55 Fa)	lbs/hr	kg/hr		
1991	94	152	140	6.3	988	45
1992	132	93	117	5.3	974	44
1993	82	129	92	4.2	767	35
1994	139	149	141	6.4	1,073	49
1995	172	205	193	8.8	1,362	62
1996	340	203	251	11.4	1,714	78
1997	206	192	194	8.8	1,454	66
1998	158	151	154	7.0	1,317	60
1999	159	146	152	6.9	1,067	48
2000	288	337	292	13.2	1,444	65
2001	100	135	109	4.9	740	34
2002	223	91	194	8.8	831	38
2003	174	215	182	8.3	1,029	47
2004	361	310	351	15.9	1,821	83
*2005	235	212	228	10.3	1,541	70
*2006	572	345	499	22.6	2,252	102

(\*preliminary data)

Table A6-1. NSTC state/federal summer survey loge-transformed, stratified mean numbers and weights, per tow\*, of northern shrimp. (1 kg = 2.2 lb)

<u>Year</u>	<u>N Tows</u>	<u>Age-1.5 Number</u>	<u>&gt;22 mm** Number</u>	<u>&gt;22 mm** Weight (kg)</u>	<u>Total Number</u>	<u>Total Weight (kg)</u>
1984		18	316	3.4	1,152	10.5
1985	44	337	1,184	11.7	1,849	17.7
1986	40	358	860	10.0	1,695	19.6
1987	41	342	854	9.5	1,533	14.8
1988	41	828	298	3.4	1,269	12.8
1989	43	276	564	6.1	1,883	17.0
1990	43	142	1,127	12.0	1,624	18.1
1991	43	482	657	8.0	1,255	11.7
1992	45	282	397	4.8	955	9.4
1993	46	757	250	2.8	1,156	9.1
1994	43	368	243	2.7	984	8.7
1995	35	292	628	7.0	1,449	13.3
1996	32	232	358	4.0	776	8.8
1997	40	374	245	2.8	762	7.7
1998	35	134	170	1.9	583	6.3
1999	42	114	174	1.9	398	5.8
2000	35	450	283	3.2	807	6.4
2001	36	18	146	1.5	451	4.3
2002	38	1,164	261	2.9	1,446	9.2
2003	37	11	173	1.7	564	5.5
2004	35	286	519	5.3	887	10.2
2005	46	1,753	871	10.3	3,661	23.3
2006	29	423	2,703	28.8	9,996	66.0
Mean	40	410	577	6.3	1,615	13.7
Median	41	337	358	4.0	1,156	10.2

\*Based on strata 1, 3, 5, 6, 7 and 8.

\*\*Will be fully recruited to the winter fishery.

Table A6-2. Summary of results from Collie-Sissenwine Analysis (CSA) of Gulf of Maine northern shrimp.

Fishing Season	New Recruits (millions)	Fully-Recruited (millions)	F (NR+FR)	Biomass		Exploitation Rate
				(1000 mt)	million lbs	
1985	839	777	0.28	11.7	25.8	22%
1986	855	949	0.26	15.3	33.8	20%
1987	652	1,089	0.32	15.9	35.1	24%
1988	510	984	0.19	13.8	30.4	15%
1989	820	963	0.20	12.3	27.1	15%
1990	803	1,140	0.30	15.0	33.1	22%
1991	545	1,126	0.24	15.9	35.0	19%
1992	406	1,021	0.23	13.9	30.6	18%
1993	367	881	0.19	11.4	25.2	15%
1994	559	801	0.25	9.2	20.3	20%
1995	913	822	0.50	12.1	26.8	35%
1996	900	816	0.73	13.9	30.5	47%
1997	557	643	1.06	10.0	22.0	57%
1998	479	322	0.73	5.6	12.3	47%
1999	357	300	0.46	4.7	10.4	32%
2000	263	324	0.51	4.7	10.5	35%
2001	337	275	0.30	4.4	9.7	22%
2002	265	353	0.08	4.7	10.4	7%
2003	560	442	0.14	5.8	12.8	11%
2004	421	681	0.23	8.0	17.6	18%
2005	938	684	0.18	13.0	28.7	14%
2006	4,330	1,058	0.03	32.1	70.9	3%
2007	6,363	4,052		71.5	157.6	
Overall average			0.34	14.1		24%
1985-94 average			0.25	13.4		19%

Table A6-3. Summary of results from surplus production analysis (ASPIC) for Gulf of Maine northern shrimp (1 kg = 2.2 lbs., 1 mt = 2,205 lbs)

Fishing Season	Input				Results			
	Fall (kg/tow)	Maine (kg/tow)	Summer (kg/tow)	Catch (mt)	Biomass (mt)	F	B/Bmsy	F/Fmsy
1968	3.20	45.8		5,708	44,700	0.13	1.49	0.72
1969	2.70	31.2		12,140	43,250	0.31	1.44	1.72
1970	3.70	40.8		11,330	35,970	0.35	1.20	1.93
1971	3.00	9.4		10,590	29,980	0.39	1.00	2.17
1972	3.30	7.0		11,220	24,710	0.53	0.82	2.94
1973	1.90	7.8		9,691	18,400	0.63	0.61	3.52
1974	0.80	4.9		8,024	12,800	0.80	0.43	4.46
1975	0.90	6.7		6,142	7,757	1.18	0.26	6.58
1976	0.60	4.8		1,387	3,309	0.44	0.11	2.46
1977	0.20	1.6		372	2,990	0.11	0.10	0.62
1978	0.40	3.2		17	3,753	0.00	0.12	0.02
1979	0.50	4.4		487	5,209	0.08	0.17	0.46
1980	0.50	2.7		339	6,624	0.05	0.22	0.25
1981	1.50	3.0		1,071	8,662	0.11	0.29	0.63
1982	0.30			1,530	10,460	0.14	0.35	0.75
1983	1.00			1,397	12,230	0.10	0.41	0.58
1984	1.90		10.47	2,951	14,550	0.20	0.48	1.09
1985	1.60		17.69	4,131	15,650	0.26	0.52	1.47
1986	2.50		19.61	4,635	15,670	0.30	0.52	1.68
1987	1.70		15.40	5,266	15,140	0.36	0.50	2.03
1988	1.20		12.76	3,036	13,820	0.21	0.46	1.19
1989	1.80		16.95	3,315	14,680	0.22	0.49	1.23
1990	2.00		18.12	4,665	15,400	0.31	0.51	1.73
1991	0.90		11.68	3,571	14,790	0.24	0.49	1.33
1992	0.60		9.43	3,444	15,250	0.22	0.51	1.23
1993	1.60		9.14	2,143	15,950	0.13	0.53	0.70
1994	2.20		8.69	2,915	18,180	0.15	0.60	0.85
1995	1.80		13.29	6,466	19,930	0.34	0.66	1.90
1996	1.10		8.77	9,166	18,120	0.60	0.60	3.32
1997	1.30		7.73	7,079	13,040	0.65	0.43	3.60
1998	2.30		6.33	4,174	9,171	0.50	0.30	2.80
1999	2.54		5.78	1,816	7,567	0.23	0.25	1.29
2000	1.28		6.39	2,390	8,203	0.29	0.27	1.61
2001	0.87		4.33	1,329	8,373	0.15	0.28	0.82
2002	0.17		9.16	424	9,802	0.04	0.33	0.21
2003	0.95		5.45	1,211	12,630	0.09	0.42	0.49
2004	0.83		10.23	1,949	15,250	0.12	0.51	0.66
2005	1.84		23.29	2,553	17,570	0.14	0.58	0.77
2006	2.77		65.95	1,877	19,620	0.09	0.65	0.50
2007					22,650		0.75	
<b>Average</b>	<b>1.54</b>			<b>4,153</b>	<b>15,545</b>	<b>0.29</b>		
				1971-74 average	21,473	0.59		
				1985-94 average	15,453	0.24		
				2004-06 average	17,480	0.12		

Table A10-1. Species and sizes of consistent pandalid predators

<b>Common Name</b>	<b>Scientific Name</b>	<b>Size</b>	<b>Size Cut-offs</b>
Thorny Skate	<i>Raja radiata</i>	M	>30 and <=60
		L	>60 and <=80
		XL	>80
Silver Hake	<i>Merluccius bilinearis</i>	S	<=20
		M	>20 and <=40
Atlantic cod	<i>Gadus morhua</i>	M	>20 and <=50
		L	>50 and <=80
Pollock	<i>Pollachius virens</i>	M	>20 and <=50
		L	>50 and <=80
White Hake	<i>Urophycis tenuis</i>	M	>20 and <=40
		L	>40 and <=60
Red Hake	<i>Urophycis chuss</i>	M	>20 and <=40
		L	>40
Four-spot Flounder	<i>Paralichthys oblongus</i>	M	>20 and <=40
Windowpane Longhorn Sculpin	<i>Scophthalmus aquosus</i> <i>Myoxocephalus octodecemspinosus</i>	M	>20 and <=40
		S	<=25
Sea Raven	<i>Hemitripterus americanus</i>	M	>25 and <=50
		S	<=25

## NORTHERN SHRIMP FIGURES

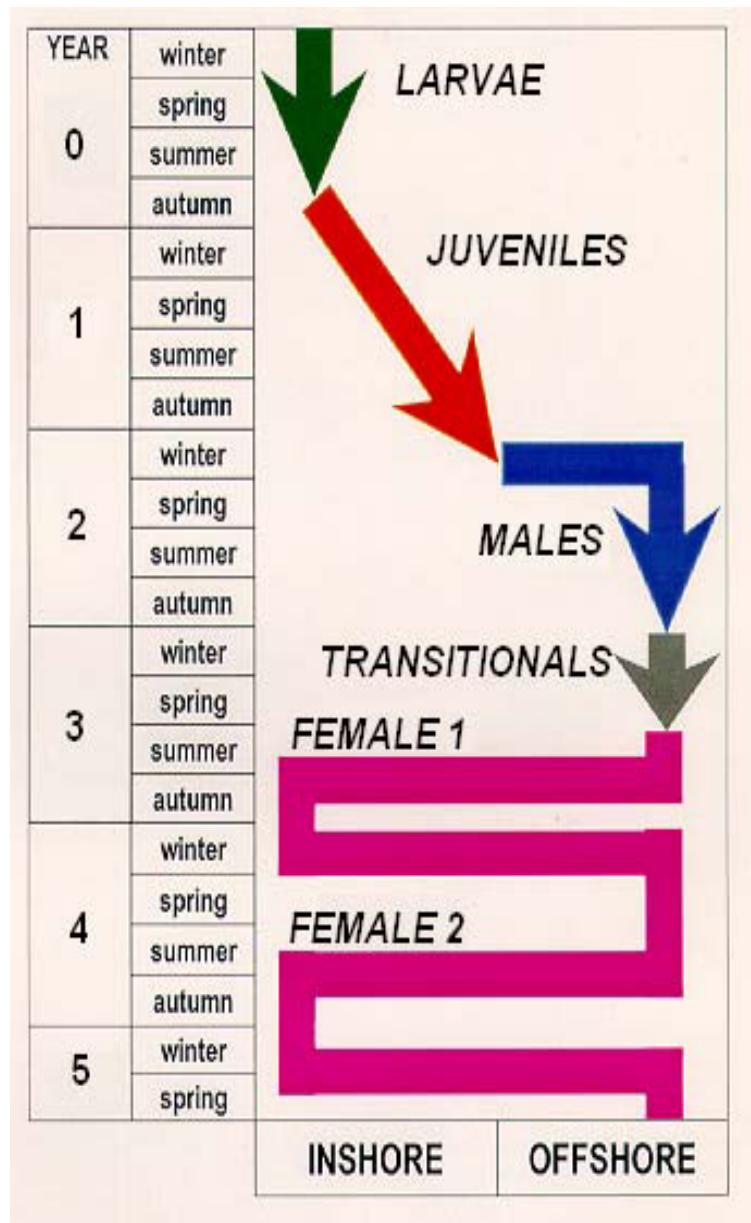


Figure A4-1. Diagram of Gulf of Maine northern shrimp life history

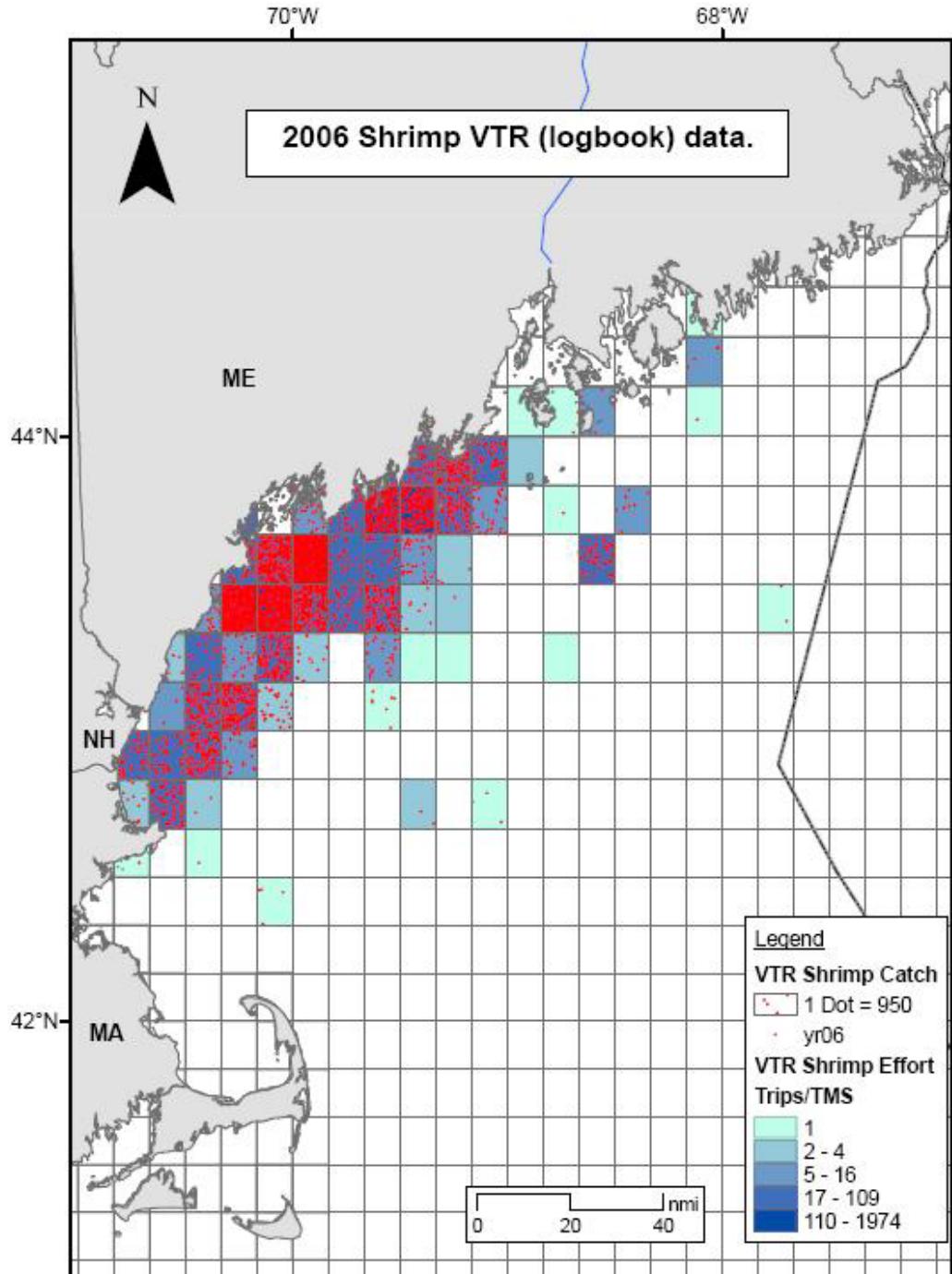


Figure A4-2. Northern shrimp catches and effort in the Gulf of Maine from VTRs (preliminary data). Does not include some non-federally permitted Maine boat trips. Dot density symbols (red dots, 1 dot = 950 lbs=431 kg) display pounds caught per 10-minute square. 950 lbs is the median value of pounds landed per trip during 2001-2006, therefore, squares with more dots reported higher landings. Effort, the number of trips per 10-minute square, is displayed in the background as the blue color palette.

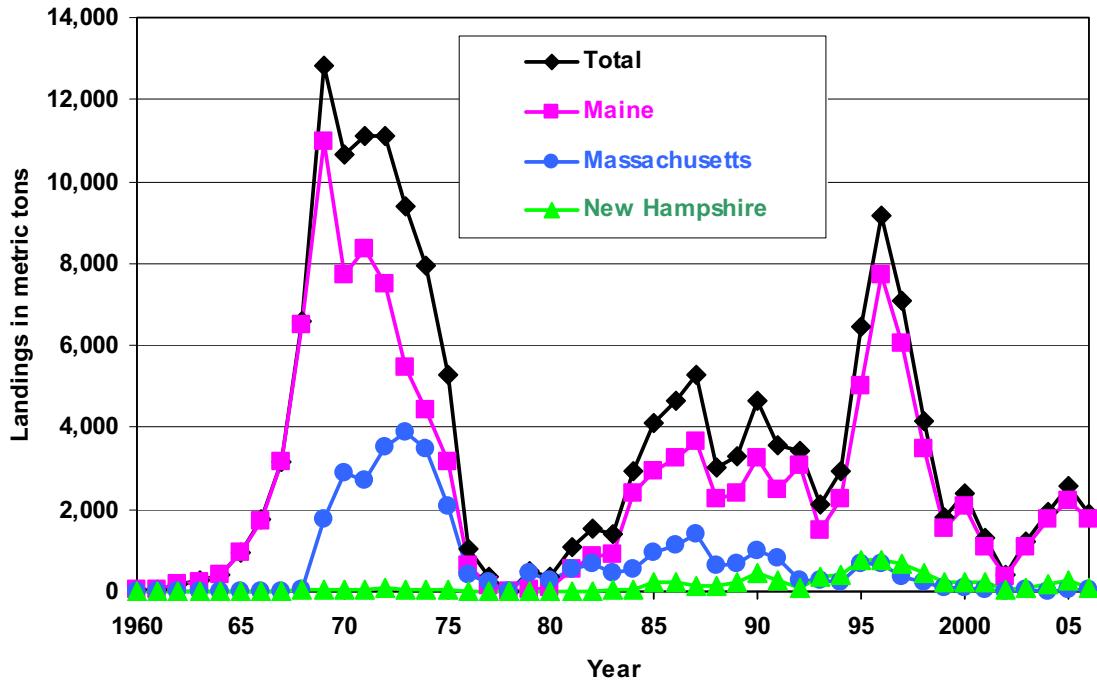


Figure A5-1. Gulf of Maine northern shrimp landings by year and state. (1 metric ton = 2,205 lbs)

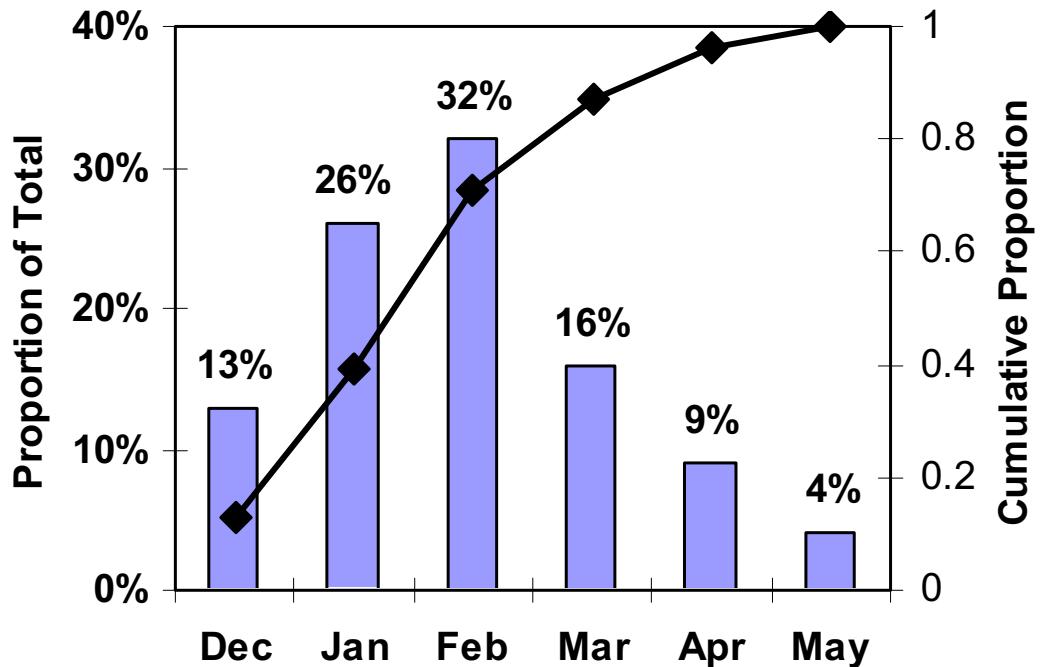


Figure A5-2. Distribution of monthly landings of Gulf of Maine northern shrimp, 1984–1996.

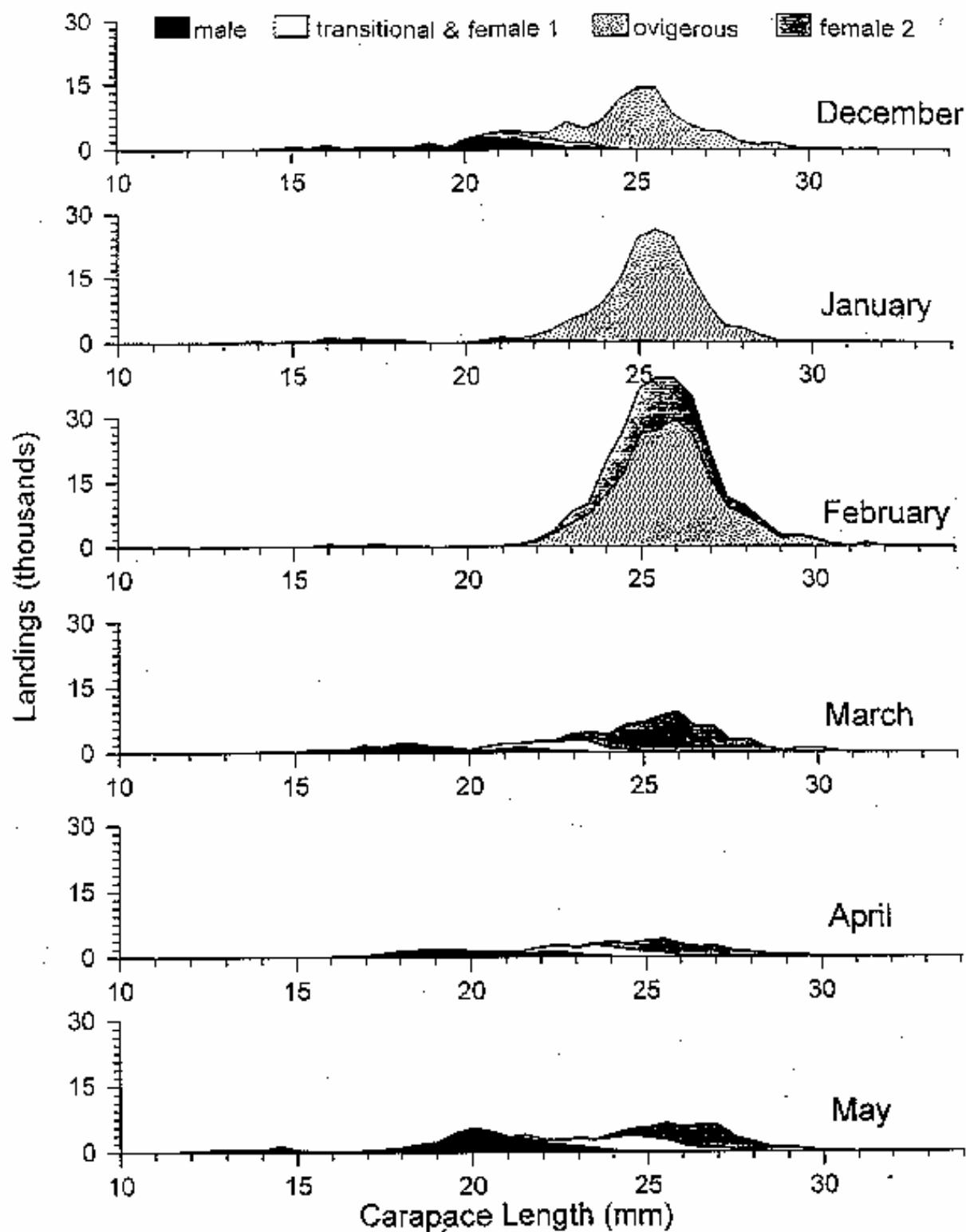


Figure A5-3. Gulf of Maine northern shrimp landings by length, developmental stage, and month, 1996 fishing season.

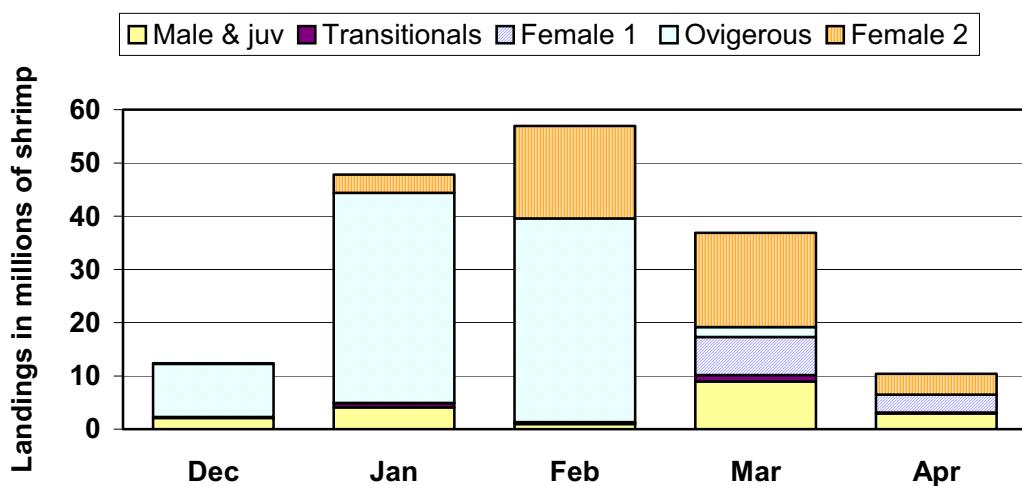
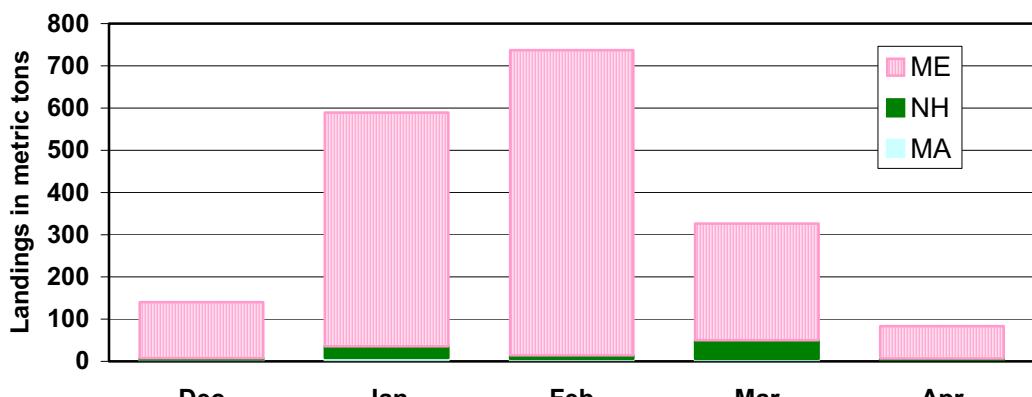


Figure A5-4. Gulf of Maine northern shrimp landings by month in the 2006 season. Landings are in metric tons by month and state (above), and in millions of shrimp by development stage (below). Landings are preliminary. (1 metric ton = 2,205 lbs)

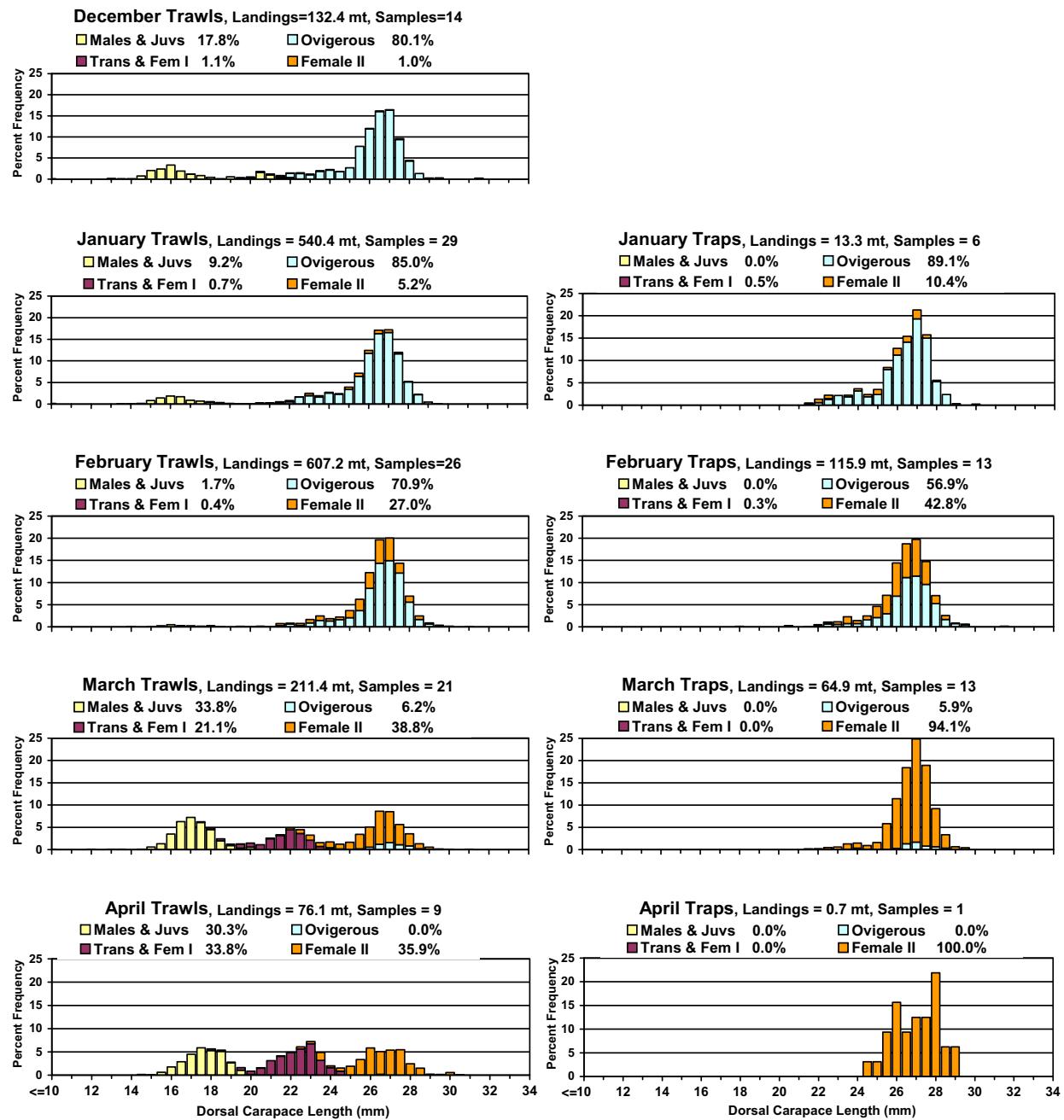


Figure A5-5. Length-frequency distribution from samples of Maine northern shrimp catches during the 2006 season by gear type and development stage. Landings are preliminary. (1 metric ton = 2,205 lbs)

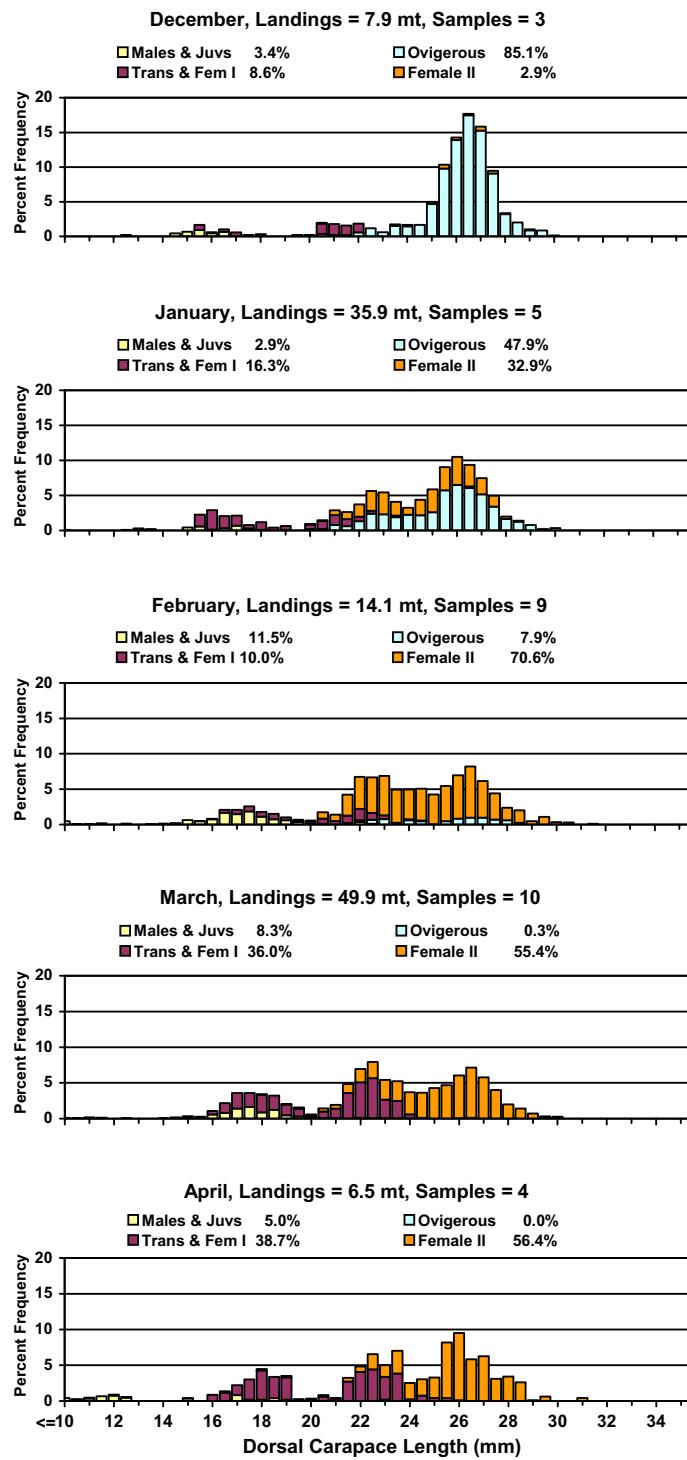


Figure A5-6. Size-frequency distribution from samples of Massachusetts and New Hampshire northern shrimp catches during the 2006 season by development stage. Landings are preliminary. (1 metric ton = 2,205 lbs)

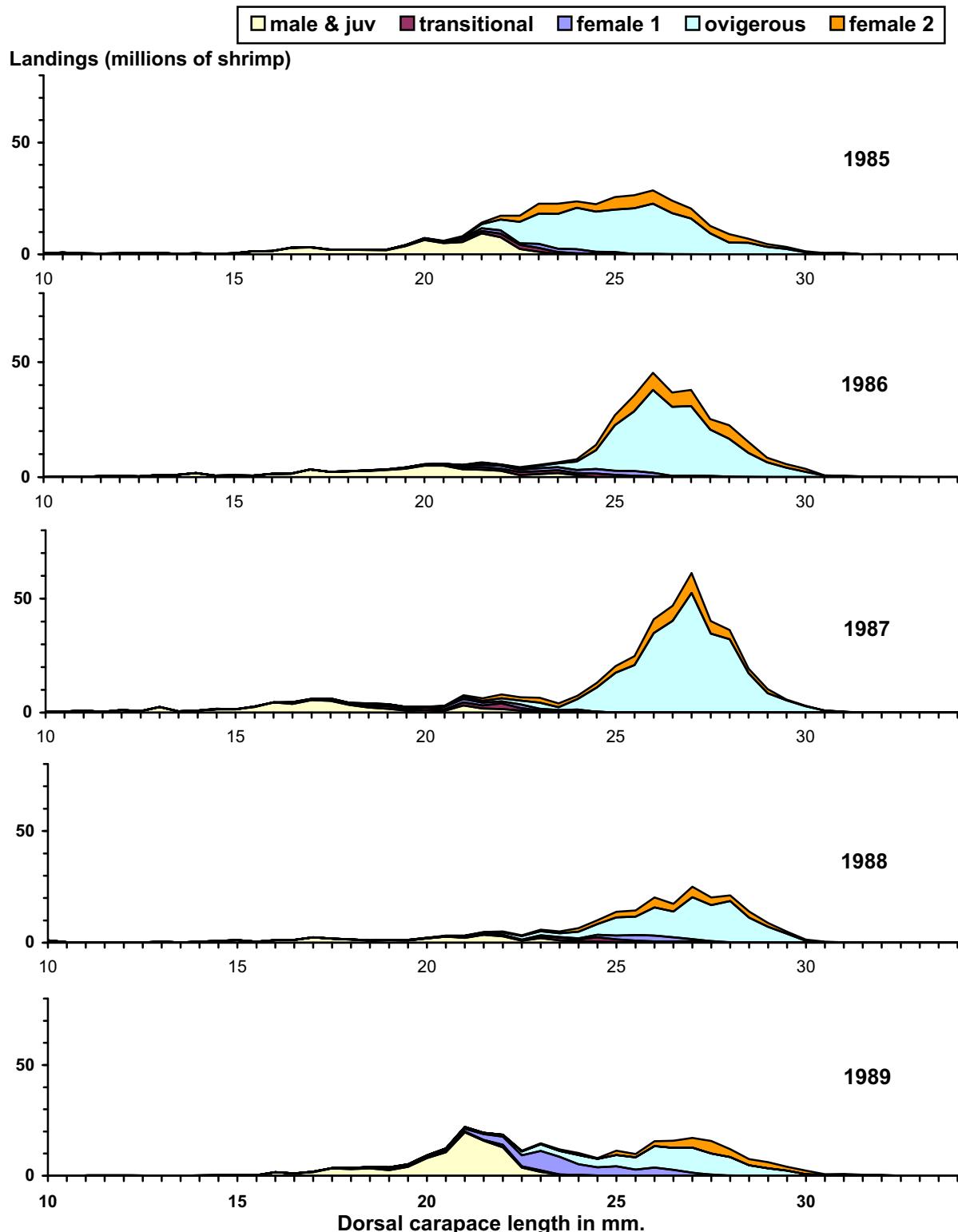


Figure A5-7. Gulf of Maine northern shrimp landings in numbers of shrimp, by length, stage, and fishing season. Landings are preliminary throughout.

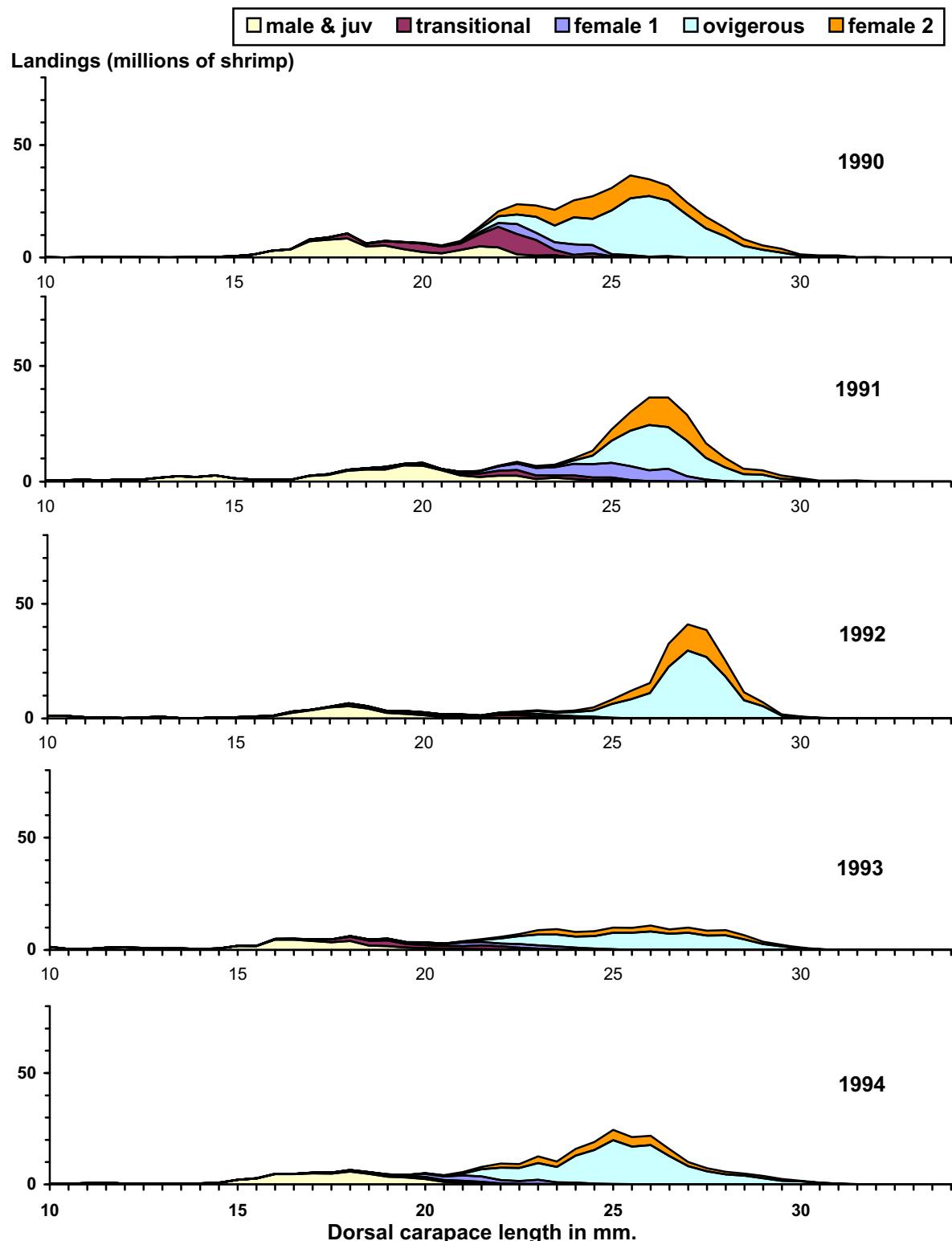


Figure A5-7 continued.

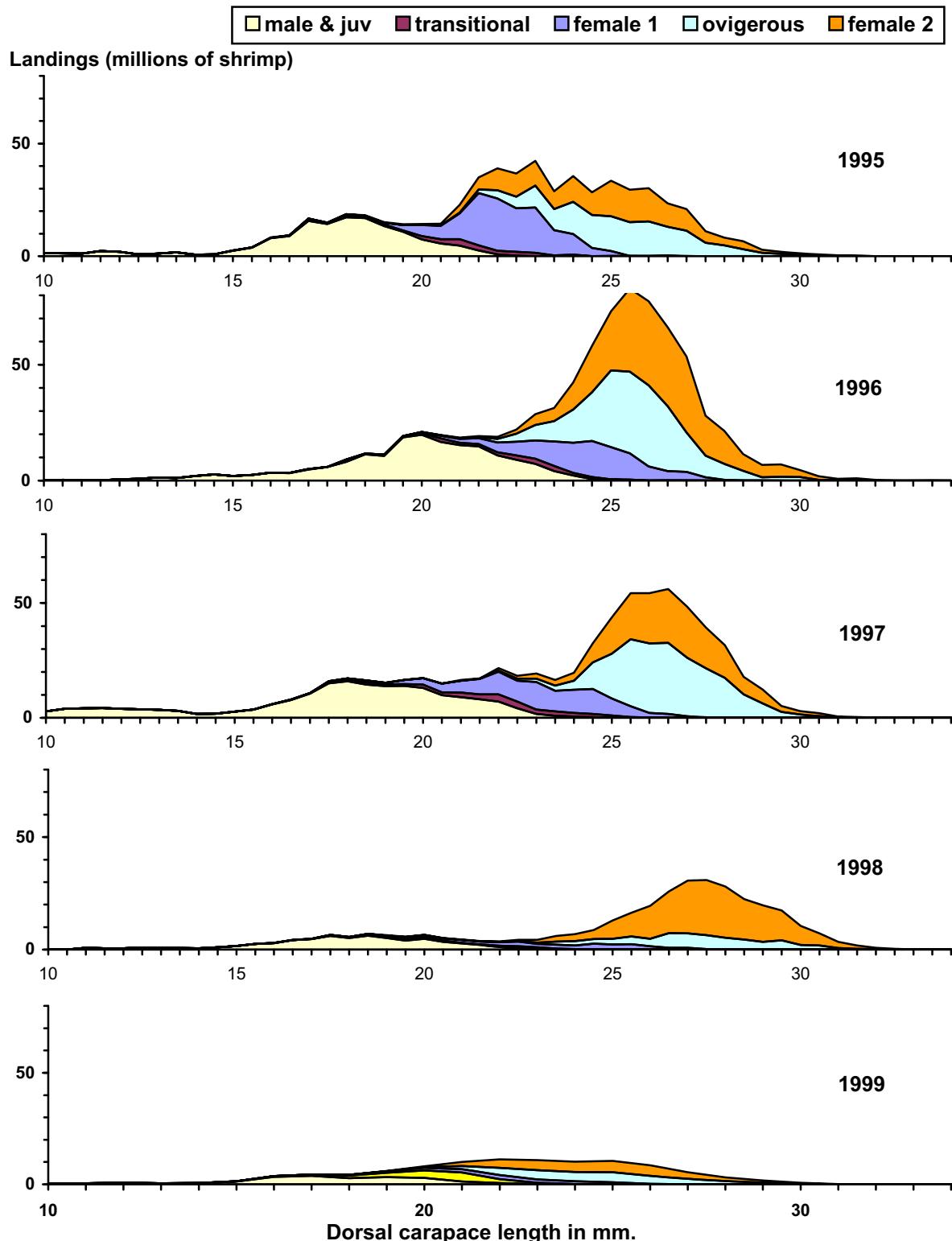


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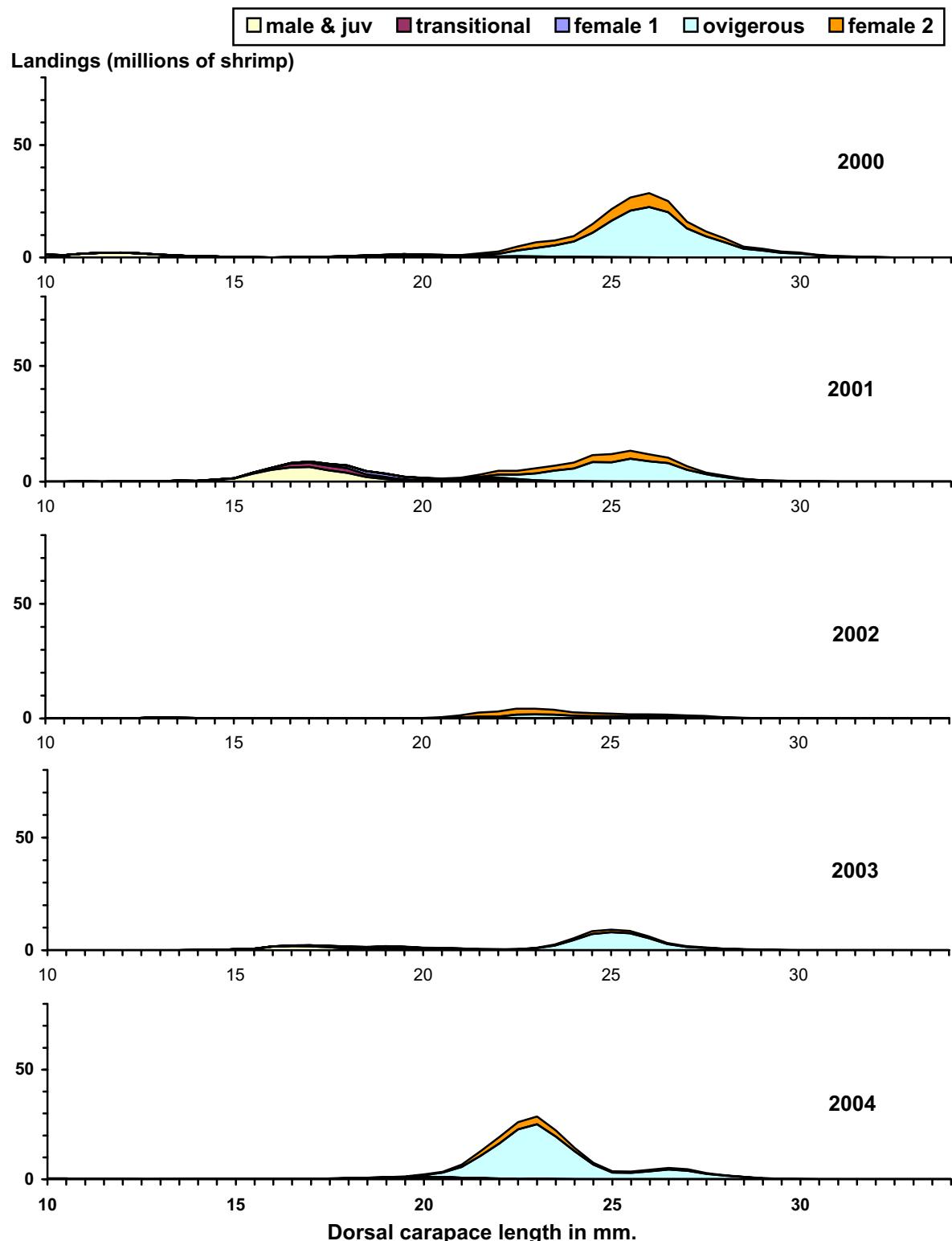


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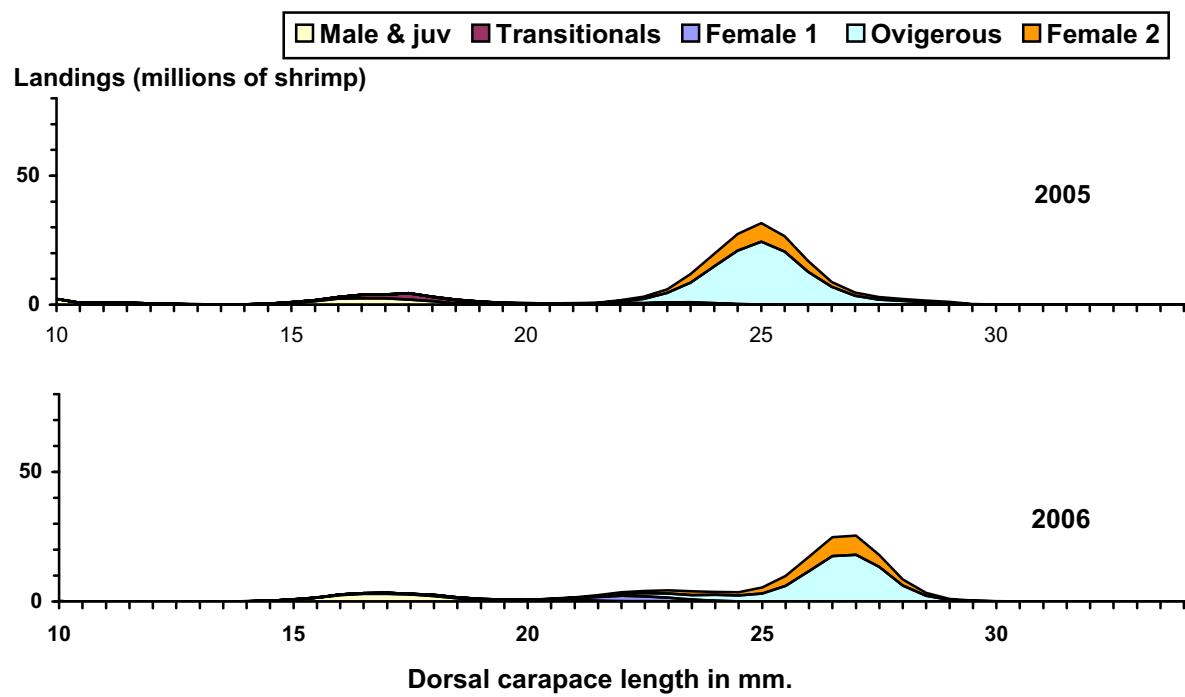


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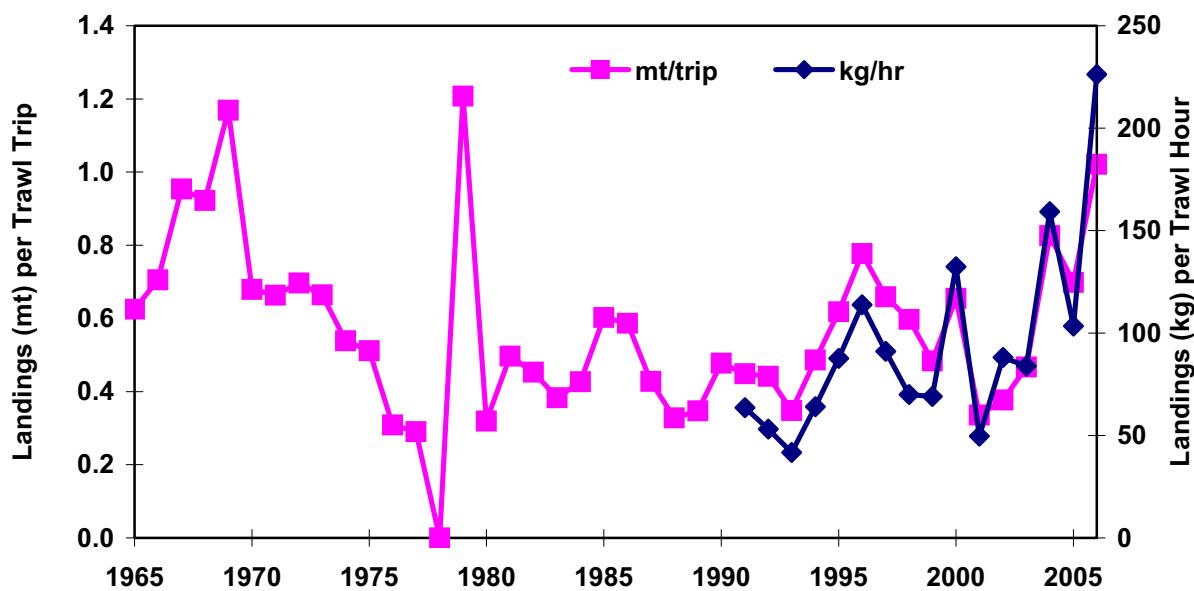
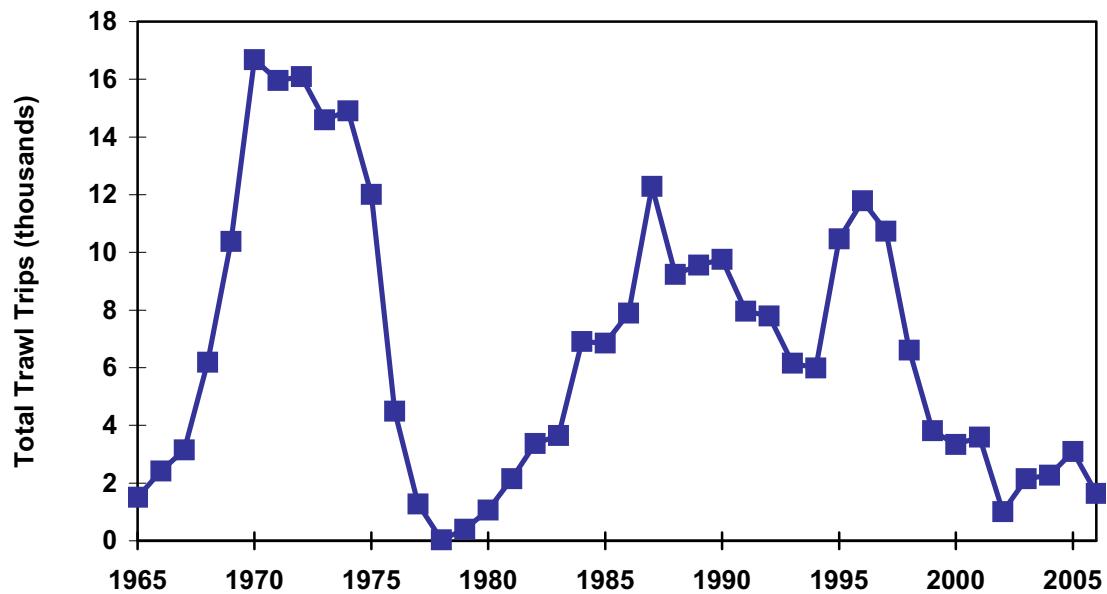


Figure A5-8. Nominal fishing effort (trawl trips) (above) and catch per unit effort (below), in the Gulf of Maine northern shrimp fishery by year. 2005 and 2006 data are preliminary. (1 mt = 2,205 lbs, 1 kg = 2.2 lbs)

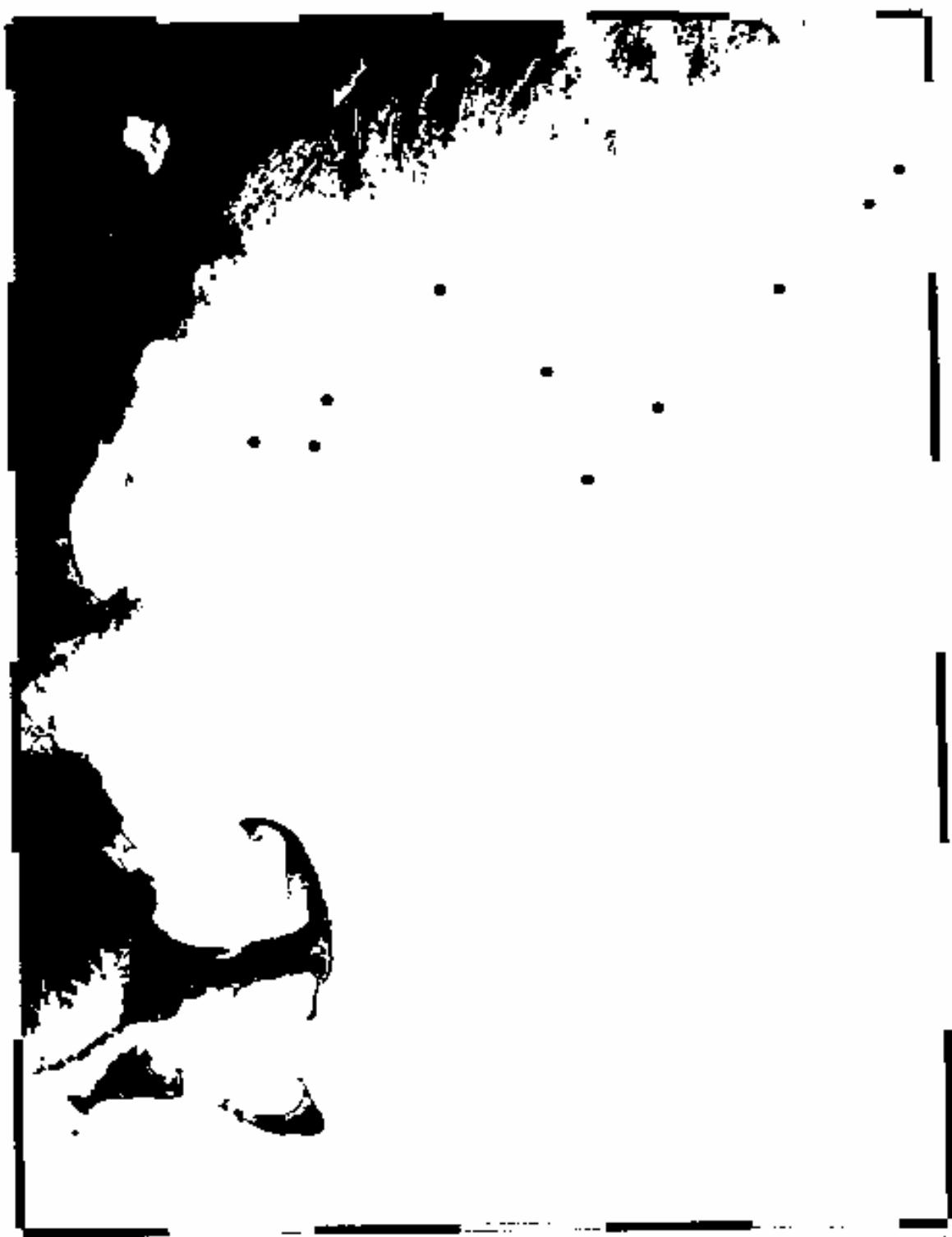


Figure A6-1. State of Maine summer northern shrimp survey station locations.

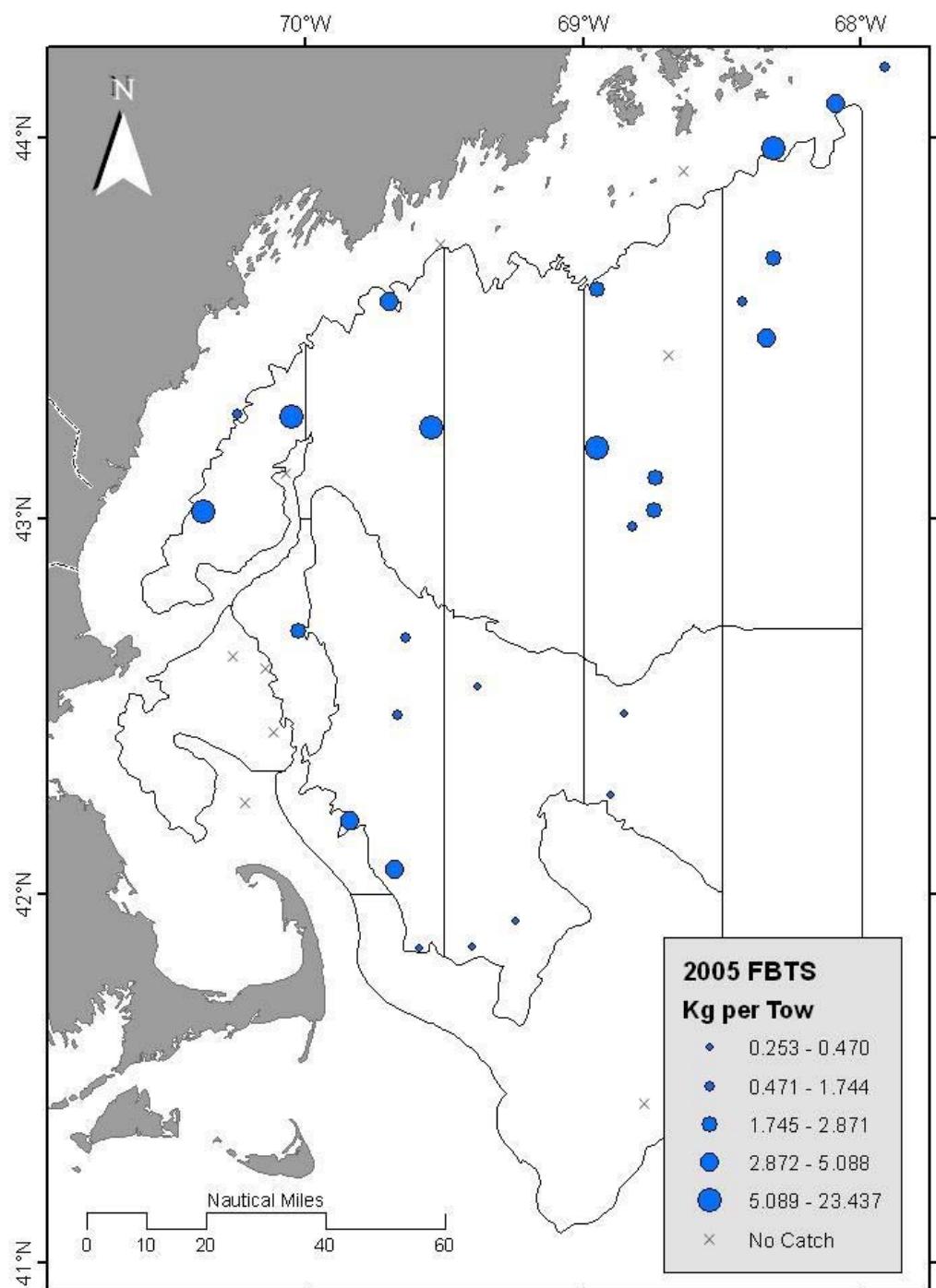


Figure A6-2. Northern shrimp survey strata and observed distribution of catch (kg) per tow of northern shrimp collected during the 2005 autumn bottom trawl survey in the western Gulf of Maine aboard the R/V Albatross IV. (1 kg = 2.2 lbs)

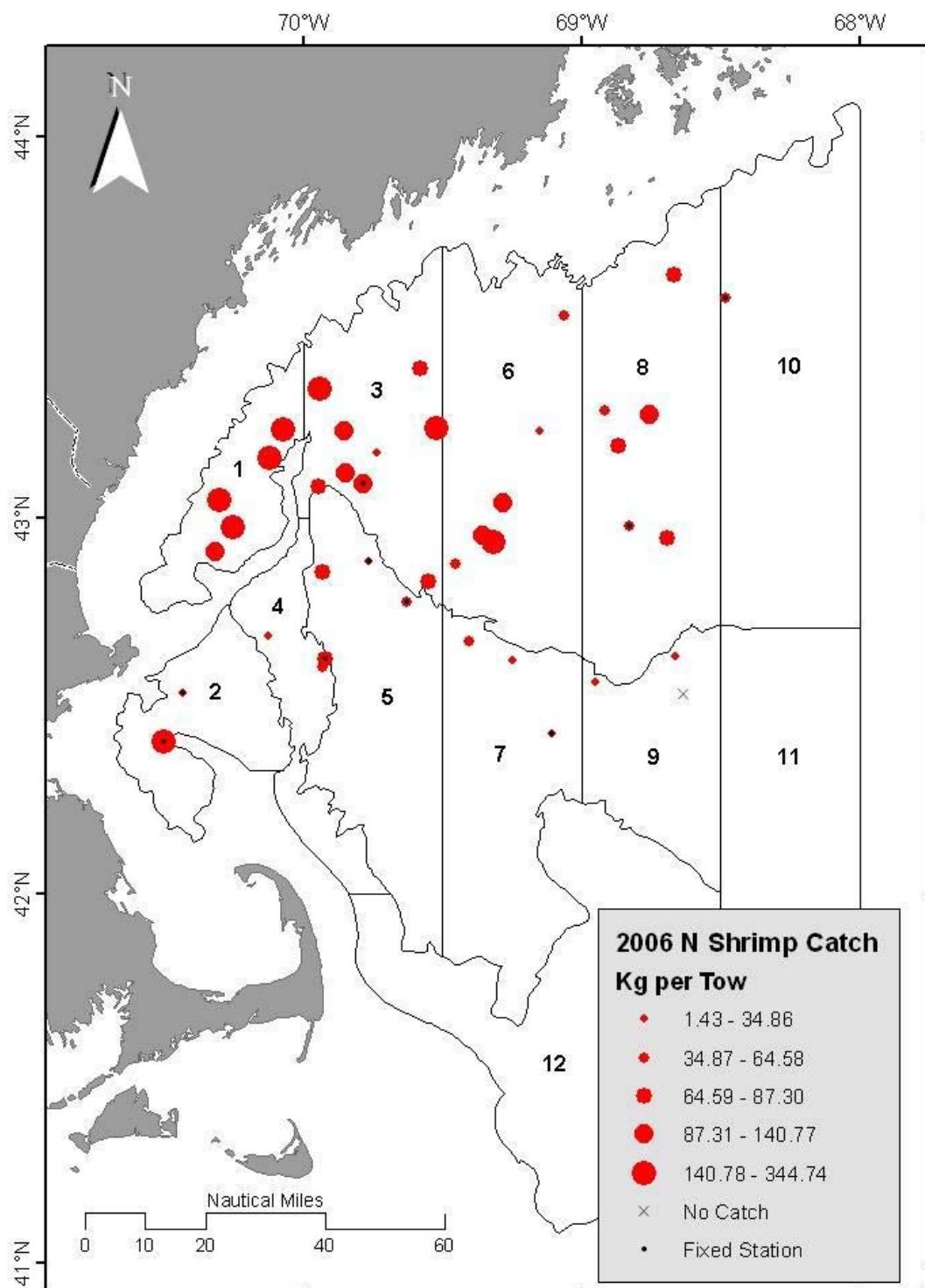


Figure A6-3. Northern shrimp survey strata and observed distribution of catch (kg) per tow of northern shrimp collected in the western Gulf of Maine aboard the R/V Gloria Michelle, July 24 – August 11, 2006. (1 kg = 2.2 lbs)

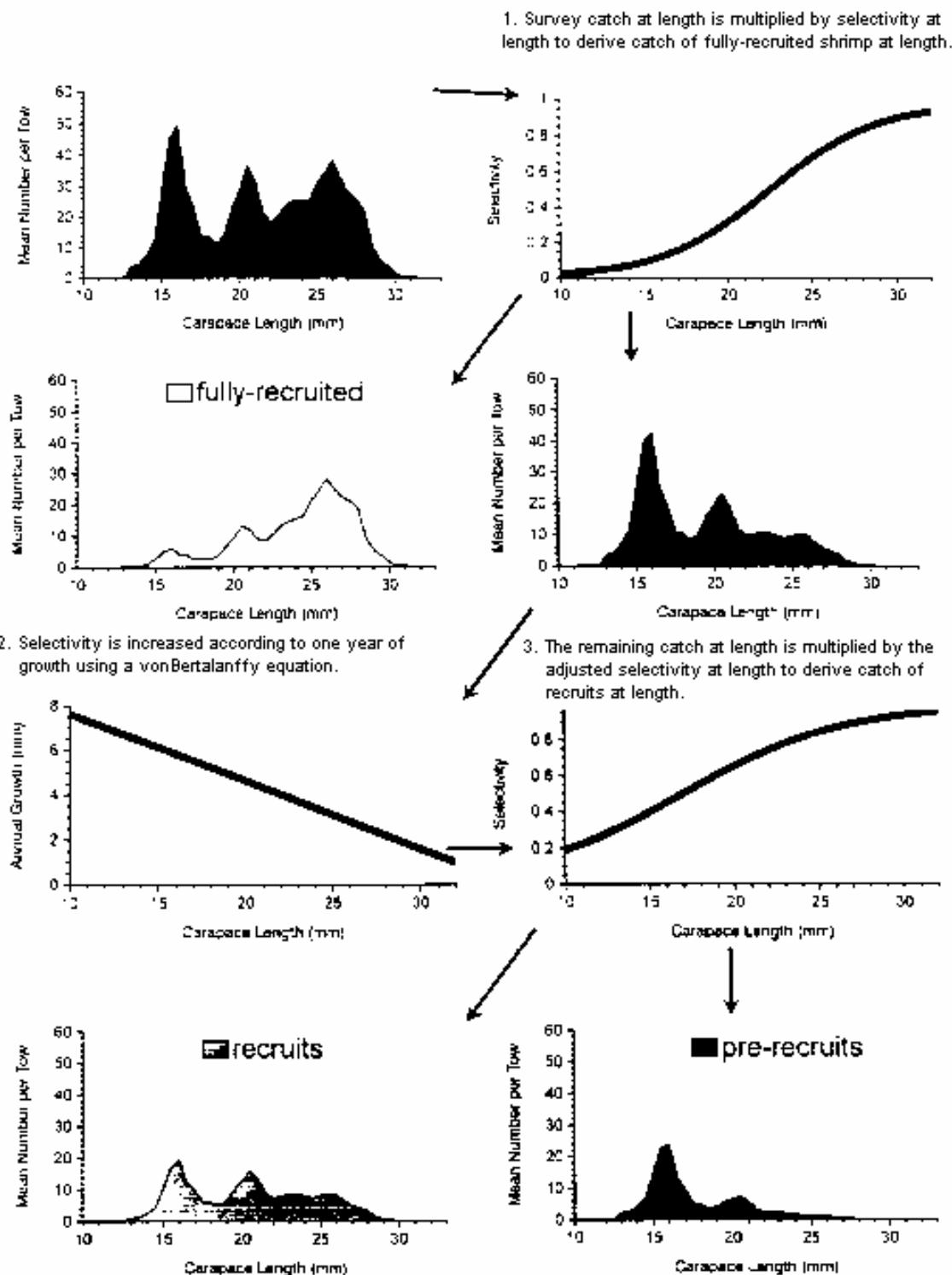


Figure A6-4. The “selectivity” method of deriving indices of abundance for fully-recruited and recruited Gulf of Maine northern shrimp from summer survey length frequencies. Example illustrated here is from 1996.

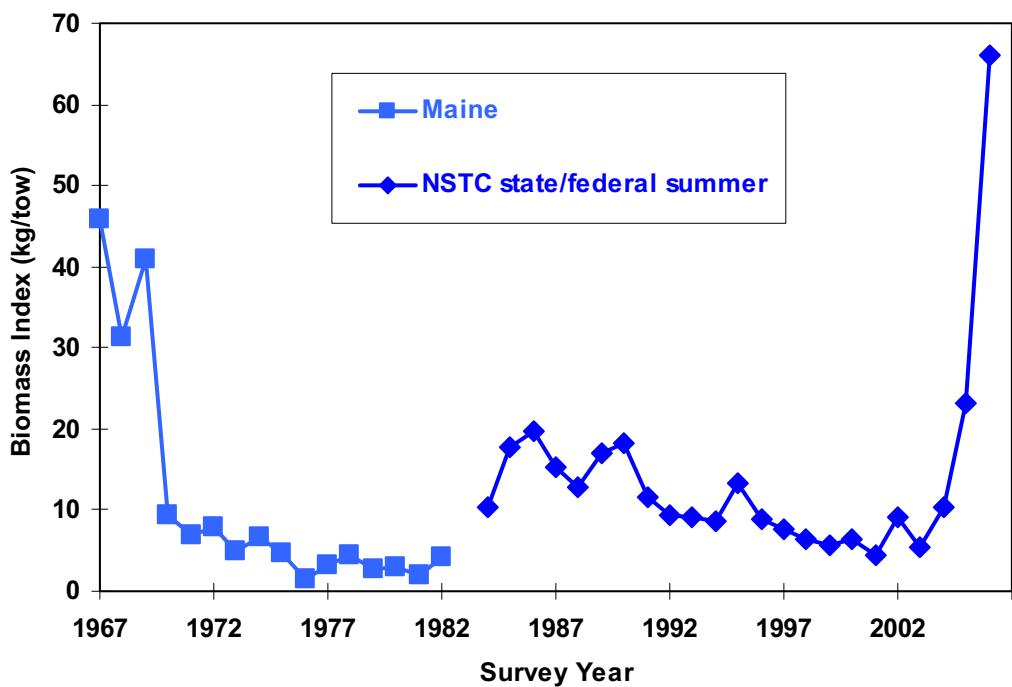
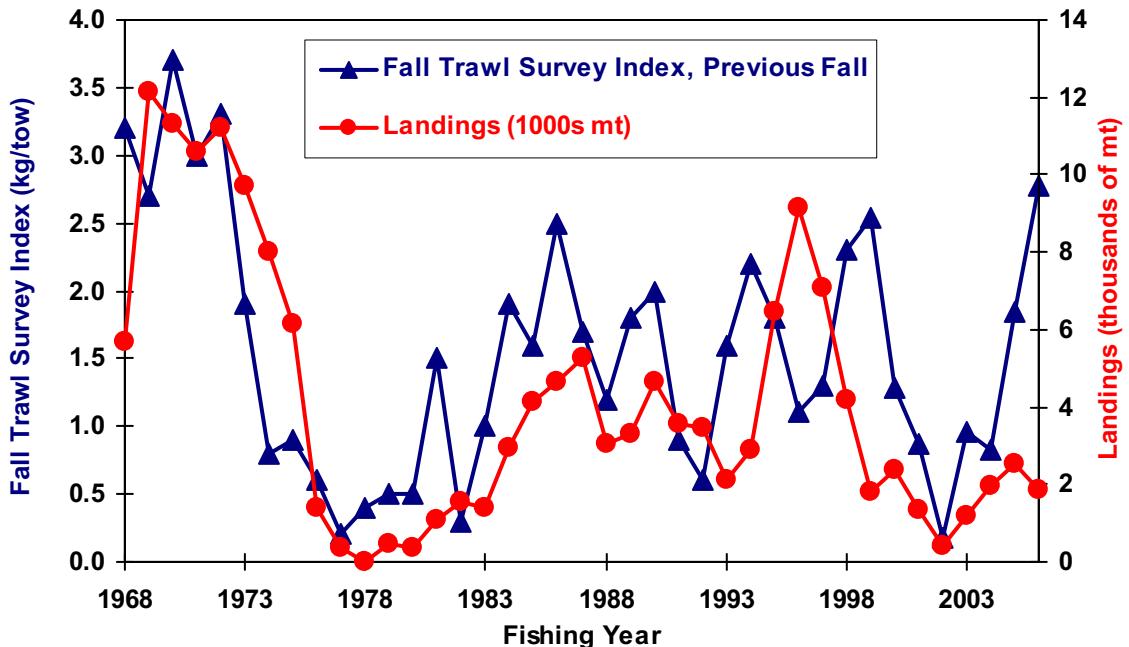


Figure A6-5. Research trawl survey indices (NEFSC fall trawl survey above; Maine and NSTC summer surveys below) and landings (above) of Gulf of Maine northern shrimp. (1 mt = 2,205 lbs, 1 kg = 2.2 lbs)

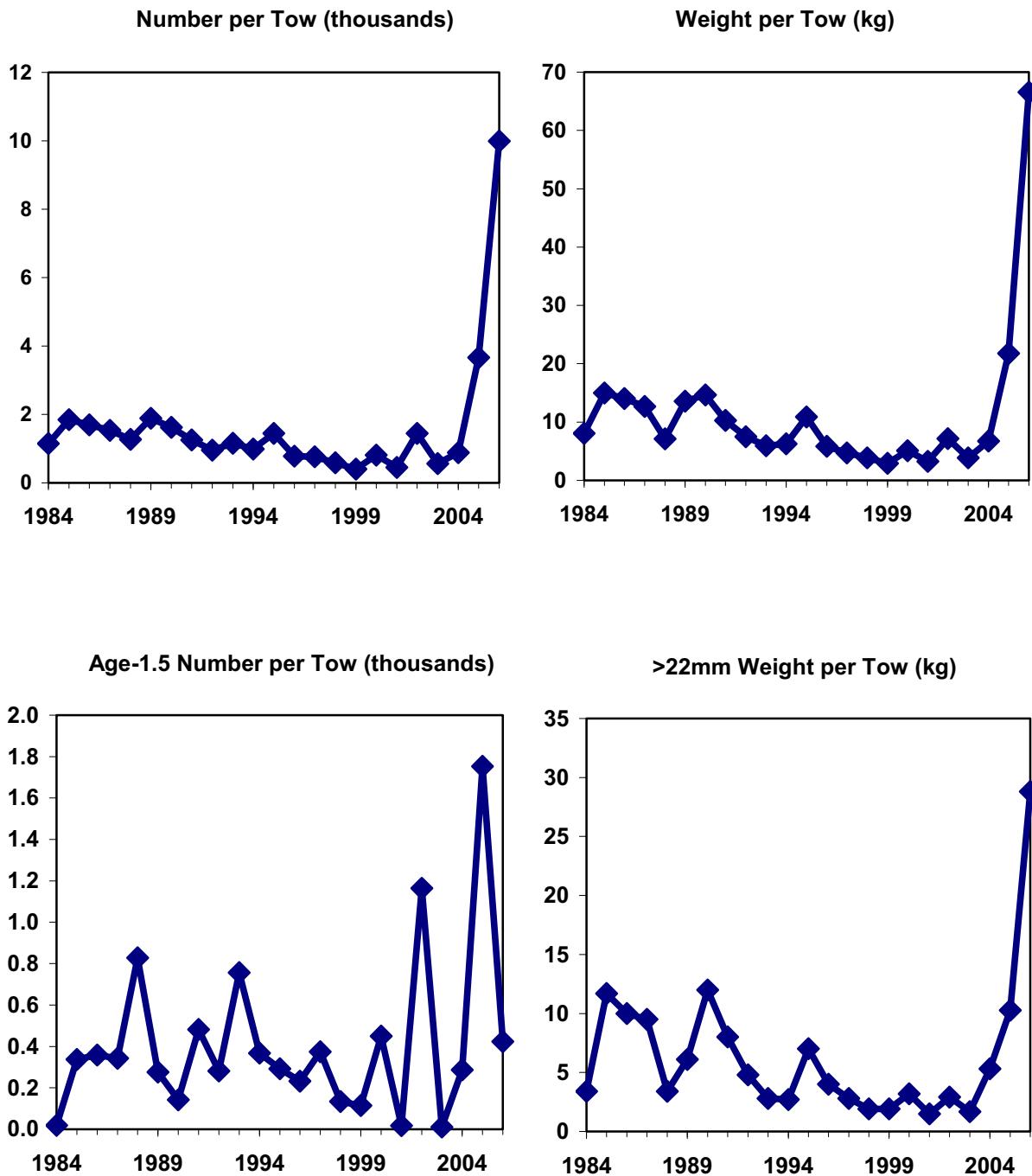


Figure A6-6. NSTC state/federal summer survey indices of abundance and biomass of Gulf of Maine northern shrimp. (1 kg = 2.2 lbs)

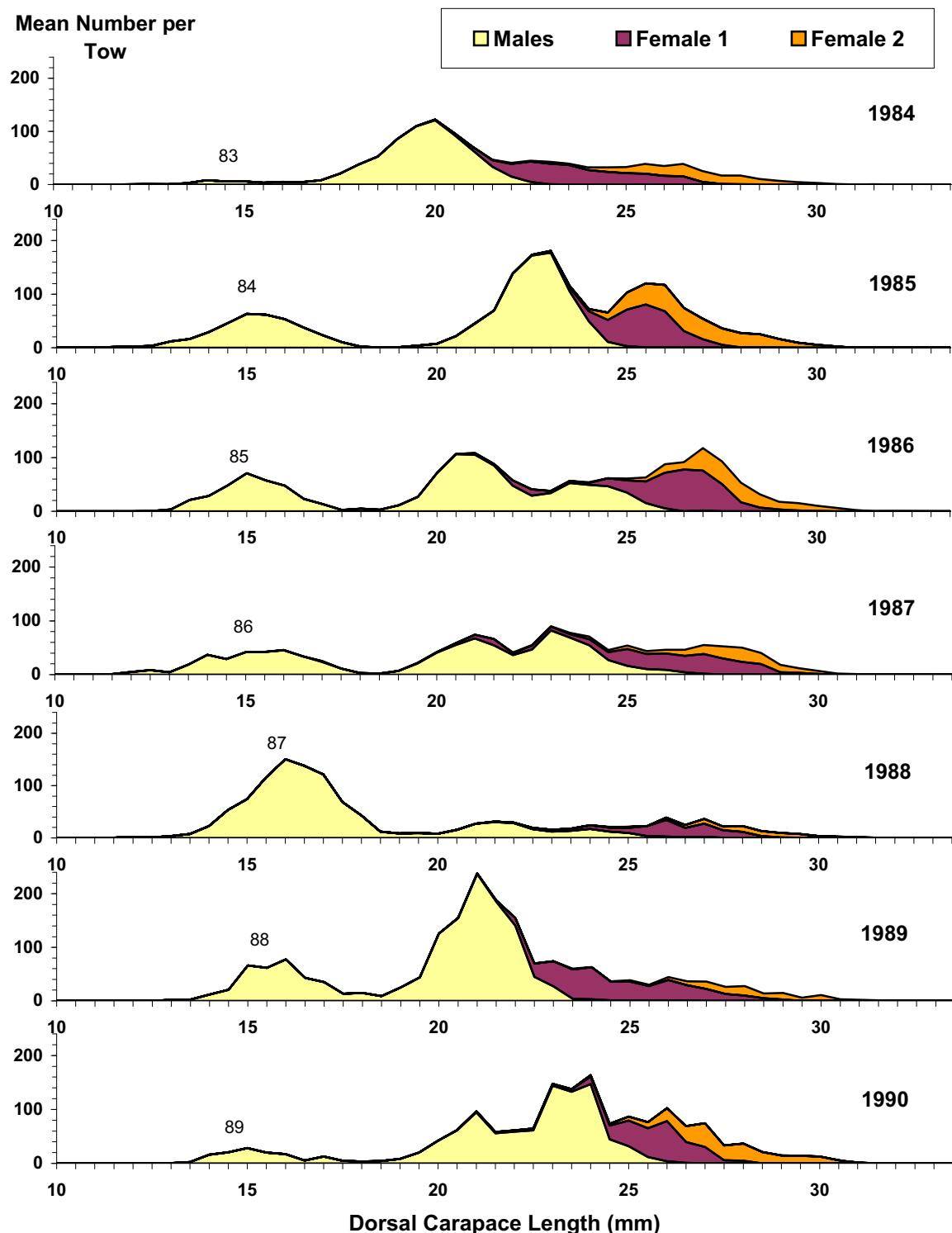


Figure A6-7. NSTC state/federal summer survey mean number caught per tow by survey year, length, and development stage for Gulf of Maine northern shrimp. Two-digit years are year class at assumed age 1.5.

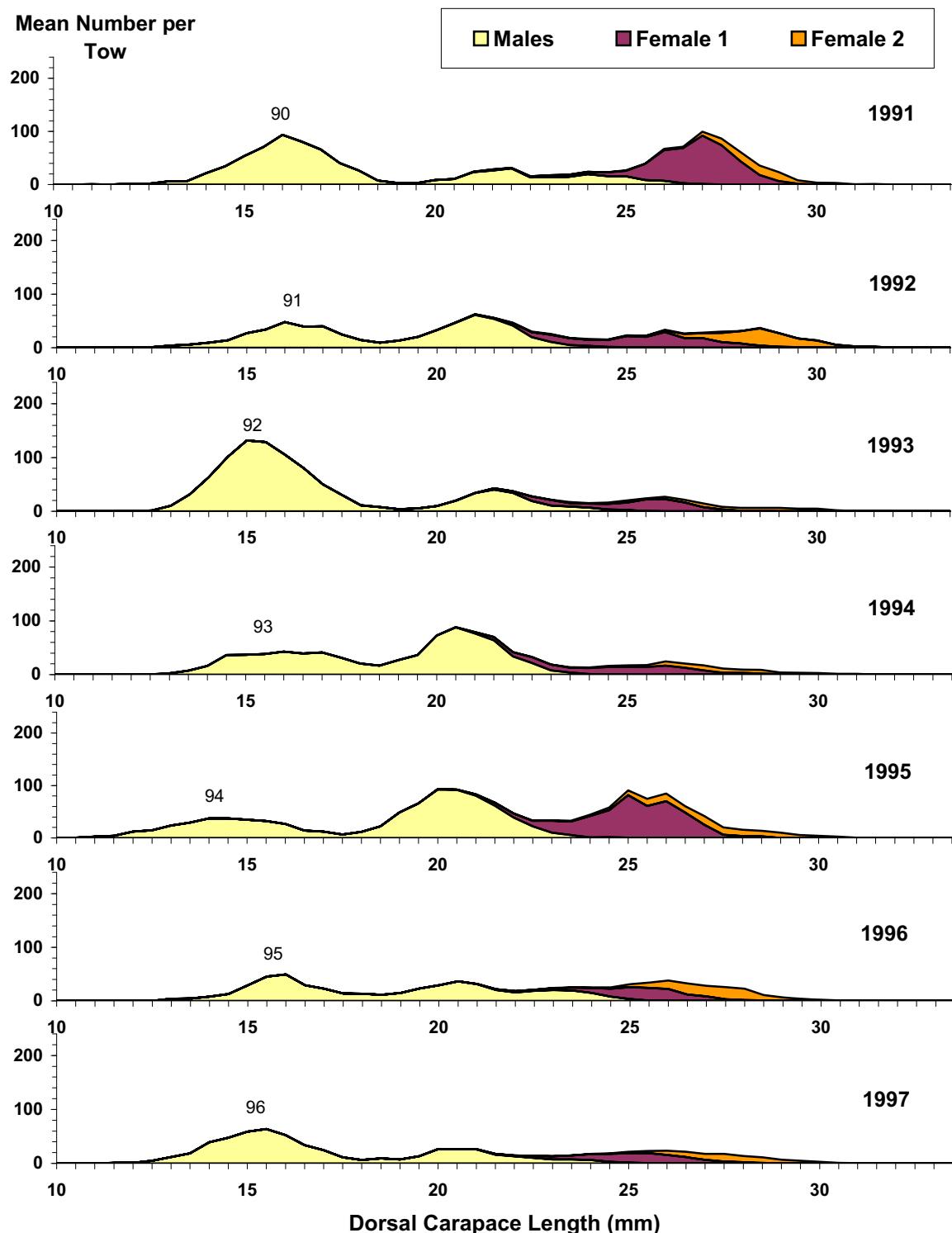


Figure A6-7 continued.

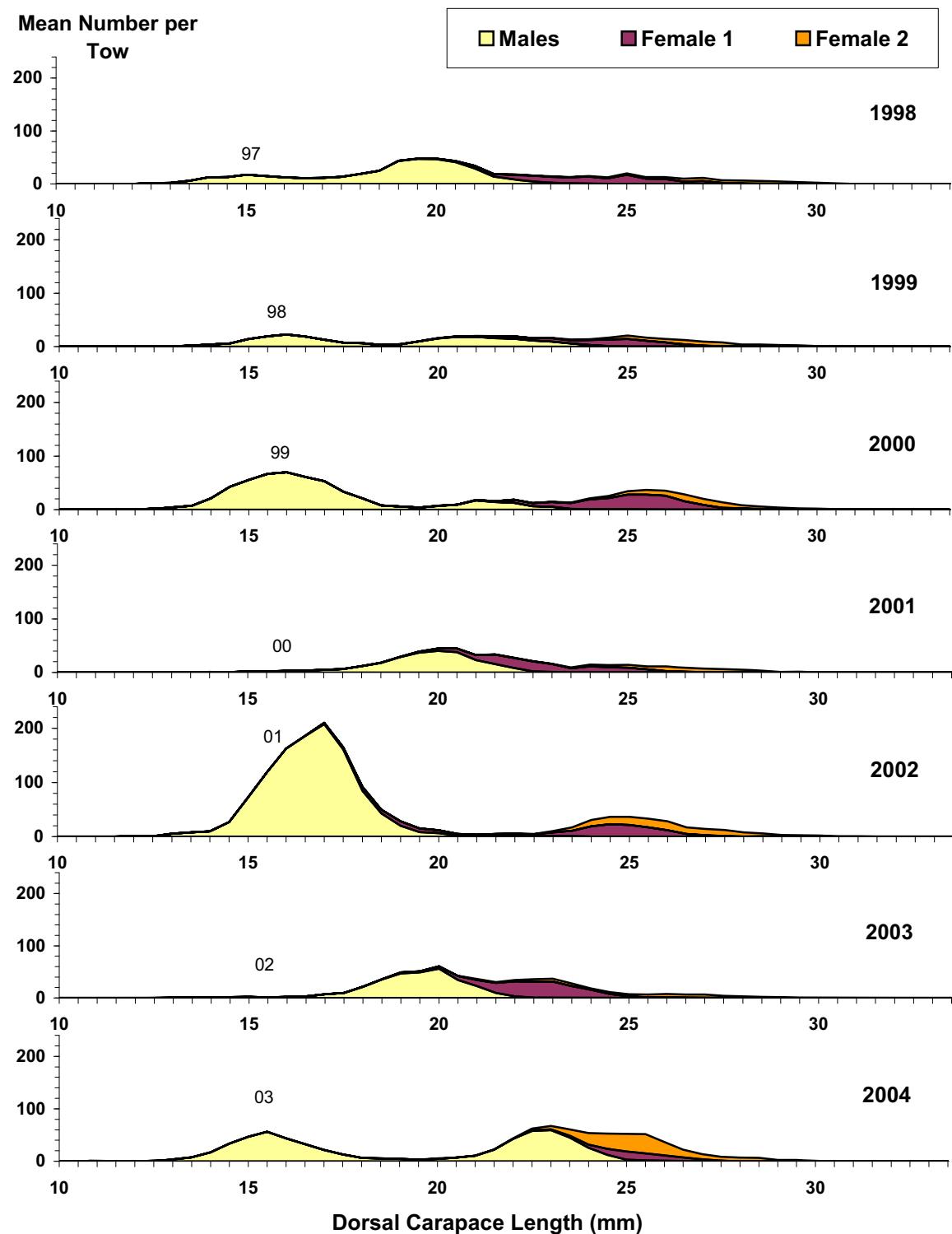


Figure A6-7 continued.

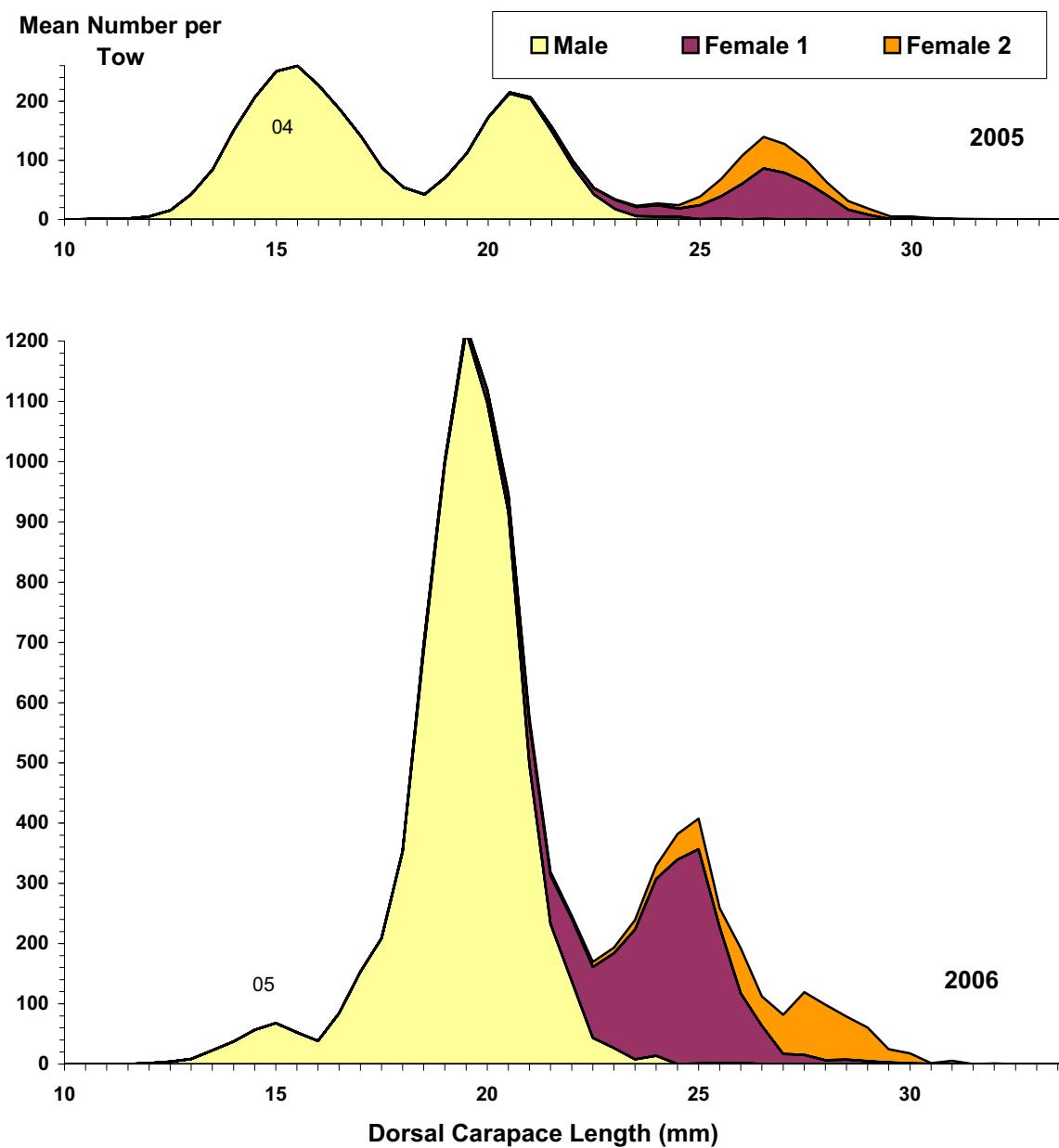


Figure A6-7 continued.

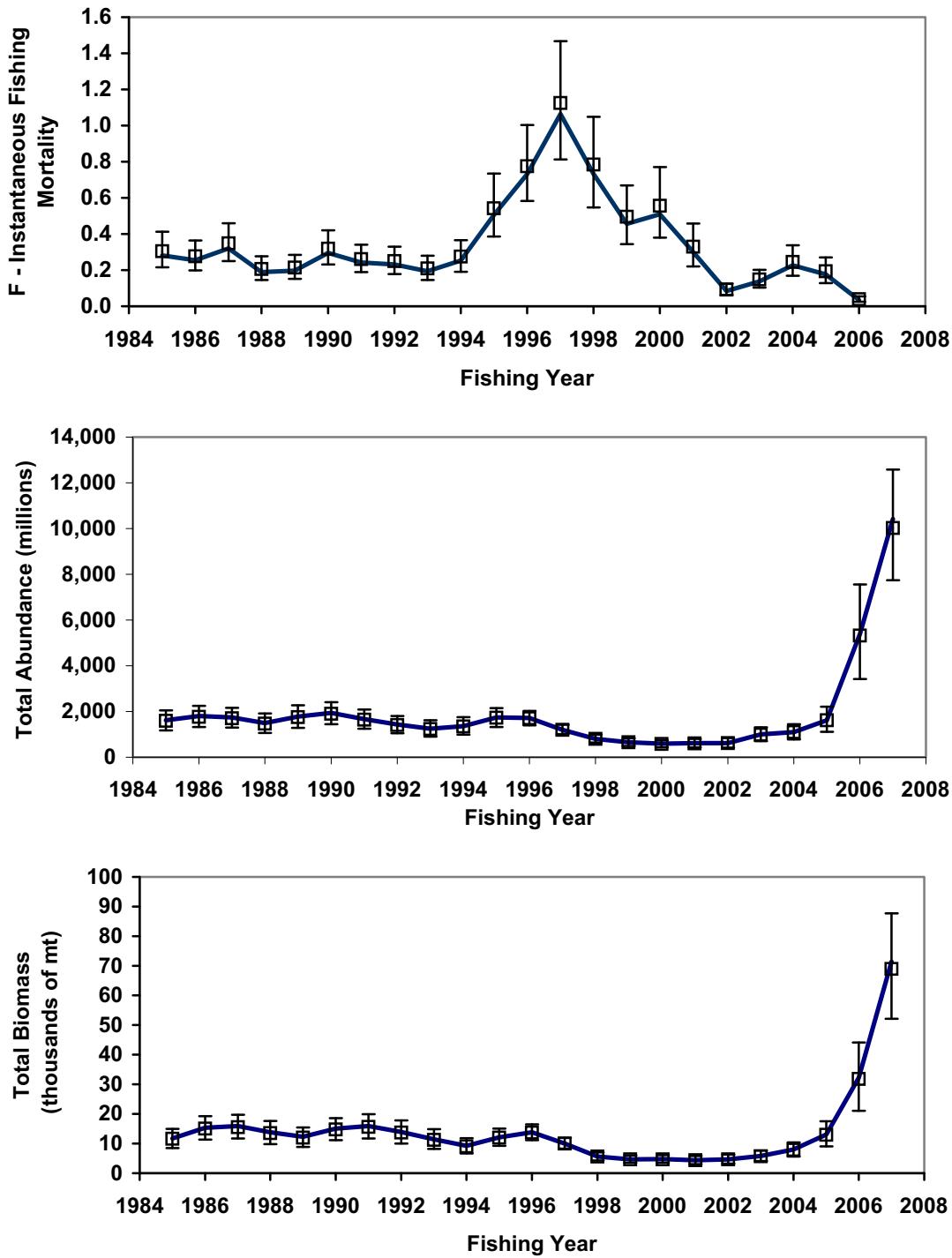


Figure A6-8. Fishing mortality, abundance, and biomass of Gulf of Maine northern shrimp as estimated by CSA, with least squares estimates, bootstrapped means (square symbols), and 80% confidence intervals.  $M=0.25$ .

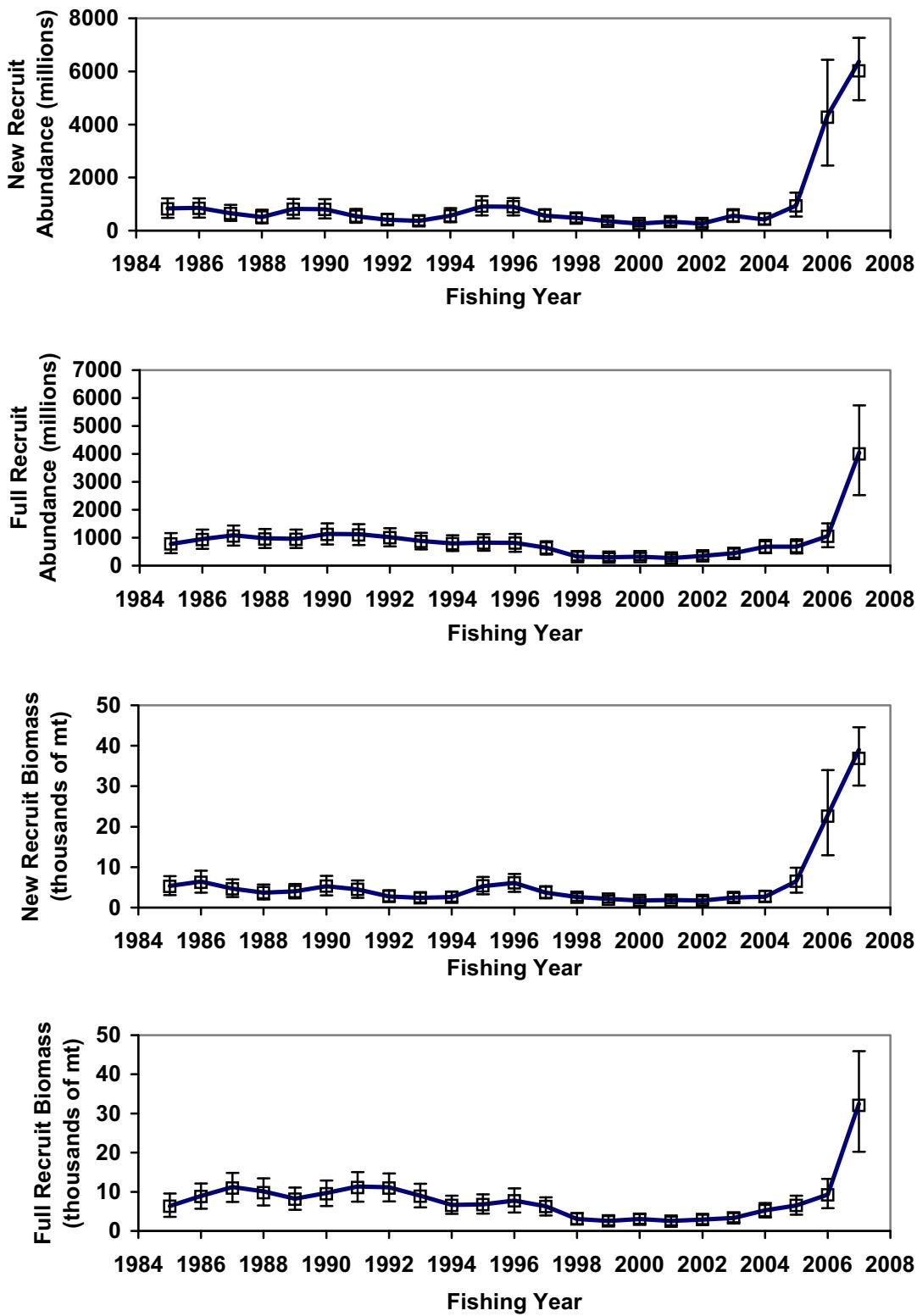


Figure A6-8 continued.

Input Data using Summer Survey			
Survey Year*	Indices of Abundance		Total Catch Millions*
	Recruits	Full Recruits	Millions*
1984	447.6	479.1	352.79
1985	619.5	925.4	361.17
1986	533.3	848.5	425.29
1987	482.9	766.9	228.43
1988	459.8	387.7	283.65
1989	701.1	817.9	442.43
1990	511.5	907.5	320.29
1991	374.3	612.1	262.43
1992	313.6	444.4	194.79
1993	410.2	320.8	270.41
1994	368.6	364.3	615.32
1995	485.8	653.3	799.37
1996	257.7	348.6	710.97
1997	257.3	267.1	373.68
1998	217.1	226.6	215.12
1999	137.4	174.6	209.28
2000	276.3	288.2	140.88
2001	171.8	196.4	44.40
2002	550.6	372.9	113.66
2003	222.9	229.9	198.74
2004	292.7	405.9	233.98
2005	1295.2	1231.7	163.62
2006	3906.5	3899.9	

\* Survey Year data are applied to the following Fishing Year

Stock Size Estimates millions at time of Survey		Fishing Mortality All sizes	Total Mortality Z all sizes
Recruits	Full Recruits		
838.6	776.6	0.28	0.53
854.6	949.2	0.26	0.51
652.4	1088.6	0.32	0.57
509.6	984.0	0.19	0.44
820.2	962.9	0.20	0.45
802.7	1140.0	0.30	0.55
544.8	1126.0	0.24	0.49
405.6	1020.7	0.23	0.48
366.7	880.9	0.19	0.44
559.1	800.9	0.25	0.50
913.5	822.4	0.50	0.75
900.0	815.9	0.73	0.98
557.1	643.2	1.06	1.31
478.8	322.4	0.73	0.98
357.2	299.9	0.46	0.71
262.5	324.2	0.51	0.76
336.8	274.7	0.30	0.55
264.8	353.0	0.08	0.33
559.9	442.1	0.14	0.39
420.9	680.6	0.23	0.48
937.7	683.7	0.18	0.43
4330.5	1057.6	0.03	0.28
6362.7	4052.3		

Input File Name	R2006_BL.dat
Tuning Dataset	Survey
Time of Survey (yr)	0
Time of Catch (yr)	0
Natural Mortality Rate	0.25
Relative Catchability: Recruits to Full Recruits s, Catchability Estimate and CV	0.6 - 1.0 0.6814 0.1817

Note that the recruit abundance index for the last year is NOT used in the least squares estimation. It is, however, used in conjunction with the least squares estimate of  $q_n$  and the selectivity of the recruits to calculate recruit population size in 2006

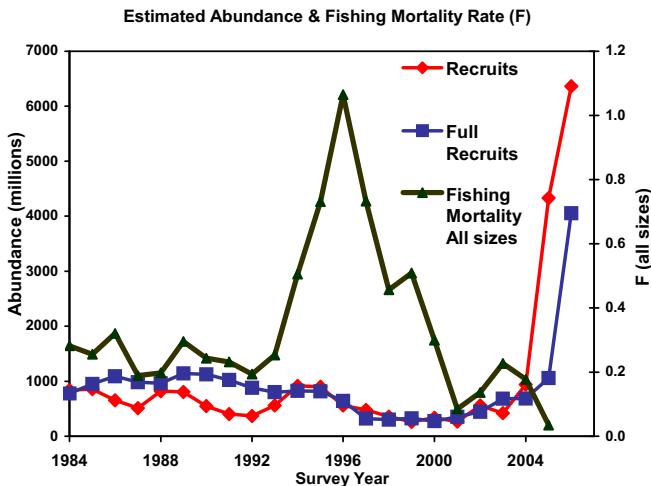
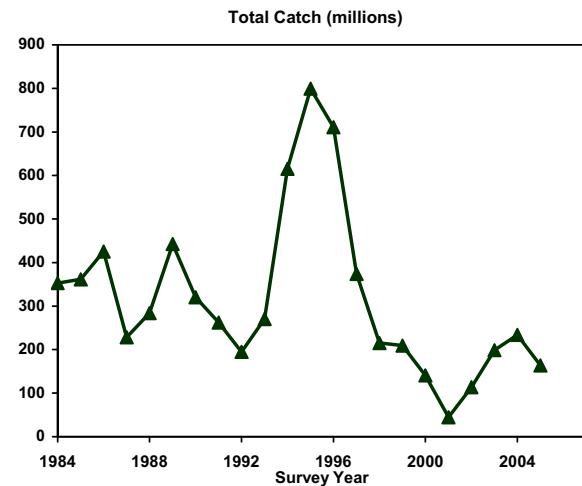


Figure A6-9. Catch-Survey model (CSA) input data and results.

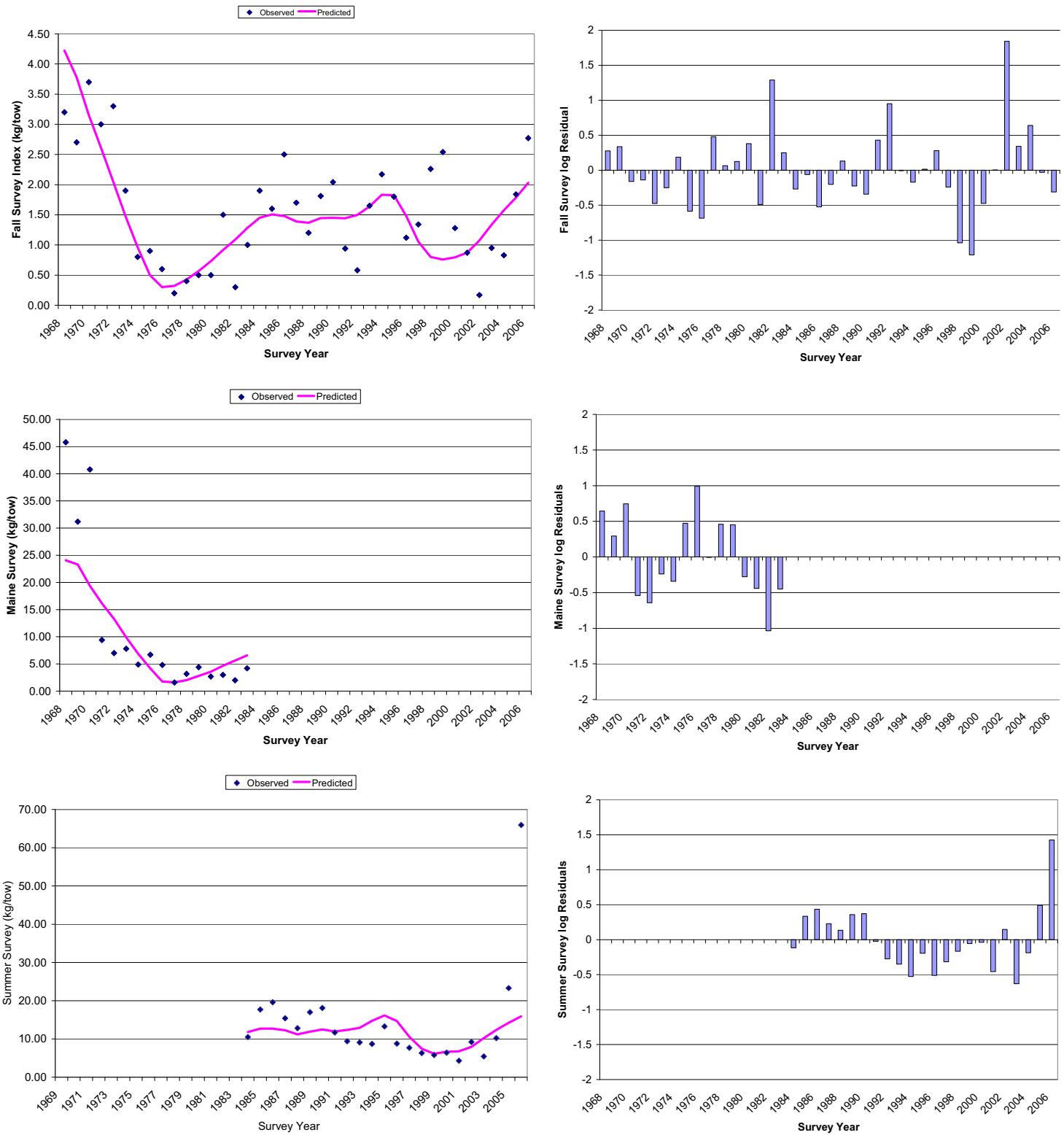


Figure A6-10. Observed survey index, predicted model fit and survey index log residuals from ASPIC analysis of Gulf of Maine northern shrimp biomass dynamics.

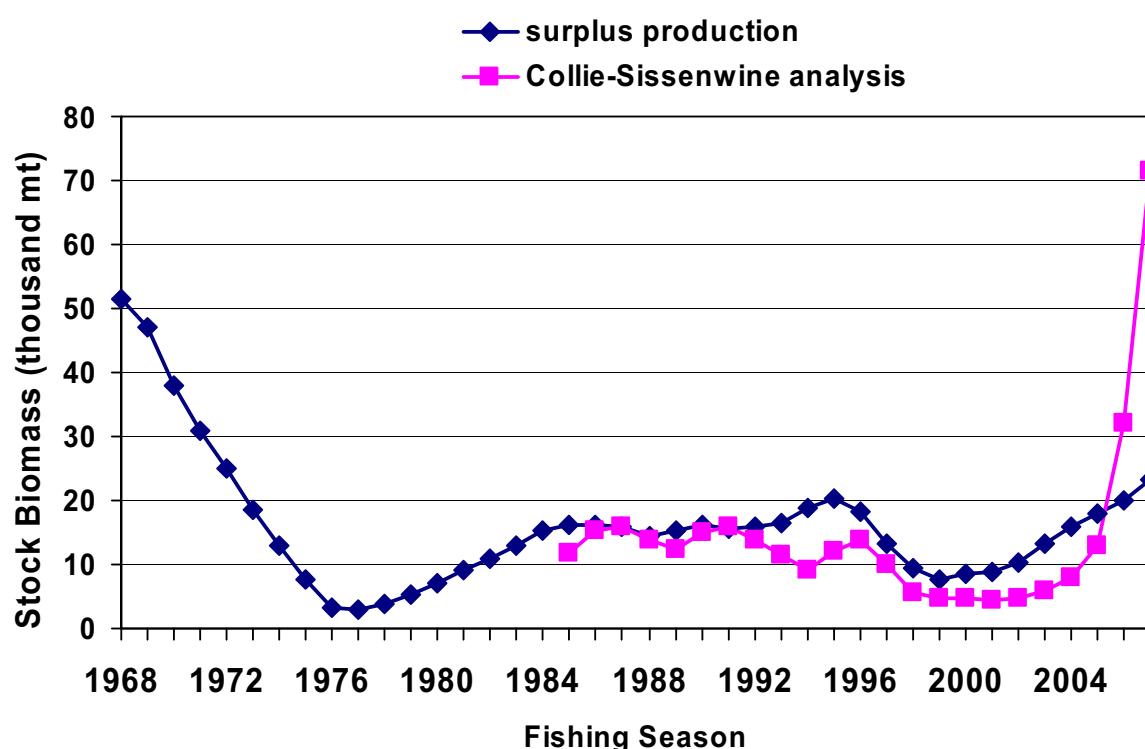
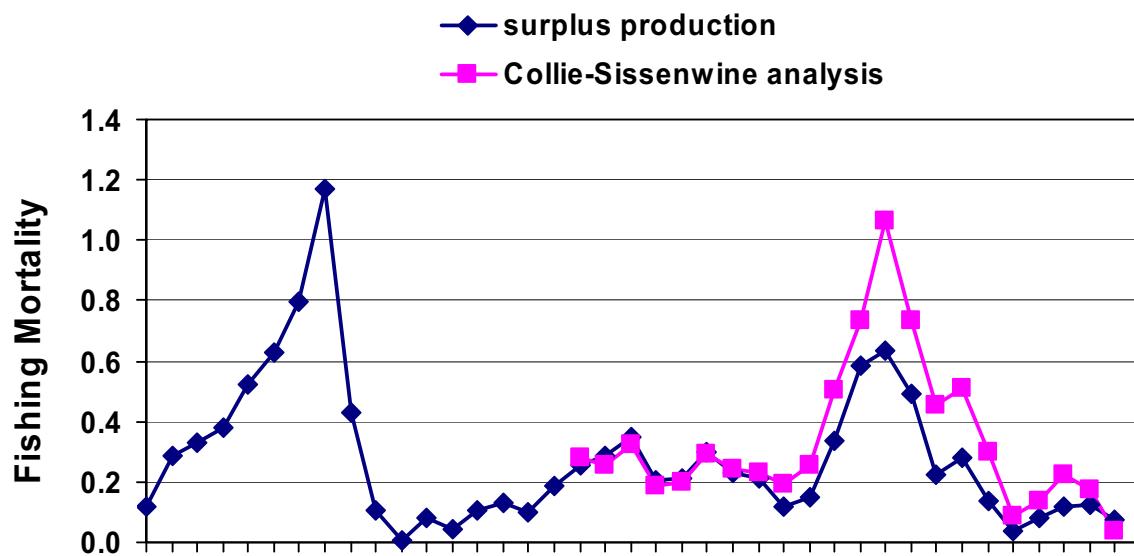


Figure A6-11. Estimates of fishing mortality (above) and stock biomass (below) for Gulf of Maine northern shrimp from CSA and surplus production (ASPIC) modeling.

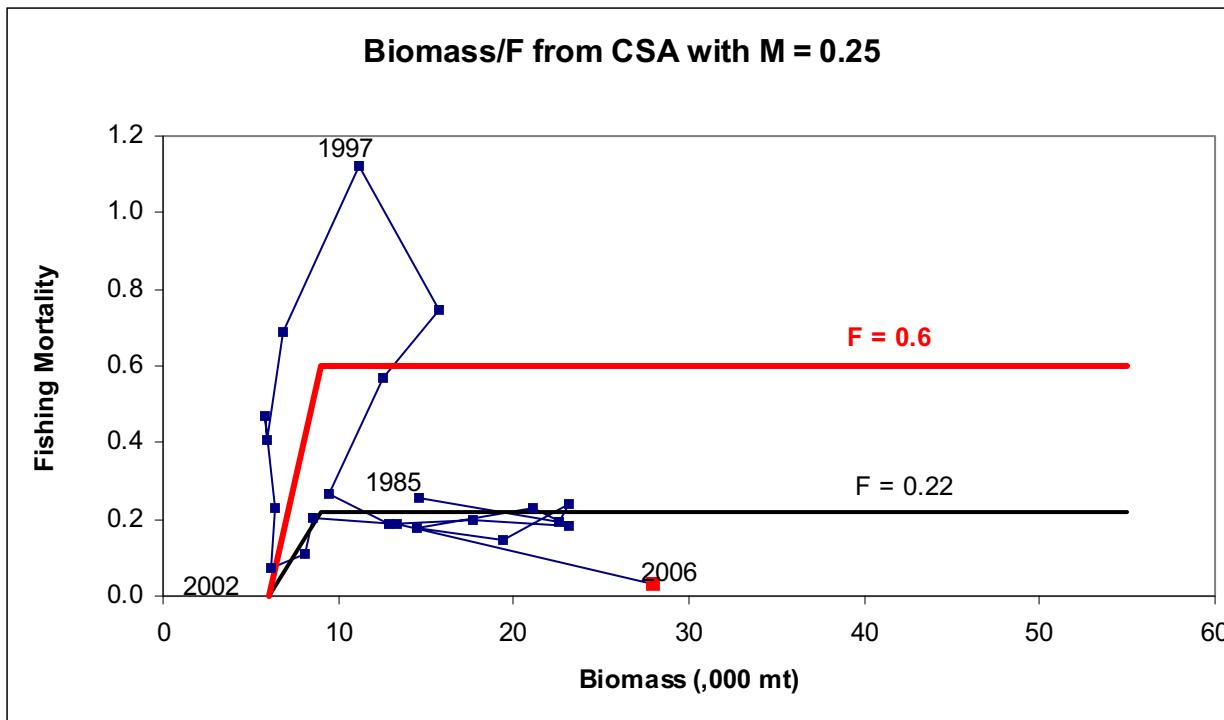
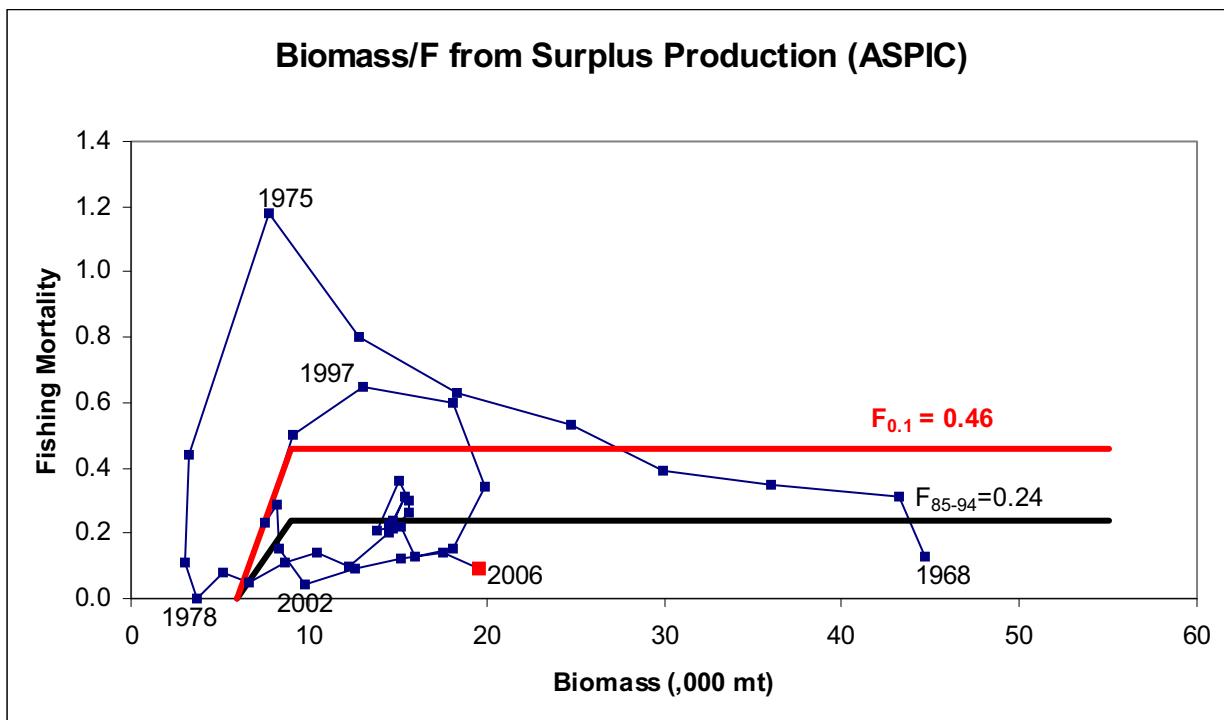


Figure A6-12. Biomass dynamics of the Gulf of Maine northern shrimp fishery, from surplus production (above) and Collie-Sissenwine (below) analyses, with fishing mortality and biomass reference points.

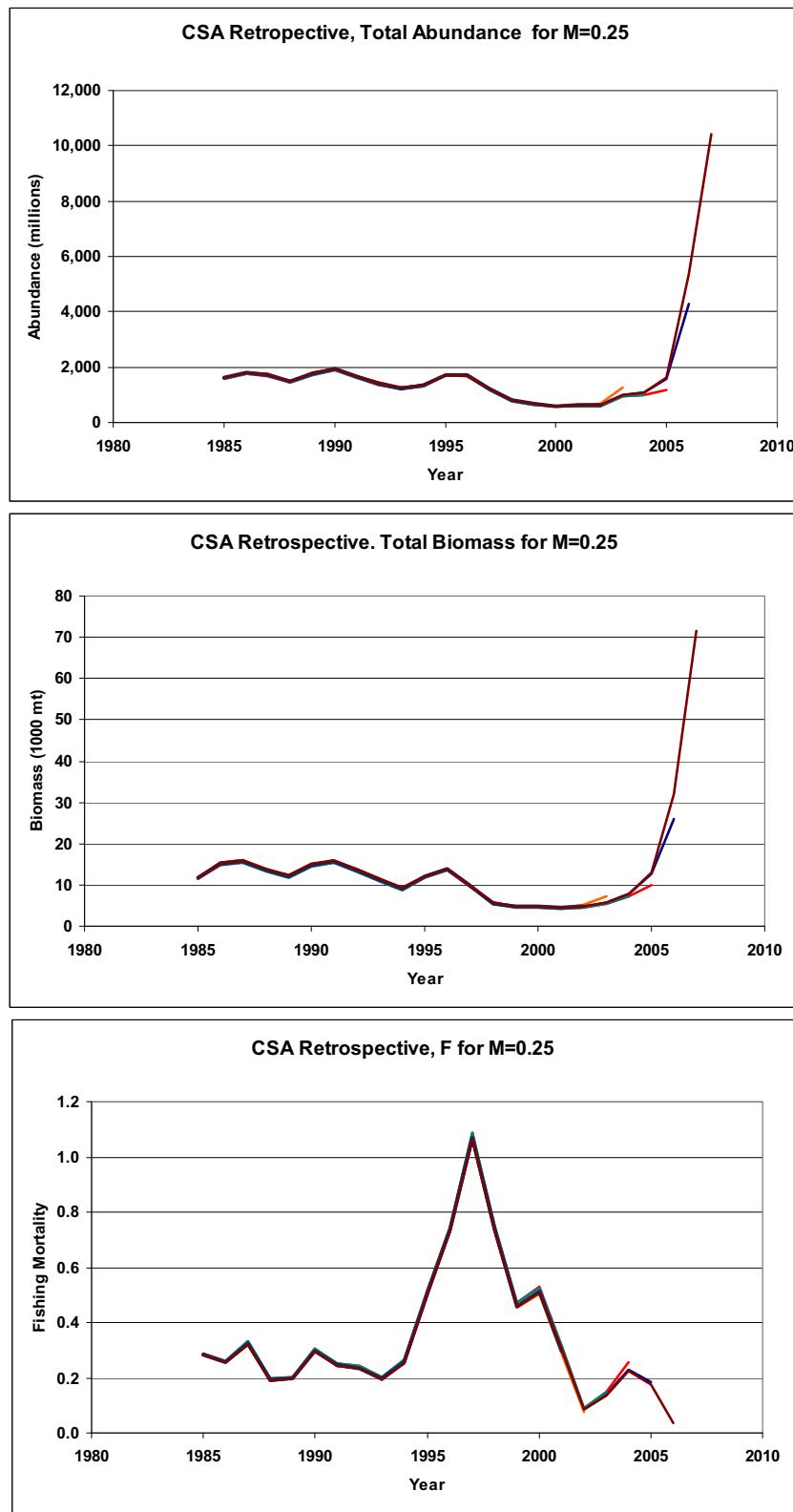


Figure A6-13. Retrospective CSA estimates of abundance (top), biomass (middle), and fishing mortality (bottom) for Gulf of Maine northern shrimp, with  $M=0.25$ .

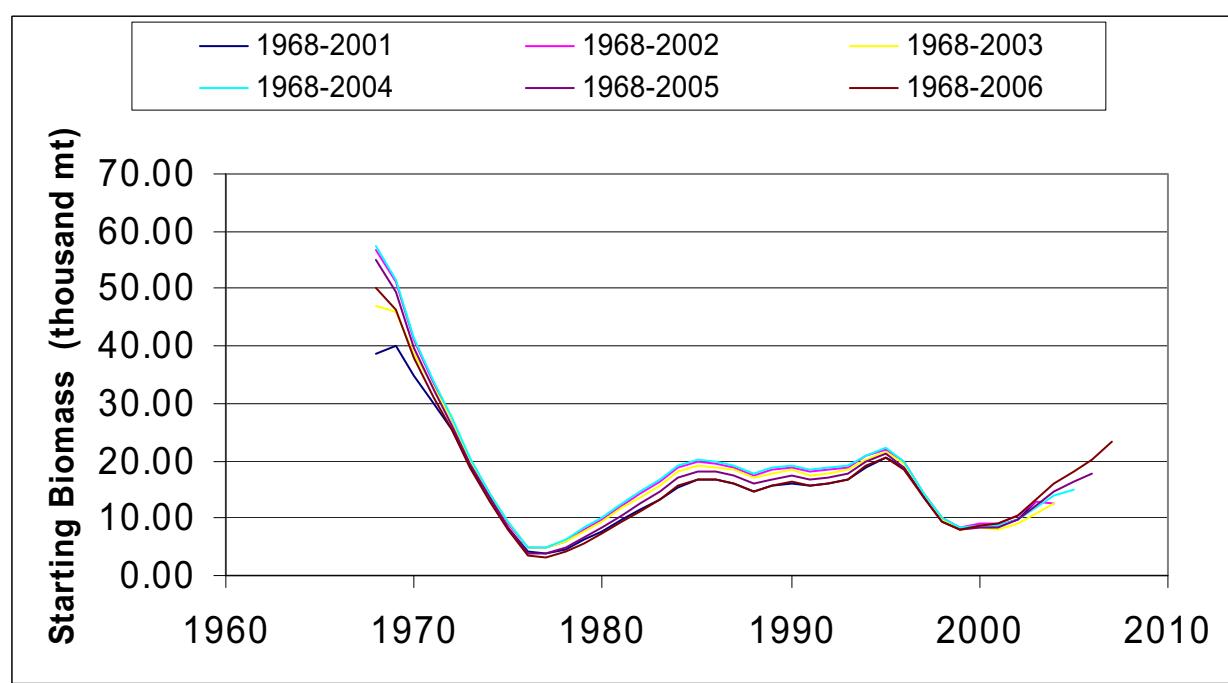
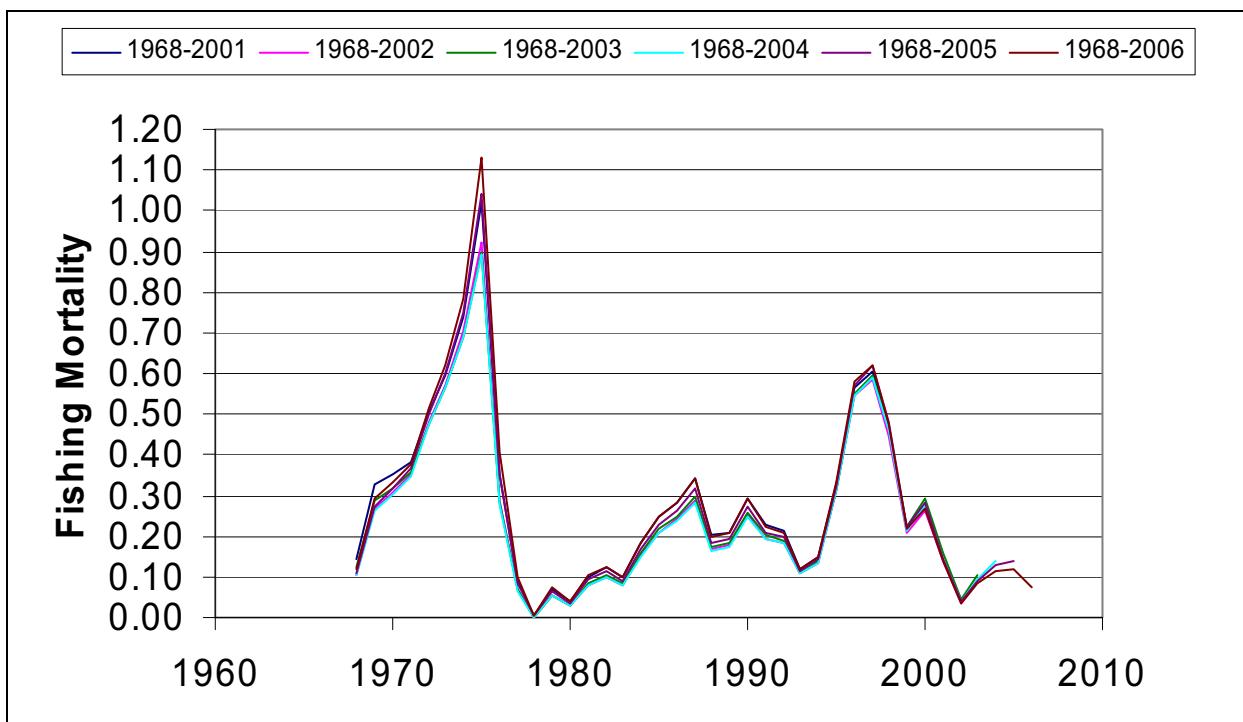


Figure A6-14. Retrospective surplus production estimates of fishing mortality (above) and biomass (below) for Gulf of Maine northern shrimp.

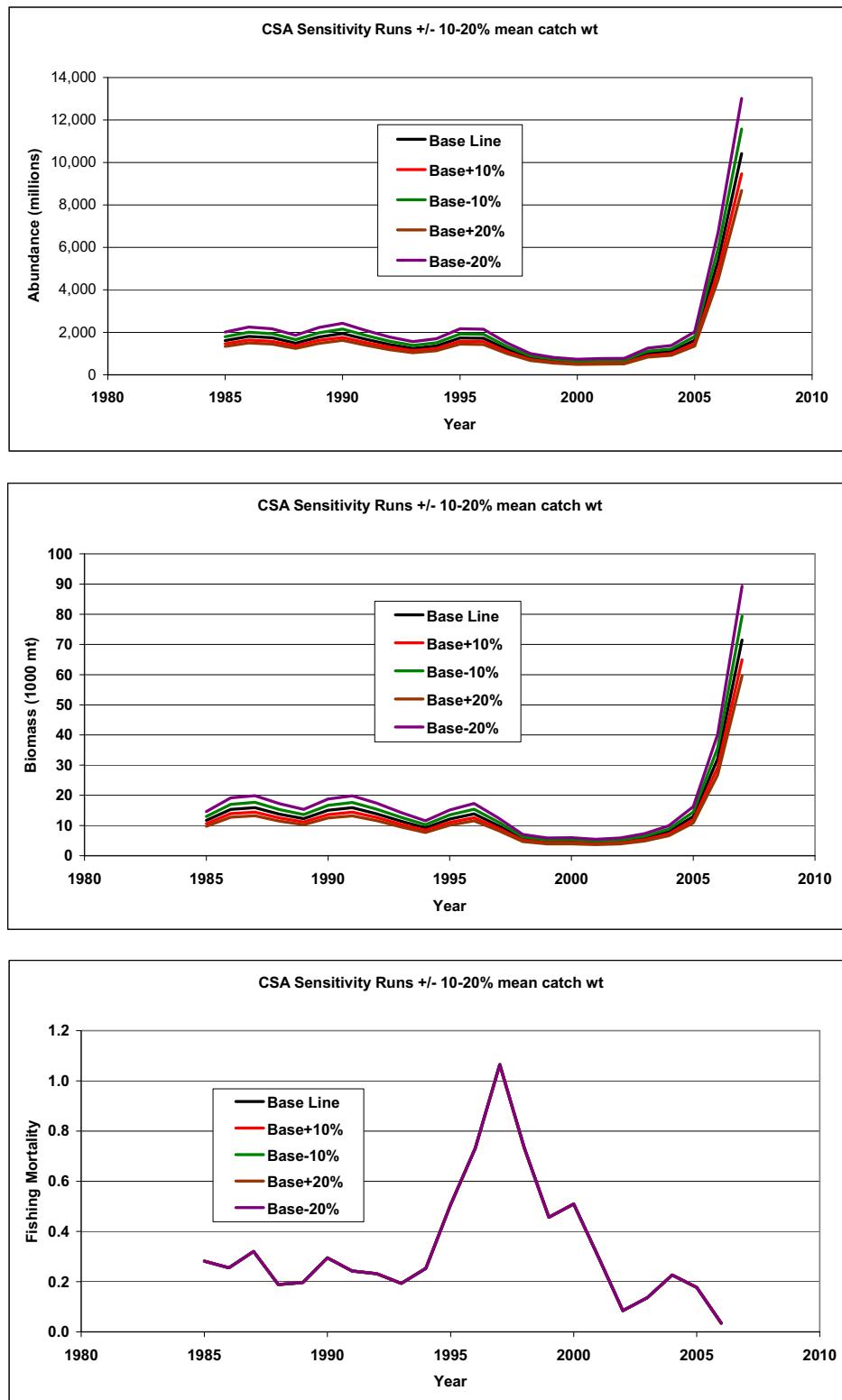


Figure A9-1.1. CSA abundance, biomass, and fishing mortality estimates when the mean weight of a landed shrimp is adjusted by +/- 10% or 20%.

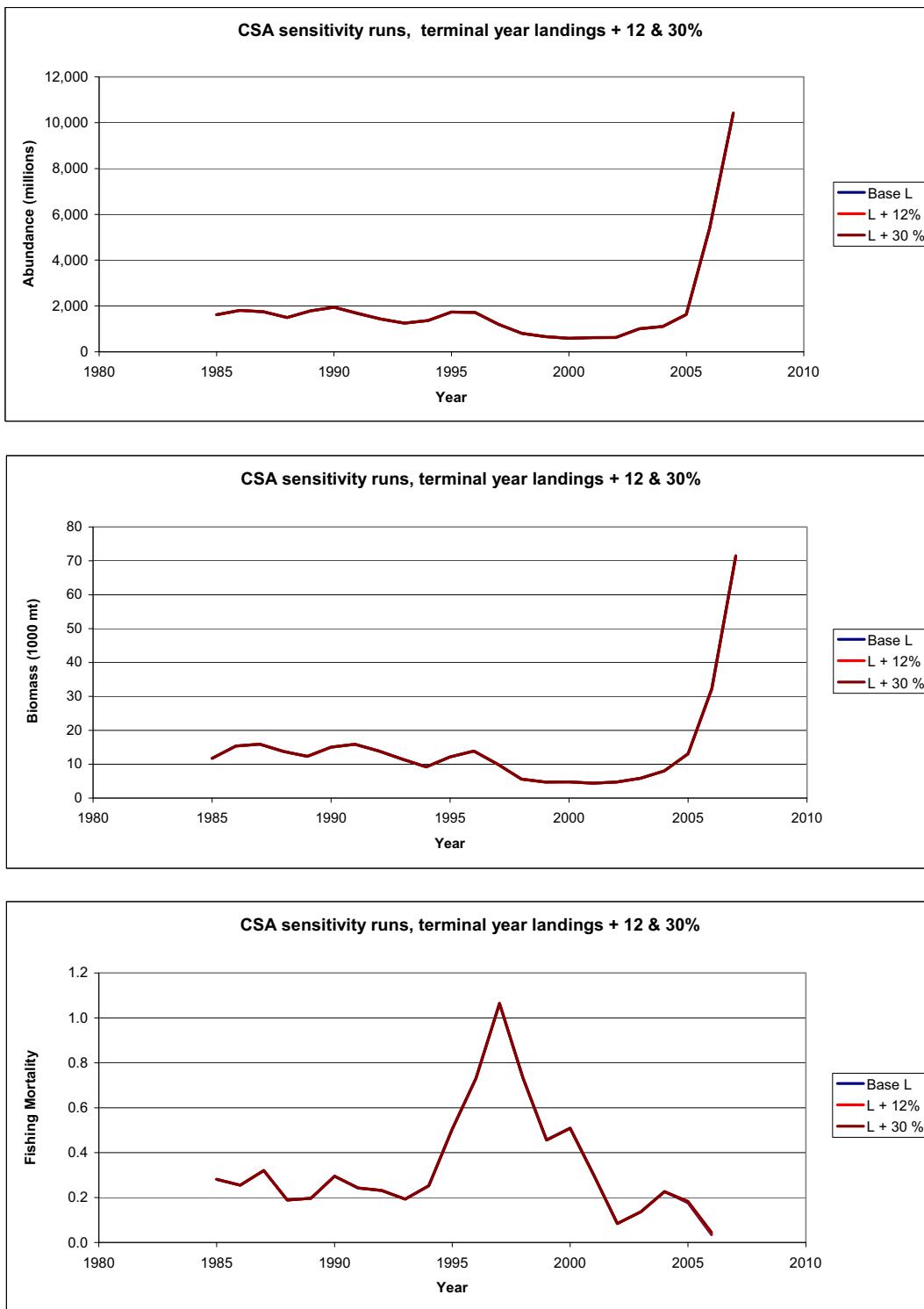


Figure A9-1.2. CSA abundance, biomass, and fishing mortality estimates when terminal year (2006) landings are adjusted by 12% and 30%, and 2005 landings are adjusted by 2%.

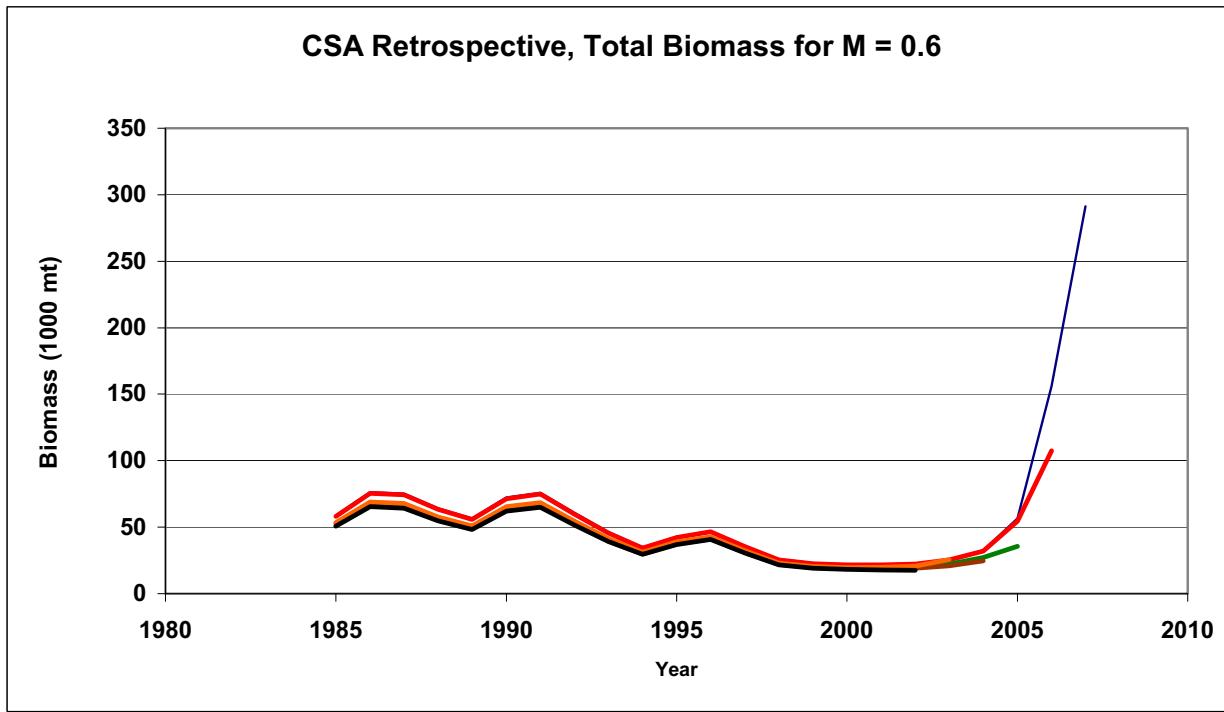
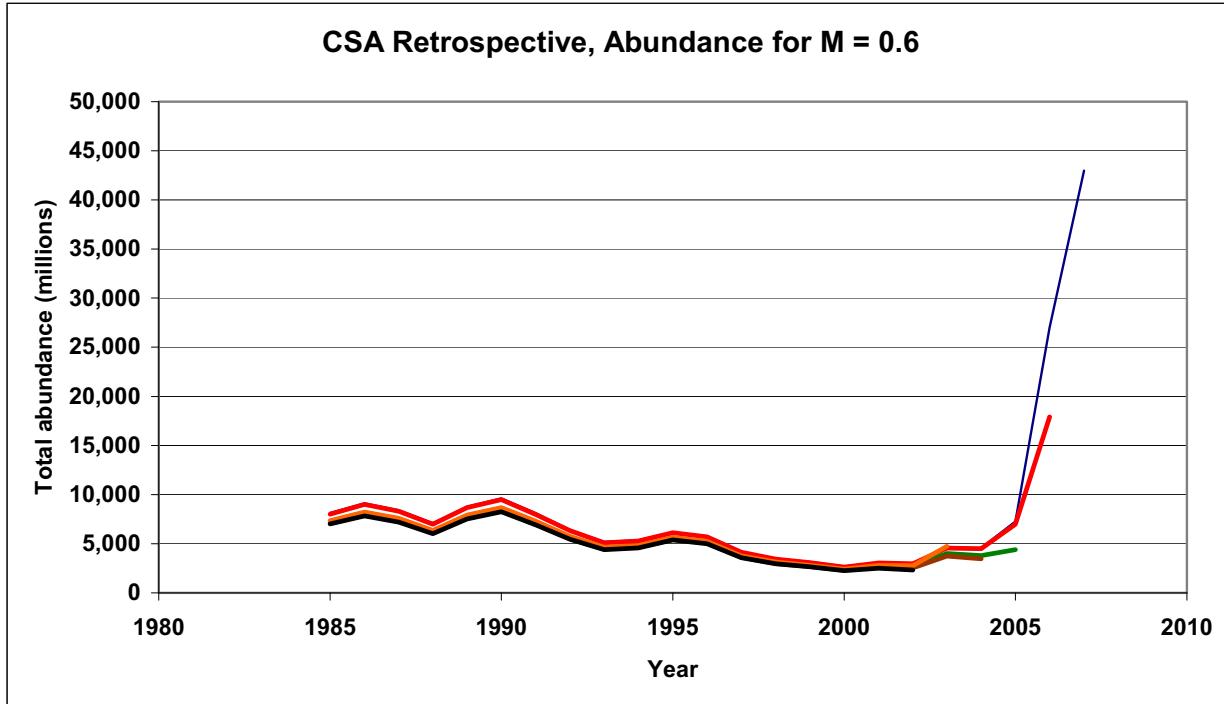


Figure A9-1.3. Retrospective CSA estimates of abundance (above) and biomass (below) for Gulf of Maine northern shrimp, with M=0.60.

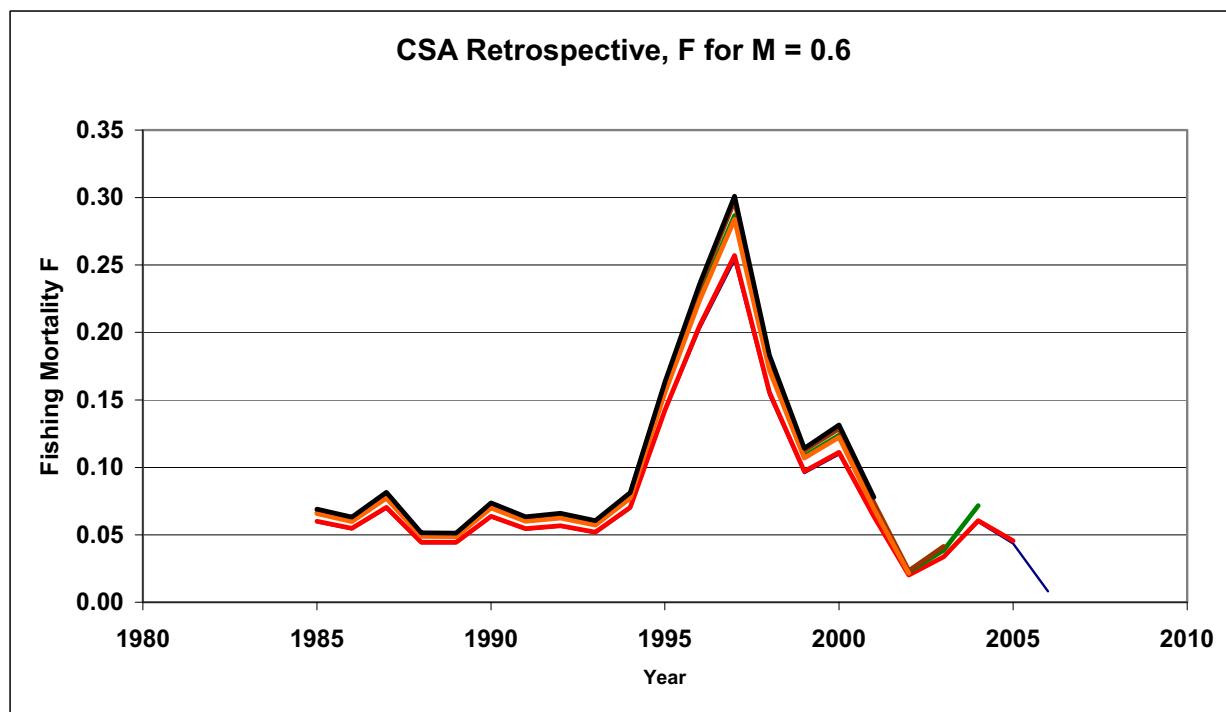
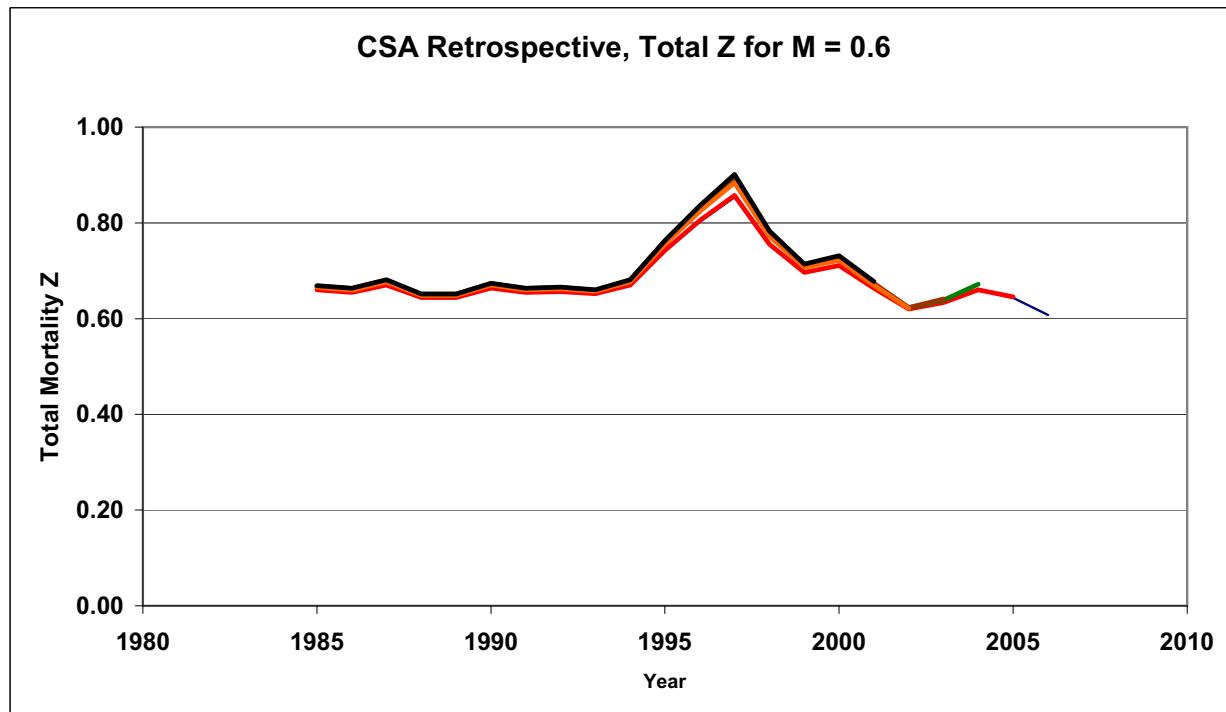


Figure A9-1.4. Retrospective CSA estimates of total mortality Z (above) and fishing mortality F (below) for Gulf of Maine northern shrimp, with M=0.60.

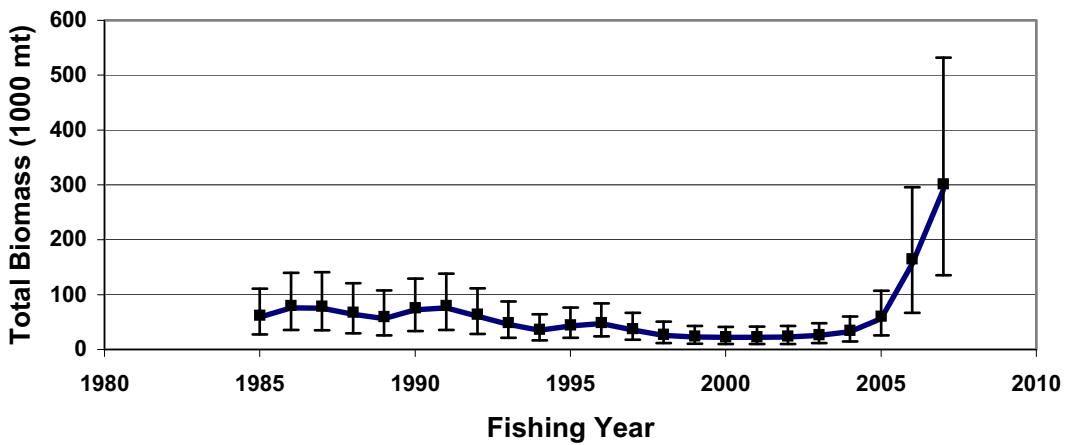
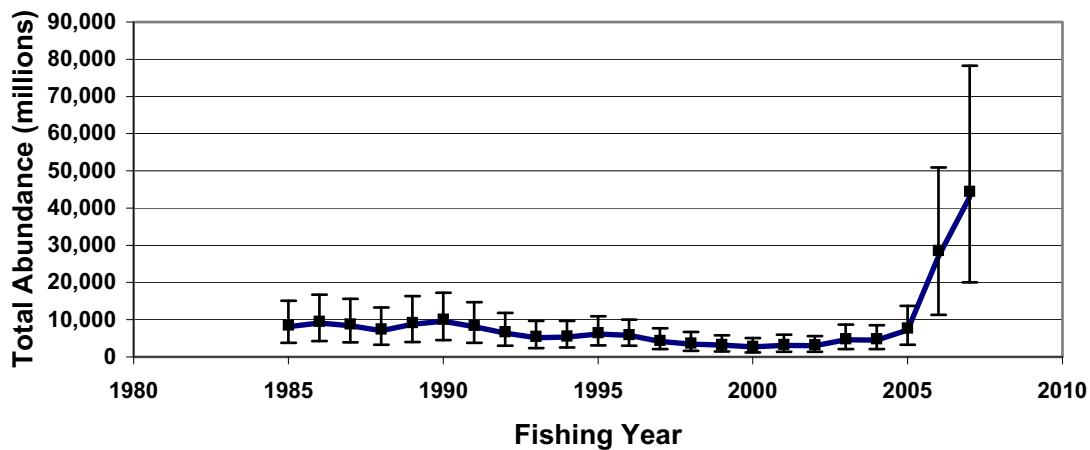
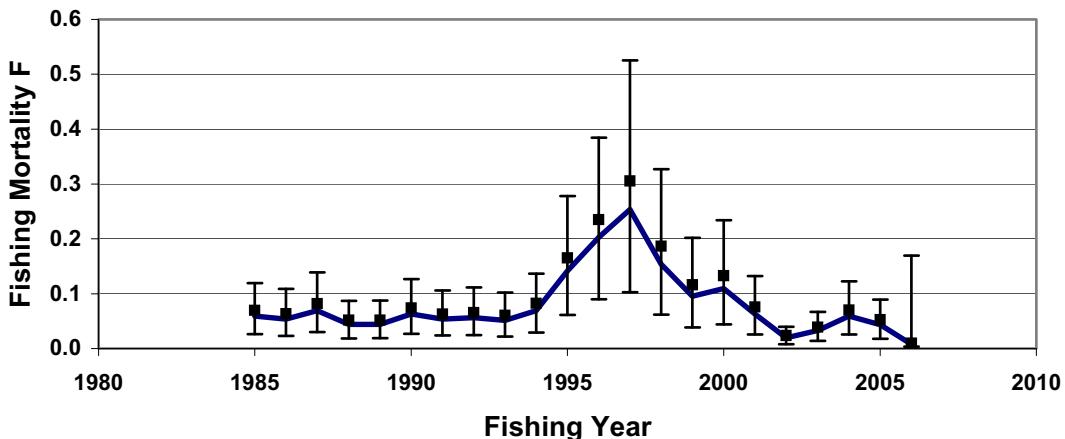


Figure A9-1.5. Fishing mortality, abundance, and biomass of Gulf of Maine northern shrimp as estimated by CSA, with least squares estimates, bootstrapped means (square symbols), and 80% confidence intervals.  $M=0.60$ .

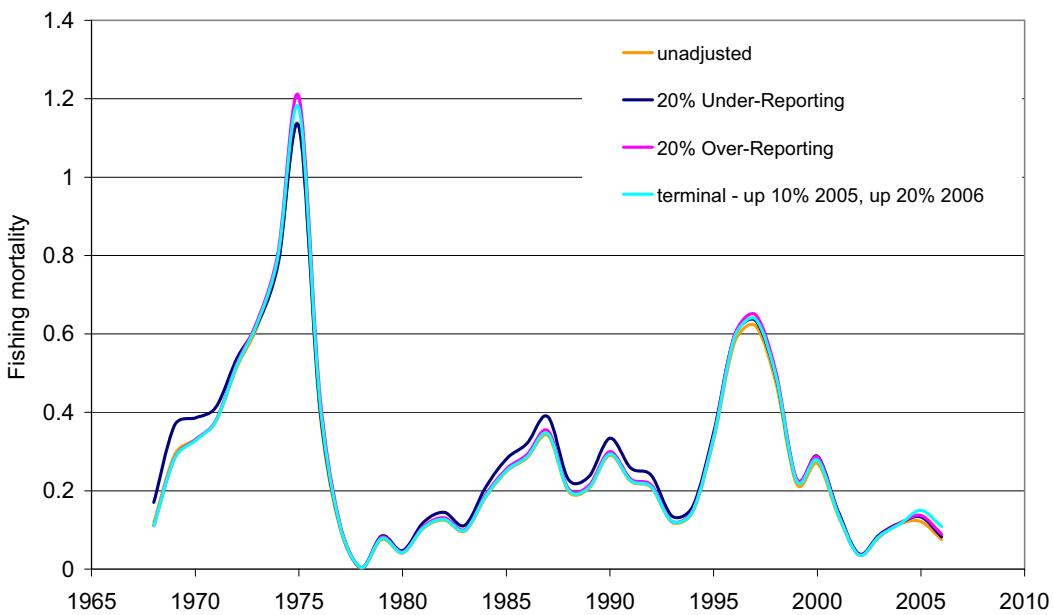


Figure A9-2.1. ASPIC fishing mortality estimates derived from unadjusted, 20% over-reported, 20% under-reported, and 10% and 20% terminal year biased commercial Northern shrimp landings.

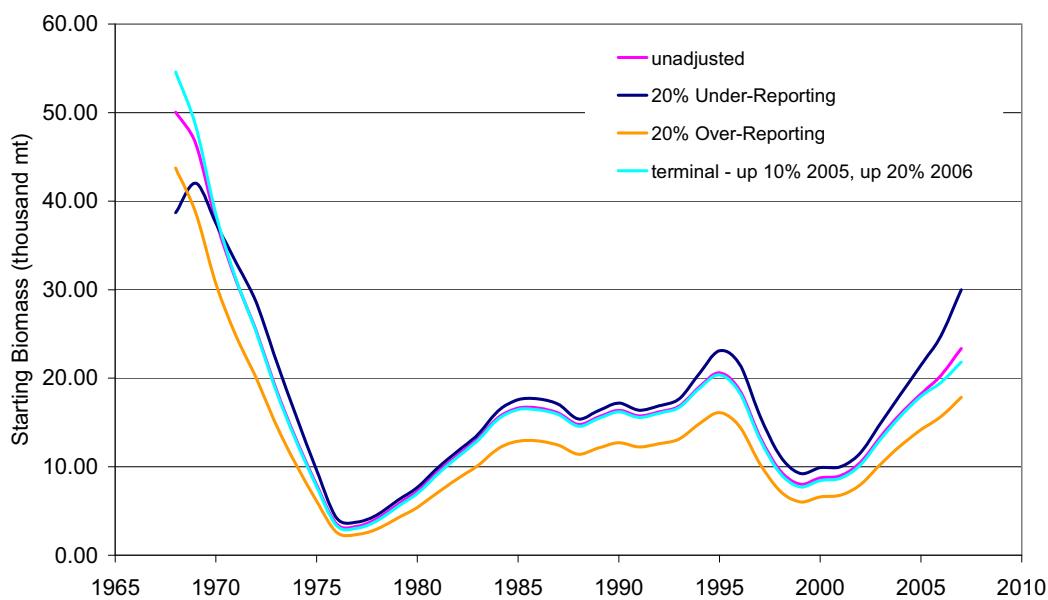


Figure A9-2.2. ASPIC starting biomass estimates derived from unadjusted, 20% over-reported, 20% under-reported, and 10% and 20% terminal year biased commercial northern shrimp landings.

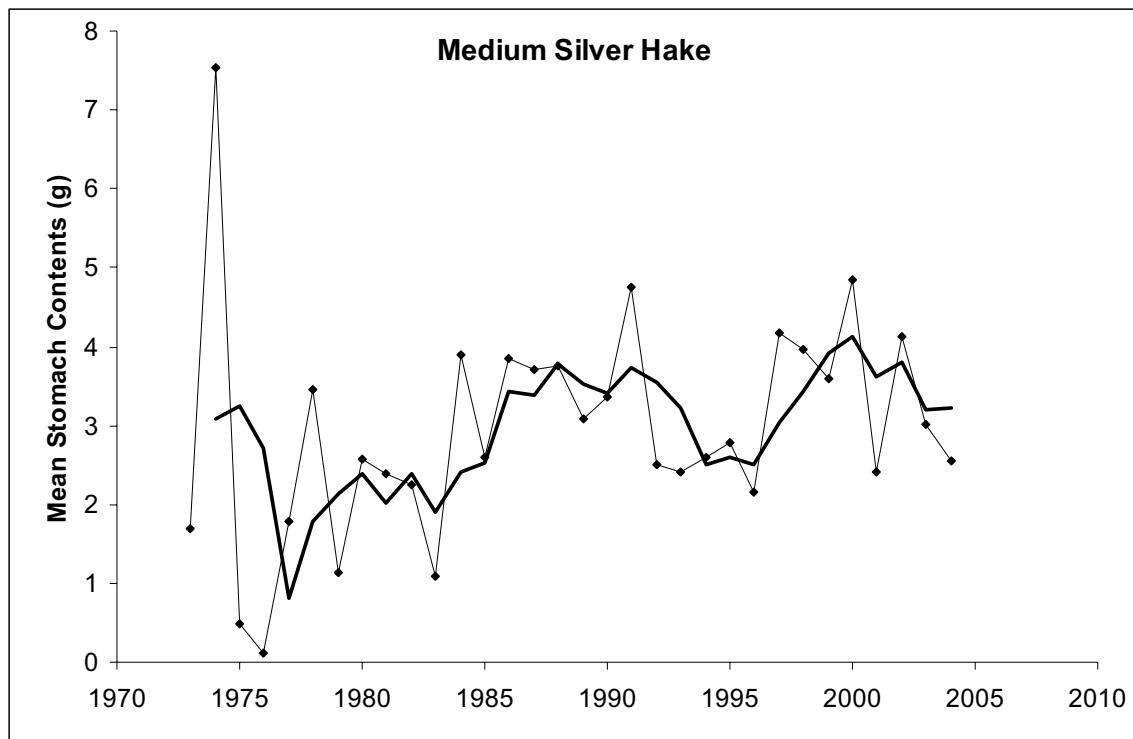


Figure A10-1a. Mean stomach contents of medium silver hake, fall season. The heavier line is the 3 year moving average.

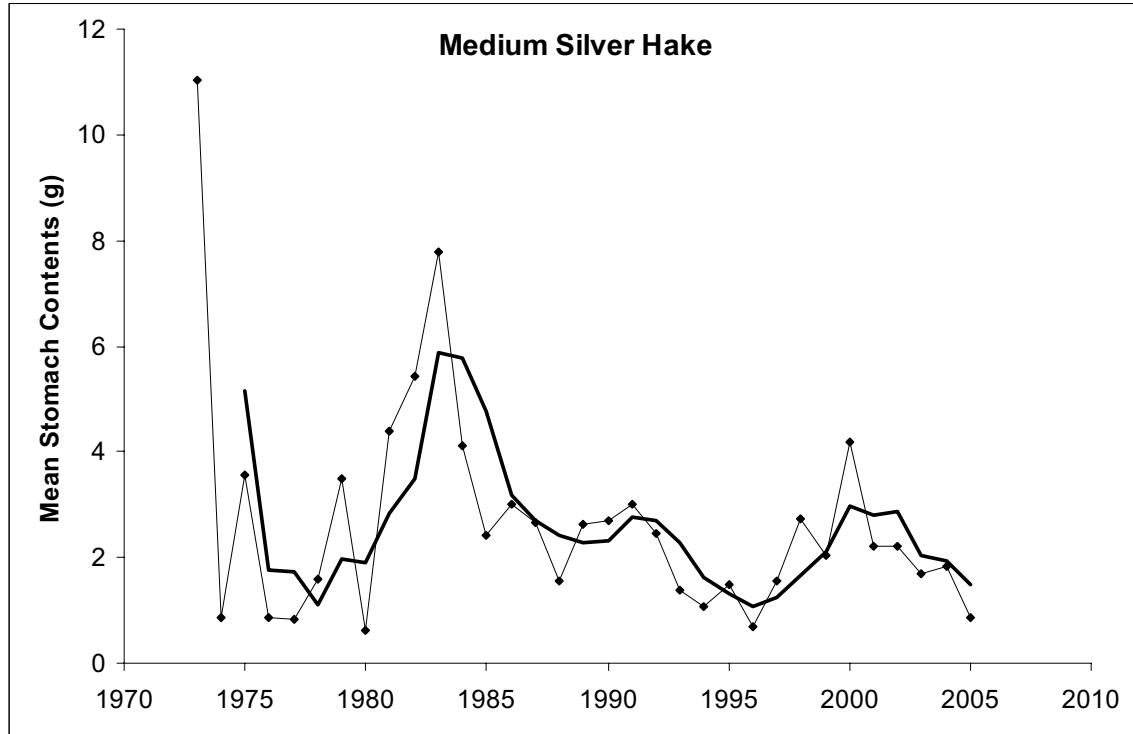


Figure A10-1b. Mean stomach contents of medium silver hake, spring season. The heavier line is the 3 year moving average.

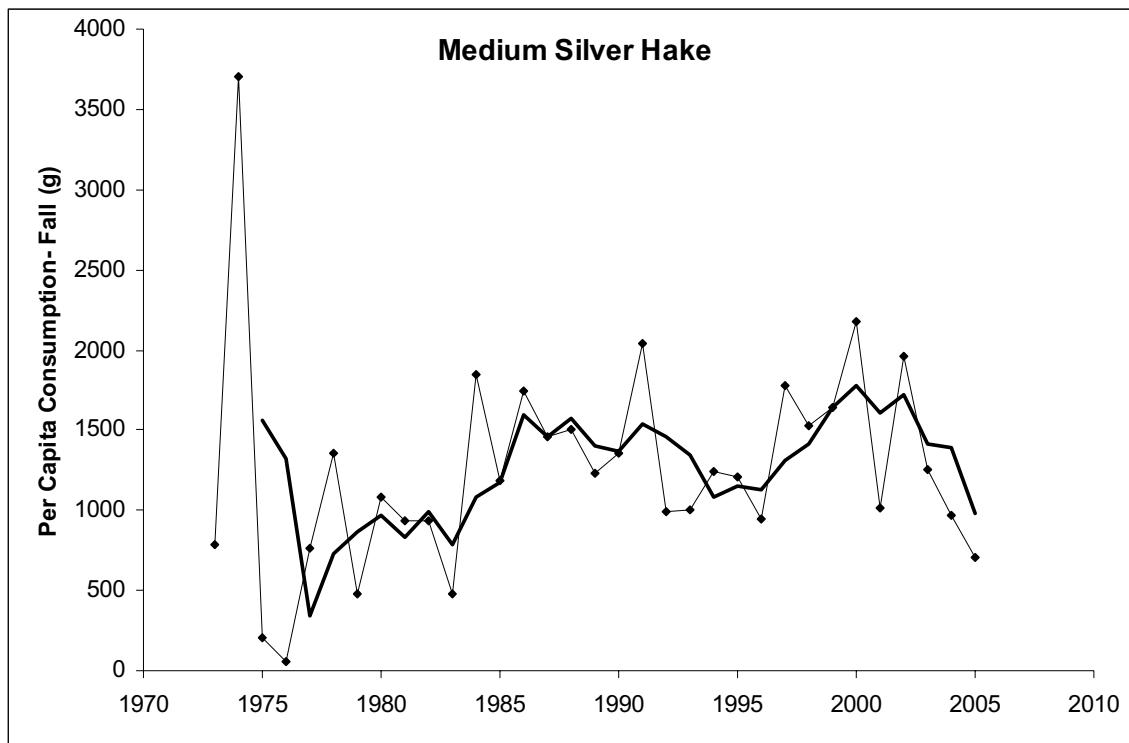


Figure A10-2a. Per capita consumption for medium silver hake, fall season. The heavier line is the 3 year moving average.

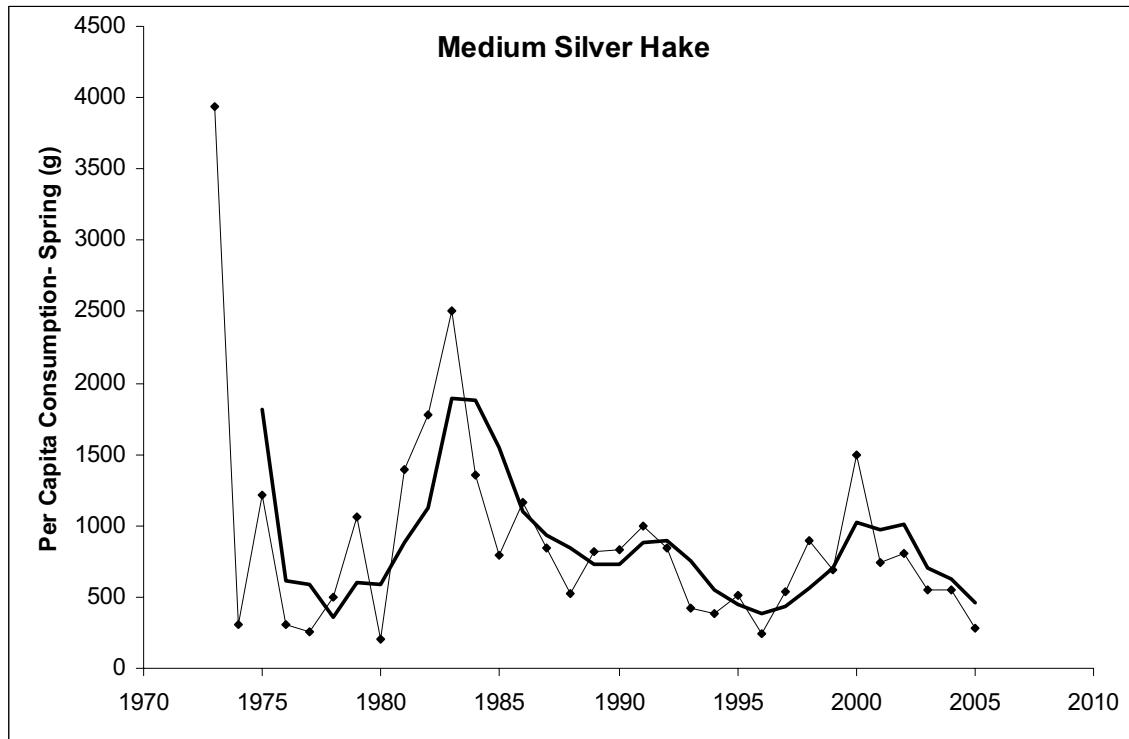


Figure A10-2b. Per capita consumption for medium silver hake, spring season. The heavier line is the 3 year moving average.

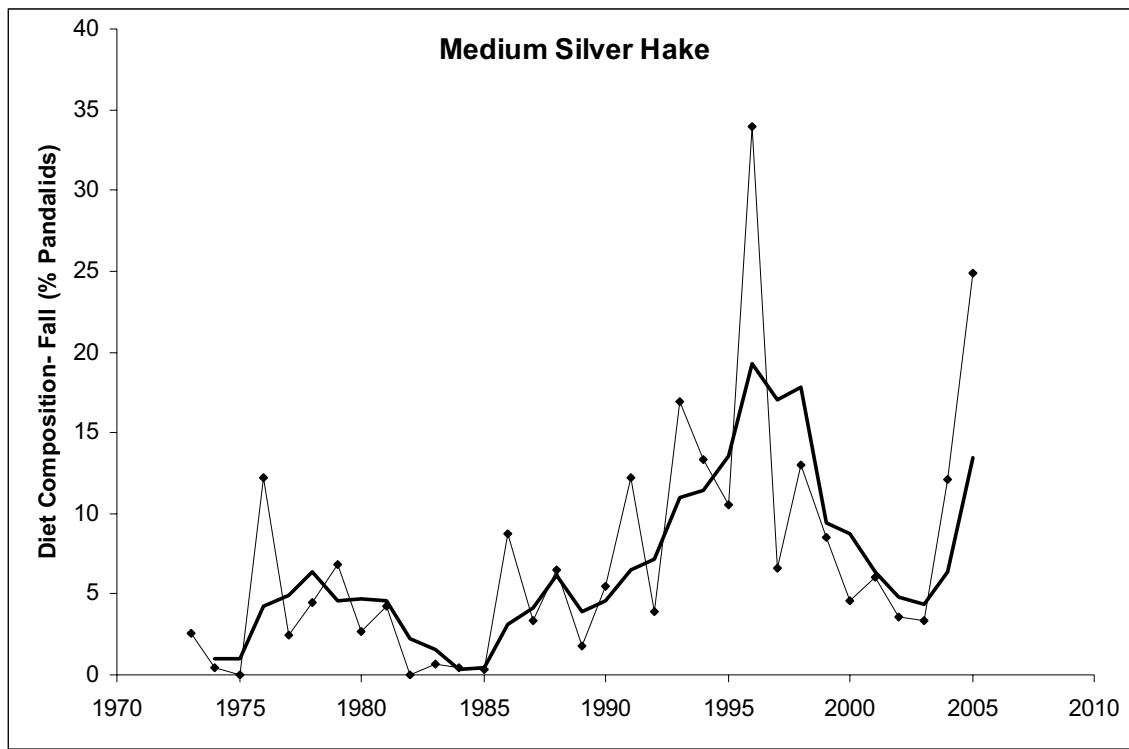


Figure A10-3a. Diet composition of pandalids in medium silver hake, fall season. The heavier line is the 3 year moving average.

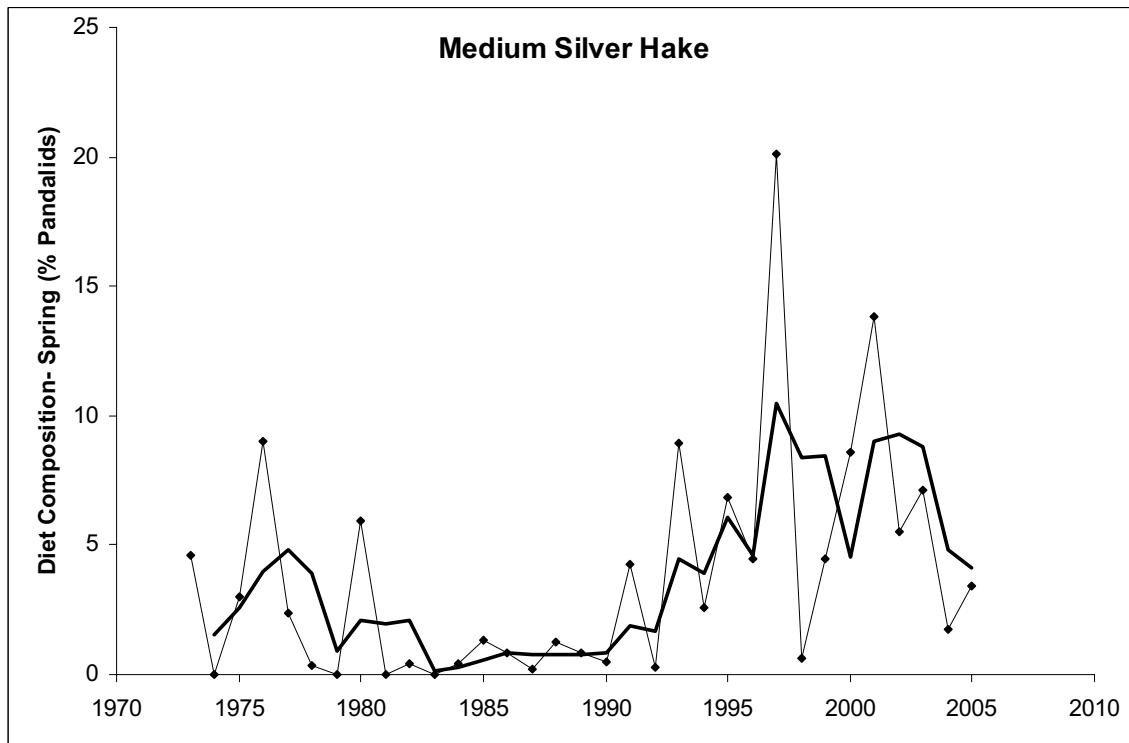


Figure A10-3b. Diet composition of pandalids in medium silver hake, spring season. The heavier line is the 3 year moving average.

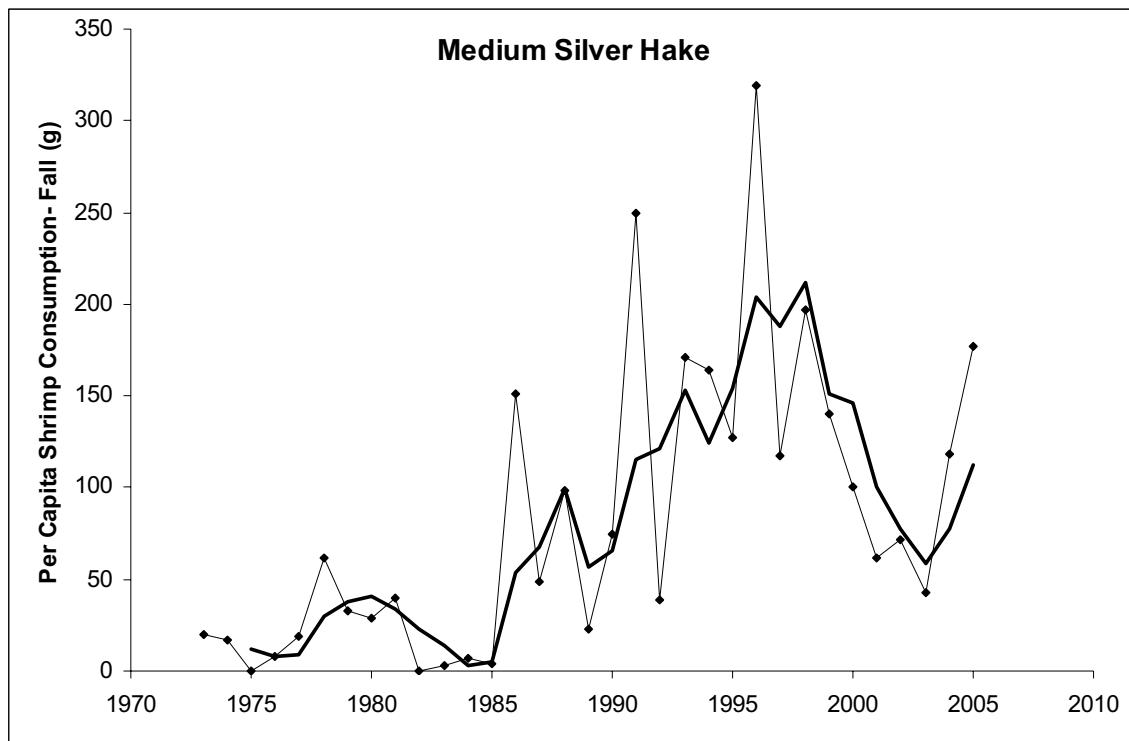


Figure A10-4a. Per capita consumption of pandalid shrimp by medium silver hake, fall season. The heavier line is the 3 year moving average.

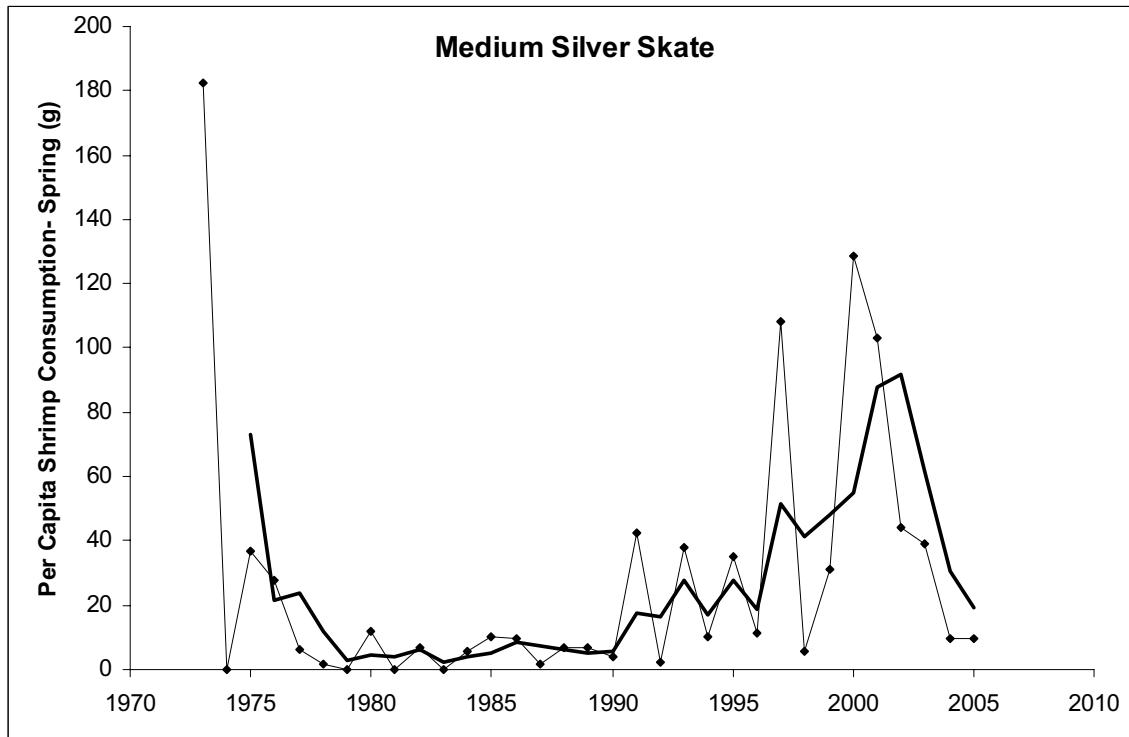


Figure A10-4b. Per capita consumption of pandalid shrimp by medium silver hake, spring season. The heavier line is the 3 year moving average.

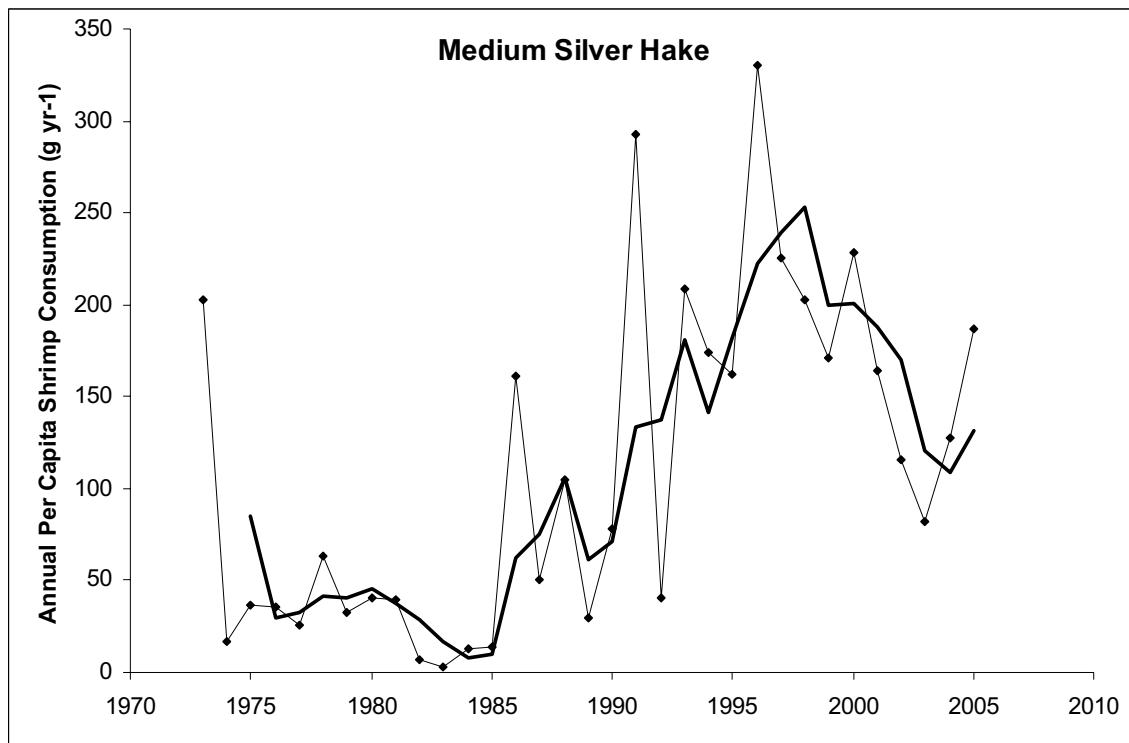


Figure A10-5. Annual per capita consumption of pandalid shrimp by medium silver hake. The heavier line is the 3 year moving average.

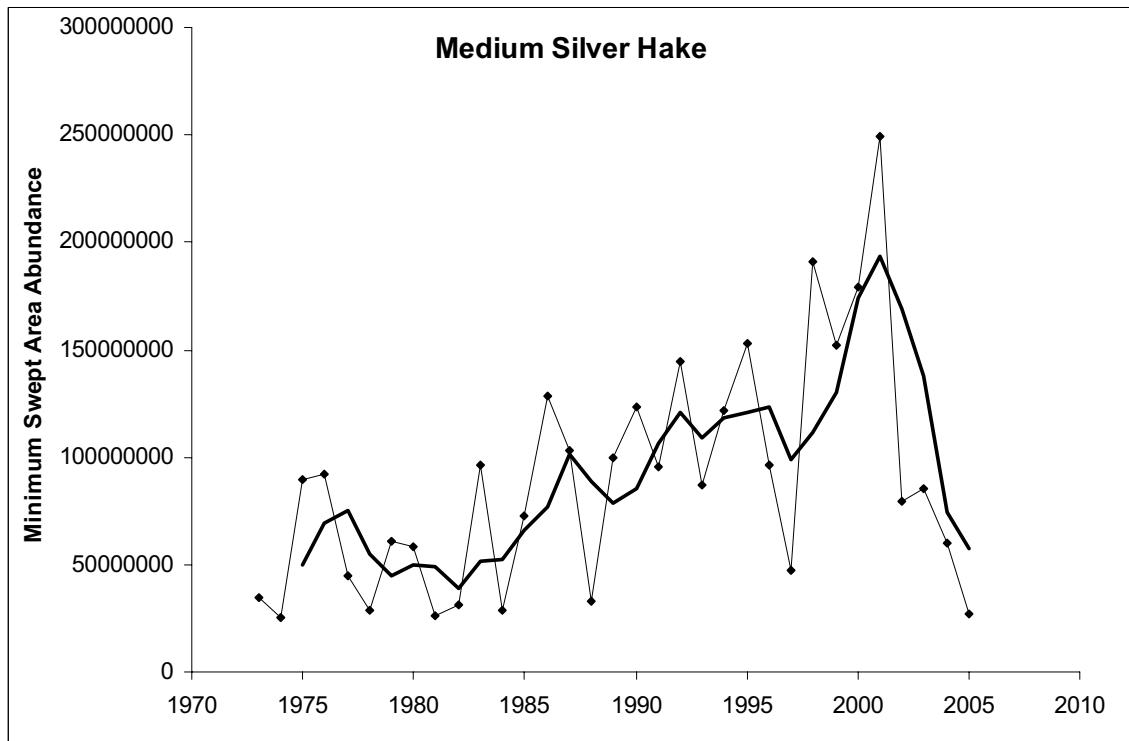


Figure A10-6. Minimum swept-area abundance of medium silver hake estimated from bottom trawl surveys. The heavier line is the 3 year moving average.

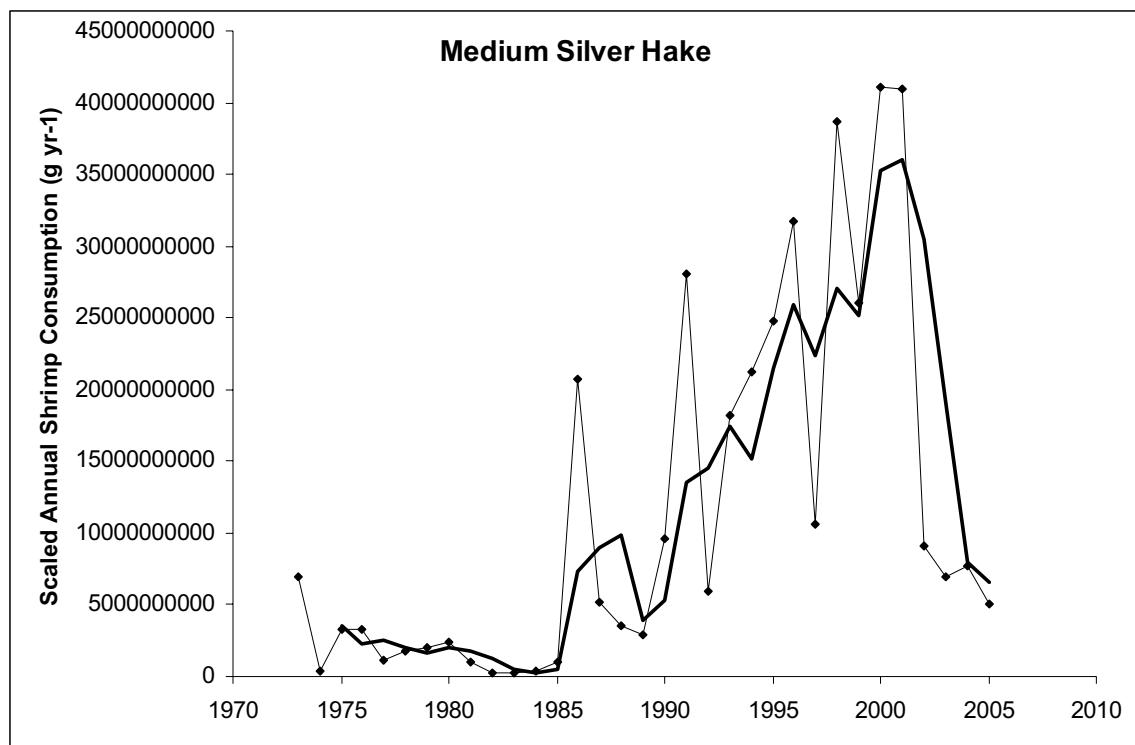


Figure A10-7. Total biomass of pandalid shrimp removed via consumption by medium silver hake. The heavier line is the 3 year moving average.

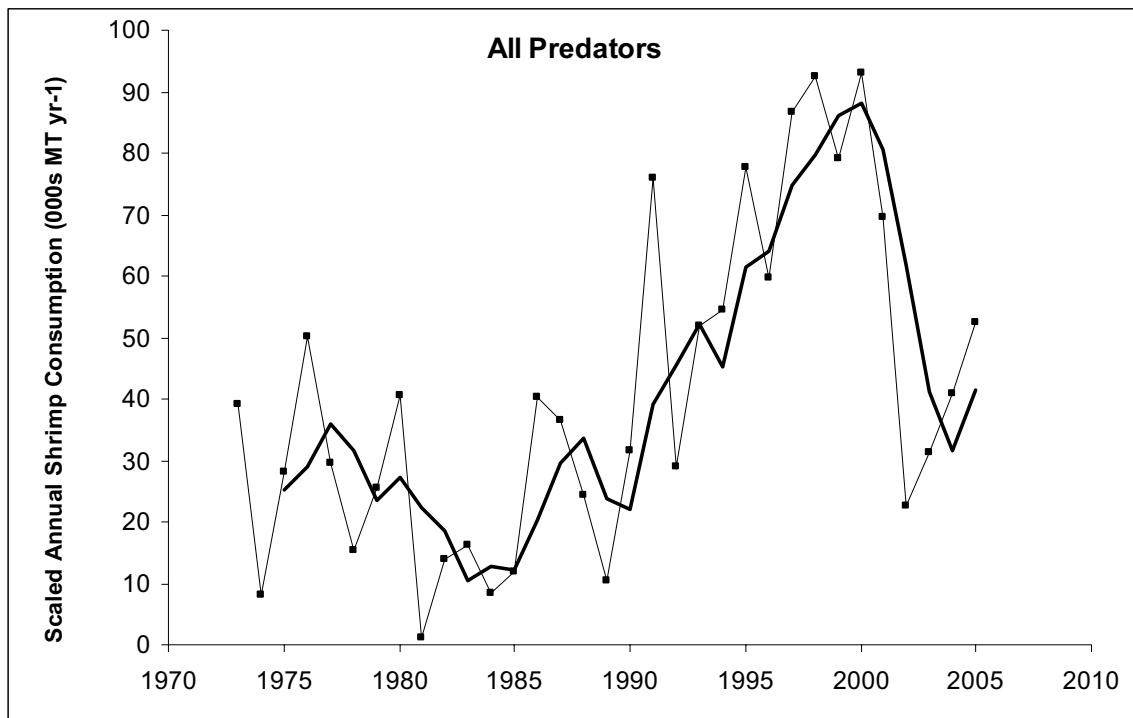


Figure A10-8a. Total pandalid shrimp biomass consumed by all predators. The heavier line is the 3 year moving average.

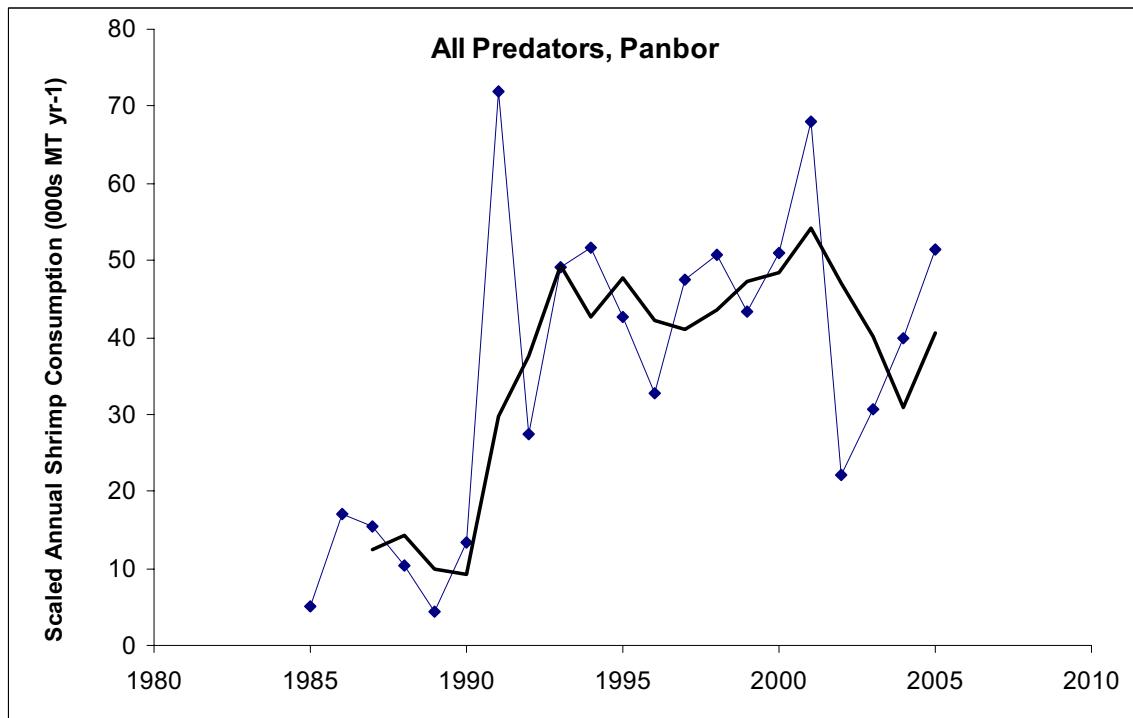


Figure A10-8b. Total *Pandalus borealis* shrimp biomass consumed by all predators. The heavier line is the 3 year moving average.

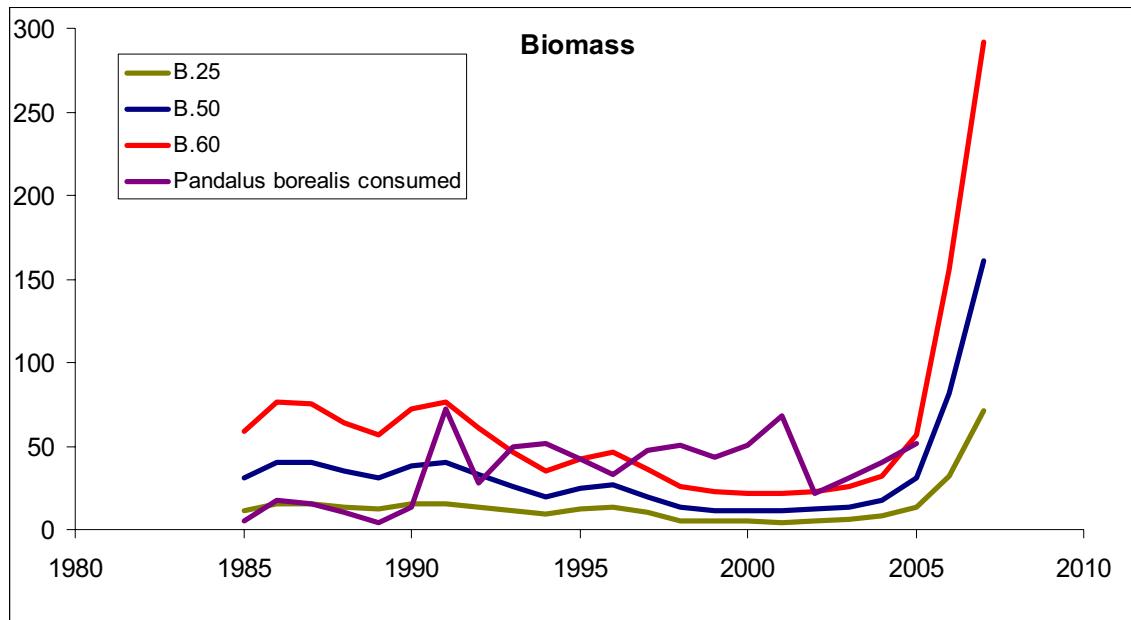


Figure A10-9a. Comparison of total *Pandalus borealis* shrimp biomass consumed by all predators compared to CSA models with different levels of natural mortality.

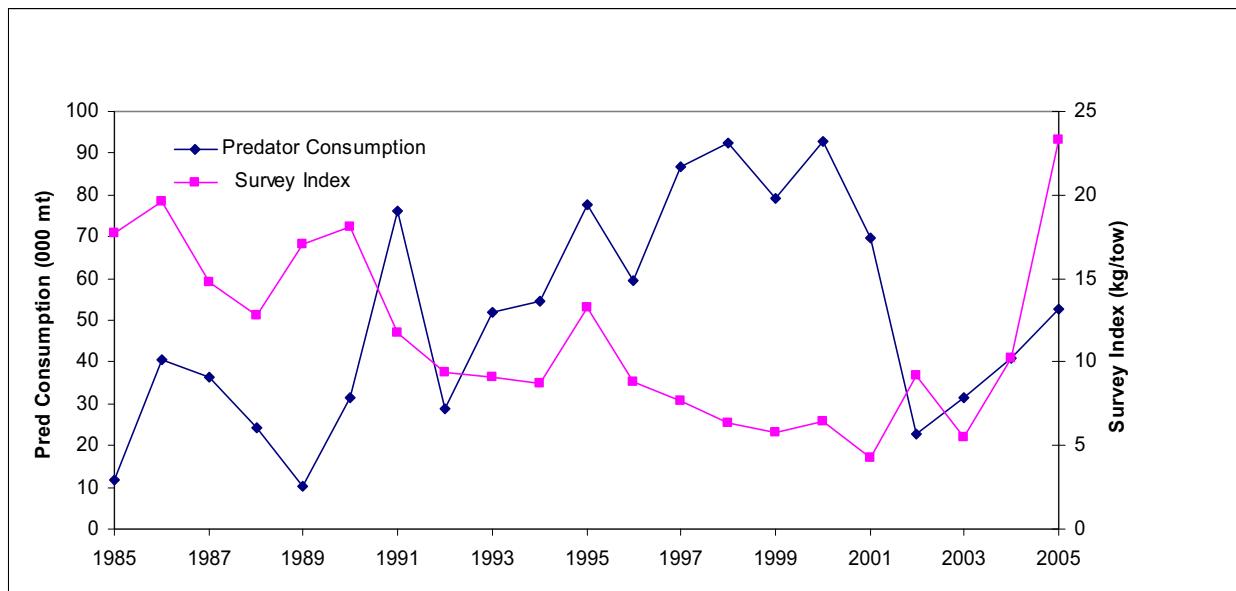


Figure A10-9b. Comparison of total *Pandalus borealis* shrimp biomass consumed by all predators compared to shrimp summer survey biomass index.

## NORTHERN SHRIMP APPENDICES

### APPENDIX A1: ASPIC BOOTSTRAP OUTPUT FOR NORTHERN SHRIMP ASSESSMENT THROUGH 2006

ASPIC -- A Surplus-Production Model Including Covariates (Ver. 3.91) BOT Mode

Author: Michael H. Prager; NOAA/NMFS/S.E. Fisheries Science Center  
101 Pivers Island Road; Beaufort, North Carolina 28516 USA

ASPIC User's Manual is available gratis from the author.

Ref: Prager, M. H. 1994. A suite of extensions to a nonequilibrium surplus-production model. *Fishery Bulletin* 92: 374-389.

#### CONTROL PARAMETERS USED (FROM INPUT FILE)

Number of Years analyzed:	39	Number of bootstrap trials:	1000
Number of data series:	3	Lower bound on MSY:	1.000E+00
Objective function computed:	in effort	Upper bound on MSY:	2.000E+01
Relative conv. criterion (simplex):	1.000E-04	Lower bound on r:	1.000E-02
Relative conv. criterion (restart):	3.000E-04	Upper bound on r:	3.000E+00
Relative conv. criterion (effort):	1.000E-04	Random number seed:	98769756
Maximum F allowed in fitting:	3.000	Monte Carlo search mode, trials:	2
		Code 0	

#### PROGRAM STATUS INFORMATION (NON-BOOTSTRAPPED ANALYSIS)

Normal convergence.

#### CORRELATION AMONG INPUT SERIES EXPRESSED AS CPUE (NUMBER OF PAIRWISE OBSERVATIONS BELOW)

1 Fall Groundfish Survey	1.000	39
2 Maine Summer Survey	0.751	1.000
3 Summer Shrimp Survey	0.485	0.000
	23	0
	1	2
	3	

## GOODNESS-OF-FIT AND WEIGHTING FOR NON-BOOTSTRAPPED ANALYSIS

Loss component number and title	Weighted SSE	N	Weighted MSE	Current weight	Suggested weight	R-squared in CPUE
Loss (-1) SSE in yield	0.000E+00					
Loss ( 0) Penalty for $B_{1R} > 2$	0.000E+00	1				
Loss ( 1) Fall Groundfish Survey	1.050E+01	39	2.838E-01	8.506E-01	8.706E-01	0.493
Loss ( 2) Maine Summer Survey	4.179E+00	16	2.985E-01	8.195E-01	7.976E-01	0.634
Loss ( 3) Summer Shrimp Survey	6.186E+00	23	2.945E-01	1.379E+00	1.360E+00	0.154
TOTAL OBJECTIVE FUNCTION:	2.08664327E+01					

Number of restarts required for convergence:

Est. B/Bmsy coverage index (0 worst, 2 best): 37  
 Est. B/Bmsy nearness index (0 worst, 1 best): 1.3854  
 < 1.0000

## MODEL PARAMETER ESTIMATES (NON-BOOTSTRAPPED)

Estimate	Starting guess	Estimated	User guess	-Parameter
$B_{1R}$	Starting $B/B_{msy}$ , year 1968	1.484E+00		
$MSY$	Maximum sustainable yield	5.395E+00		
$r$	Intrinsic rate of increase	3.584E-01		
.....	Catchability coefficients by fishery:			
$q( 1)$	Fall Groundfish Survey	9.618E-02		
$q( 2)$	Maine Summer Survey	5.393E-01		
$q( 3)$	Summer Shrimp Survey	8.101E-01		

## MANAGEMENT PARAMETER ESTIMATES (NON-BOOTSTRAPPED)

Parameter	Estimate	Formula	Related quantity
$MSY$	Maximum sustainable yield	5.395E+00	
$K$	Maximum stock biomass	6.021E+01	$K/4$
$B_{msy}$	Stock biomass at MSY	3.011E+01	
$F_{msy}$	Fishing mortality at MSY	1.792E-01	$r/2$
$F(0.1)$	Management benchmark	1.613E-01	
$Y(0.1)$	Equilibrium yield at $F(0.1)$	5.341E+00	$0.99 * MSY$
$B_{./Bmsy}$	Ratio of $B(2007)$ to $B_{msy}$	7.523E-01	
$F_{./Fmsy}$	Ratio of $F(2006)$ to $F_{msy}$	4.957E-01	
$F01-mult$	Ratio of $F(0.1)$ to $F(2006)$	1.816E+00	
$Ye./MSY$	Proportion of MSY avail in 2007 in units of each fishery:	9.386E-01	$2 * Br - Br^2$
$fmsy( 1)$	Fall Groundfish Survey	1.863E+00	$Ye(2007) = 5.064E+00$ Fishing effort at MSY
		$r/2q( 1)$	$f(0.1) = 1.677E+00$

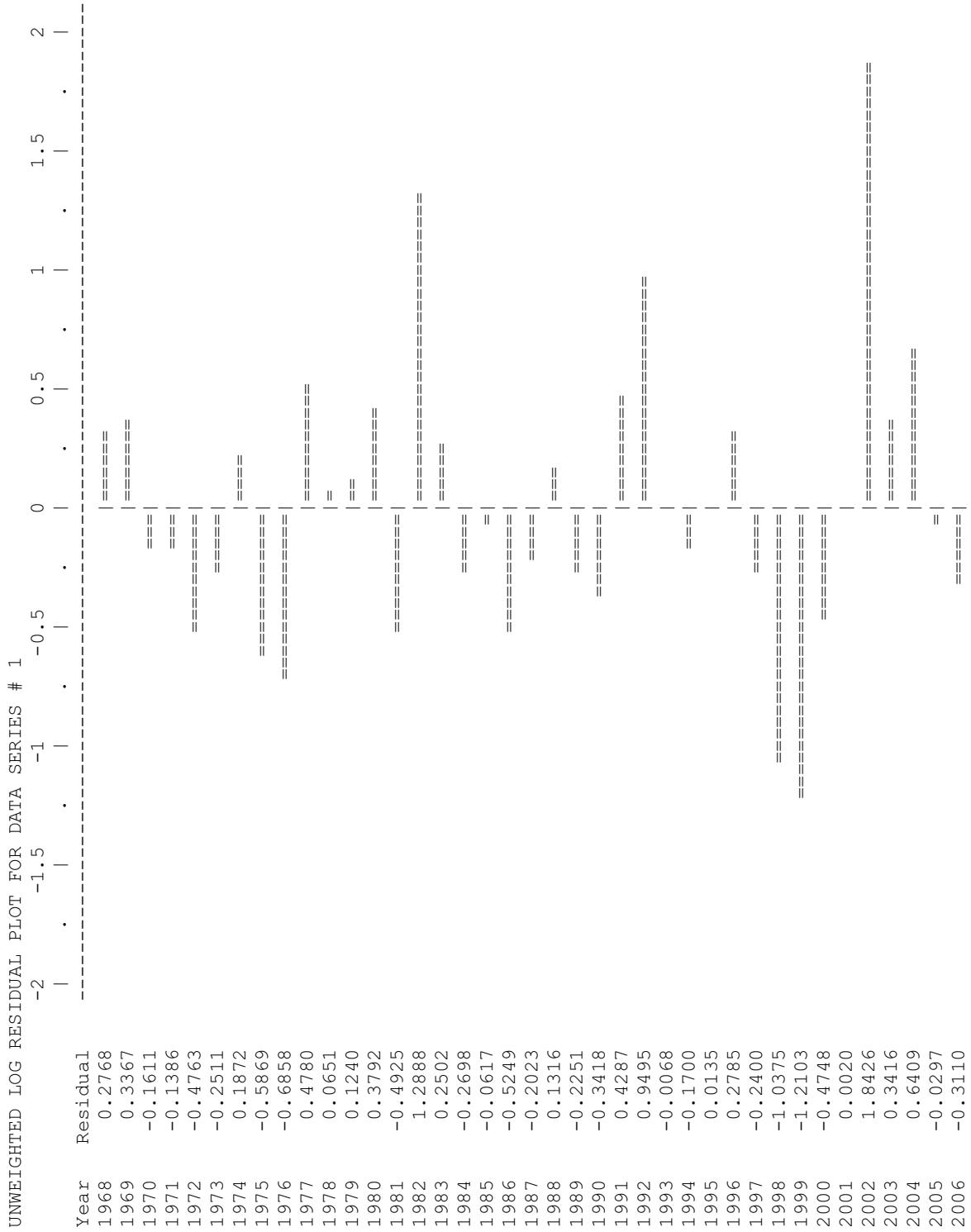
## ESTIMATED POPULATION TRAJECTORY (NON-BOOTSTRAPPED)

Obs	Year or ID	Estimated total F mort	Estimated starting biomass	Estimated average biomass	Observed total yield	Model total yield	Estimated surplus production	Ratio of F mort to Fmsy	Ratio of biomass to Bmsy
1	1968	0.130	4.470E+01	4.394E+01	5.708E+00	5.708E+00	4.259E+00	7.249E-01	1.485E+00
2	1969	0.308	4.325E+01	3.936E+01	1.214E+01	1.214E+01	4.861E+00	1.721E+00	1.437E+00
3	1970	0.346	3.597E+01	3.279E+01	1.133E+01	1.133E+01	5.333E+00	1.928E+00	1.195E+00
4	1971	0.390	2.998E+01	2.719E+01	1.059E+01	1.059E+01	5.328E+00	2.174E+00	9.957E-01
5	1972	0.526	2.471E+01	2.134E+01	1.122E+01	1.122E+01	4.914E+00	2.936E+00	8.208E-01
6	1973	0.630	1.840E+01	1.539E+01	9.691E+00	9.691E+00	4.086E+00	3.515E+00	6.112E-01
7	1974	0.799	1.280E+01	1.004E+01	8.024E+00	8.024E+00	2.983E+00	4.459E+00	4.251E-01
8	1975	1.179	7.757E+00	5.210E+00	6.142E+00	6.142E+00	1.694E+00	6.579E+00	2.576E-01
9	1976	0.441	3.309E+00	3.146E+00	1.387E+00	1.387E+00	1.067E+00	2.460E+00	1.099E-01
10	1977	0.111	2.990E+00	3.358E+00	3.716E-01	3.716E-01	1.135E+00	6.176E-01	9.930E-02
11	1978	0.004	3.753E+00	4.444E+00	1.680E-02	1.680E-02	1.473E+00	2.110E-02	1.247E-01
12	1979	0.083	5.209E+00	5.892E+00	4.865E-01	4.865E-01	1.902E+00	4.608E-01	1.730E-01
13	1980	0.045	6.624E+00	7.605E+00	3.391E-01	3.391E-01	2.377E+00	2.488E-01	2.200E-01
14	1981	0.112	8.662E+00	9.543E+00	1.071E+00	1.071E+00	2.874E+00	6.264E-01	2.877E-01
15	1982	0.135	1.046E+01	1.133E+01	1.530E+00	1.530E+00	3.292E+00	7.536E-01	3.476E-01
16	1983	0.104	1.223E+01	1.337E+01	1.397E+00	1.397E+00	3.721E+00	5.832E-01	4.061E-01
17	1984	0.195	1.455E+01	1.510E+01	2.951E+00	2.951E+00	4.051E+00	1.090E+00	4.833E-01
18	1985	0.264	1.565E+01	1.566E+01	4.131E+00	4.131E+00	4.149E+00	1.472E+00	5.198E-01
19	1986	0.301	1.567E+01	1.540E+01	4.635E+00	4.635E+00	4.103E+00	1.680E+00	5.204E-01
20	1987	0.363	1.514E+01	1.446E+01	5.253E+00	5.253E+00	3.933E+00	2.028E+00	5.028E-01
21	1988	0.213	1.382E+01	1.425E+01	3.031E+00	3.031E+00	3.894E+00	1.187E+00	4.589E-01
22	1989	0.220	1.468E+01	1.504E+01	3.315E+00	3.315E+00	4.041E+00	1.230E+00	4.876E-01
23	1990	0.309	1.540E+01	1.509E+01	4.665E+00	4.665E+00	4.049E+00	1.725E+00	5.117E-01
24	1991	0.238	1.479E+01	1.502E+01	3.571E+00	3.571E+00	4.037E+00	1.327E+00	4.912E-01
25	1992	0.221	1.525E+01	1.560E+01	3.444E+00	3.444E+00	4.139E+00	1.232E+00	5.067E-01
26	1993	0.126	1.595E+01	1.706E+01	2.143E+00	2.143E+00	4.376E+00	7.010E-01	5.298E-01
27	1994	0.153	1.818E+01	1.906E+01	2.915E+00	2.915E+00	4.663E+00	8.535E-01	6.039E-01
28	1995	0.340	1.993E+01	1.899E+01	6.466E+00	6.466E+00	4.654E+00	4.654E+00	4.912E-01
29	1996	0.595	1.812E+01	1.540E+01	9.166E+00	9.166E+00	4.092E+00	3.321E+00	6.018E-01
30	1997	0.645	1.304E+01	1.097E+01	7.079E+00	7.079E+00	3.205E+00	3.600E+00	4.333E-01
31	1998	0.501	9.171E+00	8.336E+00	4.174E+00	4.174E+00	2.570E+00	2.795E+00	3.046E-01
32	1999	0.230	7.567E+00	7.883E+00	1.816E+00	1.816E+00	2.453E+00	1.286E+00	2.513E-01
33	2000	0.288	8.203E+00	8.288E+00	2.389E+00	2.389E+00	2.559E+00	1.609E+00	2.725E-01
34	2001	0.146	8.373E+00	9.075E+00	1.329E+00	1.329E+00	2.758E+00	8.173E-01	2.781E-01
35	2002	0.038	9.802E+00	1.117E+01	4.240E-01	4.240E-01	3.254E+00	2.118E-01	3.256E-01
36	2003	0.087	1.263E+01	1.392E+01	1.211E+00	1.211E+00	3.828E+00	4.856E-01	4.196E-01
37	2004	0.119	1.525E+01	1.640E+01	1.949E+00	1.949E+00	4.271E+00	6.631E-01	5.065E-01
38	2005	0.137	1.757E+01	1.859E+01	2.553E+00	2.553E+00	4.600E+00	7.663E-01	5.836E-01
39	2006	0.089	1.962E+01	2.113E+01	1.877E+00	1.877E+00	4.907E+00	4.957E-01	6.516E-01
40	2007		2.265E+01						7.523E-01

## RESULTS FOR DATA SERIES # 1 (NON-BOOTSTRAPPED)

## Fall Groundfish Survey

Data type CC: CPUE-catch series							Series weight: 0.851		
Obs	Year	Observed CPUE	Estimated CPUE	Estim F	Observed yield	Model yield	Resid in log scale	Resid in log yield	
1	1968	3.200E+00	4.221E+00	0.1299	5.708E+00	5.708E+00	0.27684	0.27684	
2	1969	2.700E+00	3.781E+00	0.3083	1.214E+01	1.214E+01	0.33668	0.33668	
3	1970	3.700E+00	3.150E+00	0.3455	1.133E+01	1.133E+01	-0.16107	-0.16107	
4	1971	3.000E+00	2.612E+00	0.3896	1.059E+01	1.059E+01	-0.13858	-0.13858	
5	1972	3.300E+00	2.049E+00	0.5260	1.122E+01	1.122E+01	-0.47635	-0.47635	
6	1973	1.900E+00	1.478E+00	0.6298	9.691E+00	9.691E+00	-0.25108	-0.25108	
7	1974	8.000E-01	9.647E-01	0.7990	8.024E+00	8.024E+00	0.18716	0.18716	
8	1975	9.000E-01	5.004E-01	1.1789	6.142E+00	6.142E+00	-0.58690	-0.58690	
9	1976	6.000E-01	3.022E-01	0.4408	1.387E+00	1.387E+00	-0.68580	-0.68580	
10	1977	2.000E-01	3.226E-01	0.1107	3.716E-01	3.716E-01	0.47799	0.47799	
11	1978	4.000E-01	4.269E-01	0.0038	1.680E-02	1.680E-02	0.06509	0.06509	
12	1979	5.000E-01	5.660E-01	0.0826	4.865E-01	4.865E-01	0.12395	0.12395	
13	1980	5.000E-01	7.305E-01	0.0446	3.391E-01	3.391E-01	0.37915	0.37915	
14	1981	1.500E+00	9.167E-01	0.1122	1.071E+00	1.071E+00	-0.49246	-0.49246	
15	1982	3.000E-01	1.089E+00	0.1350	1.530E+00	1.530E+00	1.28881	1.28881	
16	1983	1.000E+00	1.284E+00	0.1045	1.397E+00	1.397E+00	0.25020	0.25020	
17	1984	1.900E+00	1.451E+00	0.1954	2.951E+00	2.951E+00	-0.26984	-0.26984	
18	1985	1.600E+00	1.504E+00	0.2638	4.131E+00	4.131E+00	-0.06174	-0.06174	
19	1986	2.500E+00	1.479E+00	0.3010	4.635E+00	4.635E+00	-0.52493	-0.52493	
20	1987	1.700E+00	1.389E+00	0.3634	5.253E+00	5.253E+00	-0.20227	-0.20227	
21	1988	1.200E+00	1.369E+00	0.2127	3.031E+00	3.031E+00	0.13158	0.13158	
22	1989	1.810E+00	1.445E+00	0.2204	3.315E+00	3.315E+00	-0.22514	-0.22514	
23	1990	2.040E+00	1.449E+00	0.3092	4.665E+00	4.665E+00	-0.34175	-0.34175	
24	1991	9.400E-01	1.443E+00	0.2377	3.571E+00	3.571E+00	0.42866	0.42866	
25	1992	5.800E-01	1.499E+00	0.2207	3.444E+00	3.444E+00	0.94947	0.94947	
26	1993	1.650E+00	1.639E+00	0.1256	2.143E+00	2.143E+00	-0.0683	-0.0683	
27	1994	2.170E+00	1.831E+00	0.1529	2.915E+00	2.915E+00	-0.16996	-0.16996	
28	1995	1.800E+00	1.824E+00	0.3405	6.466E+00	6.466E+00	0.01349	0.01349	
29	1996	1.120E+00	1.480E+00	0.5950	9.166E+00	9.166E+00	0.27851	0.27851	
30	1997	1.340E+00	1.054E+00	0.6451	7.079E+00	7.079E+00	-0.24002	-0.24002	
31	1998	2.260E+00	8.008E-01	0.5007	4.174E+00	4.174E+00	-1.03754	-1.03754	
32	1999	2.540E+00	7.572E-01	0.2304	1.816E+00	1.816E+00	-1.21026	-1.21026	
33	2000	1.280E+00	7.961E-01	0.2883	2.389E+00	2.389E+00	-0.47483	-0.47483	
34	2001	8.700E-01	8.717E-01	0.1464	1.329E+00	1.329E+00	0.00196	0.00196	
35	2002	1.700E-01	1.073E+00	0.0379	4.240E-01	4.240E-01	1.84262	1.84262	
36	2003	9.500E-01	1.337E+00	0.0870	1.211E+00	1.211E+00	0.34162	0.34162	
37	2004	8.300E-01	1.575E+00	0.1188	1.949E+00	1.949E+00	0.64087	0.64087	
38	2005	1.840E+00	1.786E+00	0.1373	2.553E+00	2.553E+00	-0.02972	-0.02972	
39	2006	2.770E+00	2.030E+00	0.0888	1.877E+00	1.877E+00	-0.31104	-0.31104	

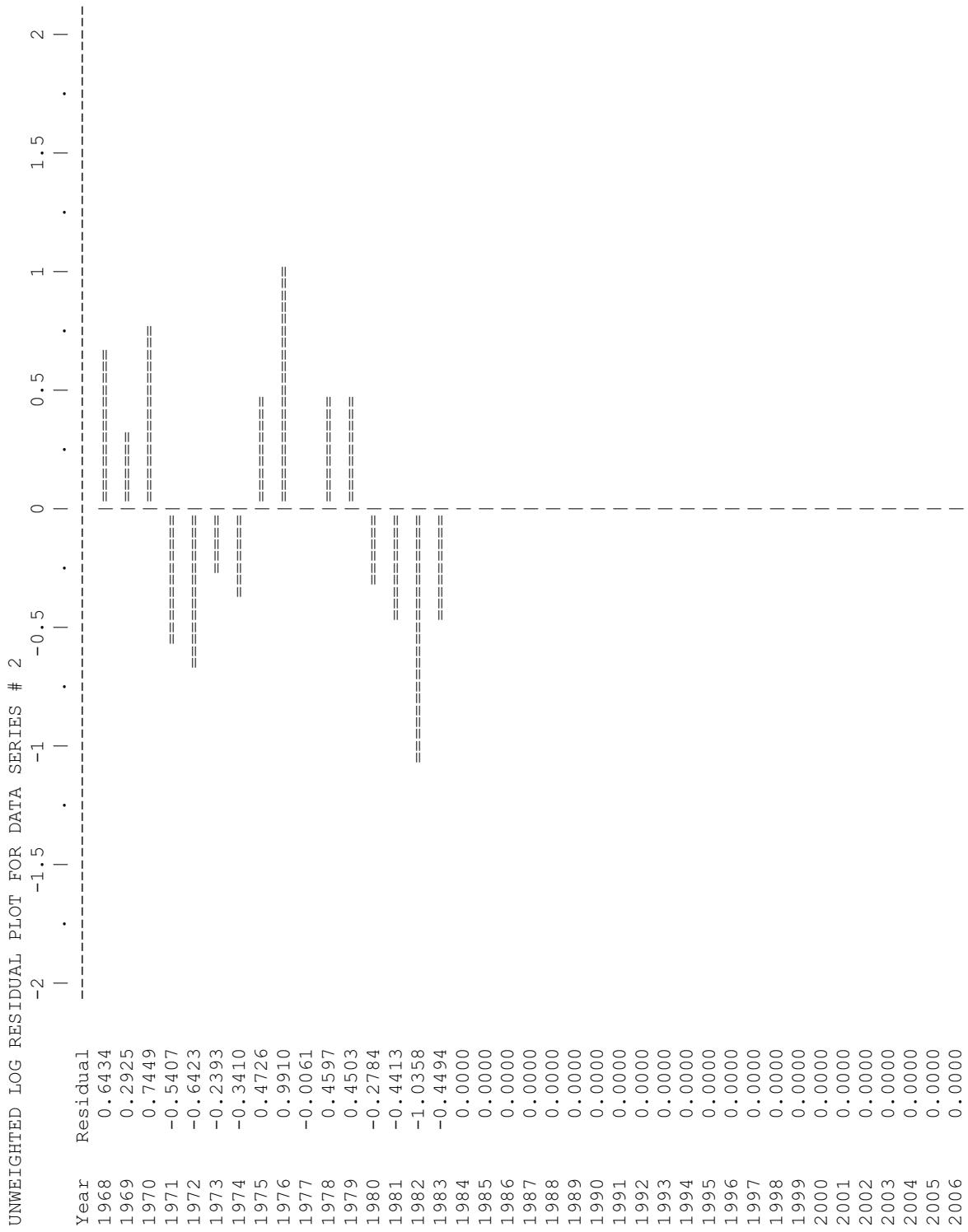


## RESULTS FOR DATA SERIES # 2 (NON-BOOTSTRAPPED)

Maine Summer Survey

Data type 10: Start-of-year biomass index

Obs	Year	Observed effort	Estimated effort	Estim F	Observed index	Model index	Resid in log index	Resid in index
1	1968	1.000E+00	1.000E+00	0.0	4.580E+01	2.407E+01	0.64338	2.173E+01
2	1969	1.000E+00	1.000E+00	0.0	3.120E+01	2.329E+01	0.29246	7.911E+00
3	1970	1.000E+00	1.000E+00	0.0	4.080E+01	1.937E+01	0.74490	2.143E+01
4	1971	1.000E+00	1.000E+00	0.0	9.400E+00	1.614E+01	-0.54072	-6.742E+00
5	1972	1.000E+00	1.000E+00	0.0	7.000E+00	1.331E+01	-0.64235	-6.307E+00
6	1973	1.000E+00	1.000E+00	0.0	7.800E+00	9.909E+00	-0.23932	-2.109E+00
7	1974	1.000E+00	1.000E+00	0.0	4.900E+00	6.891E+00	-0.34099	-1.991E+00
8	1975	1.000E+00	1.000E+00	0.0	6.700E+00	4.177E+00	0.47261	2.523E+00
9	1976	1.000E+00	1.000E+00	0.0	4.800E+00	1.782E+00	0.99096	3.018E+00
10	1977	1.000E+00	1.000E+00	0.0	1.600E+00	1.610E+00	-0.00611	-9.802E-03
11	1978	1.000E+00	1.000E+00	0.0	3.200E+00	2.021E+00	0.45968	1.179E+00
12	1979	1.000E+00	1.000E+00	0.0	4.400E+00	2.805E+00	0.45034	1.595E+00
13	1980	1.000E+00	1.000E+00	0.0	2.700E+00	3.567E+00	-0.27841	-8.668E-01
14	1981	1.000E+00	1.000E+00	0.0	3.000E+00	4.664E+00	-0.44125	-1.664E+00
15	1982	1.000E+00	1.000E+00	0.0	2.000E+00	5.634E+00	-1.03576	-3.634E+00
16	1983	1.000E+00	1.000E+00	0.0	4.200E+00	6.583E+00	-0.44944	-2.383E+00
17	1984	0.000E+00	0.000E+00	0.0	*	7.835E+00	0.00000	0.0
18	1985	0.000E+00	0.000E+00	0.0	*	8.427E+00	0.00000	0.0
19	1986	0.000E+00	0.000E+00	0.0	*	8.437E+00	0.00000	0.0
20	1987	0.000E+00	0.000E+00	0.0	*	8.150E+00	0.00000	0.0
21	1988	0.000E+00	0.000E+00	0.0	*	7.439E+00	0.00000	0.0
22	1989	0.000E+00	0.000E+00	0.0	*	7.904E+00	0.00000	0.0
23	1990	0.000E+00	0.000E+00	0.0	*	8.295E+00	0.00000	0.0
24	1991	0.000E+00	0.000E+00	0.0	*	7.963E+00	0.00000	0.0
25	1992	0.000E+00	0.000E+00	0.0	*	8.214E+00	0.00000	0.0
26	1993	0.000E+00	0.000E+00	0.0	*	8.588E+00	0.00000	0.0
27	1994	0.000E+00	0.000E+00	0.0	*	9.790E+00	0.00000	0.0
28	1995	0.000E+00	0.000E+00	0.0	*	1.073E+01	0.00000	0.0
29	1996	0.000E+00	0.000E+00	0.0	*	9.756E+00	0.00000	0.0
30	1997	0.000E+00	0.000E+00	0.0	*	7.024E+00	0.00000	0.0
31	1998	0.000E+00	0.000E+00	0.0	*	4.938E+00	0.00000	0.0
32	1999	0.000E+00	0.000E+00	0.0	*	4.074E+00	0.00000	0.0
33	2000	0.000E+00	0.000E+00	0.0	*	4.417E+00	0.00000	0.0
34	2001	0.000E+00	0.000E+00	0.0	*	4.508E+00	0.00000	0.0
35	2002	0.000E+00	0.000E+00	0.0	*	5.278E+00	0.00000	0.0
36	2003	0.000E+00	0.000E+00	0.0	*	6.802E+00	0.00000	0.0
37	2004	0.000E+00	0.000E+00	0.0	*	8.211E+00	0.00000	0.0
38	2005	0.000E+00	0.000E+00	0.0	*	9.461E+00	0.00000	0.0
39	2006	0.000E+00	0.000E+00	0.0	*	1.056E+01	0.00000	0.0

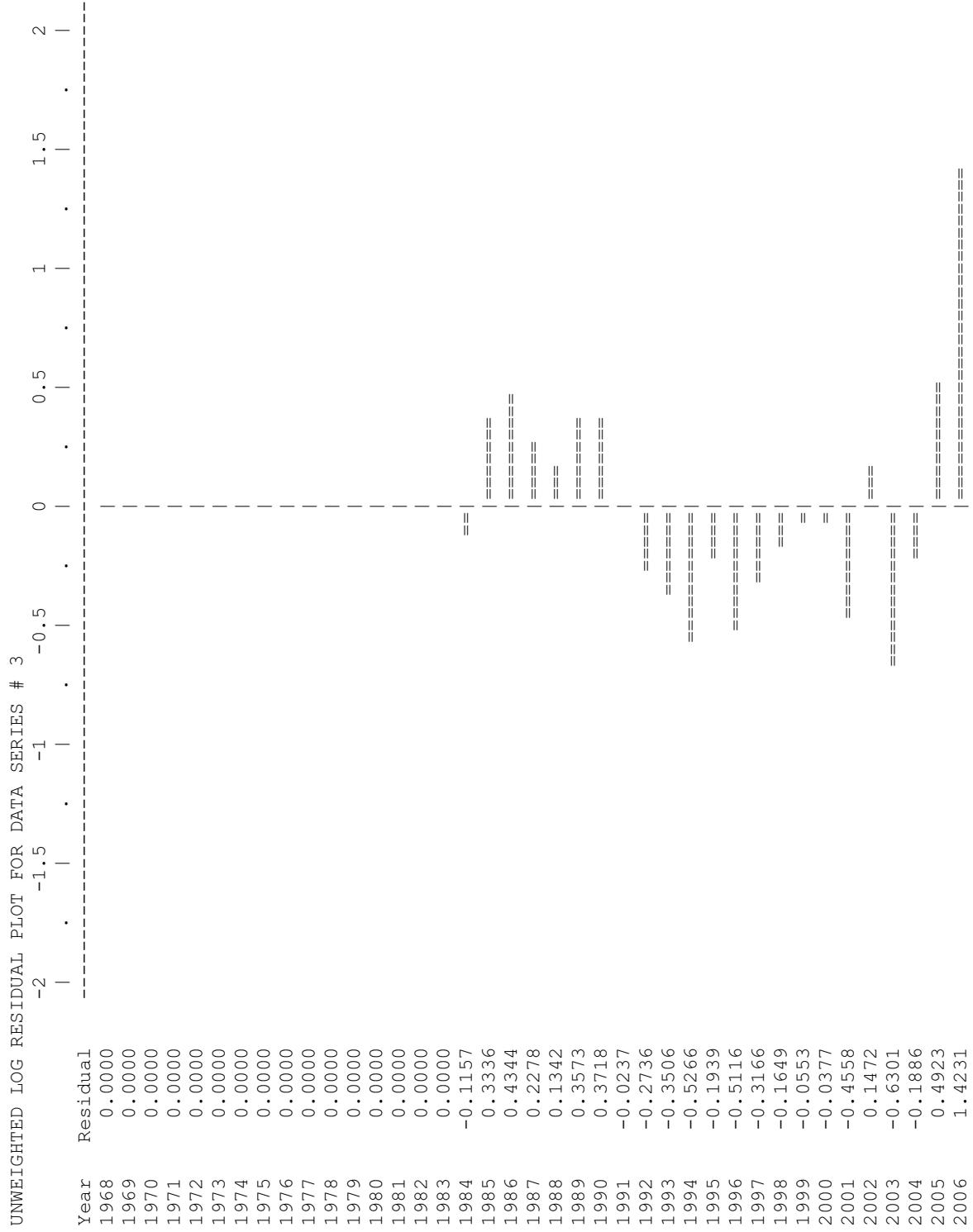


## RESULTS FOR DATA SERIES # 3 (NON-BOOTSTRAPPED)

## Summer Shrimp Survey

Data type 10: Start-of-year biomass index

Obs	Year	Observed effort		Estimated effort	Estim F	Observed index	Model index	Resid in log index	Series weight: 1.379
		Observed effort	Estimated effort						
1	1968	0.000E+00	0.000E+00	0.0	*	3.621E+01	0.00000	0.0	
2	1969	0.000E+00	0.000E+00	0.0	*	3.504E+01	0.00000	0.0	
3	1970	0.000E+00	0.000E+00	0.0	*	2.914E+01	0.00000	0.0	
4	1971	0.000E+00	0.000E+00	0.0	*	2.429E+01	0.00000	0.0	
5	1972	0.000E+00	0.000E+00	0.0	*	2.002E+01	0.00000	0.0	
6	1973	0.000E+00	0.000E+00	0.0	*	1.491E+01	0.00000	0.0	
7	1974	0.000E+00	0.000E+00	0.0	*	1.037E+01	0.00000	0.0	
8	1975	0.000E+00	0.000E+00	0.0	*	6.284E+00	0.00000	0.0	
9	1976	0.000E+00	0.000E+00	0.0	*	2.681E+00	0.00000	0.0	
10	1977	0.000E+00	0.000E+00	0.0	*	2.422E+00	0.00000	0.0	
11	1978	0.000E+00	0.000E+00	0.0	*	3.040E+00	0.00000	0.0	
12	1979	0.000E+00	0.000E+00	0.0	*	4.220E+00	0.00000	0.0	
13	1980	0.000E+00	0.000E+00	0.0	*	5.366E+00	0.00000	0.0	
14	1981	0.000E+00	0.000E+00	0.0	*	7.017E+00	0.00000	0.0	
15	1982	0.000E+00	0.000E+00	0.0	*	8.477E+00	0.00000	0.0	
16	1983	0.000E+00	0.000E+00	0.0	*	9.905E+00	0.00000	0.0	
17	1984	1.000E+00	1.000E+00	0.0	1.050E+01	1.179E+01	-0.11570	-1.288E+00	
18	1985	1.000E+00	1.000E+00	0.0	1.770E+01	1.268E+01	0.33362	5.021E+00	
19	1986	1.000E+00	1.000E+00	0.0	1.960E+01	1.269E+01	0.43444	6.906E+00	
20	1987	1.000E+00	1.000E+00	0.0	1.540E+01	1.226E+01	0.22780	3.137E+00	
21	1988	1.000E+00	1.000E+00	0.0	1.280E+01	1.119E+01	0.13416	1.607E+00	
22	1989	1.000E+00	1.000E+00	0.0	1.700E+01	1.189E+01	0.35734	5.108E+00	
23	1990	1.000E+00	1.000E+00	0.0	1.810E+01	1.248E+01	0.37181	5.620E+00	
24	1991	1.000E+00	1.000E+00	0.0	1.170E+01	1.198E+01	-0.02369	-2.805E-01	
25	1992	1.000E+00	1.000E+00	0.0	9.400E+00	1.236E+01	-0.27357	-2.958E+00	
26	1993	1.000E+00	1.000E+00	0.0	9.100E+00	1.292E+01	-0.35060	-3.821E+00	
27	1994	1.000E+00	1.000E+00	0.0	8.700E+00	1.473E+01	-0.52657	-6.030E+00	
28	1995	1.000E+00	1.000E+00	0.0	1.330E+01	1.615E+01	-0.19395	-2.847E+00	
29	1996	1.000E+00	1.000E+00	0.0	8.800E+00	1.468E+01	-0.51164	-5.879E+00	
30	1997	1.000E+00	1.000E+00	0.0	7.700E+00	1.057E+01	-0.31660	-2.868E+00	
31	1998	1.000E+00	1.000E+00	0.0	6.300E+00	7.430E+00	-0.16494	-1.130E+00	
32	1999	1.000E+00	1.000E+00	0.0	5.800E+00	6.130E+00	-0.05534	-3.300E-01	
33	2000	1.000E+00	1.000E+00	0.0	6.400E+00	6.646E+00	-0.03766	-2.456E-01	
34	2001	1.000E+00	1.000E+00	0.0	4.300E+00	6.783E+00	-0.45579	-2.483E+00	
35	2002	1.000E+00	1.000E+00	0.0	9.200E+00	7.941E+00	0.14719	1.259E+01	
36	2003	1.000E+00	1.000E+00	0.0	5.450E+00	1.023E+01	-0.63005	-4.783E+00	
37	2004	1.000E+00	1.000E+00	0.0	1.023E+01	1.235E+01	-0.18862	-2.124E+00	
38	2005	1.000E+00	1.000E+00	0.0	2.329E+01	1.423E+01	0.49235	9.055E+00	
39	2006	1.000E+00	1.000E+00	0.0	6.595E+01	1.589E+01	1.42307	5.006E+01	



## RESULTS OF BOOTSTRAPPED ANALYSIS

Param name	Point estimate	Estimated bias	Relative bias	Approx 80% lower CL	Approx 80% upper CL	Approx 50% lower CL	Approx 50% upper CL	Inter-quartile range	Relative IQ range
B1/Bmsy	1.484E+00	1.550E-02	1.04%	1.366E+00	1.565E+00	1.424E+00	1.514E+00	9.072E-02	0.061
K	6.021E+01	2.322E-01	0.39%	5.633E+01	6.695E+01	5.844E+01	6.337E+01	4.923E+00	0.082
r	3.584E-01	-1.849E-03	-0.52%	3.077E-01	4.033E-01	3.325E-01	3.816E-01	4.913E-02	0.137
q(1)	9.618E-02	-8.097E-04	-0.84%	7.689E-02	1.174E-01	8.659E-02	1.071E-01	2.051E-02	0.213
q(2)	5.393E-01	4.548E-03	0.84%	4.196E-01	6.964E-01	4.805E-01	6.245E-01	1.440E-01	0.267
q(3)	8.101E-01	-8.190E-04	-0.10%	6.501E-01	9.952E-01	7.267E-01	9.059E-01	1.792E-01	0.221
MSY	5.395E+00	-4.157E-02	-0.77%	5.088E+00	5.703E+00	5.269E+00	5.566E+00	2.968E-01	0.055
Ye (2007)	5.064E+00	-1.023E-01	-2.02%	4.484E+00	5.527E+00	4.802E+00	5.343E+00	5.402E-01	0.107
Bmsy	3.011E+01	1.161E-01	0.39%	2.817E+01	3.347E+01	2.922E+01	3.168E+01	2.461E+00	0.082
Fmsy	1.792E-01	-9.246E-04	-0.52%	1.538E-01	2.017E-01	1.662E-01	1.908E-01	2.456E-02	0.137
fmsy(1)	1.863E+00	3.226E-02	1.73%	1.605E+00	2.117E+00	1.707E+00	1.984E+00	2.771E-01	0.149
fmsy(2)	3.322E-01	4.402E-03	1.32%	2.708E-01	4.049E-01	2.972E-01	3.659E-01	6.868E-02	0.207
fmsy(3)	2.212E-01	2.450E-03	1.11%	1.893E-01	2.573E-01	2.035E-01	2.403E-01	3.678E-02	0.166
F(0.1)	1.613E-01	-8.321E-04	-0.46%	1.385E-01	1.815E-01	1.496E-01	1.717E-01	2.211E-02	0.137
Y(0.1)	5.341E+00	-4.115E-02	-0.76%	5.037E+00	5.646E+00	5.217E+00	5.510E+00	2.938E-01	0.055
B/Bmsy	7.523E-01	1.364E-02	1.81%	5.878E-01	9.313E-01	6.596E-01	8.462E-01	1.866E-01	0.248
F/Fmsy	4.957E-01	1.133E-02	2.29%	3.963E-01	6.374E-01	4.387E-01	5.677E-01	1.290E-01	0.260
Y-ratio	9.386E-01	-1.181E-02	-1.26%	8.301E-01	9.935E-01	8.850E-01	9.757E-01	9.072E-02	0.097
f0.1(1)	1.677E+00	2.904E-02	1.56%	1.445E+00	1.906E+00	1.536E+00	1.786E+00	2.494E-01	0.149
f0.1(2)	2.990E-01	3.962E-03	1.19%	2.438E-01	3.644E-01	2.675E-01	3.293E-01	6.182E-02	0.207
f0.1(3)	1.991E-01	2.205E-03	1.00%	1.704E-01	2.315E-01	1.831E-01	2.162E-01	3.310E-02	0.166
q2/q1	5.607E+00	1.566E-01	2.79%	4.497E+00	7.294E+00	4.973E+00	6.502E+00	1.530E+00	0.273
q3/q1	8.423E+00	1.431E-01	1.70%	7.033E+00	9.951E+00	7.526E+00	9.159E+00	1.633E+00	0.194

#### NOTES ON BOOTSTRAPPED ESTIMATES

- The bootstrapped results shown were computed from 1000 trials.
- These results are conditional on the constraints placed upon MSY and  $r$  in the input file (ASPIIC.INP).
- All bootstrapped intervals are approximate. The statistical literature recommends using at least 1000 trials for accurate 95% intervals. The 80% intervals used by ASPIIC should require fewer trials for equivalent accuracy. Using at least 500 trials is recommended.
- Estimates of bias and relative bias are known to be highly imprecise and may not be informative.

Trials replaced for lack of convergence:

0

Trials replaced for MSY out-of-bounds:

0

Trials replaced for  $r$  out-of-bounds:

0

Residual-adjustment factor:

1.0408

**APPENDIX A2: TABLE A5.6 SUPPLEMENT.**

Northern shrimp samples relative to landings per month (in numbers of samples taken per metric ton). Note: Data for 1999 and 2000 were unavailable for use in this assessment. Blank cells indicate there were no landings during the particular time period.

**Maine**

Year	January (n/mt)	February (n/mt)	March (n/mt)	April (n/mt)
1985	0	1	1	0
1986	1	0	0	1
1987	1	0	0	0
1988	1	1	2	0
1989	2	1	2	1
1990	1	0	2	0
1991	4	3	3	4
1992	3	2	3	3
1993	6	3	5	1
1994	3	3	4	12
1995	1	1	1	4
1996	2	2	4	8
1997	4	2	6	5
1998	2	2	6	12
2001	9	8	32	45
2002		9	12	
2003	9	6		
2004	5	4	5	
2005	9	7	5	
2006	6	4	12	15

**New Hampshire**

Year	January (n/mt)	February (n/mt)	March (n/mt)	April (n/mt)
1985	3	12	8	0
1986	12	11	21	0
1987	13	7	32	0
1988	9	10	5	0
1989	6	7	0	0
1990	5	4	21	0
1991	9	10	18	0
1992	12	40	14	0
1993	5	4	5	2
1994	3	3	11	0
1995	3	3	4	4
1996	3	2	5	2
1997	3	2	4	4
1998	6	2	3	13
2001	6	17	17	18
2002		12	40	
2003	26	9		
2004	13	7	5	
2005	25	5	11	
2006	20	100	23	71

**Massachusetts**

Year	January (n/mt)	February (n/mt)	March (n/mt)	April (n/mt)
1985	4	3	3	11
1986	0	1	2	2
1987	2	0	1	1
1988	2	2	1	9
1989	4	6	0	2
1990	3	3	2	1
1991	5	4	3	4
1992	4	3	14	0
1993	10	9	18	24
1994	13	3	16	8
1995	9	8	0	0
1996	12	9	9	0
1997	18	20	35	0
1998	23	42	13	0
2001	19	96	21	
2002		107	59	
2003	71	130		
2004	0	81	99	
2005	0	0	105	
2006	12	86	84	

## APPENDIX A3: GOODNESS OF FIT OF CSA (TABLES AND FIGURES)

APPENDIX A3 Table 1. Recruit abundance estimates ( $M = 0.25$ )

Year	NLLS Estimate	Bootstrap Mean	Bootstrap Std Error	C.V. Bootstrap	10th Percentile	90th Percentile
1985	839	820	294.56	0.36	478	1213
1986	855	835	295.28	0.35	495	1217
1987	652	641	243.51	0.38	364	970
1988	510	511	204.92	0.40	276	788
1989	820	807	299.34	0.37	462	1196
1990	803	795	285.49	0.36	459	1186
1991	545	544	213.83	0.39	292	813
1992	406	408	166.62	0.41	226	634
1993	367	366	155.38	0.42	197	565
1994	559	553	211.77	0.38	312	848
1995	913	917	290.10	0.32	569	1296
1996	900	896	259.08	0.29	576	1231
1997	557	568	178.75	0.31	348	808
1998	479	475	136.65	0.29	307	658
1999	357	350	112.54	0.32	213	496
2000	263	263	96.38	0.37	154	393
2001	337	334	117.92	0.35	198	490
2002	265	267	111.80	0.42	143	410
2003	560	547	193.69	0.35	322	810
2004	421	427	175.12	0.41	233	652
2005	938	935	375.37	0.40	534	1427
2006	4330	4275	1609.19	0.38	2452	6432

APPENDIX A3 Table 2. Post-Recruit abundance estimates ( $M = 0.25$ )

Year	NLLS Estimate	Bootstrap Mean	Bootstrap Std Error	C.V. Bootstrap	10th Percentile	90th Percentile
1985	777	775	289.54	0.37	445	1168
1986	949	934	273.58	0.29	604	1289
1987	1089	1061	288.43	0.27	718	1438
1988	984	954	272.11	0.29	635	1309
1989	963	941	264.80	0.28	627	1287
1990	1140	1112	300.84	0.27	753	1519
1991	1126	1098	293.32	0.27	740	1488
1992	1021	999	263.05	0.26	691	1345
1993	881	866	239.67	0.28	586	1178
1994	801	789	221.08	0.28	529	1087
1995	822	808	235.44	0.29	534	1129
1996	816	808	254.64	0.32	492	1140
1997	643	635	188.89	0.30	399	878
1998	322	325	124.62	0.38	182	490
1999	300	299	109.08	0.36	173	444
2000	324	318	103.80	0.33	196	458
2001	275	270	96.56	0.36	156	395
2002	353	347	117.09	0.34	211	499
2003	442	439	130.38	0.30	292	611
2004	681	668	185.97	0.28	447	919
2005	684	679	205.52	0.30	433	946
2006	1058	1052	347.33	0.33	660	1512
2007	4052	4005	1316.26	0.33	2521	5738

APPENDIX A3 Table 3. Recruit abundance estimates ( $M = 0.60$ )

Year	NLLS Estimate	Bootstrap Mean	Bootstrap Std Error	C.V. Bootstrap	10th Percentile	90th Percentile
1985	4238.72	4428.23	3646.27	0.82	1702.56	7908.18
1986	4898.39	5126.95	4279.63	0.83	2024.86	9462.34
1987	3670.55	3795.23	3207.39	0.85	1456.95	6723.02
1988	2767.83	2970.77	2605.99	0.88	1072.24	5388.80
1989	5049.27	5280.75	4474.42	0.85	2048.53	9311.49
1990	4988.84	5239.37	4460.73	0.85	2071.90	9041.27
1991	3141.33	3288.46	2841.46	0.86	1223.68	5880.25
1992	2182.50	2321.71	2046.26	0.88	897.40	4159.60
1993	1853.13	1953.96	1729.16	0.88	692.31	3574.57
1994	2650.96	2762.13	2338.27	0.85	1104.13	4920.22
1995	3430.78	3576.86	2745.81	0.77	1568.28	6260.25
1996	2798.98	2845.07	1919.47	0.67	1351.35	4775.03
1997	1597.03	1694.55	1321.46	0.78	724.53	3031.82
1998	1690.26	1756.19	1349.20	0.77	767.93	3007.46
1999	1488.19	1540.50	1240.52	0.81	626.92	2705.96
2000	1111.27	1178.28	936.20	0.79	452.64	2136.91
2001	1757.00	1880.87	1697.51	0.90	738.74	3375.96
2002	1419.33	1530.07	1416.07	0.93	551.57	2765.84
2003	3005.73	3138.17	2645.99	0.84	1248.40	5526.67
2004	2097.38	2273.75	2056.47	0.90	806.31	4017.99
2005	4906.28	5225.31	4881.67	0.93	1992.26	9484.87
2006	23210.70	24490.90	20847.30	0.85	9173.79	43883.00
2007	28286.10	28915.30	22739.00	0.79	13692.60	50165.40

APPENDIX A3 Table 4. Post-Recruit abundance estimates ( $M = 0.60$ )

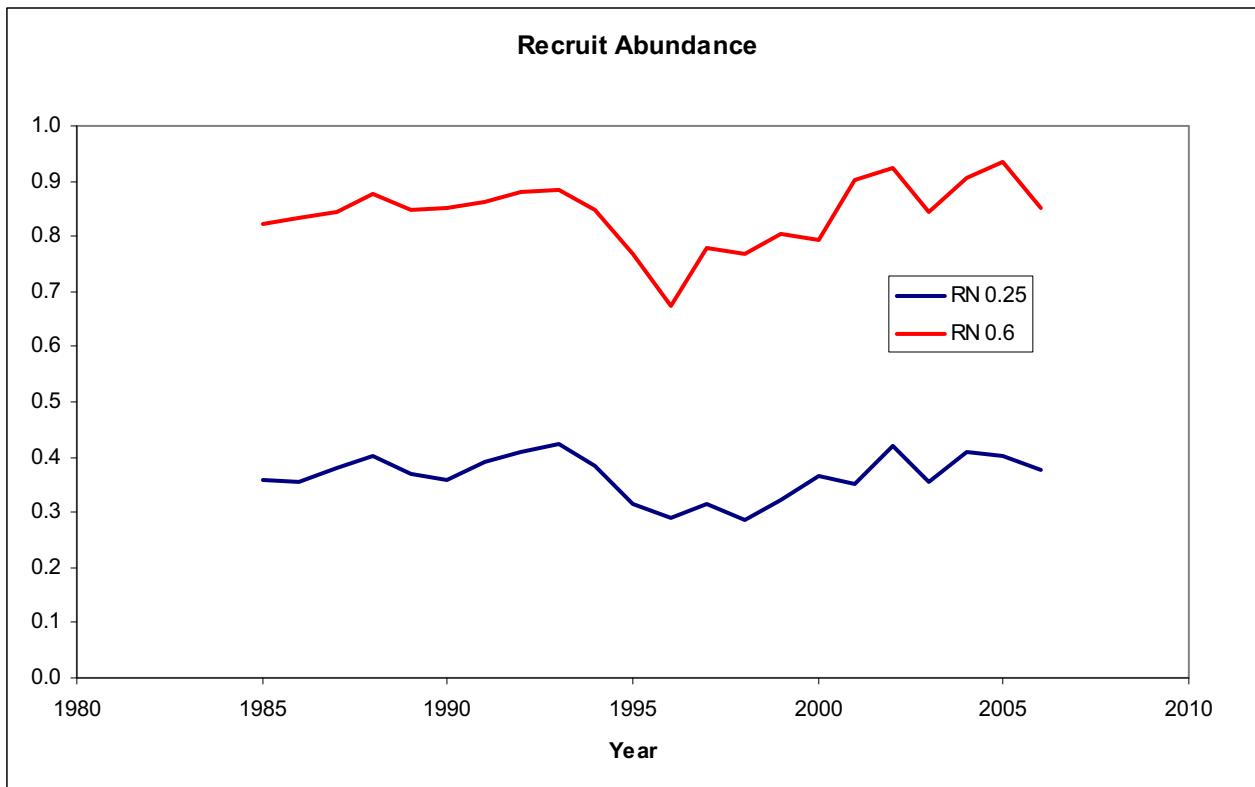
Year	NLLS Estimate	Bootstrap Mean	Bootstrap Std Error	C.V. Bootstrap	10th Percentile	90th Percentile
1985	3877.66	4162.36	3671.46	0.88	1535.93	7657.24
1986	4197.65	4468.20	3712.98	0.83	1822.60	8014.88
1987	4729.13	5013.58	4135.99	0.82	2074.61	8922.21
1988	4300.52	4537.51	3805.79	0.84	1842.66	8257.32
1989	3712.84	3960.93	3368.35	0.85	1613.33	7093.25
1990	4602.19	4873.64	4122.01	0.85	1969.63	8782.58
1991	4941.78	5241.18	4491.13	0.86	2131.77	9117.56
1992	4202.98	4457.38	3796.79	0.85	1850.14	7862.35
1993	3313.43	3537.10	3069.11	0.87	1434.43	6313.46
1994	2693.66	2877.44	2522.74	0.88	1157.71	5174.66
1995	2736.52	2906.31	2549.99	0.88	1181.29	5105.76
1996	2938.75	3130.36	2730.21	0.87	1255.78	5567.70
1997	2571.36	2725.76	2370.29	0.87	1081.30	4926.54
1998	1775.25	1935.27	1902.57	0.98	646.18	3680.45
1999	1631.26	1766.48	1684.95	0.95	618.57	3379.26
2000	1555.73	1665.01	1531.71	0.92	620.75	3032.61
2001	1311.77	1414.73	1275.99	0.90	505.23	2644.25
2002	1581.68	1710.29	1560.96	0.91	638.30	3152.76
2003	1614.62	1747.26	1552.90	0.89	695.80	3061.64
2004	2452.89	2601.67	2214.58	0.85	1079.55	4654.91
2005	2352.63	2536.88	2236.13	0.88	1005.88	4497.34
2006	3813.38	4096.41	3773.41	0.92	1617.87	7356.06
2007	14711.80	15574.40	13202.10	0.85	6081.03	27822.50

APPENDIX A3 Table 5. Estimates of Fishing Mortality ( $M = 0.25$ )

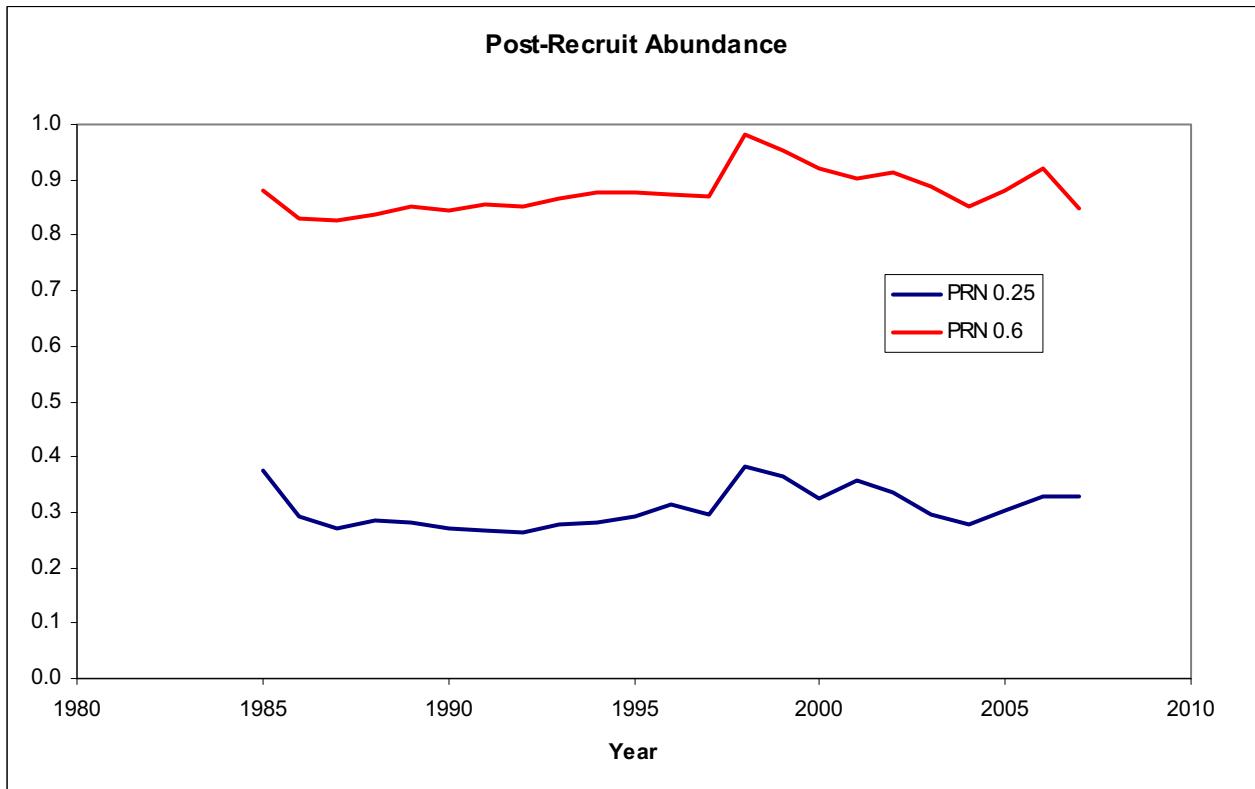
Year	NLLS Estimate	Bootstrap Mean	Bootstrap Std Error	C.V. Bootstrap	10th Percentile	90th Percentile
1985	0.28	0.30	0.08	0.26	0.21	0.41
1986	0.26	0.28	0.07	0.25	0.20	0.36
1987	0.32	0.35	0.09	0.25	0.25	0.46
1988	0.19	0.21	0.05	0.26	0.14	0.28
1989	0.20	0.21	0.05	0.25	0.15	0.28
1990	0.30	0.32	0.08	0.24	0.23	0.42
1991	0.24	0.26	0.06	0.24	0.19	0.34
1992	0.23	0.25	0.06	0.25	0.18	0.33
1993	0.19	0.21	0.05	0.26	0.15	0.28
1994	0.25	0.27	0.07	0.27	0.19	0.37
1995	0.50	0.54	0.14	0.26	0.39	0.73
1996	0.73	0.77	0.17	0.22	0.58	1.00
1997	1.06	1.12	0.27	0.24	0.81	1.47
1998	0.73	0.78	0.20	0.26	0.55	1.05
1999	0.46	0.50	0.13	0.26	0.34	0.67
2000	0.51	0.56	0.16	0.28	0.38	0.77
2001	0.30	0.33	0.10	0.29	0.22	0.46
2002	0.08	0.09	0.03	0.28	0.06	0.13
2003	0.14	0.15	0.04	0.26	0.10	0.20
2004	0.23	0.25	0.07	0.28	0.17	0.34
2005	0.18	0.19	0.06	0.30	0.13	0.27
2006	0.03	0.04	0.01	0.32	0.02	0.06

APPENDIX A3 Table 6. Estimates of Fishing Mortality ( $M = 0.60$ )

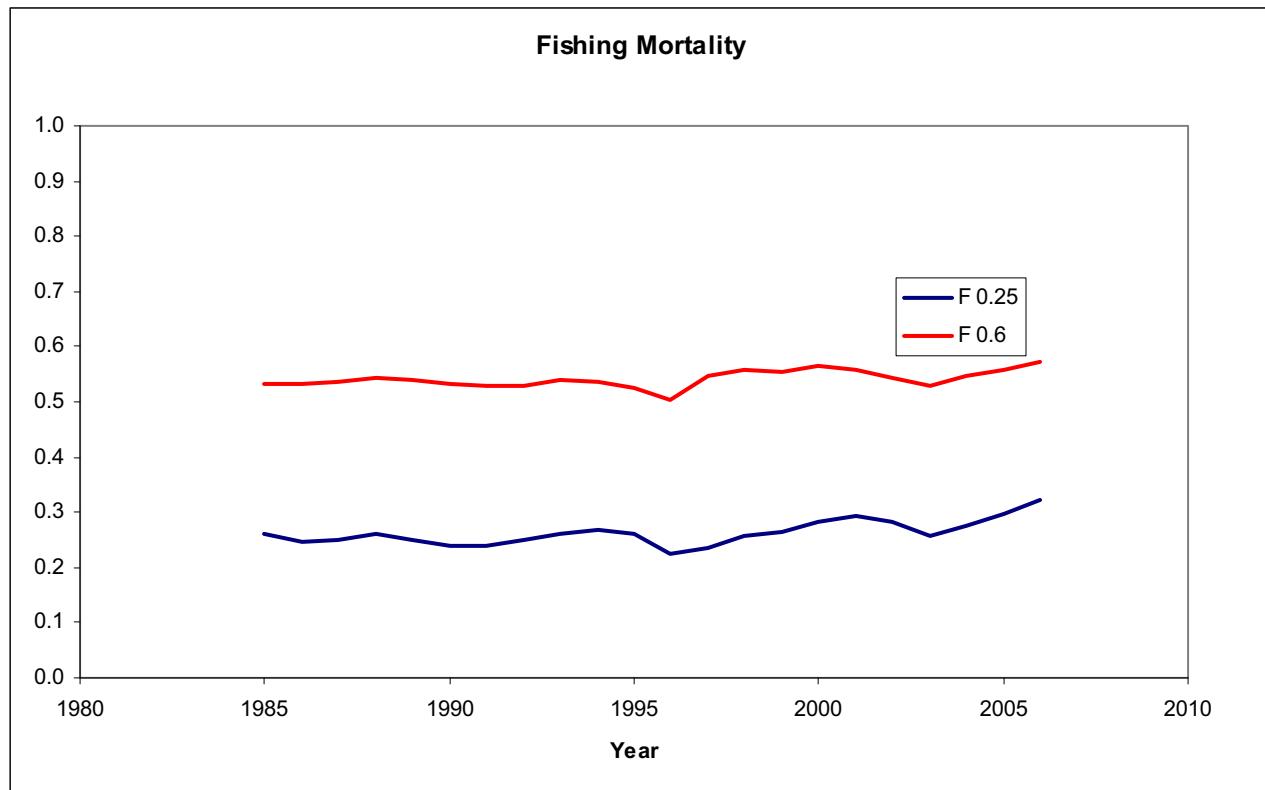
Year	NLLS Estimate	Bootstrap Mean	Bootstrap Std Error	C.V. Bootstrap	10th Percentile	90th Percentile
1985	0.06	0.07	0.04	0.53	0.03	0.12
1986	0.05	0.06	0.03	0.53	0.02	0.11
1987	0.07	0.08	0.04	0.54	0.03	0.14
1988	0.04	0.05	0.03	0.54	0.02	0.09
1989	0.04	0.05	0.03	0.54	0.02	0.09
1990	0.06	0.07	0.04	0.53	0.03	0.13
1991	0.05	0.06	0.03	0.53	0.02	0.11
1992	0.06	0.07	0.03	0.53	0.02	0.11
1993	0.05	0.06	0.03	0.54	0.02	0.10
1994	0.07	0.08	0.04	0.54	0.03	0.14
1995	0.14	0.17	0.09	0.52	0.06	0.28
1996	0.20	0.24	0.12	0.50	0.09	0.38
1997	0.25	0.31	0.17	0.55	0.10	0.53
1998	0.15	0.19	0.10	0.56	0.06	0.33
1999	0.10	0.12	0.06	0.55	0.04	0.20
2000	0.11	0.13	0.08	0.56	0.04	0.23
2001	0.06	0.08	0.04	0.56	0.03	0.13
2002	0.02	0.02	0.01	0.54	0.01	0.04
2003	0.03	0.04	0.02	0.53	0.01	0.07
2004	0.06	0.07	0.04	0.55	0.03	0.12
2005	0.04	0.05	0.03	0.56	0.02	0.09
2006	0.01	0.01	0.01	0.57	0.00	0.02



APPENDIX A3 Figure 1. CVs of recruitment abundance from CSA



APPENDIX A3 Figure 2. CVs of post-recruit abundance from CSA



APPENDIX A3 Figure 3. CVs of fishing mortality from CSA

#### **APPENDIX A4: Q RATIOS USED IN CSA**

Survey Year	sr/sn
1984	0.878
1985	0.891
1986	0.929
1987	1.000
1988	0.727
1989	0.925
1990	0.953
1991	1.000
1992	1.000
1993	1.000
1994	0.838
1995	1.000
1996	0.998
1997	0.925
1998	0.917
1999	0.950
2000	1.000
2001	0.923
2002	1.000
2003	0.852
2004	0.715
2005	0.628
2006	0.911

Selectivity ratio of recruits/post recruits used in the current CSA analyses.

## APPENDIX A5: BUBBLE PLOTS OF SUMMER SHRIMP SURVEY CATCHES

Northern Shrimp Summer Survey catches from 1985 – 2006 (two year intervals). Strata 1, 3, 5, 6, 7, and 8 are used in the assessment.

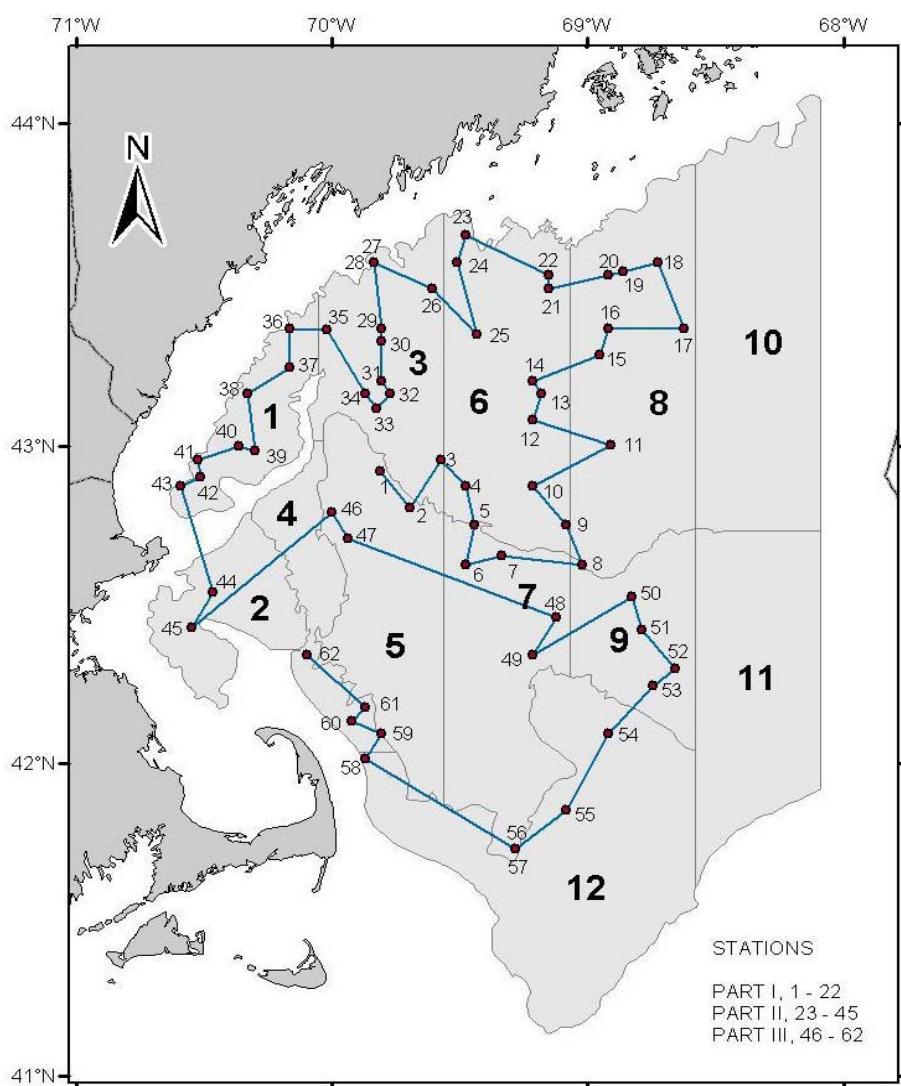
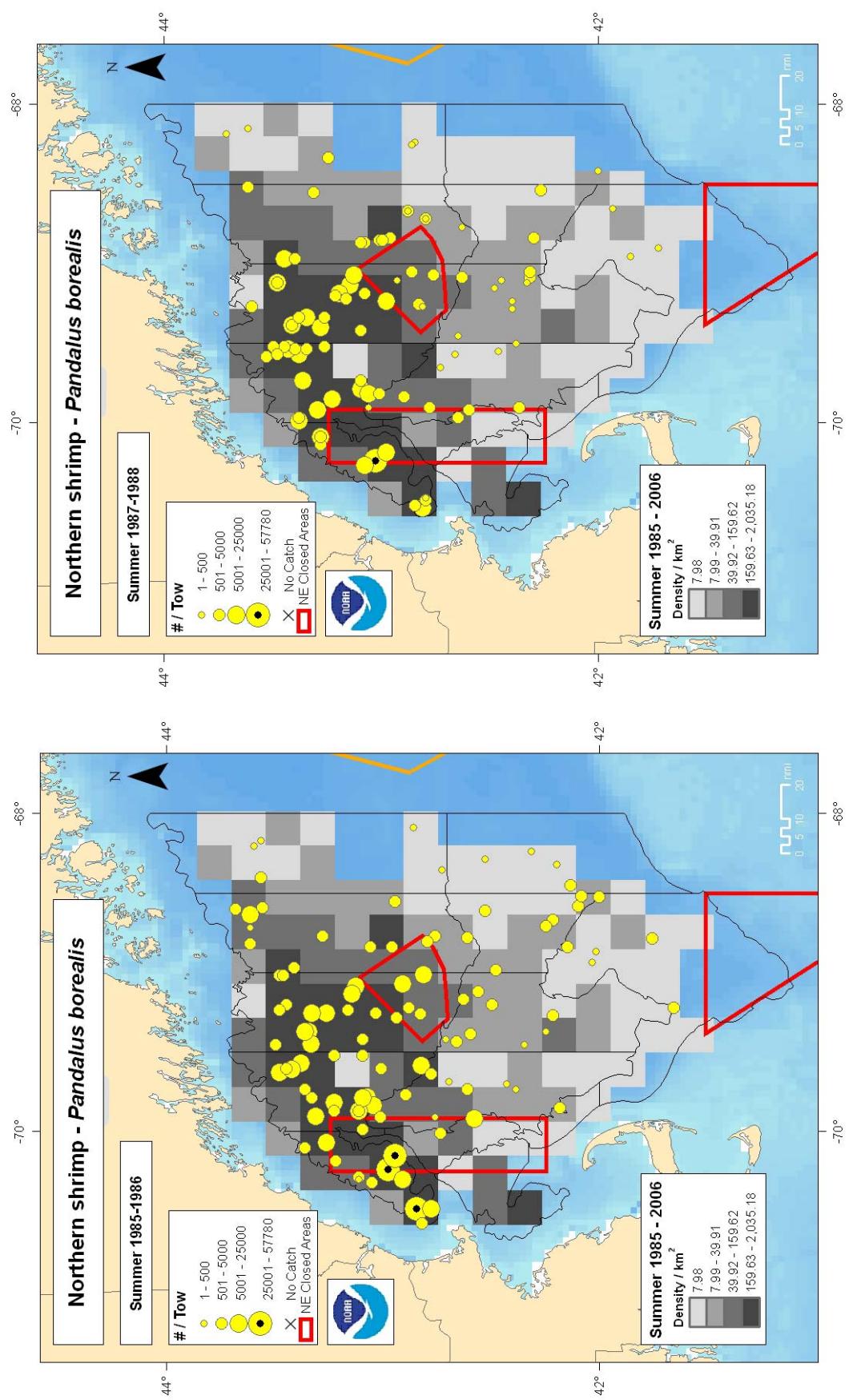
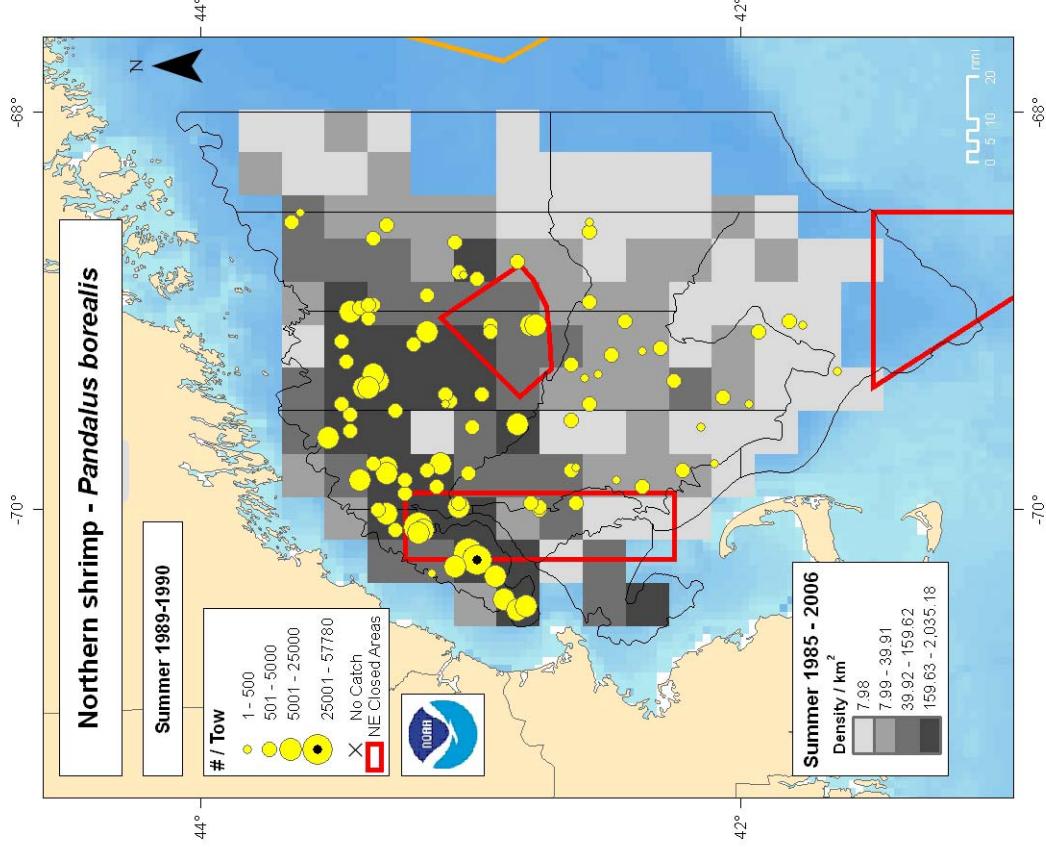
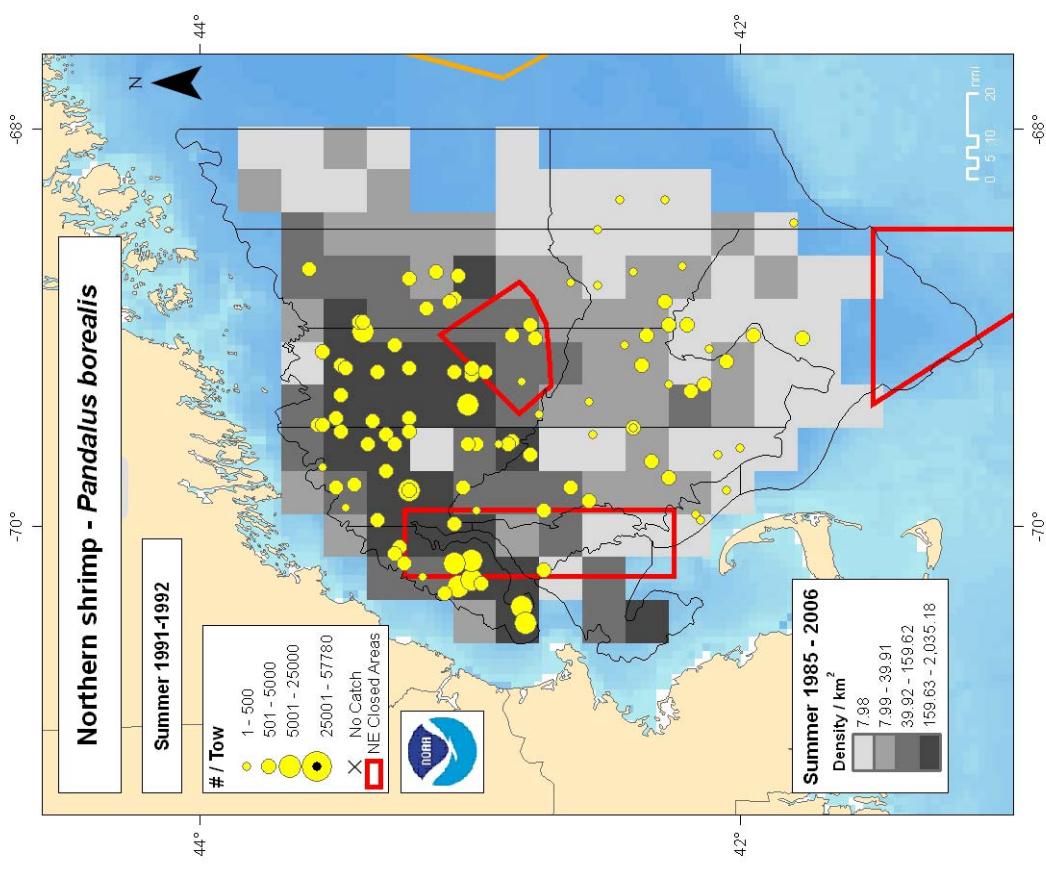


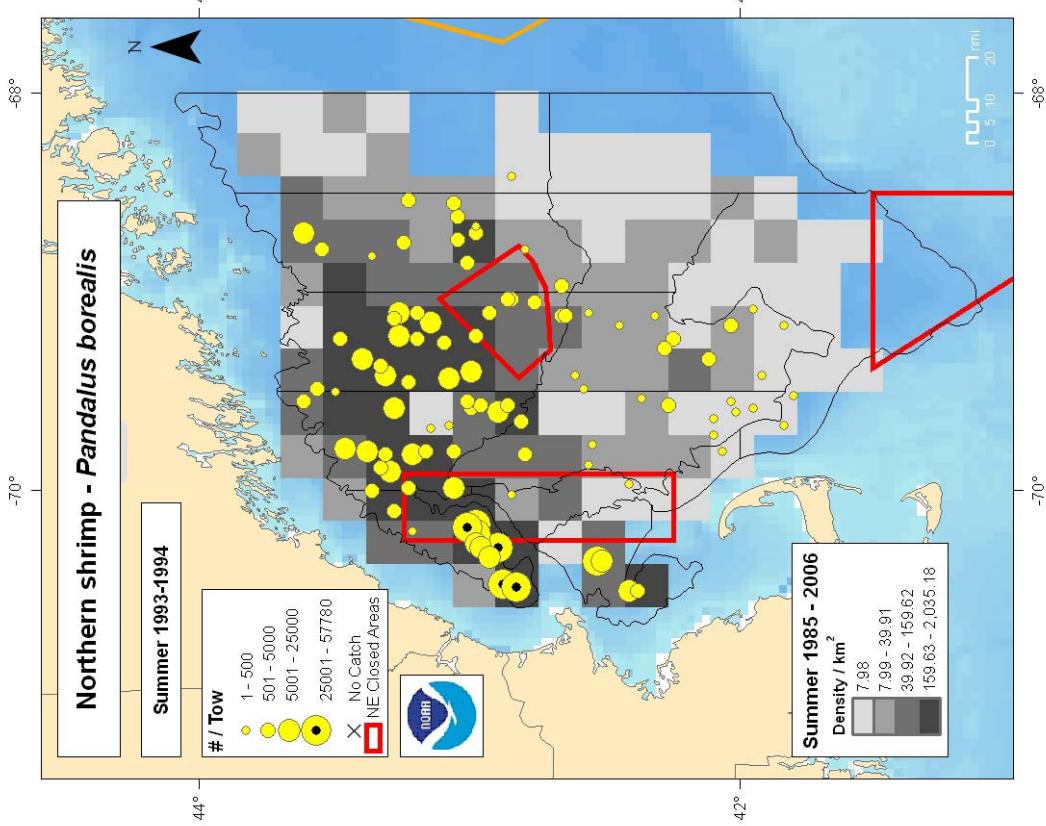
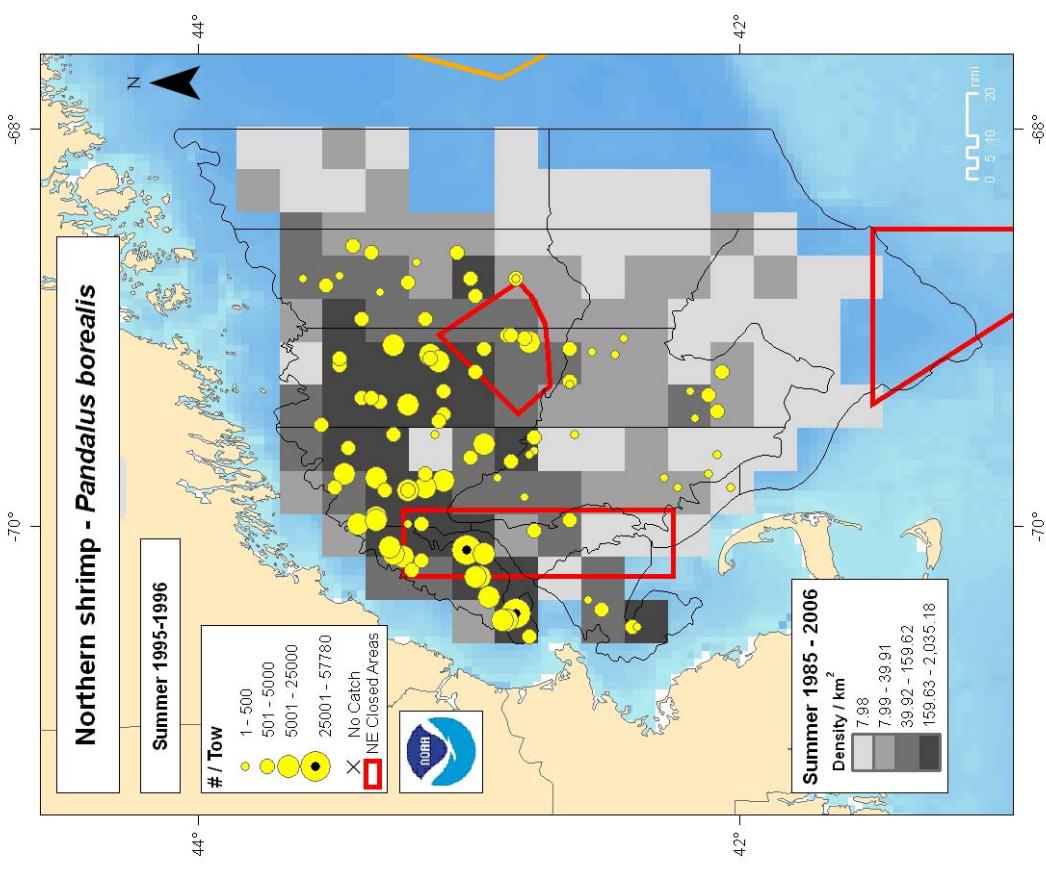
Figure 2. Trawl hauls made from the R/V GLORIA MICHELLE, during National Marine Fisheries Service, Northeast Fisheries Science Center summer northern shrimp survey (03 - 07), July 27 - August 8, 2003.

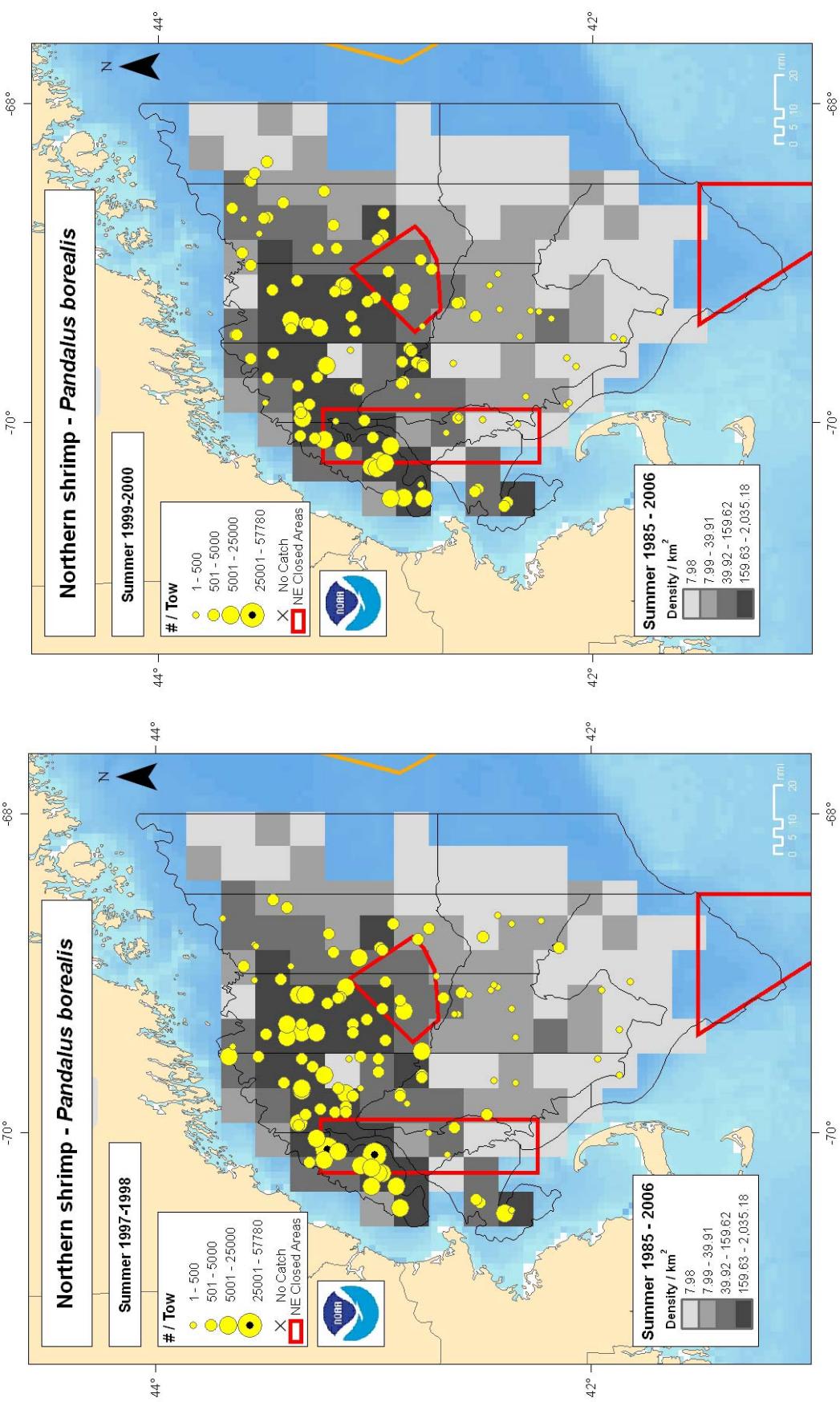


Relative species abundance and distribution from NEFSC bottom trawl survey by time block and relative species density for the full time series.

Relative species abundance and distribution from NEFSC bottom trawl survey by time block and relative species density for the full time series.

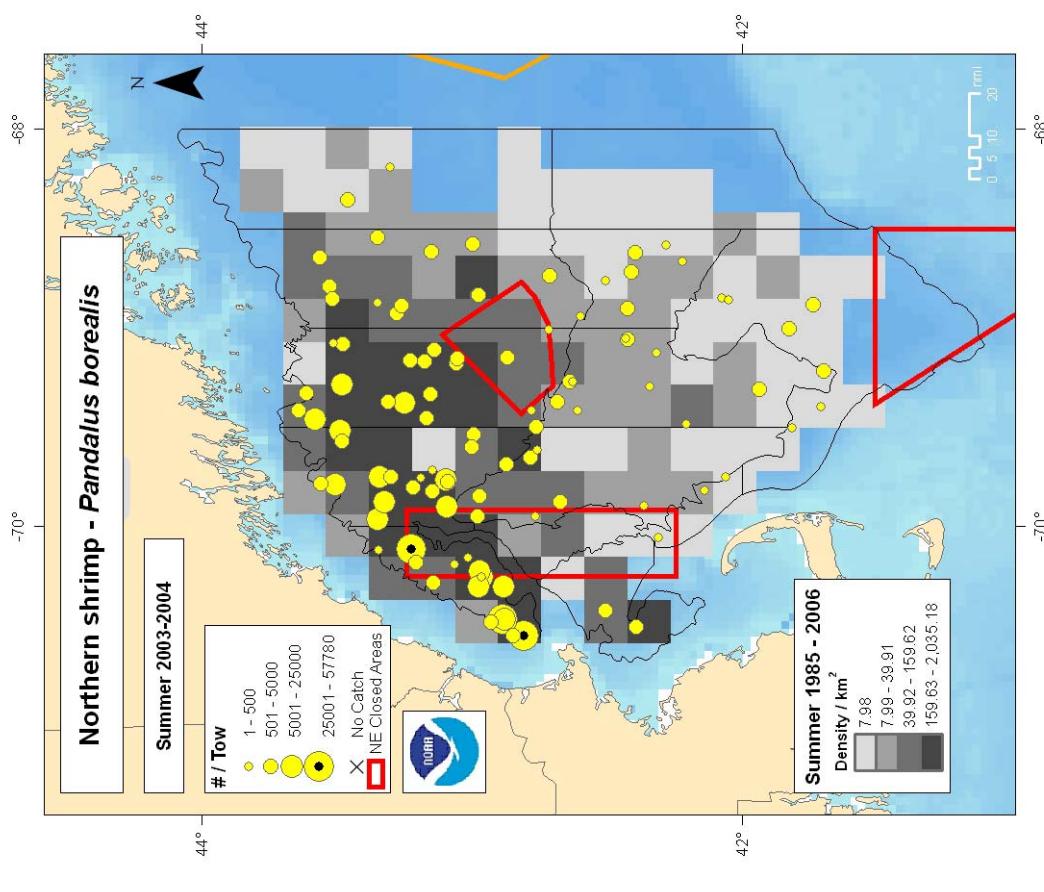




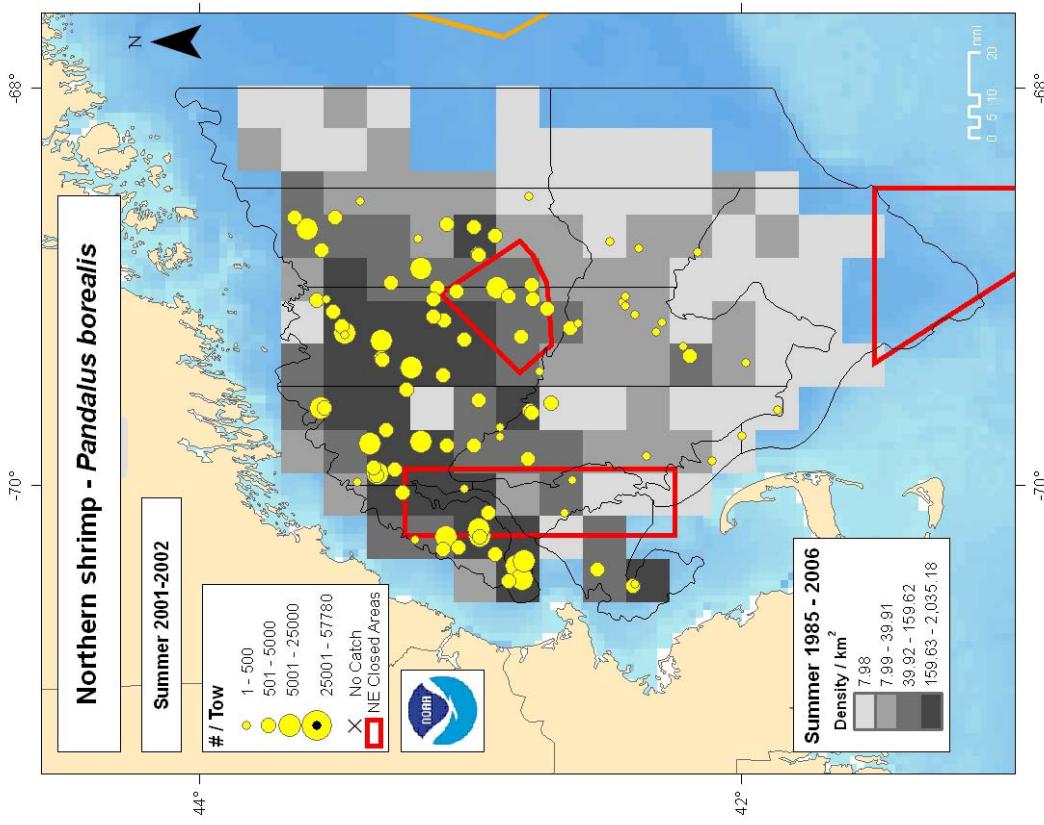


Relative species abundance and distribution from NEFSC bottom trawl survey by time block and relative species density for the full time series.

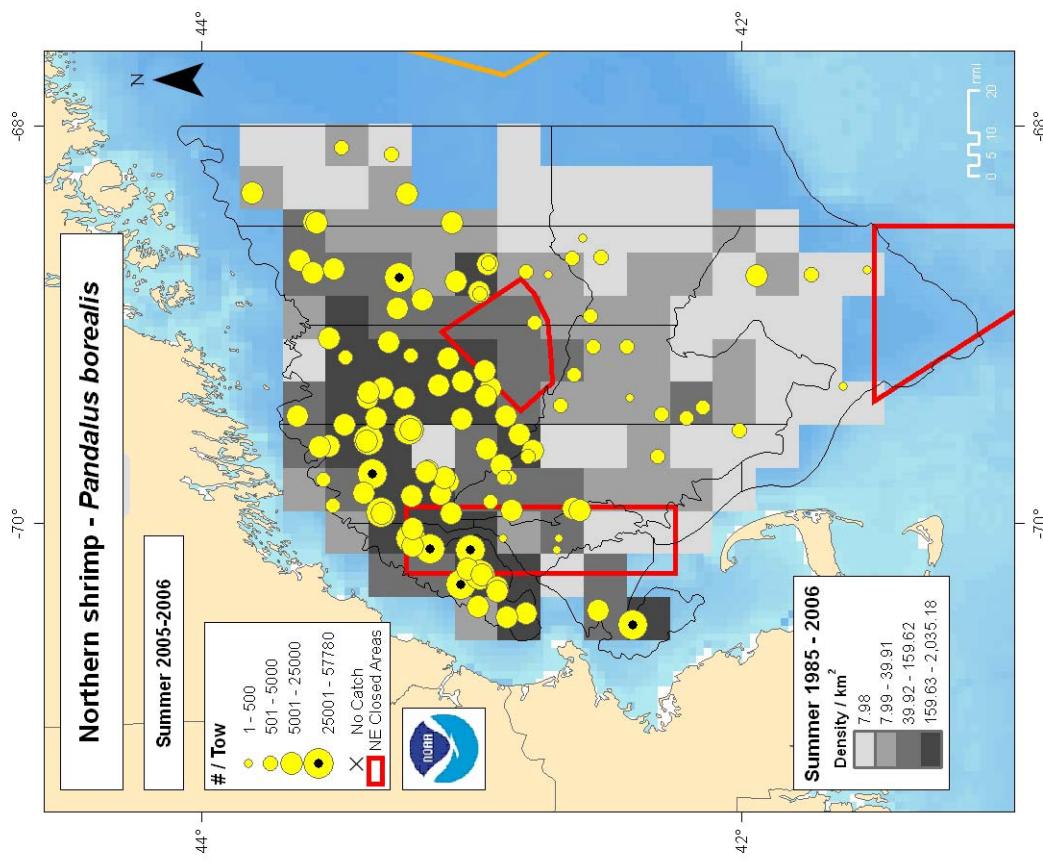
Relative species abundance and distribution from NEFSC bottom trawl survey by time block and relative species density for the full time series.



Relative species abundance and distribution from NEFSC bottom trawl survey by time block and relative species density for the full time series.



Relative species abundance and distribution from NEFSC bottom trawl survey by time block and relative species density for the full time series.



Relative species abundance and distribution from NEFSC bottom trawl survey by time block and relative species density for the full time series.

## **APPENDIX A6: NSTC RESEARCH PRIORITIES, BENEFITS, AND RESOURCES NEEDED**

In order of importance from highest to lower priority:

- 1) Continue to examine values of natural mortality, M. Revisit older work that established  $M=0.25$  (Rinaldo, Clark). Estimate M from year-sex-stage-class ratio data from surveys. Examine predation data and other environmental factors. Investigate possible annual variation in M. Benefits: better understanding of ecological role; more accurate model estimates of F and B. Resources required: several person-months for data analysis.
- 2) Examine several survey issues: recalculate fall survey indices for shrimp, eliminating the nighttime tows; verify that summer survey tow bottom tending times have been consistent; investigate survey design for optimal number and stratification of tows; explore ways to quantify age 1 and younger shrimp. Benefits: more accurate survey indices for model estimates of F and B; earlier estimates of future recruitment. Resources required: several person-months for data analysis, and further research into collecting small shrimp, possibly development of a trap survey.
- 3) Explore the stock-recruitment relationship and the impact of environmental factors on recruitment. Consider impacts of climate change. Benefits: better understanding of natural population fluctuations; better modeling of population dynamics. Resources required: many person-months for data analysis.
- 4) Better characterize shrimp discards in the shrimp and other small-mesh fisheries. Benefits: more accurate estimate of shrimp removals for modeling. Resources required: more at-sea sampling; several person-months for analysis of existing VTR and sea-sampling databases.
- 5) Recover/convert older port sampling data to useable database. Benefit: Data will be available for future queries re fishing locations, catch rates, size distributions, sex stage and timing of egg hatch, other shrimp species, etc. Resources required: several person-months for data entry, uploads, and proofing.

## B. ASSESSMENT FOR ATLANTIC SEA SCALLOPS

*(Placopecten magellanicus)*

### B1.0 CONTRIBUTORS

Invertebrate Subcommittee<sup>1</sup>

### B2.0 TERMS OF REFERENCE

1. Characterize the commercial catch, effort and CPUE, including descriptions of landings and discards of that species.
2. Estimate fishing mortality, spawning stock biomass, and total stock biomass for the current year and characterize the uncertainty of those estimates. If possible, also include estimates for earlier years.
3. Either update or redefine biological reference points (BRPs; proxies for  $B_{MSY}$  and  $F_{MSY}$ ), as appropriate. Comment on the scientific adequacy of existing and redefined BRPs.
4. Evaluate current stock status with respect to the existing BRPs, as well as with respect to updated or redefined BRPs (from TOR 3).
5. Recommend modeling approaches and data to use for conducting single and multi-year stock projections, and for computing TACs or TALs.
6. If possible,
  - a. provide numerical examples of short term projections (2-3 years) of biomass and fishing mortality rate, and characterize their uncertainty, under various TAC/F strategies and
  - b. compare projected stock status to existing rebuilding or recovery schedules, as appropriate.
7. Review, evaluate and report on the status of the SARC/Working Group Research Recommendations offered in recent SARC reviewed assessments.

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<sup>1</sup> Meetings and members of the Invertebrate Subcommittee who helped prepare this assessment are listed in Appendix B1.

## B3.0 EXECUTIVE SUMMARY

### B3.1 TOR 1. Characterize the commercial catch, effort and CPUE, including descriptions of landings and discards of that species. (Completed – Section 4)

U.S. sea scallop landings averaged about 26,000 mt meats during 2002-2006, about twice their long-term average. Fishing effort reached its maximum in 1991 (at about 52,000 days absent), and then declined during the 1990s so that effort in 1999 was less than half that in 1991. Effort has been increasing in recent years, primarily due to increased landings and effort in the open access general category (day boat) sector. Landings per unit effort (LPUE) showed general declines from the mid-1960s through the mid-1990s, with brief occasional increases due to strong recruitment. LPUE more than quadrupled between 1998 and 2001, and remained high during 2001-2006. Discards of sea scallops was unusually high during 2001-2004, averaging about 10% of landings (by weight), but declined during 2005-2006, probably due to changes in gear regulations that reduced catches of small individuals. Sea scallops are occasionally caught and discarded in other fisheries such as the *Loligo* squid and summer flounder fisheries but the overall discards in other fisheries is small relative to total sea scallop landings.

### B3.2 TOR 2. Estimate fishing mortality, spawning stock biomass, and total stock biomass for the current year and characterize the uncertainty of those estimates. If possible, also include estimates for earlier years. Completed (Section 5).

A dynamic size-based stock assessment model (CASA) was used as the primary model for sea scallops. This model was introduced in the previous benchmark sea scallop assessment but not used for estimation purposes due to its preliminary nature at that time. CASA was used in this assessment to estimate fishing mortality, (spawning) stock biomass and egg production.

Data used in CASA included commercial catch, LPUE, and commercial shell height compositions, the NMFS sea scallop and winter trawl surveys, the SMAST (School for Marine Sciences and Technology, University of Massachusetts, Dartmouth) small camera video survey, growth increment data from scallop shells, and shell height/meat weight data adjusted to take into account commercial practices and seasonality. Fishing mortality was also estimated using the rescaled  $F$  method employed in the last several assessments. The CASA and rescaled  $F$  methods gave similar results, especially for the most recent years.

The sea scallop stock was assessed in two components (Mid-Atlantic Bight and Georges Bank) separately and then combined. Estimates of fishing mortality were made from 1975-2006 in the Mid-Atlantic, and from 1982-2006 in Georges Bank and in the whole stock. Whole stock fishing mortality gradually increased during the 1980s, and peaked in 1992 at  $F = 1.3$ . Fishing mortality has generally declined afterwards, and the estimated fishing mortality  $F = 0.23$  in 2006 was the lowest in the 1982-2006 time series.

Spawning stock biomass gradually increased from around 20,000 mt meats during 1982-1983 to a peak of 37,000 mt in 1990, and then declined to less than 17,000 mt meats by 1993. Biomass has been increasing since then, and the estimated 2006 biomass of 166,200 mt meats is the highest in the 1982-2006 time series.

Possible mild retrospective patterns were observed in the model in both regions, but not in the stock as a whole because the regional retrospectives were in different directions. CASA model estimates were reasonably precise: 95% confidence intervals for 2006 fishing mortality and spawning stock biomass were (0.17,0.32) and (152,182) thousands mt meats, respectively.

**B3.3 TOR 3. Either update or redefine biological reference points (BRPs; proxies for  $B_{MSY}$  and  $F_{MSY}$ ), as appropriate. Comment on the scientific adequacy of existing and redefined BRPs. Completed (Section 6).**

The per recruit reference points  $F_{MAX}$  and biomass at  $F_{MAX}$  that are used as proxies for  $F_{MSY}$  and  $B_{MSY}$  were updated in this assessment based on new growth information and changes in fishery selectivity, using the CASA model. The new recommended fishing mortality threshold is 0.29, compared to the current reference point of 0.24. The new recommended biomass target is 108.6 thousand mt meats, and the recommended biomass threshold is half the biomass target, or 54.3 thousand mt meats. The current biomass reference points are a target of 5.6 kg/tow in the NEFSC sea scallop survey, adjusted for the assumed selectivity of the liner as in previous assessments, and a threshold of 2.8 kg/tow (adjusted).

The changes in fishery selectivity and new estimates of growth make updated yield per recruit curves flatter than previous curves so that  $F_{MAX}$  is more difficult estimate precisely and sensitive to assumption. In addition, the spatial variability in fishing mortality in the sea scallop fishery tends to cause per recruit reference points to overestimate the true (numbers-weighted) fishing mortality that maximizes yield per recruit. While this assessment recommends adoption of the new reference points, it also recommends that different types of biological reference points be considered for the next assessment.

**B3.4 TOR 4. Evaluate current stock status with respect to the existing BRPs, as well as with respect to updated or redefined BRPs (from TOR 3). Completed (Section 7).**

The U.S. sea scallop stock is not overfished and overfishing is not occurring, under both the existing and proposed new BRPs, and using the new and previous method of estimating fishing mortality. Fishing mortality in 2006 was  $F=0.23$  using the CASA model, and 0.20 using the rescaled  $F$  approach. Both of these figures are below the current overfishing threshold of 0.24, and the new proposed overfishing threshold of 0.29. Stock biomass was estimated in 2006 as 166.2 thousand mt, which is above the proposed biomass target of 108.6 thousand mt meats and the new biomass threshold of 54.3 thousand mt meats. Adjusted NEFSC survey biomass in 2006 was 7.3 kg/tow, above the current biomass target of 5.6 kg/tow, and the current biomass threshold of 2.8 kg/tow.

**B3.5 TOR 5,6. Recommend modeling approaches and data to use for conducting single and multi-year stock projections, and for computing TACs or TALs.**

*If possible, provide numerical examples of short term projections (2-3 years) of biomass and fishing mortality rate, and characterize their uncertainty, under various TAC/F strategies and compare projected stock status to existing rebuilding or recovery schedules, as appropriate.* Completed (Section 8)

The recommended projection model is spatially explicit and accommodates differences among regions in recruitment, growth, initial size structure, shell height/meat weight relationships, management approach (open vs. closed areas and catch quota vs. limits on fishing effort), intensity of fishing effort, and other factors. Two example short-term projections were conducted, both of which forecast modest increases in stock biomass and landings during 2007-2009. Sea scallop stock biomass is above its biomass target and not subject to a rebuilding or recovery plan.

**B3.6 TOR 7. Review, evaluate and report on the status of the SARC/Working Group  
Research Recommendations offered in recent SARC reviewed assessments.  
Completed (section 9)**

Collaborators made substantial progress on a number of important research recommendations since the last assessment. In particular, new growth and shell height/meat weight data and models were incorporated into the assessment, estimates of rock chain adjustment factors for survey data as well as dredge selectivity estimates were improved, the CASA stock assessment model was tested, improved and used to estimate fishing mortality and biomass for status-determination purposes, and results from collaborative research programs (i.e. video surveys and selectivity studies) were integrated into assessment calculations.

**B4.0 INTRODUCTION AND LIFE HISTORY**

The Atlantic sea scallop, *Placopecten magellanicus*, is a bivalve mollusk that occurs on the eastern North American continental shelf. Major aggregations in US waters occur in the Mid-Atlantic from Virginia to Long Island, on Georges Bank, in the Great South Channel, and in the Gulf of Maine (Hart and Rago 2006). In Georges Bank and the Mid-Atlantic, sea scallops are harvested primarily at depths of 30 to 100 m, while the bulk of landings from the Gulf of Maine are from near-shore relatively shallow waters (< 40 m). This assessment focuses on the two main portions of the sea scallop stock and fishery, Georges Bank in the north and the Mid-Atlantic in the south (Figure B3-1). Results for Georges Bank and the Mid-Atlantic are combined to evaluate the stock as a whole.

US landings during 2003-2006 exceeded 25,000 mt (meats) each year, roughly twice the long-term mean.<sup>2</sup> During 2005, US ex-vessel sea scallop revenues were over \$430 million, which was higher than for any other US fishery. Unusually strong recruitment in the Mid-Atlantic Bight area and increased yield-per-recruit due to effort reduction measures are the key reasons for high recent landings. The mean meat weight of a landed scallop in 2006 was over 25 g, compared to less than 14 g during the early to mid 1990s.

Area closures and reopenings have a strong influence on sea scallop population dynamics (Figure B3-1). Roughly one-half of the productive scallop grounds on Georges Bank and Nantucket Shoals were closed to both groundfish and scallop gear during most of the time since December 1994. Limited openings to allow scallop fishing in closed areas contributed more than half of Georges Bank landings during 1999-2000 and 2004-2006.

In the Mid-Atlantic, there have been four rotational scallop closures. Two areas (Hudson Canyon South and Virginia Beach) were closed in 1998 and then reopened in 2001. Although the small Virginia Beach closure was unsuccessful, scallop biomass built up in Hudson Canyon Closed Area while it was closed, and substantial landings were obtained from Hudson Canyon during 2001-2005. A third rotational closure, the Elephant Trunk area east of Delaware Bay, was closed in 2004, after extremely high densities of small scallops were observed by surveys during 2002 and 2003. The Elephant Trunk area reopened during March 2007 and preliminary reports indicate very high catch levels consistent with expectations and recent survey data. A fourth closed area (Delmarva), directly south of the Elephant Trunk area, was closed in 2007 and is scheduled to reopen in 2010.

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<sup>2</sup> In this assessment, landings and biomass figures are metric tons (mt) of scallop meats, unless otherwise indicated.

## B4.1 Assessment history

Early attempts to model sea scallop population dynamics (NEFSC 1992, 1995, 1997, 1999) were not useful because biomass estimates were less than the minimum swept area biomass obtained from the NEFSC scallop survey (NEFSC 1999). In lieu of model based estimates, fishing mortality in the most recent three assessments (SARC-29,32 and 39; NEFSC 1999, 2001, 2004) was estimated using a simple rescaled  $F$  method which relies heavily on survey and landings data (the rescaled  $F$  and other models were tested by simulation as part of this assessment, see Appendix B12). In the last assessment, a length-structured forward projecting model (CASA based on Sullivan et al. 1990 and Methot 2000) was introduced for preliminary evaluation. The CASA model was refined and tested and was used as the primary model for estimating fishing mortality, biomass and biological reference points for this assessment.

## B4.2 Life History and Distribution

Sea scallops are found in the Northwest Atlantic Ocean from North Carolina to Newfoundland along the continental shelf, typically on sand and gravel bottoms (Hart and Chute 2004). Sea scallops feed by filtering phytoplankton, microzooplankton, and detritus particles. Sexes are separate and fertilization is external. Larvae are planktonic for 4-7 weeks before settling to the bottom. Scallops recruit to the NEFSC survey at 40 mm SH, and to the current commercial fishery at around 90-105 mm SH, although sea scallops between 70-90 mm were common in landings prior to the mid-1990s.<sup>3</sup>

According to Amendment 10 of the Atlantic Sea Scallop Fishery Management Plan, all sea scallops in the US EEZ belong to a single stock. However, the US sea scallop stock can be divided into Georges Bank, Mid-Atlantic, Southern New England, and Gulf of Maine regional components based on survey data, fishery patterns, and other information (NEFSC 2004, Figure B3-1).

## B4.3 Age and growth

Sea scallop growth is traditionally modeled using the von Bertalanffy growth equation. Previous sea scallop assessments used the growth curves estimated by Serchuk et al. (1979), but reviewers expressed concern about lack of recent information on growth. As a result, a scallop growth study was carried out using shells collected during the 2001-2006 NEFSC scallop surveys (see Appendices B2 and 3). Growth curves based on new data have lower  $L_{\infty}$  and higher  $K$  values than previous estimates (see table below and Figure B3-2). The growth parameter  $t_0$  was not estimated and its value is not relevant to this assessment.

Growth parameters for sea scallops

Source	Region	$L_{\infty}$	SE	$K$	SE
<b>New</b>					
	Mid-Atlantic Bight	131.6	0.4	0.495	0.004
	Georges Bank	146.5	0.3	0.375	0.002
<b>Serchuk et al. (1979)</b>					
	Mid-Atlantic Bight	151.84		0.2997	
	Georges Bank	152.46		0.3374	

<sup>3</sup> Scallop body size is measured as shell height (SH, the maximum distance between the umbo and shell margin).

#### B4.4 Maturity and fecundity

Sexual maturity commences at age 2; sea scallops > 40 mm that are reliably detected in the surveys used in this assessment are all considered mature individuals. Although sea scallops reach sexual maturity at a relatively young age, individuals younger than 4 years may contribute little to total egg production (MacDonald and Thompson 1985; NEFSC 1993).

According to MacDonald and Thompson (1985) and McGarvey et al. (1992), annual fecundity (reproductive output, including maturity, spawning frequency, oocyte production, etc.) increases quickly with shell height in sea scallops ( $Eggs=0.0000003396 SH^{4.07}$ ). Spawning generally occurs in late summer or early autumn. DuPaul et al. (1989) found evidence of spring, as well as autumn, spawning in the Mid-Atlantic Bight area. Almeida et al. (1994) and Dibacco et al. (1995) found evidence of limited winter-early spring spawning on Georges Bank.

#### B4.5 Shell height/meat weight relationships

Shell height-meat weight relationships allow conversion from numbers of scallops at a given size to equivalent meat weights. They are expressed in the form  $W=\exp(\alpha+\beta \ln(L))$ , where  $W$  is meat weight in grams and  $L$  is shell height in mm. NEFSC (2001) combined the shell height/meat weight relationships from Serchuk and Rak (1983) with relationships from NEFSC (1999; later published as Lai and Helser 2004) to obtain “blended” estimates that were used in the last two assessments (see table below).

Shell height/meat weight parameters

	$\alpha$	$\beta$	$\gamma$
<b>Mid-Atlantic Bight</b>			
Haynes (1966)	-11.0851	3.0431	
Serchuk & Rak (1983)	-12.1628	3.2539	
NEFSC (2001)	-12.2484	3.2641	
Lai and Helser (2004)	-12.3405	3.2754	
New	-12.01	3.22	
New with depth effect	-9.18	3.18	-0.65
<b>Georges Bank</b>			
Haynes (1966)	-10.8421	2.9490	
Serchuk & Rak (1983)	-11.7656	3.1693	
NEFSC (2001)	-11.6038	3.1221	
Lai and Helser (2004)	-11.4403	3.0734	
New	-10.70	2.94	
New with depth effect	-8.62	2.95	-0.51

New shell height/meat weight data was collected during annual NEFSC sea scallop surveys during July of 2001-2006. Unlike previous studies, where meats were either frozen or brought in live and then weighed on land, meats were weighted at sea just after they were shucked (Appendix B4). Shell height/meat weight relationships based on new data give slightly higher predicted meat weights at a given shell height than NEFSC (2001), and nearly identical values at large shell heights (Figure B3-3).

Meat weights also depend on depth, with meat weights decreasing with depth, probably because of reduced food (phytoplankton) supply. Analysis of the new data indicated that depth had a significant effect on the intercept but not the slope of the shell height/meat weight

relationship. Estimated coefficients for the relationship  $W = \exp(\alpha + \beta \ln(L) + \gamma \ln(D))$ , where  $D$  is depth in meters, are given above (see Figure B3-4). In this assessment, depth-adjusted shell height/meat weight relationships were used to calculate survey biomass information, and traditional relationships were used in the models (CASA and SAMS), where depth is not explicit.

Meat weights for landed scallops may differ from those predicted based on research survey data for a number of reasons. First, the shell height/meat weight relationship varies seasonally, in part due to the reproductive cycle, so that meat weights collected during the NEFSC survey in July and August may differ from those in the rest of year. Additionally, commercial fishers concentrate on speed, and often leave some meat on the shell during shucking (Naidu 1987, Kirkley and DuPaul 1989). On the other hand, meats may gain weight due to water uptake during storage on ice (DuPaul et al. 1990). Finally, fishers may target areas with relatively large meat weight at shell height, and thus may increase commercial meat weights compared to that collected on the research vessel.

Observer and landings data were used to adjust survey shell height/meat relationships for use with the commercial catch. On select tows, observers measured the shell heights of about 100 scallops, and used a graduated cylinder to determine the total volume of the meats sampled after they were shucked in the normal manner by a crew member. Data collected at sea included the number of meats, sample weight, individual shell height measurements and the depth of the tow.

Volumetric measurements by observers were converted into meat weights assuming a conversion factor of 1.05 g/cc (Caddy and Radley-Walters 1972; Smolowitz et al. 1989). The observed average meat weight ( $b$ ) for each observer sample was calculated as the sample weight divided by the number of meats in the sample. In the next step, the predicted average meat weight of the sample ( $p$ ) was computed based on shell height/meat weight/depth relationships from survey data and observer shell height measurements and depth data. Anomalies ( $a$ ) were computed as  $a = (b - p)/p$  and averaged monthly for the Mid-Atlantic Bight and Georges Bank regions to estimate a monthly time series of meat weight anomalies (Figure B3-5). Gains in meat weight during storage on ice are highly variable and uncertain but for this assessment, meats were assumed to have gained by 3% to account for absorption of water during storage and transport when computing numbers of scallops landed (DuPaul et al. 1990).

Negative meat weight anomalies mean that fishery meat weights were less than predicted based on summer sea scallop survey relationships, and vice-versa. The mean anomaly during July in the Mid-Atlantic, and August on Georges Bank were slightly negative, probably due to loss of meat during commercial shucking. Both regions show a marked drop in meat weights between August and October, coinciding with the September-October spawning period, similar to the declines noted in Haynes (1966) and Serchuk and Smolowitz (1989).

Anomalies in the Mid-Atlantic were negative in all months, with the highest meat weight in July when the research vessel samples are taken. The monthly anomalies in Georges Bank were positive only in June and July. The estimated anomalies on Georges Bank for February through May are uncertain because they were based on a limited number of observed trips and samples.

Average monthly height/meat weight anomalies were averaged using the fraction of scallops landed during each month and year to calculate average annual shell height/meat weight anomalies for the commercial fishery, i.e. the dot-product between two vectors,

$$A_y = (L_{y1}, L_{y2}, \dots L_{y12}) \cdot (a_1, a_2, \dots, a_{12})$$

where  $A_y$  represents the annual shell height/meat weight anomaly,  $L_{yk}$  is the fraction of the total (regional) landings in year  $y$  landed in month  $k$ , and  $a_k$  is the average shell height/meat weight anomaly in month  $k$  (Figure B3-6).

In computing numbers of sea scallops landed in the Georges Bank and Mid-Atlantic each year for this assessment, reported landings (mt meats) were divided by the average weight of individuals in the catch. The average weight of individual sea scallops in the catch was calculated based on size composition, shell-height meat relationship, annual anomaly, and adjustment for water absorption.

#### B4.6 Natural mortality estimates from survey “clapper” data

Following previous assessments, (e.g., NEFSC 2001, 2004), the natural mortality rate for sea scallops in this assessment was assumed to be  $M = 0.1 \text{ y}^{-1}$  for scallops with shell heights > 40 mm. This estimate is based on Merrill and Posgay (1964), who estimated  $M$  based on ratios of clappers to live scallops in survey data. Clappers are shells from dead scallops that are still intact (i.e., both halves still connected by the hinge ligament). The basis of the estimate (Dickie 1955) is an assumed balance between the rate at which new clappers are produced ( $M \cdot L$ , where  $L$  is the number of live scallops) and the rate at which clappers separate ( $S \cdot C$ , where  $S$  is the rate at which shell ligaments degrade, and  $C$  is the number of clappers). At equilibrium, the rates of production and loss must be equal, so that  $M \cdot L = S \cdot C$  and:

$$M = C / (L \cdot S).$$

Merrill and Posgay estimated  $S = 1.58 \text{ y}^{-1}$  from the amount of fouling on the interior of clappers. The observed ratio  $C/L$  was about 0.066 and  $M$  was estimated to be about  $0.1 \text{ y}^{-1}$ . MacDonald and Thompson (1986) found a similar overall natural mortality rate, though they suggested that natural mortality increases at larger shell heights.

Clapper ratios were calculated for sea scallops in the Mid-Atlantic and on Georges Bank (Figure B3-7). Clapper ratios for both areas tend to be lower than observed by Merrill and Posgay (1964). It is unclear whether lower clapper ratios for recent years are because of lower natural mortality, differences in the clapper separation rate or changes in clapper catchability due to the change from an unlined to a lined dredge.

There have been recent increases in clapper ratios on Georges Bank. These may represent episodic mortality events, but also could be related to the increases in size/age in the Georges Bank stock. Larger size classes tend to have higher clapper ratios, but it is unclear whether this is due to increased separation time of larger clappers or to increased natural mortality as scallops age, or a combination of both (NEFSC 2004).

#### B5.0 COMMERCIAL AND RECREATIONAL CATCH (TOR 1)

The US sea scallop fishery is conducted mainly by about 350 vessels with limited access permits. However, landings have increased recently from vessels with open access general category permits, which tend to be smaller vessels that fish relatively near-shore beds. General category permits allow landings up to 400 lbs of scallop meats per trip or day (whichever is greater) without requiring a limited-access permit.

Principal ports in the sea scallop fishery are New Bedford, MA, Cape May, NJ, and Hampton Roads, VA. New Bedford style scallop dredges are the main gear type in all regions,

although some scallop vessels use otter trawls in the Mid-Atlantic (Table B4-1). Recreational catch is negligible; a small amount of catch in the Gulf of Maine may be due to recreational divers.

## B5.1 Management history

The sea scallop fishery in the US EEZ is managed under the Atlantic Sea Scallop Fishery Management Plan (FMP), implemented on May 15, 1982. From 1982 to 1994, the primary management control was a minimum average meat weight requirement for landings. Figure B4-1 gives a timeline of all management measures implemented since 1984.

FMP Amendment 4 (NEFMC 1993), implemented in 1994, changed the management strategy from meat count regulation to effort control for the entire US EEZ. Effort controls were included that incrementally restricted days-at-sea (DAS), minimum ring size, and crew limits (Figure B4-1). To comply with legal requirements, Amendment 7 was implemented during 1998 with more stringent days-at-sea limitations and a mortality schedule intended to rebuild the stocks within ten years. Subsequent analyses considering effects of closed areas indicated that the stocks would rebuild with less severe effort reductions than called for in Amendment 7, and the Amendment 7 days-at-sea schedule was modified by Frameworks 12-15. Frameworks 11-13 permitted temporary access to the Georges Bank closed areas in 1999-2001, and Frameworks 14-16 provided for the controlled reopening of the Mid-Atlantic rotational closures.

A new set of regulations was implemented as Amendment 10 during 2004. This amendment formalized an area based management system, with provisions and criteria for new rotational closures, and separate allocations (in days-at-sea or TACs) for reopened closed areas and general open areas. Amendment 10 closed an area offshore of Delaware Bay (the Elephant Trunk area) where high numbers of small scallops were observed in the 2002 and 2003 surveys. This area reopened in 2007, when an area directly to the south was closed (Delmarva closure). Amendment 10 also increased the minimum ring size to 4" and, together with subsequent frameworks, allowed limited reopening of portions of the groundfish closed areas. Limited-access scallop vessels are restricted to a 7-man crew, which tends to limit the processing power of scallop vessels because regulations require most scallops to be shucked at sea.

## B5.2 Landings

Landings from the Georges Bank and the Mid-Atlantic regions dominate the fishery. Proration of total commercial sea scallop landings into Georges Bank, Mid-Atlantic, Southern New England, and Gulf of Maine regions generally followed procedures in Wigley et al. (1998).

Sea scallop landings in the US increased substantially after the mid-1940s (Figure B4-2), with peaks occurring around 1960, 1978, 1990, and 2004. Maximum US landings were 29,109 mt meats during 2004. US Georges Bank landings had peaks during the early 1960's, around 1980 and 1990, but declined precipitously during 1993 and remained low through 1998 (Figure B4-3). Landings in Georges Bank during 1999-2004 were fairly steady, averaging almost 5000 mt annually, and then increased in 2005-2006, primarily due to reopening of portions of the groundfish closed areas to scallop fishing.

Until recently, the Mid-Atlantic landings were lower than those on Georges Bank. Mid-Atlantic landings during 1962-1982 averaged less than 1,800 mt per year. An upward trend in both recruitment and landings has been evident in the Mid-Atlantic since the mid-eighties. Landings peaked in 2004 at 24,494 mt before declining during 2005-2006.

Landings from other areas (Gulf of Maine and Southern New England) are minor in comparison (Table B4-1). Most of the Gulf of Maine stock is assessed and managed by the State of Maine because it is primarily in state waters. Gulf of Maine landings are generally a small percentage of the total. Gulf of Maine landings in 2006 were less than 1% of the total US sea scallop landings. Gulf of Maine landings average 475 mt meats during 1982-2006. Maximum landings in the Gulf of Maine were 1,614 mt during 1980. Southern New England landings averaged 116 mt meats during 1982-2006, with a maximum of 403 mt in 2005.

### B5.3 Fishing effort and LPUE

Regulatory and reporting changes cause uncertainty in comparing trends in fishing effort and catch rates before and after 1994. Prior to 1994, landings and effort data were collected during port interviews by port agents and based on dealer data. Since 1994, commercial data are available as dealer reports (DR) and in vessel trip report (VTR) logbooks. DR data are total landings, and, since 1998, landings by market category. VTR data contain information about area fished, fishing effort, and retained catches of sea scallops. Ability to link DR and VTR reports in data processing is reduced by incomplete data reports and other problems, although there have been significant improvements since 1994 (Wigley et al. 1998). These problems make it difficult to precisely estimate catches and fishing effort, and to prorate catches and fishing effort among areas and gear types.

Landings per unit effort (LPUE) (Figure B4-4) shows a general downward trend from the beginning of the time series to around 1998, with occasional spikes upward probably due to strong recruitment events. LPUE increased considerably from 1999-2003 as the stock recovered; further increases in LPUE on Georges Bank were seen in 2005-2006, due primarily to the reopening of portions of the groundfish closed areas. Note the close correspondence in most years between the LPUE in the Mid-Atlantic and Georges Bank, probably reflecting the mobility of the fleet; if one area has higher catch rates, it is fished harder until the rates are equalized. Although comparisons of LPUE before and after the change in data collection procedures during 1994 need to be made cautiously, there is no clear break in the LPUE trend in 1994.

Nominal fishing effort (days absent) in the US sea scallop fishery generally increased from the mid-1960s to about 1990 (Figure B4-5a). Effort decreased during the 1990s, first because of low catch rates, and later as a result of effort reduction measures. Effort increased during 2000-2006, initially due to reactivation of latent effort among limited access vessels, and more recently due to large increases in the general category fishery.

However, LPUE in the limited access fishery has averaged about 1600 lbs/day in recent years, compared to the 400 lbs per day absent (by regulation) by a general category vessel. Thus, a day absent fishing by a general category vessel does not result in the same amount of mortality as a day absent by a limited access vessel. Adjusted days absent on trips with landings less than 500 lbs was therefore calculated as pounds landed from the trip divided by the mean LPUE of trips landing more than 500 lbs that year (Figure B4-5b). After this adjustment, the increase in effort is much more modest than what would appear based on the unadjusted data.

Another factor affecting the relationship between effort and mortality is the shucking capacity of a seven-man crew. During recent years, vessels have been able to catch scallops faster than they can be shucked. Thus, these vessels often stop actively fishing to allow the crew to shuck and process the catch before putting the gear back into the water. Data from observed (open area) trips indicates that the number of hours actually fished during a day absent dropped

from around 18 in the mid-1990s to 14 or less during the most recent years (Figure B4-6a). The number of hours fished during trips to formerly closed areas is considerably less (Figure B4-6b).

Spatial distribution of effort during 1998-2006 can be assessed using data from vessel monitoring systems (VMS) that are required on most sea scallop vessels (Figure B4-7). Average speed can be inferred as distance traveled between polling events (when location data are transmitted via satellite) divided by time elapsed. Vessels traveling between 1 and 5 knots were assumed to be actively fishing. Higher speeds likely indicate steaming, whereas speeds between 0-1 knots suggest that the vessel is probably processing the catch without fishing, as discussed above. Spatial distribution of fishing effort reflects limited openings of portions of the groundfish closed areas during 1999-2001 and 2004-2006, the rotational closure of the Hudson Canyon South and Virginia Beach areas from 1998-2001, and the Elephant Trunk closure between 2004-2007.

#### B5.4 Discards and discard mortality

Sea scallops are sometimes discarded on directed scallop trips because they are too small to be economically profitable to shuck, or because of high-grading during access area trips to previously closed areas. Ratios of discard to total catch (by weight) were recorded by sea samplers aboard commercial vessels since 1992, though sampling intensity on non-access area trips was low until 2003 (Figure B4-8, Table B4-2).

Discard to kept ratios during scallop fishing were variable. Higher discards ratios tend to be related to strong recruitment, which induce higher numbers of undersized scallops in commercial catches. Discard ratios were low during 2005-2006, probably due to new gear regulations (e.g., 4" rings) that went into effect at the end of 2004. Sea scallop discards in the sea scallop fishery were calculated as the discard to landings ratio for observed sea scallop trips times total sea scallop landings.

Sea scallops are also caught and either landed or discarded in fisheries that target finfish and other invertebrates. To estimate of the scallop bycatch in trawl fisheries for other target species, observer sea sample data from trawl trips targeting other species were used to calculate the ratio of pounds of scallops caught for every pound of the target species landed (observers ask the captain to declare the target species for each tow).

To estimate total sea scallop discard in other directed fisheries, discard to landed ratios were multiplied times total landings of target species from VTR records. The target species on a VTR record was the species with the most landings. This procedure may underestimate discards to some extent because VTR records may not include all landings.

The trawl fisheries with the largest bycatch of scallops for the years analyzed (1994-2006) were longfin squid, summer flounder, yellowtail, haddock, cod and monkfish. No data were available for the clam fisheries due to lack of observer coverage but hydraulic clam dredges used in the clam fishery have minimal bycatch of fish, sea scallops, and other invertebrates. Discards of scallops in other fisheries is negligible compared to landings. In total, an estimated mean of 94 mt meats of scallops were landed and 68 mt meats were discarded per year in 1994-2006 by the six fisheries targeting other species that were most likely to catch them (Table B4-3).

Discarded sea scallops may suffer mortality on deck due to crushing, high temperatures, or desiccation. There may also be mortality after they are thrown back into the water from physiological stress and shock, or from increased predation due to shock and inability to swim or shell damage (Veale et al. 2000, Jenkins and Brand 2001). Murawski and Serchuk (1989) estimated that about 90% of tagged scallops were still living several days after being tagged and

placed back in the water. Total discard mortality (including mortality on deck) is uncertain but has been estimated as 20% in previous assessments (NEFSC 2001, 2004). Though there is considerable uncertainty due to the limited data, an estimate of about 10% (on deck) + 10% (after release) = 20% total mortality of discarded sea scallops seems reasonable.

### B5.5 Incidental Mortality

Scallop dredges likely kill and injure some scallops that are contacted but not caught, primarily due to damage (e.g., crushing) caused to the shells by the dredge. Caddy (1973) estimated that 15-20% of the scallops remaining in the track of a dredge were killed. Murawski and Serchuk (1989) estimated that less than 5% of the scallops remaining in the track of a dredge suffered non-landed mortality. Caddy's study was done in a relatively hard bottom area in Canada, while the Murawski and Serchuk study was in sandy bottom off the coast of New Jersey. It is possible that the difference in indirect mortality estimated in these two studies was due to different bottom types (Murawski and Serchuk 1989).

In order to use the above estimates to relate landed and non-landed fishing mortality in stock assessment calculations, it is necessary to know the efficiency  $e$  of the dredge (the probability that a fully recruited scallop in the path of a dredge is captured). Denote by  $c$  the fraction of scallops that suffer mortality among sea scallops in the path of the dredge but not caught. The best available information indicates that  $c = 0.15\text{--}0.2$  (Caddy 1973), and  $c < 0.05$  (Murawski and Serchuk 1989). The ratio  $R$  of scallops in the path of the dredge that were caught, to those killed but not caught is:

$$R = e/[c(1-e)]$$

If scallops suffer direct (i.e., landed) fishing mortality at rate  $F_L$ , then the rate of indirect (non-landed) fishing mortality will be (Hart 2003):

$$F_I = F_L / R = F_L c (1-e)/e.$$

If, for example, the commercial dredge efficiency  $e$  is 50%, then  $F_I = F_L c$ , where  $F_L$  is the fully recruited fishing mortality rate for sea scallops. Assuming  $c = 0.15$  to  $0.2$  (Caddy 1973) gives  $F_I = 0.15 F_L$  to  $0.2 F_L$ . With  $c < 0.05$  (Murawski and Serchuk 1989)  $F_I < 0.05 F_L$ . For this assessment, incidental mortality was assumed to be  $0.15 F_L$  in Georges Bank and  $0.04 F_L$  in the Mid-Atlantic.

### B5.6 Commercial shell height data

Since most sea scallops are shucked at sea, it has often been difficult to obtain reliable commercial size compositions. Port samples of shells brought in by fishers have been collected, but there are questions about whether the samples were representative of the landings and catch. Port samples taken during the meat count era often appear to be selected for their size rather than being randomly sampled, and the size composition of port samples from 1992-1994 differed considerably from those collected by sea samplers during this same period. For this reason, size compositions from port samples after 1984 when meat count regulations were in force are not used in this assessment.

Sea samplers have collected shell heights of kept scallops from commercial vessels since 1992, and discarded scallops since 1994. Although these data are likely more reliable than that from port sampling, sea sample data must be interpreted cautiously for years prior to 2003 (except for the access area fisheries) due to limited observer coverage. Shell heights from port and sea sampling data indicate that sea scallops between 70-90 mm often made up a considerable portion of the landings during 1975-1998, but sizes selected by the fishery have increased since then, so that scallops less than 90 mm were rarely taken during 2002-2006 (Figure B4-9).

Dealer data (landings) have been reported by market categories (under 10 meats per pound, 10-20 meats per pound, 20-30 meats per pound etc) since 1998 (Figure B4-10). These data also indicate a trend towards larger sea scallops in landings. While nearly half the landings in 1998 were in the smaller market categories (more than 30 meats per pound), nearly 80% of the 2006 landings were in the two largest market categories (10-20 count and under 10 count).

### B5.7 Commercial gear selectivity

New gear regulations, requiring at least 4" rings on dredges with 10" twine tops, were implemented with Amendment 10 in 2004. They were required in the Hudson Canyon South Access Area in July 2004, in the groundfish closure access programs when these opened in November 2004, and in all areas since December 2004. A study was conducted to determine the selectivity of the new gear by towing a commercial dredge side by side with an NEFSC lined sea scallop survey dredge (Yochum 2006; Appendix B5). The new gear has a more gradual selectivity curve that is shifted to the right compared to the gear with 3.5" rings in use during 1996-2004 (Figure B4-11).

### B5.8 Economic trends in the sea scallop fishery

Economic benefits from the sea scallop fishery have increased in recent years providing a larger supply of scallops for the consumers and higher revenue for the fishermen at lower costs. Landings from the northeast sea scallop fishery increased dramatically after 2001, surpassing all levels observed historically (Figure B4-12).<sup>4</sup> Scallop ex-vessel revenue fell to its lowest recorded level of \$92 million during 1998 (Figure B4-13). Since 1998, revenue from scallops has increased steadily each year, exceeding \$440 million in 2005 and \$380 million in 2006.

Historical trends in the sea scallop fishery for three time periods are compared in the table below. The first period, from 1989 to 1992, summarizes the scallop fishery during a period when annual landings averaged above 16,000 mt and revenues averaged \$215 million. During the period from 1993 to 1998, overfishing in the previous years combined with the effort reduction measures and closure of the Georges Bank groundfish areas resulted in a dramatic decline in scallop landings and revenues. The period from 1999 to 2006 corresponds to the rebuilding of the sea scallop biomass and the consequent increase in scallop landings, revenues and exports to historical high levels. The average revenue per year for this period, over \$270 million, was more than double the average revenue of \$116 million per year during 1993-1998.

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<sup>4</sup> Although part of the increase in 2004 was due to some overfishing in the Mid-Atlantic, which is expected to decline in 2005, there is no question that increased scallop landings since 1999 were due primarily to increased scallop biomass.

Summary of economic trends in the scallop fishery (dollar values adjusted for inflation and expressed as 2006 prices)

Data - Annual averages	Period		
	1989-1992	1993-1998	1999-2006
Ex-vessel Price of scallops (\$ per lb.)	4.2	5.8	5.2
Scallop Revenue (\$ million)	215.0	115.9	270.6
Average meat count	37.7	36.5	21.7

There were some significant changes affecting scallop ex-vessel prices and revenues after 1999:

- In the past scallop prices increased when landings declined, and vice-versa. As Figure B4-12 shows, however, both landings and the ex-vessel price of scallops increased after 2001.
- The shifts in landings towards larger scallops that command a higher price was important factor increasing revenues after 1999 (Figure B4-10).
- Scallop revenues in 2005 and 2006 were more than three times higher than in 1994-98.

## B6.0 FISHING MORTALITY AND STOCK BIOMASS (TOR #2)

NEFSC sea scallop survey data used in this assessment to estimate fishing mortality and biomass are from 1982-2006 for Georges Bank and 1975-2006 for the Mid-Atlantic. Sea scallop surveys were conducted by NEFSC in 1975 and annually after 1977 to measure abundance and size composition of sea scallops in the Georges Bank and Mid-Atlantic regions (Figure B5-1). The 1975-1978 surveys used a 3.08 m (10') unlined dredge. A 2.44 m (8') survey dredge with a 4.4 cm (1.75") plastic liner has been used consistently since 1979. The northern edge of Georges Bank was not surveyed until 1982, so survey data for this area are incomplete for this area during 1975-1981.

The *R/V Albatross IV* was used for all NEFSC scallop surveys except during 1990-1993, when the *R/V Oregon* was used instead. Surveys by the *R/V Albatross IV* during 1989 and 1999 were incomplete on Georges Bank. In 1989, the *R/V Oregon* and *R/V Chapman* were used to sample the South Channel and a section of the Southeast Part. Serchuk and Wigley (1989) found no significant differences in catch rates for the *R/V Albatross IV*, *R/V Oregon* and *R/V Chapman* based on a complete randomized block gear experiment (3 vessels x 13 stations=39 tows) in stratum 34.

The *F/V Tradition* was used to complete the 1999 survey on Georges Bank. The *F/V Tradition* towed the standard NMFS scallop survey dredge as well as a New Bedford commercial scallop dredge side by side. For the purposes of computing survey trends, only data from the NEFSC survey dredge was used. NEFSC (2001) found no statistically significant differences in catch rates between the two vessels from 21 comparison stations after adjustments were made for tow path. Therefore, as in previous assessments (e.g., NEFSC 2004), survey indices for the period 1990-93 based on data from the *R/V Oregon* were used without adjustment, and survey dredge tows from the *F/V Tradition* in 1999 were used after adjusting for tow distance.

Calculation of mean numbers of scallops per tow, mean meat weight per tow and variances in this assessment were standard calculations for stratified random surveys (Serchuk and Wigley 1989; Wigley and Serchuk 1996; Smith 1997) with some extensions described below.

## B6.1 Imputed survey data

No valid tows were performed during some years for a few strata. In these cases, survey values for the missing strata were imputed using a generalized linear model (see Appendix B6). Results were very similar to the “borrowing” procedure used in previous assessments. Imputed data were supplied after all post-stratification was completed so that survey data (real or imputed) were available for every stratum assumed in calculations.

## B6.2 Rock chains

Rock chains have been used on the NEFSC sea scallop survey dredge since 2004 in certain hard bottom strata to enhance safety at sea and increase reliability (NEFSC 2004). Preliminary analysis in the last assessment (NEFSC 2004) was augmented by additional gear experiments and statistical analysis (Appendix B9) to estimate rock chain effects on survey data. Results were difficult to interpret because rock chain effects appear to have varied from year to year. However, the best overall estimate was that rock chains increased survey catches on hard grounds by 1.31 times (CV 0.196).

To accommodate rock chain effects in hard bottom areas, survey data collected prior to 2004 from strata 49-52 were multiplied by 1.31 prior to calculating stratified random means for larger areas. Variance due to the rock chain adjustment was accommodated by calculating the variance of the adjusted strata means  $\sigma^2 = 1.32^2 \sigma_n^2 + 0.257^2 n^2$  where  $n$  is the mean catch per tow for the stratum,  $\sigma_n^2$  was the variance for mean catch per tow and  $0.257=1.31*0.196$  was the standard error of the adjustment factor.

## B6.3 Stratum areas and post-stratification

NEFSC shellfish survey stratum areas calculated using GIS by NEFSC (2001) were used in this assessment (Figure B5-1). Relatively high abundance of sea scallops in closed areas makes it necessary to post-stratify survey data by splitting NEFSC shellfish strata that cross open/closed area boundaries. After post-stratification, adjacent strata were grouped into regions corresponding to the various open and closed areas. Finally, in cases where the closed or open portion of an NEFSC survey stratum was very small, it was necessary to combine the small portion with an adjacent stratum to form a new slightly larger stratum (NEFSC 1999).

Rules for splitting strata along open/closed boundaries, assigning small portions to adjacent strata, and grouping strata into regions were the same as in NEFSC (1999) and Table B5-4 in NEFSC 2001), with a few refinements. The Closed Area II region was broken into two new regions by assigning the closed portions of survey strata 6621, 6610 and 6590 in Closed Area II to the new “Closed Area II (South)” region. All other portions of Closed Area II were assigned to the new “Closed Area II (North)” region. This allows the assessment to accommodate disparate population dynamics of the northern and southern areas of Closed Area II. The southern part of Closed Area II was heavily fished in 1999-2000. A very large (1998) year class was observed there during the 2000 and subsequent NMFS scallop surveys. By contrast, the northern portion of Closed Area II has not been fished since December, 1994.

NEFSC (2004) post-stratified the Nantucket Lightship Closed Area by defining a new stratum in the northeast corner of this area. Surveys show considerably higher recruitment and biomass in this area than elsewhere in the Nantucket Lightship area. Extra tows that have been

added to the northeast corner of the Nantucket Lightship Area in surveys during recent years are random with respect to the new stratification scheme and were used to increase the accuracy of abundance estimates.

#### B6.4 Survey dredge selectivity

Beginning in 1979, NEFSC sea scallop surveys used a 2.44-m (8-ft) wide dredge equipped with 5.1-cm (2-in) rings and a 3.8-cm (1.5 in) plastic mesh liner. Serchuk and Smolowitz (1980) compared catches from lined and unlined survey dredges, and found that the unlined dredge caught more large (>75 mm) while the lined dredge retained more small scallops. Other experiments comparing unlined commercial gear with a lined survey dredge found similar apparent reductions in catches of large scallops (NEFSC 2001, 2004; Yochum 2006). Based on these data, NEFSC (1995; 1997) assumed that the efficiency of the lined dredge was greater at small shell heights than at larger ones, and estimated a declining logistic selectivity curve with relatively low selectivity on scallops 60+ mm SH (Figure B5-2). In retrospect, the declining logistic shape of the estimated selectivity curve used in previous assessments was due to using shell height composition data from the unlined dredge in Serchuk and Smolowitz (1980) as a standard in estimating the selectivity of the lined dredge.

Shell height data from SMAST video surveys during 2003-2006 (Appendix B8) were used in this assessment as the standard in re-estimating survey dredge selectivity. The video survey data was particularly useful in this context because video cameras sample sea scallops 40+ mm SH (small camera) and 70+ mm SH (large camera, Appendix B7) with nearly full efficiency. Results (Appendix B8) indicate that the survey dredge has constant selectivity and efficiency for sea scallops 40+ mm SH, corresponding to the 38 mm mesh liner used in the survey dredge. For this reason, no adjustment was made to dredge survey shell height composition or abundance indices in this assessment to accommodate survey dredge selectivity.

The net effect of new assumptions about survey dredge selectivity is to reduce the absolute magnitude of survey abundance indices because the relative abundance of large sea scallops is not artificially increased. More importantly, the relative abundance of small scallops is higher in unadjusted dredge survey composition data. A number of analyses in this assessment are carried out using survey data with and without the selectivity adjustment to link results from new and previous methods. However, survey time series without selectivity adjustments are preferable on technical grounds.

#### B6.5 Non- and fully-recruited survey indices

Following NEFSC (2004), and for comparative purposes, unadjusted dredge survey data were partitioned into non-recruited (not vulnerable to commercial dredges) and fully recruited (completely vulnerable to commercial dredges) groups by applying a commercial 3.5" dredge selectivity function developed by consensus (NEFSC 1995):

$$s_h = \begin{cases} 0 & \text{if } h \leq h_{\min} \\ \frac{h - h_{\min}}{h_{full} - h_{\min}} & \text{if } h_{\min} < h < h_{full} \\ 1 & \text{if } h \geq h_{full} \end{cases}$$

where  $h_{min} = 65$  mm and  $h_{full} = 88$  mm. Note that fishery selectivity has changed over time, and the above curve approximates fishery selectivity during the mid- to late 1990s. Current fishery selectivity has shifted considerably towards larger scallops. However, non- and fully recruited abundance and biomass indices are useful in describing historical trends based on a familiar measure.

## B6.6 Survey abundance and biomass trends

Biomass and abundance trends for the Mid-Atlantic Bight and Georges Bank are presented in Table B5-1 and Figure B5-3. Only random tows were used except in the post-stratified portion of the Nantucket Lightship Area (see above). Variances for strata with zero means were assumed to be zero. Confidence intervals were obtained by bootstrapping (Smith 1997, Figure B5-4).

In the Mid-Atlantic Bight, abundance and biomass were at low levels during 1975-1997, and then increased rapidly during 1998-2003, due to area closures, reduced fishing mortality, changes in fishery selectivity, and strong recruitment. Biomass was relatively stable during 2003 to 2006. In Georges Bank, biomass and abundance increased during 1995-2000 after implementation of closures and effort reduction measures. Abundance and biomass have been modestly declining during recent years, due to poor recruitment and to reopening of portions of the groundfish closed areas. Survey shell height frequencies show a trend to larger shell heights in both regions in recent years, coinciding with the period of increased biomass and abundance and recent recruitment levels (Figure B5-5).

Sea scallop biomass during 1994 (just before the Georges Bank closed areas and effort reduction measures were implemented), and during the most recent 2006 survey (Figure B5-6), shows considerable increases since 1994 in most areas. Increases are especially pronounced in the Georges Bank closed areas and the Elephant Trunk area that was closed during 2004-2007 after exceptional recruitment was observed there.

## B6.7 SMAST video survey

Video survey data collected by the School for Marine Sciences and Technology (SMAST), University of Massachusetts, Dartmouth during May-September of 2003-2006 was used in this assessment. SMAST survey data are counts and shell height measurements from images that were recorded by two types of video camera. The “large” camera was mounted 1.575 m above the bottom in the center of the sampling frame with an effective sampling area of 3.235 m<sup>2</sup> of sea bottom. The “small” camera was mounted 0.7 m above the bottom with an effective sample area of 0.788 m<sup>2</sup>. The effective sampling area includes the area within the sample frame plus an extra 75 mm around the edge of the frame to account for scallops on the edge of the frame. Data from the small camera were used to estimate the size selectivity of the NEFSC scallop dredge (Appendix B8), the large camera (Appendix B7) and as an input to the CASA model. All calculations assume that the small camera has 100% sampling efficiency and flat selectivity for sea scallops 40+ mm SH. Selectivity of the large camera is >90% for scallops 70+ mm SH (Appendix B7).

The SMAST survey is based on a systematic sampling pattern with stations centered on a 5.6 x 5.6 km grid pattern (Stokesbury et al. 2004). Four “quadrats” are sampled at each station and one image taken with each camera is analyzed from each quadrat. The sampling frame and cameras are placed on the bottom at the center of the grid where video footage from the first quadrat is collected. The sampling frame is then raised until the sea floor is no longer visible and

the ship is allowed to drift approximately 50 m in the current before the sampling frame is lowered and video footage from the second quadrat image is collected. The third and fourth images are collected in the same manner. All scallops with any portion of their shell lying within the sample area are counted. Measurements are taken from images projected on a digitizing tablet from all specimens where the umbo and shell margins are clearly visible.

The precision of measurements must be considered in interpreting video shell height data. Based on work in progress (K. Stokesbury, SMAST, pers. comm.) and NEFSC (2004), video shell height measurements from the large camera have a standard deviation of 6.1 mm across a wide range of sea scallop shell heights (see NEFSC 2004, Appendix 1). The standard deviation of measurements from small camera images is assumed in this assessment to be 6.1 mm also for lack of better information.

Video survey data (Tables B5-2 and B5-3) in this assessment are expressed as densities (number m<sup>-2</sup>). Variances for estimated densities are approximated from the variance among station means in each year. Areas sampled in the video survey differ somewhat from the areas sampled in the dredge survey (Figure B5-7). There was some variability in the areas covered during each year (Figure B5-7 and Tables B5-2 and B5-3).

## B6.8 Simple biomass and fishing mortality estimates

The NEFSC survey can be used to obtain an estimate of absolute biomass provided dredge efficiency can be estimated. Commercial dredge efficiency has been estimated at 0.4 – 0.55 in Georges Bank and 0.57 in the Mid-Atlantic (NEFSC 1999, 2001; Gedamke et al. 2004, 2005). Based on the data discussed above, a liner reduces the efficiency of the survey dredge by a factor of about 0.715. Thus, these commercial dredge efficiencies translate into survey dredge efficiencies of about 0.29-0.36 in Georges Bank and 0.41 in the Mid-Atlantic. Comparison of abundances between the NEFSC dredge and SMAST video survey suggests that survey dredge efficiency is about 0.38 on Georges Bank and 0.43 in the Mid-Atlantic (Appendix B8). Based on these figures, the survey swept area biomasses and abundances were calculated using an estimated survey dredge efficiency of 0.36 on Georges Bank and 0.42 in the Mid-Atlantic, and using an estimated mean tow path of 4516 m<sup>2</sup> (NEFSC 2004), using the formula

$$B_y^* = \frac{b_y A}{\alpha e}$$

where  $b_y$  is mean meat weight per tow from the survey in year  $y$ ,  $B_y^*$  is survey stock biomass,  $\alpha$  is the area (nm<sup>2</sup>) swept by a standard tow,  $e$  is efficiency, and  $A$  is the size (nm<sup>2</sup>) of the stock area or region.

Fishing mortality rates  ${}^c F_y$  (biomass-weighted) can then be estimated as:

$${}^c F_y = \frac{C_y}{B_y^*}$$

where  $C_y$  is the meat weight of scallops killed by fishing during the calendar year (Ricker 1975). The survey is conducted during July-August, approximating the average annual biomass. However,  $C_y$  represents reported landings only, and the mortality estimate will be biased low if there were non-reported landings, or if there was non-yield fishing mortality. Additionally, these

estimates are biomass-based mortality rates, which tend to be biased low compared to numbers-based mortality rates, particularly when there is spatial heterogeneity in fishing mortality (Hart 2001). Because of these issues and uncertainty in the estimates of dredge efficiency, this simple fishing mortality estimator is used only as an indicator of fishing mortality trends (NEFSC 1999, 2001, 2004).

### B6.9 Survey-based (two-bin) method

The survey-based approach divides the survey data for each year into two shell height size bins. The first bin approximates the size range of new recruits to the fishery. The second bin includes sea scallops of all larger sizes.

Based on updated growth information, the first bin for Georges Bank consisted of scallops of 80-100.8 mm shell height and the second bin consisted of all scallops larger than 100.8 mm. An 80 mm sea scallop was almost fully recruited to the fishery (except during the most recent period) and will grow to 100.8 mm in one year, according to growth increments from collected shells. For the Mid-Atlantic region, the first bin consisted of 80-98 mm scallops and the second bin consisted of scallops larger than 98 mm. Using these data, survey-based fishing mortalities were calculated:

$${}^s F_t = -\ln\left(\frac{P_{t+1}}{R_t + P_t}\right) - M,$$

where  $R_t$  was the mean population number of scallops per standard survey tow in the first bin (new recruits) during survey year  $t$ , and  $P_t$  was the mean number of scallops per standard survey tow in the second bin. Survey years are the annual period between NEFSC sea scallop surveys (summer to summer).

### B6.10 Rescaled catch-biomass method

Rescaled catch-biomass estimates were used during the last three assessments as the primary estimator of fishing mortality rates (NEFSC 1999, 2001, 2004; Hart 2006), Rescaled survey-based estimates were computed as:

$${}^r F_y = {}^c F_y \left( \frac{{}^s \bar{F}}{{}^c \bar{F}} \right)$$

where average catch-biomass  ${}^c \bar{F}$  and survey-based  ${}^s \bar{F}$  fishing mortality rates were for a time period of many years that contains year  $y$ . This estimator is based on the idea that the catch-biomass estimate tracks the trend in fishing mortality accurately, while the appropriate overall scale is given by mean survey fishing mortality rates. The rescaled  $F$  gives a smoother trend than the survey fishing mortalities, and, unlike the simple catch/biomass method, is numbers based and does not require assumptions about dredge efficiency and incidental mortality. For this assessment, survey and landings data from 1979-2006 for sea scallops in the Mid-Atlantic and 1982-2006 for sea scallops on Georges Bank were used to estimate the ratio of  ${}^c \bar{F}$  and  ${}^s \bar{F}$ .

As in NEFSC (2004), coefficients of variation (CVs) for rescaled fishing mortality estimates were approximated considering variability in the survey data (measured by CVs for random stratified means), and landings data (assumed CV of 10%).

### B6.11 Whole-stock rescaled F estimates

Because of differences in e.g., growth rates, between Georges Bank and the Mid-Atlantic, fishing mortalities were calculated separately for the two areas. Whole-stock estimates of fishing mortality are required, however, for comparison to biological reference points used to identify overfishing and overfished stock conditions.

Whole stock estimates were calculated by averaging estimates for Georges Bank and the Mid-Atlantic using the area surveyed in the NEFSC dredge survey in each region as weights. A variety of evidence indicates that dredge efficiency on Georges Bank is lower than in the Mid-Atlantic, so swept-area abundances in the Mid-Atlantic were multiplied by 0.875 before averaging (0.875 is approximately the ratio of survey dredge efficiencies between the two areas, see Appendix B8). Results for the whole stock were only very slightly sensitive to the assumed value of this factor.

Survey-based and rescaled  $F$  estimates both show generally increasing fishing mortality until the early 1990s, with reductions during 1994–2006 (Table B5-4, Figure B5-8).

### B6.12 Model-based fishing mortality and biomass estimates

CASA model estimates are the best scientific information about sea scallop population dynamics available in this assessment (a complete technical description of the CASA model is in Appendix B10). A CASA model for sea scallops was presented for preliminary review in the last stock assessment (NEFSC 2004) and received positive comments. Simulation testing described in this assessment indicates generally good model performance. Base case model estimates for Georges Bank and the Mid-Atlantic Bight use all of the available data and appear reasonable in comparison to estimates from the rescaled  $F$  model used previously (see below). Sensitivity analyses (see below) suggest that base case estimates for sea scallops are reasonably robust. CASA models in this assessment are used to estimate fishing mortality, biomass and biological reference points based on the same assumptions and using the same computer code, ensuring that the fishing mortality and biomass measures are comparable to biological reference points. CASA model estimates appear relatively precise.

### B6.13 Whole stock biomass, abundance and mortality

Biomass, egg production, abundance, recruitment and fishable mean abundance were estimated for the whole stock by adding estimates for the Mid-Atlantic Bight and Georges Bank. Whole stock fishing mortality rates for each year were calculated  $F = (C_M + C_G)/(\bar{N}_M + \bar{N}_G)$  where  $C_M$  and  $C_G$  are catch numbers for the Mid-Atlantic Bight and Georges Bank. Terms in the denominator are average fishable abundances during each year calculated in the original CASA model  $\bar{N} = \sum_L \frac{N_L(1-e^{-Z_L})}{Z_L}$  with the mortality rate for each size group ( $L$ ) adjusted for fishery selectivity. The simple ratio formula used to calculate whole stock  $F$  is an “exact” solution because the catch equation  $C = F\bar{N}$ .

Asymptotic delta method variances calculated in CASA with AD-Model Builder software were used to compute variances and coefficients of variation (CV) for whole stock estimates assuming that estimation errors for Georges Bank and the Mid-Atlantic Bight were independent. In particular, variances for biomass, abundance and catch estimates were the sum of the variances for Georges Bank and the Mid-Atlantic Bight. CVs for the ratios estimating whole stock F were approximated  $CV_F = \sqrt{CV_C^2 + CV_N^2}$ , which is exact if catch number  $C_N$  and average abundance  $\bar{N}$  are independent (Deming 1960). The CV for measurement errors in catch for each region was 0.05, the same as assumed in fitting the CASA model.

Whole stock estimates indicate that annual abundance, annual egg production and biomass (Table B5-5 and Figures B5-9 to B5-11) were relatively high during 2006. In contrast, recruitment was relatively low during 2006 (Table B5-5 and Figure B5-12). Fishing mortality during 2006 (Table B5-5) was similar to rescaled  $F$  fishing mortality estimates used in the last assessment (Figure B5-13). CV values indicate that abundance, biomass and fishing mortality estimates were relatively precise for individual regions and for the stock as a whole (Table B5-6 and Figure B5-14). The relatively small CVs but likelihood profiles and MCMC probability intervals (not shown) confirmed the asymptotic variances for recent biomass and fishing mortality.

The apparent precision of the estimates for sea scallops may be surprising and the CVs calculated in this assessment certainly do not capture all of the underlying uncertainties. However, estimates were relatively precise because of the long time series of relatively precise dredge survey data (CVs averaging 23% for Georges Bank during 1982-2006 and 12% for the Mid-Atlantic Bight during 1979-2006) and recent video survey data (overall CVs averaging 14% during 2003-2006). The assumption of flat selectivity curves for the two surveys substantially enhances precision, as does the prior information about sampling efficiency in the video survey.

## B6.14 Retrospective patterns

CASA model runs for Georges Bank and the Mid-Atlantic show possible retrospective patterns that cancel out when estimates for the two areas were combined (Figure B5-15). The possible retrospective tendencies may be due to anomalously high dredge survey abundance for Georges Bank in 2000 and anomalously high dredge and video survey abundances for Mid-Atlantic Bight during 2003. Bootstrapped survey estimates show unusually high variances for survey data during these years (Figure B5-3). When areas are combined, effects of unusual survey data and possible uncertainties in allocating landings between the two areas are diminished. The closure of the Elephant Trunk area during 2004-2006, and closures and reopenings on Georges Bank may be partially responsible for the retrospective patterns. Preliminary model runs that included spring and fall bottom trawl survey data for the Mid-Atlantic Bight (not shown) showed no evidence of retrospective patterns.

## B6.15 CASA models for the Mid-Atlantic Bight and Georges Bank

CASA models for the Mid-Atlantic Bight and Georges Bank were configured as described in Table B5-7. Estimated parameters and asymptotic standard deviations are given in Tables B5-8 and B5-9. Diagnostics indicate that base case models for both areas fit reasonably well in most cases (Figures B5-16 to B5-19).

There was a noticeable lack of fit to commercial shell height composition data for 1975-1980 in the Mid-Atlantic Bight because shell height composition data from the 10 ft unlined

dredge survey for 1975, and 1977-1978 showed a different pattern with higher frequencies of large scallops (Figure B5-19). In retrospect, the commercial fishery during the late 1970s would have been better modeled with a separate dome-shaped fishery selectivity pattern with low selectivity on the largest scallops which were probably outside of traditional fishing grounds. However, sensitivity analysis showed that estimates were almost unchanged when data 1975-1978 were omitted (see below). Commercial shell height composition data during the late 1970s probably had little effect because the data were down-weighted using low effective sample sizes in goodness of fit calculations. Sea scallop population dynamics during years prior to 1979 and the advent of the modern sea scallop dredge survey is an important topic for future research.

### ***B6.15.1 Likelihood profile analysis***

Likelihood profile analysis indicates that base case CASA models for sea scallops on Georges Bank and in the Mid-Atlantic Bight struck a reasonable balance between different sources of information and key data sources generally supported similar estimates of recent fishing mortality and biomass. Likelihood profiles are useful because they identify the statistical support among various data sources for a range of recent biomass and fishing mortality estimates (Tables B5-10 and B5-11). Profiles were constructed by holding the survey scaling parameter (catchability coefficient) for the SMAST video small camera survey fixed at a series of values while estimating all other parameters in the model. The scaling parameter for the SMAST video survey was ideal for this purpose because it would be expected to have values near 0.5 and because this parameter has a direct impact on recent biomass and fishing mortality estimates. At each point in the likelihood profile, estimated 2006 biomass and fishing mortality and “naked” (unweighted) likelihood were recorded for each type of data and constraint.

In interpreting likelihood profiles, it is useful to know that a difference of 1.92 likelihood points is often used to identify differences that are statistically significant at the  $p=0.05$  level. The 1.92 rule of thumb is approximate and based on asymptotic arguments.

The total likelihood for the base case Georges Bank model had a well defined minimum around the base case solution (Table B5-10). The trend in the dredge survey, which is the most important source of trend information, and short trend in video survey data fit best near the base case solution. Commercial landings and LPUE data and the constraint on recruitment support higher 2006 biomass levels, although the likelihoods for commercial catch and LPUE were relatively flat. The likelihood for the prior on efficiency of the SMAST video survey was lowest at 0.5 (as expected) supporting a higher 2006 biomass estimate. All three types of shell height composition data support lower 2006 biomass estimates but the likelihoods for shell height composition data were relatively flat.

The total likelihood for the base case Mid-Atlantic Bight model had a well defined minimum around the base case solution (Table B5-11). The trend in the dredge survey, which is the most important source of trend information in the model, and short trend in video survey data fit best near the base case solution. In contrast, the winter bottom trawl survey fit best at lower 2006 biomass levels and the short trend in unlined 10 ft scallop dredge survey data fit best at higher 2006 biomass levels, although the likelihood surface for both was relatively flat. Fall and spring bottom trawl survey data (which did not affect model estimates) support lower 2006 biomass estimates. Commercial landings and LPUE data and the constraint on recruitment deviations fit best at lower 2006 biomass levels although the likelihood surface for catch and LPUE was relatively flat. The likelihood for the prior on efficiency of the SMAST video survey was lowest at 0.5 (as expected) supporting a higher 2006 biomass estimate. Commercial and

survey shell height composition data, with the exception of the unlined 10 ft scallop dredge survey, support higher biomass 2006 estimates although likelihood surfaces were relatively flat for the dredge and winter bottom trawl shell height composition data.

### **B6.15.2 Sensitivity analysis**

Several alternative model runs were carried out with CASA models for the Mid-Atlantic Bight to identify uncertainties and affects of modeling decisions. Mid-Atlantic Bight models were used for sensitivity analysis because of the similarity in structure between models for the two areas and because more types of information were available for the Mid-Atlantic Bight.

Results indicate that biomass estimates for sea scallops in the Mid-Atlantic Bight region were robust to uncertainties and modeling decisions (Table B5-12 and Figure B5-20). The only sensitivity analysis run with substantially different recent biomass and fishing mortality estimates was one that included fall and spring bottom trawl trend and shell height composition in fitting the model. As described under profile analysis, the fall and spring trend data support lower biomass estimates than the base case model.

## **B7.0 BIOLOGICAL REFERENCE POINTS (TOR 3)**

Biological reference points, fishing mortality rates and biomass estimates used in status determination here are for the entire US sea scallop stock. Because of the lack of well-defined stock-recruitment relationships for sea scallops, per recruit reference points  $F_{MAX}$  and  $B_{MAX}$  are used by managers as proxies for  $F_{MSY}$  and  $B_{MSY}$ .  $F_{MAX}$  is the fishing mortality rate for fully recruited scallops that generates maximum yield-per-recruit.  $B_{MAX}$  for sea scallops is the product of  $BPR_{MAX}$  (biomass per recruit at  $F = F_{MAX}$ , from yield-per-recruit analysis) and median numbers of recruits.

The current biological reference points are  $F_{MAX} = 0.24$  and  $B_{MAX} = 5.6$  kg/tow (in survey units, adjusted for the survey dredge liner as in previous assessments NEFSC 2001, 2004). The current  $F_{MAX}$  reference point was originally calculated by Applegate et al. (1998) using an age-based (Thompson-Bell) yield per recruit calculation. NEFSC (2004) found a similar value for  $F_{MAX}$  using a size-based yield per recruit calculation, and left this reference point unchanged. The current value of  $B_{MAX}$  was calculated in NEFMC (2003) as a product of  $BPR_{MAX}$  (from the per recruit calculations in NEFSC 2001) with median survey recruitment from 1979-2002 (Mid-Atlantic) and 1982-2002 (Georges Bank).

The CASA model was used to recalculate per recruit curves for Georges Bank and the Mid-Atlantic Bight assuming the selectivity patterns during 2006, growth increment data, etc. Yield and biomass per recruit curves for the two regions were fairly similar (Figure B6-1), although growth patterns are different and fishery selectivity curves for the two areas during 2006 were offset by about 10 mm (Figures B3-2 and B6-1).

Per recruit curves for the two areas were combined to approximate a per recruit model for the whole stock. The goal was to estimate curves that would have been calculated if the two regions had been modeled together. Whole stock yield- and biomass per recruit curves (Figure B6-1) were calculated by averaging yield per recruit curves for the two regions using median recruitment during 1983-2006 (the longest period with recruit estimates for both areas) as weights.  $F_{MAX}$  ( $F_{MSY}$  proxy) and  $B_{MAX}$  ( $B_{MSY}$  proxy, 40+ mm SH on January 1) are from the whole stock per recruit curves (Table B6-1). As in previous sea scallop assessments (NEFSC 2004), the  $B_{MSY}$  target reference point for the whole stock was estimated as the product of

biomass per recruit at  $F_{MAX}$  and median recruitment for the whole stock during 1983-2006 (Table B6-1).

The per recruit reference points  $F_{MAX}$  and  $B_{MAX}$  are reasonable proxies for  $F_{MSY}$  and  $B_{MSY}$  provided that recruitment is independent of stock size or has reached its asymptotic value at  $B_{MAX}$ , and if fishing mortality as well as other parameters do not vary over space. There was no compelling evidence of a spawner-recruit relationship for either area that would tend to undermine  $F_{MAX}$  as an  $F_{MSY}$  proxy. As in previous assessments, the biomass threshold was  $B_{MSY}/2$ .

However, there are special considerations for sedentary organisms such as sea scallops where fishing mortality is not uniform and particularly when closed areas are present. In such a case, mean yield-per-recruit, averaged over all recruits, may be different than yield-per-recruit obtained by a conventional per-recruit calculation performed on a recruit that suffers the mean fishing mortality risk (Hart 2001). This condition is exaggerated, as in the case of the scallop fishery, with use of rotational or long-term closures. Recent research indicates that the (numbers- or biomass- weighted) fishing mortality that achieves maximum or optimal yield may be less than that indicated by a conventional yield-per-recruit analysis when there is spatial variability in fishing mortality (Hart 2001, 2003).

## B7.1 Examination of possible stock-recruit relationships

This section was added at the request of the SARC panel. Sea scallop recruitment and egg production for the Mid-Atlantic and Georges Bank were estimated using the CASA model (Figure B6-2, Table B5-5). Mid-Atlantic sea scallop egg production remained low from 1975-1997, but increased about 10-fold from 1997-2006. Sea scallop recruitment was poor from 1975-1981 and was moderately strong but variable from 1982-1995. The 1996-2001 year classes were all very strong; all but the 2000 year class was larger than any year class during 1975-1995. Recruitment was below average in 2002 and 2004, but was strong in 2003. The plot of recruitment vs. egg production (Figure B6-3a) suggests the possibility that the increased egg production was at least partially responsible for the strong recent recruitment. However, the period of strong recruitment started before any increase in egg production, so that autocorrelated environmental factors may also explain the increase in recruitment. A fit of a Beverton-Holt curve to the data, assuming log-normal errors, suggests the possibility that recruitment overfishing was occurring prior to 1999, when egg production was less than 20 quintillion. This fit ignores any import of larvae from Nantucket Shoals and Georges Bank, which might be significant but is not quantifiable at this time. Assuming the proposed target biomass (108.6 thousand mt meats) was equally split between Mid-Atlantic and Georges Bank, this reference point corresponds to about 60 quintillion eggs. Egg production at the target biomass appears to be sufficient to saturate the stock-recruit relationship, so that there is little concern of recruitment overfishing if biomass remains at or over the proposed target. It also appears that the biomass threshold, corresponding to about 30 quintillion eggs, is a reasonable point to take action to prevent possible recruitment overfishing.

Georges Bank egg production was relatively low from 1982-1995, but has increased substantially since then (Figure B6-2b). Recruitment appears fairly trendless, with strong recruitment during the late 1980s, and a very strong 1998 year class. Except for the 2001 year class, recruitment during 1999-2004 has been below average. A plot of recruitment vs. egg production (Figure B6-3b) gives no indication that the recent increase in egg production has led to an increase in recruitment. A fit of these data to a Beverton-Holt stock-recruit curve, assuming log-normal errors, suggests that the stock-recruit curve is already saturated at 20 quintillion eggs,

about the number of eggs released in 1996-1997, so that the subsequent increases in egg production had little effect. However, this analysis neglects the egg production in the Canadian side of Georges Bank which in many years may have contributed 30-50% of the total egg production. Additionally, there are no observations below the estimated half-saturation point of the stock-recruit curve, so that the half-saturation point cannot be well estimated. However, again it can be concluded that there is little concern regarding recruitment overfishing if biomass is at or over its target (corresponding to about 60 quintillion eggs on Georges Bank) or even at the biomass threshold (corresponding to about 30 quintillion eggs).

## B8.0 STATUS DETERMINATION (TOR 4)

According to the Amendment 10 overfishing definition (NEFMC 2003), sea scallops are overfished when the survey biomass index for the whole stock falls below  $1/2 B_{MAX}$ . Overfishing occurs if fishing mortality exceeds  $F_{MAX}$ . As described above, managers use  $F_{MAX}$  from yield-per-recruit analysis and  $B_{MAX}$  as proxies for  $F_{MSY}$  and  $B_{MSY}$ .  $F_{MAX}$  is the fishing mortality rate for fully recruited scallops that generates maximum yield-per-recruit (see above). The current target biomass level  $B_{TARGET}$  was calculated as the median recruitment in the survey time series times  $BPR_{MAX}$ , the biomass per recruit obtained when fishing at  $F_{MAX}$ . The current management reference points are  $F_{MAX} = 0.24 \text{ y}^{-1}$  and  $B_{TARGET} = 5.6 \text{ kg/tow}$  (adjusted for the liner as in previous assessments).

Overfishing was not occurring in the sea scallop stock and overfishing was not occurring during 2006, based on the reference points currently in use and the fishing mortality estimator used in previous assessments (NEFSC 2001, 2004). Based on the 2006 NEFSC scallop survey, sea scallop biomass (adjusted for assumed dredge selectivity) was about 7.3 kg/tow, well above  $B_{MAX} = 5.6 \text{ kg/tow}$ . The overall rescaled  $F$  fishing mortality estimate for the whole stock 2006 was 0.20 (rescaled  $F$ ), which is below the overfishing threshold of  $F_{MAX} = 0.24$ .

Based on the new recommended reference points and CASA model estimates, the US sea scallop stock was not overfished and overfishing was not occurring in 2006. This assessment proposes the new reference points of  $F_{MAX} = 0.29$ , a target biomass reference point of 108.6 thousand mt meats, and a biomass threshold of 54.3 thousand mt meats. The best estimate for fully recruited fishing mortality during 2006 is  $F = 0.23$  (95% confidence interval 0.17-0.32, Figure B7-1), which is well below the proposed threshold  $F_{MAX} = 0.29$ . Based on the variance in estimated fishing mortality, there is only a 7% chance that fishing mortality was above the recommended fishing mortality threshold during 2006. Estimated stock biomass for sea scallops during 2006 was 166 thousand mt (95% confidence interval: 152-182 thousand mt, Figure B7-2). Based on the variance in estimated biomass, there is less than a 0.1% probability that the sea scallop biomass was below the biomass threshold of 54.3 mt meats.

## B9.0 STOCK PROJECTIONS (TOR 5-6)

Example stock projections were made for two assumed scenarios. Under the first scenario,  $F=0.20$  (the current target) during 2007-2009. The second set of projects assumes  $F=0.24$  (the current  $F_{MSY}$  proxy and fishing mortality threshold, and a potential new target) during 2007-2009.

Because of the sedentary nature of sea scallops, fishing mortality of sea scallops can vary considerably in space even in the absence of area specific management (Hart 2001). Area management such as rotational and long-term closures can make variation even more extreme

(Figure B4-7). Projections that ignore such variation might be unrealistic and misleading. For example, suppose 80% of the stock biomass is in areas closed to fishing (as occurred in some years in Georges Bank). A stock projection that ignored the closure and assumed a whole-stock  $F$  of 0.2 would forecast landings nearly equal to the entire stock biomass of the areas remaining open to fishing. Thus, using a non-spatial forecasting model can lead to setting a level of landings that appears sustainable if all areas were fished uniformly, but is in fact unsustainable for a given area management policy.

For this reason, a spatial forecasting model (the Scallop Area Management Simulator, SAMS) was developed for use in sea scallop management. Various versions of SAMS have been used since 1999 (NEFSC 2004). Growth is modeled in SAMS and CASA in a similar manner, except that each area of Georges Bank and the Mid-Atlantic in SAMS has its own stochastic growth transition matrix derived from the shell increments collected in that area. Mortality and recruitment are also area-specific. Fishing mortality can either be explicitly specified in each area, calculated using a simple fleet dynamics model which assumes fishing effort is proportional to fishable biomass, or a combination of the two. Shell height/meat weight relationships were from the 2001-2006 R/V data, adjusted using the mean annual fishery shell height/meat weight anomaly during 1997-2006 (see Appendix B4 and Figure B3-6).

Projected recruitment is modeled stochastically with the log-transformed mean and covariance for recruitment in each area matching that observed in NEFSC dredge survey time series. Initial conditions were based on the 2006 NEFSC sea scallop survey with uncertainty measured by bootstrapping as described by Smith (1997). Survey dredge efficiencies were set in SAMS so that the mean 2006 biomass matched estimates from the CASA model. Further details regarding the SAMS model are given in Appendix B11.

For these simulations, the stock area was split into 15 subareas, six in the Mid-Atlantic (Virginia Beach, Delmarva, Elephant Trunk, Hudson Canyon South, New York Bight, and Long Island) and nine on Georges Bank (Closed Area I, II and Nantucket Lightship EFH closures, Closed Area I, II and Nantucket Lightship access areas, Great South Channel, Northern Edge and Peak, and Southeast Part). The Delmarva area was closed on a rotational basis in 2007, and is assumed to be fished at 0.2 for the first year (since the simulation starts in July 2006), and then closed during the remainder of the simulation.

The Elephant Trunk area was reopened in 2007 after a three year closure, and scheduled to remain a special access area with its own TAC and target fishing mortality for the three years of the simulation. It is subject to an increasing pattern of fishing mortality during the three year simulations (0.16, 0.24, 0.32 in the first set of simulations; 0.16, 0.29, 0.38 in the second set of simulations). The Hudson Canyon South area was closed in 1998-2001 and 2007 is the last year of its special access program with estimated fishing mortality of 0.4. It is scheduled to be a part of the fully open areas in 2008-9.

The EFH closure portions of the three groundfish closed areas (Closed Area I, II and Nantucket Lightship Closed Area) are closed long-term to all bottom-tending mobile gear, and are assumed closed during the entire simulation period. Two out of three of the access portions of the groundfish closed areas are opened each year: Closed Area I and Nantucket Lightship in 2007, Closed Area II and Nantucket Lightship in 2008, and Closed Areas I and II in 2009.

Target total allowable catch (TAC) levels have already been set for the 2007 groundfish access area program (NEFMC 2005, about 2500 mt in each area). Fishing mortality in these areas in 2008-9 was assumed to be 0.2, as specified in sea scallop Amendment 10 (NEFMC 2003). All other areas (Virginia Beach, New York Bight, Long Island, South Channel, Northern

Edge and Peak, Southeast Part, and after 2007, Hudson Canyon South) are part of the open area pool.

In projections, fishing effort was allocated to areas so that the overall fishing mortality rate was 0.24 in the first year (based on current regulations described in NEFMC 2005) and 0.2 during 2008-2009 (first set of simulations) or 0.24 (second set of simulations). Fishing effort was distributed among the open areas according to a simple fleet dynamics model, where fishing mortality in each area was assumed to be proportional to fishable biomass.

Under both scenarios, biomass and landings are expected to increase modestly in the next three years (Figure B8-1,2). Under the first scenario ( $F = 0.20$ ), landings are expected to rise from a little more than 26,000 mt meats in 2006-2007, to over 32,000 mt in 2008-2009, compared to a range of 26,000 mt in 2006-2007 to over 34,000 mt in 2008-2009 in the  $F = 0.24$  scenario. On the other hand, biomass is projected to increase more during 2006-2009 in the  $F = 0.20$  scenario (22%) than in the  $F = 0.24$  simulation (15%). Roughly 40% of the landings are projected to come from the special access areas (Elephant Trunk and the groundfish closed areas). None of the 400 model runs resulted in a biomass below the new biomass target (108.6 thousand mt) indicating that overfished stock conditions are unlikely in the near future.

Simulated landings are more variable than biomass, because the landings stream is more dependent on the abundances of a few key areas (such as the Elephant Trunk) while total biomass includes sea scallops in closed areas and areas lightly fished. Much of the variation among the simulation runs for each scenario was due to bootstrapping of survey data to set initial conditions (rather than variable recruitment) because simulated recruits did not have time during the short simulations to grow and completely recruit to the fishery.

## B10.0 RESEARCH RECOMMENDATIONS (TOR 7)

Agencies, academic institutions, and contractors made considerable progress in key areas of scallop research since the last assessment. In this section, progress on recommendations in the previous assessment (NEFSC 2004) is reviewed and new research recommendations are presented.

### B10.1 Research recommendations from NEFSC (2004)

1. More comparison tows between standard survey dredges and those equipped with rock chains are necessary to more precisely estimate the correction factor(s) needed to convert between survey tows with and without rock chains. *Additional field work and statistical analysis has been completed although more research would be required to precisely estimate rock chain effects, which may vary from year to year (see Appendix B9).*
2. Explore potential for surveying hard bottom areas not currently covered using survey dredges equipped with rock chains. Some experimental paired tows have been carried out on the (hard-bottom) northern edge of Georges Bank, where rocks are occasionally seen. This topic is under discussion and progress is expected when the current NEFSC sea scallop survey is replaced by a proposed optical-dredge survey after 2008.
3. Explore the use of VMS and landings data to characterize condition of the resource on grounds not covered by the survey. *Some work is underway to interpret catch rates on unsurveyed grounds using VMS and other data. Grounds covered by NEFSC surveys may be expanded after 2008.*

4. Further work is required to better characterize the selectivity of the commercial dredges with 4 inch rings relative to the standard NEFSC survey dredge. *A comprehensive paired-tow field study to estimate contact selectivity of commercial dredges with 4 inch rings was completed (see Appendix B5 and Yochum 2006). In addition, CASA model estimates for 2006 provide useful estimates of fishery selectivity that integrate the effects of contact selectivity, discard and targeting.*
5. Because assumptions about growth are important in almost any stock assessment model, better estimation of scallop growth, including variability in growth, is important in improving the precision of sea scallop stock assessments. *Appendices B2-B3 describe new growth data and growth parameter estimates. Variation among regions is accommodated and variability over time is noted.*
6. Work presented during the assessment indicates substantial variability in shell height-meat weight relationships due to depth, season, year and possibly area. Additional work on this subject may be useful, especially with respect to area-based management. *See Appendix B4 and Section 3 of this report for new data, depth based shell height/meat weight relationships, and approaches to calculating shell height-meat weight in the commercial fishery.*
7. Based on recent work on scallops in the US and Canada, there is a potential for tracking year-to-year variability in natural mortality based on clapper data. Use of clapper data in stock assessment models to estimate natural mortality should be investigated. *Work on this topic is underway but has not been completed.*
8. The statistical properties of the new “CASA” model should be fully evaluated prior to the next meeting. The properties of concern include performance in the face of process errors (e.g. variability in natural mortality and growth), measurement errors in data, and characterization of uncertainty. In addition, use of smaller time steps and shell height groups might be helpful. It may prove possible to apply the model or similar models to smaller geographic areas. *Appendices B10-B12 describe progress along these lines and software used to test the sea scallop stock assessment model.*
9. There appears to be considerable scope for reducing variability in scallop survey data by changing the allocation of tows to survey strata. *A more adaptive allocation scheme has been adopted, which has resulted in lower variance in the most recent surveys (Table B5-1).*
10. Comparison of SMAST video survey with the NEFSC survey has proved valuable in estimating efficiency of survey and commercial dredges and in improving abundance estimates. The benefits of future video surveys could be enhanced by increasing coordination in carrying out the video and NEFSC surveys on the same grounds, so that the NEFSC scallop strata are fully covered by the video survey. More intense video surveys in small areas, such as was done in 1999-2002, can help reduce the variances of the efficiency estimates. *SMAST video survey data were fully incorporated in this assessment. Cooperative analyses were carried using video and dredge survey data to characterize selectivity in both surveys and to refine estimates of dredge efficiency for sea scallops in the Mid-Atlantic and on Georges Bank (see Appendices B7-B8). A paired photographic/dredge comparison study is planned for this summer.*
11. This assessment demonstrates the potential for fully incorporating results of cooperative surveys in stock assessment models for scallops. Areas where additional information could be obtained by cooperative research include abundance in areas not normally surveyed by NEFSC, gear properties, and temporal and spatial variation in shell height/meat weight relationships, mortality, recruitment and growth. *Results of a 4 inch ring selectivity study*

*conducted by the Virginia Institute of Marine Science (VIMS, Appendix B5, Yochum 2006) and SMAST video surveys (Section 5, Appendices B7-B8) were incorporated in this assessment.*

## B10.2 New Research Recommendations

1. Refine estimates of natural mortality focusing on variation among regions, size groups and over time. Abundance trends in closed areas where no fishing occurs may provide important information about the overall level of natural mortality and time trends. Survey clapper catches may provide information about spatial, temporal and size related patterns in natural mortality.
2. Evaluate the within and between reader error rates in identification and measurement of growth increments on scallop shells.
3. Improve estimates of incidental and discard mortality rates.
4. Consider using autocorrelated recruitment in SAMS projection model runs. CASA model estimates indicate that sea scallop recruitment may be autocorrelated.
5. Consider modeling the spatial dynamics of the fishing fleet in the SAMS projection model based on catch rates, rather than exploitable abundance, of scallops in each area.
6. Evaluate assumptions about the spatial dynamics of the fishing fleet in the SAMS model by comparing predicted distributions to VMS data.
7. Investigate the feasibility and benefits of using information about the size composition of sea scallops in predicting the spatial distribution of the fishing fleet in the SAMS projection model.
8. Evaluate the accuracy of the SAMS projection model retrospectively by comparison to historical survey abundance trends.
9. Consider implementing discard mortality calculations in the CASA model that are more detailed and involve discarded shell height composition data from at sea observers.
10. Consider implementing a two or more “morph” formulation in the CASA model to accommodate scallops that grow at different rates.
11. Consider approaches to implementing seasonal growth patterns in the CASA model to improve fit to shell height composition data. Scallops grow quickly at small sizes and growth rates vary by season.

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## ATLANTIC SEA SCALLOP TABLES

Table B4-1. US sea scallop landings (mt meats) 1964-2006.

Year	Gulf of Maine			Georges Bank			S. New England			Mid Atlantic Bight			Total				
	dredge	trawl	other	sum	dredge	trawl	other	sum	dredge	trawl	other	sum	dredge	trawl	other	sum	
1964	0	208	0	208	0	6,241	6,241	52	3	55	0	137	137	52	6,590	6,642	
1965	0	117	117	3	1,478	1,481	2	24	26	0	0	3,974	3,974	5	5,592	5,598	
1966	0	102	102	0	0	883	884	0	8	8	0	0	4,061	4,061	1	5,055	5,056
1967	0	80	4	1,217	1,221	0	8	8	8	0	0	1,873	1,873	4	3,178	3,182	
1968	0	113	113	0	993	994	0	56	56	0	0	2,437	2,437	0	3,599	3,599	
1969	1	122	123	8	1,316	1,324	0	18	19	5	846	851	14	2,302	2,317		
1970	0	132	132	5	1,410	1,415	0	6	6	14	459	473	19	2,006	2,026		
1971	4	358	18	1,311	1,329	0	7	7	0	0	274	274	22	1,949	1,971		
1972	1	524	525	5	816	821	0	2	2	5	653	658	11	1,995	2,006		
1973	0	460	460	15	1,065	1,080	0	3	3	4	245	249	19	1,773	1,792		
1974	0	223	223	15	911	926	0	4	5	0	937	938	16	2,076	2,091		
1975	6	741	746	13	844	857	8	42	50	52	1,506	1,558	80	3,132	3,212		
1976	3	364	366	38	1,723	1,761	4	3	7	819	2,972	3,791	361	5,061	5,422		
1977	4	254	258	27	4,709	4,736	1	10	11	255	2,819	2,564	58	7,536	7,595		
1978	242	1	0	243	5,532	37	0	5,569	25	2	0	27	4,435	207	0	10,481	
1979	401	5	1	407	6,253	25	7	6,285	61	5	0	66	2,857	29	1	9,645	
1980	1,489	122	3	1,614	5,382	34	2	5,419	130	3	0	133	2,202	85	79	9,532	
1981	1,225	73	7	1,305	7,787	56	0	7,843	68	1	0	69	772	14	2	788	
1982	631	28	5	664	6,204	119	0	6,322	126	0	0	126	1,602	6	2	1,610	
1983	815	72	7	895	4,247	32	4	4,284	243	1	0	243	3,092	19	10	3,121	
1984	651	18	10	678	3,011	29	3	3,043	161	3	0	164	3,695	53	2	3,750	
1985	408	3	10	421	2,860	34	0	2,894	77	4	0	82	3,230	49	2	3,281	
1986	308	2	6	316	4,428	10	0	4,438	76	2	0	78	3,407	386	6	3,799	
1987	373	0	9	382	4,821	30	0	4,851	67	1	0	68	7,639	1,168	1	8,808	
1988	506	7	13	526	6,036	18	0	6,054	65	4	0	68	6,071	938	8	7,017	
1989	600	0	44	644	5,637	25	0	5,661	127	11	0	138	7,894	534	5	8,433	
1990	545	0	28	574	9,972	10	0	9,982	110	6	0	116	6,364	541	10	6,915	
1991	527	3	75	605	9,235	77	0	9,311	55	16	0	71	6,408	878	14	7,300	
1992	676	2	45	722	8,230	7	0	8,238	119	5	0	124	4,562	570	5	5,137	
1993	763	2	32	797	3,637	18	0	3,655	65	1	0	66	2,412	393	3	2,808	
1994	375	17	0	392	1,191	13	1	1,205	34	1	0	35	5,180	792	0	5,972	
1995	446	3	6	455	1,175	17	7	1,199	44	4	0	48	5,780	317	1	6,069	
1996	634	9	3	646	1,992	69	0	2,061	78	3	0	82	4,156	759	3	4,918	
1997	601	9	12	622	2,030	23	0	2,053	85	2	0	87	2,391	337	0	2,728	
1998	474	7	2	483	2,021	18	0	2,039	98	2	0	100	2,356	531	5	2,891	
1999	239	2	2	243	5,079	6	0	5,085	80	1	0	80	3,516	890	8	4,414	
2000	139	5	1	144	5,016	20	3	5,039	73	2	0	74	7,652	1,200	0	8,852	
2001	251	8	1	260	4,563	35	0	4,597	28	1	1	29	13,989	1,621	0	15,611	
2002	492	6	1	499	5,478	63	0	5,541	19	1	0	20	15,435	1,616	5	17,056	
2003	394	8	1	403	4,799	23	0	4,823	101	2	0	103	18,796	1,292	1	20,089	
2004	125	9	0	134	4,343	14	0	4,357	102	18	0	120	23,082	1,402	13	24,497	
2005	134	9	0	143	9,381	118	3	9,502	381	21	1	403	14,588	1,040	6	15,634	
2006	227	1	1	229	17,239	47	0	17,286	365	4	0	370	8,232	584	3	8,819	

Table B4-2. Estimated discards on directed scallop trips 1992-2006 (mt meats).

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Mid-Atlantic	143	13	853	324	24	8	60	11	871	854	1637	2417	2644	579	213
Georges Bank	448	282	3	38	135	29	5	162	1129	865	128	313	91	286	628
<b>Total</b>	<b>591</b>	<b>295</b>	<b>856</b>	<b>363</b>	<b>159</b>	<b>37</b>	<b>65</b>	<b>173</b>	<b>2000</b>	<b>1719</b>	<b>1765</b>	<b>2729</b>	<b>2735</b>	<b>864</b>	<b>842</b>

Table B4-3. Estimated scallop landings and discards in non-scallop otter trawl fisheries, 1994-2006 (mt meats, “\*” indicates < 1 mt meats)

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
<b>longfin squid</b>	32	26	42	51	42	47	46	1	9	22	42	86	115
<b>summer flounder</b>	7	13	20	12	10	11	12	*	3	10	18	31	34
<b>scup</b>	2	3	5	3	3	2	1	*	1	4	4	10	13
<b>yellowtail flounder</b>	2	1	2	3	3	5	7	*	1	4	7	7	4
<b>haddock</b>	*	*	*	1	1	2	2	*	1	2	4	7	3
<b>cod</b>	1	1	2	2	1	1	1	*	*	1	*	1	1
<b>monkfish</b>	*	*	1	1	*	*	*	*	*	*	*	*	*

#### Scallops discarded by otter trawl fisheries (mt):

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
<b>longfin squid</b>	52	58	33	38	68	65	60	112	108	57	68	42	13
<b>summer flounder</b>	12	28	15	9	17	15	16	26	33	26	30	15	4
<b>scup</b>	4	6	4	2	4	2	2	4	8	10	7	5	1
<b>yellowtail flounder</b>	4	2	2	2	5	6	9	17	11	9	12	4	*
<b>haddock</b>	*	*	*	*	2	2	3	7	9	6	6	3	*
<b>cod</b>	2	2	1	1	1	1	1	3	2	2	1	*	*
<b>monkfish</b>	1	1	1	*	*	1	1	1	*	*	*	*	*
<b>prop landed</b>	0.38	0.31	0.56	0.57	0.38	0.42	0.43	0.01	0.08	0.28	0.38	0.67	0.90
<b>total landings (mt)</b>	46	43	72	72	60	67	69	2	15	42	76	142	172
<b>total discards (mt)</b>	74	97	57	54	98	93	92	170	171	109	124	70	19
												mean	68
												mean	94

Table B5-1. NEFSC survey stratified mean indices for (a) Mid-Atlantic sea scallop survey, (b) Georges Bank sea scallop dredge survey, (c) combined Mid-Atlantic and Georges Bank sea scallop dredge survey, and (d) winter bottom trawl survey (Mid-Atlantic only). Unlike previous assessments, no adjustments were made to sea scallop dredge survey data for the liner. Holes were filled with imputed data (Appendix B6).

(a) Mid-Atlantic Bight

	Abundance Year index (mean N/tow)	Biomass CV (kg/tow)	Biomass index CV	N tows	N positive tows	Proportion Positive Tows	N Strata Surveyed	Area (nm <sup>2</sup> )	Mean Surveyed Julian Date	Mean Weight (g / scallop)
1979	30.7	0.09	0.571	0.11	166	152	0.92	30	8,350	141
1980	41.1	0.11	0.498	0.08	167	157	0.94	30	8,350	149
1981	30.8	0.16	0.390	0.12	167	152	0.91	29	8,316	169
1982	30.7	0.11	0.408	0.08	185	168	0.91	30	8,350	174
1983	27.7	0.09	0.358	0.08	193	171	0.89	30	8,350	216
1984	29.4	0.11	0.341	0.09	204	186	0.91	29	8,172	213
1985	67.0	0.12	0.541	0.08	201	188	0.94	30	8,350	210
1986	117.9	0.10	0.954	0.09	226	210	0.93	30	8,350	218
1987	122.3	0.09	0.843	0.07	226	211	0.93	30	8,350	195
1988	131.2	0.10	1.281	0.07	227	206	0.91	29	8,229	200
1989	166.6	0.09	1.166	0.07	244	226	0.93	30	8,350	170
1990	205.6	0.22	1.254	0.17	216	192	0.89	30	8,350	214
1991	75.7	0.10	0.729	0.12	229	211	0.92	30	8,350	216
1992	40.6	0.11	0.414	0.07	229	200	0.87	30	8,350	218
1993	127.5	0.10	0.573	0.07	214	205	0.96	30	8,350	217
1994	125.8	0.11	0.772	0.08	227	214	0.94	30	8,350	181
1995	168.7	0.13	1.160	0.10	227	217	0.96	30	8,350	179
1996	55.8	0.08	0.564	0.07	211	188	0.89	30	8,350	217
1997	41.3	0.13	0.428	0.06	225	209	0.93	30	8,350	208
1998	157.6	0.18	0.808	0.14	226	208	0.92	30	8,350	208
1999	234.0	0.22	1.708	0.18	226	209	0.92	30	8,350	204
2000	283.6	0.15	2.979	0.13	229	201	0.88	30	8,350	203
2001	306.3	0.13	3.322	0.13	227	205	0.90	30	8,350	188
2002	301.0	0.11	3.743	0.12	206	184	0.89	30	8,350	206
2003	641.3	0.16	5.678	0.10	201	181	0.90	30	8,350	217
2004	468.8	0.11	5.232	0.07	248	220	0.89	30	8,350	194
2005	360.1	0.09	6.045	0.09	241	223	0.93	30	8,350	203
2006	378.1	0.10	5.883	0.07	230	215	0.93	30	8,350	201

(b) Georges Bank

Year	Abundance index (mean N/tow)	CV	Biomass index (kg/tow)	CV	N tows	N positive tows	Proportion Positive Tows	N Strata Surveyed	Area (nm2)	Mean Surveyed Julian Date	Mean Weight (g / scallop)
1982	133.4	0.56	0.847	0.32	129	103	0.80	28	7,250	204	6.4
1983	50.7	0.29	0.600	0.24	138	117	0.85	29	7,216	232	11.8
1984	30.1	0.12	0.411	0.10	138	114	0.83	29	7,172	227	13.7
1985	53.8	0.19	0.560	0.18	170	144	0.85	30	7,281	235	10.4
1986	90.4	0.18	0.689	0.12	194	164	0.85	29	7,029	234	7.6
1987	106.6	0.21	0.903	0.17	190	156	0.82	30	7,281	214	8.5
1988	81.8	0.18	0.715	0.15	192	150	0.78	30	7,281	217	8.7
1989	39.6	0.26	0.364	0.17	254	209	0.82	30	7,281	217	9.2
1990	175.9	0.29	1.093	0.23	194	155	0.80	30	7,281	226	6.2
1991	241.2	0.48	1.160	0.28	194	170	0.88	30	7,281	228	4.8
1992	247.1	0.55	1.683	0.47	191	165	0.86	30	7,281	230	6.8
1993	62.5	0.30	0.427	0.19	182	150	0.82	30	7,281	230	6.8
1994	38.0	0.18	0.357	0.13	194	156	0.80	30	7,281	195	9.4
1995	109.7	0.25	0.672	0.17	193	164	0.85	30	7,281	213	6.1
1996	113.5	0.18	1.124	0.16	189	164	0.87	30	7,281	234	9.9
1997	80.6	0.14	1.273	0.15	206	175	0.85	30	7,281	224	15.8
1998	271.2	0.28	3.703	0.35	230	197	0.86	30	7,281	222	13.7
1999	159.8	0.15	2.559	0.16	198	186	0.94	30	7,281	215	16.0
2000	715.5	0.29	6.336	0.21	188	168	0.89	30	7,281	222	8.9
2001	357.8	0.15	5.128	0.15	225	211	0.94	30	7,281	217	14.3
2002	297.9	0.14	5.976	0.13	229	207	0.90	30	7,281	221	20.1
2003	225.8	0.12	5.419	0.14	225	206	0.92	30	7,281	233	24.0
2004	269.9	0.10	7.132	0.11	230	212	0.92	30	7,281	210	26.4
2005	210.5	0.12	5.698	0.11	227	211	0.93	30	7,281	213	27.1
2006	151.0	0.10	4.502	0.11	231	212	0.92	30	7,281	216	29.8

## (c) Whole stock

Year	Abundance index (mean N/tow)	CV	Biomass index (kg/tow)	CV	N tows	N positive tows	Proportion Positive Tows	N Strata Surveyed	Area Surveyed (nm2)	Mean Julian Date	Mean Meat Weight (g / scallop)
1982	78.6	0.44	0.613	0.21	314	271	0.86	58	15,600	188	7.8
1983	38.4	0.18	0.471	0.15	331	288	0.87	59	15,566	224	12.3
1984	29.7	0.08	0.374	0.06	342	300	0.88	58	15,344	220	12.6
1985	60.8	0.11	0.550	0.10	371	332	0.89	60	15,631	222	9.0
1986	105.1	0.09	0.831	0.07	420	374	0.89	59	15,378	226	7.9
1987	115.0	0.10	0.871	0.09	416	367	0.88	60	15,631	204	7.6
1988	108.2	0.09	1.017	0.07	419	356	0.85	59	15,510	208	9.4
1989	107.4	0.09	0.792	0.07	498	435	0.87	60	15,631	192	7.4
1990	191.8	0.18	1.179	0.14	410	347	0.85	60	15,631	219	6.1
1991	152.8	0.36	0.930	0.17	423	381	0.90	60	15,631	222	6.1
1992	136.8	0.46	1.006	0.36	420	365	0.87	60	15,631	224	7.4
1993	97.3	0.12	0.505	0.09	396	355	0.90	60	15,631	223	5.2
1994	84.9	0.10	0.579	0.07	421	370	0.88	60	15,631	187	6.8
1995	141.2	0.12	0.932	0.09	420	381	0.91	60	15,631	195	6.6
1996	82.7	0.12	0.825	0.10	400	352	0.88	60	15,631	225	10.0
1997	59.6	0.10	0.822	0.11	431	384	0.89	60	15,631	215	13.8
1998	210.5	0.18	2.157	0.28	456	405	0.89	60	15,631	214	10.2
1999	199.4	0.15	2.104	0.12	424	395	0.93	60	15,631	209	10.6
2000	484.8	0.21	4.542	0.14	417	369	0.88	60	15,631	212	9.4
2001	330.3	0.10	4.163	0.10	452	416	0.92	60	15,631	201	12.6
2002	299.6	0.09	4.783	0.09	435	391	0.90	60	15,631	213	16.0
2003	447.7	0.12	5.557	0.08	426	387	0.91	60	15,631	224	12.4
2004	376.1	0.08	6.117	0.07	478	432	0.90	60	15,631	201	16.3
2005	290.4	0.07	5.883	0.07	468	434	0.93	60	15,631	208	20.3
2006	272.3	0.08	5.240	0.06	461	427	0.93	60	15,631	208	19.2

(d) Winter trawl survey (Mid-Atlantic only)

Year	Abundance index (mean N/tow)	CV	N tows	N positive tows	Proportion Positive Tows	N Bottom Trawl Strata Surveyed	Area Surveyed (nm <sup>2</sup> )	Mean Julian Date
1992	50.4	0.49	79	40	0.506	18	22,118	50
1993	25.8	0.25	84	46	0.548	18	22,092	43
1994	84.5	0.56	54	41	0.759	18	22,118	37
1995	43.9	0.30	81	42	0.519	20	22,536	46
1996	49.9	0.31	91	44	0.484	18	22,118	43
1997	4.7	0.21	83	40	0.482	22	22,701	41
1998	57.3	0.22	90	38	0.422	23	22,625	45
1999	71.3	0.49	91	46	0.505	24	22,813	38
2000	96.7	0.32	103	39	0.379	23	22,583	49
2001	22.6	0.24	118	50	0.424	24	22,813	37
2002	101.9	0.43	118	48	0.407	23	22,753	47
2003	158.0	0.82	86	24	0.279	24	22,813	47
2004	53.3	0.35	106	36	0.340	24	22,813	45
2005	81.0	0.44	82	41	0.500	23	22,753	43
2006	65.1	0.29	106	57	0.538	24	22,813	45

Table B5-2. SMAST large camera video survey data for sea scallops 40+ mm SL in the Mid-Atlantic Bight and Georges Bank regions, 2003-2006. Four camera images were taken at each station.

Year	Density (N/m <sup>2</sup> )	SE	CV	N stations	Area surveyed (km <sup>2</sup> )
Mid-Atlantic Bight					
2003	0.4420	0.0756	16.5	851	26,270
2004	0.2236	0.0219	9.8	840	25,930
2005	0.2038	0.0246	11.9	868	26,794
2006	0.1897	0.0188	9.9	903	27,875
Georges Bank					
2003	0.1474	0.0124	8.4	924	28,523
2004	0.1202	0.0143	11.8	941	29,048
2005	0.1115	0.0121	10.8	943	29,110
2006	0.1060	0.0112	10.6	943	29,110
Georges Bank - Open Areas					
2003	0.0900	0.0085	9.3	513	15,836
2004	0.0711	0.0091	12.6	531	16,392
2005	0.0621	0.0073	11.6	536	16,546
2006	0.0597	0.0084	14.1	531	16,546
Georges Bank - Closed Areas					
2003	0.2191	0.0253	11.5	411	12,687
2004	0.1838	0.0304	16.5	410	12,656
2005	0.1767	0.0259	14.6	407	12,564
2006	0.1658	0.0230	13.8	412	12,564

Table B5-3. SMAST small camera video survey data for sea scallops 40+ mm SL in the Mid-Atlantic Bight and Georges Bank regions, 2003-2006. Four camera images were taken at each station.

Year	Density (N/m <sup>2</sup> )	SE	CV	N stations	Area surveyed (km <sup>2</sup> )
Mid-Atlantic Bight					
2003	0.4899	0.1179	20.2	845	26,084
2004	0.2119	0.0242	11.3	837	25,837
2005	0.1957	0.0248	12.2	866	26,733
2006	0.1896	0.0200	10.5	895	27,628
Georges Bank					
2003	0.1538	0.0163	10.3	905	27,937
2004	0.1155	0.0136	11.2	929	28,677
2005	0.0975	0.0125	12.7	917	28,307
2006	0.1348	0.0138	10.0	939	28,986
Georges Bank - Open Areas					
2003	0.0798	0.0103	12.1	503	15,527
2004	0.0743	0.0129	16.0	521	16,083
2005	0.0549	0.0084	14.8	526	16,237
2006	0.0936	0.0125	13.1	531	16,392
Georges Bank - Closed Areas					
2003	0.2468	0.0338	13.5	402	12,409
2004	0.1679	0.0260	15.1	408	12,595
2005	0.1557	0.0268	17.2	391	12,070
2006	0.1885	0.0270	14.0	408	12,595

Table B5-4. Survey and rescaled fishing mortality estimates for (a) Mid-Atlantic, (b) Georges Bank, (c) overall.

(a) Mid-Atlantic		80-98	98+	SurveyF	SE	Landings	MinEBms	EBms	CV	CBI	CV	RescaledF	CV
1979	7.2	14.2				2,888	3,003	7,150	0.10	0.40	0.14	0.58	0.15
1980	4.8	11.7	0.50	0.12	1,975	2,471	5,884	0.07	0.34	0.12	0.48	0.13	
1981	6.6	7.5	0.69	0.12	731	1,853	4,411	0.10	0.17	0.14	0.24	0.15	
1982	7.9	7.9	0.48	0.15	1,610	1,953	4,649	0.08	0.35	0.13	0.50	0.13	
1983	4.4	7.9	0.58	0.14	3,109	1,713	4,077	0.08	0.76	0.13	1.09	0.13	
1984	10.0	6.2	0.60	0.11	3,675	1,674	3,985	0.09	0.92	0.13	1.32	0.14	
1985	11.6	9.0	0.49	0.15	3,276	2,210	5,263	0.07	0.62	0.12	0.89	0.13	
1986	30.8	12.5	0.40	0.13	3,359	3,846	9,158	0.07	0.37	0.12	0.53	0.13	
1987	28.8	11.1	1.26	0.12	7,803	3,355	7,989	0.06	0.98	0.12	1.40	0.12	
1988	46.6	18.8	0.65	0.10	6,178	5,829	13,878	0.07	0.45	0.12	0.64	0.13	
1989	36.3	13.3	1.49	0.12	7,973	4,482	10,670	0.07	0.75	0.12	1.07	0.13	
1990	35.6	9.7	1.54	0.11	6,435	4,034	9,606	0.10	0.67	0.14	0.96	0.15	
1991	22.9	11.7	1.25	0.18	7,011	3,237	7,707	0.11	0.91	0.15	1.30	0.15	
1992	10.8	8.5	1.30	0.13	4,955	1,939	4,616	0.07	0.07	0.12	1.54	0.13	
1993	9.5	6.0	1.08	0.11	2,778	1,596	3,800	0.07	0.73	0.12	1.05	0.13	
1994	31.4	5.8	0.88	0.12	5,912	3,010	7,166	0.08	0.82	0.13	1.18	0.13	
1995	38.1	10.8	1.13	0.11	5,976	4,140	9,858	0.09	0.61	0.13	0.87	0.14	
1996	27.8	8.5	1.65	0.11	4,828	2,668	6,353	0.06	0.76	0.12	1.09	0.13	
1997	8.9	10.3	1.16	0.10	2,728	2,110	5,024	0.06	0.54	0.11	0.78	0.12	
1998	21.5	8.0	0.78	0.09	2,891	2,453	5,840	0.14	0.50	0.17	0.71	0.17	
1999	61.4	22.0	0.19	0.23	4,414	6,826	16,251	0.15	0.27	0.18	0.39	0.18	
2000	121.5	57.1	0.28	0.21	8,852	14,163	33,720	0.13	0.26	0.16	0.38	0.17	
2001	93.5	94.3	0.54	0.22	15,611	16,137	38,422	0.14	0.41	0.17	0.58	0.18	
2002	102.5	110.7	0.43	0.22	17,056	19,003	45,246	0.12	0.38	0.16	0.54	0.16	
2003	107.7	146.5	0.28	0.17	20,089	25,929	61,736	0.09	0.33	0.14	0.47	0.14	
2004	133.0	90.8	0.93	0.13	24,497	23,419	55,760	0.06	0.44	0.12	0.63	0.12	
2005	97.4	182.4	0.10	0.11	15,634	32,115	76,464	0.09	0.20	0.13	0.29	0.14	
2006	91.5	163.6	0.21	0.13	8,819	29,905	71,203	0.08	0.12	0.13	0.18	0.13	
Mean7906	43.2	38.1	0.77	0.03	7,181	8,038	19,139	0.03	0.54	0.03	0.77	0.03	
Mean7994	19.1	10.1	0.88	0.03	4,354	2,888	6,876	0.02	0.64	0.02	0.92	0.04	
Mean9506	75.4	0.6	0.05	10,950	14,906	35,490	0.03	0.40	0.04	0.57	0.05		

Table B5-4 continued  
(b) Georges Bank

	<b>80-100.8</b>	<b>100.8+</b>	<b>SurveyF</b>	<b>SE</b>	<b>Landings</b>	<b>MinEBms</b>	<b>Ebms</b>	<b>CV</b>	<b>CBI</b>	<b>CV</b>	<b>RescaledF</b>	<b>CV</b>
1982	7.2	7.7	0.64	0.24	6,322	2,429	6,747	0.12	0.94	0.15	0.87	0.17
1983	5.7	7.1	0.29	0.31	4,284	2,509	6,970	0.10	0.61	0.14	0.57	0.16
1984	6.9	8.7	0.42	0.29	3,043	1,958	5,439	0.10	0.56	0.14	0.52	0.16
1985	6.4	6.4	0.79	0.40	2,894	2,272	6,310	0.14	0.46	0.17	0.43	0.19
1986	8.2	7.6	0.42	0.29	4,438	2,384	6,621	0.09	0.67	0.13	0.62	0.16
1987	18.2	7.3	0.67	0.18	4,851	3,461	9,614	0.13	0.50	0.16	0.47	0.18
1988	18.9	6.4	1.28	0.21	6,054	2,812	7,812	0.10	0.77	0.14	0.72	0.16
1989	5.1	6.9	1.20	0.22	5,661	1,401	3,891	0.32	1.46	0.34	1.35	0.35
1990	38.1	7.0	0.45	0.18	9,982	3,511	9,753	0.22	1.02	0.24	0.95	0.25
1991	18.8	21.6	0.63	0.28	9,311	2,997	8,326	0.09	1.12	0.14	1.04	0.16
1992	18.2	15.4	0.87	0.16	8,238	3,764	10,457	0.17	0.79	0.19	0.73	0.21
1993	6.4	15.0	0.70	0.21	3,655	1,297	3,604	0.10	1.01	0.14	0.94	0.16
1994	8.9	17.6	0.10	0.15	1,205	1,522	4,229	0.12	0.28	0.16	0.27	0.17
1995	6.3	28.0	-0.15	0.24	1,199	1,955	5,430	0.12	0.22	0.15	0.21	0.17
1996	18.7	21.5	0.36	0.23	2,061	4,568	12,688	0.14	0.16	0.17	0.15	0.19
1997	41.5	30.6	0.17	0.24	2,053	6,084	16,900	0.14	0.12	0.17	0.11	0.19
1998	45.9	70.6	-0.08	0.41	2,039	17,818	49,493	0.39	0.04	0.40	0.04	0.41
1999	46.1	55.3	0.65	0.40	5,085	12,928	35,911	0.31	0.14	0.32	0.13	0.33
2000	83.3	227.6	-0.91	0.30	5,039	23,790	66,084	0.20	0.08	0.23	0.07	0.24
2001	84.9	82.7	1.22	0.26	4,597	24,426	67,849	0.15	0.07	0.18	0.06	0.20
2002	83.5	128.7	0.16	0.21	5,541	31,380	87,166	0.13	0.06	0.17	0.06	0.18
2003	20.2	136.2	0.34	0.20	4,823	28,510	79,195	0.13	0.06	0.17	0.06	0.18
2004	50.0	162.4	-0.14	0.18	4,357	38,419	106,721	0.11	0.04	0.15	0.04	0.17
2005	31.0	141.7	0.00	0.16	9,502	30,882	85,783	0.11	0.11	0.15	0.10	0.17
2006	22.4	99.5	0.66	0.16	17,286	24,271	67,418	0.11	0.26	0.15	0.24	0.17
<i>Mean8206</i>	28.0	52.8	0.43	0.05	5,341	11,094	30,816	0.05	0.46	0.06	0.43	0.06
<i>Mean8294</i>	12.8	10.4	0.64	0.07	5,380	2,486	6,905	0.04	0.78	0.06	0.71	0.07
<i>Mean9506</i>	44.5	98.8	0.19	0.08	5,299	20,419	56,720	0.05	0.11	0.06	0.11	0.07

Table B5-4 continued  
(c) Whole stock

	<b>SurveyF</b>	<b>Landings</b>	<b>Ebms</b>	<b>CBI</b>	<b>RescaledF</b>	<b>CV</b>
1982	0.63	7933	11396	0.70	<b>0.74</b>	0.08
1983	0.63	7392	11047	0.67	<b>0.72</b>	0.07
1984	0.44	6718	9424	0.71	<b>0.91</b>	0.07
1985	0.65	6170	11573	0.53	<b>0.64</b>	0.08
1986	0.41	7797	15779	0.49	<b>0.56</b>	0.07
1987	0.95	12654	17603	0.72	<b>0.91</b>	0.08
1988	0.87	12232	21690	0.56	<b>0.67</b>	0.07
1989	1.43	13634	14561	0.94	<b>1.13</b>	0.13
1990	1.02	16417	19358	0.85	<b>0.96</b>	0.10
1991	0.92	16323	16034	1.02	<b>1.16</b>	0.08
1992	0.96	13192	15073	0.88	<b>0.91</b>	0.09
1993	0.89	6433	7404	0.87	<b>1.00</b>	0.07
1994	0.64	7116	11395	0.62	<b>0.90</b>	0.08
1995	0.79	7175	15288	0.47	<b>0.69</b>	0.08
1996	0.87	6889	19041	0.36	<b>0.52</b>	0.08
1997	0.42	4780	21924	0.22	<b>0.28</b>	0.08
1998	0.09	4930	55334	0.09	<b>0.17</b>	0.15
1999	0.43	9499	52162	0.18	<b>0.25</b>	0.13
2000	-0.43	13891	99805	0.14	<b>0.19</b>	0.10
2001	0.92	20208	106272	0.19	<b>0.29</b>	0.09
2002	0.28	22597	132412	0.17	<b>0.27</b>	0.09
2003	0.30	24911	140932	0.18	<b>0.31</b>	0.08
2004	0.43	28855	162481	0.18	<b>0.35</b>	0.07
2005	0.43	25136	162481	0.15	<b>0.22</b>	0.08
2006	0.06	26105	162247	0.16	<b>0.20</b>	0.07
<i>Mean8206</i>	0.60	13160	52509	0.48	<b>0.75</b>	
<i>Mean8294</i>	0.82	10506	14245	0.74	<b>0.87</b>	
<i>Mean9506</i>	0.38	16248	94198	0.21	<b>0.33</b>	

Table B5-5. CASA model estimates for sea scallop recruitment, stock biomass, stock abundance (*top panel*), catch numbers, fishable biomass and fully recruited fishing mortality (*lower panel*) on Georges Bank (1982-2006), in the Mid-Atlantic Bight (1975-2006), and for the whole stock (1982-2006). CVs for all estimates are given in a separate table.

Year	Recruitment (January 1, millions)			Stock biomass (January 1, 40+ mm SL, mt)			Stock abundance (January 1, 40+ mm SL, millions)		
	Georges Bank	Mid- Atlantic Bight	Whole stock	Georges Bank	Mid- Atlantic Bight	Whole stock	Georges Bank	Mid- Atlantic Bight	Whole stock
1975	--	--	--	--	11,318	--	--	571	--
1976	--	413	--	--	11,865	--	--	753	--
1977	--	250	--	--	11,319	--	--	824	--
1978	--	109	--	--	11,897	--	--	750	--
1979	--	71	--	--	9,546	--	--	528	--
1980	--	164	--	--	8,061	--	--	469	--
1981	--	136	--	--	7,664	--	--	473	--
1982	--	135	--	10,966	8,907	19,873	1,828	524	2,351
1983	181	208	388	11,457	9,221	20,678	1,141	582	1,723
1984	269	305	574	9,465	8,130	17,595	752	654	1,406
1985	369	780	1,149	10,898	7,739	18,637	832	1,044	1,875
1986	826	732	1,558	13,078	10,508	23,585	1,237	1,446	2,684
1987	640	984	1,624	14,782	15,503	30,284	1,445	1,921	3,365
1988	478	647	1,125	16,623	15,698	32,321	1,413	1,823	3,236
1989	1,111	837	1,948	17,453	17,491	34,944	1,720	1,894	3,614
1990	859	423	1,281	20,955	16,211	37,166	2,005	1,600	3,605
1991	1,004	231	1,235	18,876	14,837	33,713	1,941	1,206	3,147
1992	243	217	460	14,476	10,366	24,842	1,317	804	2,121
1993	315	1,145	1,460	7,894	8,780	16,674	736	1,293	2,029
1994	265	682	947	5,923	13,632	19,554	587	1,747	2,334
1995	658	303	960	9,249	14,359	23,608	967	1,435	2,402
1996	352	103	455	14,989	12,177	27,167	1,220	925	2,146
1997	418	500	918	19,500	10,027	29,526	1,313	881	2,194
1998	752	2,048	2,800	24,385	14,202	38,587	1,641	2,257	3,898
1999	752	1,695	2,447	31,783	27,069	58,852	2,054	3,599	5,653
2000	1,850	1,451	3,302	39,549	44,664	84,212	3,093	4,418	7,511
2001	470	1,444	1,915	52,681	59,007	111,688	3,366	4,825	8,191
2002	367	1,121	1,488	64,628	64,744	129,372	3,174	4,657	7,831
2003	744	3,211	3,956	72,724	70,580	143,305	3,186	6,014	9,200
2004	262	312	575	78,623	78,448	157,071	2,987	5,563	8,550
2005	453	1,776	2,229	84,106	78,387	162,493	2,935	5,360	8,295
2006	225	370	594	81,047	85,161	166,208	2,637	4,833	7,469

Table B5-5 continued

Year	Catch numbers (all sizes, millions)			Fishable mean abundance ( all sizes, millions)			Fully recruited fishing mortality (F, annual)		
	Georges Bank	Mid- Atlantic Bight	Whole stock	Georges Bank	Mid- Atlantic Bight	Whole stock	Georges Bank	Mid- Atlantic Bight	Whole stock
1975	--	67	--	--	393	--	--	0.171	--
1976	--	138	--	--	349	--	--	0.395	--
1977	--	134	--	--	424	--	--	0.316	--
1978	--	230	--	--	437	--	--	0.526	--
1979	--	145	--	--	341	--	--	0.427	--
1980	--	90	--	--	266	--	--	0.339	--
1981	--	36	--	--	290	--	--	0.125	--
1982	298	75	373	127	300	427	2.346	0.249	0.873
1983	431	142	573	455	271	726	0.947	0.525	0.789
1984	149	180	330	383	220	603	0.390	0.819	0.547
1985	153	196	349	354	216	569	0.432	0.909	0.613
1986	239	262	501	342	401	742	0.701	0.653	0.675
1987	300	585	885	475	490	964	0.631	1.196	0.918
1988	371	499	870	557	591	1,148	0.667	0.843	0.758
1989	322	599	921	520	589	1,109	0.619	1.018	0.831
1990	592	500	1,092	560	590	1,150	1.057	0.847	0.949
1991	619	496	1,115	465	503	968	1.331	0.987	1.152
1992	586	312	898	363	328	691	1.614	0.952	1.300
1993	268	174	442	223	251	474	1.201	0.696	0.934
1994	74	499	573	234	439	673	0.317	1.136	0.851
1995	57	512	569	346	555	900	0.166	0.922	0.632
1996	125	343	468	344	469	813	0.363	0.731	0.576
1997	138	136	275	452	270	722	0.306	0.504	0.380
1998	111	140	250	470	274	744	0.236	0.510	0.337
1999	185	259	444	603	544	1,147	0.308	0.475	0.387
2000	167	536	703	747	1,201	1,948	0.223	0.447	0.361
2001	185	838	1,023	1,048	1,629	2,677	0.177	0.515	0.382
2002	224	745	969	999	1,251	2,250	0.224	0.596	0.431
2003	206	812	1,019	1,068	1,331	2,399	0.193	0.610	0.425
2004	129	955	1,084	1,576	1,305	2,881	0.082	0.731	0.376
2005	250	685	935	1,580	1,678	3,258	0.158	0.408	0.287
2006	431	368	799	1,390	2,105	3,495	0.310	0.175	0.229

Table B5-6. Coefficients of variation for CASA model estimates of sea scallop recruitment, stock biomass, stock abundance (top panel), catch numbers, fishable biomass and fully recruited fishing mortality (bottom panel) on Georges Bank (1982-2006), in the Mid-Atlantic Bight (1975-2006), and for the whole stock (1982-2006).

Year	Recruitment (January 1, millions)			Stock biomass (January 1, 40+ mm SL, mt)			Stock abundance (January 1, 40+ mm SL, millions)		
	Georges Bank	Mid- Atlantic Bight	Whole stock	Georges Bank	Mid- Atlantic Bight	Whole stock	Georges Bank	Mid- Atlantic Bight	Whole stock
1975	--	--	--	--	0.042	--	--	0.042	--
1976	--	0.116	--	--	0.043	--	--	0.037	--
1977	--	0.137	--	--	0.037	--	--	0.034	--
1978	--	0.169	--	--	0.032	--	--	0.031	--
1979	--	0.165	--	--	0.033	--	--	0.031	--
1980	--	0.097	--	--	0.037	--	--	0.033	--
1981	--	0.125	--	--	0.040	--	--	0.036	--
1982	--	0.148	--	0.030	0.037	0.024	0.030	0.037	0.025
1983	0.173	0.126	0.105	0.042	0.039	0.029	0.038	0.039	0.029
1984	0.145	0.143	0.102	0.048	0.045	0.033	0.043	0.051	0.033
1985	0.163	0.111	0.092	0.051	0.050	0.036	0.051	0.054	0.038
1986	0.119	0.151	0.095	0.047	0.046	0.033	0.048	0.044	0.032
1987	0.151	0.113	0.091	0.044	0.039	0.029	0.044	0.038	0.029
1988	0.189	0.152	0.119	0.044	0.039	0.030	0.046	0.038	0.030
1989	0.125	0.112	0.086	0.042	0.038	0.028	0.047	0.035	0.029
1990	0.159	0.137	0.116	0.035	0.036	0.025	0.046	0.036	0.030
1991	0.092	0.147	0.080	0.035	0.037	0.025	0.039	0.035	0.027
1992	0.185	0.137	0.117	0.037	0.038	0.027	0.038	0.038	0.028
1993	0.109	0.059	0.052	0.040	0.040	0.028	0.039	0.036	0.027
1994	0.123	0.090	0.073	0.044	0.034	0.027	0.042	0.032	0.026
1995	0.071	0.128	0.063	0.041	0.036	0.027	0.034	0.032	0.023
1996	0.113	0.200	0.098	0.037	0.036	0.026	0.033	0.035	0.024
1997	0.101	0.108	0.074	0.037	0.043	0.029	0.036	0.048	0.029
1998	0.080	0.059	0.048	0.039	0.039	0.028	0.038	0.036	0.026
1999	0.098	0.081	0.064	0.040	0.030	0.026	0.041	0.029	0.024
2000	0.069	0.101	0.059	0.044	0.028	0.025	0.042	0.027	0.023
2001	0.210	0.102	0.093	0.047	0.027	0.026	0.046	0.026	0.024
2002	0.181	0.122	0.102	0.051	0.028	0.029	0.050	0.028	0.026
2003	0.102	0.061	0.053	0.056	0.030	0.032	0.055	0.034	0.029
2004	0.183	0.240	0.155	0.061	0.036	0.035	0.061	0.039	0.033
2005	0.134	0.088	0.075	0.065	0.047	0.041	0.065	0.047	0.038
2006	0.226	0.256	0.181	0.075	0.057	0.047	0.074	0.056	0.045

Table B5-6 continued

Year	Catch numbers (all sizes, millions)			Fishable mean abundance ( all sizes, millions)			Fully recruited fishing mortality (F, annual)		
	Georges Bank	Mid- Atlantic Bight	Whole stock	Georges Bank	Mid- Atlantic Bight	Whole stock	Georges Bank	Mid- Atlantic Bight	Whole stock
1975	--	0.050	--	--	0.046	--	--	0.065	--
1976	--	0.050	--	--	0.055	--	--	0.069	--
1977	--	0.050	--	--	0.058	--	--	0.065	--
1978	--	0.050	--	--	0.045	--	--	0.055	--
1979	--	0.050	--	--	0.039	--	--	0.056	--
1980	--	0.050	--	--	0.043	--	--	0.062	--
1981	--	0.050	--	--	0.046	--	--	0.067	--
1982	0.050	0.050	0.041	0.072	0.044	0.038	0.070	0.065	0.190
1983	0.050	0.050	0.040	0.056	0.050	0.040	0.077	0.066	0.103
1984	0.050	0.050	0.036	0.060	0.068	0.046	0.082	0.084	0.138
1985	0.050	0.050	0.036	0.068	0.094	0.055	0.087	0.112	0.178
1986	0.050	0.050	0.035	0.083	0.082	0.058	0.099	0.098	0.139
1987	0.050	0.050	0.037	0.070	0.077	0.052	0.089	0.095	0.138
1988	0.050	0.050	0.036	0.065	0.065	0.046	0.082	0.087	0.121
1989	0.050	0.050	0.037	0.074	0.060	0.047	0.090	0.080	0.118
1990	0.050	0.050	0.035	0.065	0.048	0.040	0.075	0.068	0.103
1991	0.050	0.050	0.036	0.057	0.044	0.035	0.060	0.056	0.084
1992	0.050	0.050	0.037	0.051	0.051	0.036	0.050	0.063	0.078
1993	0.050	0.050	0.036	0.054	0.070	0.045	0.060	0.089	0.102
1994	0.050	0.050	0.044	0.061	0.063	0.046	0.076	0.078	0.108
1995	0.050	0.050	0.045	0.054	0.047	0.035	0.072	0.064	0.095
1996	0.050	0.050	0.039	0.066	0.043	0.037	0.079	0.062	0.093
1997	0.050	0.050	0.035	0.063	0.071	0.047	0.086	0.084	0.131
1998	0.050	0.050	0.036	0.074	0.078	0.055	0.098	0.094	0.158
1999	0.050	0.050	0.036	0.082	0.079	0.057	0.084	0.091	0.130
2000	0.050	0.050	0.040	0.089	0.065	0.053	0.091	0.077	0.111
2001	0.050	0.050	0.042	0.092	0.052	0.048	0.093	0.065	0.097
2002	0.050	0.050	0.040	0.180	0.071	0.089	0.189	0.078	0.146
2003	0.050	0.050	0.041	0.188	0.067	0.092	0.203	0.074	0.141
2004	0.050	0.050	0.044	0.082	0.070	0.055	0.091	0.075	0.147
2005	0.050	0.050	0.039	0.083	0.082	0.058	0.093	0.091	0.139
2006	0.050	0.050	0.035	0.098	0.076	0.060	0.109	0.092	0.164

Table B5-7. Configuration of basecase CASA models for sea scallops in the Mid-Atlantic Bight and Georges Bank.

Category	Mid-Atlantic Bight (MAB)	Georges Bank (GBK)	Explanation
<b>Model configuration</b>			
Modeled years	1975-2006	1982-2006	Models start in first year with dredge survey data; Unlined dredge survey for MAB starts in 1975; Lined dredge survey for GBK with complete coverage starts 1982
L-infinity (mm SH) Population shell height bins (mm SH)	131.6 5	147 5	New growth studies based on shell increments (used only to define plus group in model) Same as resolution of shell height composition data for lined dredge survey
First size in model (mm SH)	20	20	Biomass and fishing mortality estimates are for 40+ mm SH; Starting model at 20 mm SH allows for 20 mm of "burn-in" before recruits enter size groups (40+ mm SH) used to calculate biomass and fishing mortality
Size range new recruits (mm)	20-69.9 (shell height size groups 1-10)	20-69.9 (shell height size groups 1-10)	Based on inspection of trawl survey shell height composition data for years with strong recruitment; model estimates a unimodal beta distribution with two parameters to represent the shell height distribution for new recruits across this range of sizes
<b>Population dynamics</b>			
Stock shell height/meat weight parameters	a = -10.7; b = 2.942	a = -12.2484; b = 3.2641	Same as previous assessment; based on dredge survey data collected during June
Incidental mortality multiplier	0.04	0.15	Total mortality of all size groups is increased by this proportion of full recruited F, based on published studies although available information is limited and uncertain; assumed same for all size groups
Population shell height composition in 1st year	1975 unlined dredge survey, adjusted for selectivity	1982 lined dredge survey, no adjustments	Not estimable in model
Natural mortality rate (y-1)	0.1	0.1	Same for all years and shell height groups
Growth matrix method	Observed increments (n=2,244)	Observed increments (n=2,692)	Observed increment from each are used to form growth transition matrix; Different increment data sets and transition matrices for GBK and MAB
Size range used to summarize stock biomass and mortality rates	40-130+	40-145+	Survey data reliable for 40+ mm SH
Fecundity at size			Annual fecundity at size parameters from McGarvey et al. (1992)

Table B5-7 continued.

<b>Commercial</b>									
Fishery shell height/meat weight parameters		Population shell height/meat weight are modified by annual anomalies based on observer data and seasonal landings patterns to account for seasonal patterns in shell height/meat weight relationships, meat loss during shucking and absorption of water during storage							
Commercial LPUE	1992-2006	Predicted values are a nonlinear function of abundance and biomass							
	1975-2006 1982-1995 (logistic); 1996-1998 (domed); 1999-2001 (logistic); 2002-2003 (domed); 2004-2006 (logistic)	Logistic patterns used for MAB in all years and GBK when fishery had access to entire scallop size range; Dome (double logistic) pattern used for GBK when substantial numbers of large scallops were in closed areas not open to fishing							
Fishery selectivity periods	1975-1981; 1982-1995; 1997-2001; 2002-2006 (all logistic)	The average weight of scallops in the commercial catch was calculated in the model based on predicted shell heights and survey shell-height meat weight relationships, with adjustments based on annual mean meat weight anomalies.							
Shell height-meat weight			Likelihood calculations use CV for stratified random means; 40+ mm SH; Flat selectivity pattern (not estimated)						
<b>Survey trends</b>			Likelihood calculations use CV for stratified random means; 40+ mm SH; Flat selectivity pattern; Assumed 100% efficiency; Densities ( $N/m^2$ ) converted to swept area biomass based on area covered by dredge survey, then multiplied by 0.5 for use with prior (see below)						
NEFSC lined dredge	1979-2006	Likelihood calculated based on internally estimated variance; 40+ mm SH; Logistic selectivity pattern							
SMAST video (small camera)	2003-2006	Less reliable than dredge or video surveys (particularly for GBK); Used only for comparison, did not affect model estimates; Likelihood calculated based on internally estimated variance; 40+ mm SH; Domed (double logistic) selectivity pattern							
Winter bottom trawl	1992-2006	Likelihood calculations use CV for stratified random means; 40+ mm SH; Logistic selectivity pattern fixed per reanalysis of paired tow experiments in Serchuk and Smolowicz (1980) using Millars (1980) SELECT model							
Fall and spring bottom trawl	1964-2006 (fall); 1968-2006 (spring)	NA							
10 ft unlined dredge	1975-1976, 1978								

Table B5-7 continued.

<b>Shell height composition data</b>				
Dredge and video survey shell height composition	All years with trend data	All years with trend data	Five mm shell height groups; Assumed effective sample size used in likelihood calculations was adjusted based on preliminary model fits; Assumed standard deviation for shell height measurement errors = 1.6 mm for dredge survey and 6 mm for video survey	
Bottom trawl shell height composition	All years with trend data	All years with trend data	Ten mm shell height groups; Assumed effective sample size used in likelihood calculations was adjusted based on preliminary model fits; Assumed standard deviation for shell height measurement errors = 1.6 mm	
Commercial shell height composition	1969-1984 (port samples); 1992-2006 (observers)	1982-1984 (port samples); 1992-2006 (observers)	Five mm shell height groups; Assumed effective sample size used in likelihood calculations was adjusted based on preliminary model fits; Assumed standard deviation for shell height measurement errors = 6 mm	
<b>Prior information</b>			Video survey trend data were scaled up to swept area biomass and then multiplied by 0.5 before use in model assuming 100% sampling efficiency, a flat survey selectivity pattern and areas of grounds covered in dredge survey (see above); Under these conditions, the expected survey scaling parameter is 0.5; 20% CV is ad-hoc but based on standard deviation of eight video-dredge survey comparisons and meant to imply a moderate level of uncertainty	
		Beta distribution with mean 0.5 and CV=20%		
	Prior on SMAST survey scaling parameter (catchability coefficient)			

Table B5-8. Parameters, standard errors, and CVs estimated in the basecase model for sea scallops on Georges Bank during 1982-2006.

ID	Parameter	Estimate	Standard error	CV
1	Log N first year	21.3870	0.0299	0.00
2	Log beta distribution parameter for shell height distribution of new recruits	-0.6388	0.4253	0.67
3	Log beta distribution parameter for shell height distribution of new recruits	-1.9992	0.6445	0.32
4	Log mean recruitment	20.0020	0.0306	0.00
5	Log survey scaling parameter for lined dredge survey	-2.4385	0.0517	0.02
6	Log survey scaling parameter for video small camera survey	-0.4984	0.0795	0.16
7	Log mean F	-0.8534	0.0365	0.04
8	Log LPUE scaling parameter	-2.9814	0.0624	0.02
9	Log LPUE shape parameter	-2.8181	1.3191	0.47
10	Log fishery selectivity parameter 1982-1995 (logistic)	3.5776	0.1877	0.05
11	Log fishery selectivity parameter 1982-1995 (logistic)	-0.7623	0.1916	0.25
12	Log fishery selectivity parameter 1996-1998 (domed, double logistic)	3.1260	0.0973	0.03
13	Log fishery selectivity parameter 1996-1998 (domed, double logistic)	-1.3862	0.1090	0.08
14	Log fishery selectivity parameter 1996-1998 (domed, double logistic)	-4.9991	2.8192	0.56
15	Log fishery selectivity parameter 1996-1998 (domed, double logistic)	-3.1237	0.1567	0.05
16	Log fishery selectivity parameter 1999-2001 (logistic)	2.8067	0.1696	0.06
17	Log fishery selectivity parameter 1999-2001 (logistic)	-1.7953	0.1876	0.10
18	Log fishery selectivity parameter 2002-2003 (domed, double logistic)	4.0713	0.6400	0.16
19	Log fishery selectivity parameter 2002-2003 (domed, double logistic)	-0.5435	0.6571	1.21
20	Log fishery selectivity parameter 2002-2003 (domed, double logistic)	2.6844	0.5917	0.22
21	Log fishery selectivity parameter 2002-2003 (domed, double logistic)	-2.1137	0.4999	0.24
22	Log fishery selectivity parameter 2004-2006 (logistic)	3.2284	0.2959	0.09
23	Log fishery selectivity parameter 2004-2006 (logistic)	-1.4596	0.3071	0.21
24	Log F deviation 1982	1.7063	0.0736	0.04
25	Log F deviation 1983	0.7985	0.0754	0.09
26	Log F deviation 1984	-0.0893	0.0781	0.87
27	Log F deviation 1985	0.0146	0.0807	5.53
28	Log F deviation 1986	0.4978	0.0903	0.18
29	Log F deviation 1987	0.3929	0.0815	0.21
30	Log F deviation 1988	0.4486	0.0771	0.17
31	Log F deviation 1989	0.3733	0.0858	0.23
32	Log F deviation 1990	0.9088	0.0749	0.08
33	Log F deviation 1991	1.1395	0.0655	0.06
34	Log F deviation 1992	1.3323	0.0580	0.04
35	Log F deviation 1993	1.0368	0.0629	0.06
36	Log F deviation 1994	-0.2955	0.0744	0.25
37	Log F deviation 1995	-0.9403	0.0707	0.08
38	Log F deviation 1996	-0.1595	0.0755	0.47

Table B5-8 continued.

39	Log F deviation 1997	-0.3299	0.0809	0.25
40	Log F deviation 1998	-0.5921	0.0927	0.16
41	Log F deviation 1999	-0.3259	0.0753	0.23
42	Log F deviation 2000	-0.6465	0.0804	0.12
43	Log F deviation 2001	-0.8802	0.0815	0.09
44	Log F deviation 2002	-0.6432	0.1731	0.27
45	Log F deviation 2003	-0.7901	0.1868	0.24
46	Log F deviation 2004	-1.6484	0.0768	0.05
47	Log F deviation 2005	-0.9907	0.0780	0.08
48	Log F deviation 2006	-0.3177	0.0921	0.29
49	Log recruitment deviation 1983	-0.9893	0.1688	0.17
50	Log recruitment deviation 1984	-0.5931	0.1437	0.24
51	Log recruitment deviation 1985	-0.2772	0.1613	0.58
52	Log recruitment deviation 1986	0.5302	0.1225	0.23
53	Log recruitment deviation 1987	0.2751	0.1528	0.56
54	Log recruitment deviation 1988	-0.0176	0.1863	10.57
55	Log recruitment deviation 1989	0.8262	0.1300	0.16
56	Log recruitment deviation 1990	0.5687	0.1566	0.28
57	Log recruitment deviation 1991	0.7252	0.0985	0.14
58	Log recruitment deviation 1992	-0.6924	0.1815	0.26
59	Log recruitment deviation 1993	-0.4355	0.1112	0.26
60	Log recruitment deviation 1994	-0.6060	0.1202	0.20
61	Log recruitment deviation 1995	0.3021	0.0732	0.24
62	Log recruitment deviation 1996	-0.3227	0.1121	0.35
63	Log recruitment deviation 1997	-0.1527	0.0973	0.64
64	Log recruitment deviation 1998	0.4361	0.0763	0.17
65	Log recruitment deviation 1999	0.4364	0.0920	0.21
66	Log recruitment deviation 2000	1.3361	0.0640	0.05
67	Log recruitment deviation 2001	-0.0337	0.2072	6.14
68	Log recruitment deviation 2002	-0.2821	0.1729	0.61
69	Log recruitment deviation 2003	0.4255	0.0946	0.22
70	Log recruitment deviation 2004	-0.6168	0.1725	0.28
71	Log recruitment deviation 2005	-0.0713	0.1244	1.75
72	Log recruitment deviation 2006	-0.7711	0.2133	0.28

Table B5-9. Parameters, standard errors, and CVs estimated in the basecase model for sea scallop sin the Mid-Atlantic Bight during 1975-2006.

ID	Parameter	Estimate	Standard error	CV
1	Log N first year	20.1720	0.0420	0.00
	Log beta distribution parameter for shell height distribution of new recruits	0.4947	0.1284	0.26
2	Log beta distribution parameter for shell height distribution of new recruits	0.1924	0.1167	0.61
3	Log mean recruitment	19.9660	0.0197	0.00
4	Log survey scaling parameter for lined dredge survey	-2.4483	0.0261	0.01
5	Log survey scaling parameter for video small camera survey	-0.4457	0.0686	0.15
6	Log survey scaling parameter for winter bottom trawl survey	-3.8376	0.0878	0.02
7	Log survey scaling parameter for unlined dredge survey	-1.6114	0.1289	0.08
8	Log selectivity parameter for winter bottom trawl survey (logistic)	2.1731	0.2215	0.10
9	Log selectivity parameter for winter bottom trawl survey (logistic)	-1.8471	0.2392	0.13
10	Log mean F	-0.6134	0.0266	0.04
11	Log LPUE scaling parameter	-2.4049	0.1715	0.07
12	Log LPUE shape parameter	0.0779	0.2555	3.28
13	Log fishery selectivity parameter 1975-1981 (logistic)	2.9808	0.2115	0.07
14	Log fishery selectivity parameter 1975-1981 (logistic)	-1.2975	0.2258	0.17
15	Log fishery selectivity parameter 1982-1995 (logistic)	3.1507	0.1119	0.04
16	Log fishery selectivity parameter 1982-1995 (logistic)	-1.2083	0.1189	0.10
17	Log fishery selectivity parameter 1997-2001 (logistic)	3.0164	0.0871	0.03
18	Log fishery selectivity parameter 1997-2001 (logistic)	-1.5086	0.0943	0.06
19	Log fishery selectivity parameter 2002-2006 (logistic)	3.0759	0.1205	0.04
20	Log fishery selectivity parameter 2002-2006 (logistic)	-1.5409	0.1304	0.08
21	Log F deviation 1975	-1.1534	0.0661	0.06
22	Log F deviation 1976	-0.3152	0.0693	0.22
23	Log F deviation 1977	-0.5374	0.0645	0.12
24	Log F deviation 1978	-0.0289	0.0552	1.91
25	Log F deviation 1979	-0.2376	0.0554	0.23
26	Log F deviation 1980	-0.4680	0.0593	0.13
27	Log F deviation 1981	-1.4691	0.0629	0.04
28	Log F deviation 1982	-0.7775	0.0606	0.08
29	Log F deviation 1983	-0.0312	0.0614	1.97
30	Log F deviation 1984	0.4141	0.0758	0.18
31	Log F deviation 1985	0.5184	0.1025	0.20
32	Log F deviation 1986	0.1876	0.0892	0.48
33	Log F deviation 1987	0.7921	0.0891	0.11
34	Log F deviation 1988	0.4431	0.0816	0.18
35	Log F deviation 1989	0.6315	0.0766	0.12
36	Log F deviation 1990	0.4471	0.0672	0.15
37	Log F deviation 1991	0.5999	0.0563	0.09
38	Log F deviation 1992	0.5641	0.0610	0.11
39	Log F deviation 1993	0.2510	0.0852	0.34
40	Log F deviation 1994	0.7407	0.0745	0.10
41	Log F deviation 1995	0.5324	0.0618	0.12
42	Log F deviation 1996	0.3007	0.0590	0.20
43	Log F deviation 1997	-0.0719	0.0769	1.07
44	Log F deviation 1998	-0.0603	0.0864	1.43

Table B5-9 continued

46	Log F deviation 1999	-0.1305	0.0835	0.64
47	Log F deviation 2000	-0.1924	0.0721	0.37
48	Log F deviation 2001	-0.0511	0.0617	1.21
49	Log F deviation 2002	0.0952	0.0735	0.77
50	Log F deviation 2003	0.1194	0.0690	0.58
51	Log F deviation 2004	0.3004	0.0692	0.23
52	Log F deviation 2005	-0.2832	0.0837	0.30
53	Log F deviation 2006	-1.1299	0.0860	0.08
54	Log recruitment deviation 1976	-0.1280	0.1159	0.91
55	Log recruitment deviation 1977	-0.6291	0.1383	0.22
56	Log recruitment deviation 1978	-1.4576	0.1678	0.12
57	Log recruitment deviation 1979	-1.8824	0.1627	0.09
58	Log recruitment deviation 1980	-1.0493	0.0984	0.09
59	Log recruitment deviation 1981	-1.2355	0.1246	0.10
60	Log recruitment deviation 1982	-1.2455	0.1465	0.12
61	Log recruitment deviation 1983	-0.8155	0.1268	0.16
62	Log recruitment deviation 1984	-0.4310	0.1423	0.33
63	Log recruitment deviation 1985	0.5085	0.1145	0.23
64	Log recruitment deviation 1986	0.4442	0.1509	0.34
65	Log recruitment deviation 1987	0.7404	0.1151	0.16
66	Log recruitment deviation 1988	0.3209	0.1502	0.47
67	Log recruitment deviation 1989	0.5787	0.1134	0.20
68	Log recruitment deviation 1990	-0.1046	0.1367	1.31
69	Log recruitment deviation 1991	-0.7094	0.1461	0.21
70	Log recruitment deviation 1992	-0.7706	0.1345	0.17
71	Log recruitment deviation 1993	0.8925	0.0623	0.07
72	Log recruitment deviation 1994	0.3743	0.0900	0.24
73	Log recruitment deviation 1995	-0.4386	0.1283	0.29
74	Log recruitment deviation 1996	-1.5190	0.1952	0.13
75	Log recruitment deviation 1997	0.0643	0.1067	1.66
76	Log recruitment deviation 1998	1.4737	0.0627	0.04
77	Log recruitment deviation 1999	1.2844	0.0826	0.06
78	Log recruitment deviation 2000	1.1293	0.1015	0.09
79	Log recruitment deviation 2001	1.1245	0.1030	0.09
80	Log recruitment deviation 2002	0.8712	0.1189	0.14
81	Log recruitment deviation 2003	1.9235	0.0609	0.03
82	Log recruitment deviation 2004	-0.4066	0.2325	0.57
83	Log recruitment deviation 2005	1.3312	0.0861	0.06
84	Log recruitment deviation 2006	-0.2387	0.2479	1.04

Table B5-10. Likelihood profile analysis for the basecase Georges Bank CASA model. For ease of interpretation, the likelihood for each type of data and constraint in the basecase model was subtracted from the likelihoods for the same type of data or constraint at each point.

Data type or constraint	Survey scaling parameter for small camera video survey								
	0.31	0.41	0.51	0.60	Basecase 0.61	0.70	0.80	0.90	0.98
Fishing mortality 2006	<b>0.18</b>	0.22	0.27	0.31	0.31	0.35	0.39	0.43	0.46
Stock biomass 2006 (mt)	132,919	108,337	92,633	81,798	81,088	73,374	66,930	61,843	<b>58,486</b>
Neg. log likelihood for major components									
<i>Commercial catch weight</i>	0.07	<b>-0.07</b>	-0.07	-0.01	0.00	0.09	0.21	0.34	0.46
<i>Commercial LPUE</i>	<b>-0.05</b>	-0.03	-0.02	0.00	0.00	0.01	0.03	0.04	0.05
<i>Recruitment deviations</i>	0.24	<b>-0.30</b>	-0.29	-0.03	0.00	0.40	0.89	1.43	1.86
<i>Efficiency prior - camera survey</i>	1.18	-0.15	<b>-0.52</b>	-0.07	0.00	1.39	4.36	10.62	26.79
<i>Total for survey trends</i>	20.13	6.98	1.39	<b>-0.01</b>	0.00	1.21	4.24	8.52	12.59
<i>Total for shell height composition</i>	8.07	4.56	2.02	0.13	0.00	-1.40	-2.58	-3.49	-4.08
Total major components (unweighted)	29.63	10.98	2.51	0.01	0.00	1.70	7.16	17.46	37.68
Survey trends									
<i>Dredge survey</i>	12.37	4.21	0.84	0.00	<b>0.00</b>	0.63	2.19	4.32	6.28
<i>Camera survey</i>	7.76	2.77	0.55	<b>-0.01</b>	0.00	0.58	2.05	4.20	6.31
Shell height composition data									
<i>Commercial fishery</i>	1.09	0.65	0.30	0.02	0.00	-0.22	-0.43	-0.61	<b>-0.73</b>
<i>Dredge survey</i>	6.54	3.66	1.61	0.10	0.00	-1.11	-2.03	-2.74	<b>-3.19</b>
<i>Camera survey</i>	0.43	0.24	0.11	0.01	0.00	-0.07	-0.12	-0.15	<b>-0.16</b>

Table B5-11. Likelihood profile analysis for the basecase Mid-Atlantic Bight CASA model. For ease of interpretation, the likelihood for each type of data and constraint in the basecase model was subtracted from the likelihoods for the same type of data or constraint at each point. The table includes likelihoods for NEFSC fall and winter bottom trawl surveys which were included for information only and did not affect model estimates.

Data type or constraint	Survey scaling parameter for small camera video survey								
	0.30	0.40	0.50	0.60	Basecase 0.64	0.70	0.80	0.90	1.00
Fishing mortality 2006	<b>0.34</b>	0.38	0.41	0.43	0.44	0.45	0.47	0.49	0.50
Stock biomass 2006 (mt)	107,515	96,247	88,483	82,709	80,771	78,193	74,534	71,490	<b>68,905</b>
Neg. log likelihood for major components									
<i>Commercial catch weight</i>	1.171	0.482	0.155	0.020	0.000	<b>-0.003</b>	0.046	0.141	0.268
<i>Commercial LPUE</i>	0.37	0.24	0.13	0.03	0.00	-0.05	-0.12	-0.19	<b>-0.25</b>
<i>Recruitment deviations</i>	5.69	3.30	1.64	0.41	0.00	-0.54	-1.31	-1.93	<b>-2.45</b>
<i>Efficiency prior - camera survey</i>	0.98	-0.47	<b>-0.90</b>	-0.45	0.00	1.01	3.98	10.23	55.01
<i>Total for survey trends</i>	50.89	22.20	7.82	1.22	0.00	<b>-0.71</b>	0.36	3.42	7.86
<i>Total for shell height composition</i>	<b>-7.26</b>	-5.06	-2.88	-0.80	0.00	1.16	3.01	4.75	6.40
Total major components (unweighted)	51.84	20.70	5.96	0.43	<b>0.00</b>	0.87	5.96	16.41	66.84
Survey trends used to fit model									
<i>Dredge survey</i>	13.73	5.48	1.65	0.17	<b>0.00</b>	0.07	0.81	2.11	3.78
<i>Camera survey</i>	32.27	13.93	4.80	0.71	0.00	<b>-0.33</b>	0.59	2.84	6.00
<i>Winter bottom trawl survey</i>	4.90	2.79	1.37	0.34	0.00	-0.44	-1.05	-1.53	<b>-1.92</b>
<i>Unlined 10 ft scallop dredge survey</i>	<b>-0.02</b>	-0.01	-0.01	0.00	0.00	0.00	0.01	0.01	0.01
Survey trends that did not affect model estimates									
<i>Fall bottom trawl survey</i>	15.10	9.01	4.59	1.17	0.00	-1.58	-3.87	-5.81	<b>-7.49</b>
<i>Spring bottom trawl survey</i>	15.43	9.26	4.74	1.22	0.00	-1.65	-4.04	-6.09	<b>-7.87</b>
Shell height composition data									
<i>Commercial fishery</i>	<b>-3.36</b>	-2.16	-1.16	-0.31	0.00	0.44	1.10	1.71	2.26
<i>Dredge survey</i>	0.49	-0.06	<b>-0.18</b>	-0.08	0.00	0.14	0.44	0.77	1.13
<i>Camera survey</i>	<b>-3.35</b>	-2.17	-1.17	-0.31	0.00	0.44	1.12	1.74	2.31
<i>Winter bottom trawl survey</i>	<b>-1.16</b>	-0.75	-0.40	-0.11	0.00	0.15	0.38	0.58	0.77
<i>Unlined 10 ft scallop dredge survey</i>	0.11	0.07	0.03	0.01	0.00	-0.01	-0.03	-0.05	<b>-0.06</b>

Table B5-12. Sensitivity analysis runs using the CASA model for sea scallops in the Mid-Atlantic Bight.

Scenario	Estimates for 2006	
	Biomass (mt)	Fishing mortality (y <sup>-1</sup> )
Basecase	85,161	0.18
Eliminate prior on video survey efficiency	83,061	0.18
Drop anomalous 2003 dredge and video trend observations	83,520	0.18
No constraint on recruitment variability	88,815	0.17
Use spring and fall bottom trawl surveys	69,440	0.22
Start 1979	85,870	0.17

Table B6-1. Biological reference points and stock status measures for the whole stock of sea scallops from CASA model runs.

Estimate	Value
$F_{MSY}$ proxy ( $F_{MAX}$ , y-1)	0.29
Current $F$ ( $y^{-1}$ )	0.23
BPR at $F_{MAX}$ (g)	86.3
Median 83-06 recruitment (millions)	1,258
$B_{MSY}$ proxy	108,628
Biomass threshold (mt)	54,314
Current biomass (mt)	166,208

## ATLANTIC SEA SCALLOP FIGURES

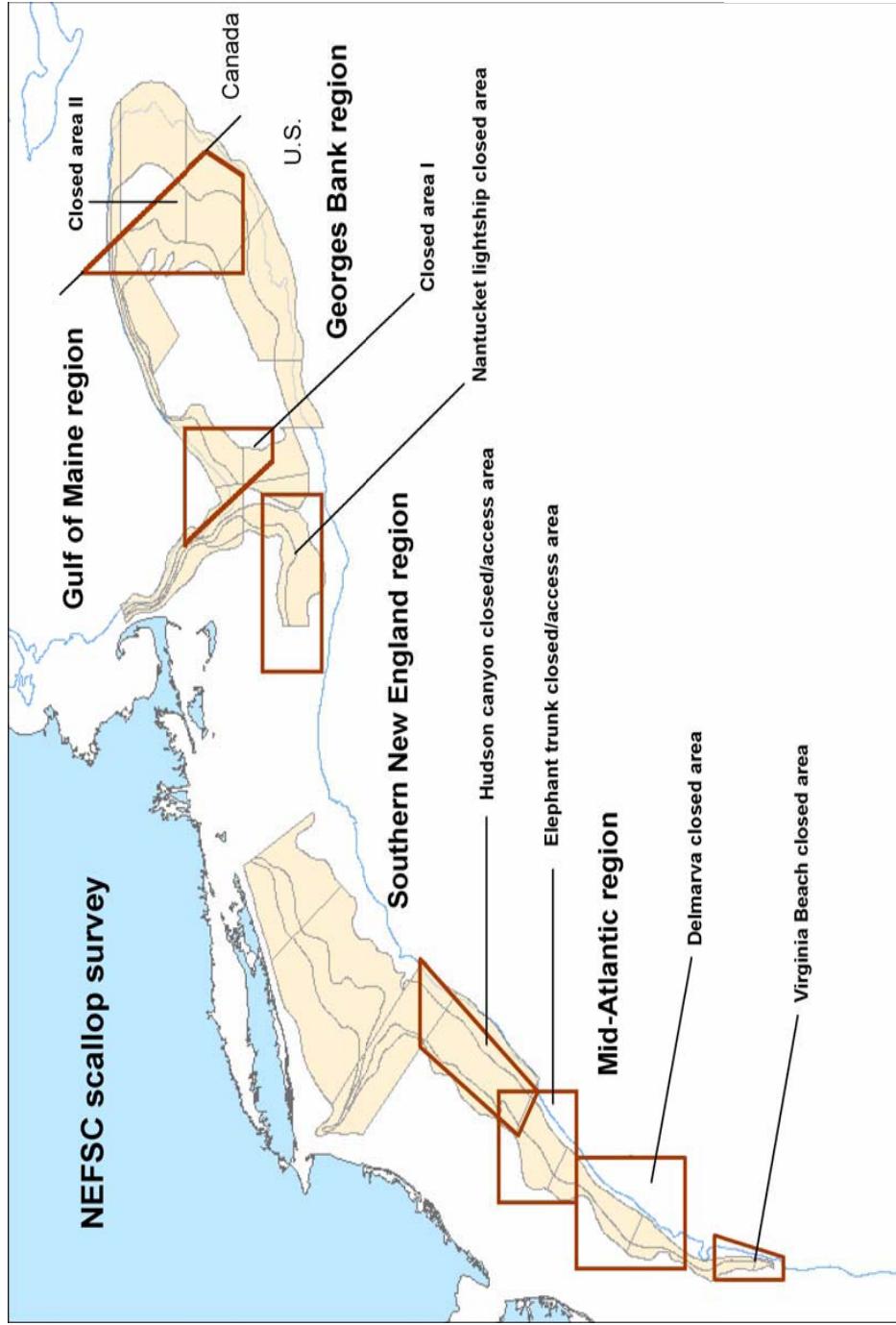


Figure B3-1. Map of sea scallop grounds and regions. The shaded regions are the shellfish strata regularly sampled in the NEFSC sea scallop survey

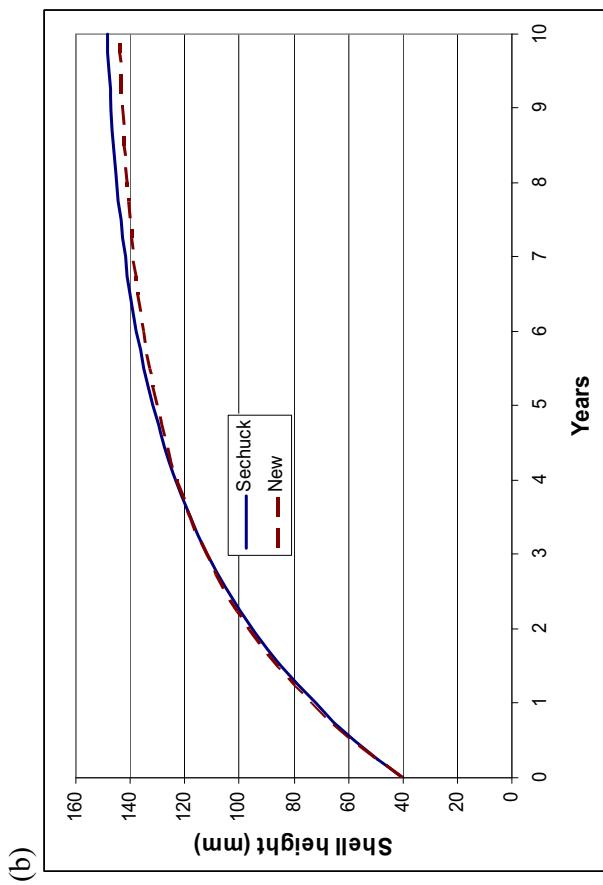
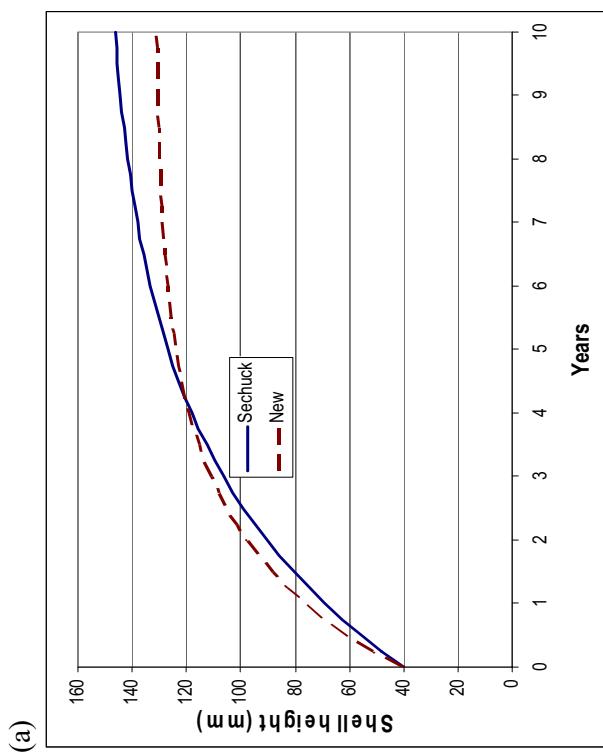


Figure B3-2. Comparison of growth rates for a hypothetical sea scallop starting at 40 mm SH based on growth curves from Serchuk et al. (1979) and new growth curves in (a) Mid-Atlantic Bight and (b) Georges Bank.

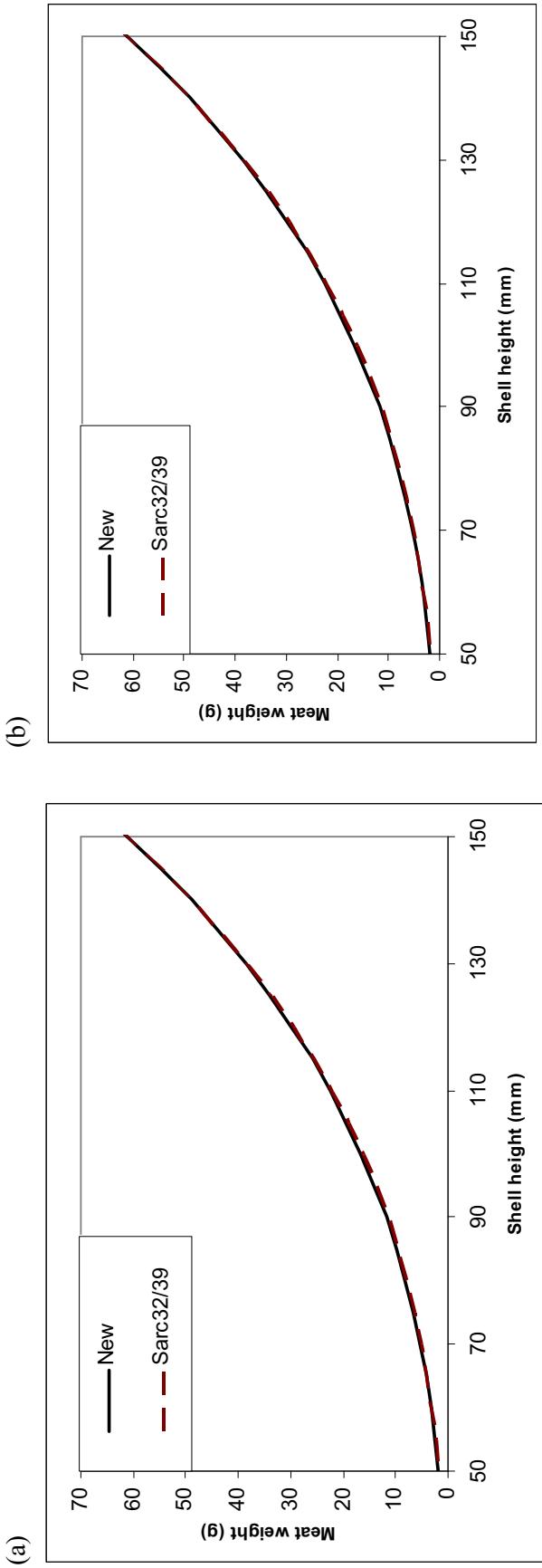


Figure B3-3. Comparison of new shell height/meat weight relationships (calculated ignoring depth effects) for (a) Georges Bank and (b) Mid-Atlantic with relationship used in the previous two assessments (NEFSC 2001, 2004).

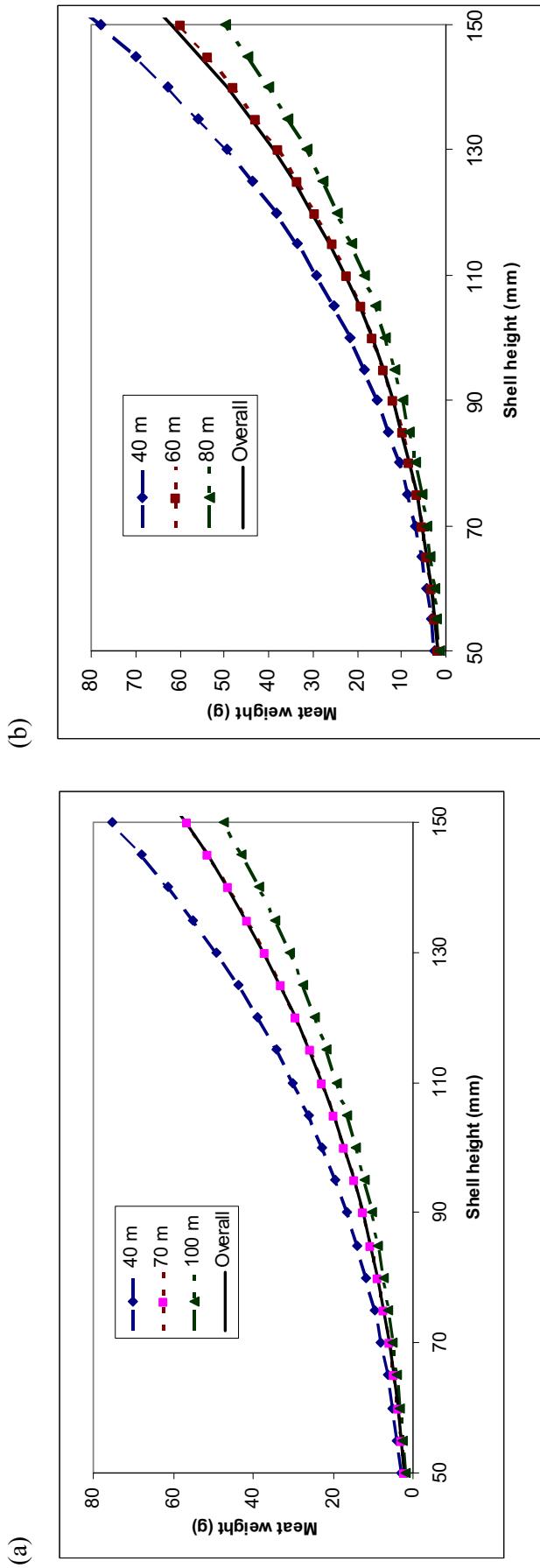


Figure B3-4. Depth effects on shell height/meat weight relationships for sea scallops (a) on Georges Bank and (b) in the Mid-Atlantic.

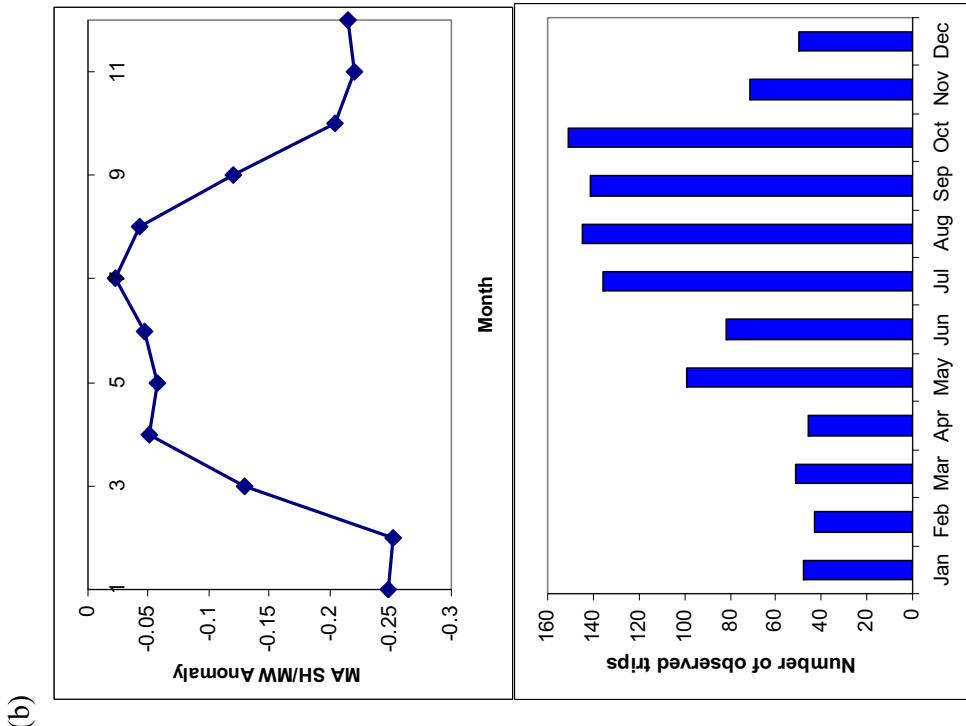
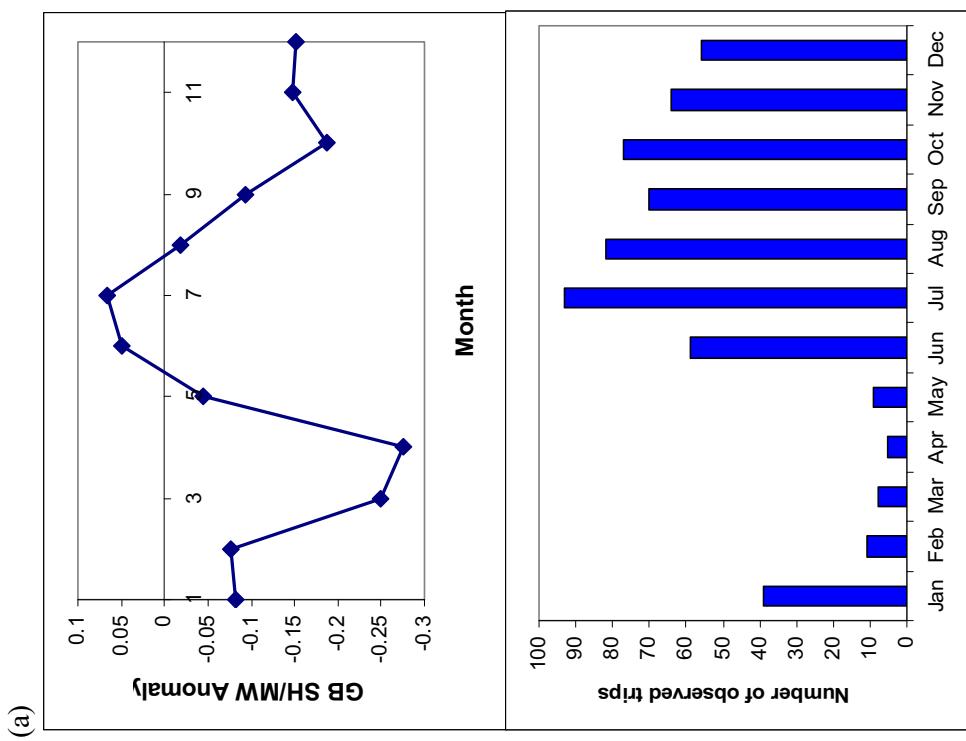


Figure B3-5. Monthly shell height/meat weight anomalies on (a) Georges Bank and (b) in the Mid-Atlantic, together with the number of observed trips by month.

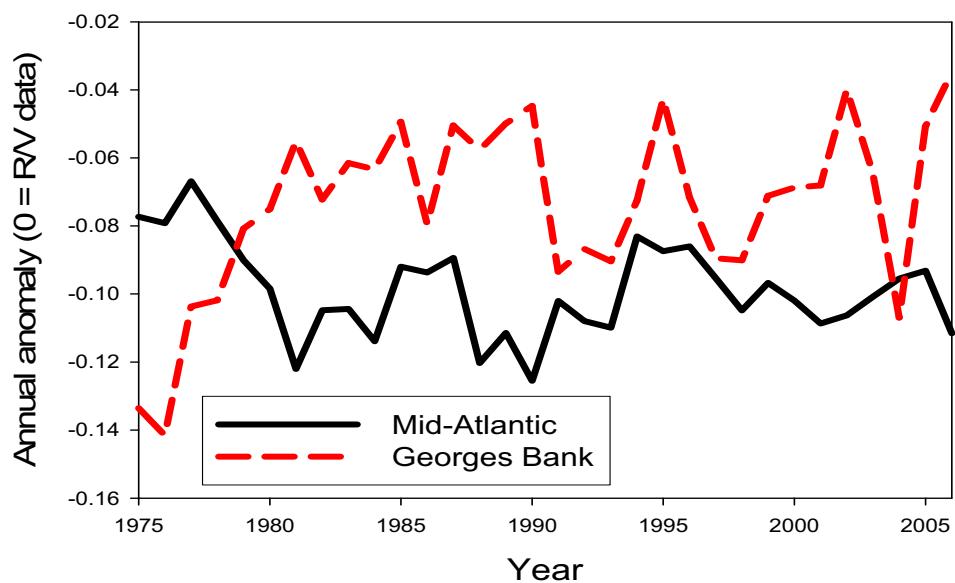


Figure B3-6. Estimated annual shell height/meat weight anomalies for sea scallops on Georges Bank and in the Mid-Atlantic, with no adjustment for water uptake.

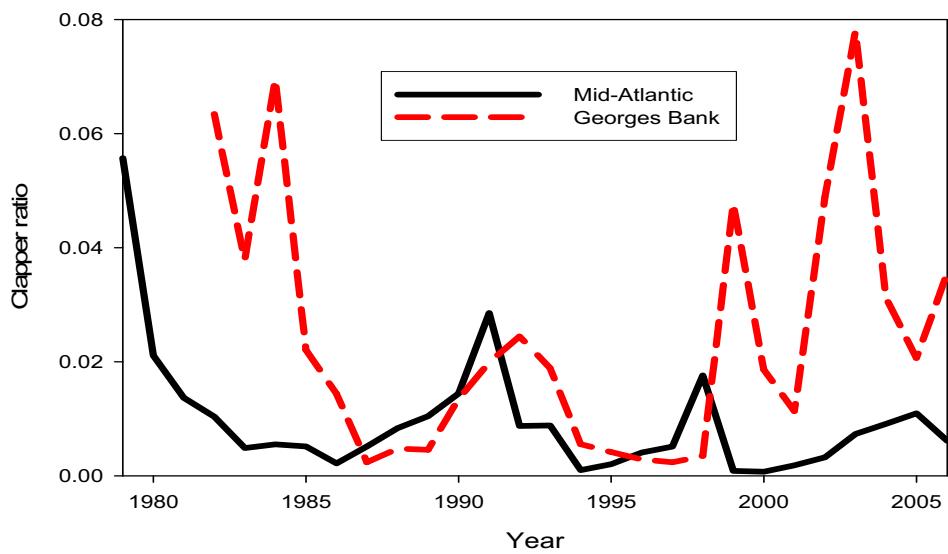


Figure B3-7. Ratio of clapper to live sea scallops in the NEFSC sea scallop survey

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Meat Count	J	A	J	O	J	O	J	O	J	O	J	O	J	O	J	O	J	O	J	O	J	O	J
Minimum Shell Height	35 mpp																						
DAS Full Time																							
Part Time																							
Occasional																							
Minimum Ring Size																							
Gear																							
Maximum Crew																							
Area Closure																							
Area Reopening																							

38 mpp  
3 1/2"  
204 182 164 142 120 51  
91 82 66 57 48 42 open area  
18 16 14 12 10 17 open area 20  
3" 3 1/4" 3 1/2" 4" 4 open area 5  
No chafing gear or cookies  
Double links  
Double links, triple links in belly  
5 1/2" mesh twine top  
Maximum twine top length  
8" mesh twine top  
10" twine top  
9 crew 7 crew  
3 closures in George's Bank region  
2 closures in Mid-Atlantic region 1 closure  
MAB  
GBK

Figure B4-1. Summary of management measures from 1984-2006. "mpp" means meats per pound.

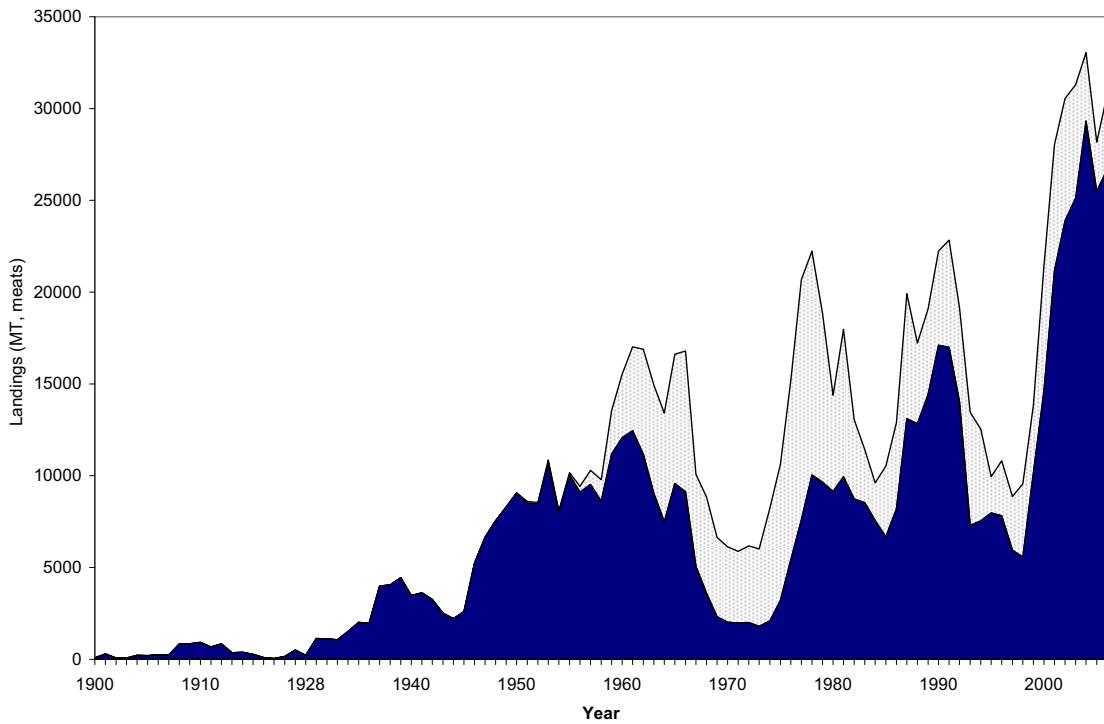


Figure B4-2. Sea scallop landings in NAFO areas 5 and 6 (US plus the Canadian portion of Georges Bank). US landings are shown by dark fill. Canadian landings are shown by light fill.

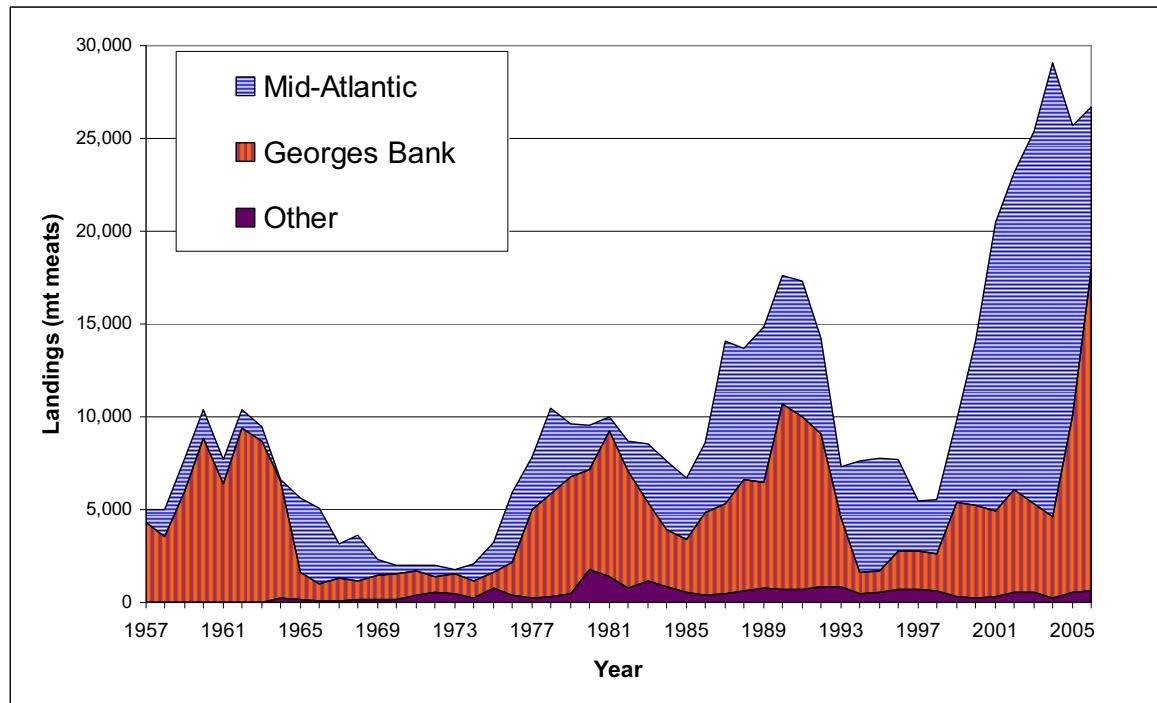


Figure B4-3. US sea scallop landings by area, 1957-2006. “Other” landings (i.e., southern New England and the Gulf of Maine) are not available prior to 1964.

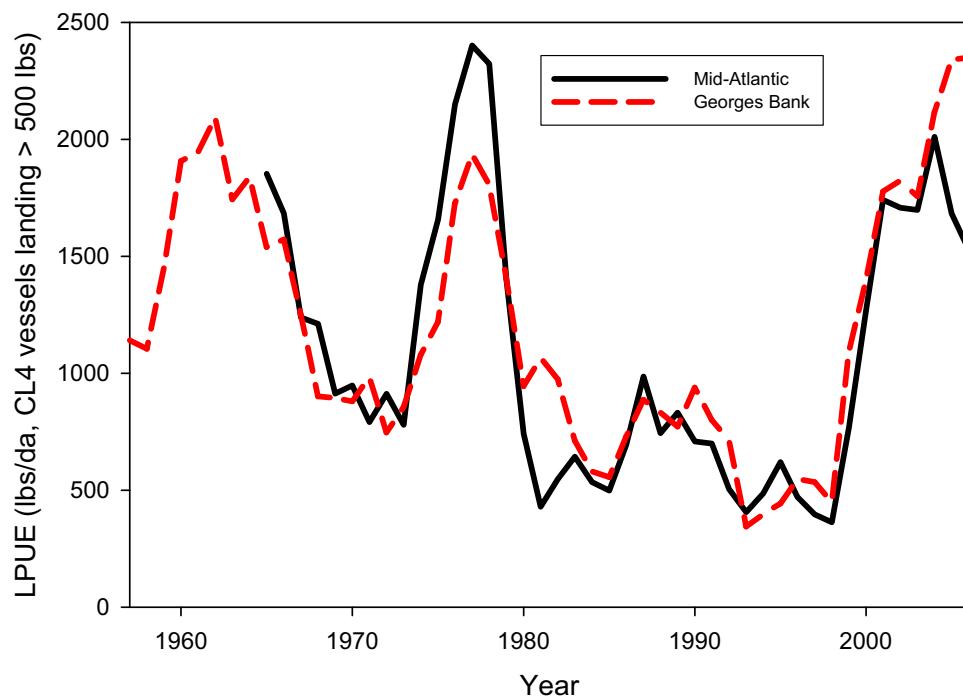


Figure B4-4. Landings per unit effort (lbs meats per days absent for vessels >150 GRT and trips >500 lbs meats) in the sea scallop fishery.

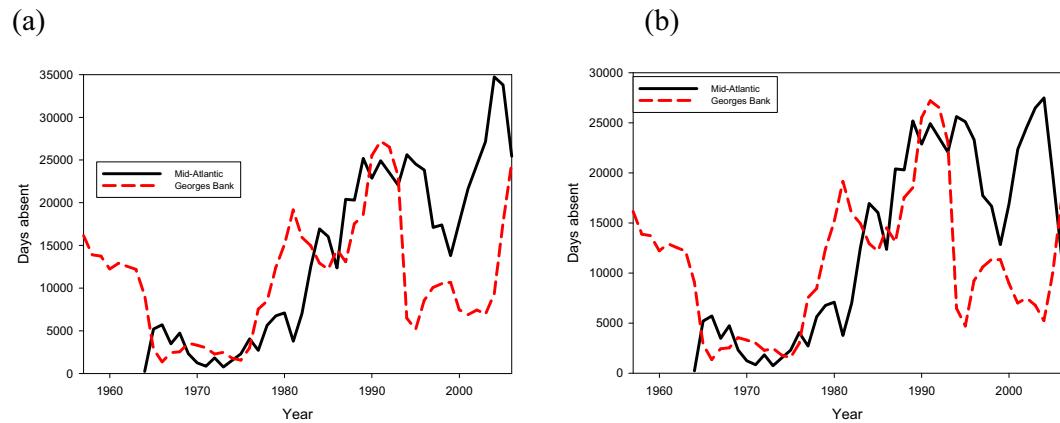
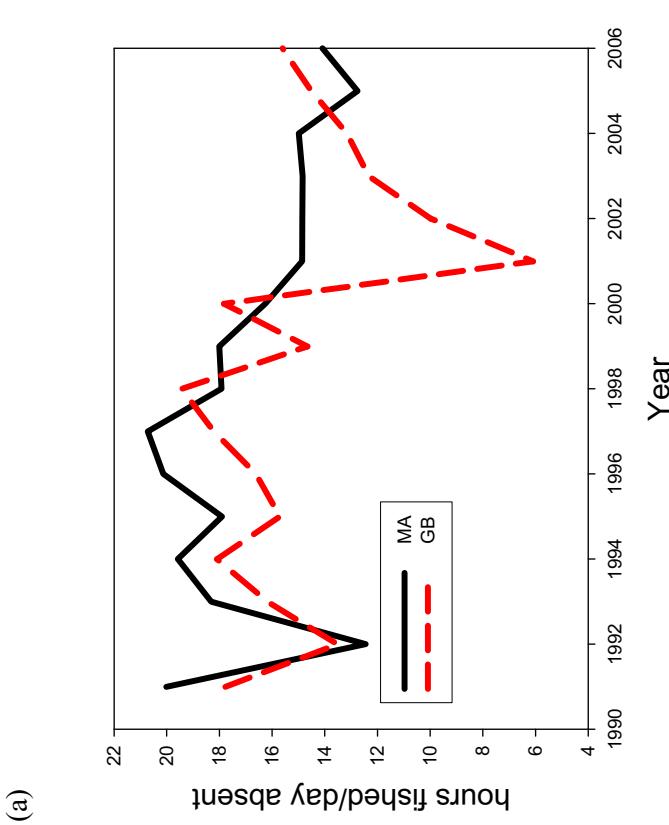


Figure B4-5. Fishing efforts (days absent) for the sea scallops fishery. (a) unadjusted, (b) adjusted for trips landing less than 500 lbs meats.



(b)

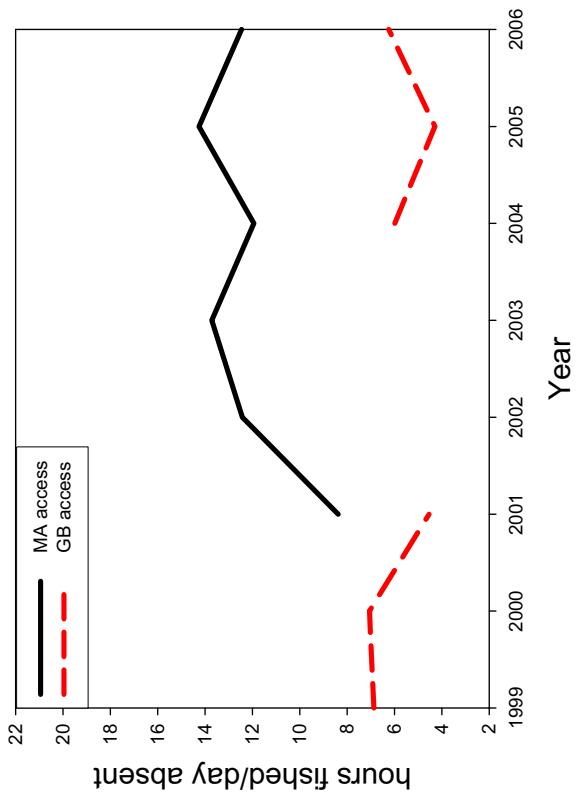


Figure B4-6. Hours fished per day absent in (a) regular trips in open area, and (b) special access area trips in previously closed areas, derived from observer sea sampling data

Figure B4-7. The spatial distribution of fishing effort based on VMS data for the limited access scallop fleet during 1998-2006 (through Sept. 15), and general category vessels during 2006 (through Sept. 15). Effort categories are classified based on 20<sup>th</sup> percentiles of effort during FY 2000.

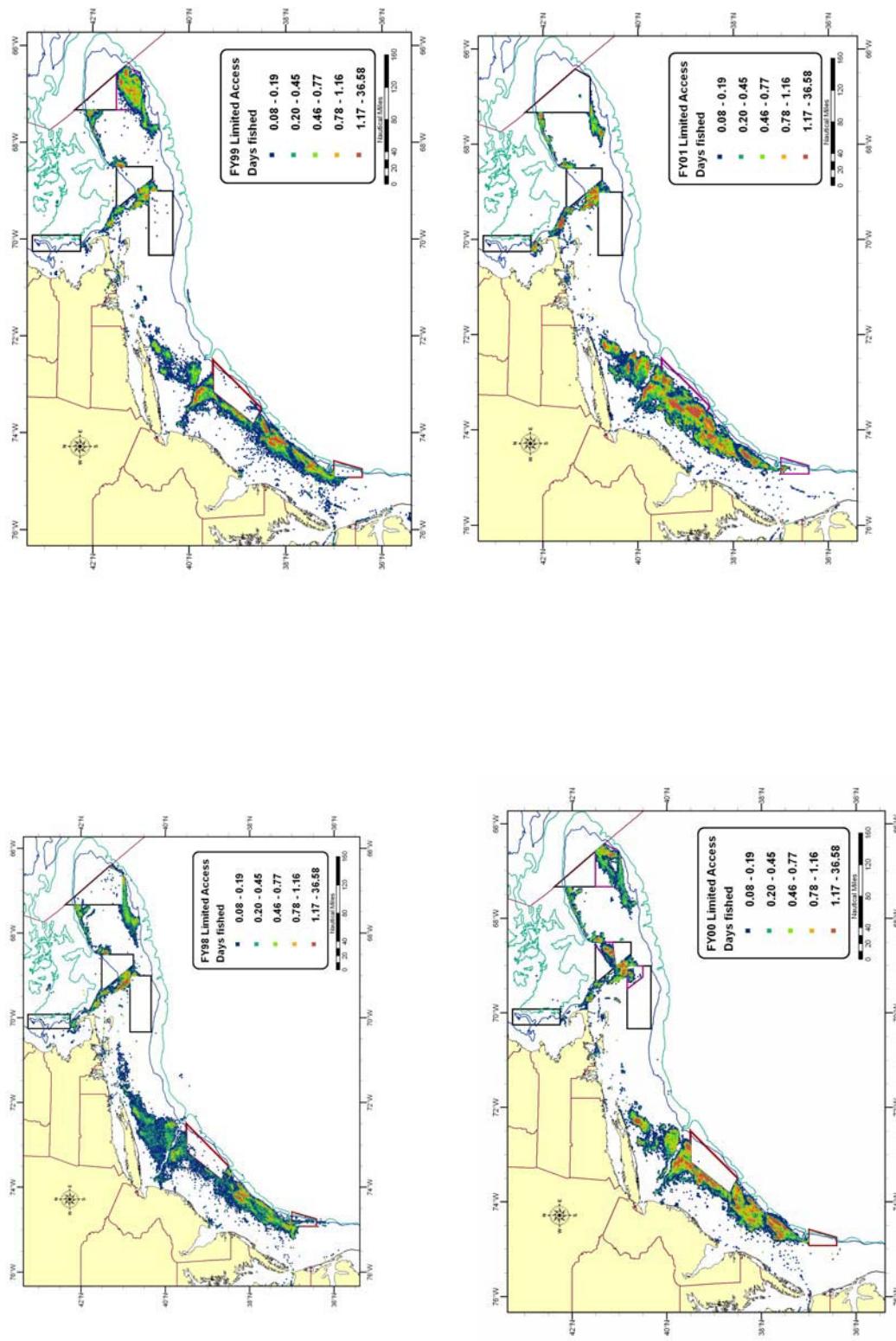


Figure B4-7 continued

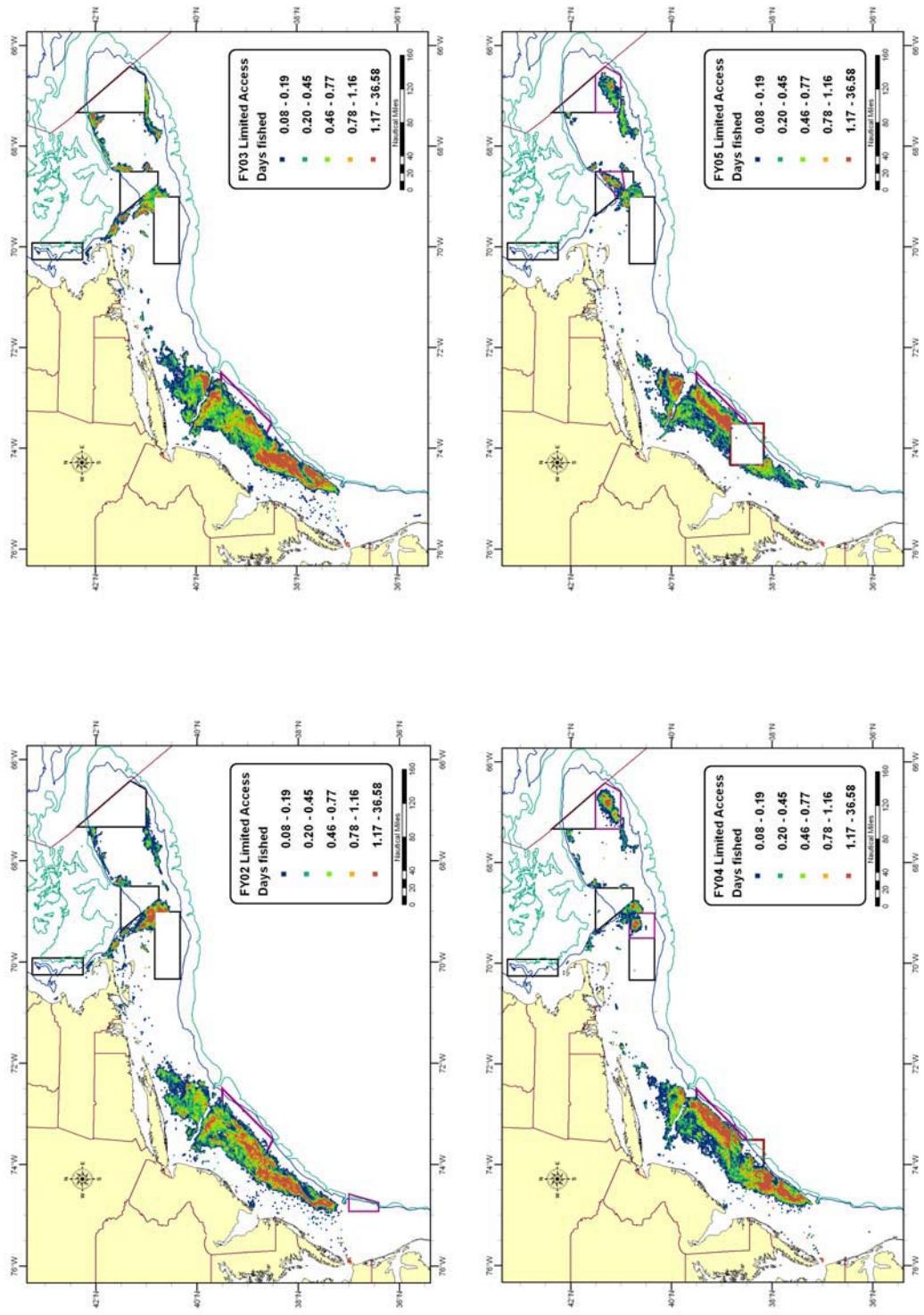


Figure B4-7 continued

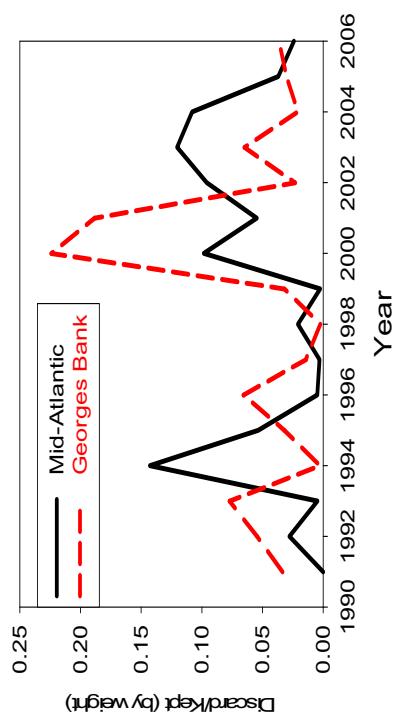
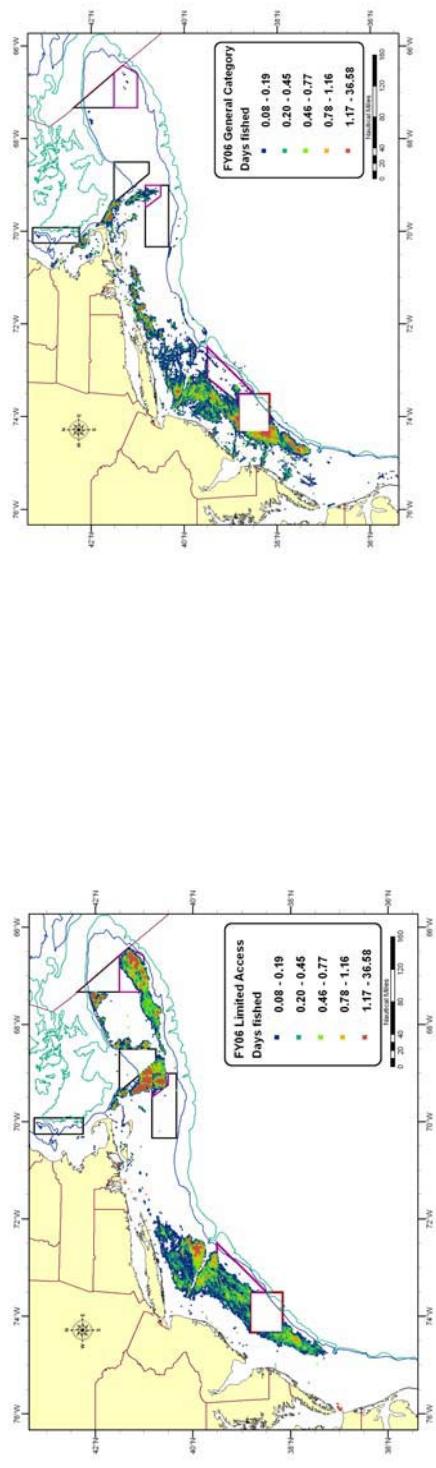


Figure B4-8. Discard to kept ratio for sea scallops in directed sea scallop trips.

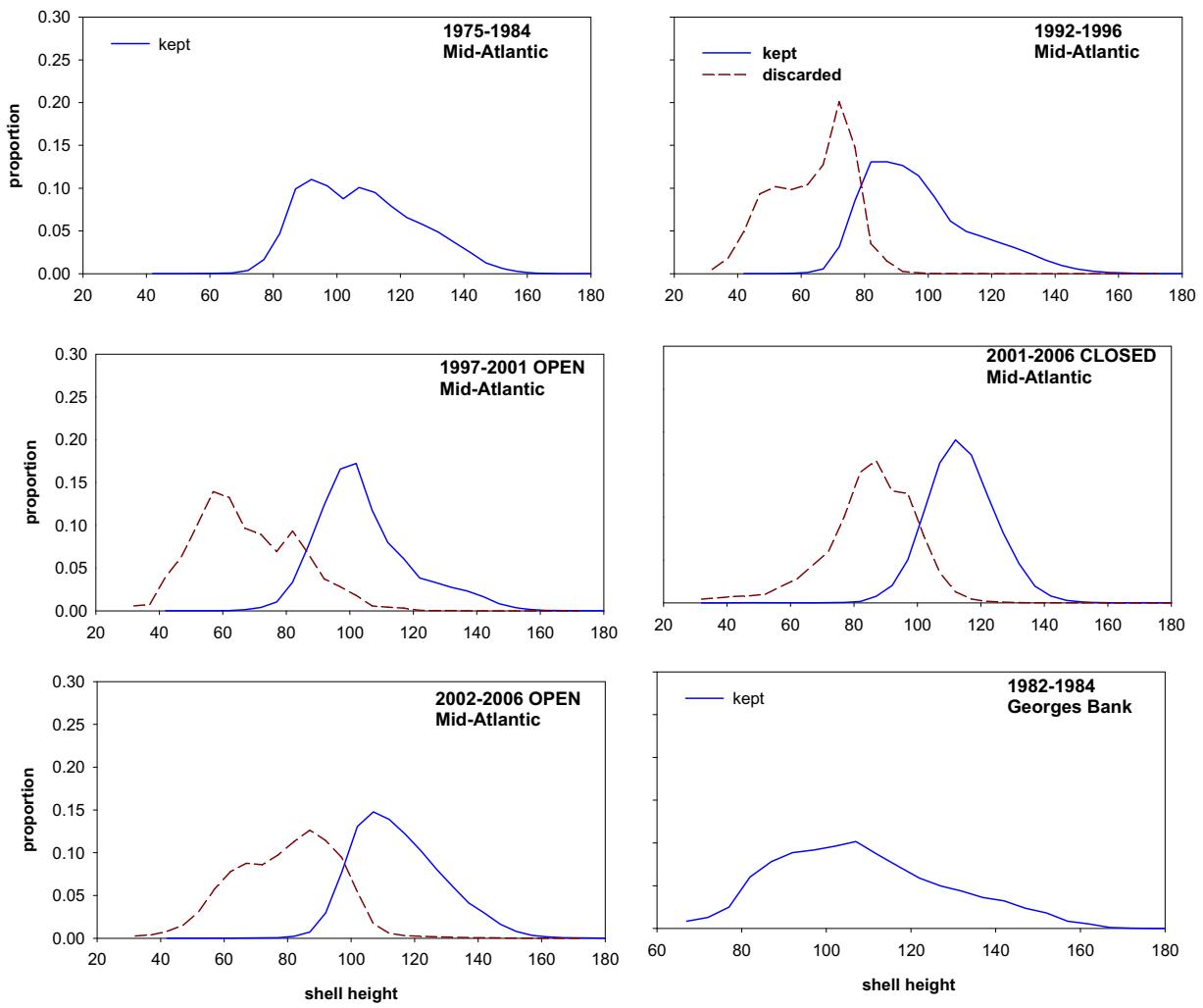
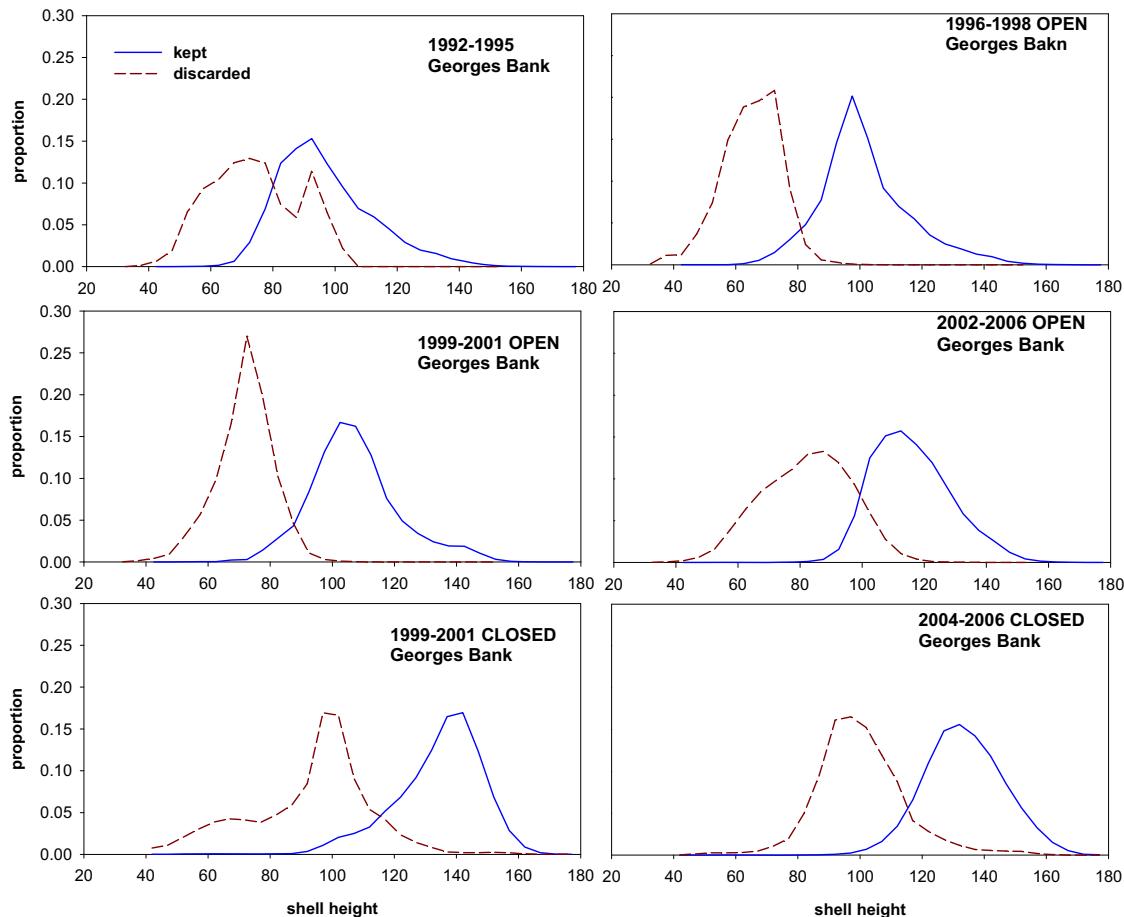


Figure B4-9. Shell heights of commercial kept (solid line) and discarded (dashed line) sea scallops, from port sampling (1975-1984) and sea sampling (1992-2006).

Figure B4-9 continued



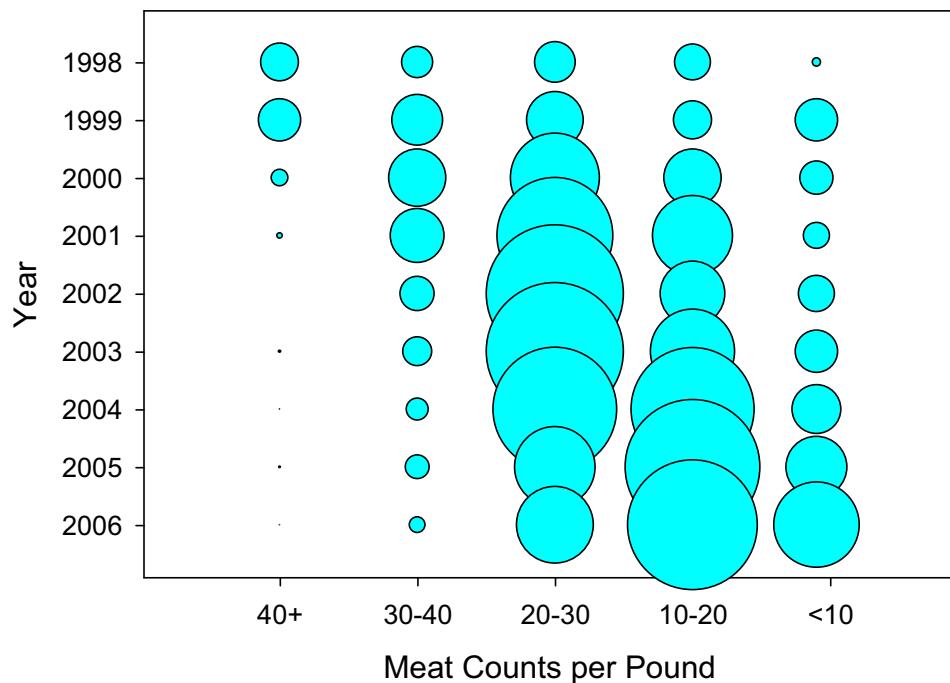


Figure B4-10. Commercial landings by meat count category, 1998-2006.

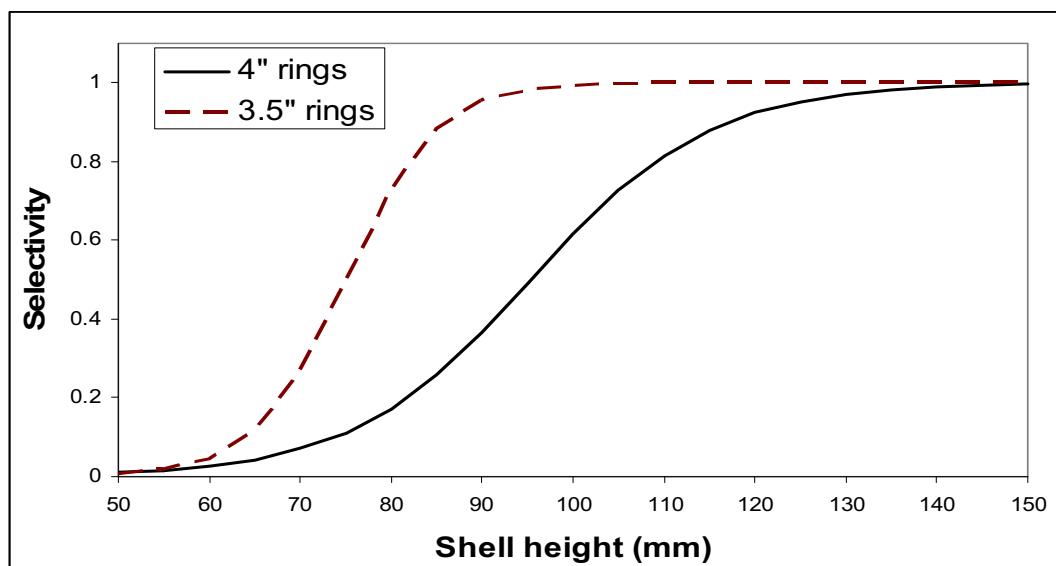


Figure B4-11. Selectivity of commercial scallop dredges with 3.5" and 4" rings (Yochum 2006, Appendix 5). The 3.5" ring selectivity is from NEFSC (2004).

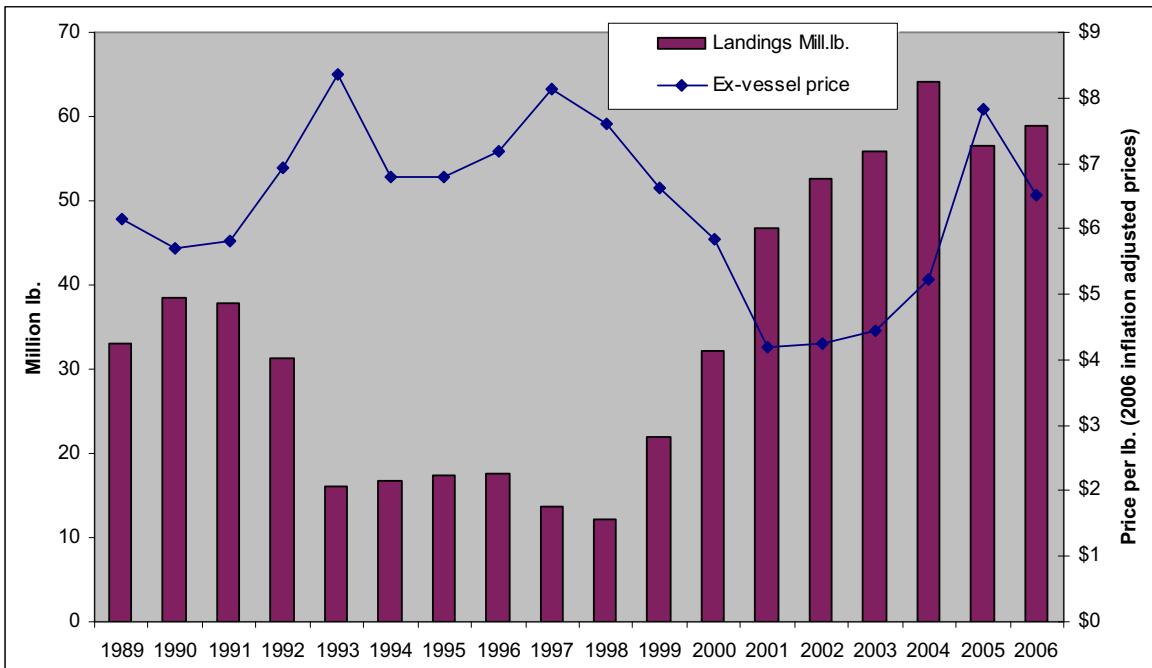


Figure B4-12. Trends in landings and ex-vessel prices in the U.S. sea scallop fishery.

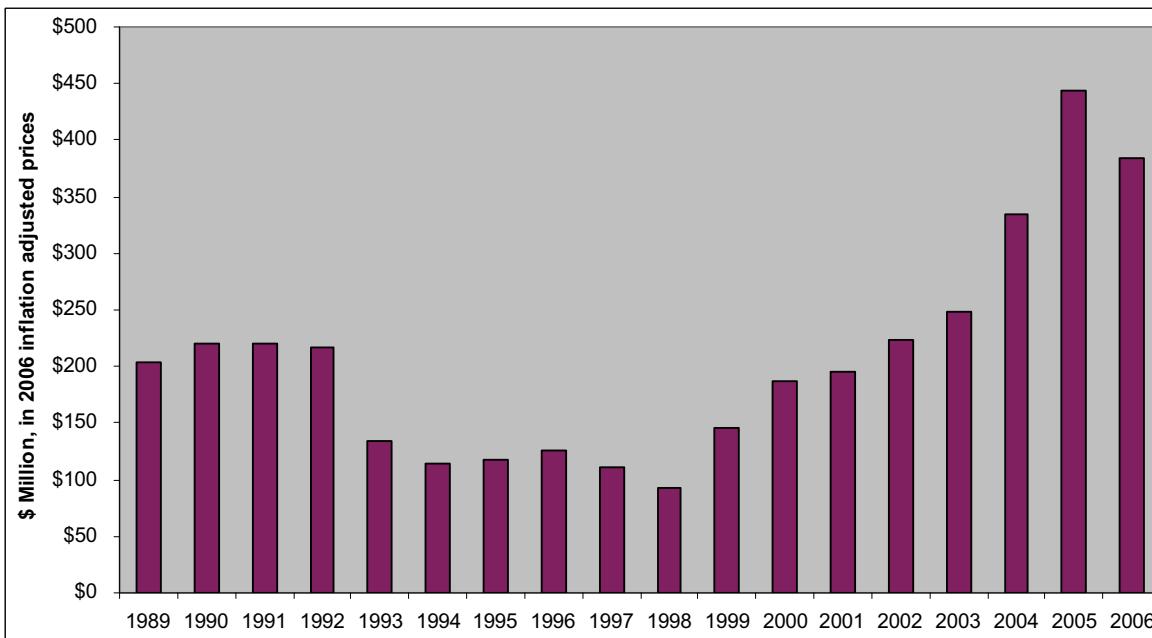


Figure B4-13. Trends in U.S. ex-vessel sea scallop revenues (adjusted for inflation to 2006 equivalent prices)

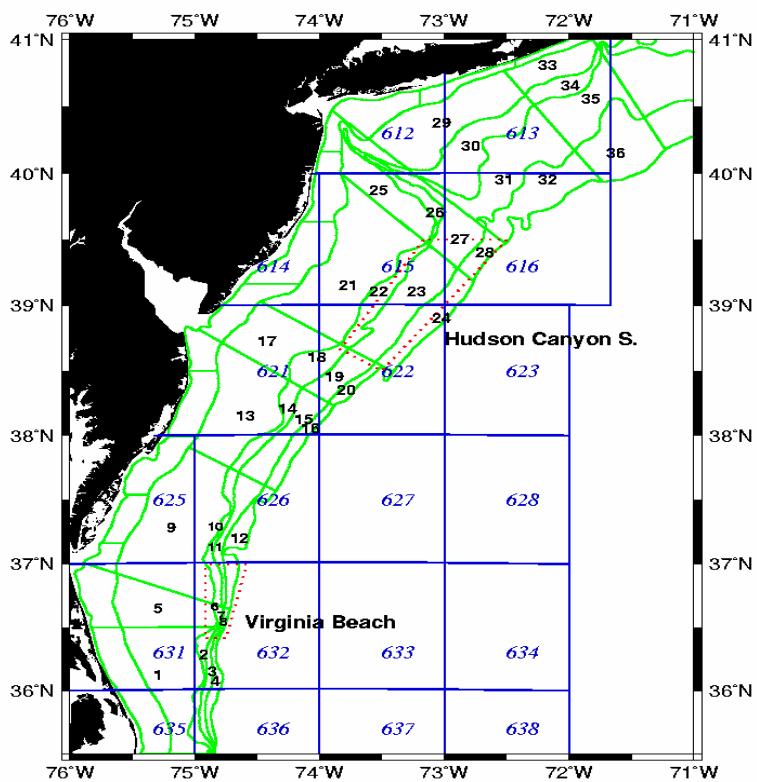
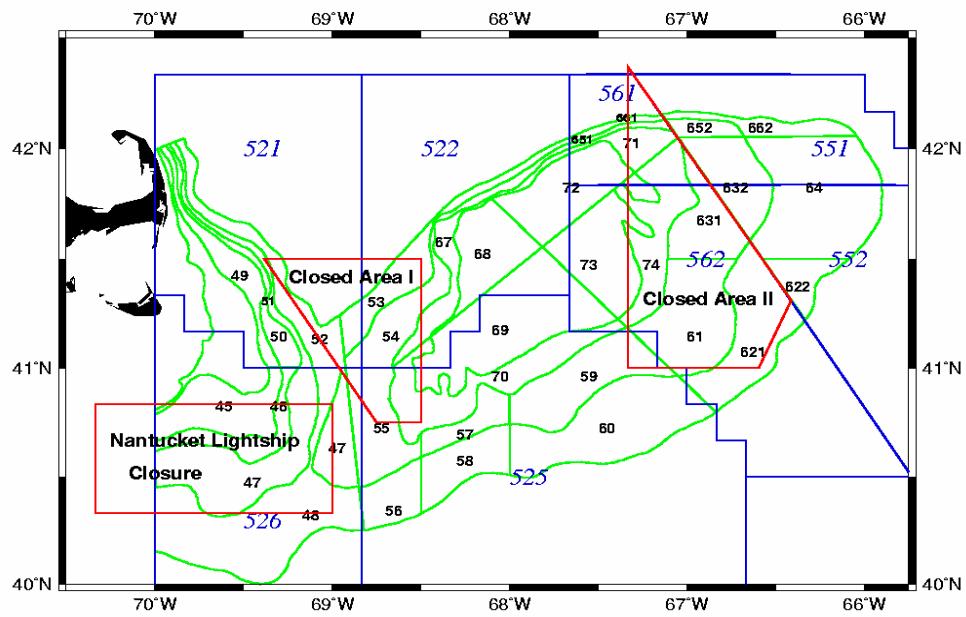


Figure B5-1. Georges Bank and Mid-Atlantic shellfish strata, statistical areas, groundfish closed areas and the original Mid-Atlantic rotational areas.

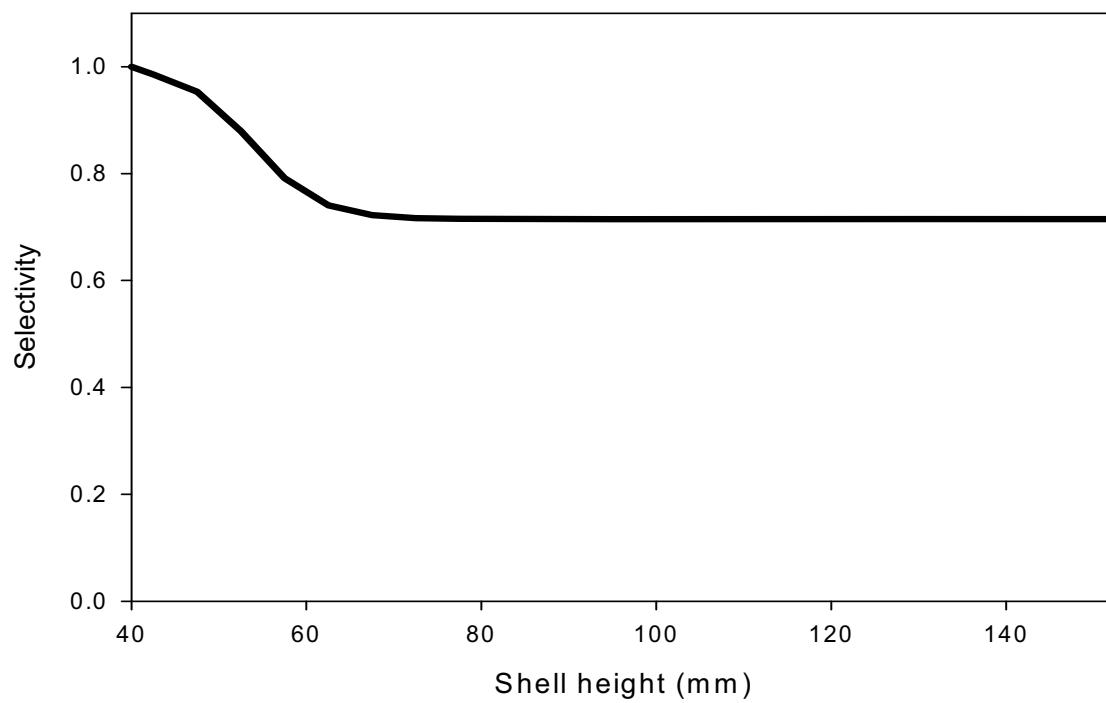
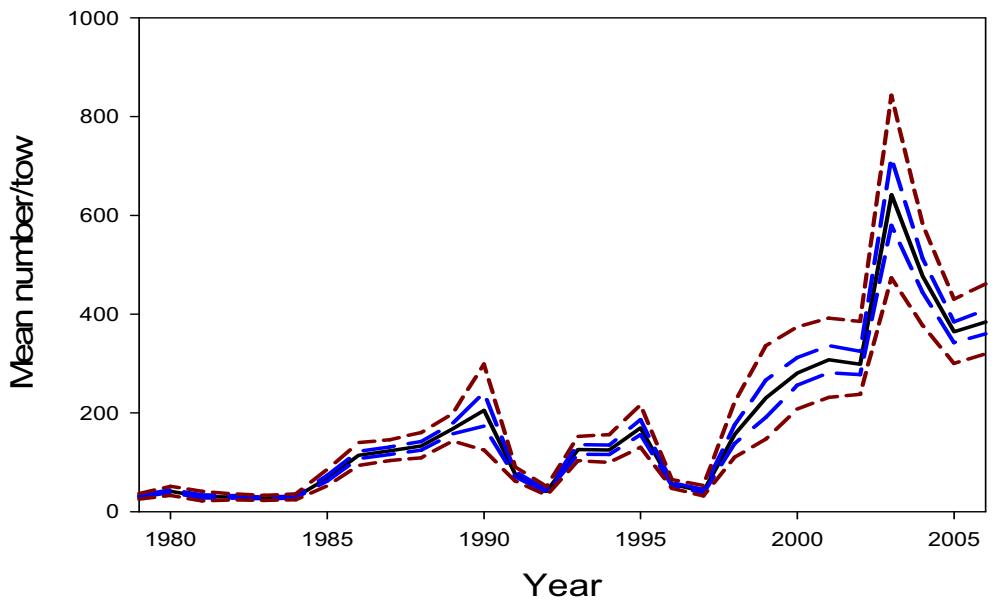


Figure B5-2. Selectivity of the lined dredge assumed in previous assessments (e.g., NEFSC 2001, 2004).

(a)



(b)

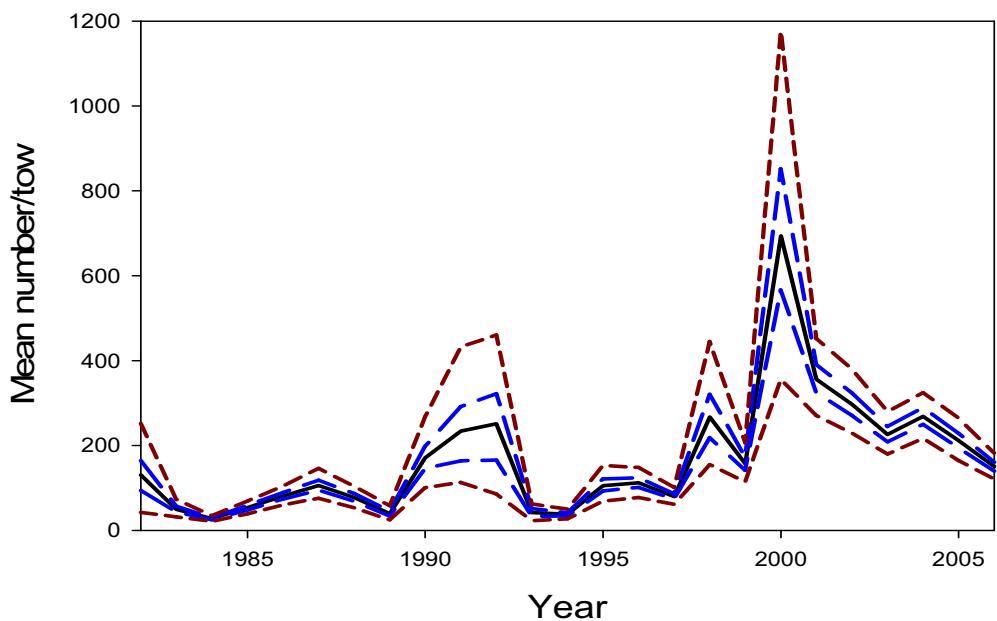


Figure B5-3. Bootstrapped estimates of abundance from NEFSC sea scallop survey for (a) Mid-Atlantic and (b) Georges Bank, showing median (solid line), 1<sup>st</sup> and 3<sup>rd</sup> quartiles (long dash), and 95% confidence interval (short dashed lines).

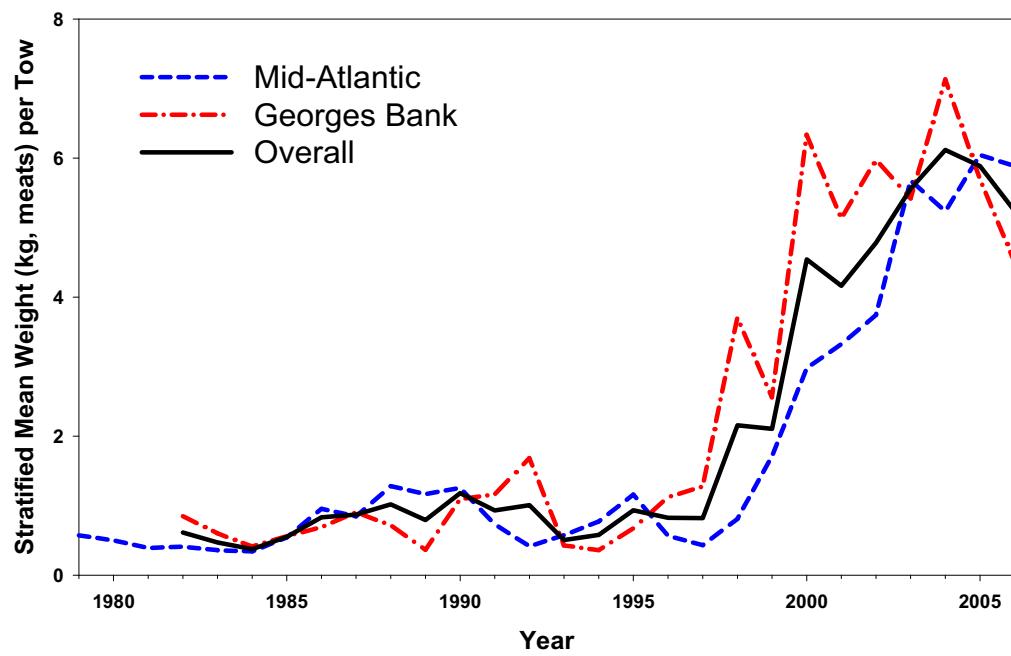
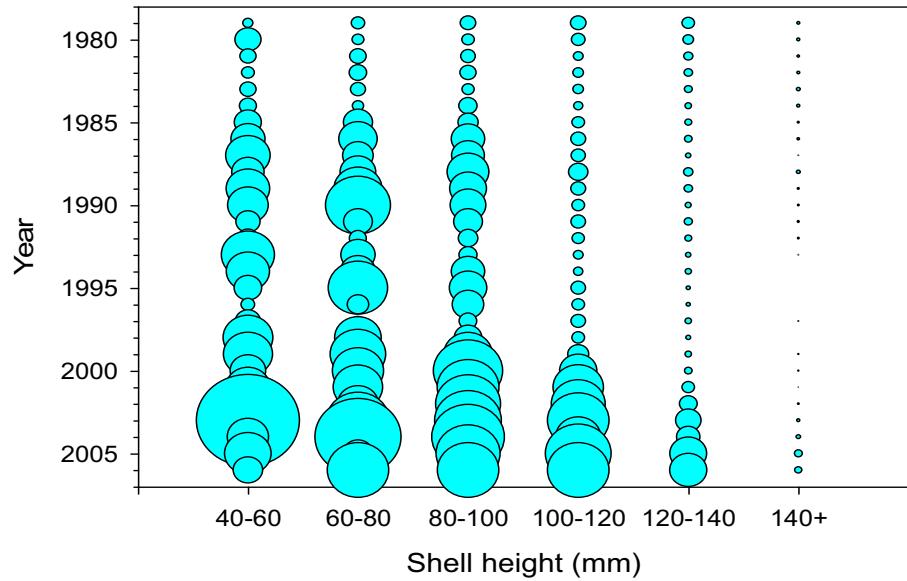


Figure B5-4. NEFSC sea scallop biomass indices.

(a)



(b)

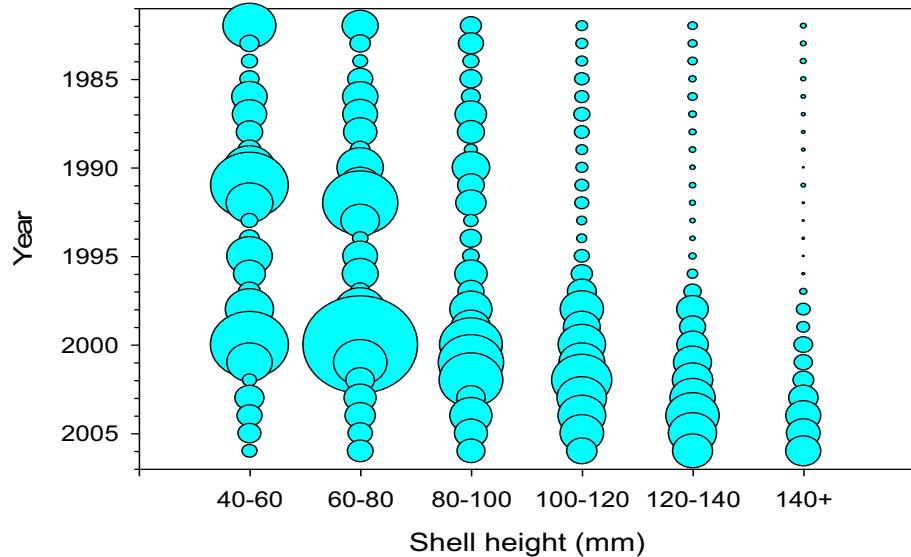
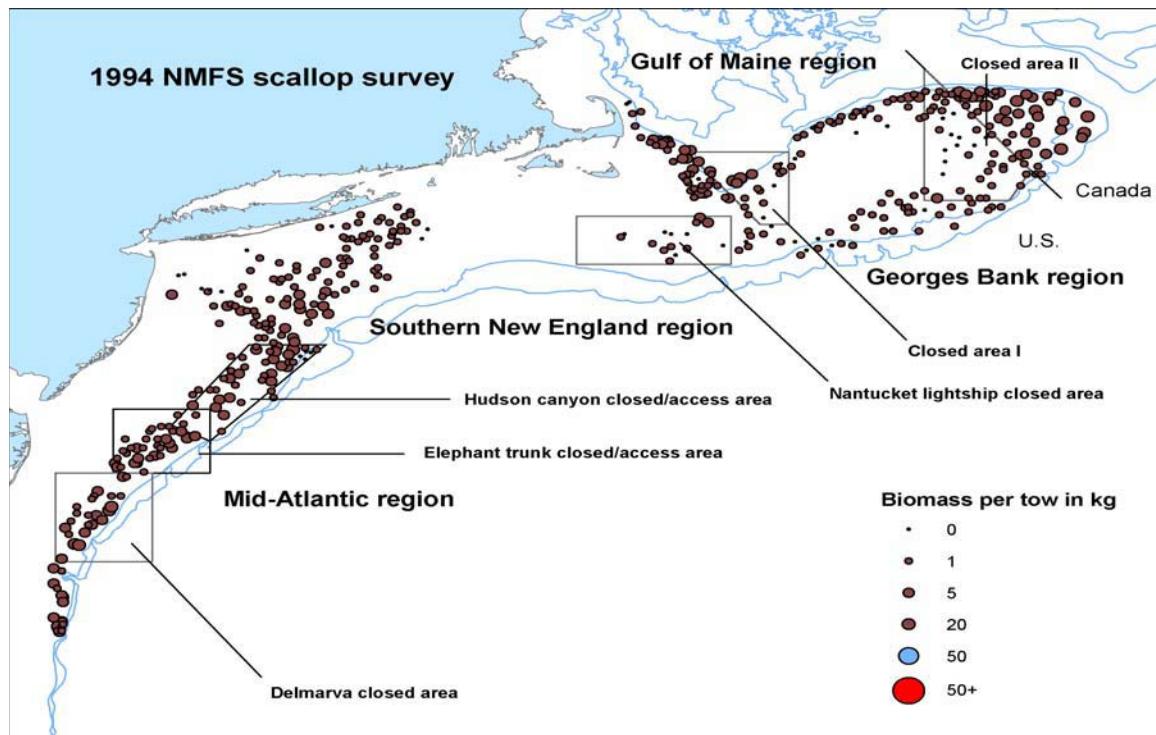


Figure B5-5. NEFSC sea scallop survey numbers at shell heights, in 20 mm intervals for  
(a) Mid-Atlantic Bight and (b) Georges Bank

(a)



(b)

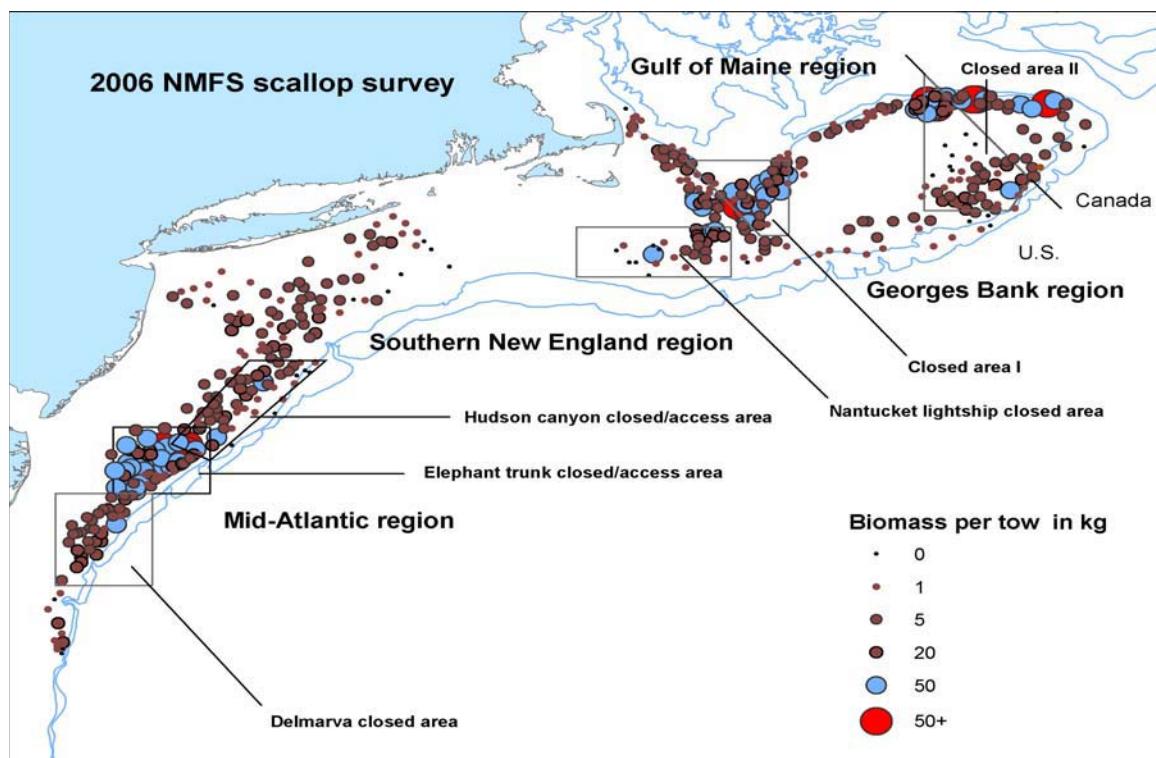


Figure B5-6. Distributions of sea scallops from the NEFSC sea scallop survey in (a) 1994 and (b) 2006.

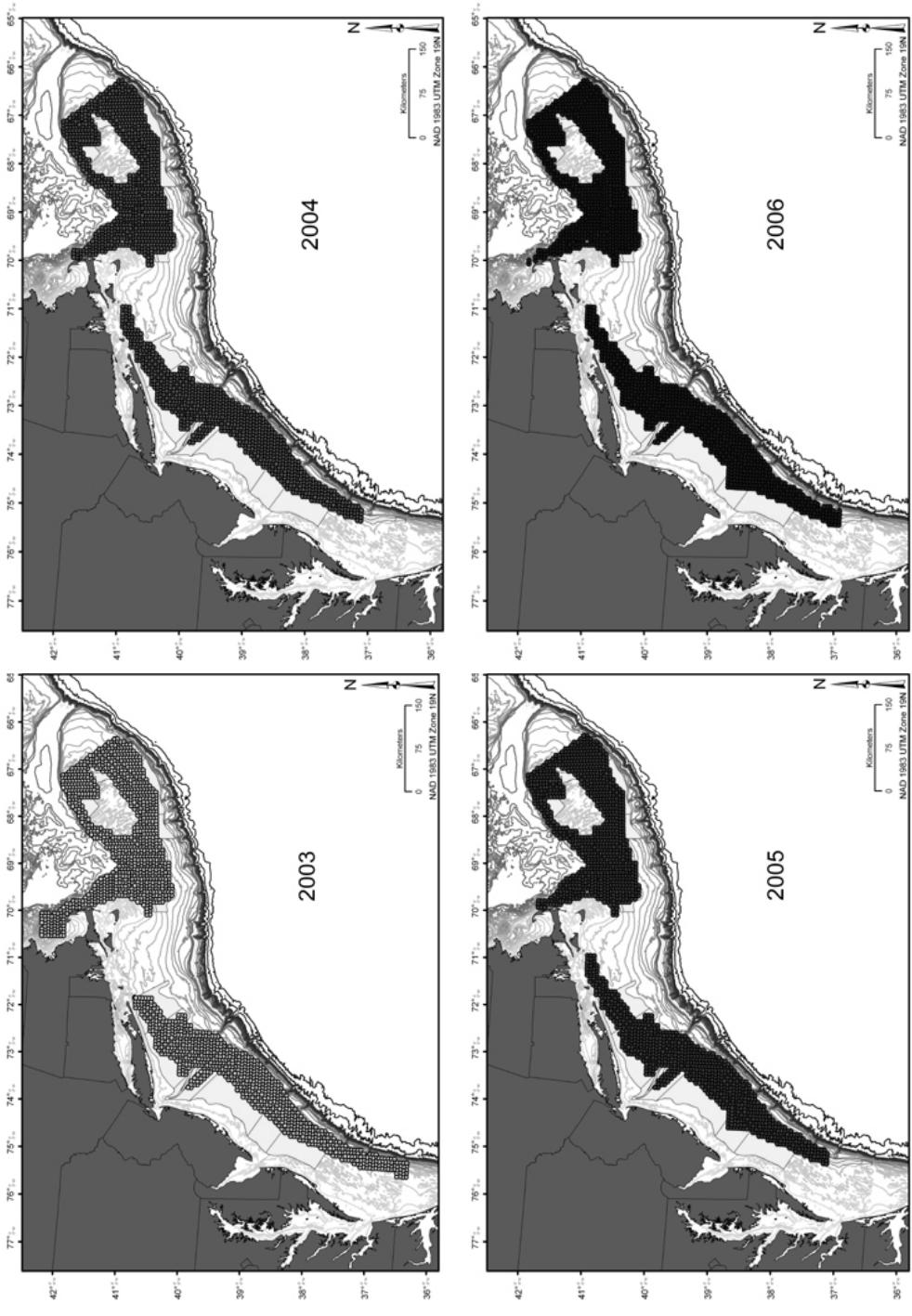
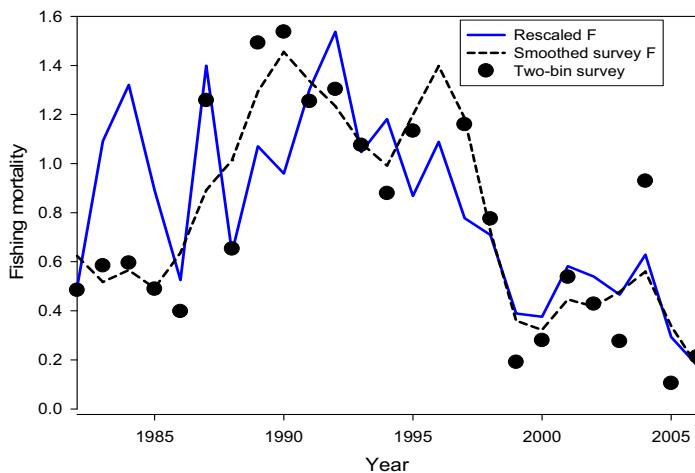
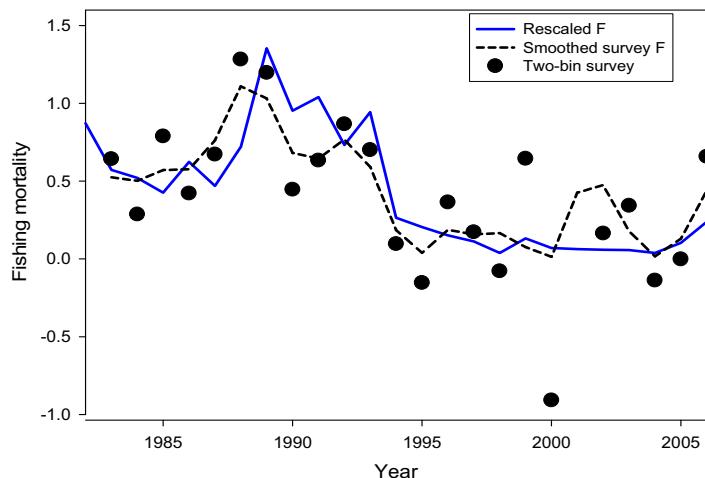


Figure B5-7. Stations occupied in SMAST video surveys during 2003-2006. NEFSC shellfish strata are shown for comparison.

(a)



(b)



(c)

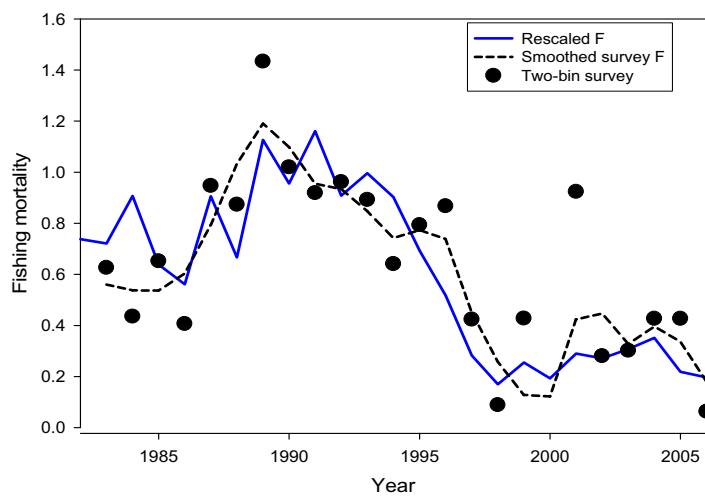


Figure B5-8. Survey-based (with moving average smoother) and rescaled-F estimates of fishing mortality for sea scallops (a) in the Mid-Atlantic, (b) on Georges Bank, and (c) overall.

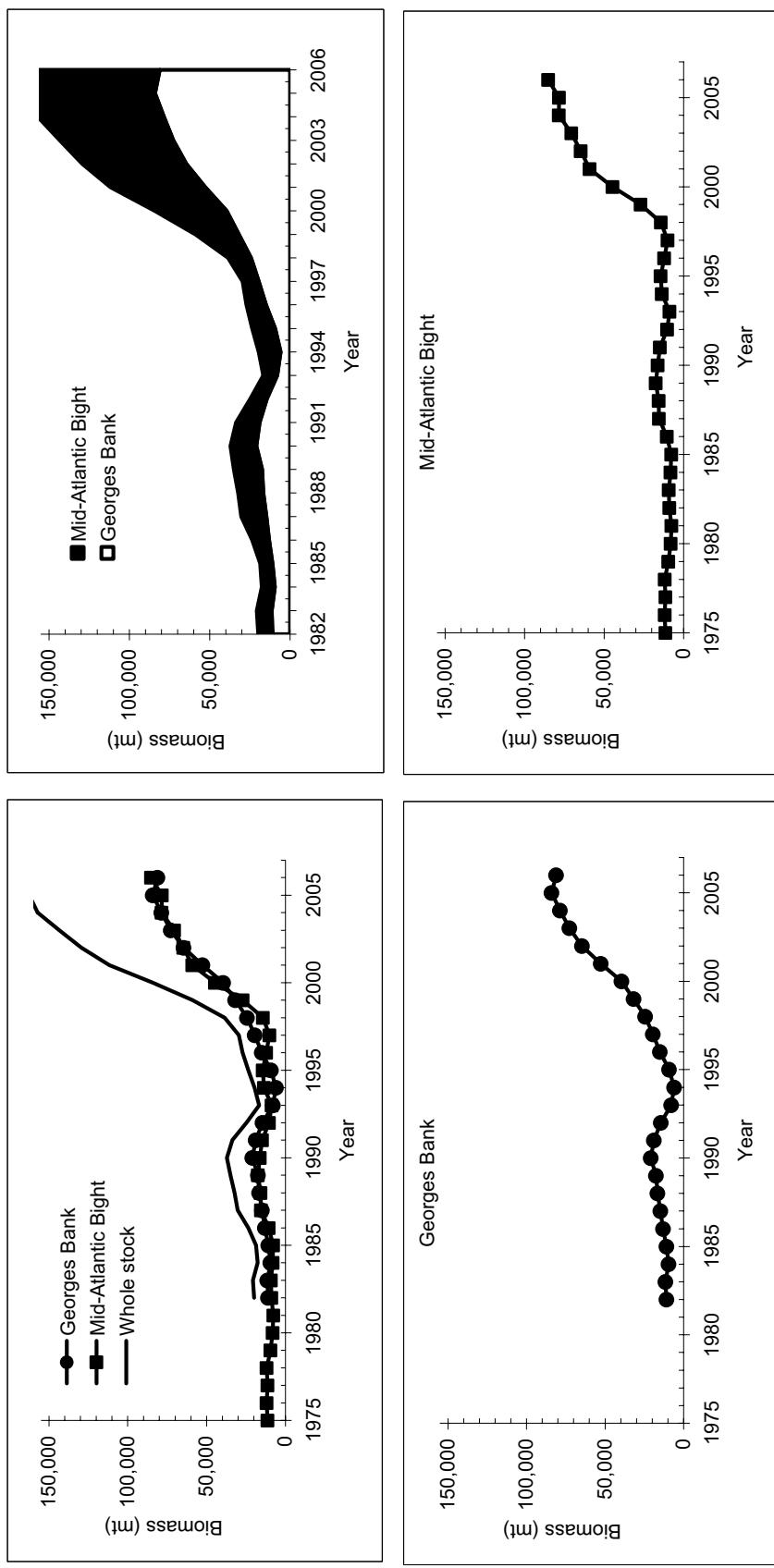


Figure B5-9. Biomass estimates (40+ mm on January 1) from the CASA model for sea scallops on Georges Bank during 1982-2006, in the Mid-Atlantic Bight during 1975-2005 and for the whole stock during 1982-2006.

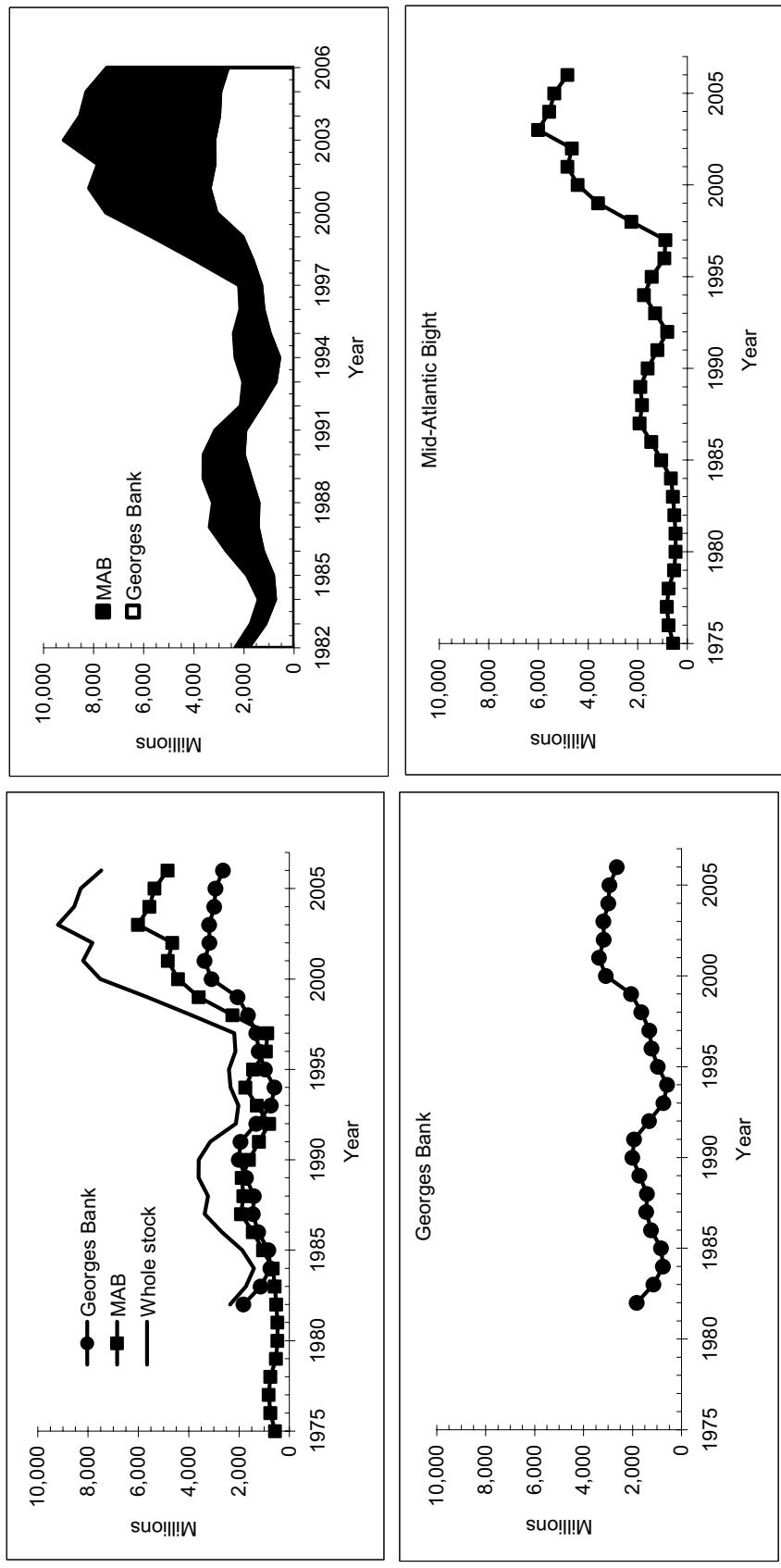


Figure B5-10. Abundance estimates (40+ mm on January 1) from the CASA model for sea scallops on Georges Bank during 1982-2006, in the Mid-Atlantic Bight during 1975-2006 and for the whole stock during 1982-2006.

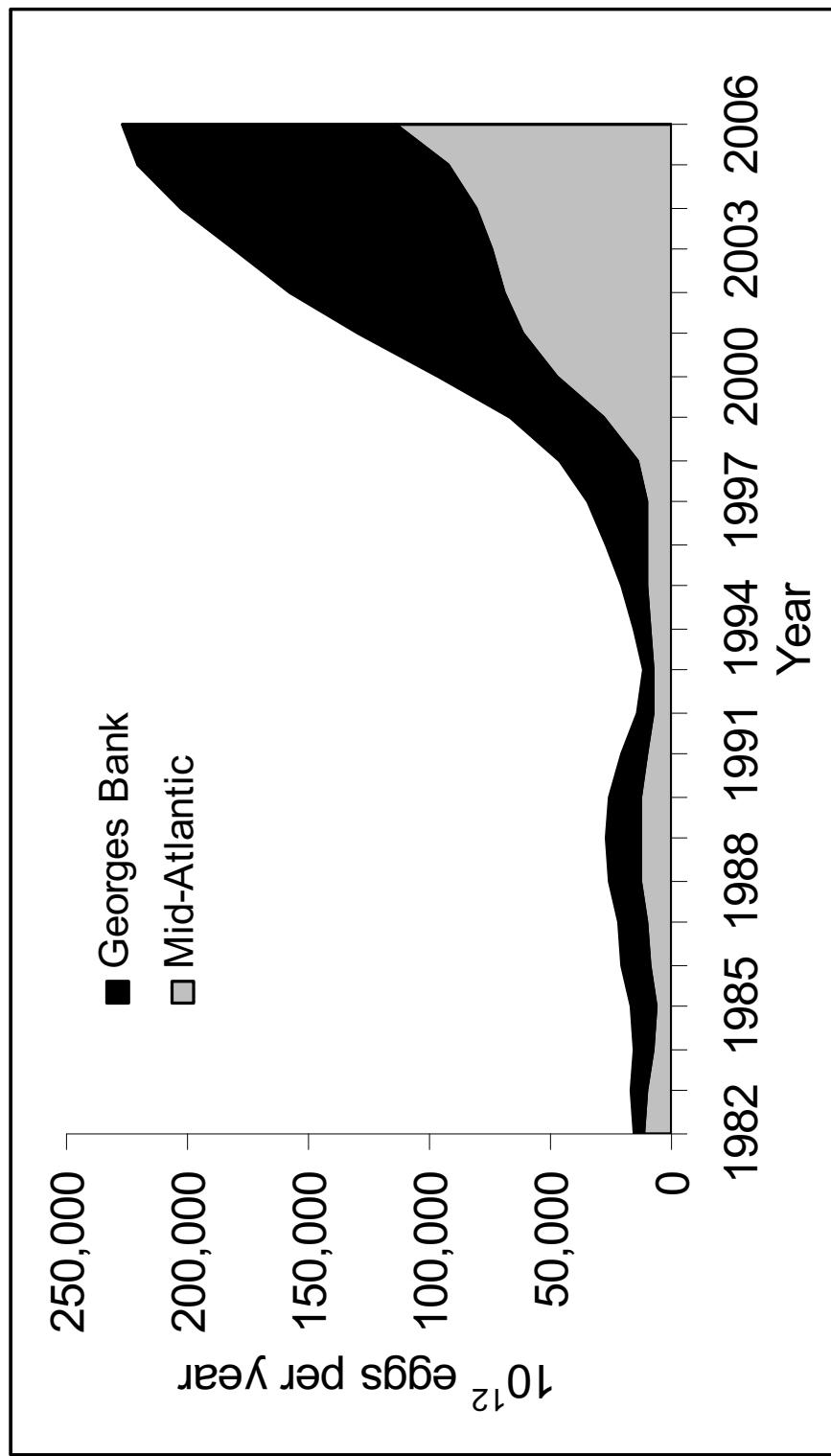


Figure B5-11. Estimated annual egg production by the sea scallop stock during 1982-2006.

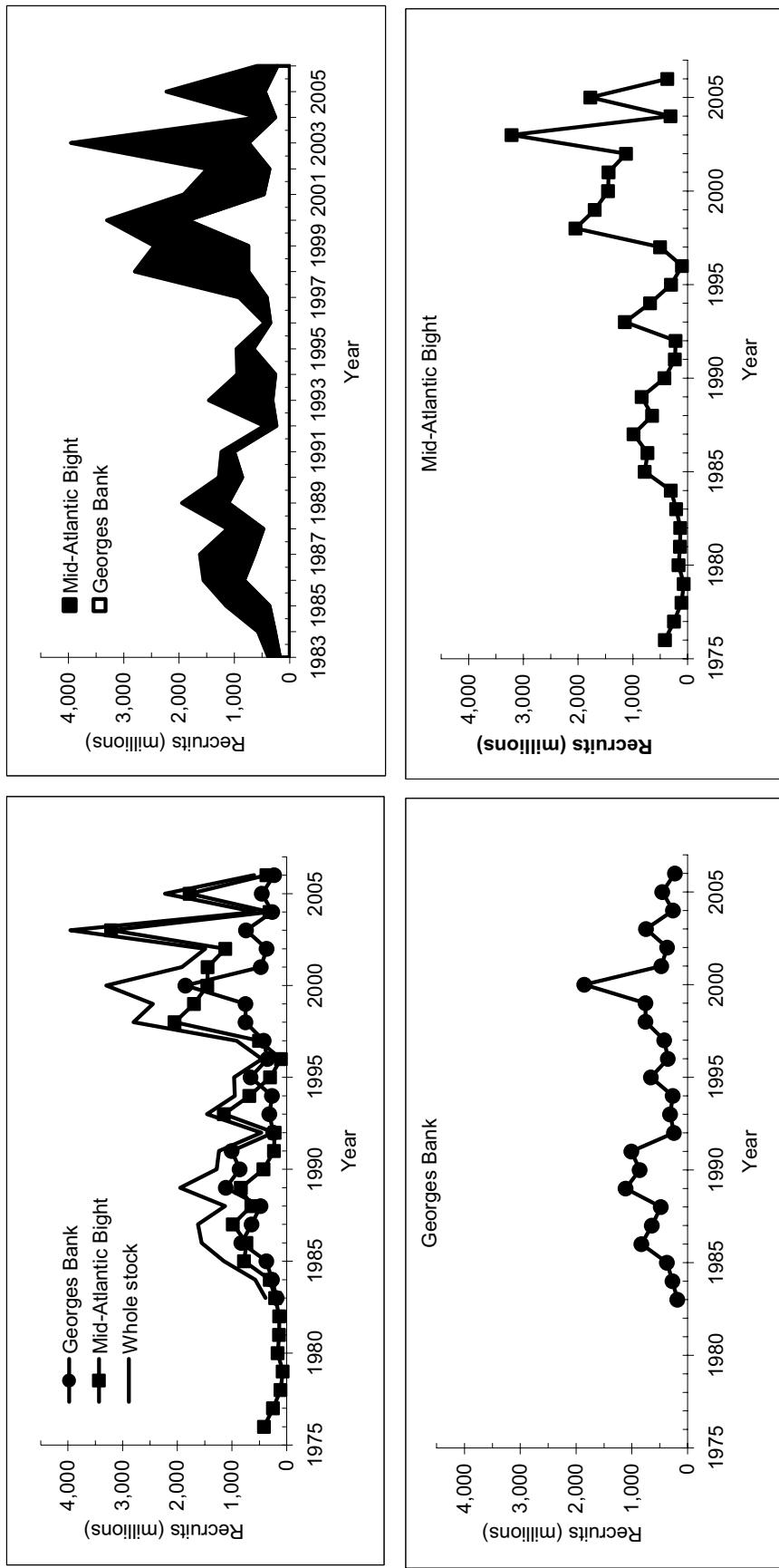


Figure B5-12. Recruitment estimates (40+ mm on January 1) from the CASA model for sea scallops on Georges Bank during 1983-2006, in the Mid-Atlantic Bight during 1976-2006 and for the whole stock during 1983-2006.

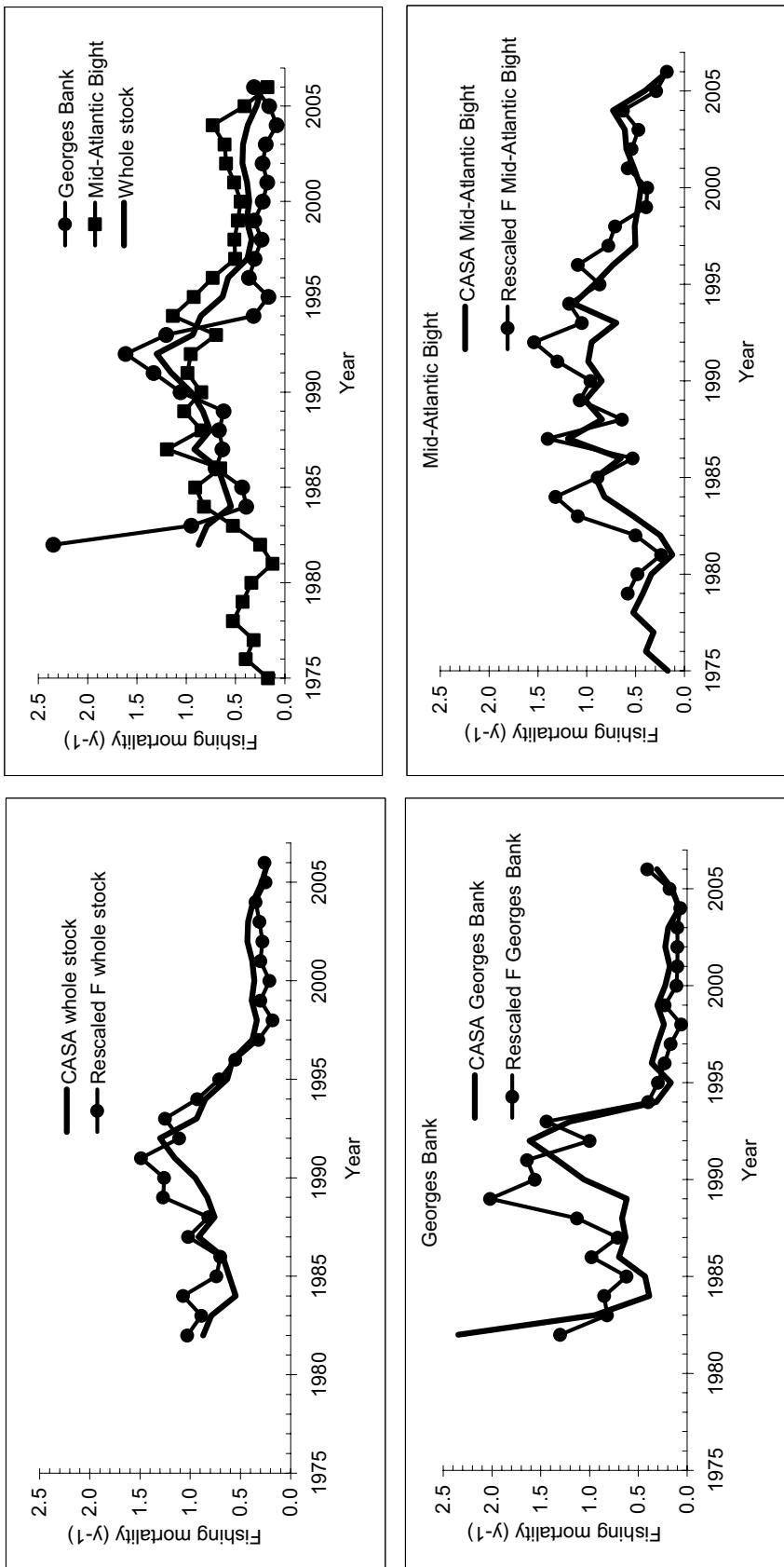


Figure B5-13. Fishing mortality estimates ( $y^{-1}$ ) from the CASA model for sea scallops on Georges Bank, in the Mid-Atlantic Bight and for the whole stock during 1975-2006.

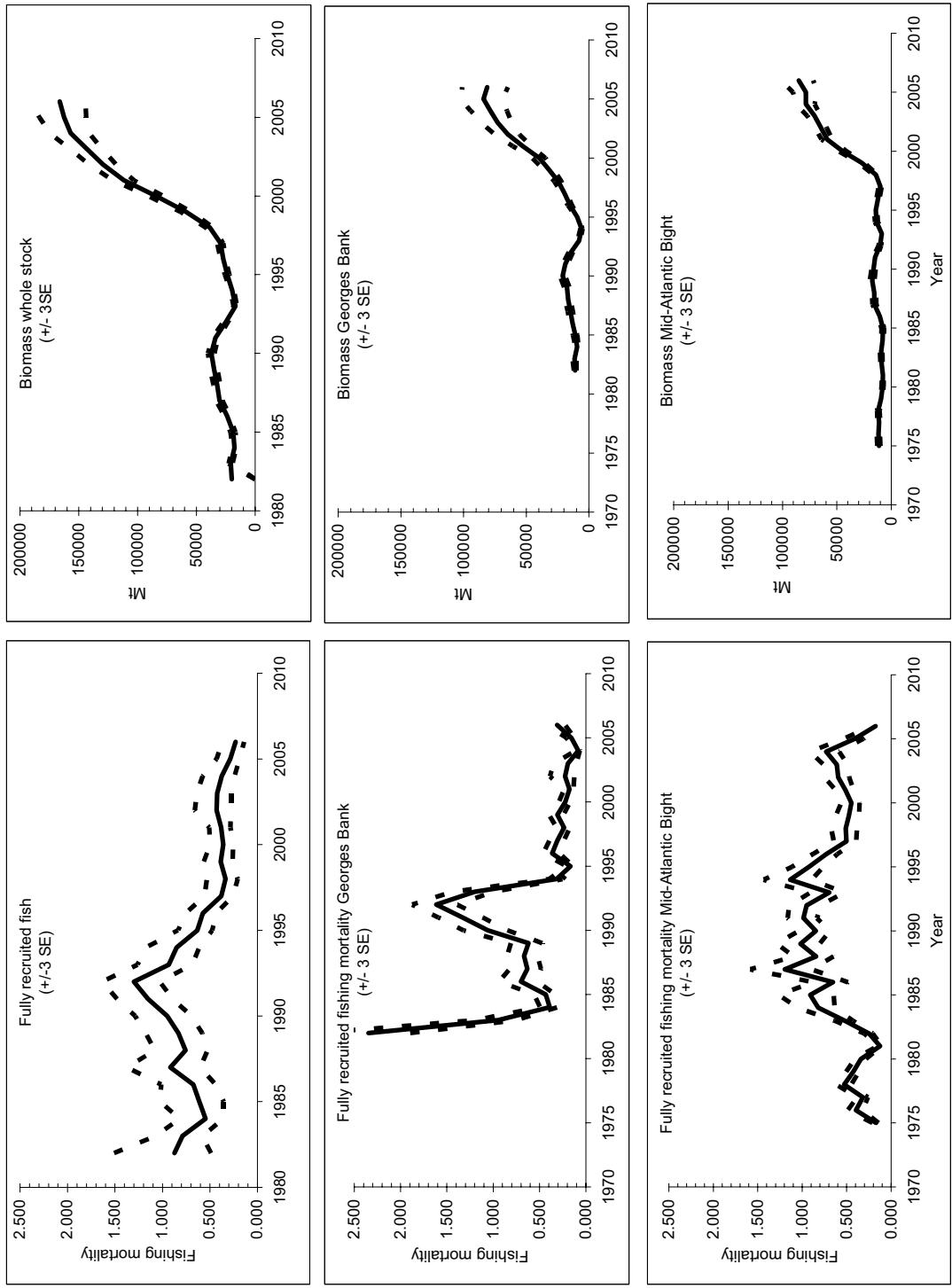


Figure B5-14. CASA model estimates of fishing mortality and biomass ( $\pm 3$  standard errors) for sea scallops on Georges Bank, the Mid-Atlantic Bight and for the stock as a whole.

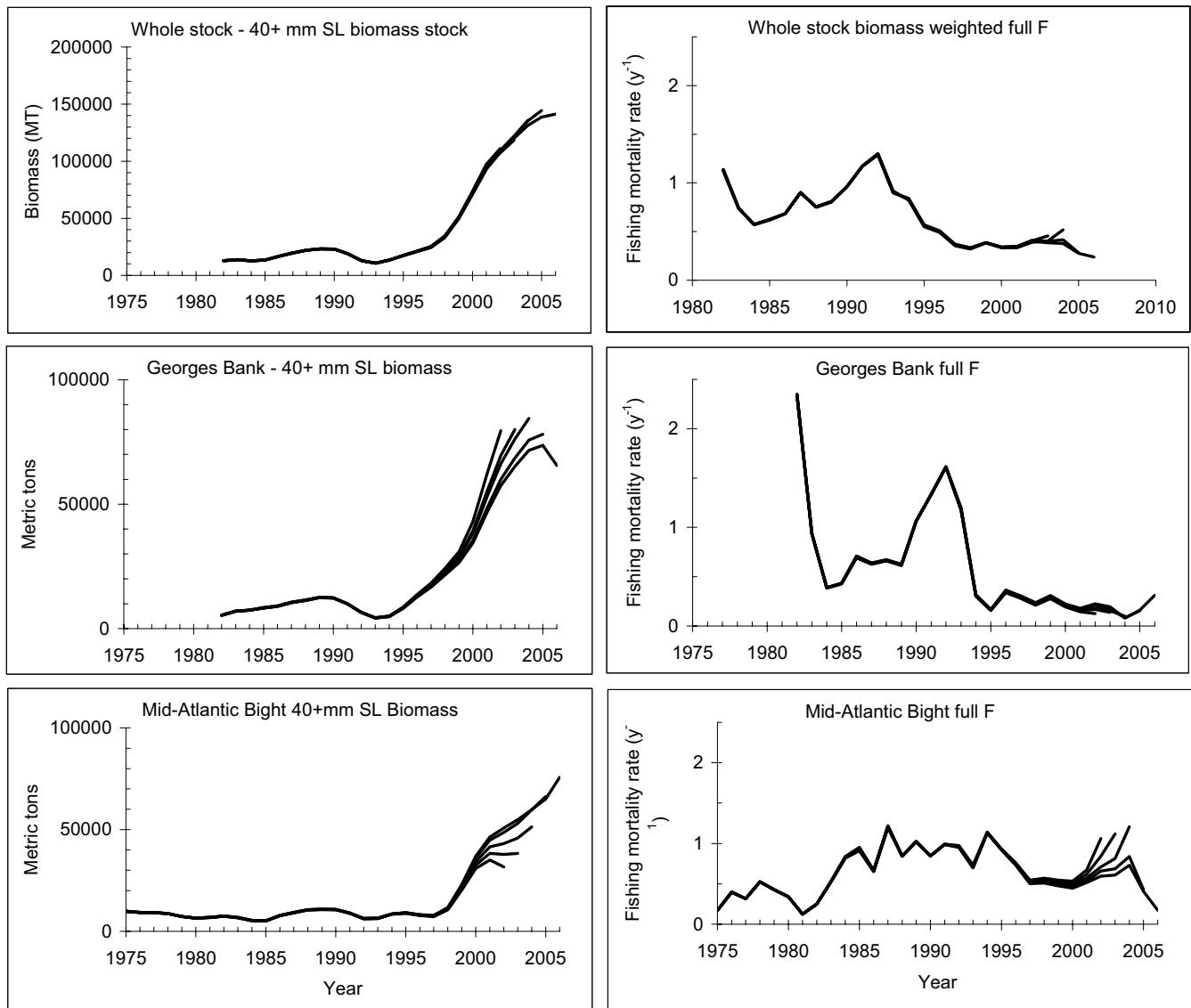


Figure B5-15. Retrospective analysis for basecase CASA model estimates of sea scallop stock biomass on Georges Bank, in the Mid-Atlantic Bight and for the stock as a whole. Fishing mortality rates for the whole stock are the biomass weighted fully recruited fishing mortality rates for Georges Bank and the Mid-Atlantic Bight, rather than catch numbers divided by mean fishable abundance, because biomass weighted values were easier to compute in retrospective analyses and should give approximately the same result.

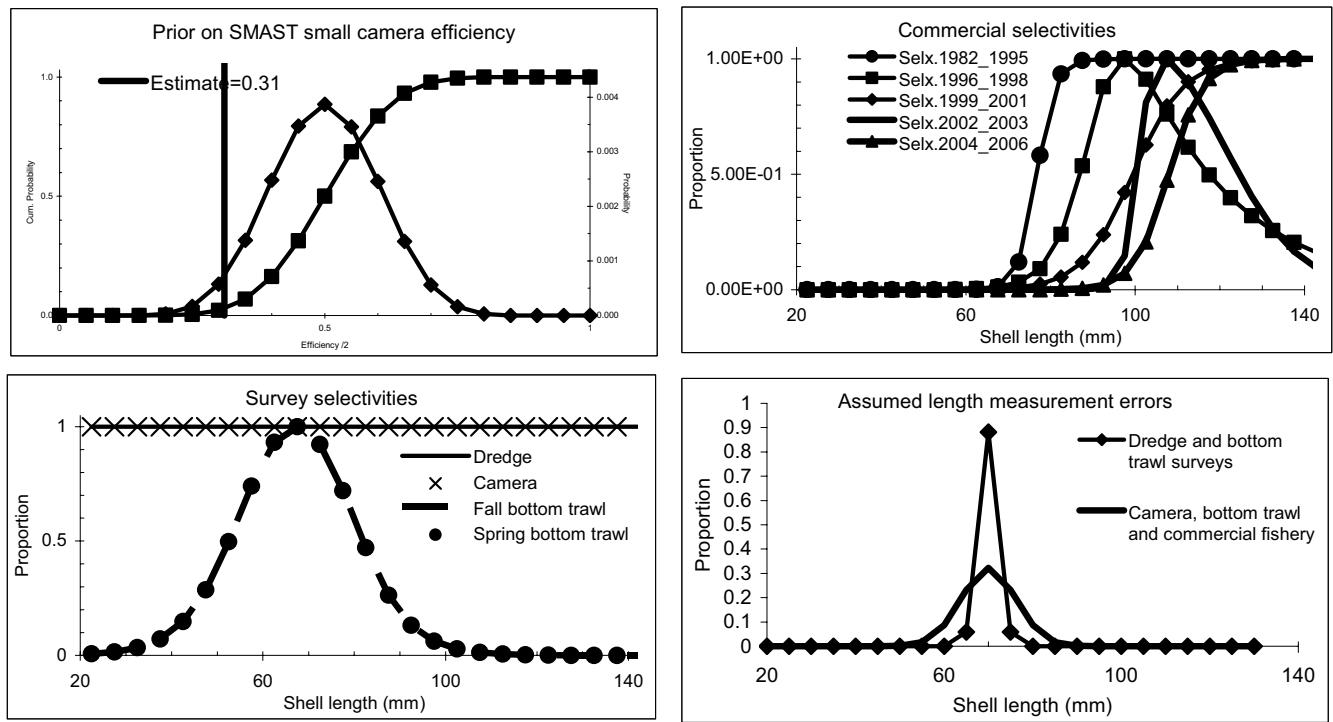


Figure B5-16. Diagnostics from base-case CASA model for sea scallops on Georges Bank.

### Dredge survey

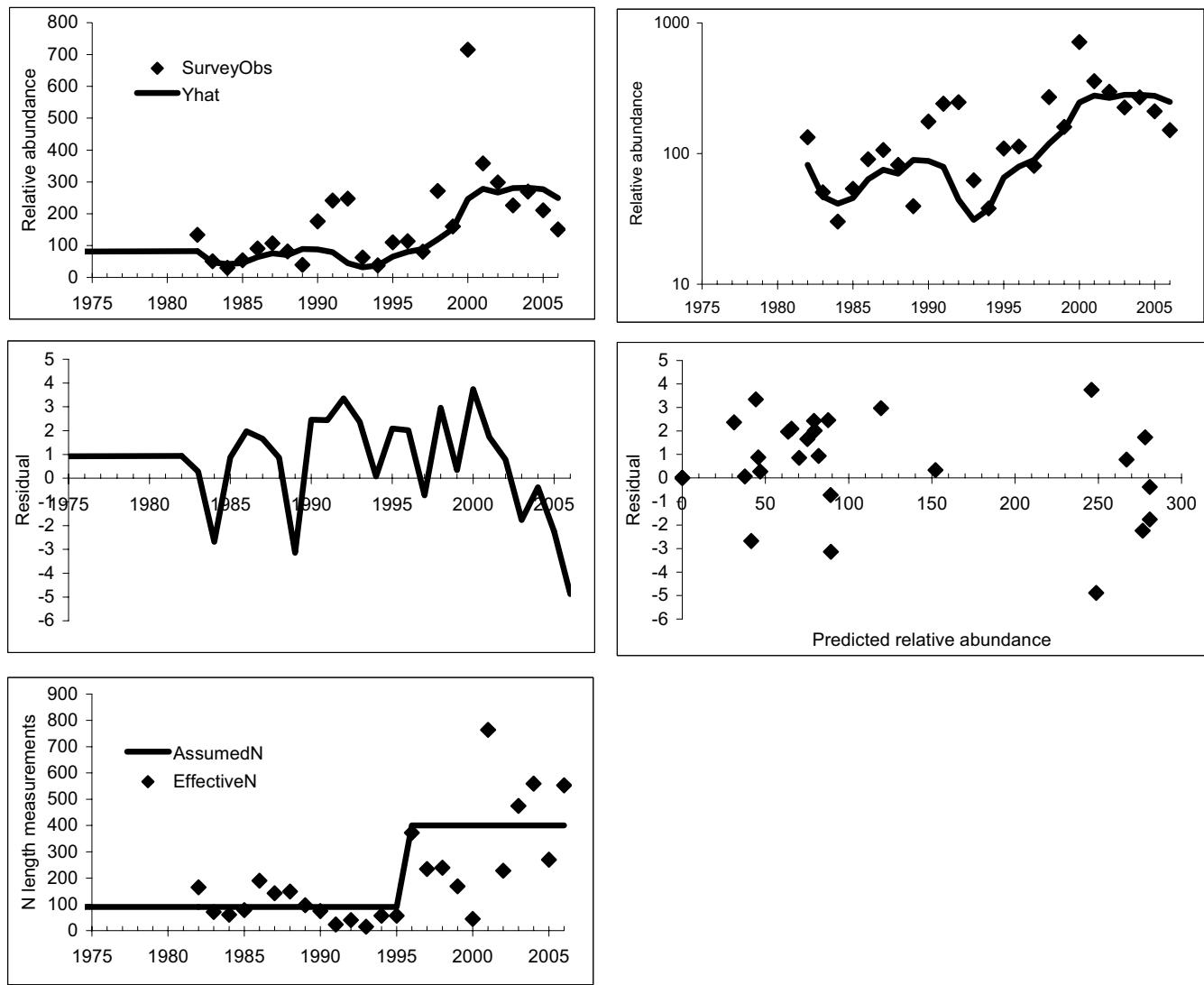


Figure B5-16 continued.

### Small camera survey

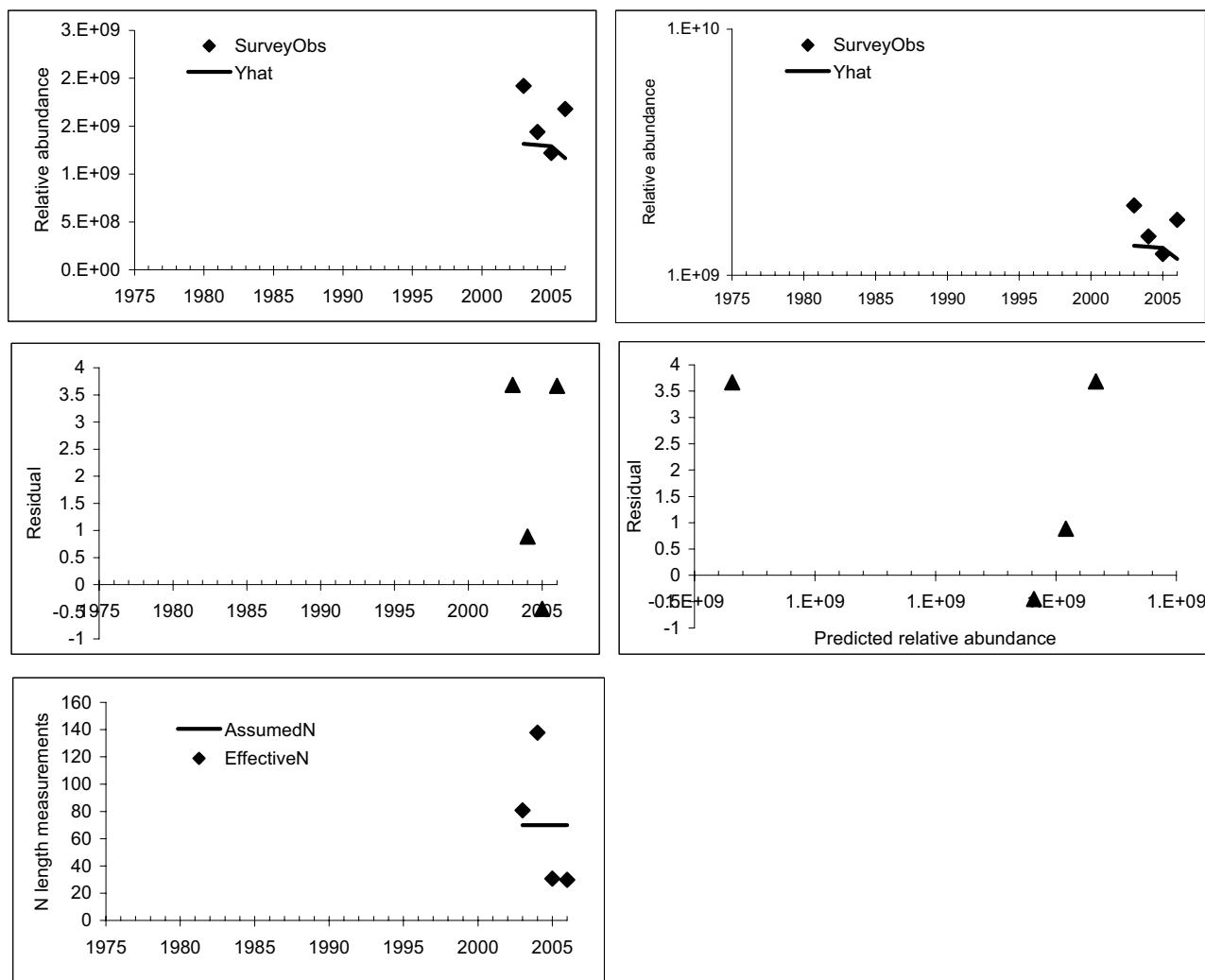


Figure B5-16 continued.

**Landings per unit effort (LPUE)**

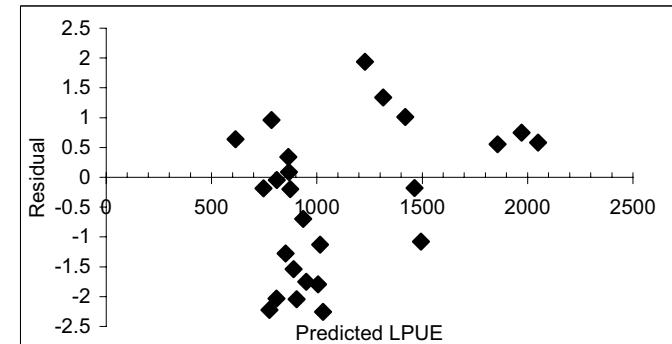
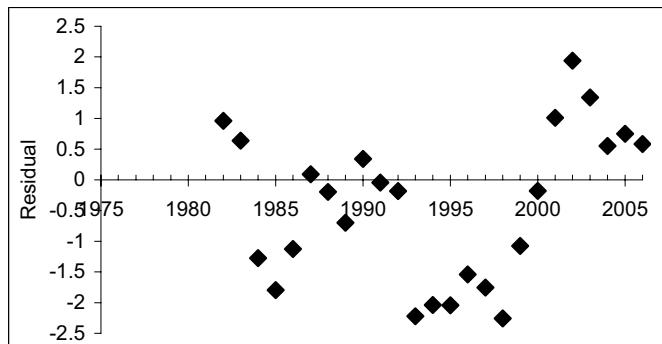
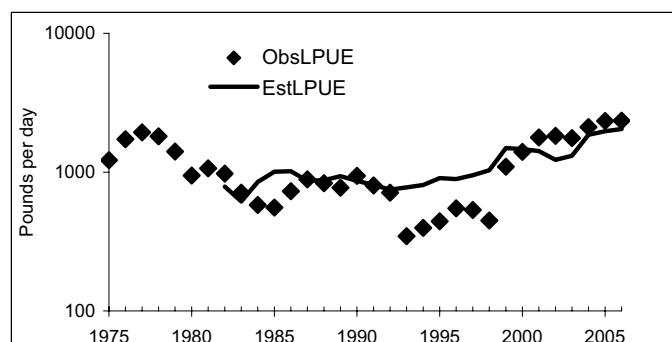
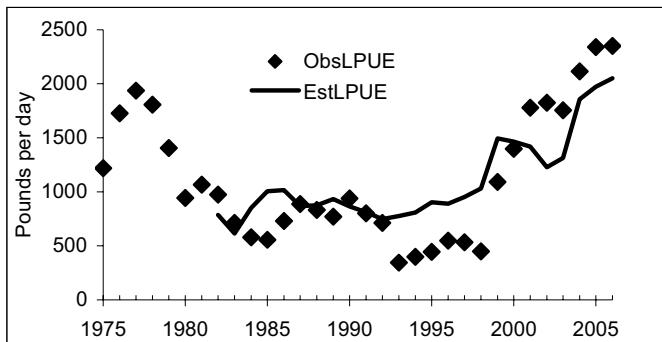


Figure B5-16 continued.

### Landings

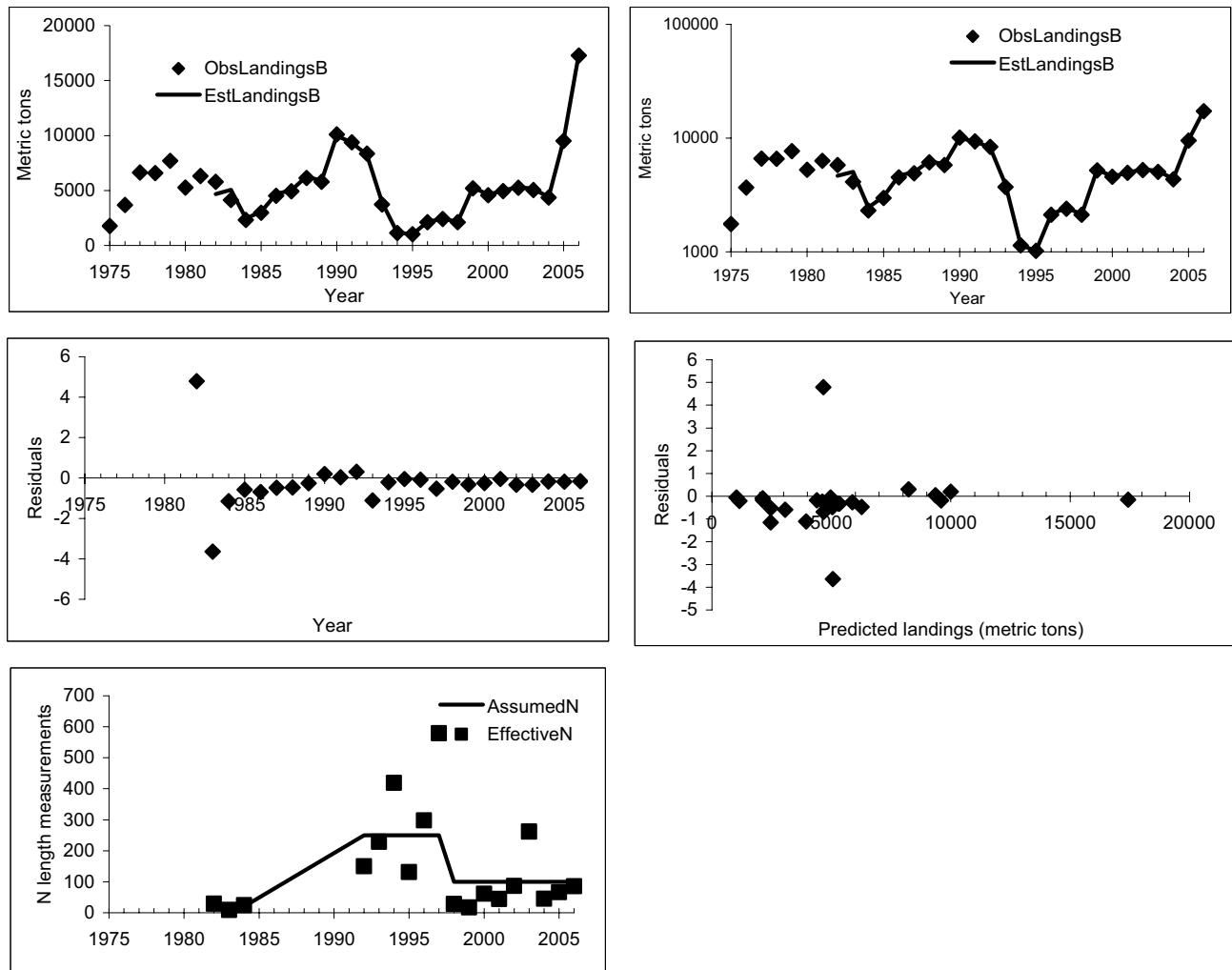


Figure B5-16 continued.

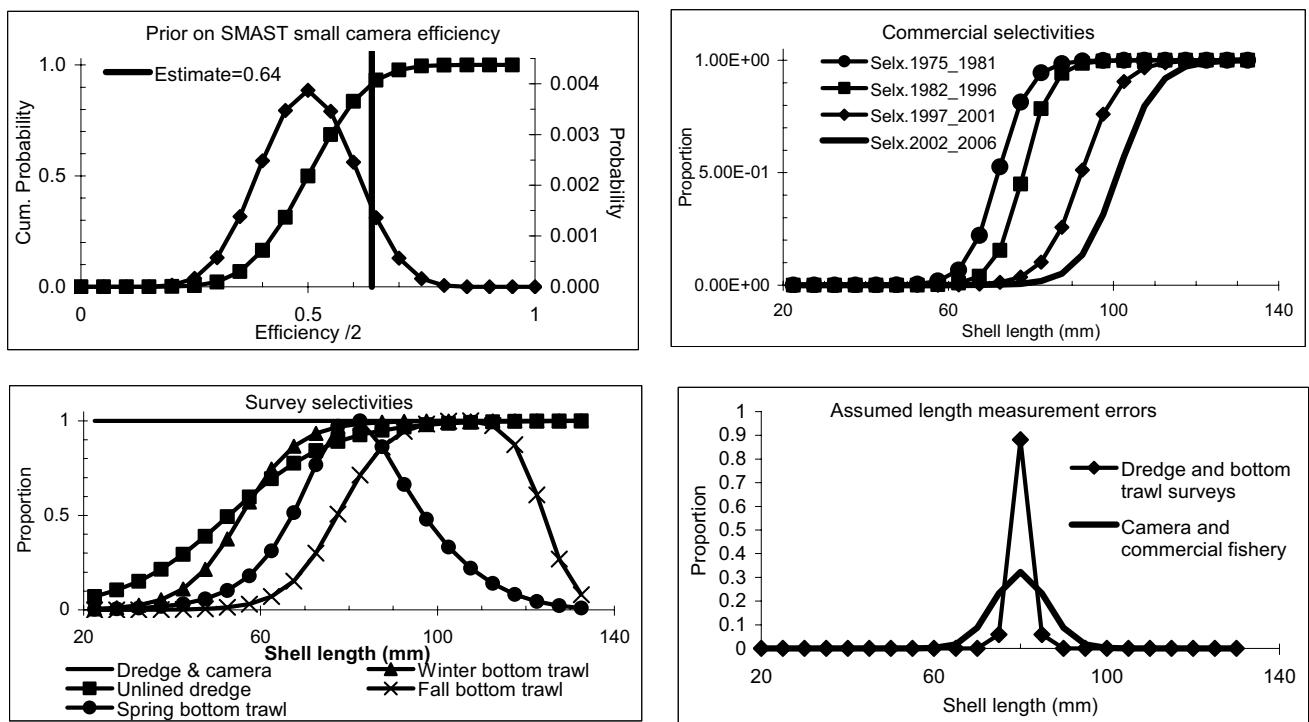


Figure B5-17. Diagnostics from basecase CASA model for sea scallops in the Mid-Atlantic Bight.

### Dredge survey

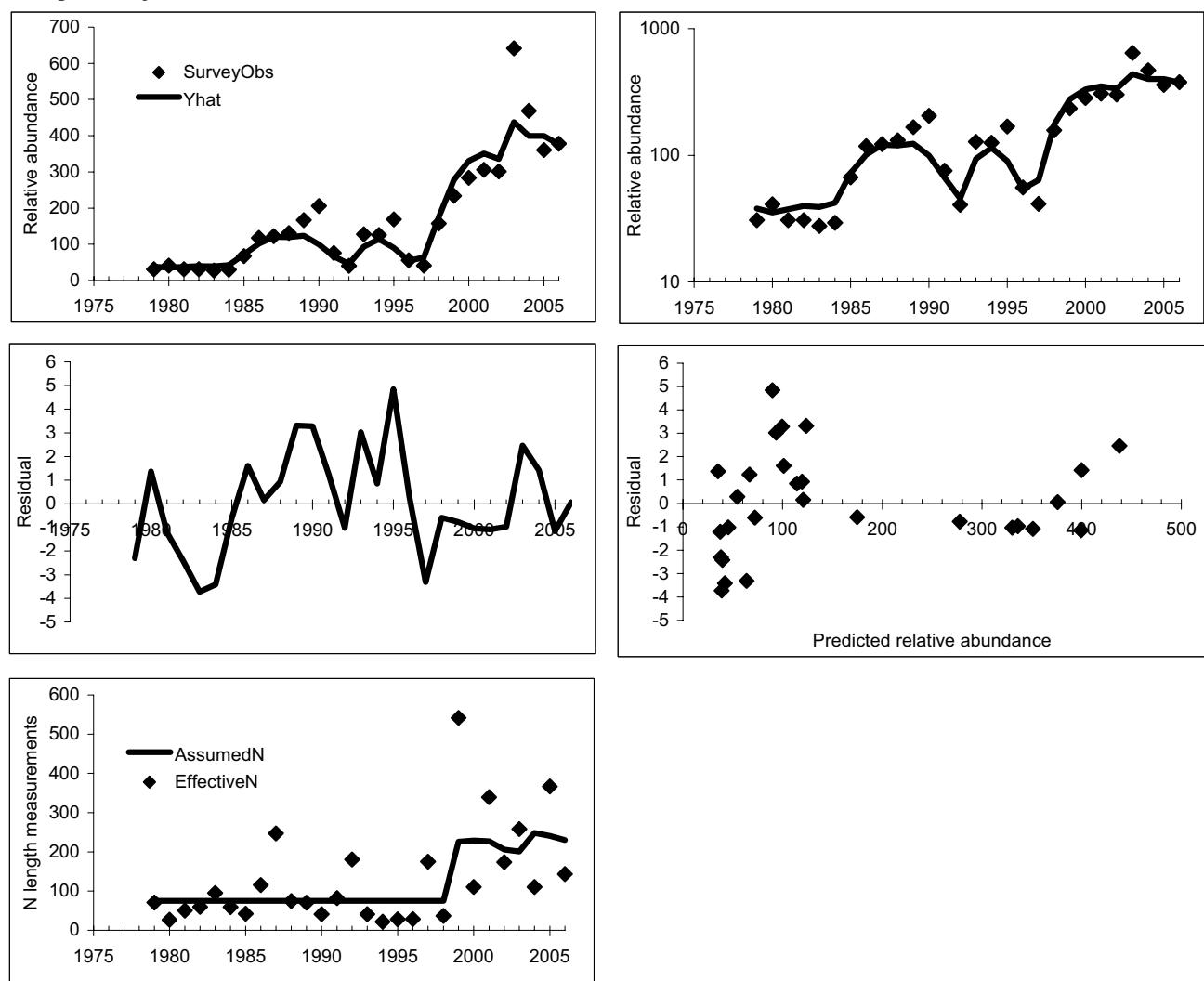


Figure B5-17 continued.

### Small camera survey

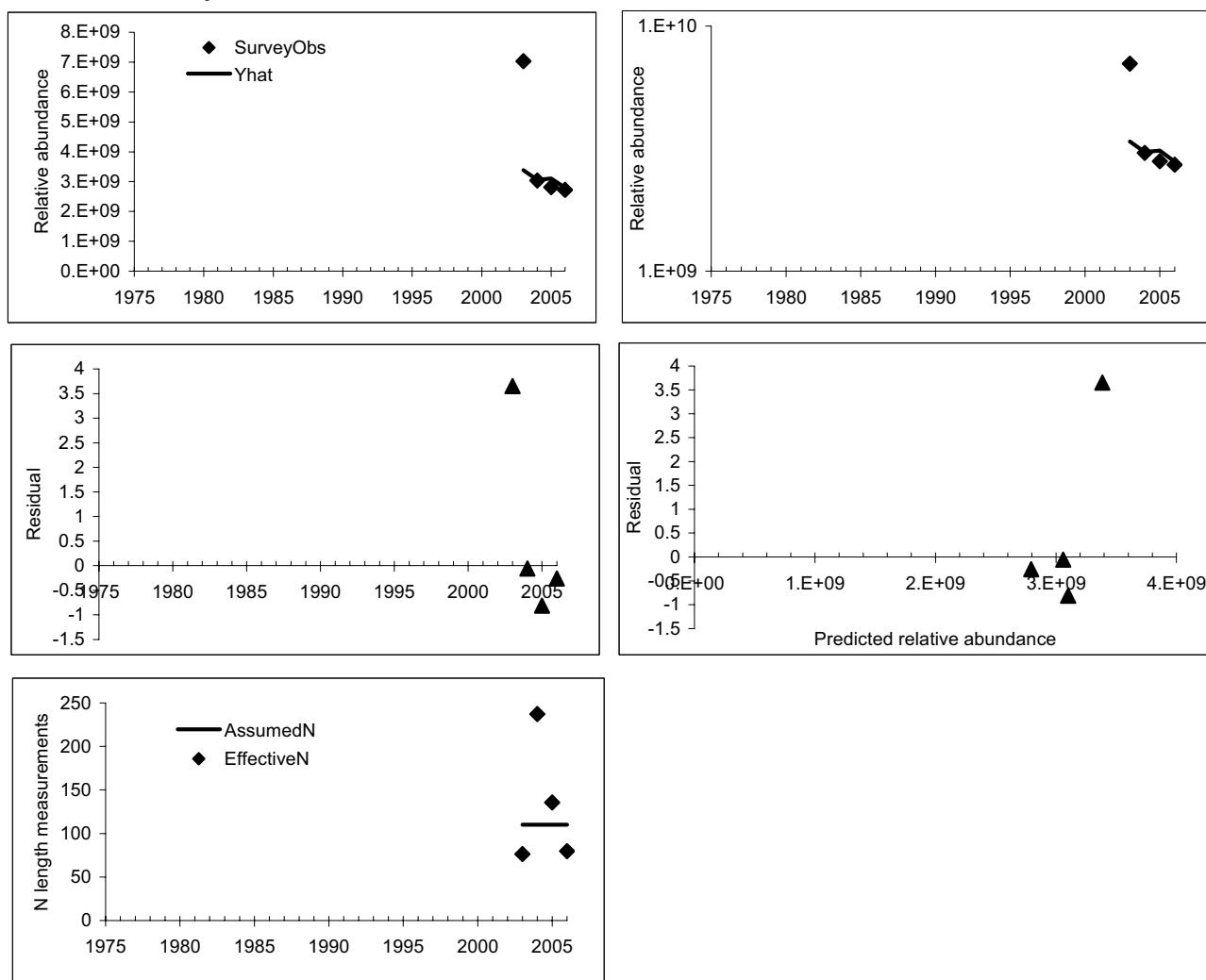


Figure B5-17 continued.

**Winter bottom trawl survey**

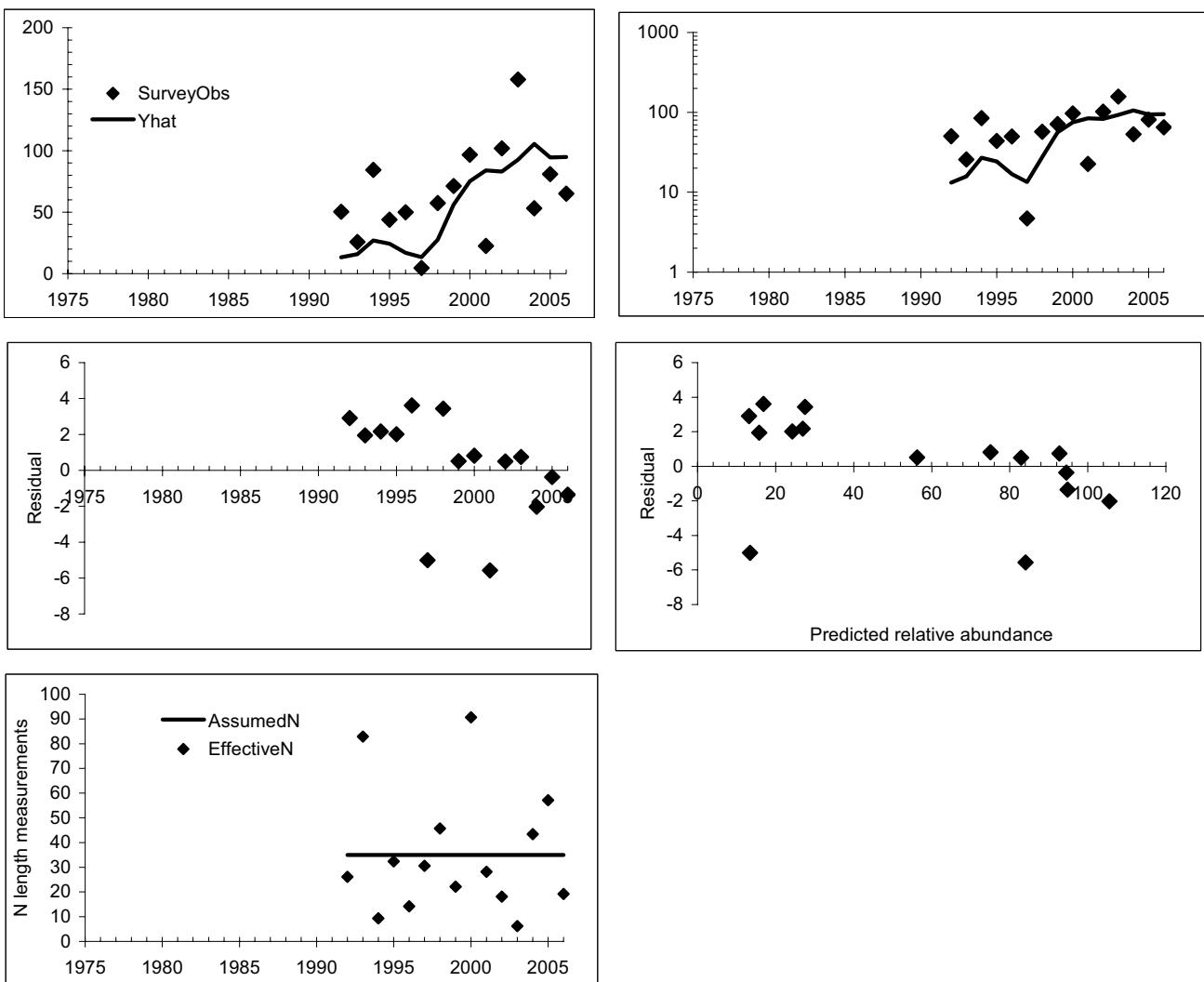


Figure B5-17 continued.

### Unlined dredge

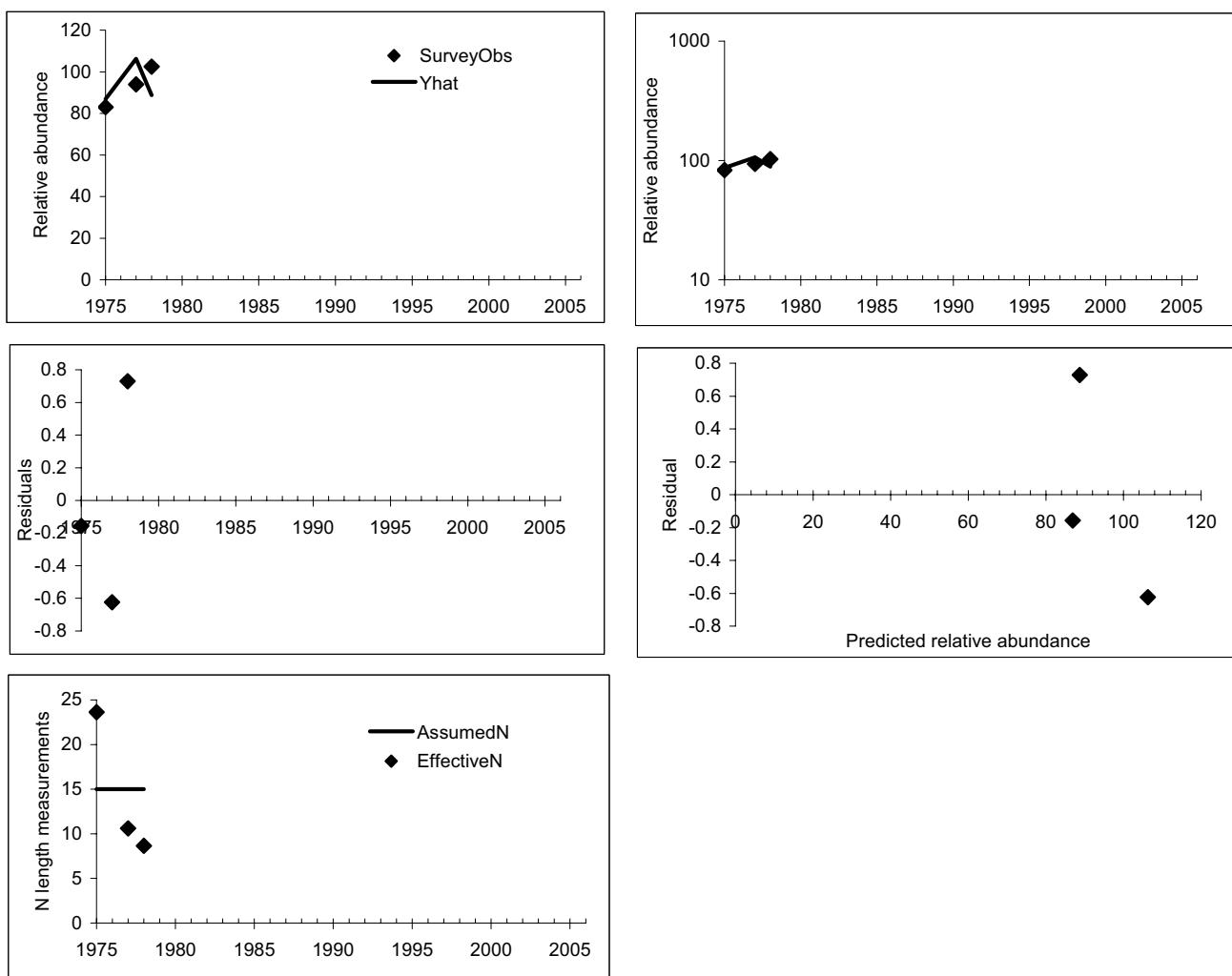


Figure B5-17 continued.

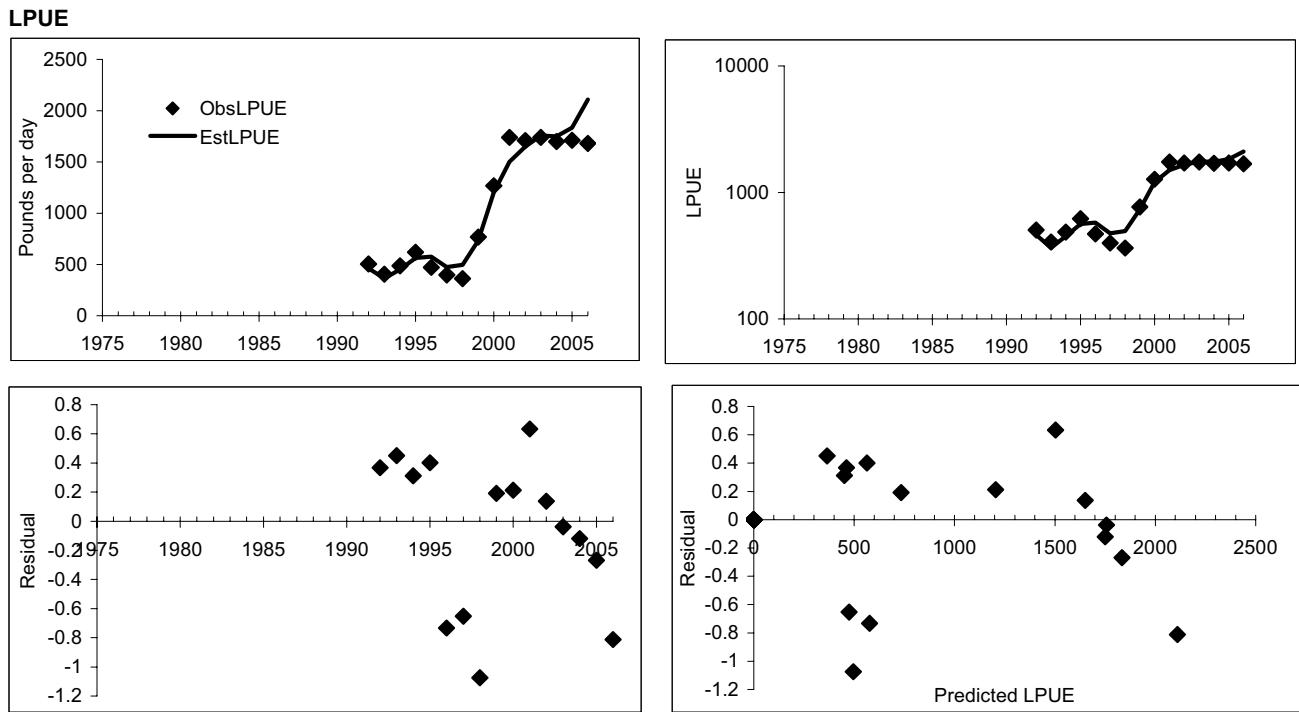


Figure B5-17 continued.

### Landings

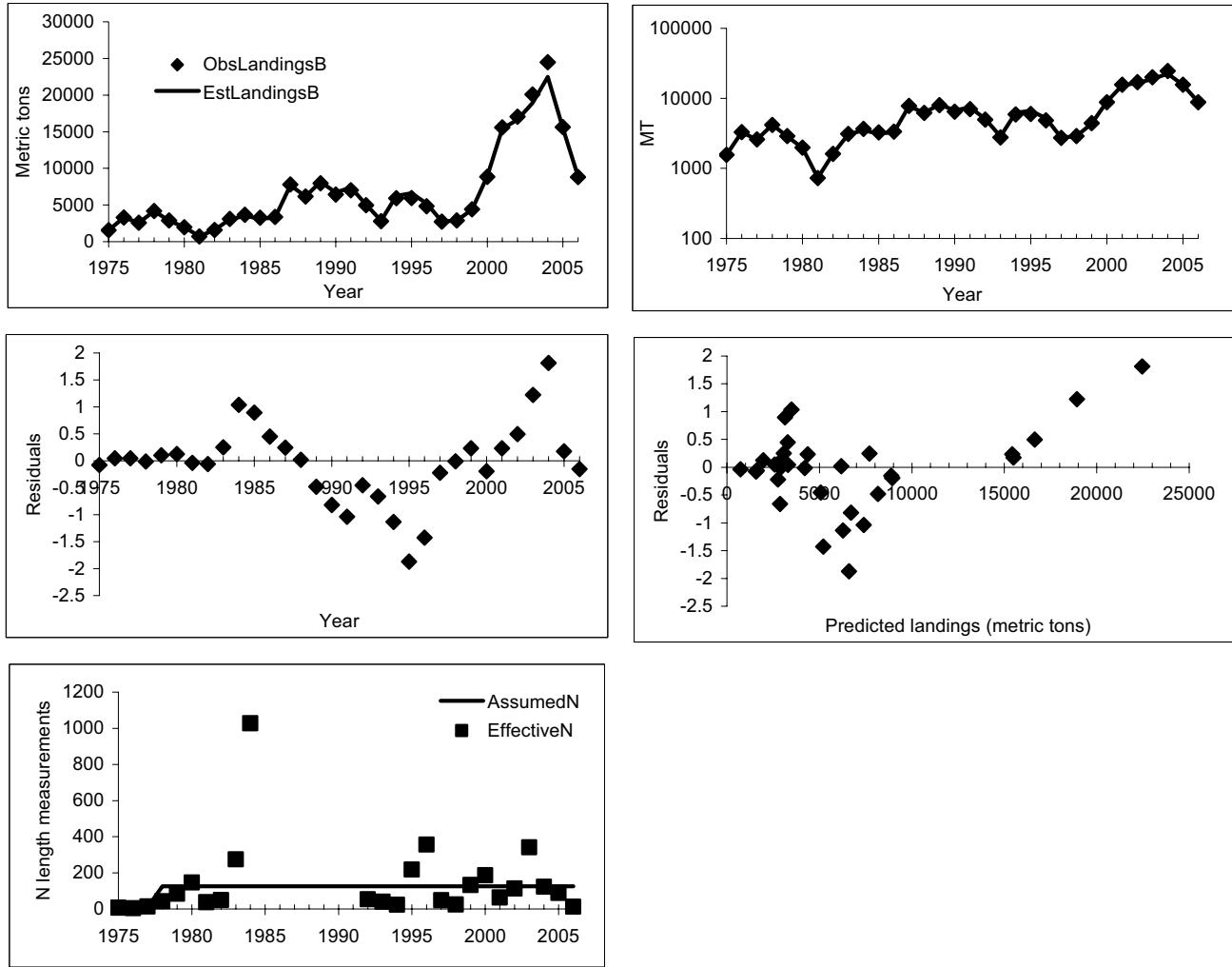


Figure B5-17 continued.

**Fall bottom trawl (for illustration only, does not affect CASA estimates)**

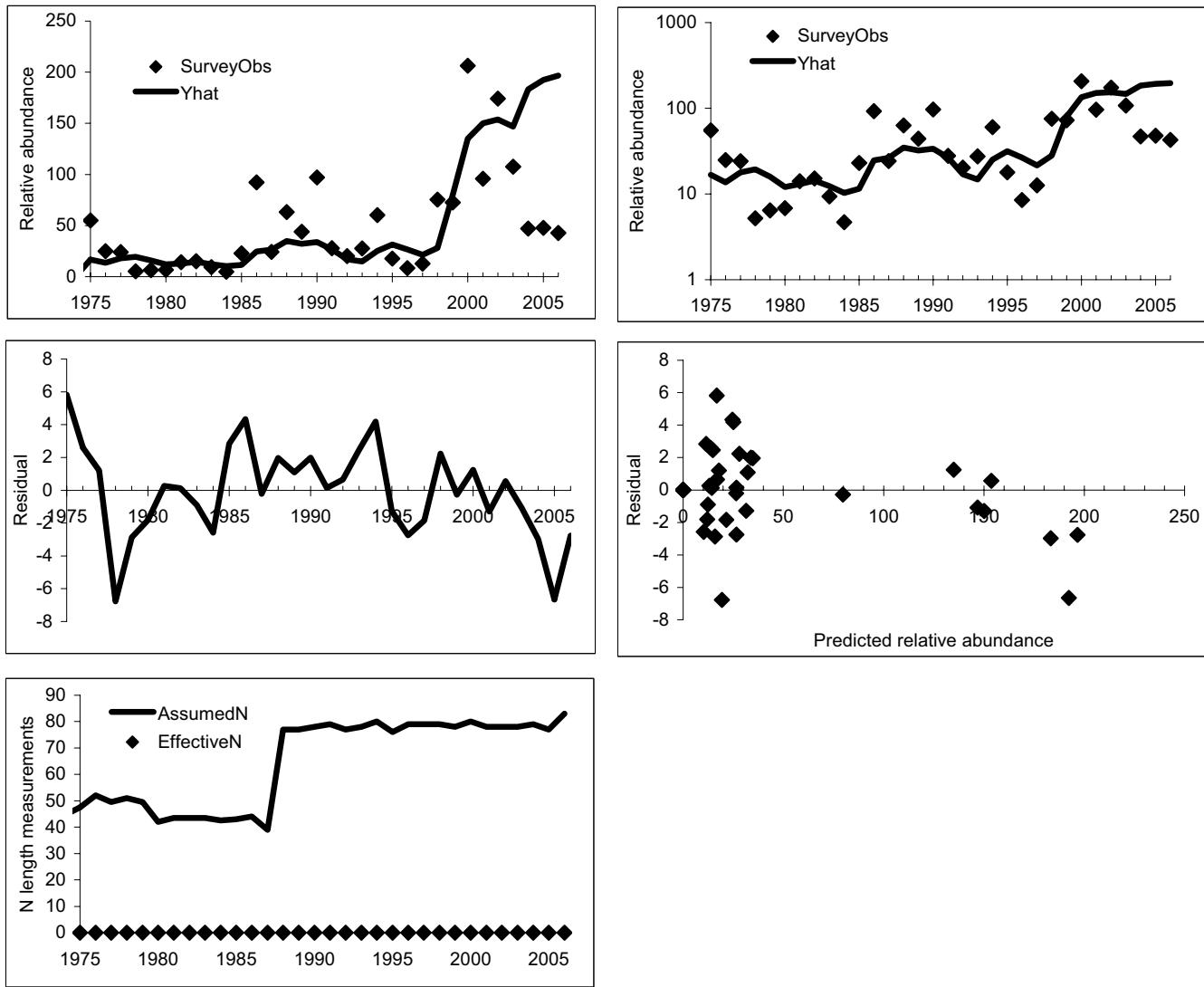


Figure B5-17 continued. Fall and spring bottom trawl data were used in the CASA model for sea scallops in the Mid-Atlantic for comparison only. Survey trend and shell height data from the fall and spring bottom trawl survey did not affect model estimates.

**Spring bottom trawl (for illustration only, does not affect CASA estimates)**

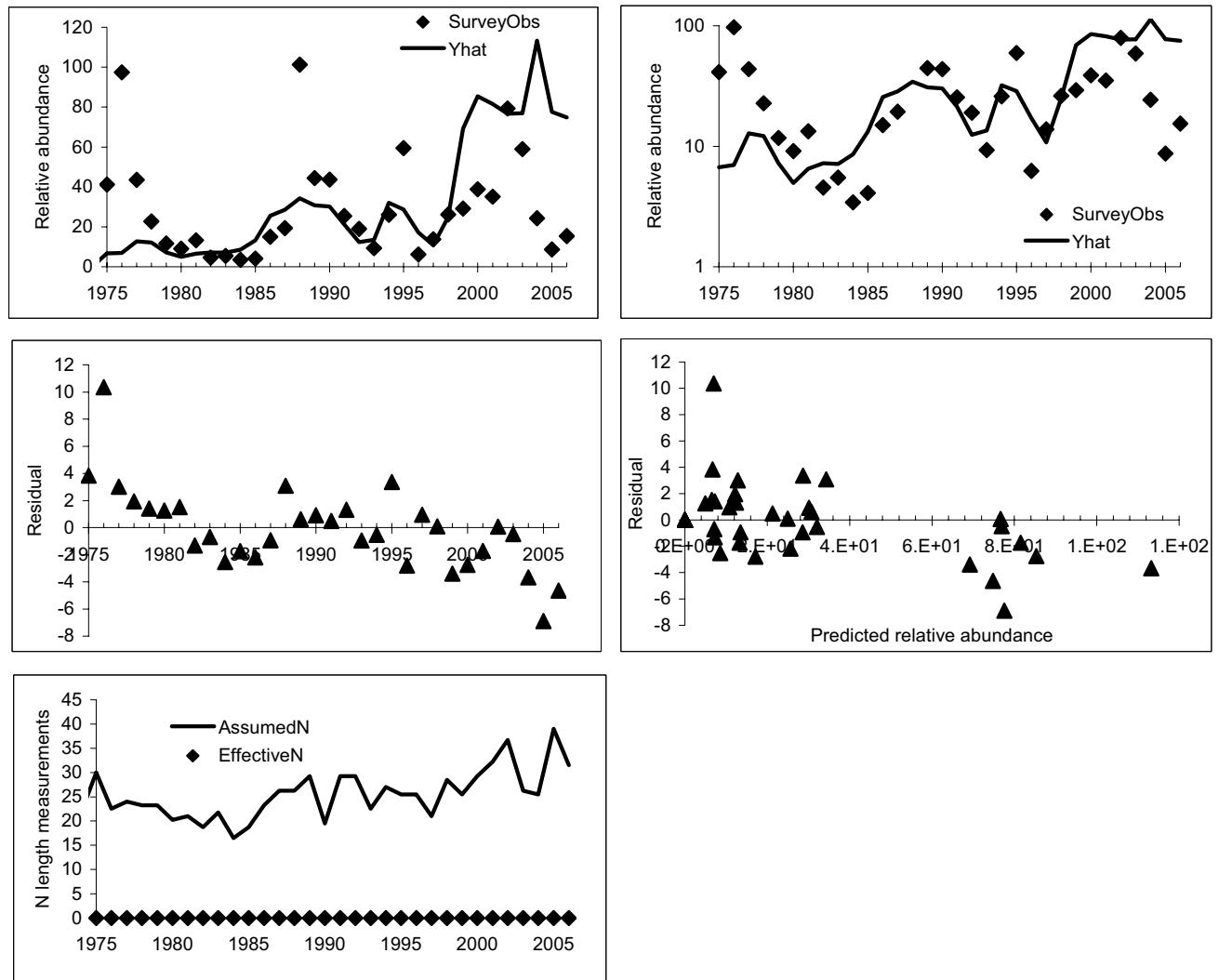


Figure B5-17 continued. Fall and spring bottom trawl data were used in the CASA model for sea scallops in the Mid-Atlantic for comparison only. Survey trend and shell height data from the fall and spring bottom trawl survey did not affect model estimates.

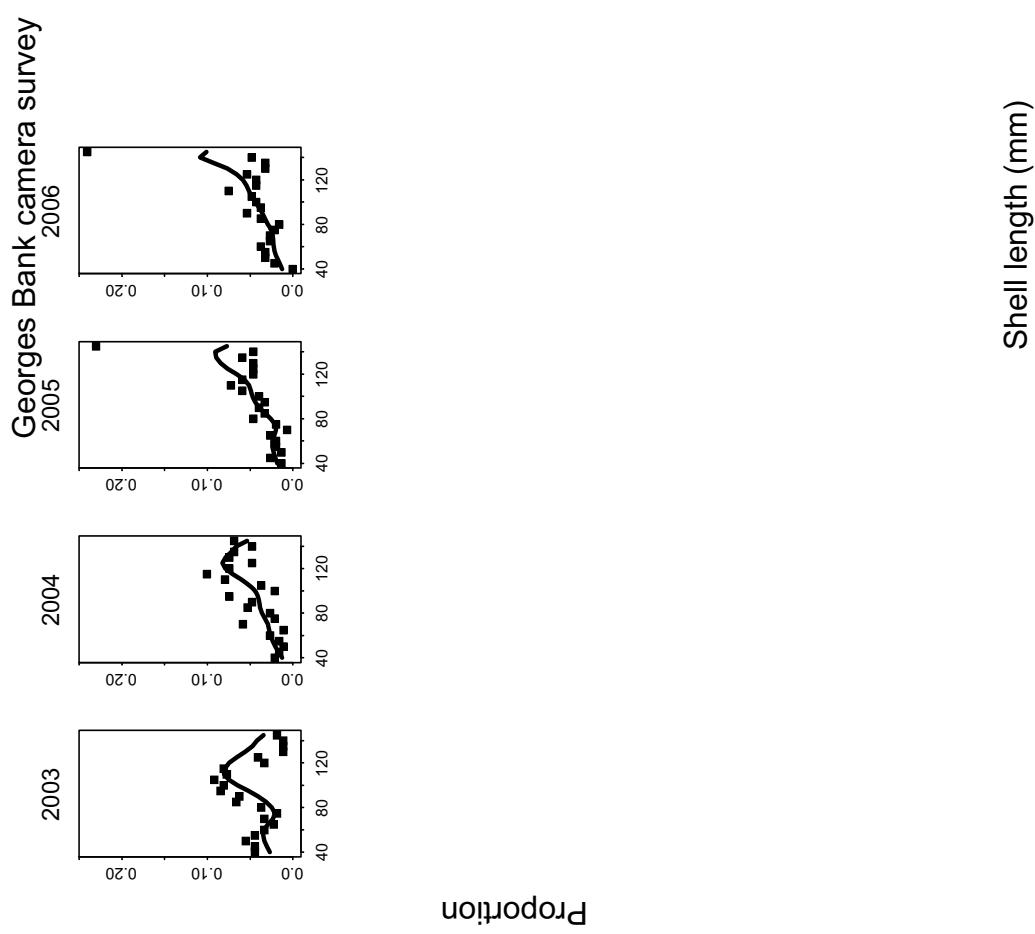


Figure B5-18. Observed and predicted shell height composition data from the basecase CASA model for sea scallops on Georges Bank.

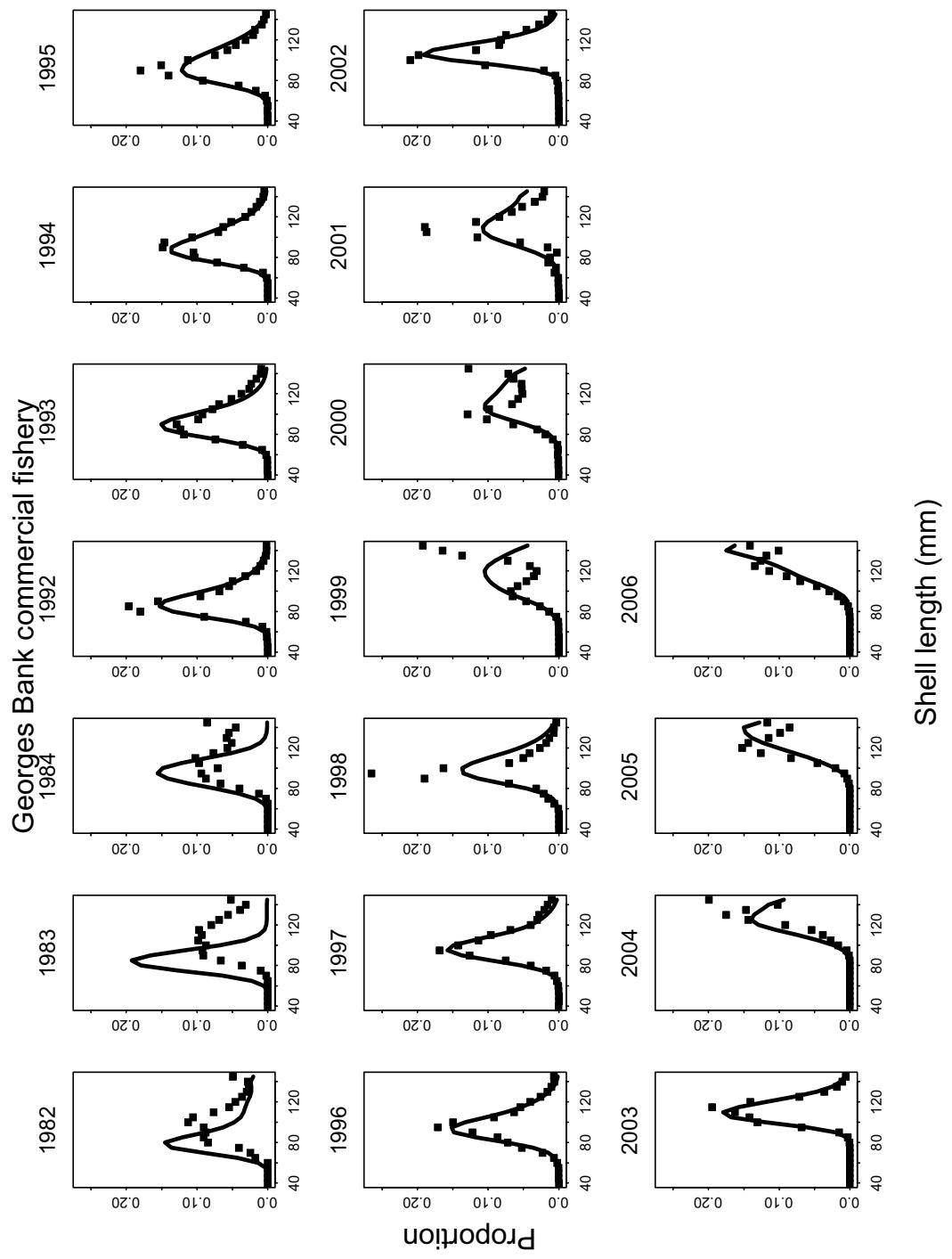


Figure B5-18 continued.

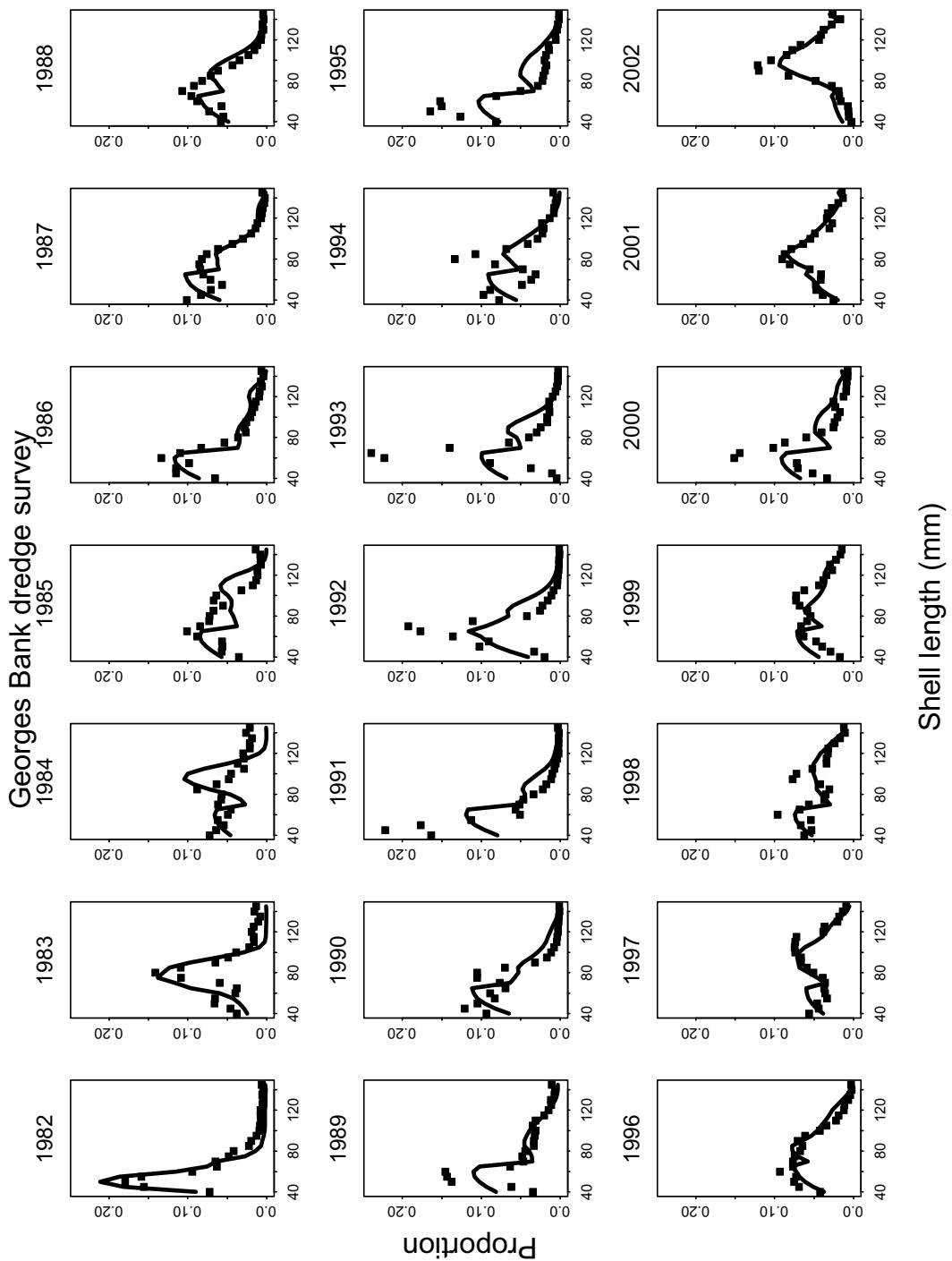


Figure B5-18 continued.

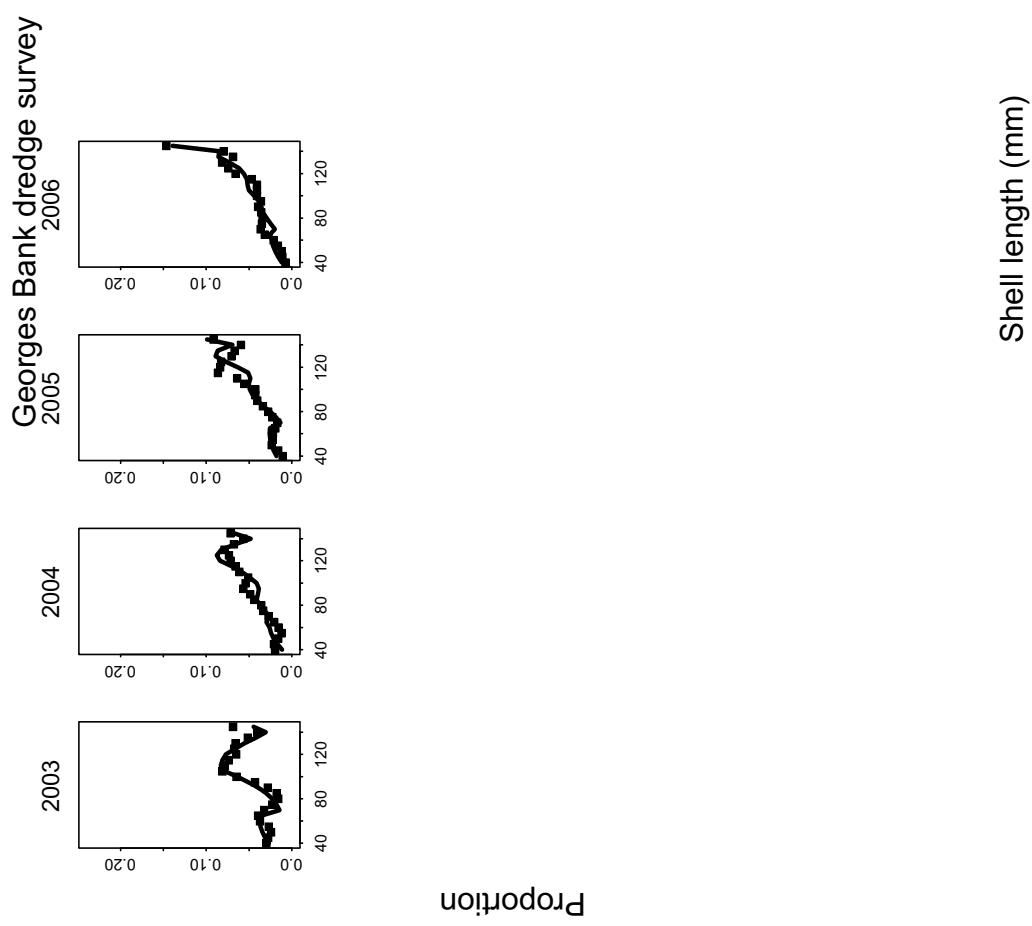


Figure B5-18 continued.

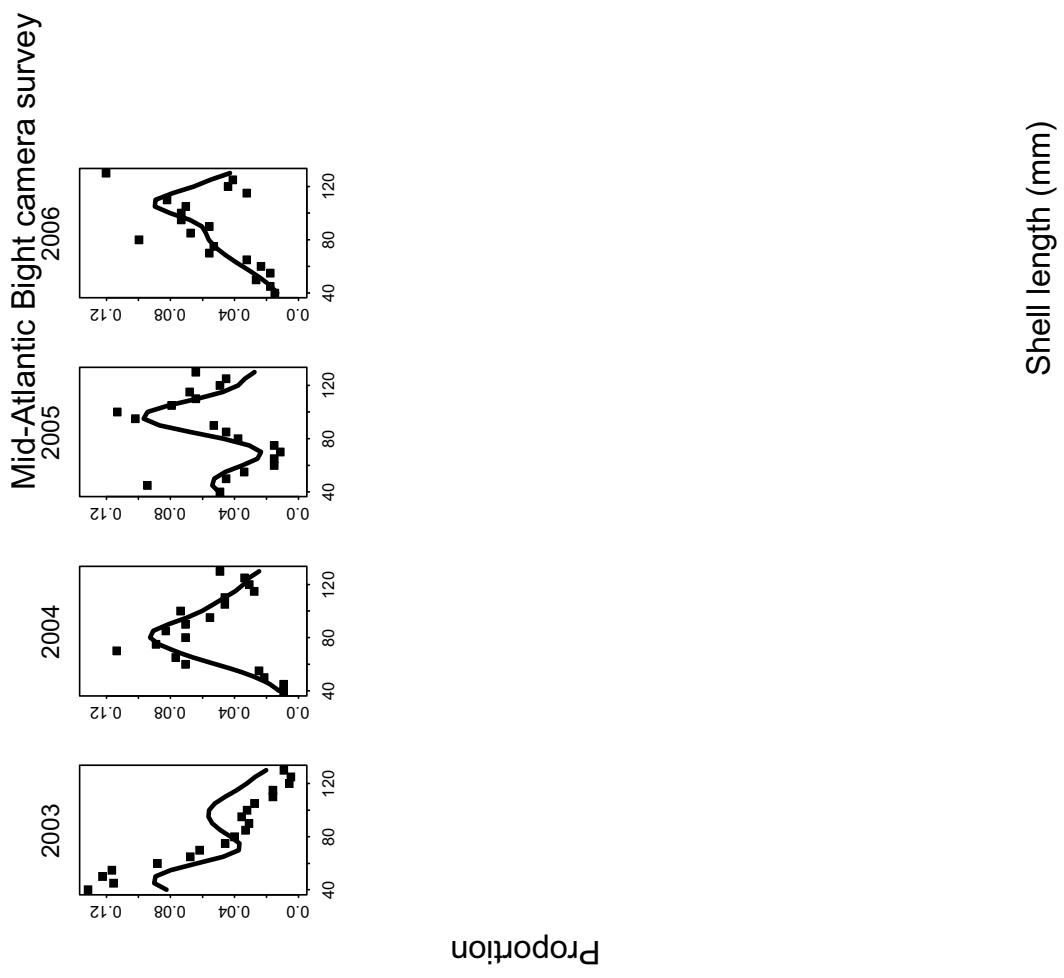


Figure B5-19. Observed and predicted shell height composition data from the basecase CASA model for sea scallops in the Mid-Atlantic.

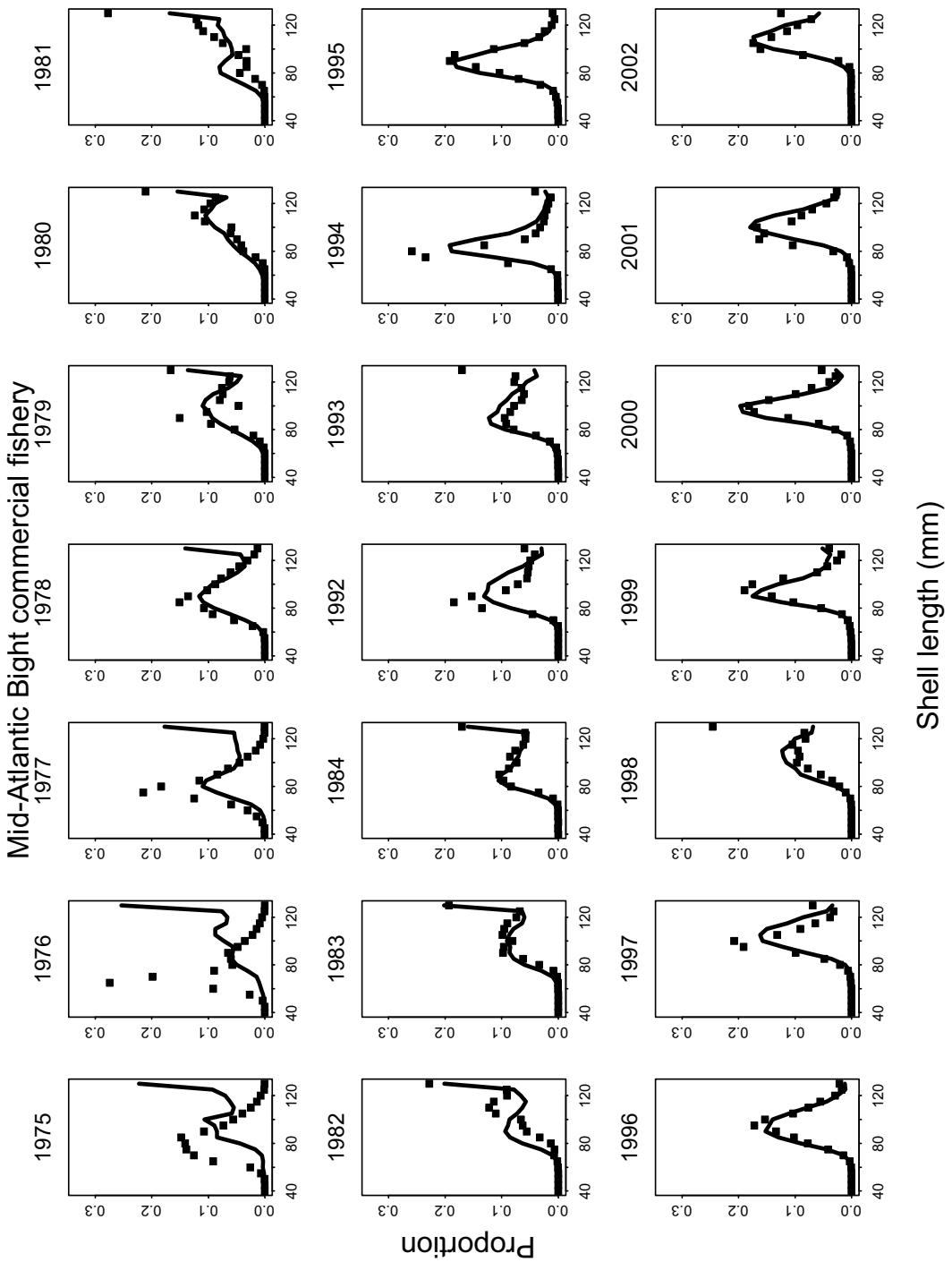


Figure B5-19 continued.

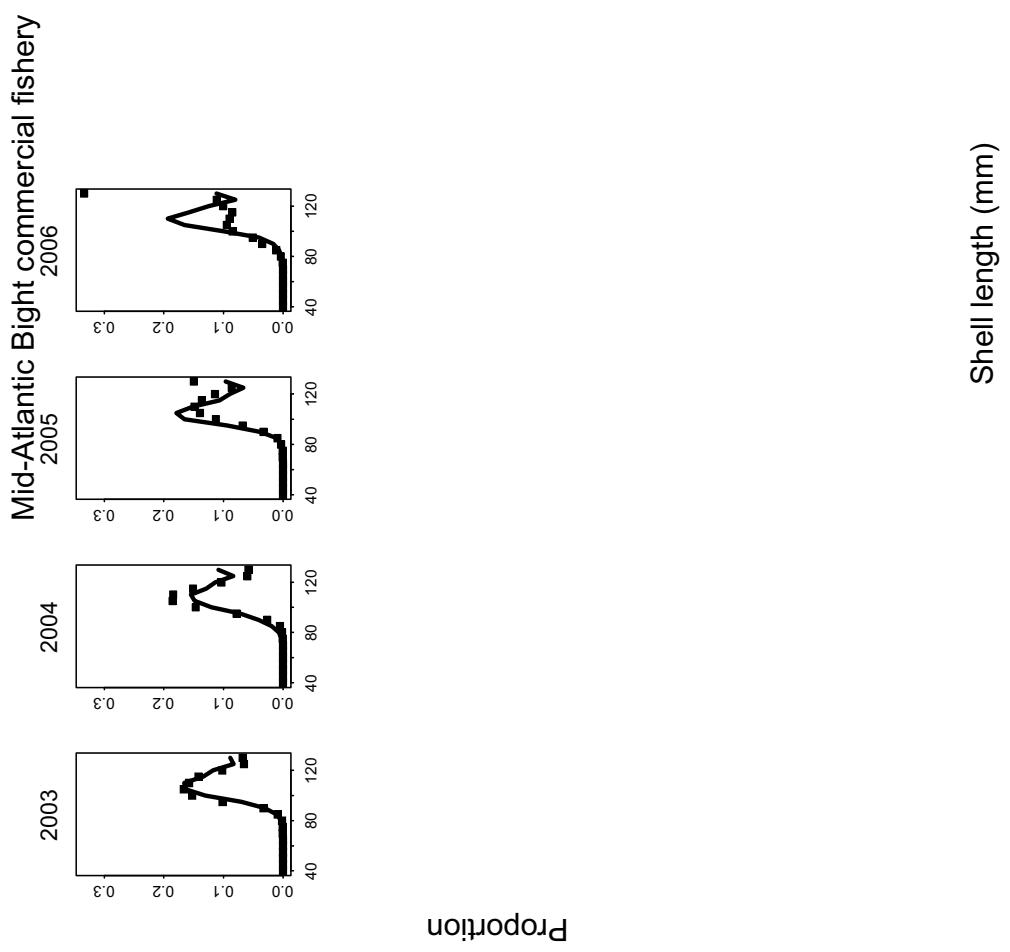


Figure B5-19 continued.

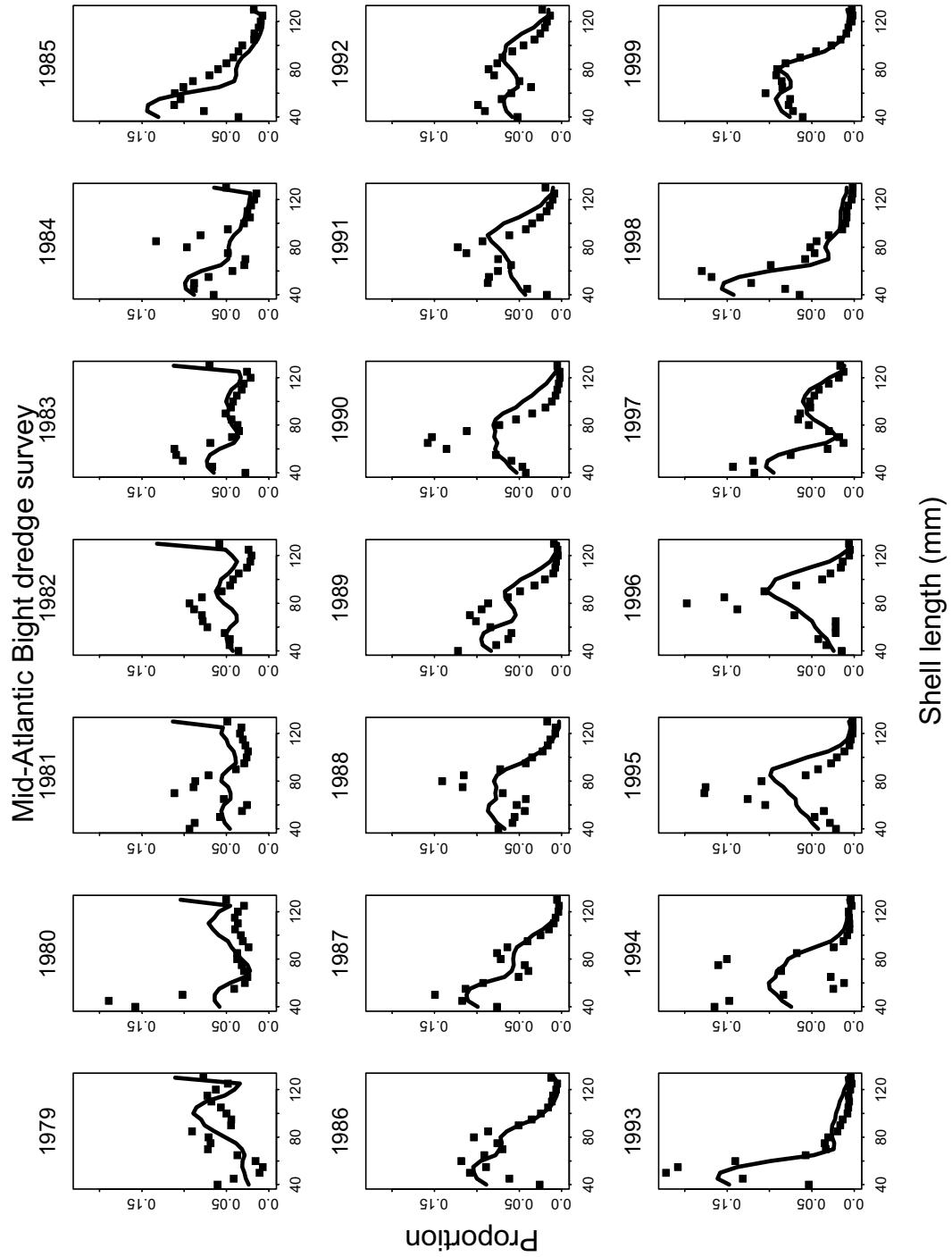


Figure B5-19 continued.

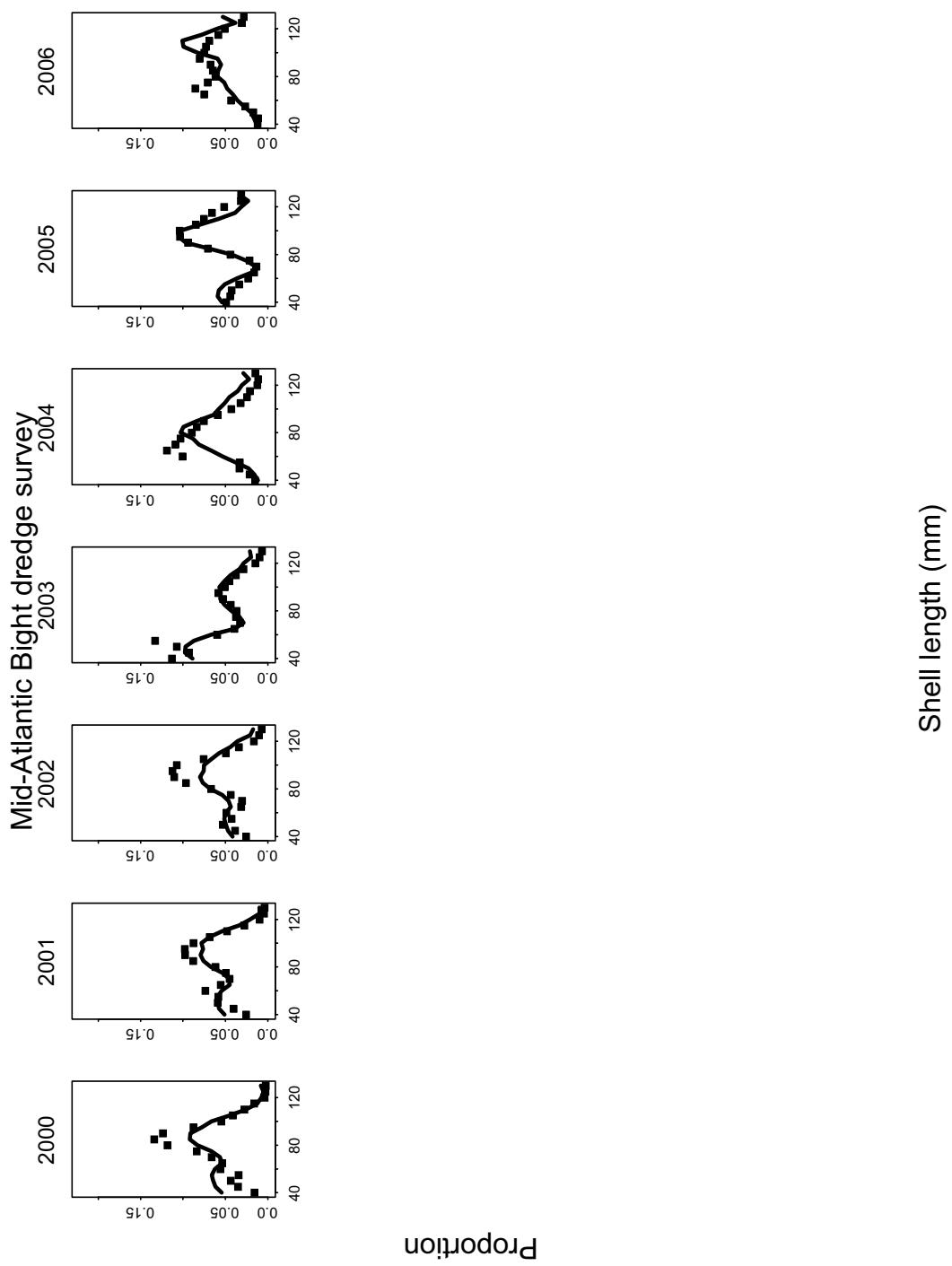


Figure B5-19 continued.

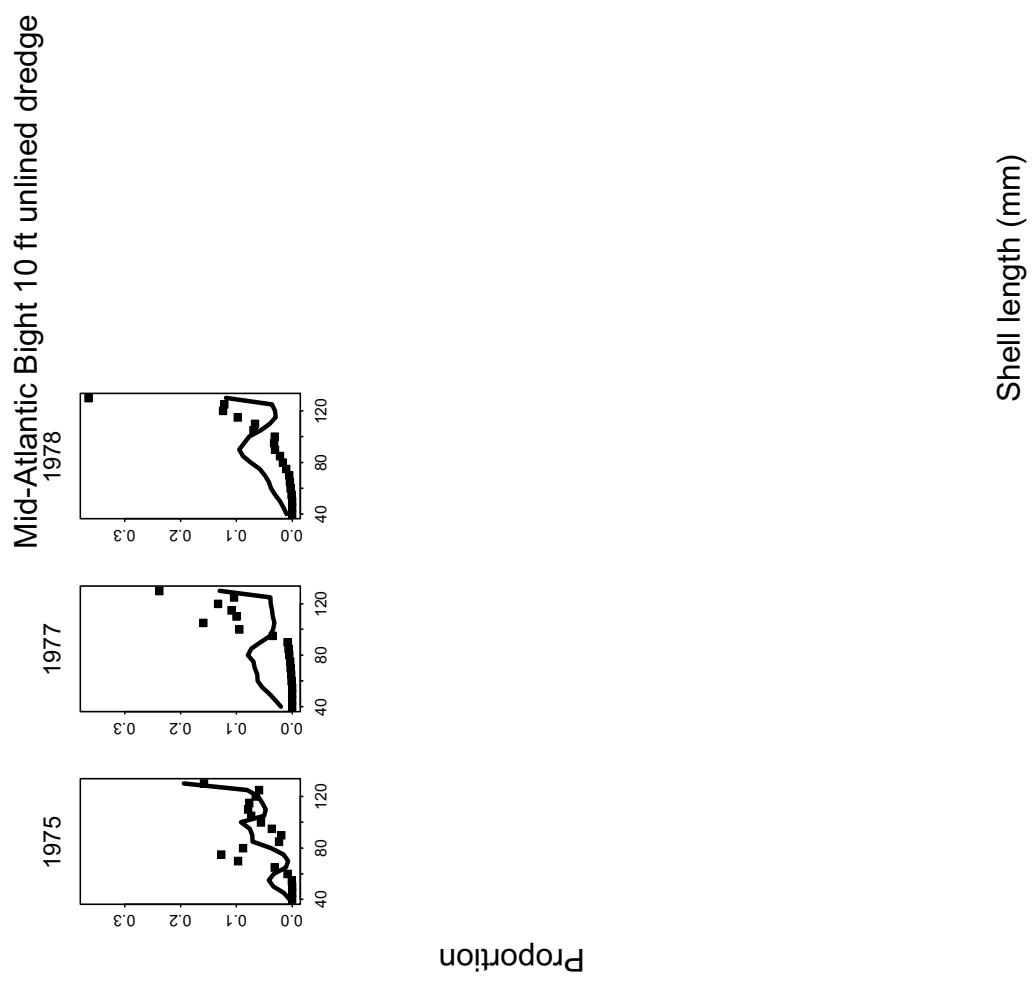


Figure B5-19 continued.

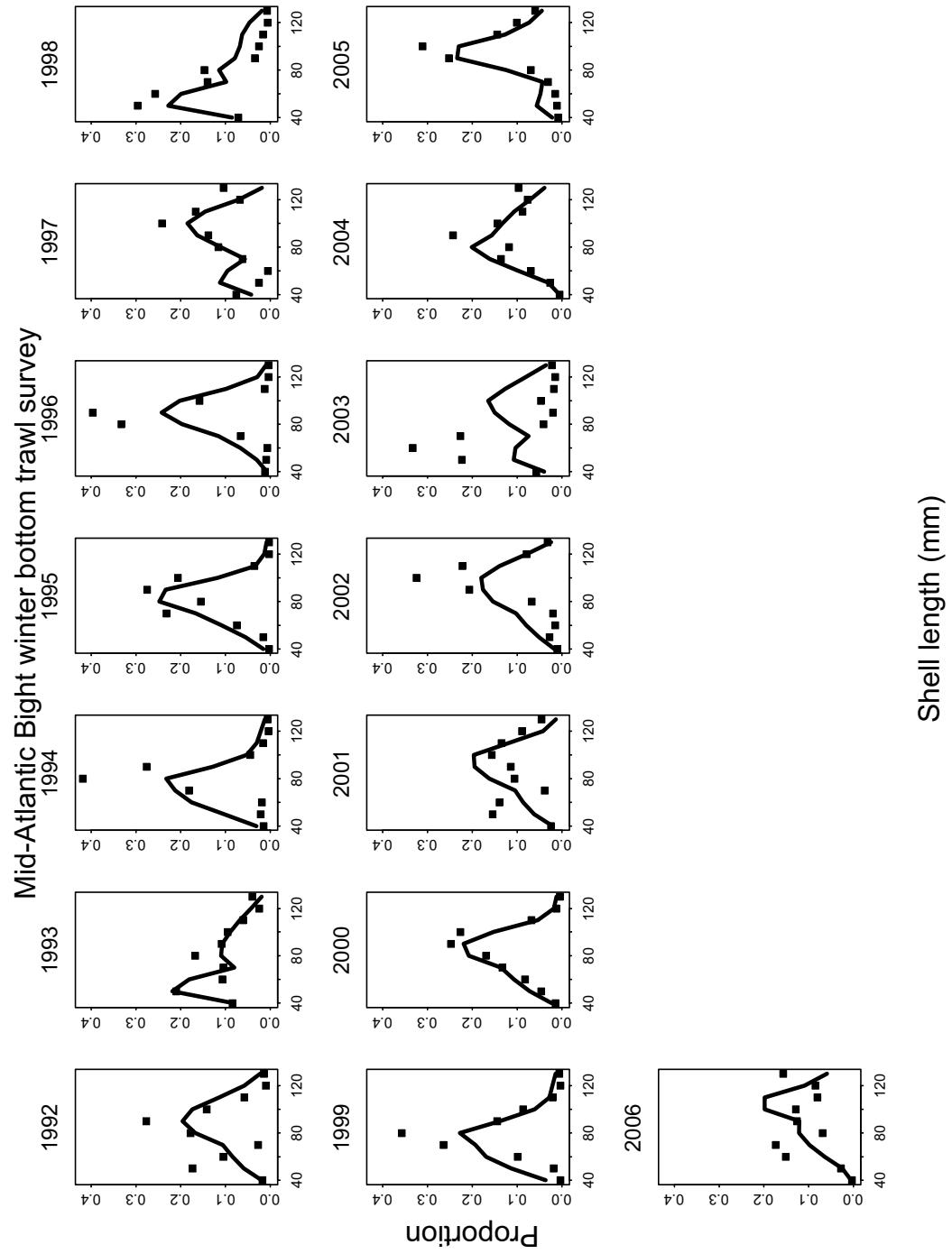


Figure B5-19 continued.

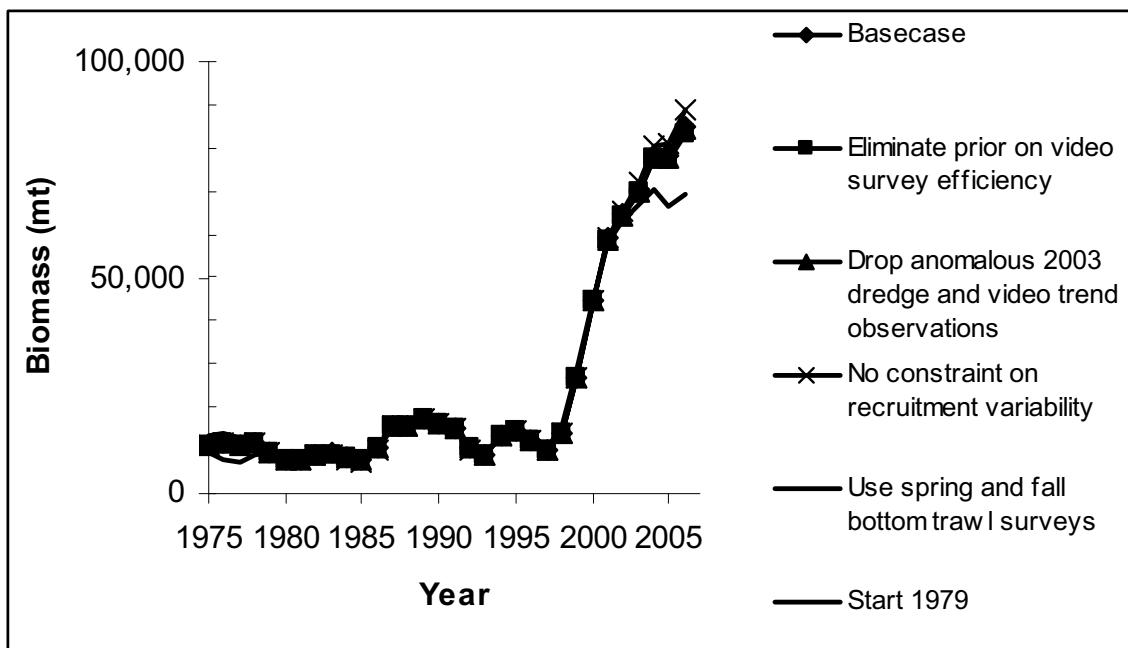


Figure B5-20. Biomass estimates for sea scallops in the Mid-Atlantic Bight from the basecase and a variety of sensitivity analysis runs.

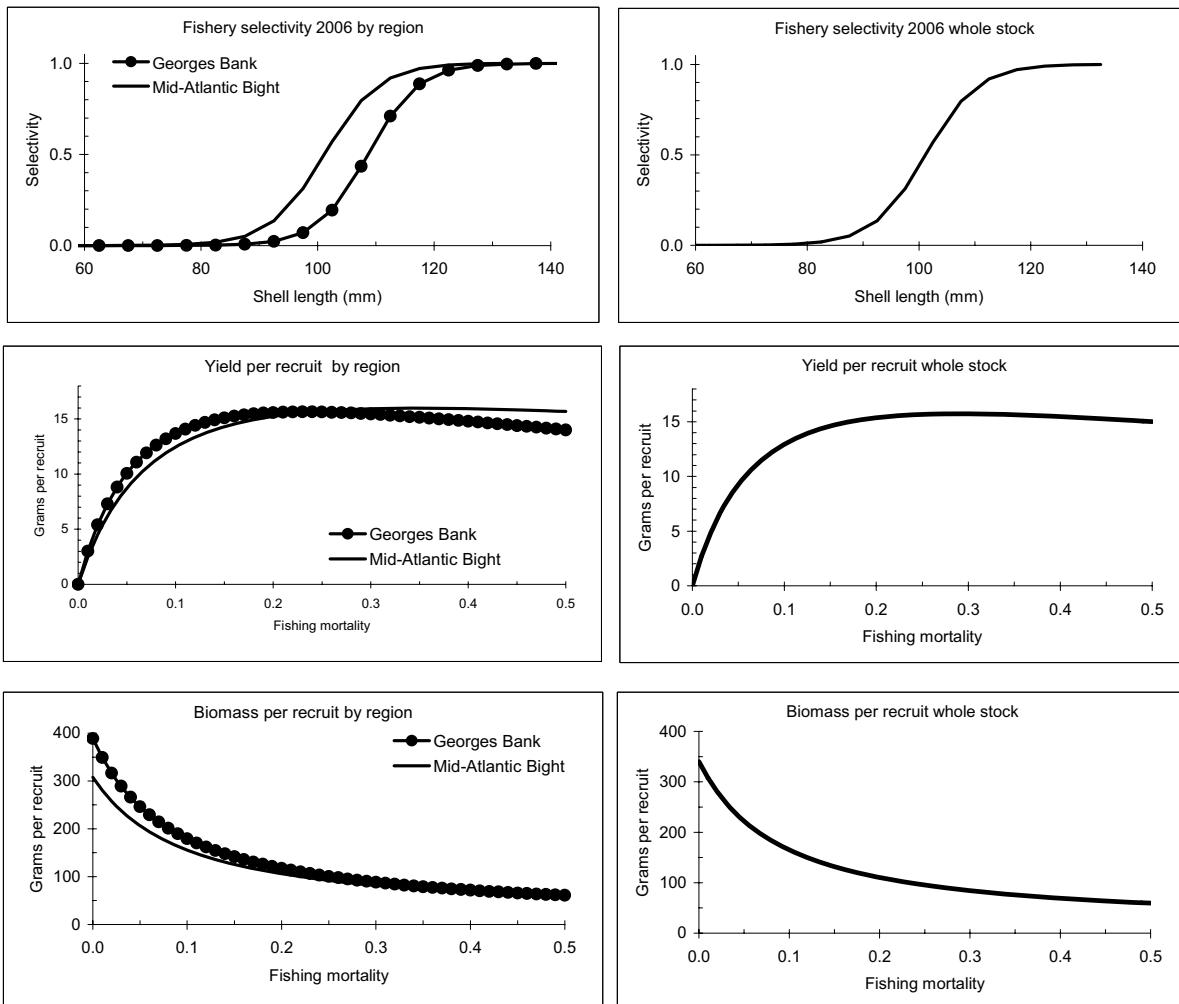


Figure B6-1. Fishery selectivity, yield per recruit, and biomass per recruit curves for the Mid-Atlantic Bight, Georges Bank and for the whole stock. Estimates for the whole stock are averages weighted by median recruitment during 1983-2006 in the Mid-Atlantic Bight and Georges Bank. The whole stock selectivity curve was not used in calculations and is shown as information only.

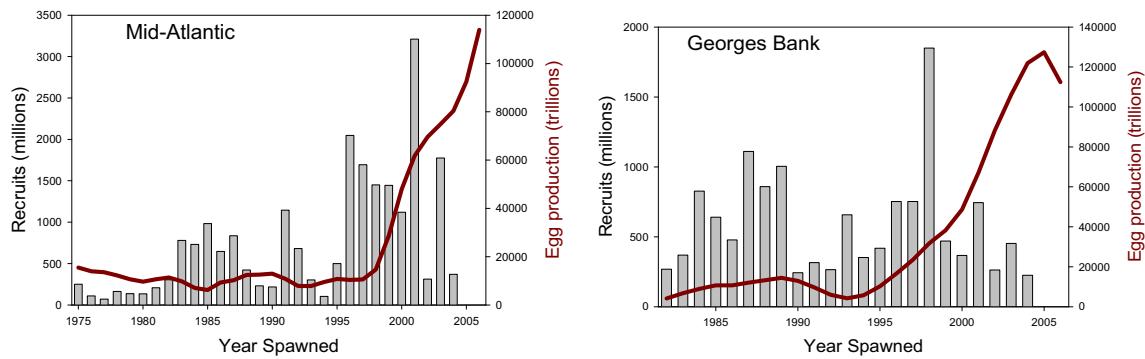


Figure B6-2. Sea scallop recruitment (bars) and egg production (lines) in the Mid-Atlantic and Georges Bank.

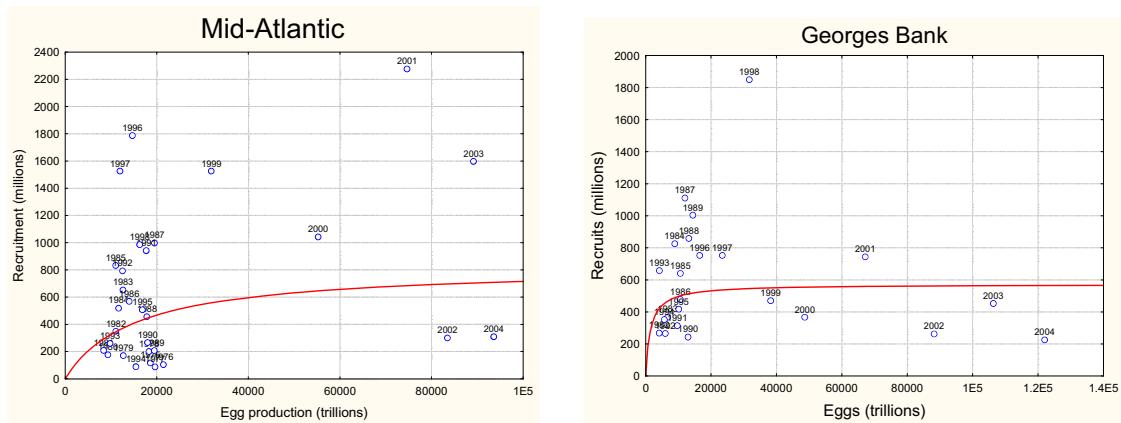


Figure B6-3. Stock-recruit plots and estimated Beverton-Holt stock-recruitment fits for the Mid-Atlantic and Georges Bank.

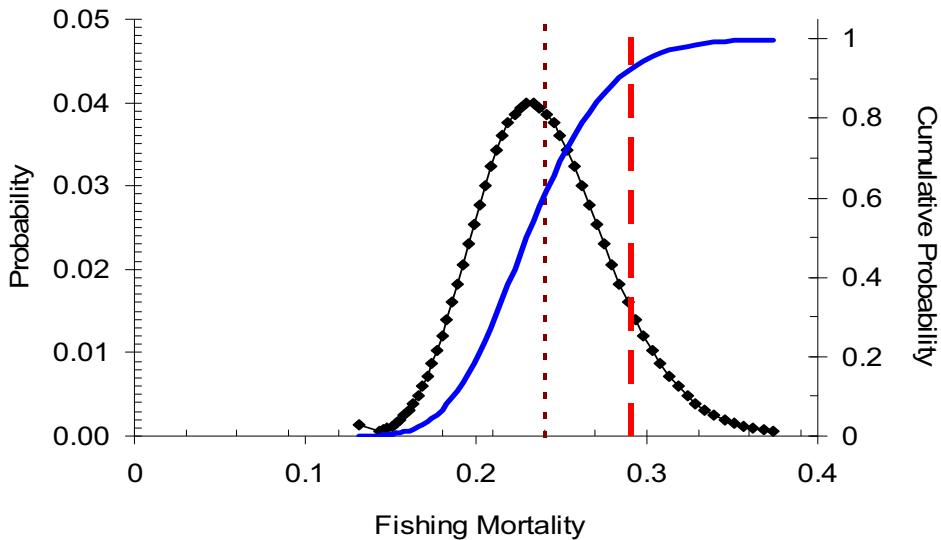


Figure B7-1. Uncertainty in estimated fishing mortality during 2006 from the (baseline) CASA model run. The proposed (dashed line) and current (dotted line) overfishing thresholds are shown.

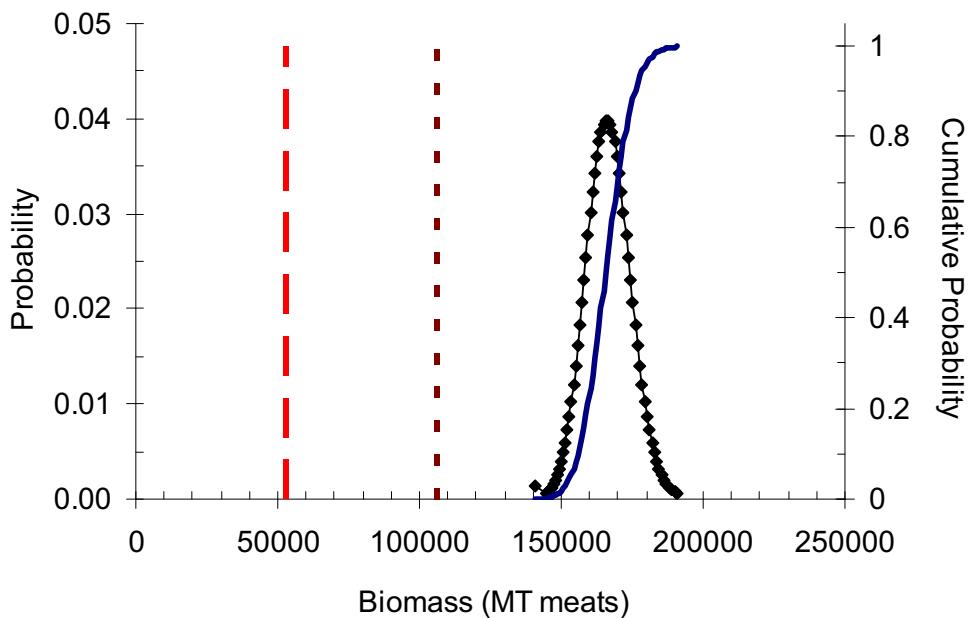


Figure B7-2. Uncertainty in estimated biomasses from the (baseline) CASA model run. The new proposed biomass target (dotted line) and threshold (dashed line) are also shown.

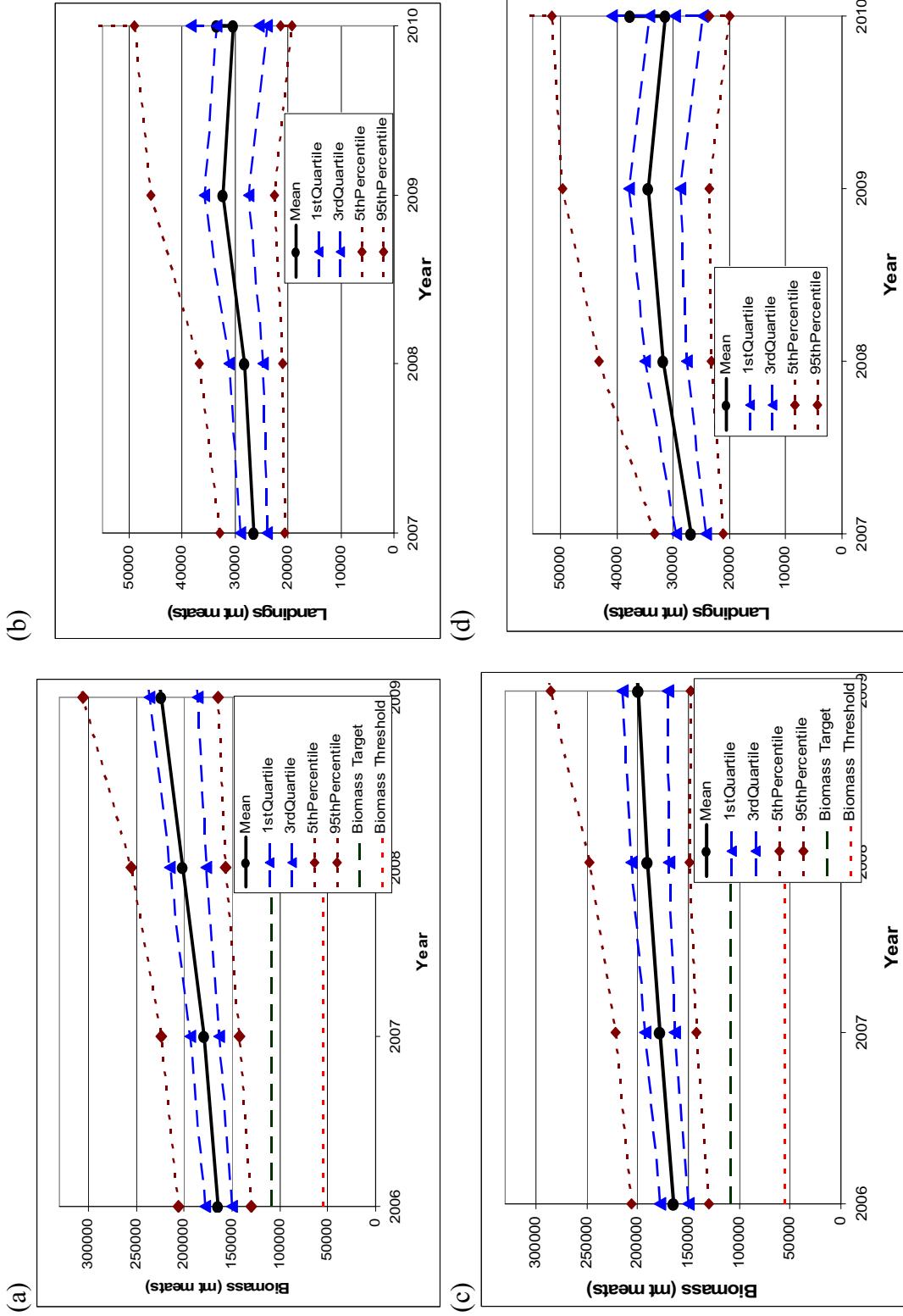


Figure B8-1. Short-term projections of the US sea scallop biomass (a, c) and landings (b, d) assuming 2007-2009 fishing mortalities are  $F = 0.20$  (a, b) and  $F = 0.24$  (c, d). The mean of 400 stochastic runs is shown, together with the 5<sup>th</sup>, 25<sup>th</sup>, 75<sup>th</sup>, and 95<sup>th</sup> percentiles. The simulations were initialized in July 2006, so that biomass estimates are for July, and landings in a given year represent landings from July of the previous year until June of that year.

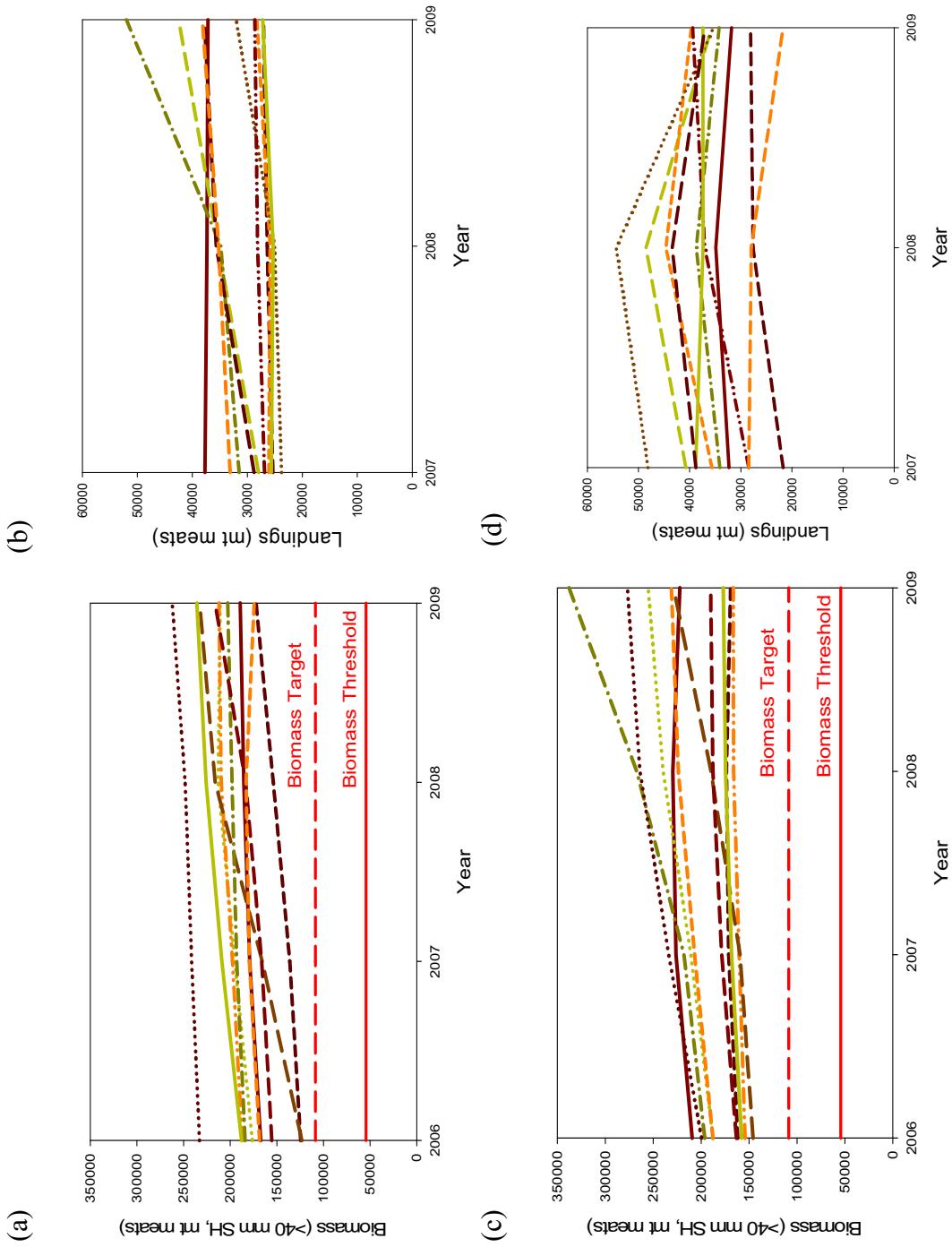


Figure B8-2. Ten example trajectories of the short-term sea scallop projections with differing initial population bootstraps and stochastic recruitment streams. Sea scallop biomass (a, c) and landings (b, d) assume 2007-2009 fishing mortalities are  $F = 0.20$  (a, b) and  $F = 0.24$  (c, d). The simulations were initialized in July 2006, so that biomass estimates are for July, and landings in a given year represent landings from July of the previous year until June of that year.

## **APPENDIX B1: Invertebrate subcommittee meetings and participants**

The Invertebrate Subcommittee held four meetings during 2007 on March 8-9, April 9-11, April 30-May 1, and May 8-9 to work on the sea scallop stock assessment for SAW/SARC-45. All of the meetings were held in the Stephen H. Clark Conference Room at the Northeast Fisheries Science Center in Woods Hole. Participating members and affiliations are listed below.

Larry Jacobson (Invertebrate Subcommittee Chair, NEFSC, Woods Hole)  
Dvora Hart (Sea Scallop Assessment Lead Scientist, NEFSC, Woods Hole)  
Chuck Adams (School for Marine Science and Technology, UMASS Dartmouth)  
Andrew Applegate (New England Fishery Management Council)  
Deirdre Boelke (New England Fishery Management Council)  
Danielle Brezinski (University of Maine)  
Antonie Chute (Rapporteur, NEFSC, Woods Hole)  
Chad Demarest (Massachusetts Marine Fisheries Institute)  
Bill Du Paul (Virginia Institute of Marine Science)  
Demet Haksever (New England Fishery Management Council)  
Brad Harris (School for Marine Science and Technology, UMASS Dartmouth)  
Chad Keith (NEFSC, Woods Hole)  
Chris Legault (NEFSC, Woods Hole)  
Michael Marino (School for Marine Science and Technology, UMASS Dartmouth)  
Bob Mohn (Invited outside expert, Department of Fisheries and Oceans, Canada)  
Paul Nitschke (NEFSC, Woods Hole)  
Victor Nordahl (NEFSC, Woods Hole, MA)  
Cate O'Keefe (School for Marine Science and Technology, UMASS Dartmouth)  
Paul Rago (NEFSC, Woods Hole)  
Stacy Rowe (NEFSC, Woods Hole)  
David Rudders (Virginia Institute of Marine Science)  
Chris Sarro (School for Marine Science and Technology, UMASS Dartmouth)  
David Simpson (NEFMC and Connecticut Marine Fisheries Division)  
Stephen Smith (Invited outside expert, Department of Fisheries and Oceans, Canada)  
Ron Smolowitz (Fisheries Survival Fund)  
Kevin Stokesbury (School for Marine Science and Technology, UMASS Dartmouth)  
Jim Weinberg (NEFSC, Woods Hole)  
Noelle Yochum (Virginia Institute of Marine Science)

## **APPENDIX B2: Verification of annual shell growth increments**

This appendix will examine the question of whether the growth increments obtained from shell rings are truly annual, and whether the growth matrices obtained from shell growth increment data gives appropriate predictions of growth. Early work examining monthly shell samples (Stevenson and Dickie 1954), or comparing growth from shell rings to tagging (Merrill et al. 1966) concluded that shell growth rings are laid down annually. Kranz et al. (1984) used stable isotope analysis to age two shells in the Mid-Atlantic Bight, and suggested that sea scallops lay down two shell rings a year. However, this conclusion is only really supported by one of their two shells. Stable isotope analysis of two shells from Brown's Bank was supportive of the 1 ring per year hypothesis (Tan et al. 1988).

Here, we followed the growth of large cohorts found in sites in the closed areas, to test whether the shell increments collected from these cohorts matched the observed growth. Four stations where large sets of small scallops were observed were selected for this study, two in Closed Area II, one in Nantucket Lightship Closed Area, and one in the Elephant Trunk Closed Area (Figure 1). These stations were revisited in subsequent years to obtain size-frequency frequency information. Starting in 2003 (2004 for sites #2 and #4) between 60-100 shells were saved at each station for growth analysis, as described in Appendix B3. Growth increment matrices were constructed for each site based on shells collected there. Growth from one year could then be projected to the next year and compared to the observed size frequency for that year to evaluate whether the growth matrix gave accurate predictions. In some cases, size-frequencies were not available for some years, in which case a multiyear projection was made by applying the matrix to the original size frequency the appropriate number of times.

### **Site #1 (Closed Area II)**

This site was repeatedly sampled after a large set of small scallops (1998 year class) was observed there in 2000. In 2004 and 2006, the number of scallops caught at this site was small (141 in 2004, 81 in 2006), either because the dredge missed the main bed, or (in 2006), because of heavy fishing after the area was reopened. These years were therefore dropped from the analysis. The growth of scallops at this site during the remaining years is shown in Figure 2. Figure 3 compares the observed (normalized) size-frequency with that predicted from the previous observation and the site-specific growth matrix. In all cases the fit was very good.

### **Site #2 (Closed Area II)**

This site, which is close to Station #1, was also selected because a large set of small scallops was observed there in 2000. The site was resampled in 2002, 2004, 2005, and 2006 (Figure 4). Comparison of the observed size-frequencies to that projected using the growth matrix matrix were good with the exception of the projection from 2002-2004, where the projected sizes were somewhat greater than that observed (Figure 5).

### **Site #3 (Nantucket Lightship Area)**

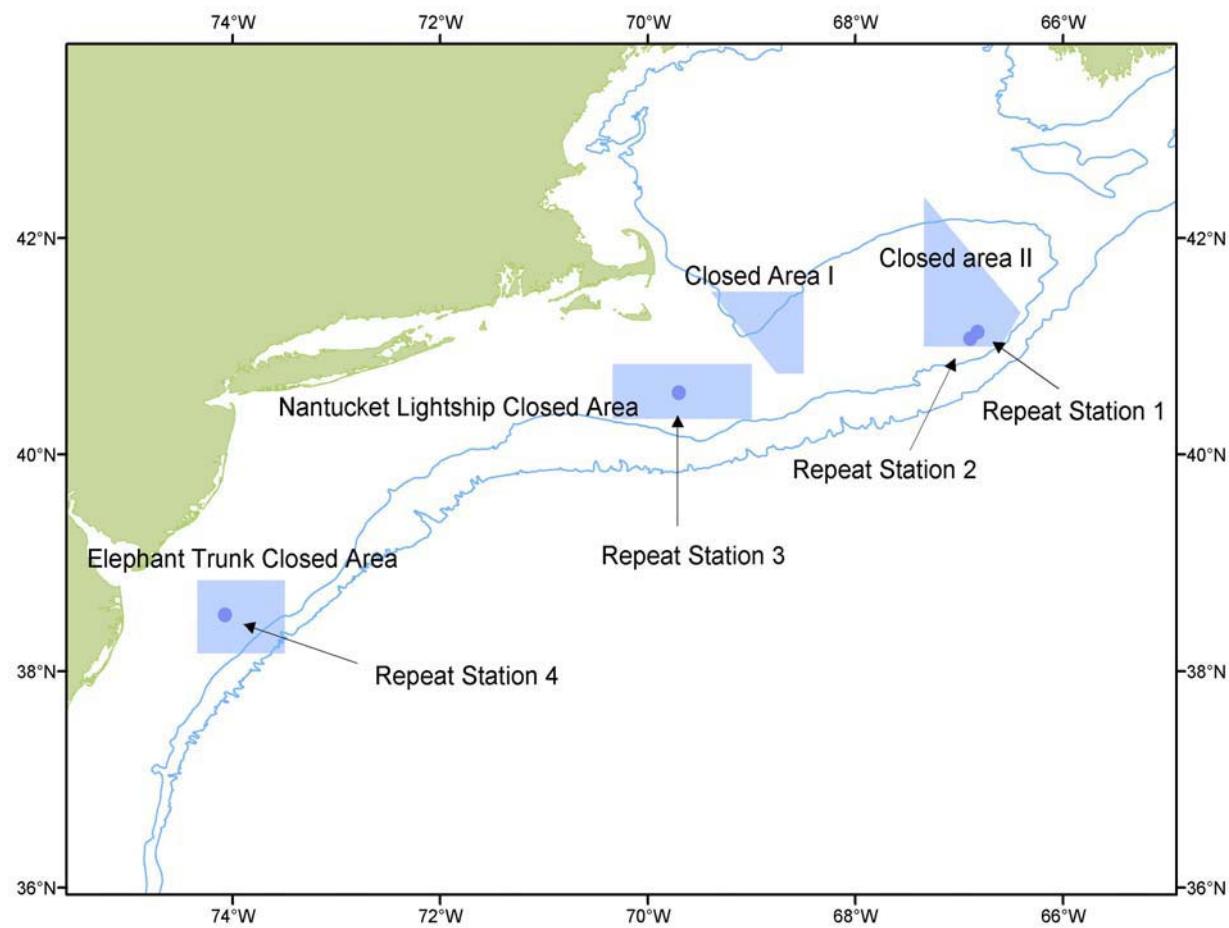
This site was originally sampled in 1999, and was revisited in 2000, 2003, 2004, 2005, and 2006 (Figure 6). In 2000, a second strong cohort was observed in addition to the one observed in 1999. Comparisons between predicted and observed growth was always quite good (Figure 7).

### **Site #4 (Elephant Trunk Closed Area)**

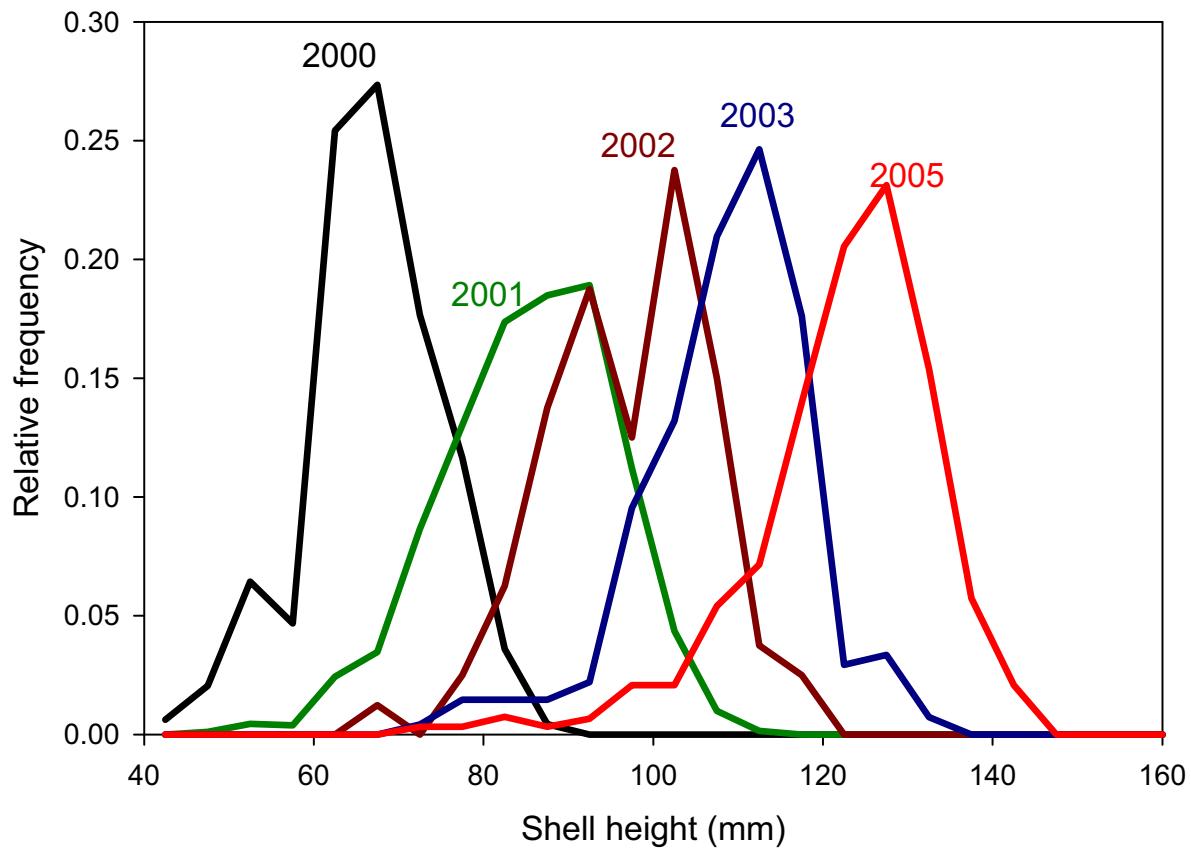
This site was first sampled in 2003, a year before this area was closed. However, nearly all of the scallops observed in 2003 were well below commercial size, so that the fishing that occurred in this area until it was closed in July 2004 should not have affected growth or mortality at this site. It was resampled each year thereafter (2004, 2005, 2006, Figure 8). There was little growth between 2005 and 2006, which was also observed in the Elephant Trunk as a whole. The growth between these years was inconsistent with that observed between 2004 and 2005. Comparisons between observed and projected size-frequencies showed good agreement in 2004 and 2005, but the projection from 2005 to 2006 predicted considerably greater growth than actually occurred (Figure 9). Projections were also made based on the Kranz et al. (1984) hypothesis that two growth rings are laid down each year, so that the growth matrix was applied twice to obtain the predicted shell heights in the next year (Figure 10). The observations do not support Kranz et al.'s hypothesis of semi-annual rings.

## **Discussion and Conclusions**

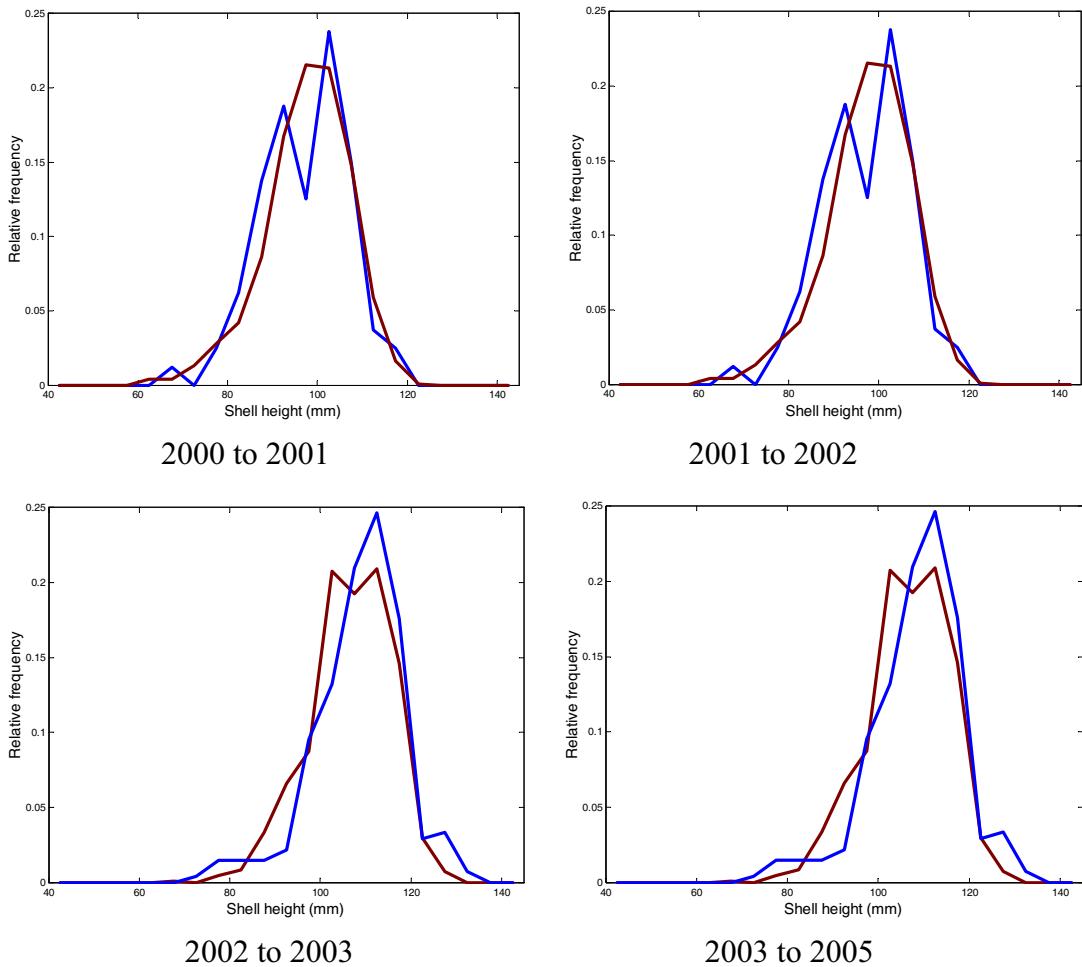
In all but two of the 16 comparisons made here, size-frequencies predicted from growth matrices were in good agreement with observations. One case was a modest deviation at site #2 for a two-year projection between 2002 and 2004. The other was a stronger deviation in site #4 between 2005 and 2006. None of the shells collected at this site would have reflected any growth since the last shell ring (probably in the fall of 2005) was laid down, since the partial increment from the last ring to the edge of the shell was not used. Thus, the projected sizes reflect what would have occurred if growth during 2005-6 was the same as in previous years. The deviation between observed and predicted growth does not imply that the shell rings are not annual. Rather, they indicate a change in growth between 2005 and 2006, probably related to environmental conditions (e.g., food supply). None of the data are consistent with the Kranz et al. hypothesis of semi-annual rings, since that would predict much faster growth than was observed. It can be concluded that growth matrices derived from shell ring data, under the assumption that the growth lines are laid down annually, generally give good predictions for growth, and are appropriate for use in this assessment.



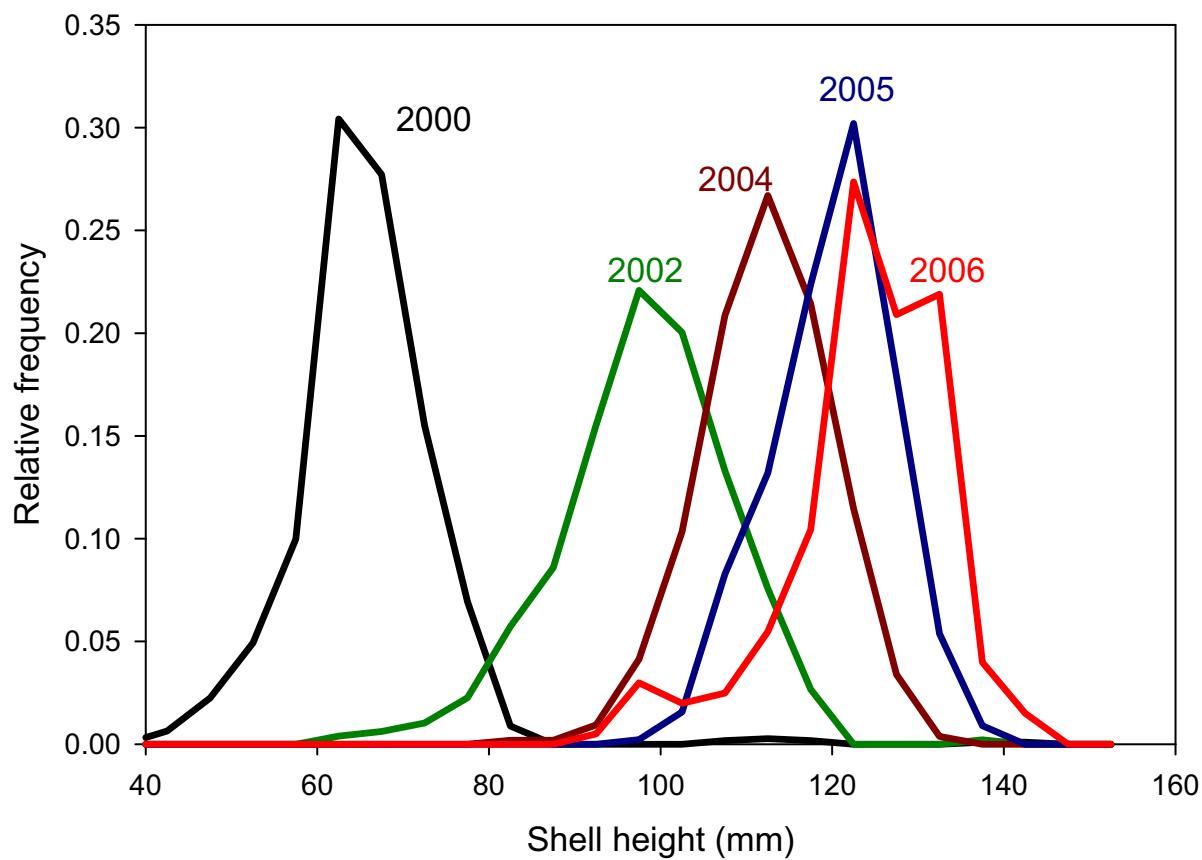
APPENDIX B2 Figure 1. Locations of the four repeat sites in this study.



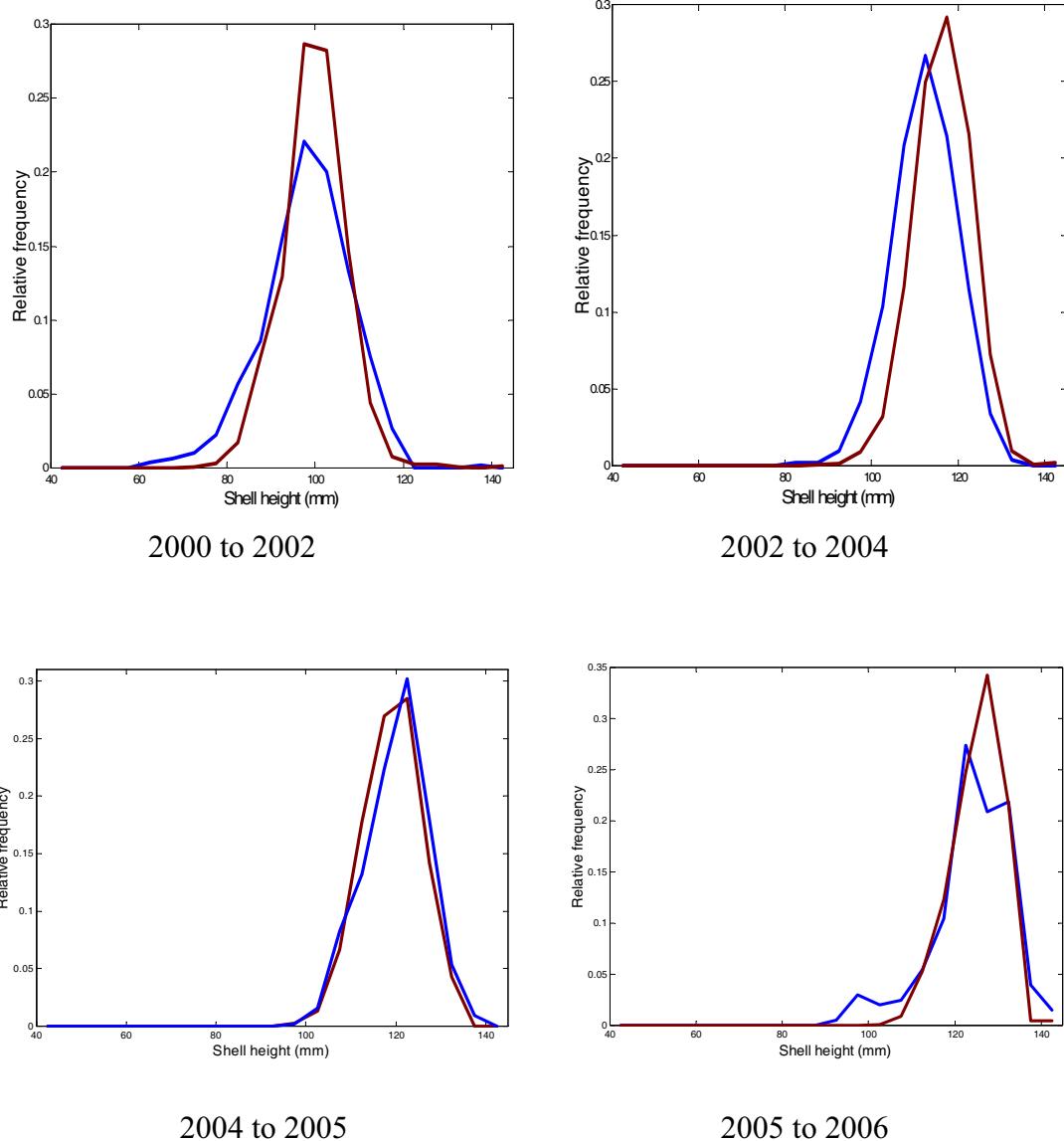
APPENDIX B2 Figure 2. Normalized size-frequencies by year at site #1 (Closed Area II).



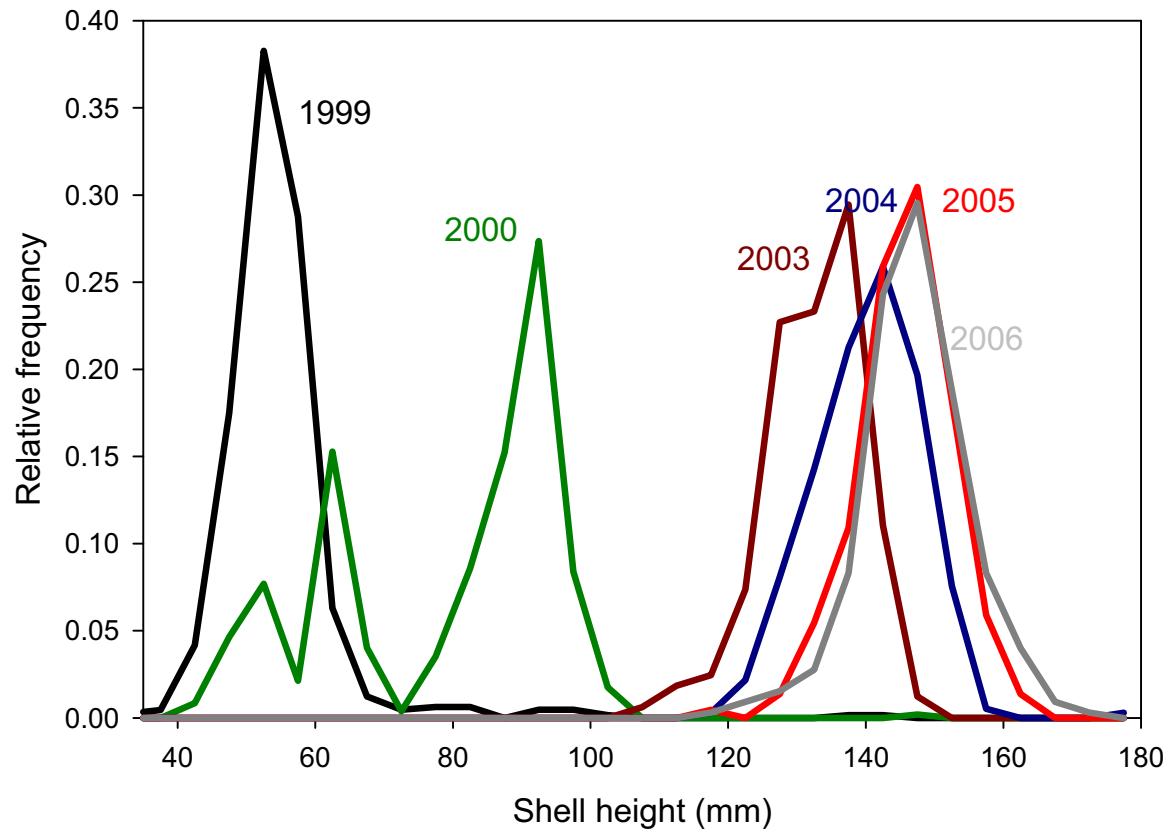
APPENDIX B2 Figure 3. Comparison between observed (solid blue line) and projected (dashed-dotted brown line) normalized size-frequencies at site #1 (Closed Area II).



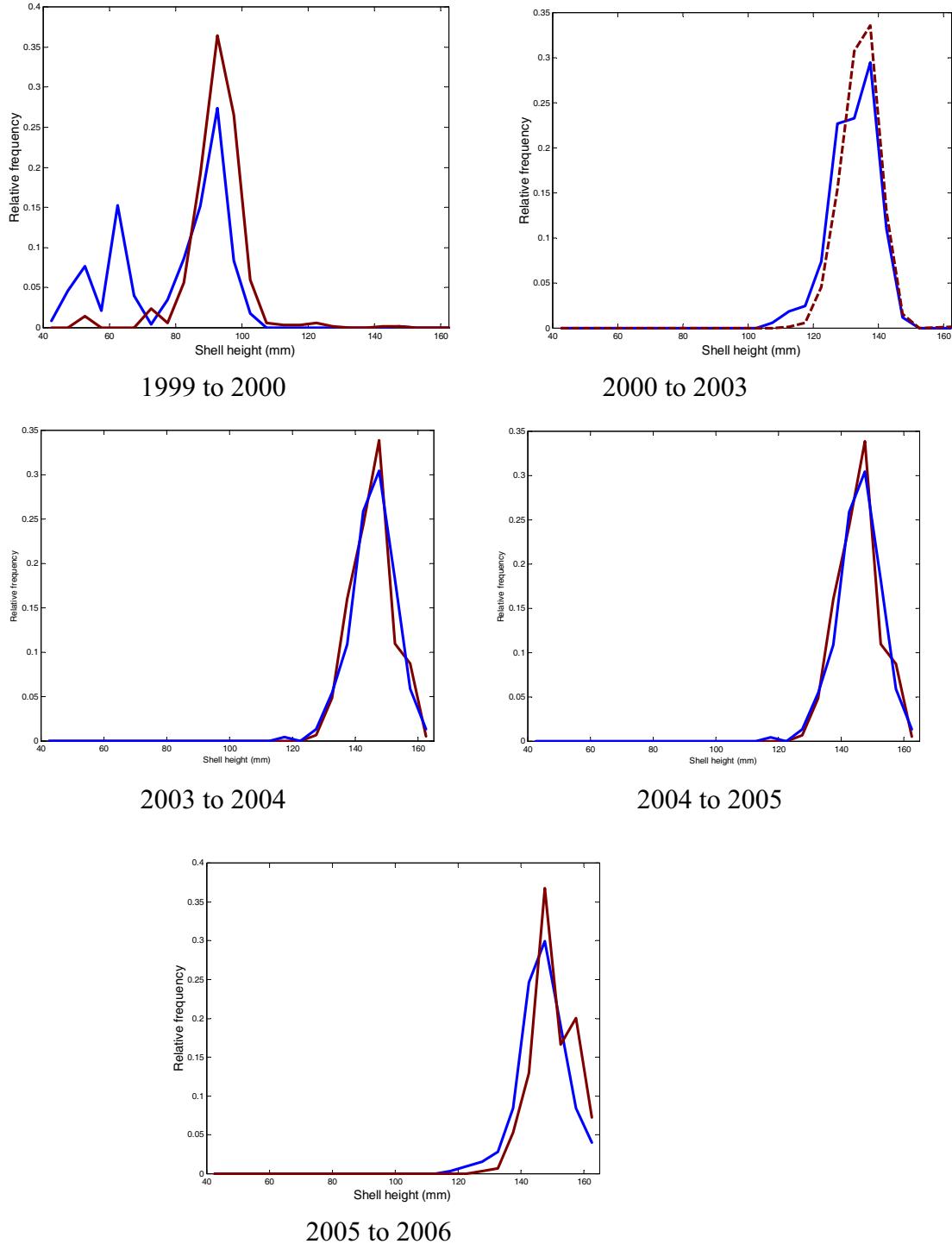
APPENDIX B2 Figure 4. Normalized size-frequencies at site #2 (Closed Area II).



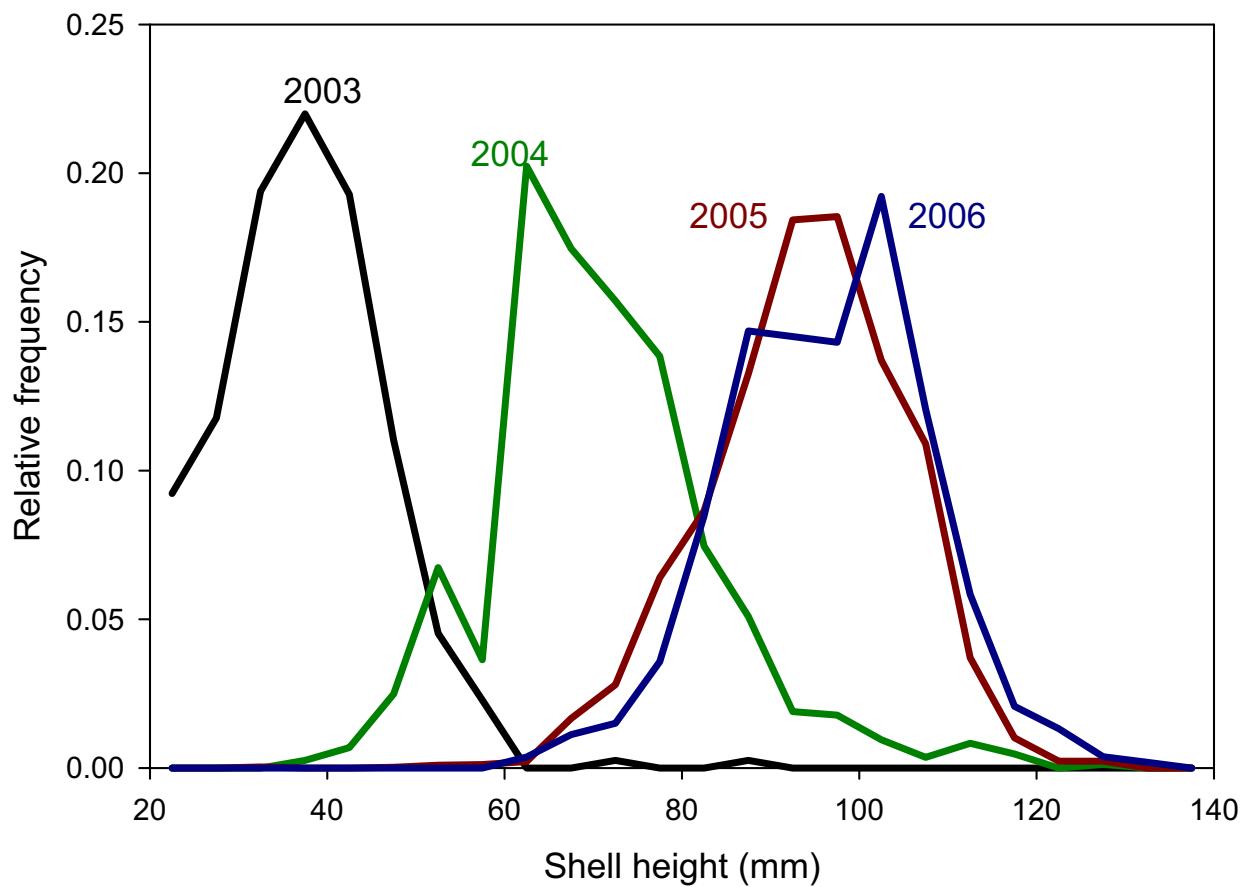
APPENDIX B2 Figure 5. Comparison between observed (solid blue line) and projected (dashed-dotted brown line) normalized size-frequencies at site #2 (Closed Area II).



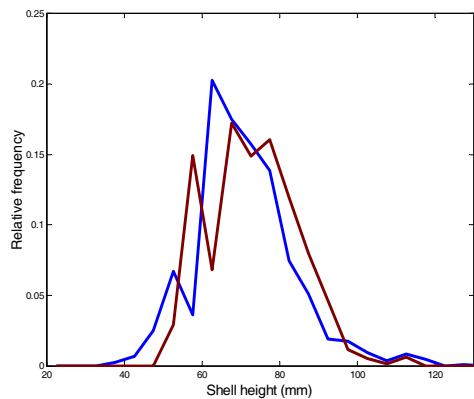
APPENDIX B2 Figure 6. Normalized size-frequencies at site #3 (Nantucket Lightship Closed Area).



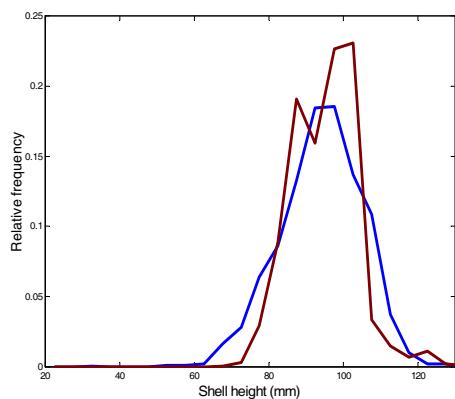
APPENDIX B2 Figure 7. Comparison between observed (solid blue line) and projected (dashed-dotted brown line) normalized size-frequencies at site #3 (Nantucket Lightship Closed Area).



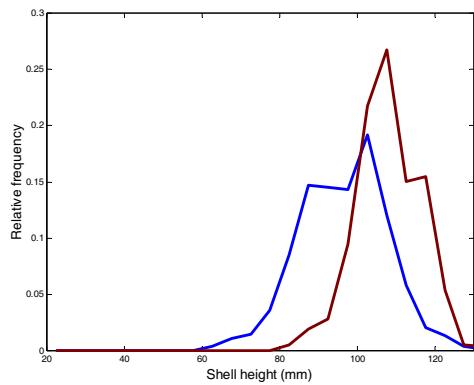
APPENDIX B2 Figure 8. Normalized size-frequencies at site #4 (Elephant Trunk Closed Area).



2003 to 2004

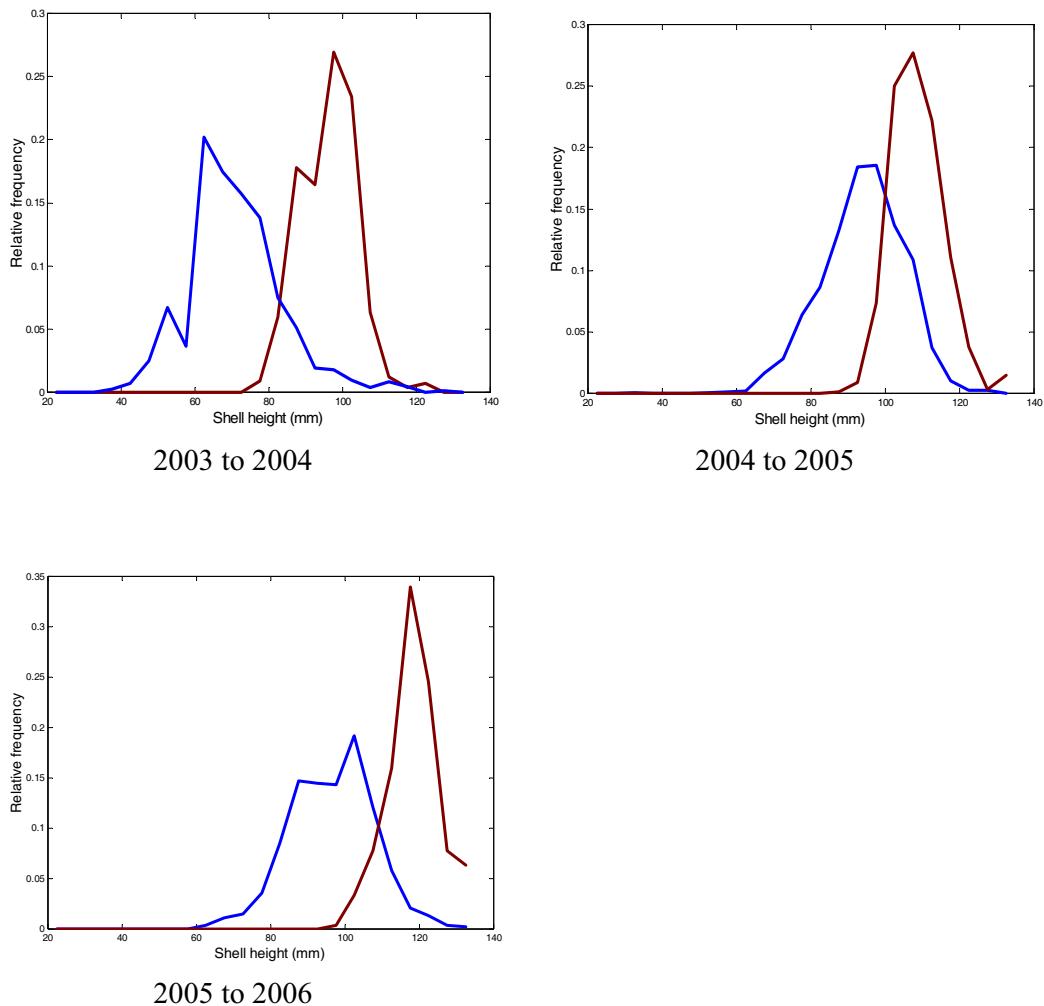


2004 to 2005



2005 to 2006

APPENDIX B2 Figure 9. Comparison between observed (solid blue line) and projected (dashed-dotted brown line) normalized size-frequencies at site #4 (Elephant Trunk Closed Area).



APPENDIX B2 Figure 10. Comparison between observed (solid blue line) and projected (dashed-dotted brown line) normalized size-frequencies at site #4, under the assumption that two shell growth lines are laid down annually, as suggested in Kranz et al. (1984).

### (Appendix B3)

## APPENDIX III: Methodology for estimation of growth from shell rings

Shells were collected on the 2001-2006 NEFSC surveys. At about half the valid tows in the survey, scallops were chosen randomly (averaging about 6 per station) to be used for the growth analysis. The scallops were scrubbed with a wire brush, shucked, and both valves were frozen and transported back to shore for later analysis. After the shells were thawed and cleaned, rings on the top valve of each shell that represented annuli were marked with a pencil. On some shells, one or more “shock marks” were evident. These were distinguishable from annuli by their irregular nature and because a point of injury was usually evident in the form of a crack or deformation of the shell. After the shells were marked, the distance in millimeters from the umbo to each of the ring marks was measured with calipers. Since the first ring is often very small and difficult to discern, the data only include the measurements to the second ring and above. Growth increments were calculated as the distance between the rings (in mm). The partial increment from the last ring to the edge of the shell was not used in the analysis.

Growth matrices were calculated by binning the growth ring shell heights into 5 mm classes (e.g., 40-44 mm shell height), and labeling the bins  $1, 2, \dots, n$ , where the last bin represents a plus group. The  $ij$ th entry of the matrix represents the fraction of scallops that started in bin  $i$  that grew in a year’s time to bin  $j$ . Growth matrices based on the shell increments for Georges Bank and the Mid-Atlantic are given in Table App3-1.

To estimate growth parameters from the increment data, we used the growth increment form of the Von Bertalaffy equation:

$$\Delta L = (L_\infty - L)[1 - \exp(-K\Delta t)], \quad (1)$$

where  $L$  is the starting length,  $\Delta L$  is the growth increment that occurred over time  $\Delta t$ , and  $L_\infty$  and  $K$  are the two growth parameters to be estimated. Equation (1) predicts that a plot of the increments ( $\Delta L$ ) vs. starting length ( $L$ ) will be a straight line with slope  $m = -[1 - \exp(-K\Delta t)]$ ,  $x$ -intercept  $L_\infty$  and  $y$ -intercept  $b = -mL_\infty$ . Thus, one could estimate  $K$  and  $L_\infty$  from a plot of increment vs. starting length, with

$$K = -\frac{1}{\Delta t} \ln(1 + m) \quad (2)$$

and

$$L_\infty = -b/m \quad (3)$$

$L_\infty$  and  $K$  may vary considerably among individuals in real populations. If this is the case, the naive estimation using equations (2) and (3) that ignores this variability can be seriously biased (Sainsbury 1980). We will derive here approximately unbiased estimates of  $L_\infty$  and  $K$  when these parameters have individual variability.

The growth increment of the  $i$ th individual,  $\Delta L_i$  depends on a fixed effect (the starting length  $L$ ) and random effects depending on the individual:

$$\Delta L_i = (m + m_i)L + (b + b_i) + \epsilon, \quad (4)$$

where  $m$  and  $b$  are the mean slope and intercept (averaging over all individuals),  $m_i$  and  $b_i$  are deviations from the mean slope and intercept for the  $i$ th individual,  $\epsilon$  is a random independent error, and  $E(\epsilon) = E(m_i) = E(b_i) = 0$ . Note that the slope and intercept obtained from a simple linear regression of  $\Delta L_i$  vs.  $L$  will not necessarily be the same as  $m$  and  $b$ .

The parameters associated with the  $i$ th individual can be calculated as:

$$K_i = -\ln(1 + m + m_i) \quad (5)$$

and

$$L_{\infty,i} = -(b + b_i)/(m + m_i). \quad (6)$$

We define  $K = E(K_i)$ , i.e., the mean of the individual  $K_i$ s in the population. We have

$$K = E(K_i) = E(-\ln(1+m+m_i)) \geq -\ln(E(1+m+m_i)) = -\ln(1+m). \quad (7)$$

Thus, estimating  $E(K_i)$  as  $-\ln(1+m)$  using the mean slope only will result in an estimate that is biased low.

Approximating  $\ln(1 + m + m_i)$  by a second order Taylor polynomial,

$$\ln(1 + m + m_i) \simeq \ln(1 + m) + \frac{1}{1 + m}m_i - \frac{1}{2(1 + m)^2}m_i^2. \quad (8)$$

Taking expectations in the above equation gives:

$$K = -E(\ln(1 + m + m_i)) \simeq -\ln(1 + m) + \frac{\text{Var}(m_i)}{2(1 + m)^2} \quad (9)$$

An approximately unbiased estimate of  $L_\infty = E(L_{\infty,i})$  can be computed similarly:

$$E(L_{\infty,i}) = -E\left(\frac{b + b_i}{m + m_i}\right) \simeq -\frac{b}{m} - \frac{1}{m^2}\left[\frac{b}{m}\text{Var}(m_i) - \text{Cov}(b_i, m_i)\right] \quad (10)$$

Approximate formulas for the standard errors of  $K$  and  $L_\infty$ ,  $\sigma_K$  and  $\sigma_{L_\infty}$ , are

$$\sigma_K \simeq \frac{\sigma_m}{(1+m)} \quad (11)$$

and

$$\sigma_{L_\infty}^2 \simeq L_\infty^2\left(\frac{\sigma_b^2}{b^2} + \frac{\sigma_m^2}{m^2} - \frac{2\sigma_b\sigma_m\rho(b, m)}{bm}\right) \quad (12)$$

where  $\sigma_b$  and  $\sigma_m$  are the standard errors of  $b$  and  $m$  respectively, and  $\rho(b, m)$  is the correlation coefficient of  $b$  with  $m$  (see e.g., Rice 1987).

All analysis were conducted using the statistical program *R* (v2.3.1), using the mixed-effects (Pinheiro and Bates 2000) package lme4. The above techniques require shells to have at least two increments, in order to estimate the two parameters  $L_{\infty,i}$  and  $K_i$ . The increments included in the analysis included all shells collected at random stations with at least two growth increments.

## Numerical simulations

As a verification technique of the above formulas, increments were simulated using the statistical program *R*, assuming  $L_\infty$  and  $K$  are gamma random variables, with means 140 and 0.5, respectively, and a specified CV. 1000 animals were simulated, with each contributing 4 increments. The simulated growth increments were subject to a 10% CV. Naive and mixed-effects estimates were made for various CVs (Fig App3-1). As expected, growth variability caused fairly considerable biases in the naive estimates, with  $K$  underestimated and  $L_\infty$  overestimated (Sainsbury 1980). Mixed-effect estimates were always within 3% of the true values.

## Results

In Georges Bank, 15685 increments were measured from 3656 shells (Fig App3-2). In the Mid-Atlantic, 5706 increments were measured from 2098 shells (Fig App3-2). Parameter estimates, with standard errors, are given in

the table below, together with some previous estimates. Comparison of the new mean growth curve with previous curves indicate that the new Georges Bank parameters give similar growth to that of Serchuk et al. (1979) until about 120 mm, and then predict slower mean growth (Fig A3-4). The new Mid-Atlantic curve predicts somewhat faster growth for small scallops (< 80 mm), but slower growth at larger sizes, with a considerably smaller asymptotic size. Further analysis, demonstrating that growth depends on such factors as depth and closure status, will be detailed in a forthcoming publication (Hart and Chute in prep.).

### Growth Parameter Estimates

Source	$L_\infty$	sd	$K$	sd
<b>Georges Bank</b>				
New	146.5	0.3	0.375	0.002
Harris and Stokesbury (2006)	140.0	2.1	0.51	0.04
Harris and Stokesbury (2006)	148.6	4.0	0.36	0.04
Harris and Stokesbury (2006)	121.1	6.2	0.27	0.09
Thouzeau et al. (1991)	144.87		0.2814	
Serchuk et al. (1979)	152.46		0.3374	
Posgay (1979)	143.6		0.37	
Merrill et al. (1966)	143.3		0.2324	
Merrill et al. (1966)	145.1		0.2258	
<b>Mid-Atlantic</b>				
New	131.6	0.4	0.495	0.004
Serchuk et al. (1979)	151.84		0.2997	

Table App3-1. Growth matrices for (a) Georges Bank and (b) Mid-Atlantic, derived from shell growth increments.

(a)

	42	47	52	57	62	67	72	77	82	87	92	97	102	107	112	117	122	127	132	137	142	147
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
57	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
62	0.06	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
67	0.2	0.06	0.03	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
72	0.31	0.16	0.07	0.04	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
77	0.3	0.3	0.14	0.13	0.09	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
82	0.11	0.3	0.25	0.15	0.17	0.16	0.05	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	
87	0.02	0.14	0.29	0.19	0.22	0.29	0.18	0.08	0.03	0	0	0	0	0	0	0	0	0	0	0	0	
92	0	0.03	0.16	0.24	0.21	0.26	0.3	0.18	0.11	0.06	0.01	0	0	0	0	0	0	0	0	0	0	
97	0	0	0.05	0.18	0.18	0.12	0.27	0.3	0.23	0.2	0.07	0.01	0	0	0	0	0	0	0	0	0	
102	0	0	0	0.06	0.1	0.11	0.15	0.25	0.26	0.29	0.23	0.11	0.01	0	0	0	0	0	0	0	0	
107	0	0	0	0	0.02	0.04	0.04	0.11	0.25	0.26	0.31	0.29	0.15	0.02	0	0	0	0	0	0	0	
112	0	0	0	0	0	0	0.01	0.05	0.09	0.13	0.25	0.31	0.29	0.19	0.02	0	0	0	0	0	0	
117	0	0	0	0	0	0	0	0.01	0.01	0.05	0.12	0.2	0.29	0.34	0.22	0.03	0	0	0	0	0	
122	0	0	0	0	0	0	0	0	0	0	0.02	0.07	0.21	0.28	0.37	0.34	0.04	0	0	0	0	
127	0	0	0	0	0	0	0	0	0	0	0.02	0.05	0.13	0.29	0.38	0.44	0.05	0	0	0	0	
132	0	0	0	0	0	0	0	0	0	0	0	0.01	0.03	0.09	0.2	0.4	0.55	0.07	0	0	0	
137	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.05	0.11	0.32	0.67	0.12	0	0	
142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.08	0.23	0.67	0.19	
147	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.21	0.81	1	

(b)

	42	47	52	57	62	67	72	77	82	87	92	97	102	107	112	117	122	127	132
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	0.014	0.005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	0.089	0.024	0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
67	0.183	0.043	0.047	0.015	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	0.307	0.134	0.097	0.072	0.046	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	0.239	0.262	0.13	0.135	0.114	0.068	0.031	0	0	0	0	0	0	0	0	0	0	0	0
82	0.133	0.348	0.258	0.15	0.193	0.143	0.07	0.038	0.002	0	0	0	0	0	0	0	0	0	0
87	0.034	0.152	0.296	0.272	0.196	0.233	0.191	0.137	0.054	0.002	0	0	0	0	0	0	0	0	0
92	0	0.027	0.139	0.249	0.216	0.267	0.312	0.261	0.144	0.083	0.007	0	0	0	0	0	0	0	0
97	0	0.005	0.028	0.069	0.176	0.196	0.219	0.269	0.311	0.206	0.103	0.007	0	0	0	0	0	0	0
102	0	0	0.003	0.039	0.046	0.09	0.152	0.202	0.302	0.315	0.267	0.193	0.007	0	0	0	0	0	0
107	0	0	0	0	0.013	0.003	0.025	0.081	0.146	0.282	0.337	0.315	0.22	0.017	0	0	0	0	0
112	0	0	0	0	0	0	0	0.013	0.041	0.098	0.235	0.289	0.374	0.292	0.036	0	0	0	0
117	0	0	0	0	0	0	0	0	0	0.013	0.048	0.16	0.241	0.407	0.331	0.022	0	0	0
122	0	0	0	0	0	0	0	0	0	0	0.005	0.033	0.143	0.234	0.435	0.455	0.037	0	0
127	0	0	0	0	0	0	0	0	0	0	0.002	0.016	0.039	0.173	0.404	0.511	0.089	0	0
132	0	0	0	0	0	0	0	0	0	0	0	0.011	0.025	0.118	0.452	0.911	1	0	0

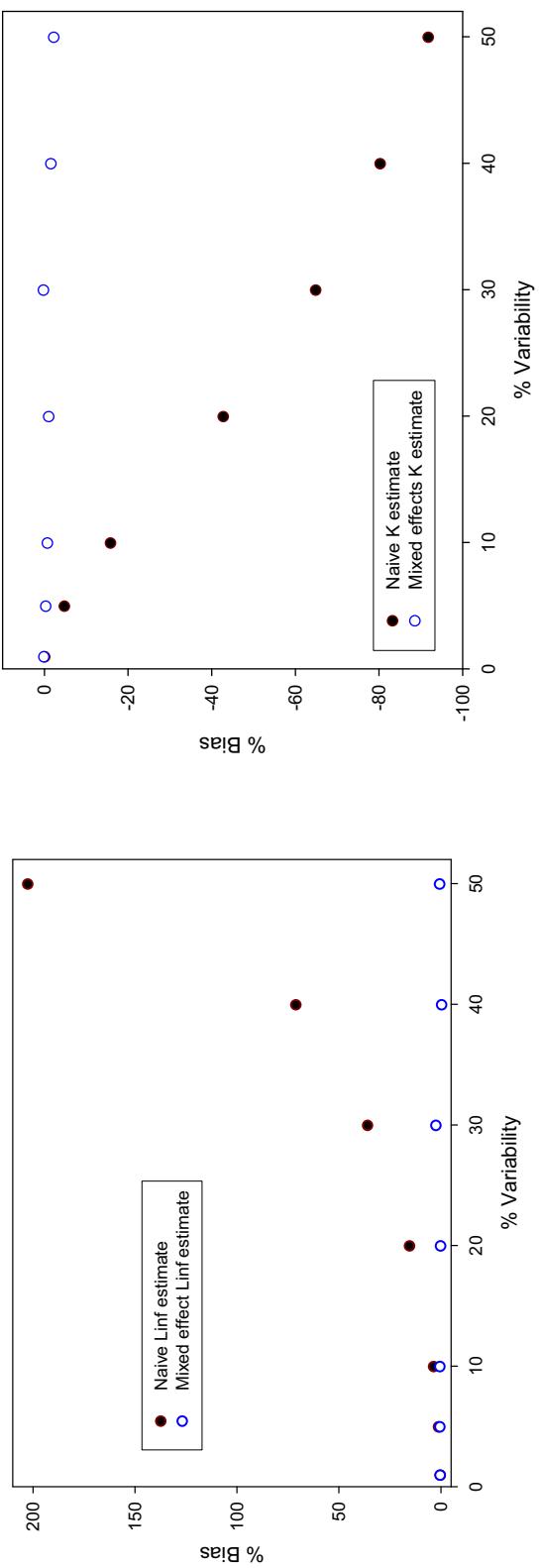


Fig App3-1. Percentage bias in simulated data for naïve and mixed-effect estimates of growth parameters, where both growth parameters are assumed to vary.

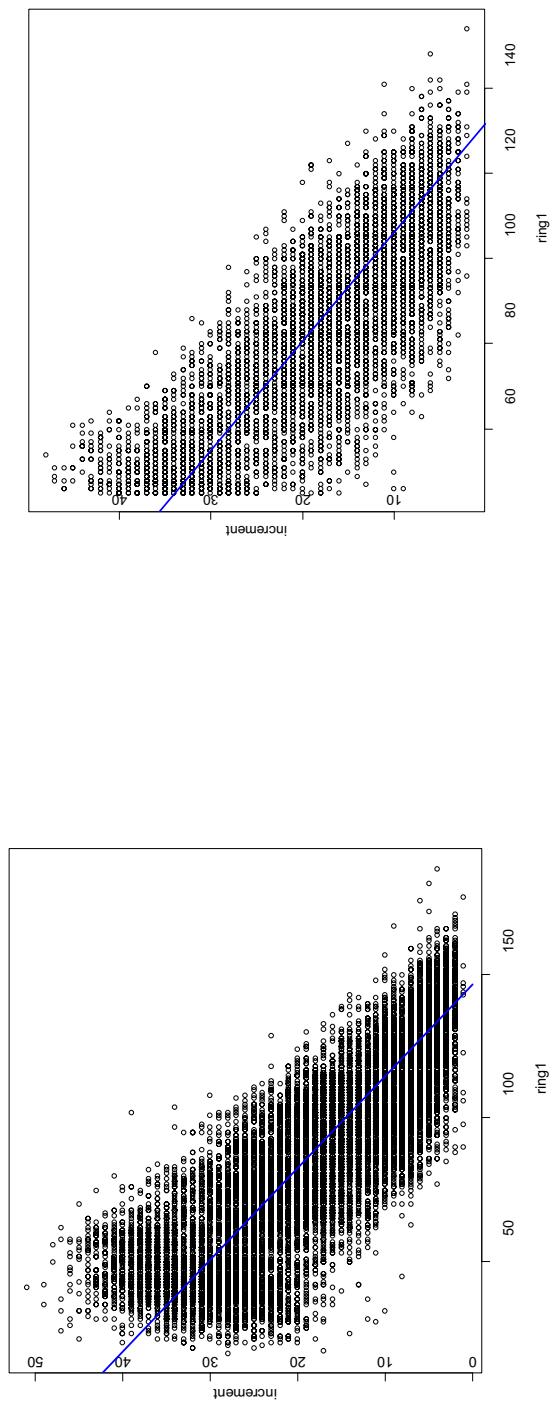


Fig App3-2. Georges Bank (left) and Mid-Atlantic (right) growth increments with mixed-effect regression lines.

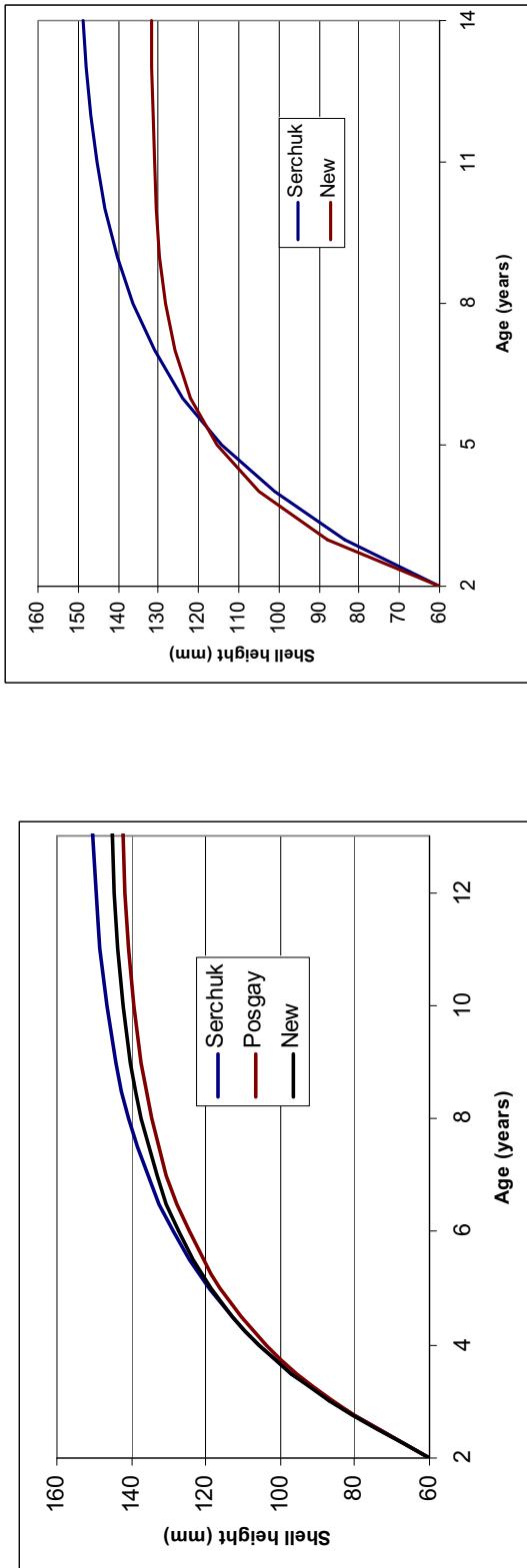


Fig App3-3. Comparison of the new growth curves (left is those for Georges Bank and right are the two for the Mid-Atlantic) with those of Serchuk et al. (1979) and Posgay (1979), for a scallop starting (at age 2) at 60 mm.

## APPENDIX B4: Shell Height/Meat Weight Relationships

New shell height/meat weight data was collected on the annual NMFS sea scallop survey during 2001-2006. This appendix will present and analyze these data.

### Methods

Sea scallops (averaging about 6 per station) were selected for analysis on roughly half of all stations (511 stations in the Mid-Atlantic, 592 stations on Georges Bank). The scallops were measured to the nearest millimeter, carefully shucked, excess water was removed from the meat, and the meat was weighed to the nearest gram. Data was also collected in 2003, but there was partial data loss when the data was transferred from ship to shore, so these data will not be used. In 2004-2006, whole and gonad weights were also recorded, but these data will not be presented here. The data here was separated into two regions (Mid-Atlantic and Georges Bank); further separation into subareas is possible, but will not be presented here.

Preliminary analysis indicated a residual pattern for those scallops with shell height less than 70 mm due to the small weights of these scallops (1-3 g) combined with the fact that meat weight could only be measured to the nearest gram. For this reason, the analysis was restricted to scallops that are at least 70 mm shell height. Scallops less than this height are below commercial size and thus their meat weight has no influence on CASA model calculations.

A generalized linear mixed-effects (GLMM) model was used to fit the equations

$$W = \exp(\alpha + \beta \ln(L)) \quad (\text{A4-1})$$

and

$$W = \exp(\alpha + \beta \ln(L) + \gamma \ln(D)), \quad (\text{A4-2})$$

where  $W$  is meat weight (grams),  $L$  is shell height (mm), and  $D$  is depth (meters), to the data. The GLMM used a gamma likelihood with a log link, appropriate for data (such as these) with “constant CV” error (McCullagh and Nelder 1989). This method avoids log-transforming the response variable (meat weight) that can lead to biased estimates when back-transformed. Because samples collected at the same station may be more similar than those from other stations, “station” was used as a random effect, and this random effect was weighted by the total number of scallops caught on that station so that stations at high abundances would be appropriately represented. The results were compared to those using a simple log-log regression and a GLM with just fixed effects. Both of these gave nearly identical results after applying a bias correction to the log-log regression, and differed only slightly from the GLMM presented here. All data analysis was conducted using the R statistical program (v2.3.1), with the lme4 mixed-effects package.

### Results

#### *Mid-Atlantic*

A total of 2945 observations were sampled from 511 stations (Figure 1). Parameters (Table App4-1) were well estimated with no evidence of a residual pattern (Table 2, Figure 2).

Predictions from the new estimates are similar to most previous estimates, with the exception of Lai and Helser (2004) (Figure 3). Compared to the estimates used in previous assessments, the new estimates predict slightly heavier meats at small shell heights, but lighter meats at very large shell heights, but these differences are very small. The relationship that includes a depth effect indicates that sea scallops have considerably heavier meats at shallower depths (Figure 4).

#### *Georges Bank*

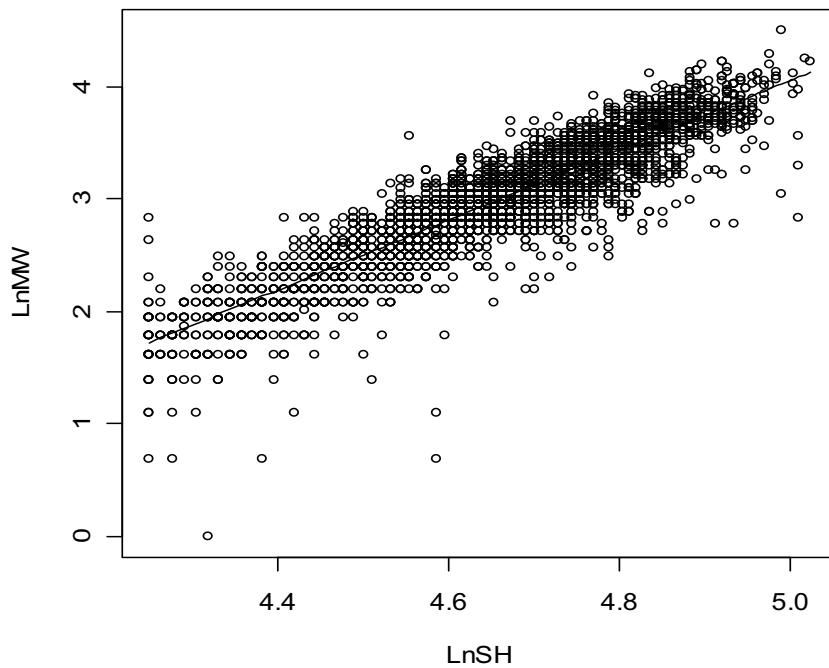
Based on 3824 scallops at 592 stations, model fits appeared good with little or no residual pattern (Figures 5-6). Parameters reasonably precise (Tables 1-2), and, as was the case for the Mid-Atlantic relationships, predict slightly greater meat weights at small shell heights, and slightly lower meat weights at large shell heights than does the relationship used in the previous two assessments (Figure 7). Predictions from the new relationship fall about in the middle of other estimates. Meat weights were substantially greater at shallower depths (Figure 8).

**APPENDIX B4 Table 1.** New shell height/meat weight parameters, with those from other studies for comparisons

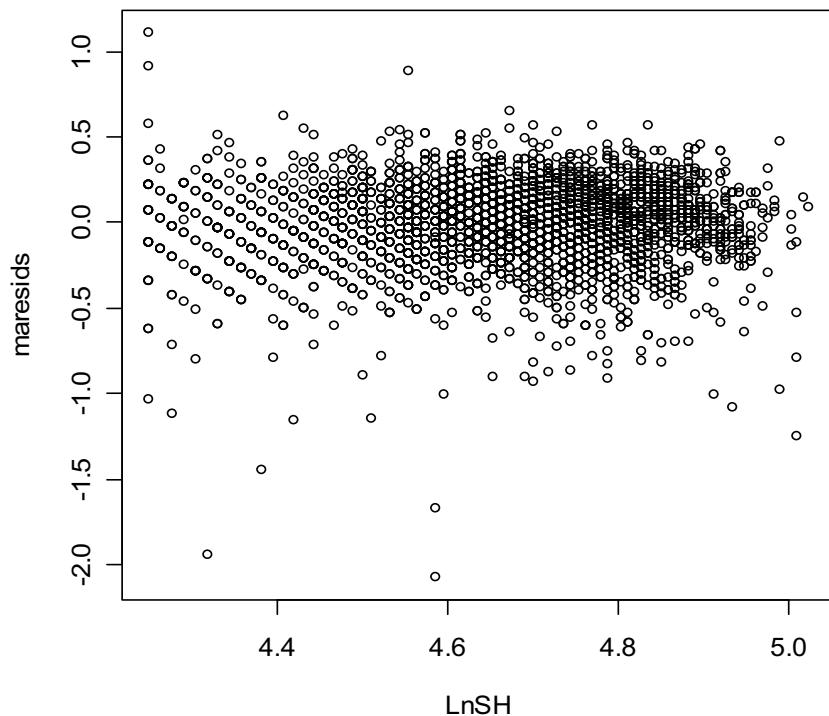
	$\alpha$	$\beta$	$\gamma$
<b>Mid-Atlantic Bight</b>			
Haynes (1966)	-11.0851	3.0431	
Serchuk & Rak (1983)	-12.1628	3.2539	
NEFSC (2001)	-12.2484	3.2641	
Lai and Helser (2004)	-12.3405	3.2754	
New	-12.01	3.22	
New with depth effect	-9.18	3.18	-0.65
<b>Georges Bank</b>			
Haynes (1966)	-10.8421	2.9490	
Serchuk & Rak (1983)	-11.7656	3.1693	
NEFSC (2001)	-11.6038	3.1221	
Lai and Helser (2004)	-11.4403	3.0734	
New	-10.70	2.94	
New with depth effect	-8.62	2.95	-0.51

**APPENDIX B4 Table 2.** Standard errors for the new parameter estimates

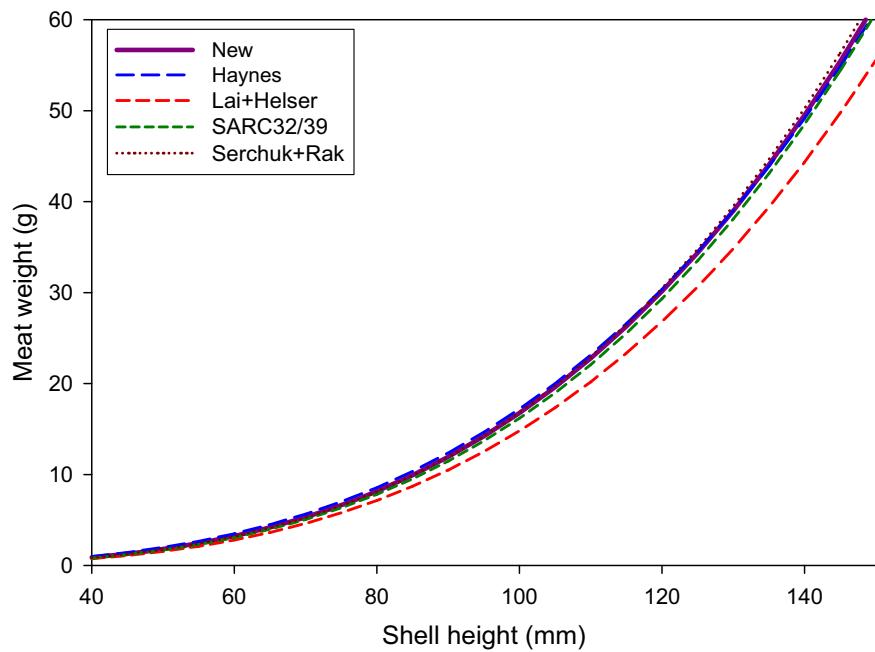
	$\alpha$	$\beta$	$\gamma$
<b>Mid-Atlantic Bight</b>			
New	0.15	0.05	
New with depth effect	0.39	0.05	0.08
<b>Georges Bank</b>			
New	0.27	0.06	
New with depth effect	0.17	0.05	0.05



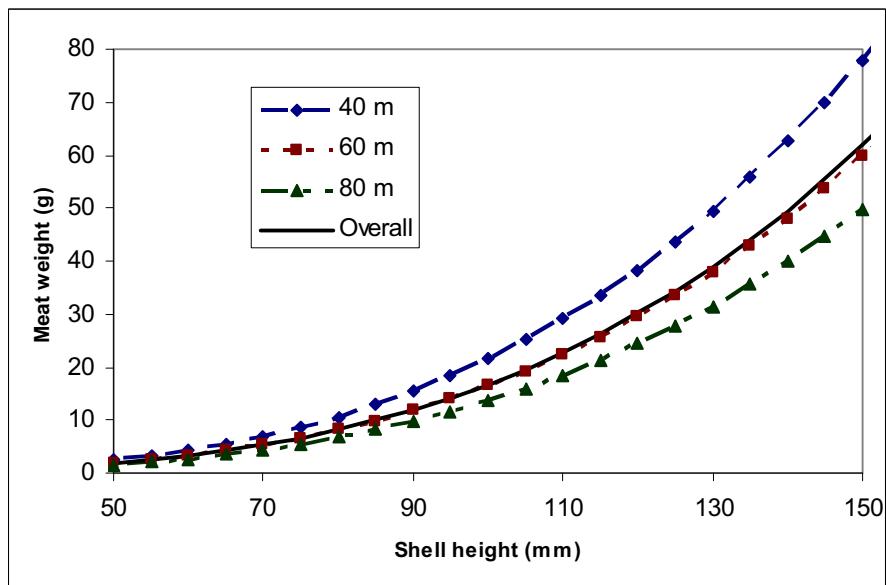
APPENDIX B4 Figure 1. Mid-Atlantic shell height/meat weight data



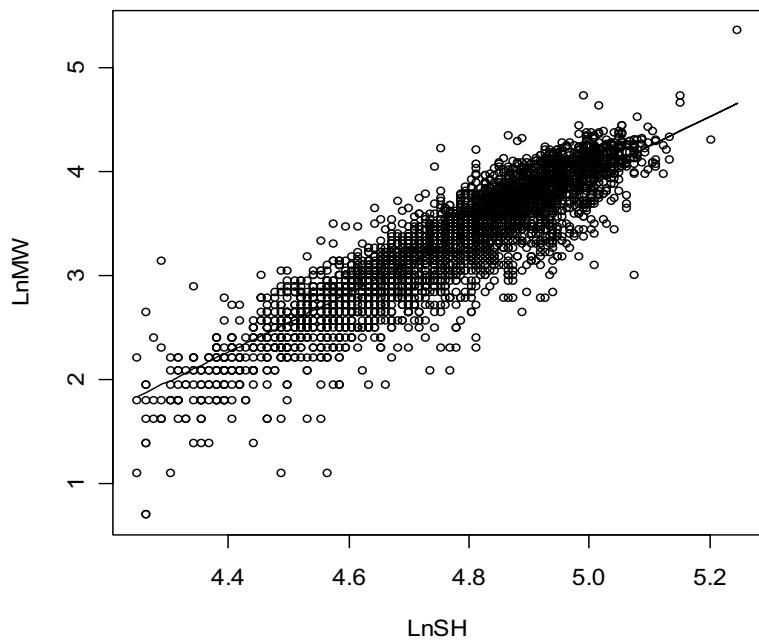
APPENDIX B4 Figure 2. Residual plot of Mid-Atlantic SH/MW data



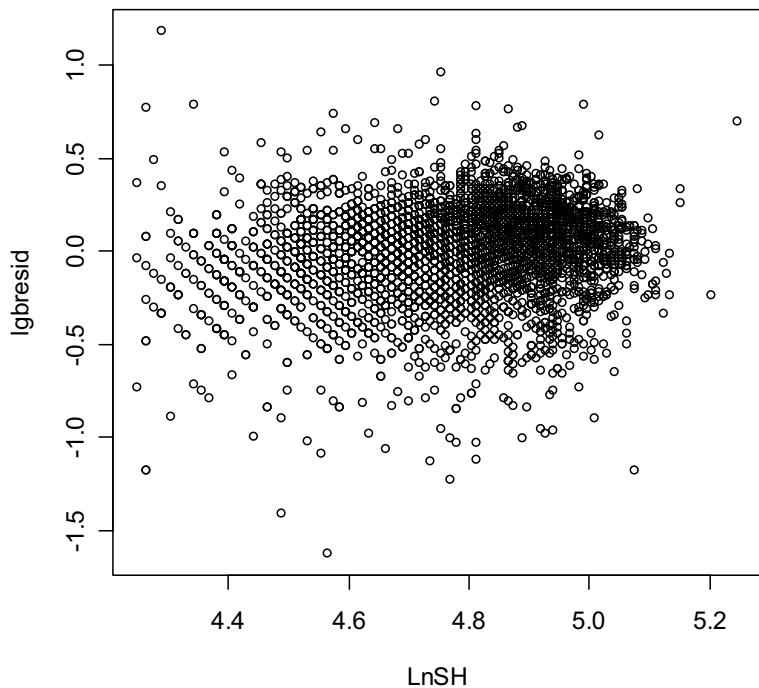
APPENDIX B4 Figure 3. Comparison of shell height/meat weight in the Mid-Atlantic



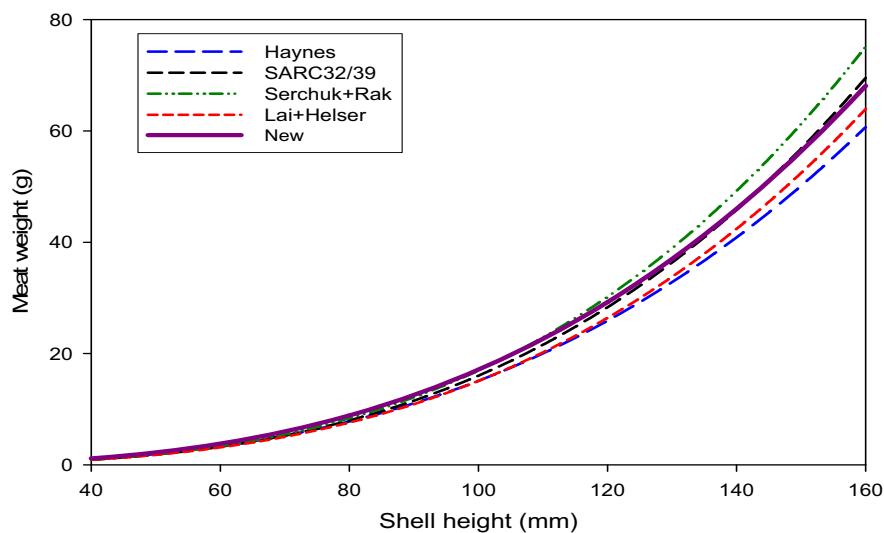
APPENDIX B4 Figure 4. Shell height/meat weight relationships at relationships 40, 60, and 80 m depth, and overall



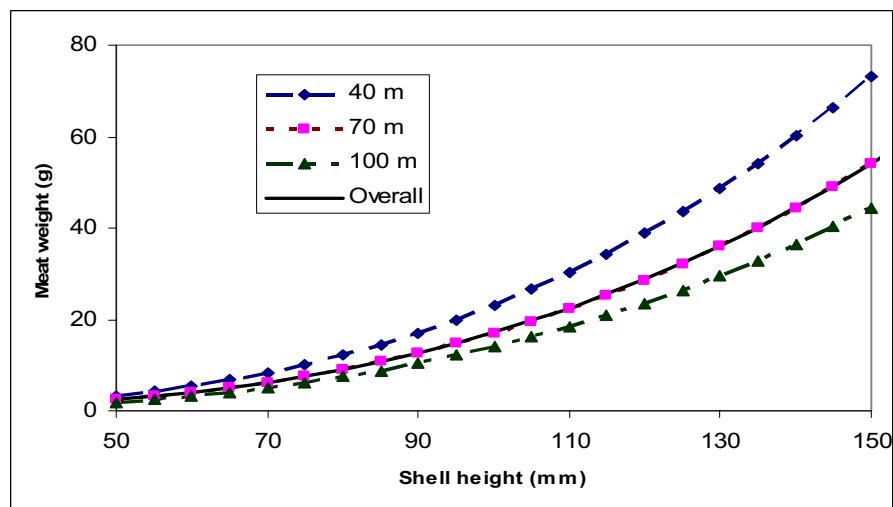
APPENDIX B4 Figure 5. Georges Bank shell height/meat weight data



APPENDIX B4 Figure 6. Residual plot of Georges Bank SH/MW data



APPENDIX B4 Figure 7. Comparison of SH/MW relationships in Georges Bank



APPENDIX B4 Figure 8. Georges Bank SH/MW relationships at 40, 70, 100 m depth and overall

## **APPENDIX B5: Selectivity of commercial sea scallop dredges with 4" rings**

A size-selectivity curve was constructed to characterize the performance of the commercial New Bedford style sea scallop (*Placopecten magellanicus*) (“commercial”) dredge, configured to meet the requirements of Amendment #10 to the Sea Scallop Fishery Management Plan. In order to construct an absolute size-selectivity curve, the commercial (experimental) gear must be compared to a non-selective (control) gear. The National Marine Fisheries Service (NMFS) survey dredge (“survey”) served as the control gear in this study. The survey dredge is assumed to be non-selective because there is a liner sewn into the dredge bag which prohibits scallops from escaping. With the catch-at-length data from the two dredges, the Share Each Length’s Catch Total (SELECT) model developed by Millar (1992) was used to generate the curve.

### **Data Collection and Analysis**

The catch-at-length data needed to generate the selectivity curve was gathered during three cruises aboard commercial sea scallop vessels between 2005 and 2006. One cruise was completed in Georges Bank (in the Groundfish Closed Area II (CA2 2005)) and two in the mid-Atlantic (both in the Elephant Trunk Closed Area (ETCA 2005 and 2006)). Within each area, pre-determined stations, selected within a systematic random grid, were sampled. At each station, a standard NMFS survey dredge was towed simultaneously with a New Bedford style commercial sea scallop dredge. Simultaneously towing the two dredges from the same vessel allowed for similar type of substrate and population of scallops to be sampled. The survey dredge was 8-feet (2.4 m) in width, was configured with 2-inch (51 mm) rings, a 3.5-inch (89 mm) diamond mesh twine top, and a 1.5-inch (3.8 cm) diamond mesh liner and the commercial dredges were 15-feet (4.6 m) in width, had 4-inch (102mm) rings, a 10-inch (25.4 cm) mesh twine top and no liner. Rock chains and chafing gear were used on both dredges as dictated by the area surveyed and current regulations.

Each tow, from all cruises, was evaluated and deemed invalid if any of the following conditions were observed: hangs, flips, crossing or tangling of the gear, the tow was not deemed “good” in the comments section of the deck or bridge log, the inclinometer indicated that the gear was not fishing correctly, no scallops were caught or there were fewer than 20 scallops caught in either dredge. A catch of less than 20 suggests that there were actually no scallops present at the station; rather, scallops from a preceding tow may have been lodged in the dredge or left on deck.

The number of scallops caught per each 5 mm length class (evaluated as the mid-point of the length class, i.e., length “7.5 mm” represents the length class 5-10 mm) from each gear, was multiplied by an expansion factor equal to the number of baskets of scallops caught divided by the number of baskets measured. The tows were then combined by cruise, closed area, year and all tows together. For each tow and combination of tows, a plot was made of the ratio of the number of scallops in each length class in the commercial dredge to the total in both dredges (Commercial/Total) in order to determine if the commercial gear was behaving selectively. This assessment validated proceeding with the analysis.

The catch-at-length data for each tow combination were then analyzed with the Share Each Length’s Catch Total (SELECT) model developed by Millar (1992). The SELECT model generates the parameters needed to create the selectivity curve as well as a parameter that denotes relative fishing intensity between the two gears (experimental and control). This is the

split parameter,  $p_j$ , which accounts for how catch among gears ( $j=1, \dots, n$ ) will vary due to affects such as differential fishing effort, fish avoidance behavior and localized fish concentrations.

Due to variation in wind speed, water depth, sea state, scallop density and other factors that cannot be controlled, there is variation in selectivity from one tow to the next. This must be considered when tows are combined. A test for overdispersion (variation exceeding that which is predicted by the model) was completed using the replication estimate of between-haul variation (REP) combined hauls approach discussed in Millar et al. 2004. In order to avoid over-inflating the degrees of freedom for this analysis, only length classes where, when all tows are combined, one dredge has caught at least 20 scallops were used. In order to determine if this affected the estimated parameters, the model was run under this criterion as well as under the criteria that, for each length class, at least one dredge had more than: 1) zero scallops, 2) 60 scallops and 3) 1,000 scallops. In general, with fewer length classes used in the analysis, the 50% retention length, selection range, split parameter and log likelihood values all increased; however, these changes were not substantial.

In order to create a selectivity curve that is representative of the offshore commercial fleet, sampling was conducted aboard commercial scallop vessels, under conditions that mimicked commercial practices and the experiments were performed during different months and in different areas, which contained a variety of substrates. The only aspect of this study that is not representative of commercial practices is tow duration; however, an assessment of how the number of baskets of scallops and trash caught in the commercial dredge affects the parameters of the selectivity curve was made. This served as a proxy for how tow duration might affect the selection process. It must be noted, though, that tow duration does not predict the size of the catch. For this assessment, tows from all three cruises were grouped into five categories based on the number of baskets of scallops caught in the commercial dredge: 1) fewer than three, 2) three to six, 3) six to twelve, 4) twelve to twenty-four, and 5) more than twenty-four. These increments were chosen because there were a similar number of tows that fit into each group. A selectivity curve was generated for each category, using the same length classes that were used to evaluate all tows combined. A Spearman's rank correlation coefficient analysis was then completed on the resulting 50% Retention Length ( $l_{50}$ ), Selection Range (SR) and split parameter ( $p_c$ ) values. This procedure was repeated with increasing baskets of trash. Categories for this analysis were based on the number of baskets of trash in the commercial dredge: 1) less than 0.25, 2) 0.25 to one, 3) one, 4) one to two, and 5) more than two.

## Results and Discussion

The catch-at-length data obtained during this study were evaluated with the SELECT model using the logistic as well as Richards, log-log and complementary-log-log curves in order to determine the most appropriate model for the data. The deviance residuals from the logistic fit showed no considerable trends and the curve adequately fit the data. The other three curves did not significantly improve the fit, based on AIC values, and, therefore, the results will only be presented for the logistic SELECT model. Also, the REP assessment for combining multiple tows indicated that there was extra variation for all tow combinations (by cruise, year, area and all combined) and, therefore, the standard errors for the estimated parameters were multiplied by the square root of REP.

The logistic parameters estimated for each combination of tows were inserted into the selectivity curve equation. The range of  $l_{50}$  values from the different combinations of data was

98.1-105.2 mm and of selection range values was 18.6-28.7. However, the final results are those that were estimated for all valid tows for the CA2 and ETCA cruises combined since an evaluation of the resulting parameters and confidence intervals from all combinations of data (by cruise, area and year) revealed little significant difference. Additionally, by including tows from multiple cruises on different vessels, during different times of the year and in different areas and substrates the selectivity curve becomes more representative of the commercial fleet. The resulting SR for this analysis is 23.6 mm, the  $l_{50}$  is 100.1 mm and the estimated split parameter is 0.77.

The next assessment evaluated how increasing number of baskets of trash and scallops caught in the commercial dredge might affect the estimated selectivity parameters. This served as an indication of whether the results were affected by the reduced tow duration used in this study. The Spearman's rank correlation coefficient significantly indicated that with increasing number of scallops the selection range and the split parameter values increase. While the results for the 50% retention length appear to show a similar trend, the results were not significant. In contrast, none of the evaluated parameters showed a significant relationship with increasing number of baskets of trash; however, the  $l_{50}$  values show a decreasing trend with increasing baskets of trash. It can be assumed that the selectivity curve generated in this study does represent commercial practices since there is not a significant difference in the  $l_{50}$  values with increasing baskets of scallops or trash. Additionally, during the survey cruises, the dredge bag ranged from being empty to completely full, which mirrors the range observed during commercial operations.

Lastly, the final results for this study were compared to those obtained from an additional cruise in the Nantucket Lightship Closed Area (NLCA). This cruise was conducted under the same conditions and during the same time period as the aforementioned cruises; however, the survey and commercial dredges used in the NLCA were not configured as they were in the other areas. For this reason, data from the NLCA were not combined with the other cruises. The estimated parameters for the NLCA cruise yielded a 50% retention length of 101.6 mm, a selection range of 17.63 mm and a split parameter value of 0.76. Standard errors for the estimated parameters were multiplied by the square root of REP because the data were overdispersed. Results from the NLCA are comparable to the results from the other cruises combined. An assessment of these parameters with confidence intervals reveals that there is no significant difference between the two 50% retention lengths and split parameters, but that there is between the selection ranges. Regardless, the similarity of the results for the NLCA cruise and for the other cruises combined indicates that the selection curve generated for this study is robust to changes in gear configuration. Additionally, the length frequency distribution in the NLCA is different from the other closed areas. This implies that the selection curve is also robust to differences in length frequency distribution.

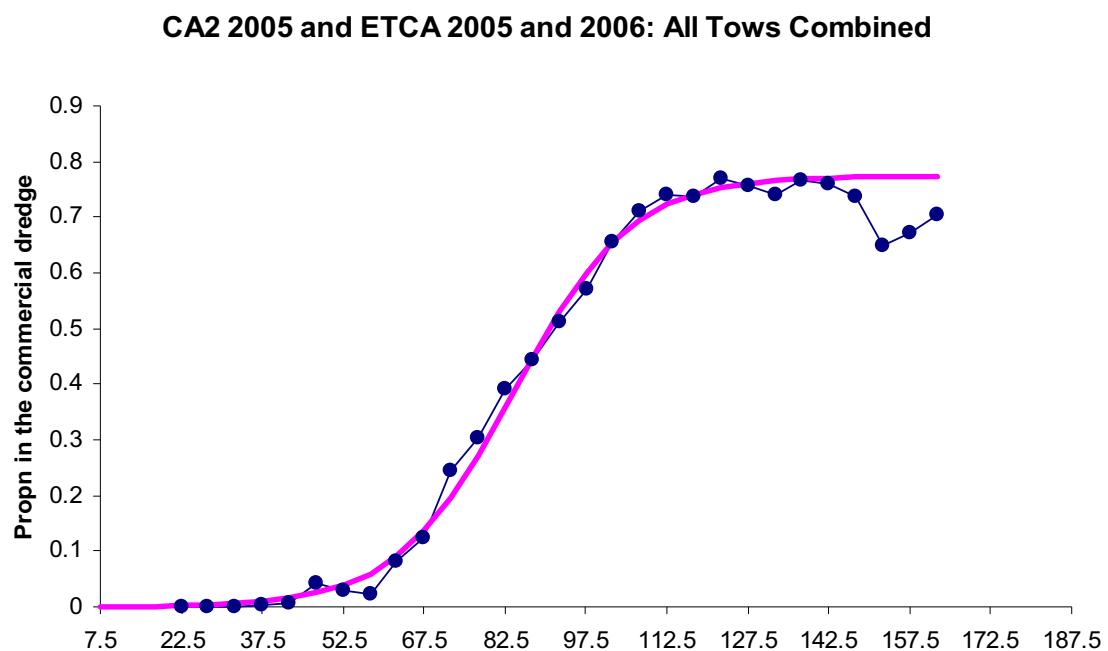
To maximize the effectiveness of the resulting curve from this study, more information is required regarding incidental mortality and the fate of scallops that interact with or escape from the commercial dredge and of the scallops that are landed on deck but are not harvested.

APPENDIX B5 Table 1. Estimated parameters from the logistic SELECT analyses on catch-at-length data for all length classes with at least 20 scallops in one of the dredges. Listed are lengths used in the analyses and the starting values to estimate the parameters in both R and Excel. The estimated values (left column) for logistic parameters  $a$  and  $b$ , as well as the 50% retention length ( $l_{50}$ ), the selection range (SR =  $l_{75} - l_{25}$ ) and the relative efficiency split parameter ( $p_c$ ) are given. The number of tows (No. Tows) used for each analysis, log likelihood (L) and the replication estimate of between-haul variation (REP) are specified as well as the standard errors (right column), which have been multiplied by the square root of REP.

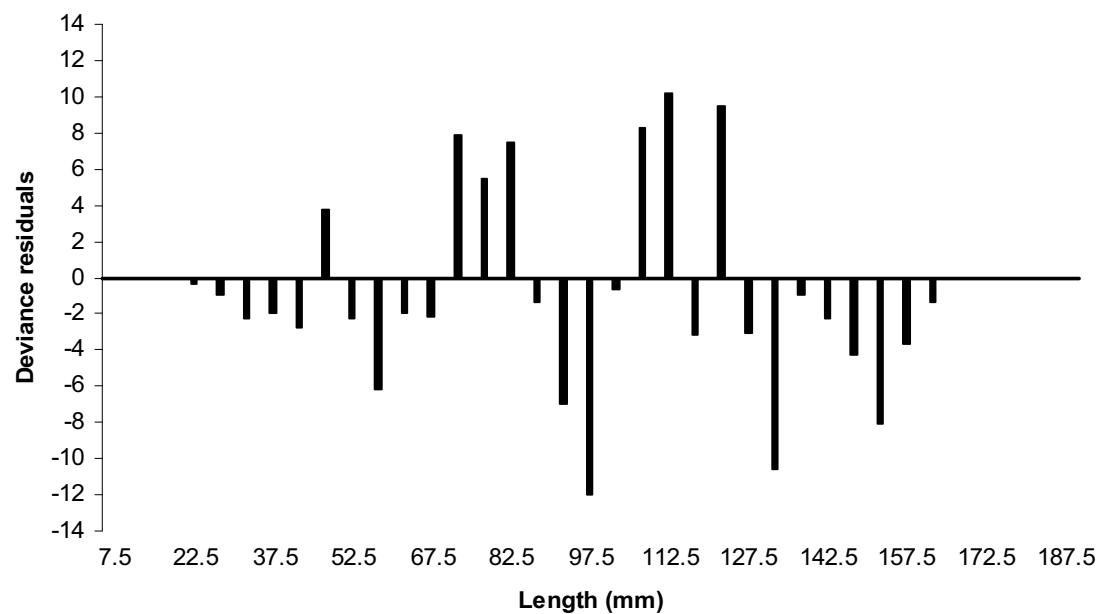
	<b>NLCA 2005</b>	<b>CA2 2005, ETCA 2005 &amp; 2006</b>		
<b>Lengths</b>	42.5-172.5		22.5-162.5	
<b>Start values</b>	(-12, 0.12, 0.8)		(-12, 0.12, 0.8)	
<b>a</b>	-12.6700		-9.32	
<b>b</b>	0.12		0.09	
<b><math>p_c</math></b>	0.76	0.005	0.77	0.004
<b><math>l_{50}</math> (mm)</b>	101.63	1.42	100.11	0.60
<b>SR (mm)</b>	17.63	1.85	23.61	0.59
<b>L</b>	-50672		-311035	
<b>REP</b>	8.01		7.98	
<b>No. Tows</b>	35		1052	

APPENDIX B5 Figure 1. (A) Logistic SELECT curve fitted to the proportion of the total catch in the commercial gear and (B) deviance residuals for CA2 2005, ETCA 2005 and ETCA 2006 cruises combined.

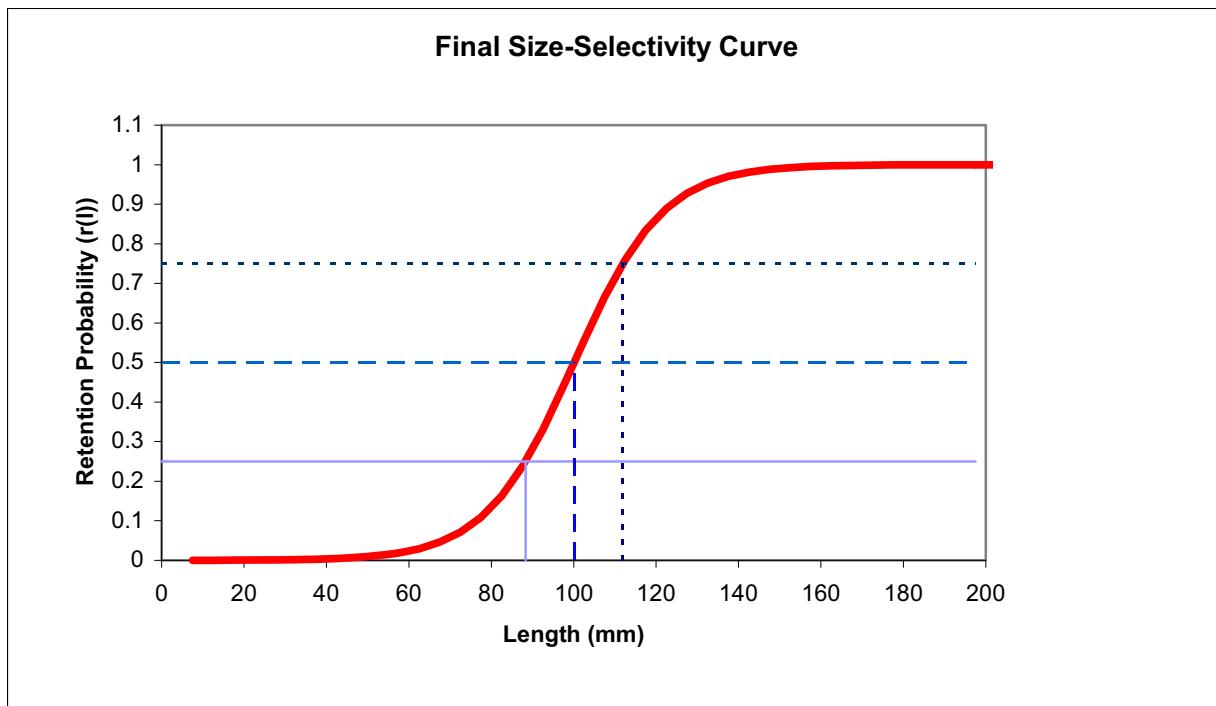
A



B



APPENDIX B5 Figure 2. Logistic selection curve for the New Bedford style dredge which incorporates all valid tows from the three cruises. The lengths at 25%, 50% and 75% probability of retention are shown. The selection range is the difference between the 75% and 25% retention lengths ( $l_{75} - l_{25}$ ).



## **APPENDIX B6: Imputed NEFSC scallop survey data for unsampled strata**

Some strata were unsampled during 1979-2006 NEFSC scallop surveys, particularly in the Georges Bank region (Tables 1 and 2). In NEFSC (2004), these “holes” in the survey data for a particular year ( $y$ ) were filled automatically in database retrieval software by borrowing data from the same survey strata collected during the previous ( $y-1$ ) and/or next ( $y+1$ ) annual surveys. Borrowed data were used to compute means for survey holes and stratified random means for larger areas in the normal manner. Borrowing was one-sided in cases where data from  $y-1$  or  $y+1$  were lacking, and in the most recent survey year in particular where data for year  $y+1$  are never available.

The borrowing procedure and variance calculations are ad-hoc but have a number of advantages: 1) survey indices for year  $y$  do not change after year  $y+1$ ; 2) a minimum of programming and staff time is required; 3) the most relevant data are used, and 4) the calculations (linear interpolation between adjacent surveys) are simple, objective and make few assumptions about spatial patterns in population dynamics. No allowance is made for measurement errors in borrowed data. However, scallop survey data are relatively precise and important strata with high scallop abundance were generally not missed.

A more complicated statistical model based procedure was used in this assessment to fill all of the holes in NEFSC scallop survey data. However, data for Georges Bank during 1979-1981 were not used in the assessment, even after holes were filled, because the number of unsampled strata was relatively high (Figure 1).

The new statistical model was fit to tow-by-tow survey data (number of 40+ mm SH sea scallops per tow) by maximum likelihood using the `glm.nb()` function in Splus with a log link and assuming that measurement errors in the survey data were from a negative binomial distribution. Years and “newstrata” (see below) were categorical variables in the model and separate models were used for each subregion and post-stratification scheme. Residuals plots indicated that the model used to predict strata means fit the data reasonably well (Figure 1).

Subregions and newstrata are specific to the post-stratification scheme employed in a particular database run. Newstrata are original survey strata split into open and closed management areas. Subregions are contiguous groups of newstrata that define areas of particular interest. Data used in models that fill holes and in calculating abundance indices are from random stations within the original survey strata so that statistical assumptions are not violated in splitting strata into newstrata. Post-stratification exacerbates problems with holes because sections of a stratum assigned to newstrata might not have been sampled during a particular survey even if the larger stratum was sampled.

After fitting, the statistical model was used to calculate and store predicted values for every combination of subregion, year and newstrata. Predicted survey length composition for each subregion, year and newstrata was calculated by applying the shell height composition (total numbers in each 5 mm bin) from tows in the same subregion during the same year to predicted total numbers per tow from the model. Survey database software automatically retrieves predicted values for each shell height group to fill holes, as required. Predicted biomass per tow was calculated in the survey database software in the normal manner by applying a shell height/meat weight relationship.

The standard error for predicted number or biomass per tow is used in database variance calculations for larger subregions and regions. The standard error for predicted catch per tow in

a particular size bin was  $\sqrt{p_L^2 s^2}$  where  $s$  is the standard error for predicted mean number per tow from the model (all sizes) and  $p$  is the observed proportion of mean numbers per tow for shell height bin  $L$ . Variances in the proportion  $p$  are not considered because the number of shell height measurements in a subregion is normally high.

The major benefit of the new modeling approach is that secondary holes in newstrata that occur after poststratification are automatically filled and that variance calculations have a better statistical basis. Differences in abundance and biomass indices between the complicated model based- and simple borrowing procedures were modest for Georges Bank as a whole and almost identical for the Mid-Atlantic Bight as a whole. Differences between model based and borrowing estimates were more substantial, however, for some subregions on Georges Bank.

APPENDIX Table B6-1. Numbers of random tows in NEFSC scallop surveys on Georges Bank by survey stratum and year (including tows by the F/V Tradition during 1999). Black areas indicate strata that were not sampled.

Year	Stratum									
	46	47	49	50	51	52	53	54	55	58
1979	4	9	5	4	7	3	3	5	7	2
1980		4	5	5	7	5		4	10	2
1981	5	9	5	5	8	5	5	6	9	2
1982	6	9	6	8	8	6	6	6	6	3
1983	6	9	6	12	11	6	6	6	6	4
1984	6	9	7	12	12	6	6	6	5	4
1985	6	10	9	11	12	7	7	7	7	4
1986	6		9	16	12	11	7	7	1	8
1987	6	12	9	16	11	11	7	7	9	8
1988	6	12	9	16	12	12	7	7	10	8
1989	6	12	8	15	12	12	7	6	10	8
1990	6	12	9	15	13	12	7	7	10	8
1991	6	12	9	16	12	12	7	7	10	8
1992	6	12	9	16	11	11	7	7	10	8
1993	6	12	9	13	9	10	7	7	10	8
1994	6	12	9	16	12	12	7	7	10	8
1995	6	12	9	16	11	12	7	7	10	8
1996	6	12	5	16	12	11	7	7	10	8
1997	6	13	7	16	12	14	9	10	10	8
1998	15	22	9	16	11	12	7	7	10	8
1999	6	15		5	6	14	11	15	14	8
2000	6	12	7	13	9	9	6	7	10	8
2001	6	14	9	15	14	14	15	11	12	6
2002	6	14	6	13	14	13	16	11	12	6
2003	6	13	9	14	10	14	15	13	10	6
2004	4	18	9	12	12	11	15	20	10	4
2005	5	20	10	11	12	12	12	19	10	4
2006	4	18	7	14	10	16	13	17	14	4

APPENDIX Table B6-1 continued

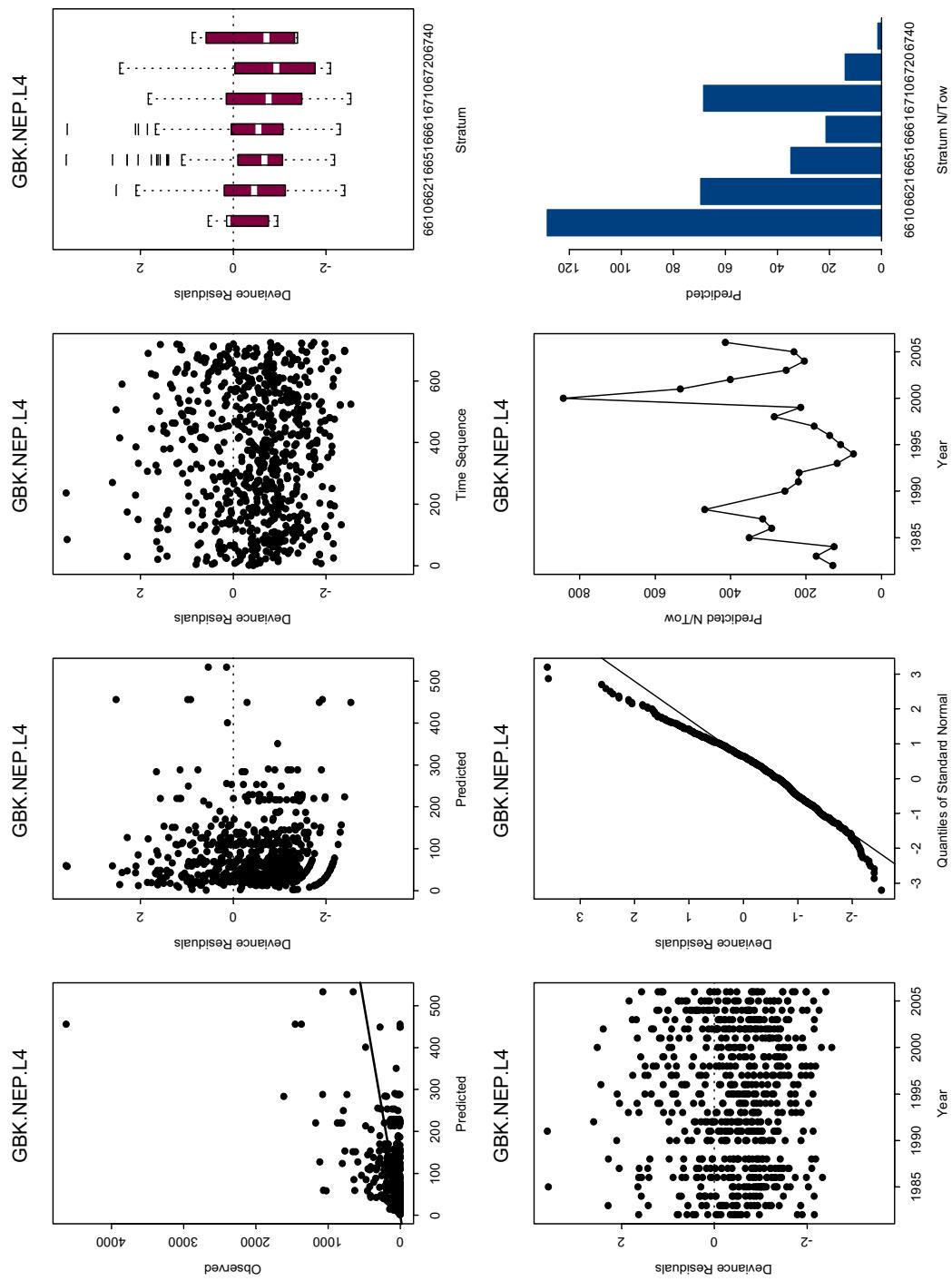
Year	Stratum									
	59	60	61	62	63	65	66	71	72	
1979	10	8								
1980	10	8								
1981	9	8								
1982	10	9	7	9	4	6	6	4	5	
1983	8	8	7	8	5	9	8	4	4	
1984	8	8	7	8	3	9	8	5	4	
1985	12	12	8	12	7	10	10	6	6	
1986	12	12	8	13	7	12	12	6	6	
1987	12	12	8	12	7	12	12	5	6	
1988	12	12	8	12	6	11	12	6	6	
1989	12	12								
1990	12	12	8	12	7	12	12	6		
1991	12	12	8	12	7	12	12	6	6	
1992	12	12	8	12	7	11	12	6	6	
1993	12	12	8	12	7	10	10	6	6	
1994	12	12	8	12	7	12	12	6	6	
1995	12	12	8	12	7	12	12	6	6	
1996	12	12	8	12	7	12	12	6	6	
1997	12	12	8	12	7	15	14	8	5	
1998	11	11	8	12	7	12	10	6	6	
1999	12	12	8	14	6	11	11	4	2	
2000	12	12	7	12	7	11	12	6		
2001	10	12	18	23	6	10	11	5		
2002	10	10	18	24	4	12	14	8	5	
2003	8	9	16	21	4	12	12	8		
2004	7	6	24	24	3	12	10	12	3	
2005	8	7	22	24	3	11	9	12		
2006	6	7	24	17	3	12	9	19		

APPENDIX Table B6-2. Numbers of random tows in NEFSC scallop surveys in the Mid-Atlantic Bight by survey stratum and year (including tows by the F/V Tradition during 1999). Black areas indicate strata that were not sampled.

Year	Stratum										
	6	7	10	11	14	15	18	19	22	23	24
1979	2	1	5	7	7	12	7	5	12	20	3
1980	1	2	5	7	7	12	7	5	12	20	3
1981	2	1	5	6	7	12	7	5	12	20	3
1982	4	3	8	6	6	12	7	5	12	20	6
1983	4	4	8	8	8	12	6	7	8	16	6
1984	5	4	8	8	10	12	6	8	8	16	6
1985	5	5	8	8	10	12	8	8	8	16	6
1986	5	5	8	8	12	12	10	13	8	16	6
1987	5	5	8	8	12	11	10	12	8	16	4
1988	6	4	8	8	12	12	10	12	8	16	6
1989	5	5	8	8	12	12	10	12	8	16	6
1990	3	3	8	8	12	12	10	12	8	16	5
1991	5	5	8	8	12	12	10	11	8	16	6
1992	5	5	8	8	12	12	10	12	8	16	6
1993	5	5	8	8	12	12	8	10	8	16	6
1994	5	5	8	8	12	12	10	12	8	16	5
1995	5	5	8	8	12	12	10	12	8	16	6
1996	5	5	8	8	12	12	8	10	8	16	6
1997	5	5	8	8	11	12	9	12	8	16	6
1998	5	5	8	8	12	12	10	12	8	16	6
1999	5	5	8	8	12	12	10	12	8	16	6
2000	5	5	8	8	12	12	10	13	8	16	6
2001	5	5	9	14	10	12	8	12	10	22	8
2002	5	5	9	12	10	12	8	11	12	22	8
2003	5	5	8	12	10	12	10	12	10	20	6
2004	3	2	8	12	14	16	24	21	14	25	10
2005	2	3	7	10	15	16	26	22	14	26	8
2006	3	2	6	10	14	20	20	25	14	25	5

APPENDIX Table B6-2 continued.

Year	Stratum									
	25	26	27	28	29	30	31	33	34	35
1979	4	8	12	2	8	14	24	2	4	7
1980	4	9	11	2	8	14	24	4	4	6
1981	5	8	12	2	8	14	24	4	4	6
1982	7	9	12	3	8	14	24	7	7	5
1983	6	13	10	7	6	15	24	10	10	5
1984	7	14	10	6	8	15	24	10	14	5
1985	4	14	12	6	6	15	24	10	10	6
1986	4	14	20	10	6	15	24	7	13	10
1987	4	14	20	10	6	15	24	10	14	10
1988	4	14	19	10	6	15	23	10	14	10
1989	4	14	20	10	6	15	24	10	29	10
1990	3	12	17	10	5	14	24	10	14	10
1991	5	14	20	10	6	15	24	10	14	10
1992	4	14	20	10	6	15	24	10	14	10
1993	4	14	20	10	6	15	22	7	10	8
1994	4	14	20	10	6	15	23	10	14	10
1995	4	12	20	10	6	15	24	10	14	10
1996	4	13	19	10	6	15	20	8	10	8
1997	4	14	20	10	6	14	24	10	13	10
1998	4	14	19	9	██████████	14	23	6	14	10
1999	4	14	20	10	6	15	24	7	14	10
2000	4	13	20	10	6	15	24	10	14	10
2001	8	14	20	8	6	12	18	8	10	8
2002	6	10	19	7	6	10	16	6	6	6
2003	6	10	20	8	4	9	16	6	6	6
2004	5	8	20	8	4	6	20	5	5	18
2005	5	7	21	7	4	6	21	5	6	10
2006	6	7	16	5	5	9	20	5	5	8



APPENDIX Figure B6-1. Model residuals and diagnostics for a negative binomial model used to impute NEFSC scallop survey mean numbers per tow (40+ mm SH) based on tow by tow survey data from the Northeast Peak subregion of Georges Bank. Goodness of fit results for the Northeast Peak were typical although spatial and temporal patterns in predicted abundance varied among subregions.

## **APPENDIX B7: Selectivity and efficiency of large camera video data from the SMAST video survey during 2003-2006<sup>5</sup>**

Selectivity curves were estimated for sea scallops in the SMAST video (“large” camera) survey using the Millar’s maximum likelihood SELECT model (Millar and Fryer, 1999) and “small” camera video data as a standard measure of sea scallop length composition and density at study sites. The small camera is believed to be fully efficient (100% detection probability) for sea scallops about 35+ mm SL. The data were ideal because large and small camera data were collected at each station so that stations can be analyzed as replicate “paired tow” experiments. Estimates for Georges Bank and Mid-Atlantic Bight combined during 2003-2006 indicate that the large camera system has an increasing logistic selectivity pattern for sea scallops with selectivity  $\geq 50\%$  at 48+ mm,  $\geq 90\%$  at 71+ mm SL, and  $\geq 95\%$  at 79+ mm (approximate SE 1.7 mm for all estimates). The selectivity range for the large camera ( $L_{75}-L_{25}$ ) was 22 mm (SE 2.4 mm). The SELECT model was configured so that the estimated split parameter  $p$  measured the ratio of total catches of sea scallops large enough to be fully selected by both cameras. Estimates of the split parameter  $p$  averaged 0.84 (SE 0.003 mm), which is approximately the same as the ratio expected based on assumed sample areas ( $A$ ) for the two cameras, i.e. expected  $p = A_{large} / (A_{small} + A_{large}) = 3.235 / (3.235 + 0.788) = 0.80$ . This suggests that the large camera also has 100% detection probability for large fully selected scallops in its sample area.

### **Introduction / Methods**

The primary purpose of the SMAST video survey camera selectivity comparisons was to identify the shell height at which the large camera was fully selective, assuming that the small camera was 100% selective at 35+mm shell height. SMAST camera survey selectivity curves were estimated by comparing large camera to small camera data from Georges Bank and the Mid-Atlantic Bight area combined during 2003-2006. Only stations where data was available for both cameras were included; any stations that were missing data from more than 2 quadrats were excluded. The number of stations varied each year with survey coverage (Figure 1).

Because the large and small cameras simultaneously collect data from the same locations, they can be directly compared for selectivity estimates. The large camera effective field of view is  $3.235 \text{ m}^2$  at each quadrat and the small camera effective field of view is  $0.788 \text{ m}^2$  (Stokesbury et al., 2004). The large camera’s view field allows for a larger number of scallops to be identified and measured, whereas the small camera with higher resolution allows for detection of smaller scallops (Figure 2).

Selectivity comparisons were based on shell height measurements from the large and small cameras by year and area (Table 1). Shell height measurements were binned in 10 mm increments to minimize potential effects of imprecise shell height measurements. Increment mid-points were used in all calculations (e.g. 5 mm for the 1-9.99 mm bin). Millar’s SELECT model (EXCEL Solver Version<sup>6</sup>) was used to fit an increasing logistic shape curve of selectivity for the large camera using the small camera as a standard. The model is:

<sup>5</sup> Michael C. Marino II1, Catherine O’Keefe (School of Marine Science and Technology (SMAST, University of Massachusetts Dartmouth, 706 South Rodney French Boulevard, New Bedford, MA 02744-1221), and Larry D. Jacobson (Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA, 02543)

<sup>6</sup> <http://www.stat.auckland.ac.nz/~millar/selectware/code.html>

$$s_L = \left[ \frac{e^{a+bL}}{1+e^{a+bL}} \right]$$

where  $s_L$  is selectivity at length and  $a$  and  $b$  are parameters (Millar and Fryer, 1999). A third “split” parameter  $p$  represents relative sampling intensity between the two gears and was initially estimated by taking the average of the ratio of the sample in the large camera to the total sample (large / large + small) at each shell height bin. The model was used to estimate the shell heights with selectivity values of 50% ( $L_{50}$ ), 90% ( $L_{90}$ ) and 95% ( $L_{95}$ ) as well as the selectivity range (SR =  $L_{75} - L_{25}$ ).

## Results / Discussion

The estimated selectivity curves for all years in both Georges Bank and the Mid-Atlantic showed a similar pattern of low selectivity at small sizes, increasing between approximately 35mm to 80 mm and reaching an asymptote of 1.0 around 85 mm (Figures 3-6). Parameter estimates (Table 2) were generally similar although  $L_{50}$  and related statistics were relatively high and imprecise for 2004. Simple averages were used to calculate “best” overall selectivity parameters for sea scallops in the large camera (Table 3). Similar results were obtained when means were computed using inverse variance weights.

Deviance residuals indicate generally good model fit (Figure 7). There were some runs of positive and negative residuals in 2003 and 2004. In 2005 and 2006 the model seemingly overestimated selectivity for the very large scallop size bins but this is most likely a result of low sample sizes for large scallops due to their low abundance.

Appendix B7 Table 1. Numbers of sea scallops measured and counted used in this analysis from video surveys during 2003-2006 in the Mid-Atlantic Bight and Georges Bank.

	LARGE			SMALL		
	MA+GB	MA all	GB all	MA+GB	MA all	GB all
Measured Total Counted	<b>2003</b>			<b>2003</b>		
	4001	3018	993	1322	1041	281
Measured Total Counted	6860	5043	1817	2014	1554	460
	<b>2004</b>			<b>2004</b>		
Measured Total Counted	2216	1363	853	528	330	198
	3902	2430	1472	917	564	353
Measured Total Counted	<b>2005</b>			<b>2005</b>		
	1866	1196	670	430	276	154
Measured Total Counted	3696	2333	1363	839	555	284
	<b>2006</b>			<b>2006</b>		
Measured Total Counted	2265	1528	737	535	344	191
	3549	2218	1331	940	536	404

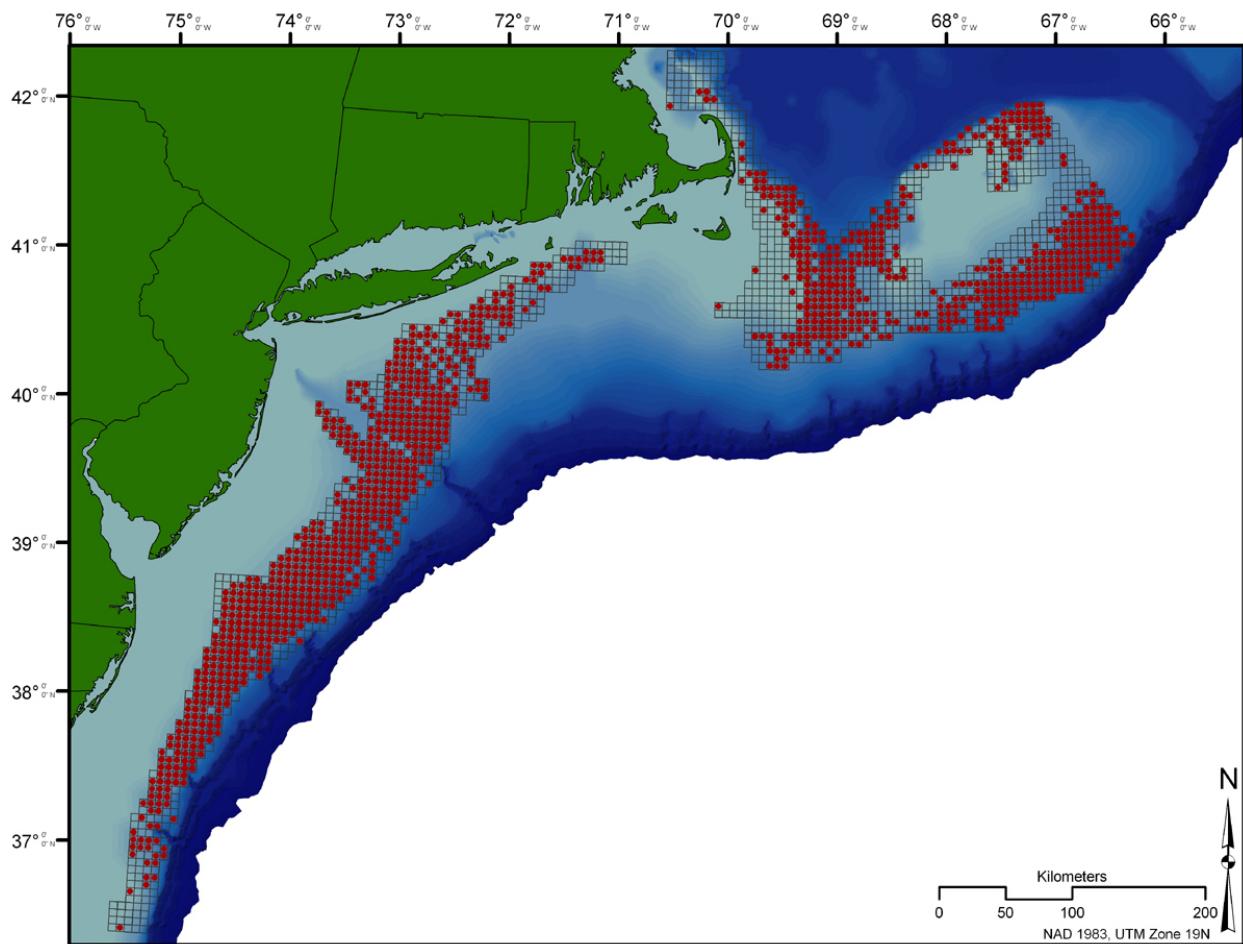
Appendix B7 Table 2. Estimated selectivity parameters  $p$ ,  $a$ ,  $b$ ,  $L_{95}$ ,  $L_{90}$ ,  $L_{50}$  and SR with standard errors and variances from SELECT models fit to large and small camera video data collected during 2003-2006 on Georges Bank and in the Mid-Atlantic.

<b>Year</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>
<b>Split (%)</b>	88.5	83.8	82.5	81.8
SE(Split)	0.005	0.012	0.008	0.008
Var(Split)	2.75E-05	1.44E-04	6.40E-05	6.40E-05
weights	0.364	0.159	0.238	0.238
<b>L95(mm)</b>	85.71	103.07	63.99	64.96
SE(L90)	1.720	5.070	3.080	2.780
Var(L90)	2.959	25.705	9.486	7.728
weights	0.397	0.135	0.222	0.246
<b>L90(mm)</b>	77.62	90.62	57.43	59.98
SE(L90)	1.720	5.070	3.080	2.780
Var(L90)	2.959	25.705	9.486	7.728
weights	0.397	0.135	0.222	0.246
<b>L50(mm)</b>	54	54	38	45
SE(L50)	1.720	5.070	3.080	2.780
Var(L50)	2.959	25.705	9.486	7.728
weights	0.397	0.135	0.222	0.246
<b>SR(mm)</b>	24	36	19	15
SE(SR)	2.709	9.430	7.980	4.400
Var(SR)	7.341	88.925	63.680	19.360
weights	0.446	0.128	0.151	0.275
<b>a</b>	-4.98	-3.24	-4.35	-6.8
SE(a)	0.470	0.730	1.740	1.880
Var(a)	0.221	0.533	3.028	3.534
weights	0.462	0.297	0.125	0.115
<b>b</b>	0.09	0.06	0.11	0.15
SE(b)	0.011	0.016	0.047	0.045
Var(b)	1.11E-04	2.56E-04	0.002	0.002
weights	0.473	0.311	0.106	0.111

Appendix B7 Table 3. Average values for selectivity parameters  $p$ ,  $a$ ,  $b$ ,  $L_{95}$ ,  $L_{90}$ ,  $L_{50}$  and SR with standard errors, variances, CVs and 90% confidence intervals from SELECT models fit to large and small camera video data collected during 2003-2006 on Georges Bank and in the Mid-Atlantic.

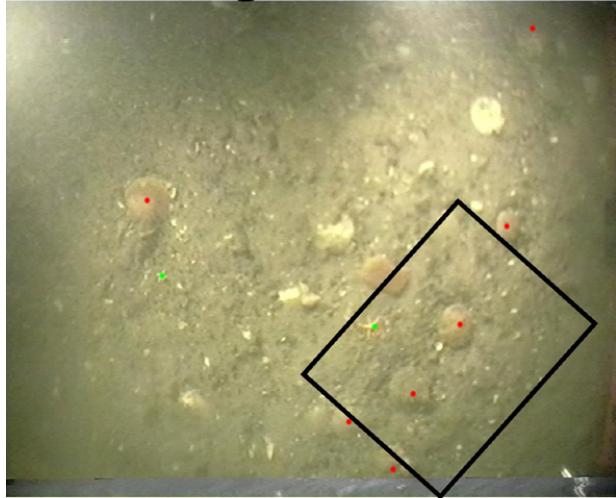
*n=4 for experiment from 2003- 2006*

	<b>Split (%)</b>	<b>L95(mm)</b>	<b>L90(mm)</b>	<b>L50(mm)</b>	<b>SR(mm)</b>	<b>a</b>	<b>b</b>
<b>Average</b>	84.15	79.43	71.41	47.71	23.44	-4.84	0.10
<b>Var</b>	1.87E-05	2.867	2.867	2.867	11.207	0.457	0.000
<b>SE</b>	0.004	1.693	1.693	1.693	3.348	0.676	0.017
<b>CV</b>	5.14E-05	0.021	0.024	0.035	0.143	-0.140	0.163
<b>CI90</b>	0.008	3.319	3.319	3.319	6.561	1.325	0.033
<b>Upper</b>	84.16	82.75	74.73	51.03	30.01	-3.52	0.14
<b>Lower</b>	84.14	76.11	68.09	44.39	16.88	-6.17	0.07



Appendix B7 Figure 1. SMAST video stations during 2003-2006. Stations where scallops were detected by both cameras in at least two quadrats were used to estimate selectivity curves and are highlighted in red.

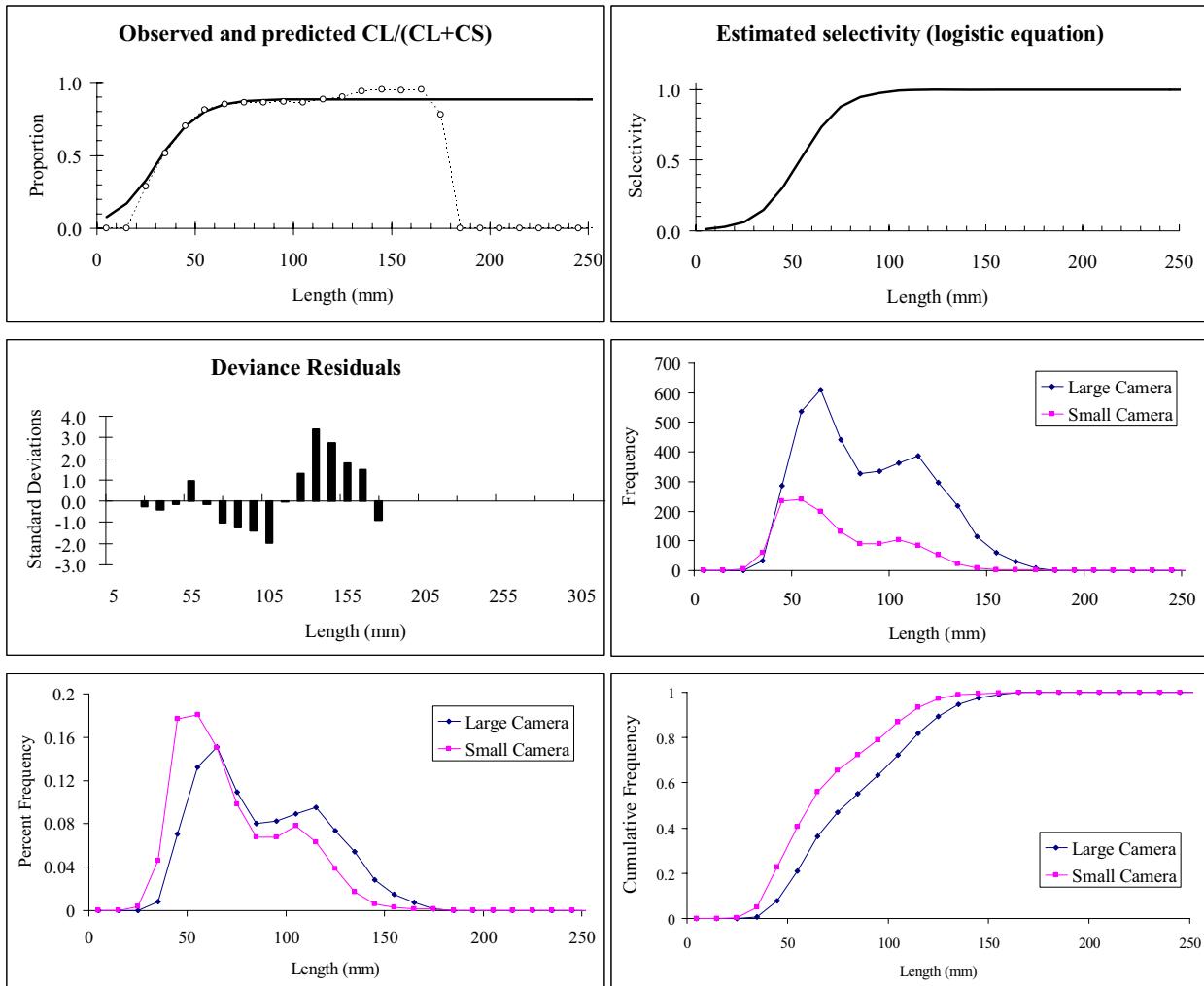
**Large Camera**



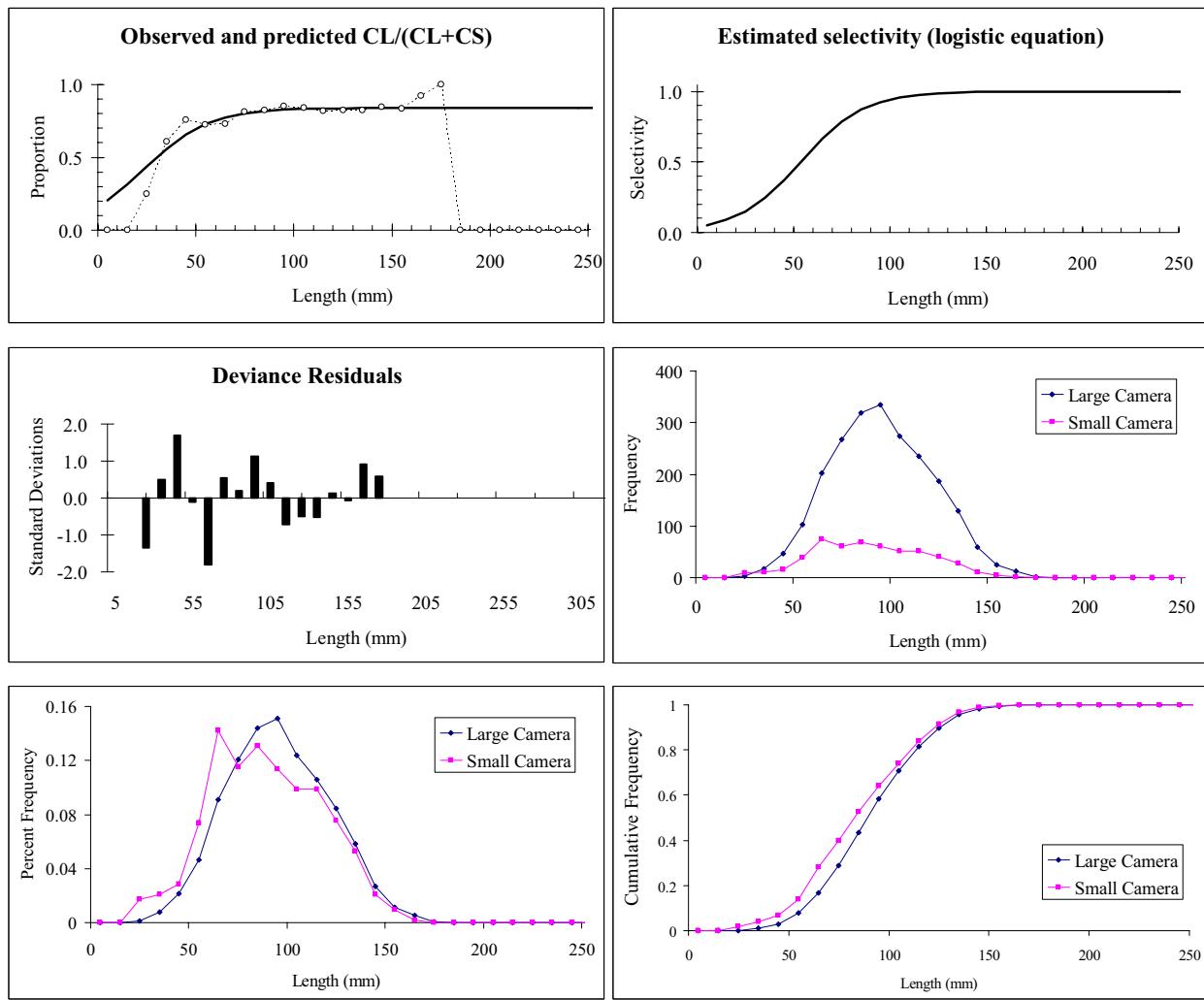
**Small Camera**



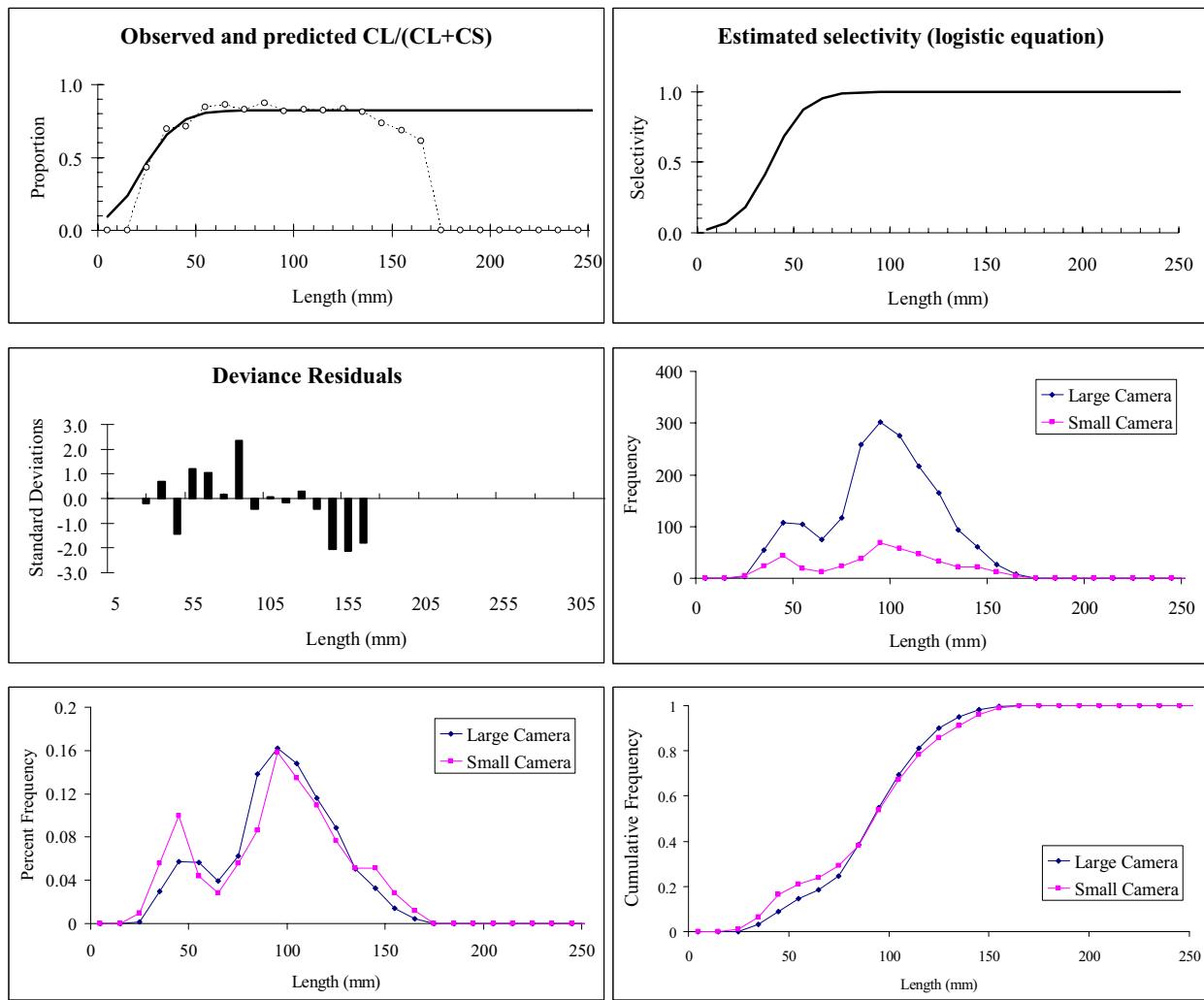
Appendix B7 Figure 2. *Left:* Large camera image with small camera inset. *Right:* Small camera inset enlarged



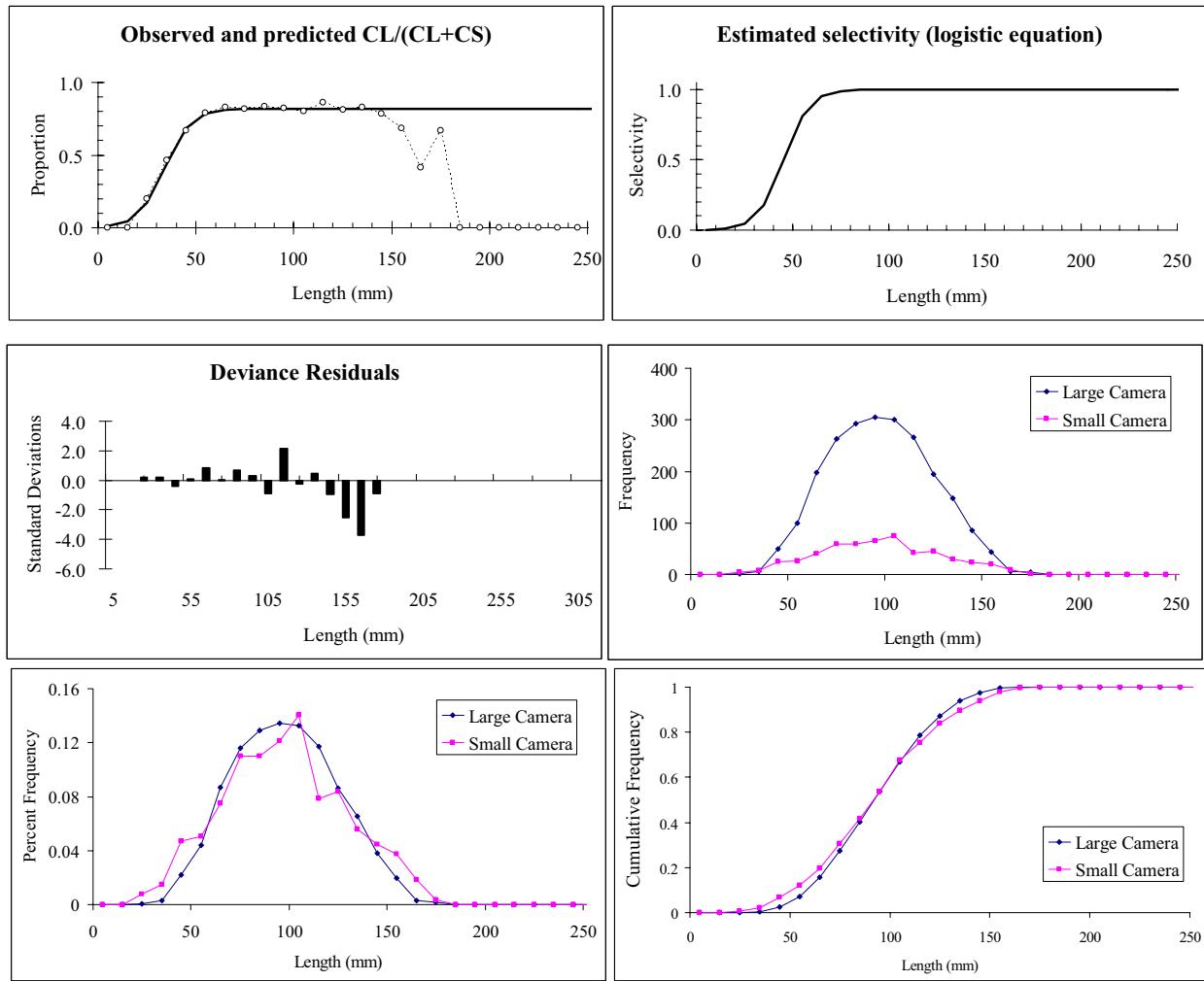
Appendix B7 Figure 3. Observed and predicted shell height measurements, Millar SELECT estimated selectivity logistic curve, deviance residuals for SELECT model, original shell height composition data (frequencies, percent, and cumulative frequencies) for video survey data from the Mid-Atlantic Bight and Georges Bank during 2003.



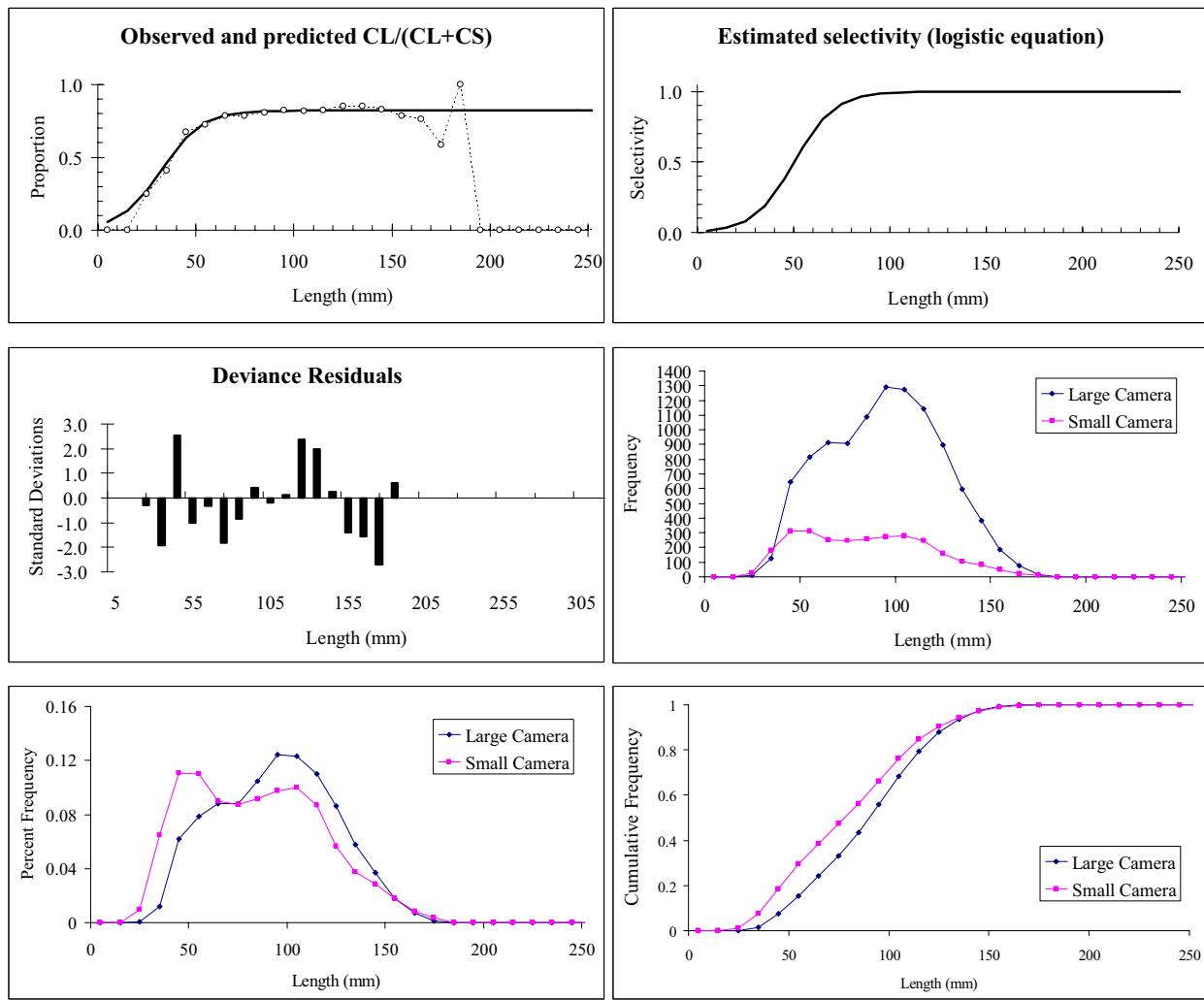
Appendix B7 Figure 4. Observed and predicted shell height measurements, Millar SELECT estimated selectivity logistic curve, deviance residuals for SELECT model, original shell height composition data (frequencies, percent, and cumulative frequencies) for video survey data from the Mid-Atlantic Bight and Georges Bank during 2004.



Appendix B7 Figure 5. Observed and predicted shell height measurements, Millar SELECT estimated selectivity logistic curve, deviance residuals for SELECT model, original shell height composition data (frequencies, percent, and cumulative frequencies) for video survey data from the Mid-Atlantic Bight and Georges Bank during 2005.



Appendix B7 Figure 6. Observed and predicted shell height measurements, Millar SELECT estimated selectivity logistic curve, deviance residuals for SELECT model, original shell height composition data (frequencies, percent, and cumulative frequencies) for video survey data from the Mid-Atlantic Bight and Georges Bank during 2006.



Appendix B7 Figure 7. Observed and predicted shell height measurements, Millar SELECT estimated selectivity logistic curve, deviance residuals for SELECT model, original shell height composition data (frequencies, percent, and cumulative frequencies) for video survey data from the Mid-Atlantic Bight and Georges Bank during 2003-2006 (combined).

## **APPENDIX B8: NEFSC survey dredge selectivity and efficiency estimates for sea scallops on Georges Bank and in the Mid-Atlantic Bight during 2003-2006, based on SMAST video survey data<sup>7</sup>**

Selectivity curves and sampling efficiency were estimated for the NEFSC sea scallop dredge survey by using a statistical model to compare length composition data from the dredge survey to length composition data from the large camera and small camera SMAST video surveys. In comparisons, the video data were assumed to sample a range of size groups with full efficiency and selectivity. Selectivity curves for the NEFSC survey dredge based on SMAST video small camera survey data indicate that the survey dredge has constant selectivity for sea scallops 40+ mm SH (Figure 1). Curves based on SMAST large camera survey data show the same general pattern but are not as useful for characterizing dredge selectivity for sea scallops less than 70+ mm SH (Figure 2).

Overall, survey dredge efficiency averaged 0.38 (CV 10%). Averaging estimates from large and small camera comparisons, survey dredge efficiency was 0.40 (CV 7%) for the Mid-Atlantic Bight and 0.37 (CV 18%) for Georges Bank. Based on small camera comparisons for scallops 45+ mm SH, survey dredge efficiency averaged 0.43 (CV 9%) in Mid-Atlantic Bight and 0.38 (CV 32%) on Georges Bank during 2003-2006 (Table 1). Based on large camera comparisons for scallops 70+ mm SH, dredge survey efficiency averaged 0.36 (CV 11%) in the Mid-Atlantic Bight and 0.36 (CV 18%) on Georges Bank during 2003-2006 (Table 2). The CV calculated using the standard deviation of all eight dredge efficiency estimates was 19%.

Assumptions about measurement errors in length data from the video survey did not appreciably affect results.

### **Introduction and Methods**

In this analysis, NEFSC scallop dredge survey selectivity curves and efficiency were estimated using SMAST video survey data for Georges Bank and the Mid-Atlantic Bight during 2003-2006. Efficiency estimates for the NEFSC survey dredge from this analysis should be more accurate than previous estimates based on SMAST video data (NEFSC 2004) because they are based on a wider range of sea scallop shell height data, data from additional surveys, and refined assumptions about survey dredge selectivity. Efficiency estimates in NEFSC (2004) were for subregions while estimates from this analysis are for Georges Bank and the Mid-Atlantic Bight as a whole.

The assumed survey dredge selectivity curve used in previous sea scallops assessments (NEFSC 2004) indicates survey dredge survey selectivity is highest between 40 and 50 mm SH, declines rapidly and is relatively constant after 60 mm SH (Figure 3). One hypothesis used to explain this selectivity pattern is that the small mesh liner in the survey dredge generates a pressure wave in front of the dredge that differentially reduces catches of large scallops. Results from this analysis suggest that the liner probably affects catches over a wider range of shell heights to the same extent. The selectivity curve used in previous assessments was estimated by

<sup>7</sup> Larry D. Jacobson (Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA 02543), Catherine O'Keefe, Michael C. Marino III (School for Marine Science and Technology, University of Massachusetts Dartmouth, 706 South Rodney French Boulevard, New Bedford, MA 02744-1221), and Antonie Chute (Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA, 02543)

comparing catch at shell height data from the current survey dredge, which has a small mesh liner, to catch at length data from a similar unlined dredge (Serchuk and Smolowitz 1980).<sup>8</sup> Based on these selectivity assumptions, efficiency estimates for the NEFSC survey dredge in the last assessment (NEFSC 2004) were for sea scallops 90+ mm SH.

Data used in the analysis were for NEFSC shellfish strata sampled randomly by the dredge survey and sampled completely by the video survey (Figure 4).<sup>9</sup> Only a few dredge surveys tows were available for some strata in most years because the dredge survey has a stratified random design with sampling roughly proportional to stratum area in most cases. The video survey uses a fixed survey design with a relatively large number of stations across the entire area of each stratum.

The dredge and video surveys do not constitute paired tow experiments, which would be ideal for estimating selectivity and efficiency. Therefore, the underlying population length composition sampled in the dredge and video surveys is the same only in expectation across a large area and large number of samples. Histograms of numbers per tow in the dredge survey and numbers counted per tow in each video image indicate skewed and highly variable distributions for catch in both surveys (Figures 5-10).

Video survey data are available from both “large” and “small” cameras, which are both used at each station. Marino et al.’s (2007; see Appendix B6) results indicate that the survey dredge has ≥90% selectivity for sea scallops 70+ mm SH. The large camera samples a larger number of scallops and is therefore better for estimating densities of medium to large scallops. The effective sampling area for the small camera ( $0.788 \text{ m}^2$ ) is a portion of the effective area ( $3.235 \text{ m}^2$ ) for large camera. However, small camera resolution and probability of detection are higher for small scallops.

To scale video data for analysis, densities at size were calculated

$$\eta_L = n_L \frac{N}{n} \frac{1}{4AK} 100$$

where  $N$  is the total number counted (but not necessarily measured),  $n$  is the total number measured,  $n_L$  is the number measured for length group  $L$ , and  $K$  is the number of video stations. Data were collected from 4 images per station and the effective area of the video camera is  $A$  ( $A=3.235 \text{ m}^2$  for the large camera and  $0.788 \text{ m}^2$  for the small camera, including adjustments for the scallops seen on the edge of the sampling area). Densities as numbers per  $\text{m}^2$  were scaled for analysis to numbers per  $100 \text{ m}^2$  for convenience.  $N$  and  $n$  include all size groups.

To scale dredge survey data for analysis, densities at size were calculated

$$\delta_L = \frac{d_L}{8(0.3048)1853} 100$$

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<sup>8</sup> Parameters for the dredge selectivity curve used in the previous assessment (NEFSC 2004) are:  $a=14.3322$ ,  $b=0.266807$  and  $c=0.714879$  (see below).

<sup>9</sup> NEFSC shellfish strata used for the Georges Bank region in each year were: 46, 47, 49, 50, 51, 52, 53, 54, 55, 59, 61, 621, 631, 651, 661, 71 and 74 except that stratum 74 was not used for 2005 because it was not sampled during the 2005 dredge survey. Strata used for the Mid-Atlantic Bight region in each year were: 6, 7, 10, 11, 14, 15, 18, 19, 22, 23, 24, 26, 27, 28, 30, 31, 33 and 34.

where the survey data was  $d_L$  in units of mean numbers per standard tow, the survey dredge is 8 ft or 8(0.3048) m wide and the standard tow is 1 nm=1,853 m.

### Selectivity

Length measurements are less precise in the video survey than in the dredge survey, with standard deviations for measurement errors of about 6.1 mm (Stokesbury et al., in prep.). To make dredge and video length data as comparable as possible, selectivity curves were fit with and without adding simulated measurement errors to the dredge survey data. The idea was to generate measurement errors in the dredge survey data that were of similar magnitude to the measurement errors in the video survey. It was not possible to remove measurement errors from the video survey, although the latter approach might be seem ideal intuitively. Based on Stokesbury et al. (in prep.), simulated length measurement errors were additive and from a truncated normal distribution with a standard deviation of 6.1 mm.

Millar's (1992) SELECT model was modified and used to fit a three parameter declining logistic selectivity curve with a right hand offset. The model is:

$$s_L = \left[ 1 - \frac{1}{1 + e^{a-bL}} \right] (1 - c) + c$$

and

$$S_L = s_L / \max(s_L)$$

where  $a$ ,  $b$  and  $c$  are parameters and  $SH$  is the final estimate. Note that the curve is scaled to a maximum value of one in contrast to Millar's original approach, which did not rescale selectivity curves. Rescaling makes the curves more flexible, easier to interpret and enhances estimability.

It was difficult to calculate effective sample size for data from either survey in this analysis, particularly after the data were scaled to units of numbers per 100 m<sup>2</sup>. Uncertainty about effective sample size prevented calculation of variances for selectivity parameter estimates within the SELECT model used to fit the selectivity curves but had no effect on estimates or general results. Bootstrapping or Bayesian procedures for estimating variance are a topic for future research.

The choice of curve was based on precedent and preliminary analysis of dredge and video survey data. The selectivity curves used in this analysis for the NEFSC dredge are the same general type and shape as the curve used for the NEFSC survey dredge in recent assessments (Figure 3). The most important feature of this type of curve is that selectivity decreases towards an asymptote selectivity as sea scallop shell height increases. The general shape of the selectivity curve used in this analysis was reasonable (see below). In retrospect, it may have been possible to use a simpler, 2 parameter curve with some statistical advantages but there would be no appreciable effect on conclusions.

The primary purpose of the analysis with large camera comparisons was to determine the general shape of the dredge selectivity curve and efficiency for 70+ mm SH. Large camera comparisons may be particularly useful for estimating dredge survey efficiency because the large camera samples more scallops (over a narrow range of full selectivity) than the small camera. Small camera comparisons were used to include sea scallops < 70 mm SH, at the expense of lower numbers of samples, particularly for larger sizes.

Based on preliminary analysis and available data, size groups included in the analysis were 35-140 mm for large camera comparisons and 20-135 mm for small camera comparisons. Use of smaller or larger size groups complicated parameter estimation, possibly because the smallest and largest size groups were poorly sampled. In contrast, the lower bound for dredge survey data in the previous assessment was 40 mm SH. Forty mm is approximately the same as the spacing of mesh in the liner of the dredge (38 mm). As described in Marino et al. (2007), the large camera video survey has an increasing logistic shaped selectivity curve that reaches 90% at about 70 mm SH. For large scallops, the dredge survey selectivity is thought to be low and constant while the large camera video survey selectivity is known to be high and constant. For small scallops, selectivity is low and changing with size in the large camera survey and uncertain but thought to be relatively high and changing with size in the dredge survey. For small scallops, the ratio of catch in the dredge gear to total catch (dredge + video gear), which is used to estimate selectivity, is variable and selectivity estimates for small scallops are likely to be imprecise and biased.

### Dredge efficiency

Dredge efficiency in this analysis is the probability of capture for scallops above a certain minimum size in the path of the survey dredge. This definition differs from conventional definitions (and the definition used in the CASA model) that define efficiency in terms of capture efficiency for sizes that are fully selected by the gear. However, the definitions are basically the same if sea scallops are all above the size at which the dredge selectivity curve is flat.

When estimating selectivity curves with typical ascending logistic selection patterns surveys, the split parameter in the SELECT model can be used to estimate gear efficiency. This is not possible for sea scallops using dredge and video survey because the sizes at 100% selection may not overlap and because the flat portion of the selectivity curves occurred at minimum selectivity values.

Based on Marino et al. (2007) efficiency was calculated for scallops 70+ mm based on large camera comparisons because the selectivity curves for both gears appear to be flat by about 70 mm SH. Based on selectivity curve results shown below, efficiency was calculated for scallops 45+ mm based on small camera comparisons.

## Results

Selectivity curves were reasonably easy to fit once the poorly sampled largest and smallest sea scallop size groups were eliminated from the analysis. Large camera comparisons generally indicate that selectivity curves for the NEFSC survey dredge (Table 3) is flat for scallops 70+ mm SH (Figure 2). The curve for Mid-Atlantic Bight during 2004 from the large camera comparison was the notable exception (Figure 9). Small camera comparisons consistently indicate that survey dredge selectivity curves (Table 4) are flat or nearly flat for scallops 40+ mm SH (Figure 1).

Diagnostics indicate reasonable SELECT model fit in most cases (Figures 11-14), although runs of positive and negative residuals occurred in many cases. Assumptions about length measurement errors had minor effect on estimated selectivity curves (Figure 15).

Selectivity curve estimates appear to be robust to measurement errors in length data. The shapes of selectivity curves for small scallops based on large camera comparisons were variable

for reasons described above. In particular, the apparently steep increases in dredge selectivity below 70 mm SH based on large camera comparisons are artifacts due to possibly increasing selectivity in the dredge survey and declining selectivity in the large camera video survey. The apparently high selectivity at sizes less than 60 mm SH in the survey dredge selectivity curve used in the last assessment (Figure 3) was probably due to constant selectivity in the lined dredge and declining selectivity in the unlined dredge, which was used as the standard in comparisons (Serchuk and Smolowitz 1980).

### Dredge efficiency

Dredge efficiency estimates were relatively consistent (Tables 1-2) and similar to estimates from the last assessment (NEFSC 2004). Based on large camera comparisons, dredge survey efficiency for scallops 70+ mm SH averaged 0.36 (CV 11%) in the Mid-Atlantic Bight (Mid-Atlantic Bight) and 0.36 (CV 18%) on Georges Bank (Georges Bank) during 2003-2006. Based on small camera comparisons, survey dredge efficiency for scallops 45+ mm SH averaged 0.43 (CV 9%) in Mid-Atlantic Bight and 0.38 (CV 32%) on Georges Bank during 2003-2006. Averaging large and small camera results, survey dredge efficiency was 0.40 (CV 7%) for Mid-Atlantic Bight and 0.37 (CV 18%) for Georges Bank. Overall, survey dredge efficiency averaged 0.38 (CV 10%). The consistency in efficiency estimates from the large and small camera comparisons is additional support for the hypothesis that survey dredge efficiency is flat above 35 mm SH.

### **References**

- Marino MC, O'Keefe C, Jacobson LD. 2007. Selectivity of the SMAST camera video survey. (Appendix to this assessment)
- Millar RB. 1992. Estimating the size-selectivity of fishing gear by conditioning on the total catch. J Amer Stat Assoc. 87:962-968.
- Serchuk FM, Smolowitz RJ. 1980. Size selection of sea scallops by an offshore scallop survey dredge. ICES C.M. 1980/K:24.
- Stokesbury KDE, Jacobson LD, Allard M, Chute A, Harris BP, Jaffarian T, Marino MC II, Nogueira JI, Rago P. In prep. Quantification, effects and stock assessment modeling approaches for dealing with measurement error in body size data using Atlantic sea scallops as an example.

APPENDIX B8 Table 1. Efficiency estimates for sea scallop 70+ mm SH in the NEFSC survey dredge based on SMAST video survey (large camera) data.

Region	2003	2004	2005	2006	Average	CV
Mid-Atlantic Bight	0.308	0.353	0.402	0.374	0.359	0.110
Georges Bank	0.304	0.445	0.369	0.314	0.358	0.181

APPENDIX B8 Table 2. Efficiency estimates for sea scallop 45+ mm SH in the NEFSC survey dredge based on SMAST video survey (small camera) data.

Region	2003	2004	2005	2006	Average	CV
Mid-Atlantic Bight	0.467	0.424	0.456	0.382	0.432	0.088
Georges Bank	0.295	0.554	0.350	0.314	0.378	0.316

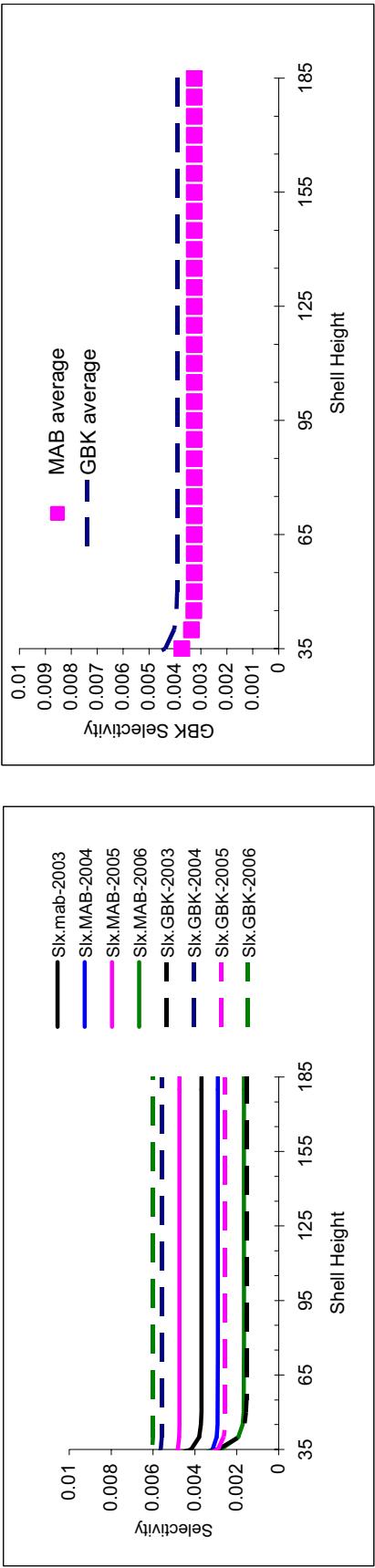
APPENDIX B8 Table 3. Selectivity curve parameter estimates for sea scallop 70+ mm SH in the NEFSC survey dredge based on SMAST video (large camera) comparisons (assuming length measurement errors with standard deviation = 6.1 mm). Estimates assuming no length measurement errors were similar.

Parameter	2003	2004	2005	2006
<b>Mid-Atlantic Bight</b>				
<i>a</i>	0.00006	0.00005	0.00006	0.00006
<i>b</i>	0.22548	0.03905	0.00010	0.07868
<i>c</i>	0.00010	0.00676	1.02865	0.01839
Split parameter <i>p</i>	0.99625	0.81521	0.30149	0.86735
Log likelihood	-43.5	-25.2	-23.1	-21.0
<b>Georges Bank</b>				
<i>a</i>	0.00006	0.00006	0.00006	0.00006
<i>b</i>	0.34678	0.88794	0.99988	0.76524
<i>c</i>	0.11557	0.78192	0.99988	0.57430
Split parameter <i>p</i>	0.03842	0.68330	0.99989	0.42654
Log likelihood	-11.9	-14.0	-11.0	-7.7

APPENDIX B8 Table 4. Selectivity curve parameter estimates for sea scallop 35+ mm SH in the NEFSC survey dredge based on SMAST video (small camera) comparisons (assuming length measurement errors with standard deviation = 6.1 mm). Estimates assuming no length measurement errors were similar.

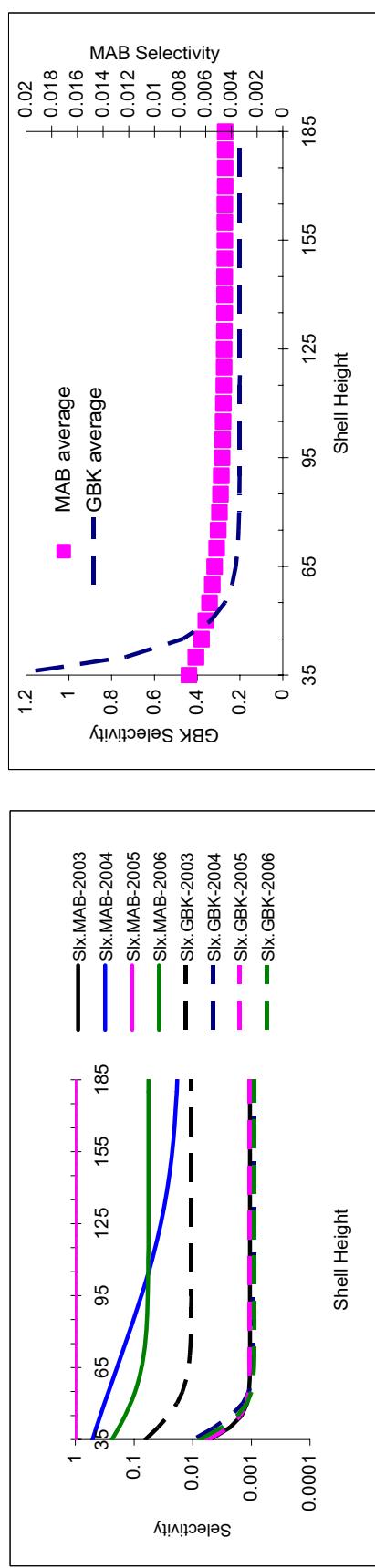
Parameter	2003	2004	2005	2006
<b>Mid-Atlantic Bight</b>				
<i>a</i>	0.00006	0.00006	0.00006	0.00006
<i>b</i>	0.30574	0.33378	0.38423	0.27451
<i>c</i>	0.00017	0.00010	0.00010	0.00010
Split parameter <i>p</i>	0.98729	0.99423	0.98980	0.99622
Log likelihood	-55.5	-26.9	-23.0	-20.8
<b>Georges Bank</b>				
<i>a</i>	0.00006	0.00006	0.00006	0.00006
<i>b</i>	0.22758	0.19620	0.15315	0.26664
<i>c</i>	0.05262	0.03953	0.02653	0.06963
Split parameter <i>p</i>	0.01431	0.00982	0.00793	0.01894
Log likelihood	-12.7	-13.3	-10.1	-7.0

## Dredge survey selx based on small camera survey assuming 7% CV for length measurement errors

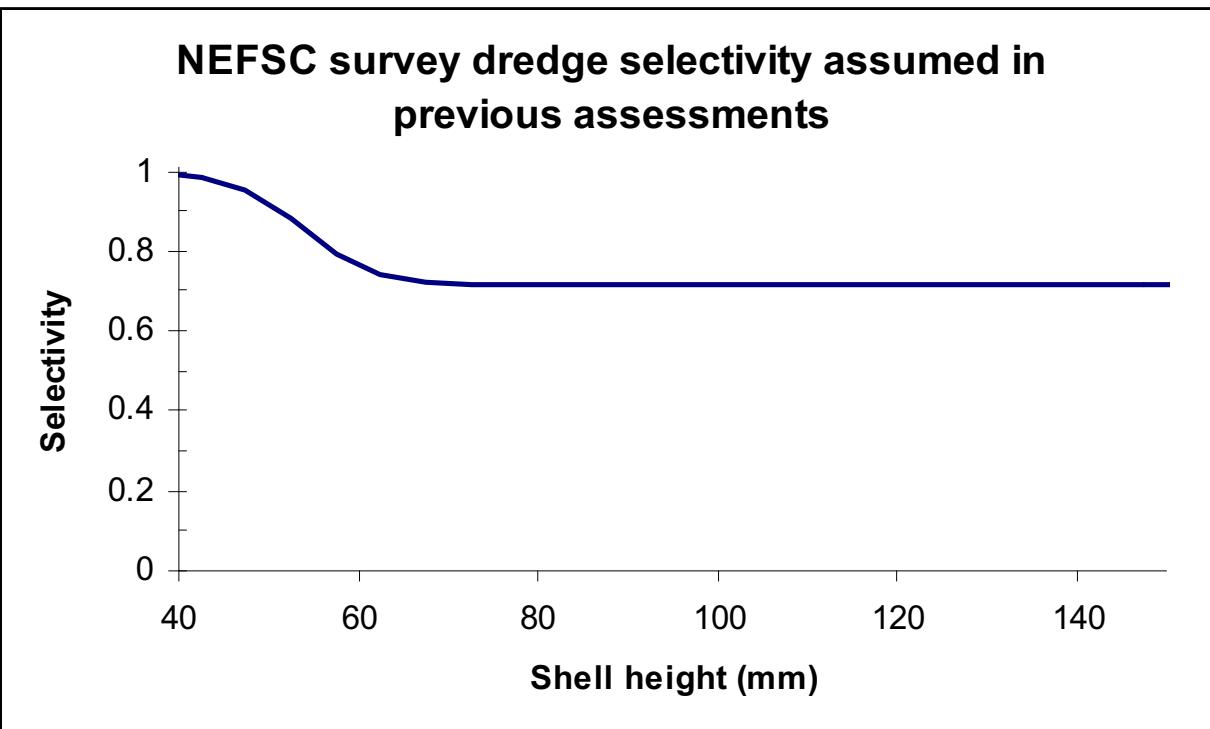


APPENDIX B8 Figure 1. Estimated selectivity curves based on small camera comparisons.

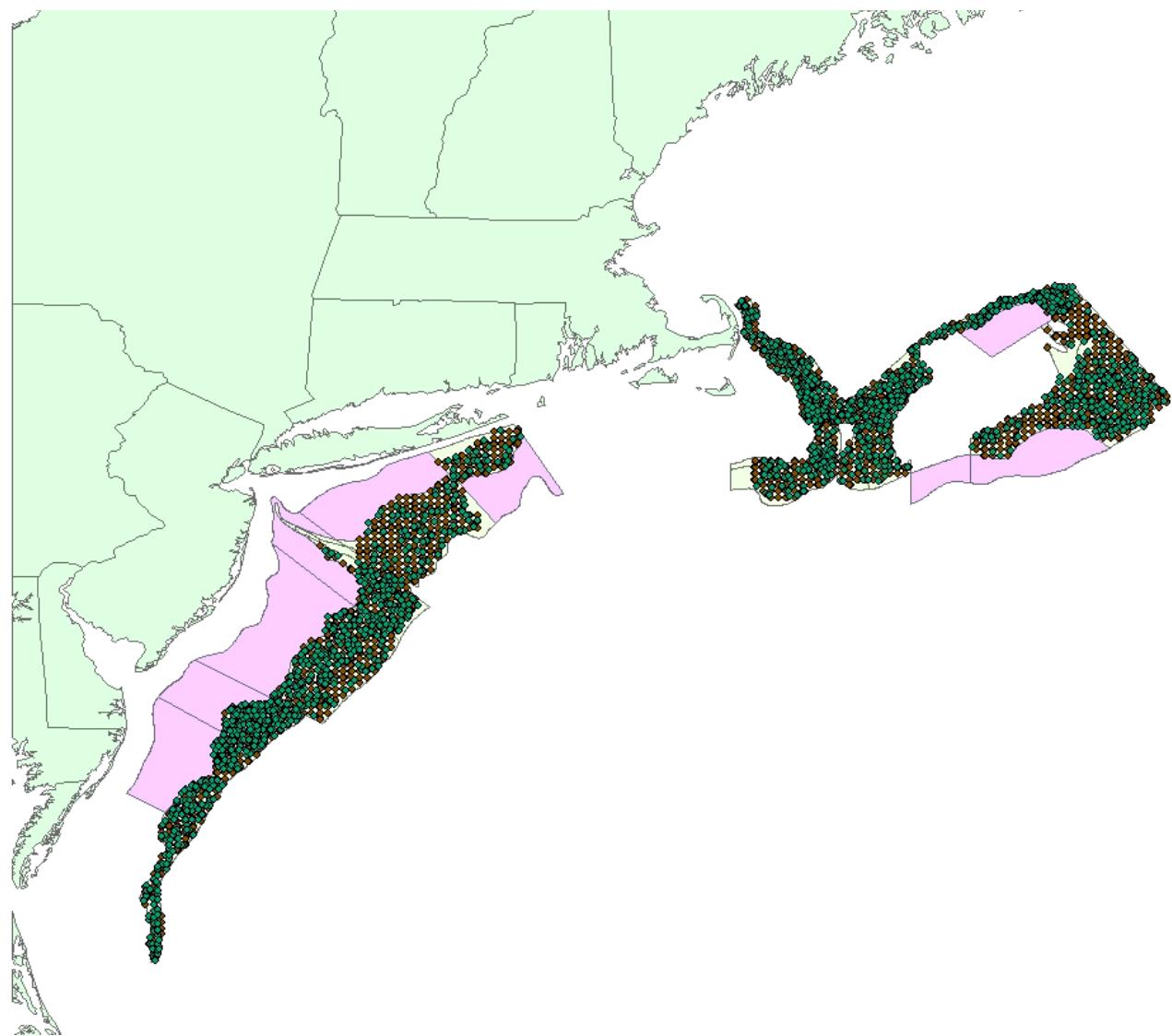
## Dredge survey selx based on large camera survey assuming 7% CV for length measurement errors



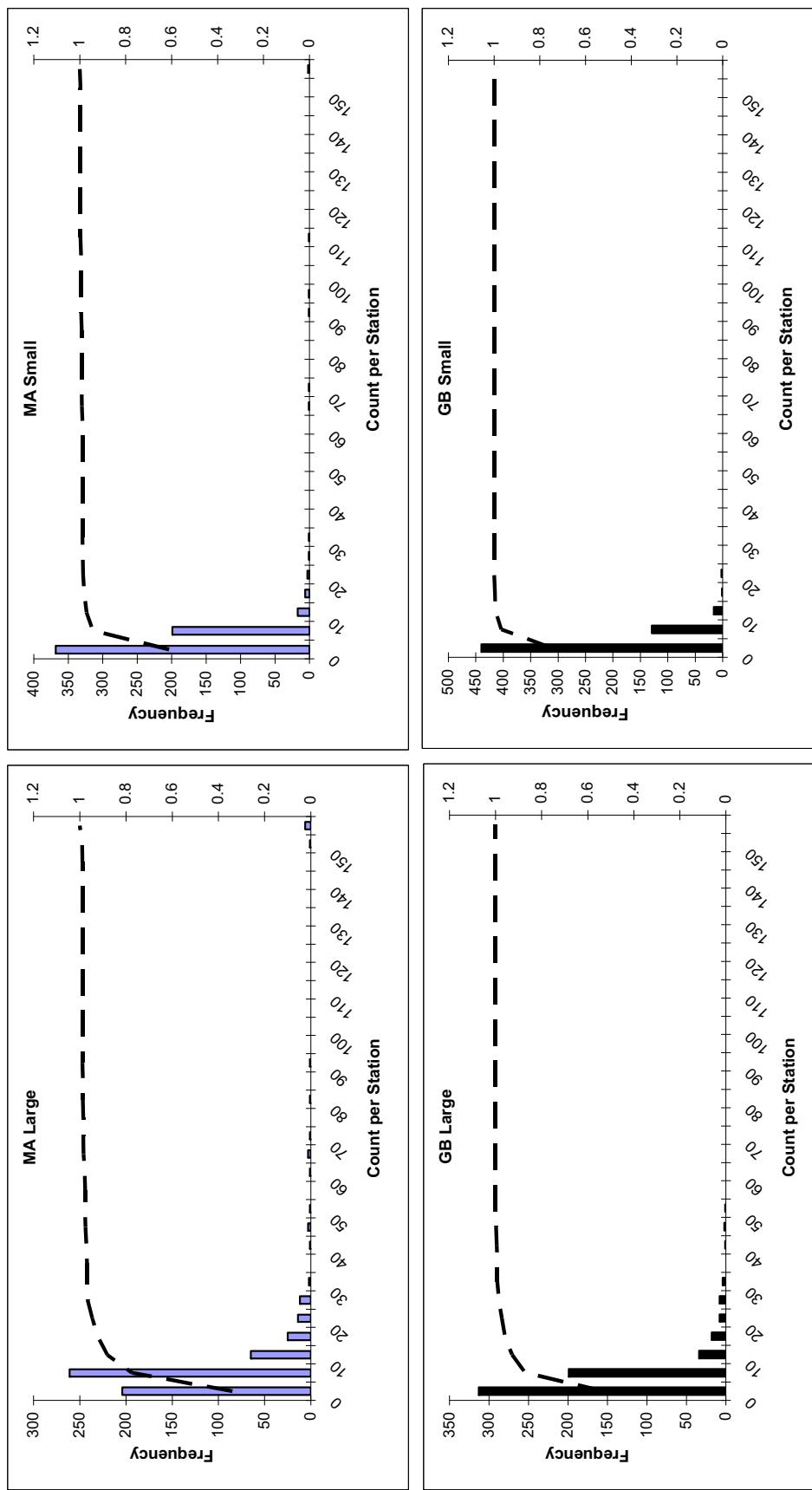
APPENDIX B8 Figure 2. Estimated selectivity curves based on large camera comparisons.



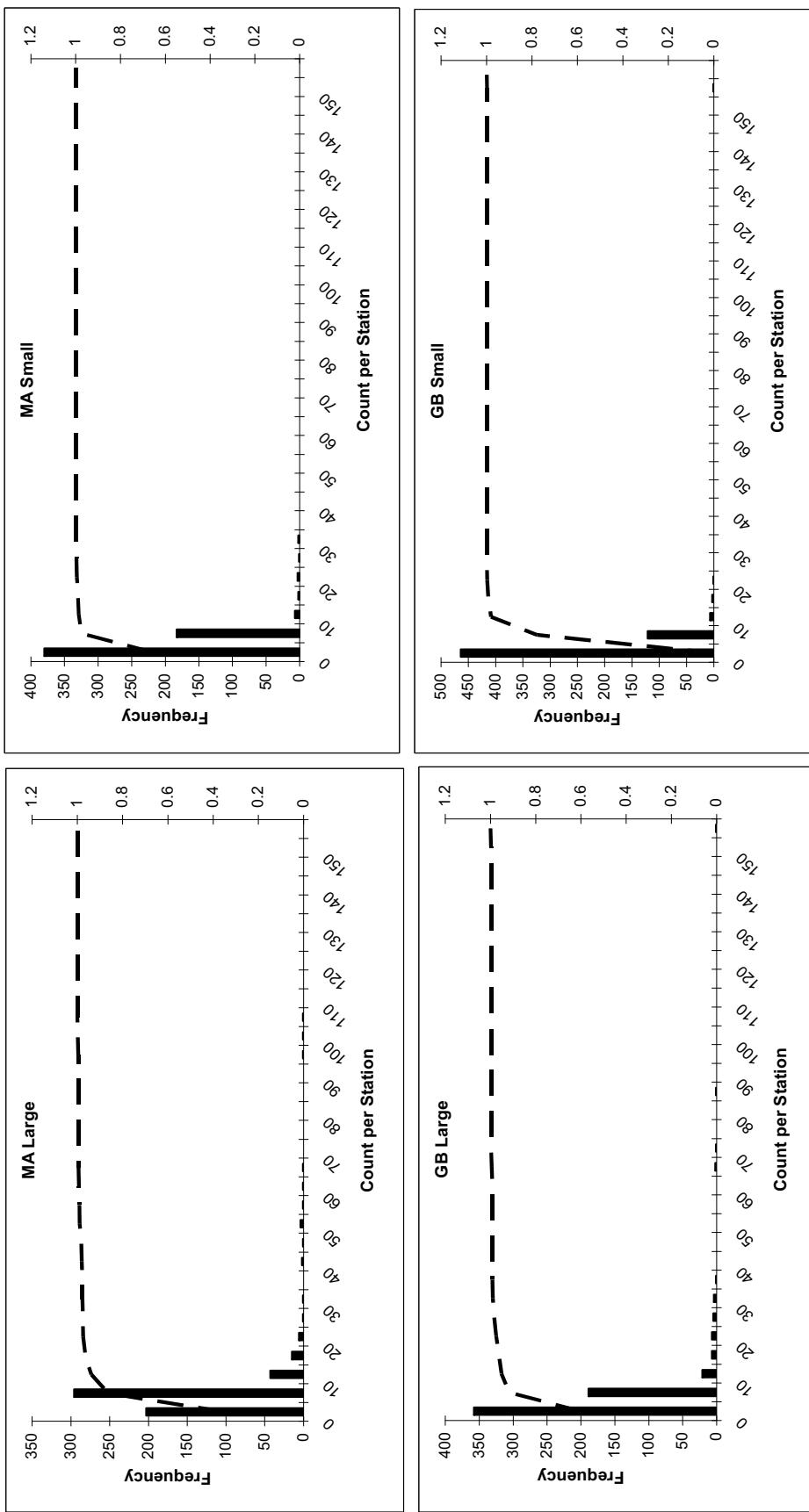
APPENDIX B8 Figure 3. Survey dredge selectivity curve for sea scallops assumed in previous assessments.



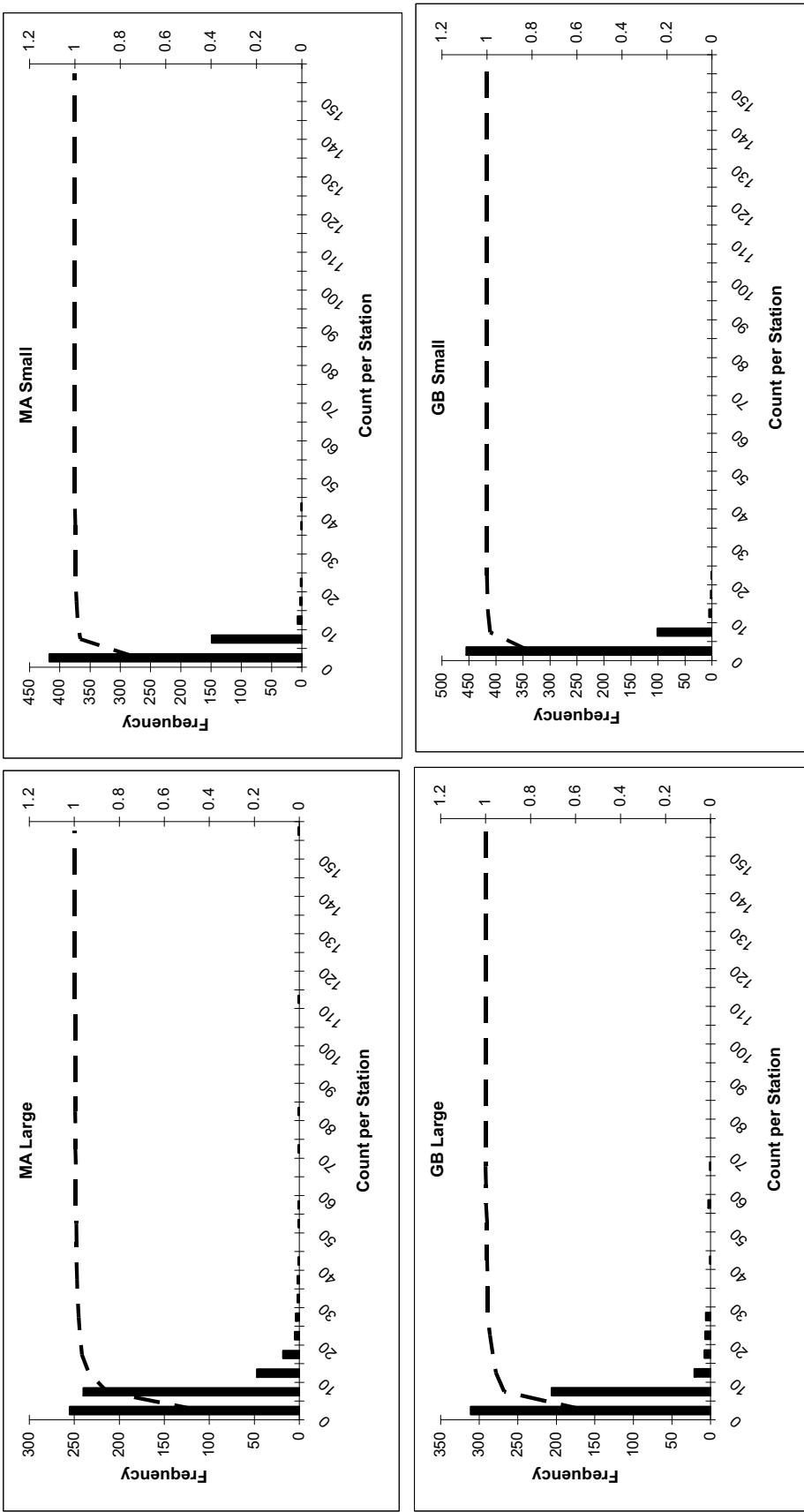
APPENDIX B8 Figure 4. Location of NEFSC shellfish strata and video stations for data used to estimate dredge survey selectivity and efficiency.



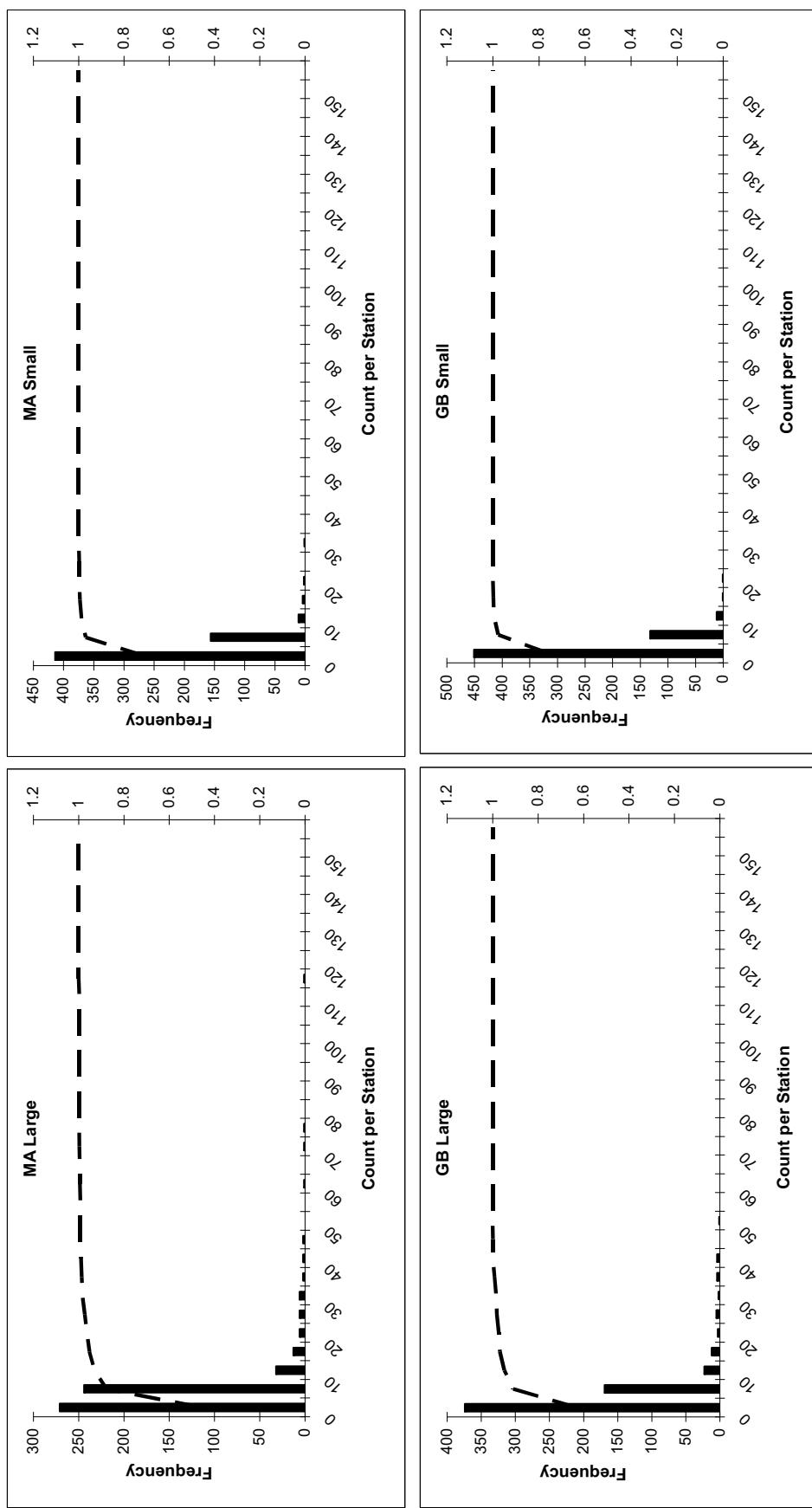
APPENDIX B8 Figure 5. Frequency distributions (bars) and cumulative distributions (broken line) for sea scallops counted in video images for video stations during 2003 used in this analysis.



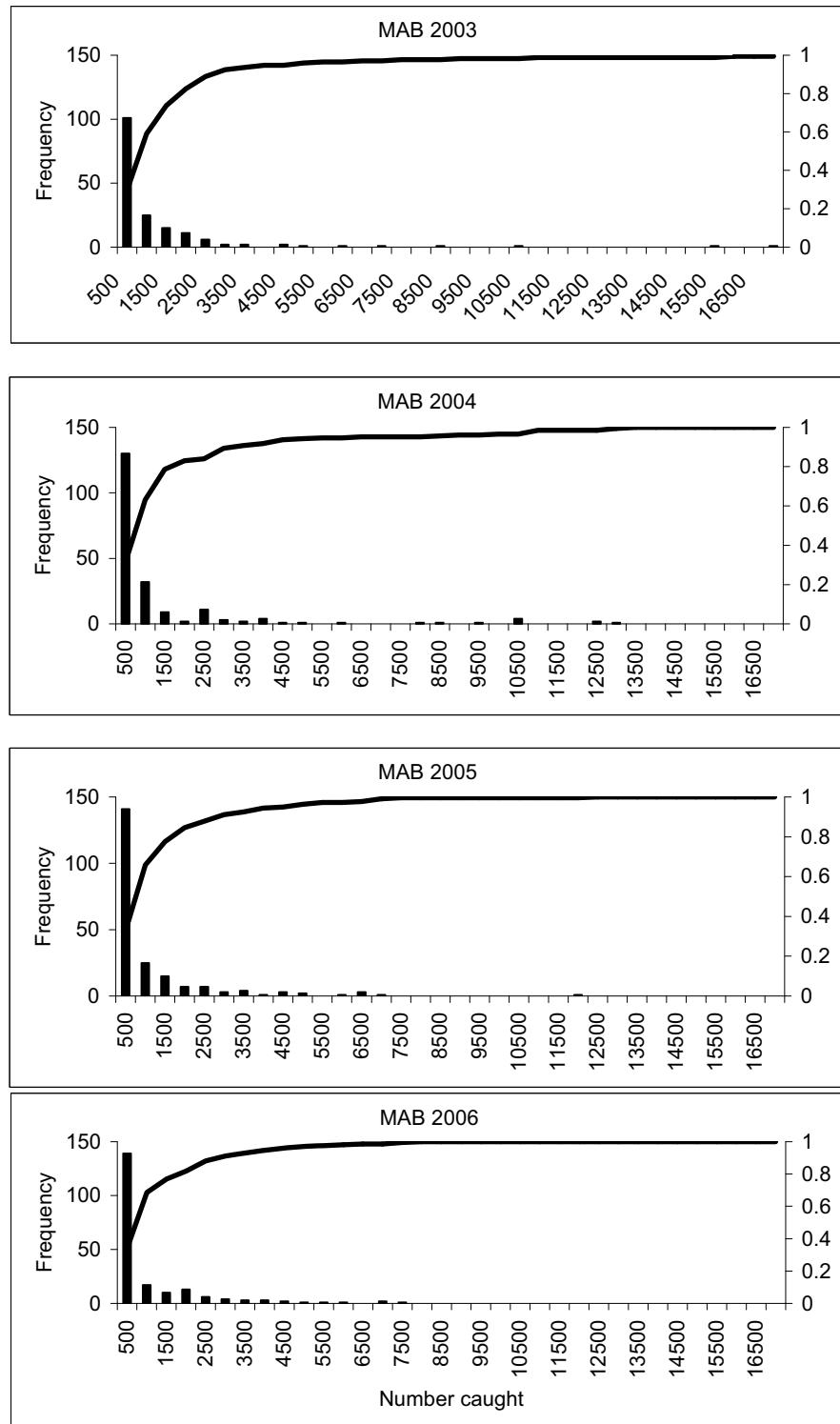
APPENDIX B8 Figure 6. Frequency distributions (bars) and cumulative distributions (broken line) for sea scallops counted in video images for video stations during 2004 used in this analysis.



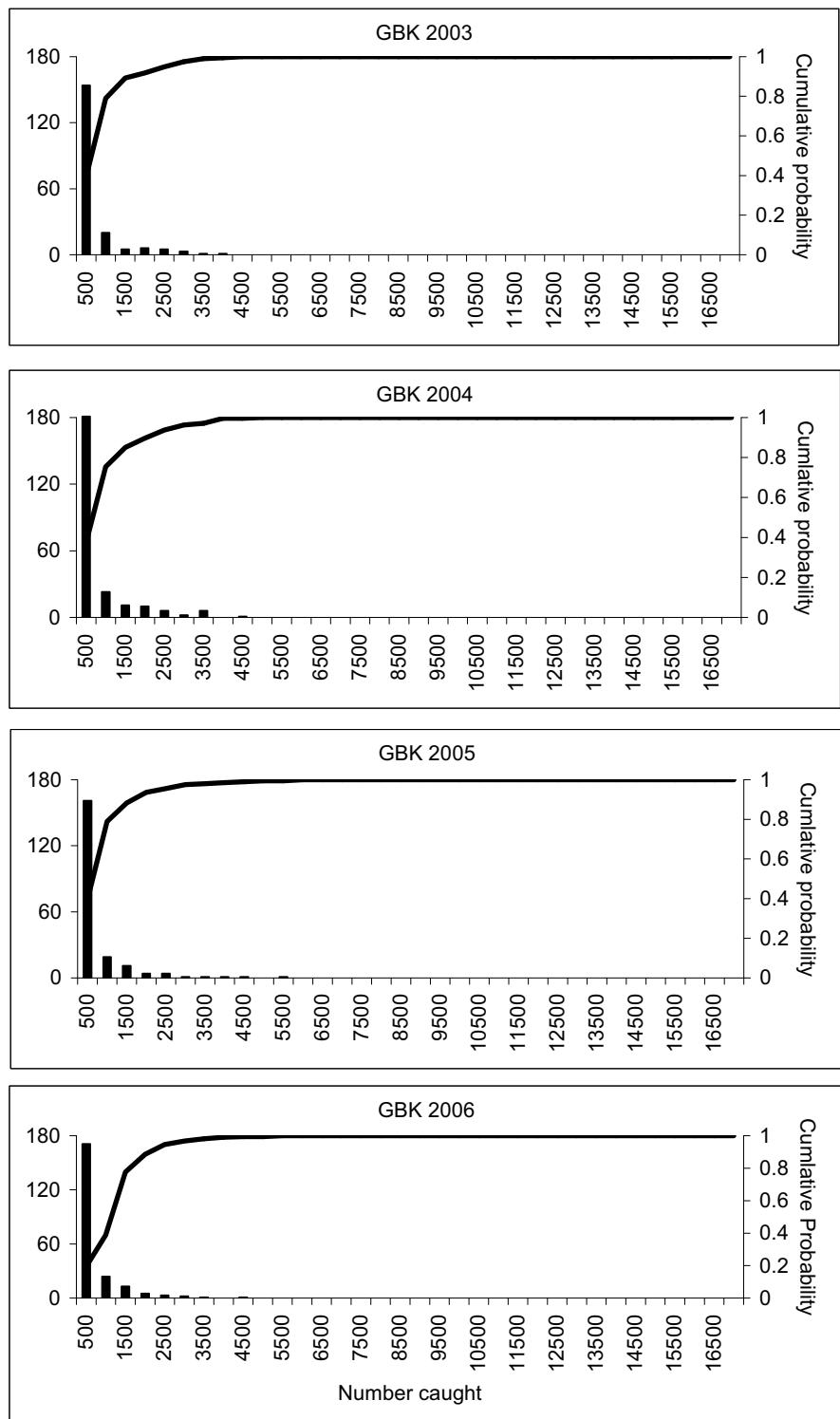
APPENDIX B8 Figure 7. Frequency distributions (bars) and cumulative distributions (broken line) for sea scallops counted in video images for video stations during 2005 used in this analysis.



APPENDIX B8 Figure 8. Frequency distributions (bars) and cumulative distributions (broken line) for sea scallops counted in video images for video stations during 2006 used in this analysis.

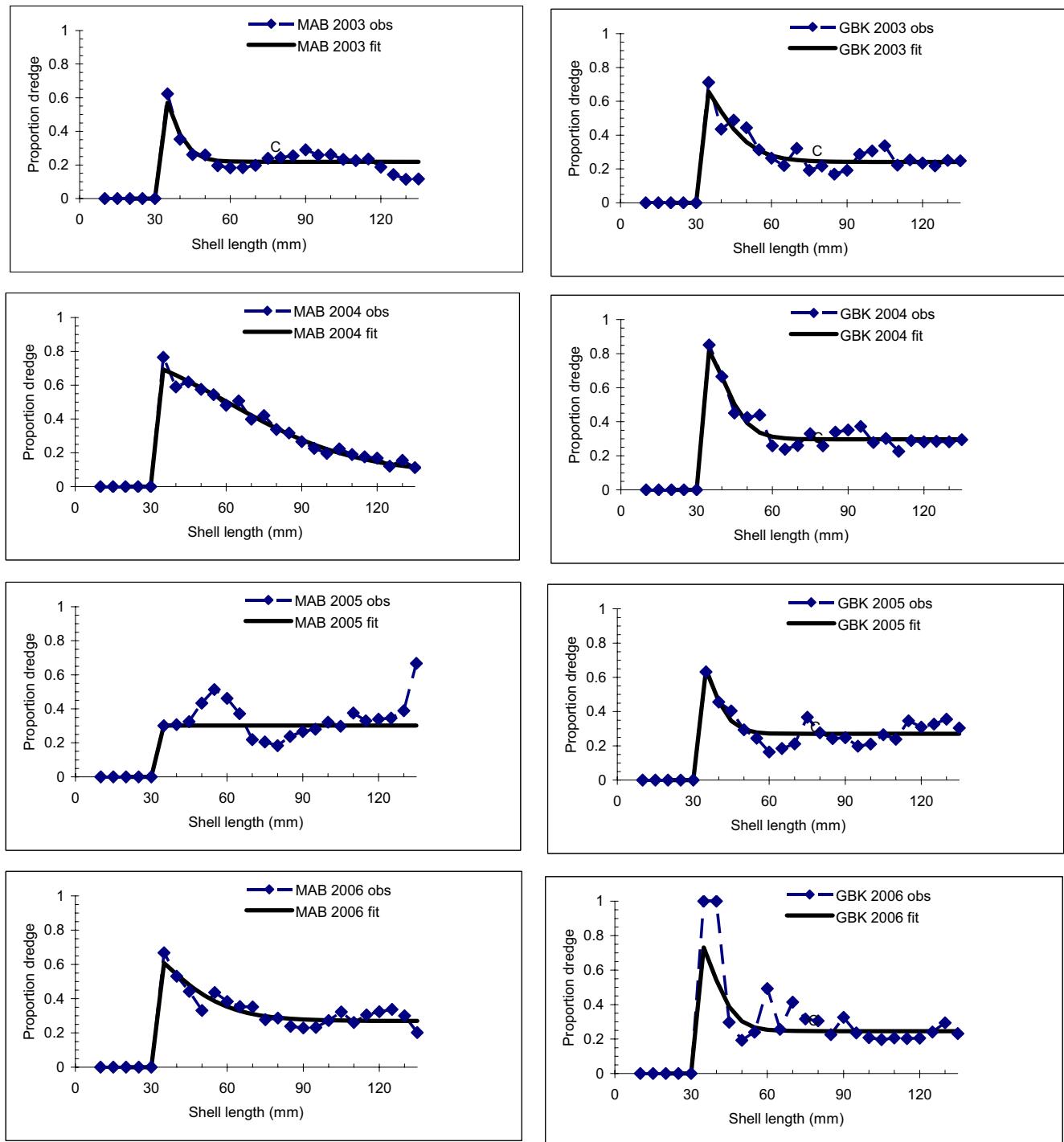


APPENDIX B8 Figure 9. Frequency distributions (bars) and cumulative distributions (solid lines) for sea scallops numbers per tow in dredge survey catches in the Mid-Atlantic Bight during 2003-2006.



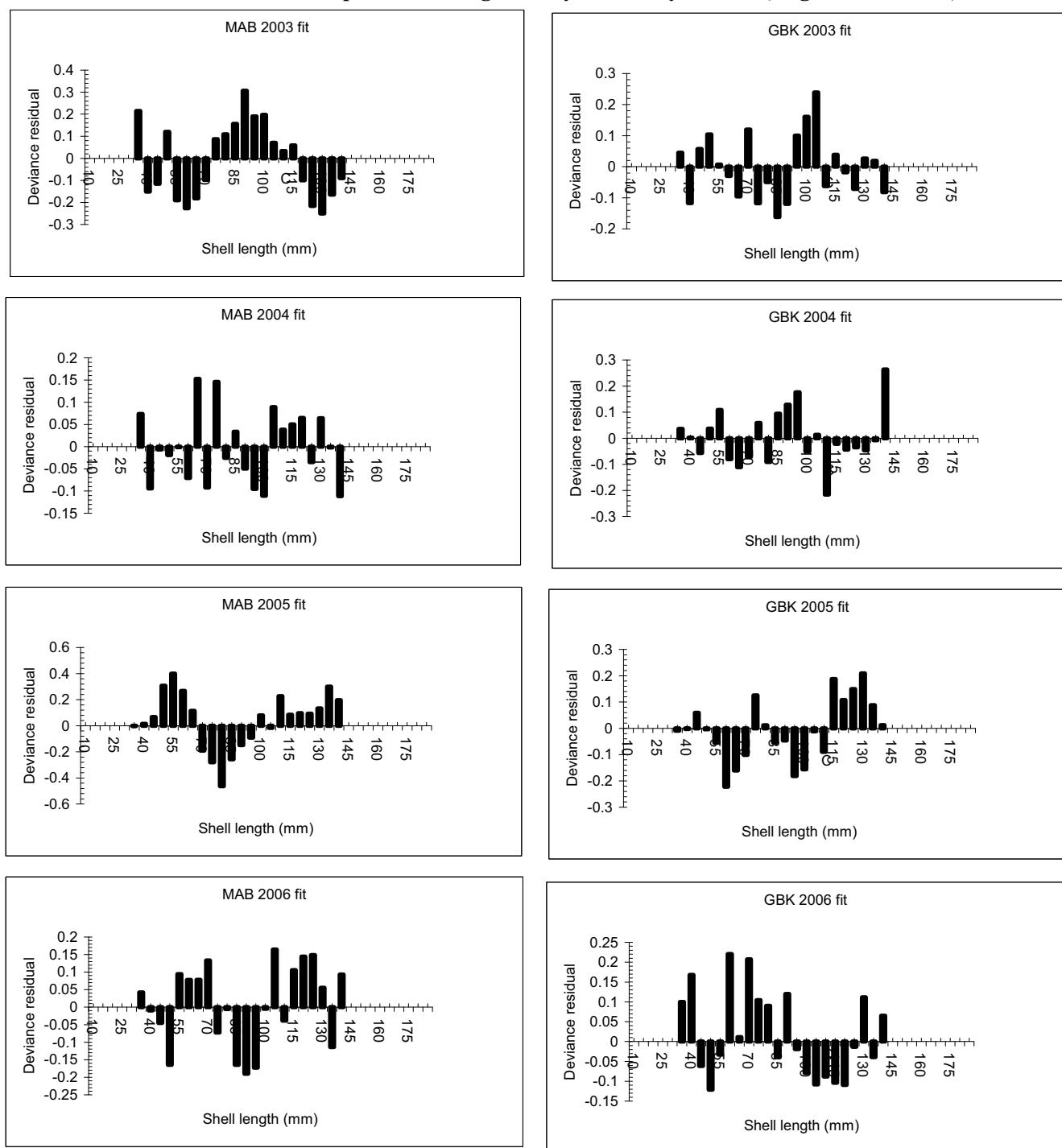
APPENDIX B8 Figure 10. Frequency distributions (bars) and cumulative distributions (solid lines) for sea scallops numbers per tow in dredge survey catches on Georges Bank during 2003-2006.

### Goodness of fit plots for dredge survey selectivity models (large camera data)



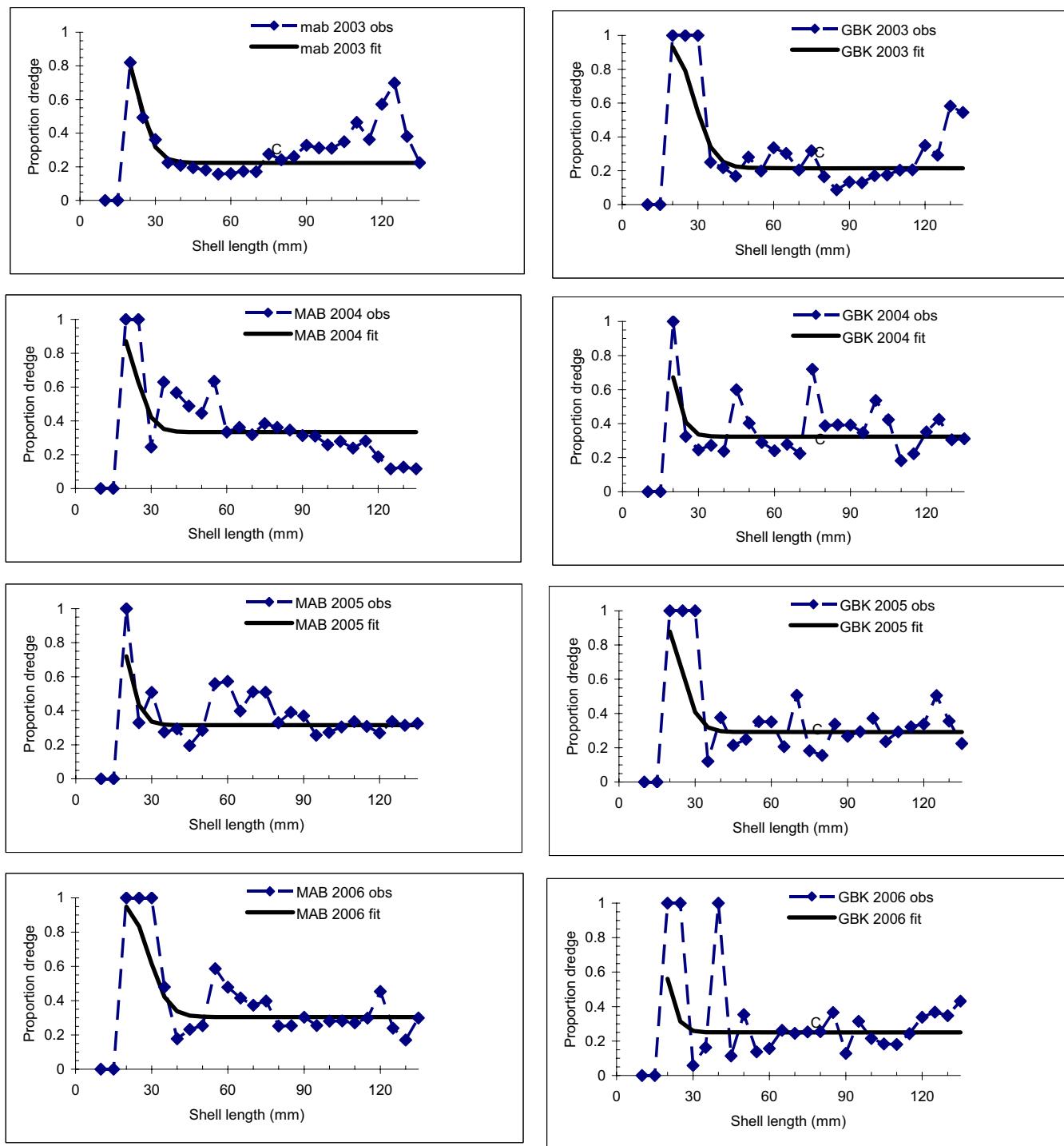
APPENDIX B8 Figure 11. Observed and predicted plots for selectivity estimates from large camera comparisons.

### Deviance residual plots for dredge survey selectivity models (large camera data)



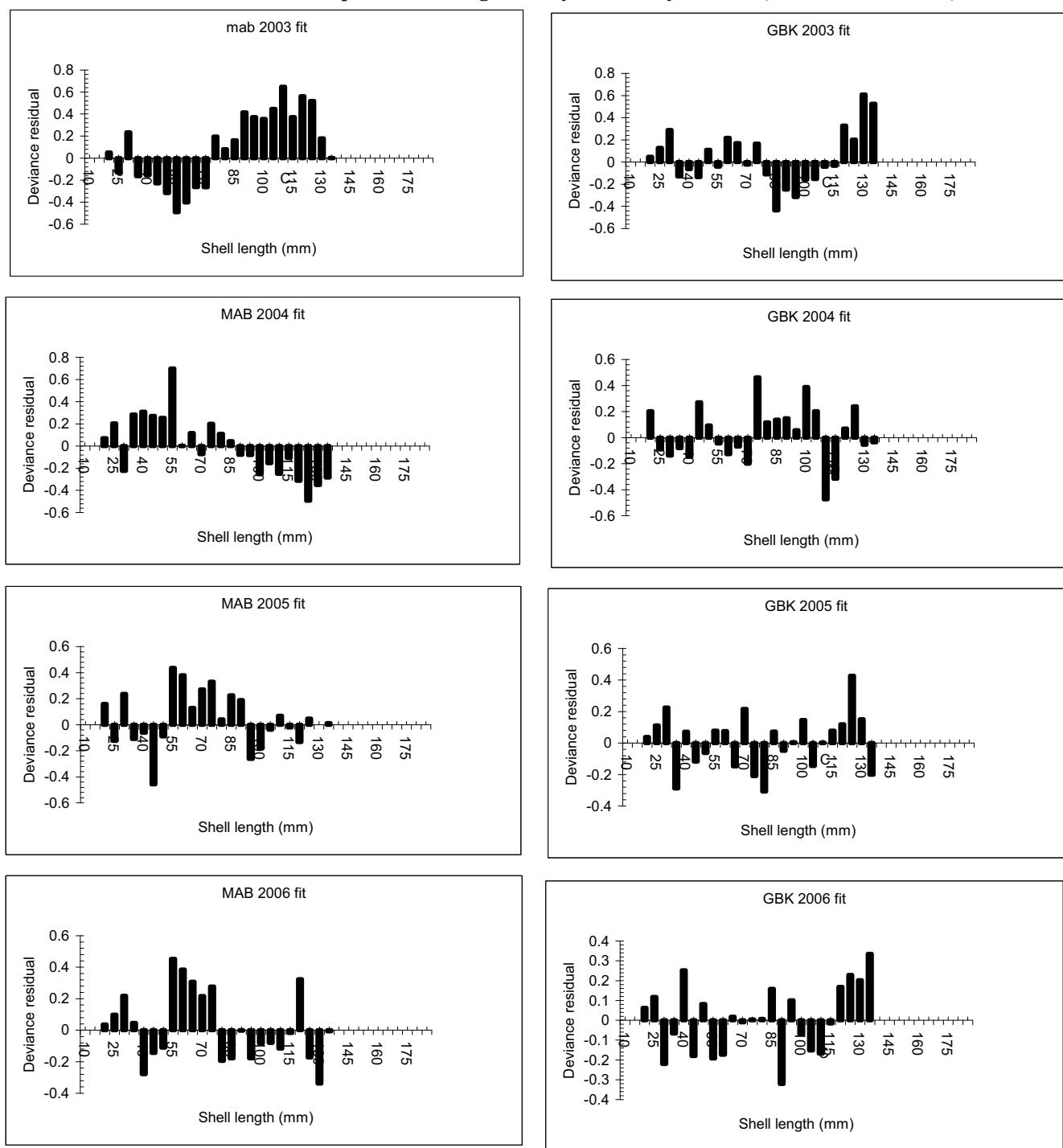
APPENDIX B8 Figure 12. Deviance residuals for selectivity estimates from large camera comparisons.

### Goodness of fit plots for dredge survey selectivity models (small camera data)



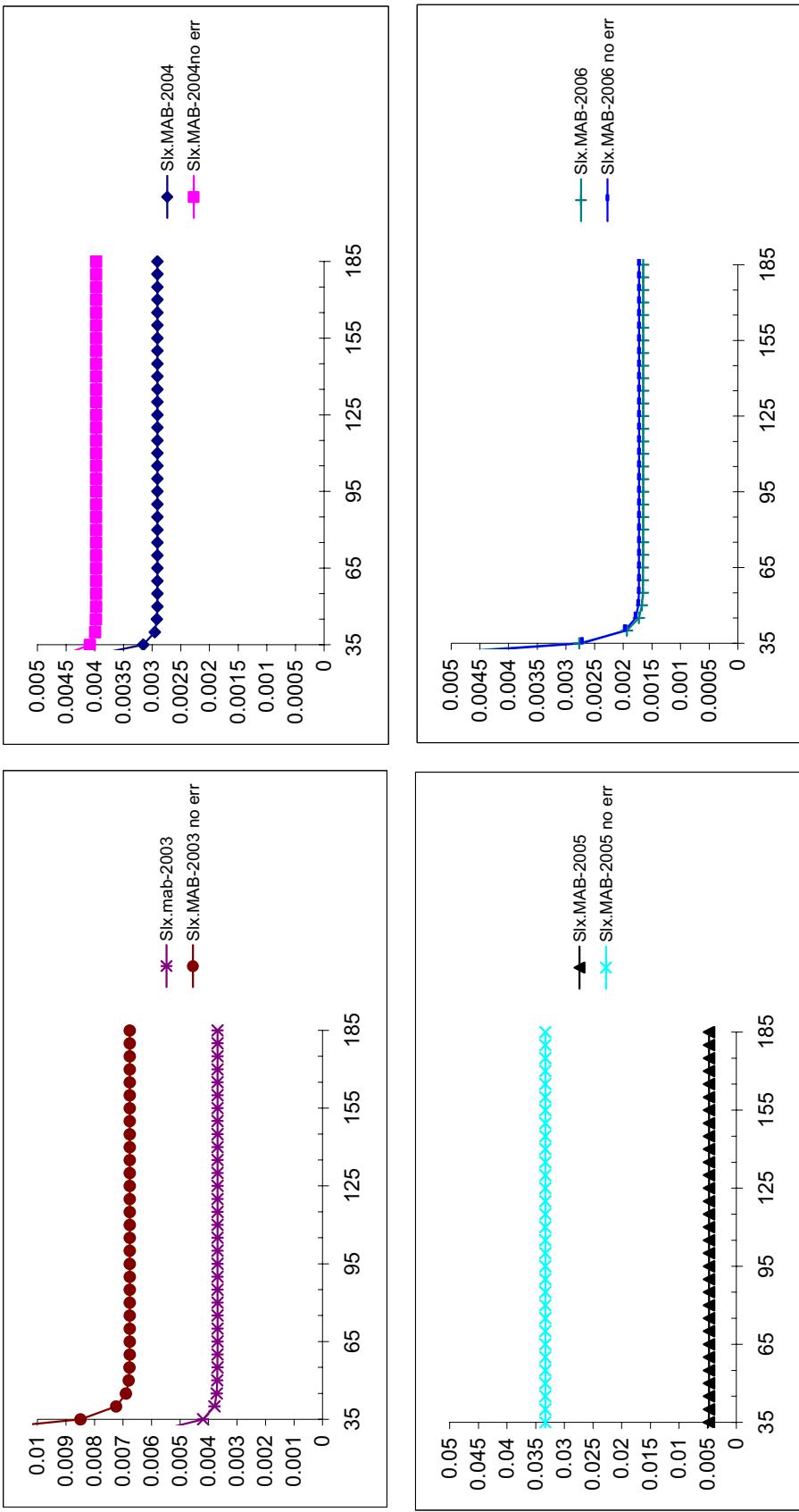
APPENDIX B8 Figure 13. Observed and predicted plots for selectivity estimates from small camera comparisons.

### Deviance residual plots for dredge survey selectivity models (small camera data)



APPENDIX B8 Figure 14. Deviance residuals for selectivity estimates from small camera comparisons.

### Dredge survey selx based on small camera survey with and without length measurement errors



APPENDIX B8 Figure 15. Comparison of selectivity curves for Mid-Atlantic Bight based on small camera comparisons with and without length measurement errors.

## APPENDIX B9: Scallop Dredge Rock Chain Analysis and Calibration

It is believed that the capture of large rocks during standard scallop survey dredge hauls reduces scallop dredge performance. In addition, the interception of large rocks can cause delays to the standard survey, reduce effective strata sampling in marginal habitat (rocky), can be a safety issue and more often than not, result in gear damage. To resolve this issue in the past, an attempt was made to repeat dredge hauls at all random sites that captured large rocks. Because of the uncertainty, the following study was conducted.

Starting in 2001, NEFSC collected annual comparative paired dredge hauls during the standard summer survey. The comparison dredge hauls were between the standard 8 foot wide New Bedford style scallop dredge and another of the same design but rigged with rock excluding chains. The rock chains are laid across and vertically over the dredge mouth opening to create smaller windows in order to exclude rocks but still catch scallops in strata where there is a prevalence of rocks. Paired tows were conducted at random sites within the Great South Channel (GSC) strata set (49, 50, 51, and 52) aboard the R/V Albatross IV (Figure 1). These 4 channel strata were the only strata considered for comparison due to the rugged habitat (Figure 2). The purpose of the study was to identify a statistical difference in terms of catch between the standard dredge and the rock chain dredge configuration and then produce a calibration coefficient to apply to historical catches from the study strata set.

NEFSC conducted 79 paired dredge hauls in the hard habitat site (GSC) for the survey years of 2001, 2002, 2004, 2005, and 2006 (Figure 1). No comparative tows were conducted in 2003. See Table 1 for a year by year breakdown of pairs per sampling year. Presented below are the results of 6 comparisons. The first three tests were conducted using raw scallop catches, while the last three tests had an adjustment to the catch based on longer tow distances. Tow distances were determined by a dredge angle recording device to calculate total bottom time. All catch values were log transformed for each comparison and pairs with zero catch in either both or one were excluded from the analysis. See Table 2 for a listing of catch by dredge type, year, and pair.

The first set of three comparisons (A, B, and 1) were conducted to look at just the raw catch numbers without any tow distance effect. See Figure 3 for a catch distribution by pair. A parametric t-test and a non-parametric Wilcoxon Rank Sum test were conducted for all tests (Table 3).

Test A was comprised of the 39 pairs from 2001 and 2002; test B was the 40 pairs from 2004, 2005, and 2006, while test 1 was all 79 pairs (all years).

The results of test A produced a significant difference for the parametric test ( $p=0.006$ ) between the two dredge types. The non parametric test was the same result ( $p=0.005$ ). The mean difference (0.504) back transformed was 1.655, a bias correction yielded 1.794 and approximate correction was 2.969. The bias correction was performed to compensate for the transformation of normal random variable to a log transformed one. [Calculation  $\exp(S.D.^2/2)$ ]. The approximate correction was calculated by multiplying the bias correction by the mean difference

Test B (40 pairs from 2004 – 2006) was not significant for both parametric ( $p=0.126$ ) and non-parametric ( $p=0.102$ ). If a calibration was needed, the approximate correction for Test B was 1.099 (mean difference = -0.185) and would be a negative adjustment to the rock chain catches, which is opposite of Test A.

Test 1 (79 pairs all years) was not significant for both parametric ( $p=0.166$ ) and non-parametric ( $p=.188$ ). If a calibration was needed, the approximate correction for Test 1 was 1.896 (mean difference = 0.155) and would be a positive adjustment to the non rock chain catches, which is opposite of Test A as well

The second set of comparisons was C, D, and test 6. These comparisons are set up the same way as the three described above, except that the catch data has been standardized by

tow distance. Also, the tow distances were a combination of calculated distances from the inclinometer exercise and 7 regression predicted tow distances referred to as the “combo”. The catches were then standardized to (.95nm/new trackline) ratio before being analyzed. The attempt was to reduce the affect of the tow distances on the mean difference

Test C (39 pairs from 2001 to 2002 with combo tow distance adjustment) yielded a significant result ( $p=0.006$ ) for the parametric test and for the nonparametric test ( $p=0.006$ ). Even with the tow distance adjustment to catch, the statistical results were the same as test A. The approximate correction for the calibration from test C. was 2.958 to positive adjust the non rock chain tows. Test D (40 pairs from 2004 to 2006 with combo tow distance adjustment) yielded non-significant parametric results ( $p=0.109$ ) and non-parametric results ( $p=0.097$ ). The approximate correction for the calibration for test D. was 1.096 but in a negative adjustment to the rock chain catches. Test 6 (79 pairs from 2001 to 2006 with combo tow distance adjustment) yielded non-significant parametric results (0.189) and non-parametric results ( $p=0.198$ ). The approximate correction for the 79 pairs was 1.892 to positive adjust the non rock chain catches

The same result occurs whether the tow distance adjustment is included or not. The approximate correction (1.896) for Test 1 (unadjusted catches) is almost the same as approximate correction (1.892) for Test 6 (adjusted catches by tow distance combo). This seems to indicate that a correction factor could be made for historical catches by just using the un-adjusted catches and the approximate calibration from them

A third comparison was conducted that separated the catches by strata groupings rather than years. One test compared strata (49, 50, and 51). The results were significant ( $p=0.042$ ) for the parametric, but not significant for the non-parametric ( $p=0.061$ ). The other test was not significant for both parametric and non-parametric.

Because the catch differences seemed to shift by period (2001/2002 vs. 2004-2006) and the direction of the differences between periods, an additional analysis was performed to look at the affect of strata set and year. A generalized linear model approach was chosen to test for year and strata differences using a unified approach. A gamma likelihood was used for the data to avoid the log transformation and incorporate the linear relationship between the mean and variance (Figure 4)<sup>10</sup>. In addition, an identity link was used as the catches from the rock chain tows appeared to be linearly related to the catches from the tows made without rock chains (Figure 4). A full factorial model with factors Year.Period (2001, 2002 vs. 2004, 2005, and 2006) and Strata.group (49, 50, 51 vs. 52) was fit to the data (Annex 1). The resulting analysis of deviance indicates that only the coefficient for the non-rock chain catch covariate and terms containing Year.Period were significant (Table 4). Model selection using Akaike’s information criteria resulted agreed with this and the final model was of the form (Table 5):

$$\text{Catch}_{\text{RC}} = \text{Year.Period} + \text{Catch}_{\text{NRC}} + \text{Year.Period:Catch}_{\text{NRC}}$$

The implications of this result are that for the period 2001/2002, non-rock chain catches would be converted to rock chain catches as:

$$\text{Catch}_{\text{RC}} = 6.755303 + 1.43794 \times \text{Catch}_{\text{NRC}}$$

while for the experiments run in 2004 to 2006:

$$\text{Catch}_{\text{RC}} = (6.755303 - 4.661788) + (1.43794 - 0.4364523) \times \text{Catch}_{\text{NRC}}$$

---

<sup>10</sup> SPLUS was used to conduct analysis of these data.

These results are not useful for converting non-rock chain catches to rock chain equivalent catches for the time series given the differences found between years. Dredge loading differences between time periods will be investigated from the existing dataset for the next SARC.

## Annex 1.

SPLUS commands used in this analysis:

Fit full factorial model:

```
>vics.data.corrected.full.glm<-glm(formula = RC.Test.1 ~ NRC.Test.1 * Year.Period * Strata.group, family = Gamma(link = identity), data = vicsdata.corrected)
```

Analysis of deviance:

```
>anova(vics.data.corrected.full.glm,test="F")
```

Model selection using Akaike Information criteria (AIC):

```
>vics.data.corrected.red.glm<-step.AIC(vics.data.corrected.full.glm)11
```

<sup>2</sup>Step.AIC is available in the MASS library.

APPENDIX B9 Table 1: Distribution of Pairs Among Years and Strata.

Year	Pairs	Strata 49	Strata 50	Strata 51	Strata 52
2001	21	0	10	3	8
2002	18	1	8	5	4
2004	23	6	5	7	5
2005	3	1	2	0	0
2006	14	0	3	4	7
Total:	79	8	28	19	24

APPENDIX B9 Table 2: Raw Catches by Year

Year	Pair #	RC	NRC	Year	Pair #	RC	NRC
2001	1	1809	1917	2004	40	1391	1408
2001	2	27	8	2004	41	80	30
2001	3	104	19	2004	42	10	30
2001	4	618	159	2004	43	47	54
2001	5	100	13	2004	44	17	81
2001	6	2701	2012	2004	45	503	454
2001	7	117	37	2004	46	32	38
2001	8	1756	1860	2004	47	302	662
2001	9	99	45	2004	48	303	723
2001	10	310	395	2004	49	2	1
2001	11	279	244	2004	50	550	815
2001	12	19	5	2004	51	83	180
2001	13	21	18	2004	52	275	172
2001	14	872	411	2004	53	56	57
2001	15	300	567	2004	54	18	29
2001	16	75	273	2004	55	2	3
2001	17	27	15	2004	56	48	23
2001	18	124	286	2004	57	14	9
2001	19	41	81	2004	58	141	246
2001	20	12	2	2004	59	3191	2923
2001	21	3	5	2004	60	468	78
2002	22	573	346	2004	61	31	10
2002	23	12	96	2004	62	56	110
2002	24	367	41	2005	63	39	275
2002	25	170	45	2005	64	454	670
2002	26	38	7	2005	65	368	180
2002	27	384	437	2006	66	1296	2127
2002	28	219	402	2006	67	361	1065
2002	29	173	96	2006	68	179	218
2002	30	223	53	2006	69	7	6
2002	31	24	250	2006	70	283	267
2002	32	5	2	2006	71	112	380
2002	33	419	108	2006	72	65	49
2002	34	35	19	2006	73	17	15
2002	35	59	20	2006	74	20	40
2002	36	1142	927	2006	75	18	17
2002	37	29	16	2006	76	722	1572
2002	38	1384	306	2006	77	244	154
2002	39	12	2	2006	78	267	486
				2006	79	1389	1968

APPENDIX B9 Table 3. Statistical Results and Calibration Coefficients

Paired Sample Comparisons										
Test	Mean Dif.	S.D.	S.E.	t stat	df	Sign.	Wilcox.	Calibration EXP(Mean Diff)	Bias Correc.	Approx. Correc.
A	0.504	1.081	0.173	2.91	38	0.006	0.005	1.655	1.794	2.969
B	-0.185	0.748	0.118	-1.57	39	0.126	0.102	0.831	1.323	1.099
1	0.155	0.985	0.111	1.399	78	0.166	0.188	1.168	1.624	1.896
C	0.501	1.080	0.173	2.895	38	0.006	0.006	1.650	1.792	2.958
D	-0.197	0.759	0.120	-1.64	39	0.109	0.097	0.821	1.334	1.096
6	0.148	0.990	0.111	1.325	78	0.189	0.198	1.159	1.632	1.892

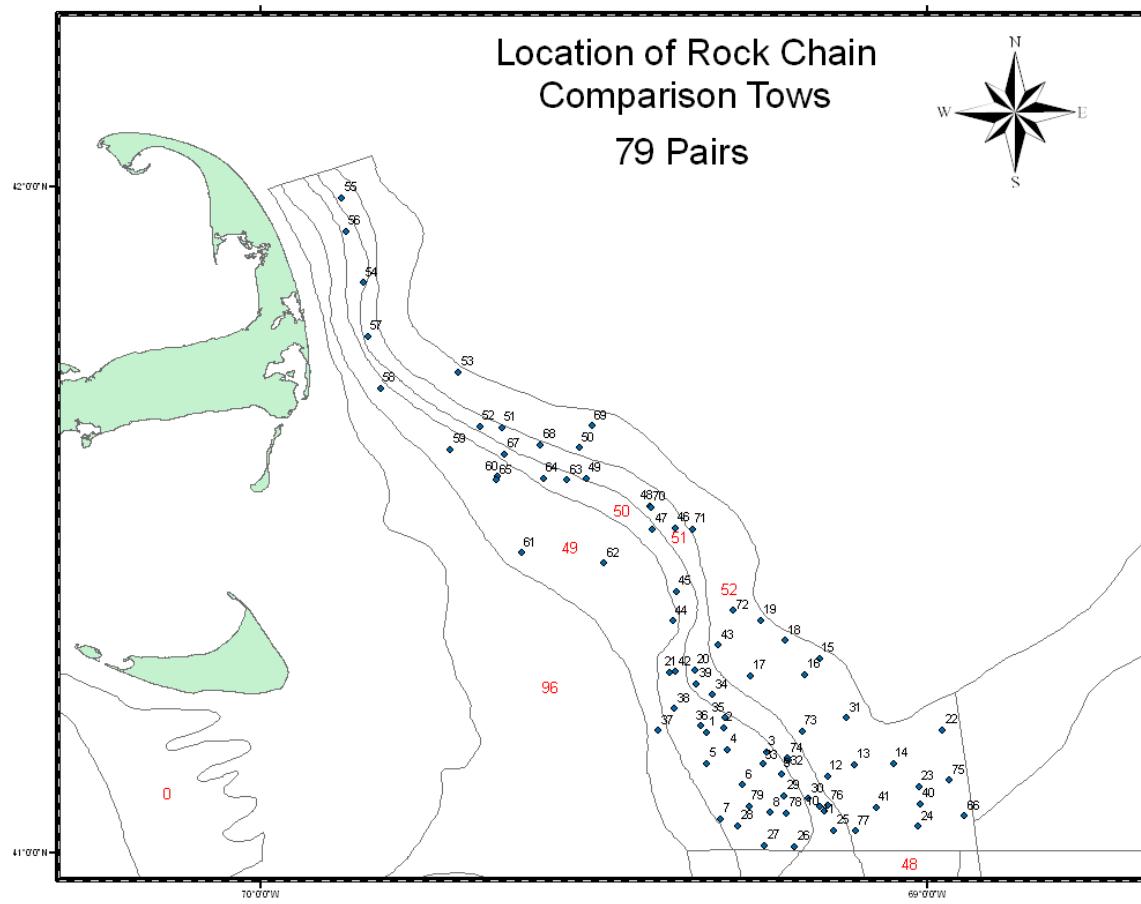
39 pairs = 2001 and 2002  
 40 pairs = 2004 to 2006  
 79 pairs = all years

APPENDIX B9 Table 4. Analysis of deviance for full factorial model

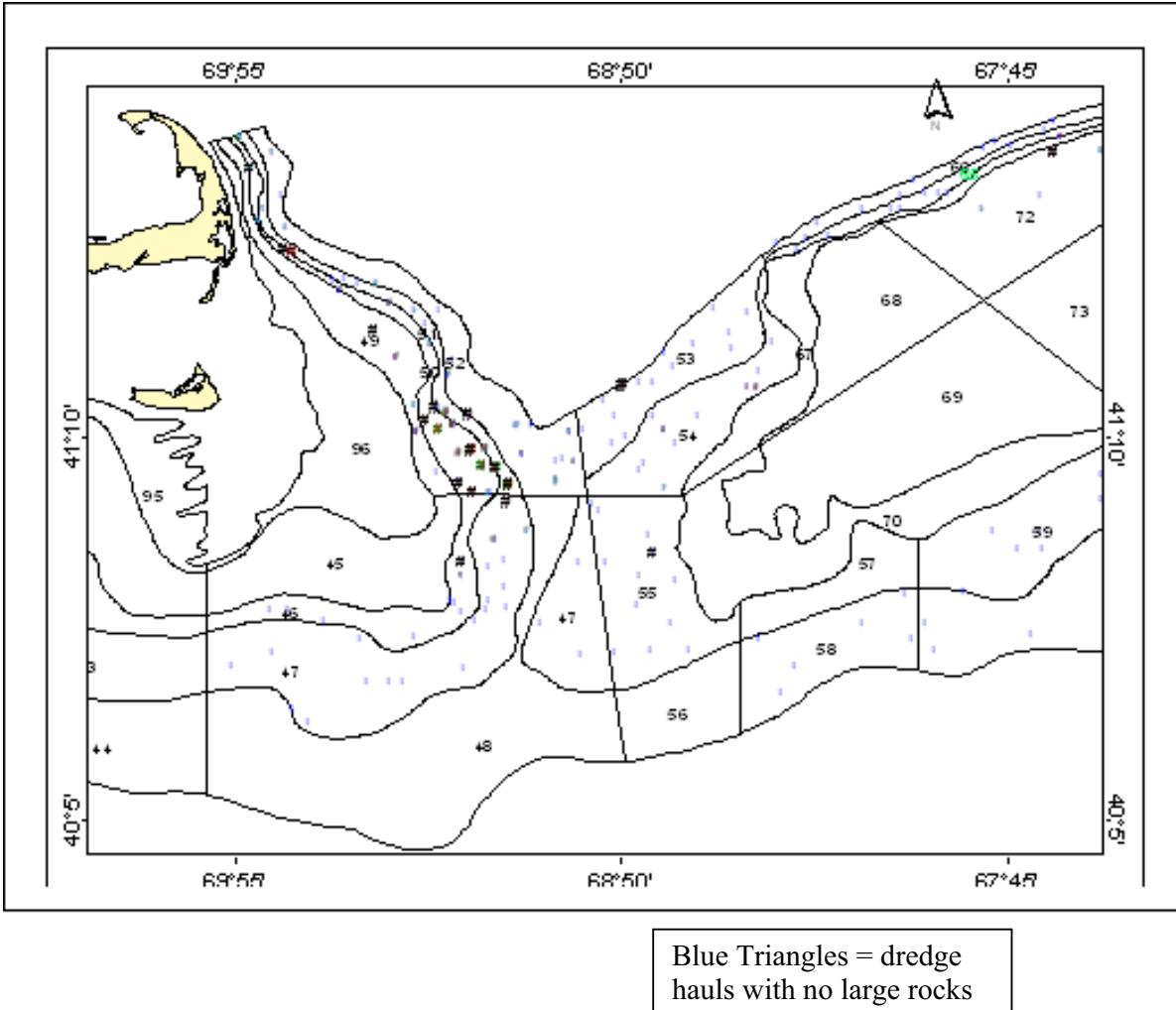
Terms added sequentially	Df	Deviance	Residual Df	Residual Deviance	F- Value	Pr(F)
NULL			78	189.781		
+NRC.Test.1	1	125.792	77	63.988	128.271	0.000
+Year.Period	1	7.081	76	56.908	7.220	0.009
+Strata.group	1	0.033	75	56.875	0.033	0.855
+NRC.Test.1:Year.Period	1	3.382	74	53.493	3.449	0.067
+NRC.Test.1:Strata.group	1	0.428	73	53.065	0.436	0.511
+Year.Period:Strata.group	1	0.014	72	53.051	0.014	0.905
+NRC.Test.1:Year.Period:Strata.group	1	1.928	71	51.123	1.966	0.165

APPENDIX B9 Table 5. Analysis of deviance for reduced model

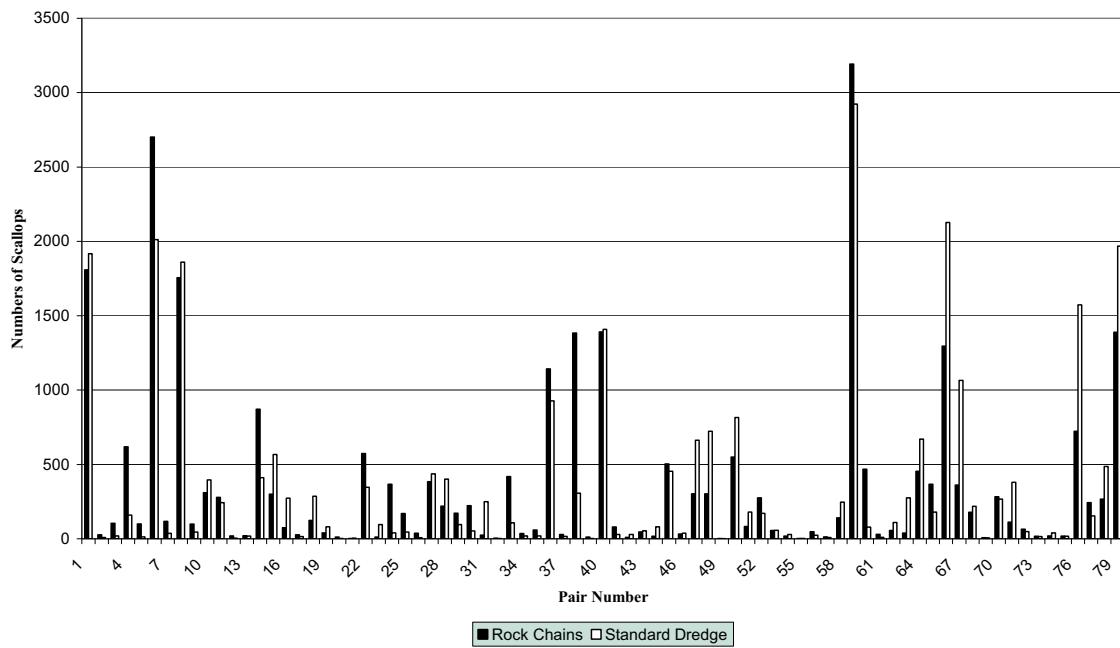
Terms added sequentially	Df	Deviance	Residual Df	Residual Deviance	F Value	Pr(F)
NULL			78	189.781		
+NRC.Test.1	1	125.792	77	63.988	141.816	0.000
+Year.Period	1	7.081	76	56.908	7.983	0.006
+NRC.Test.1:Year.Period	1	3.411	75	53.497	3.846	0.054



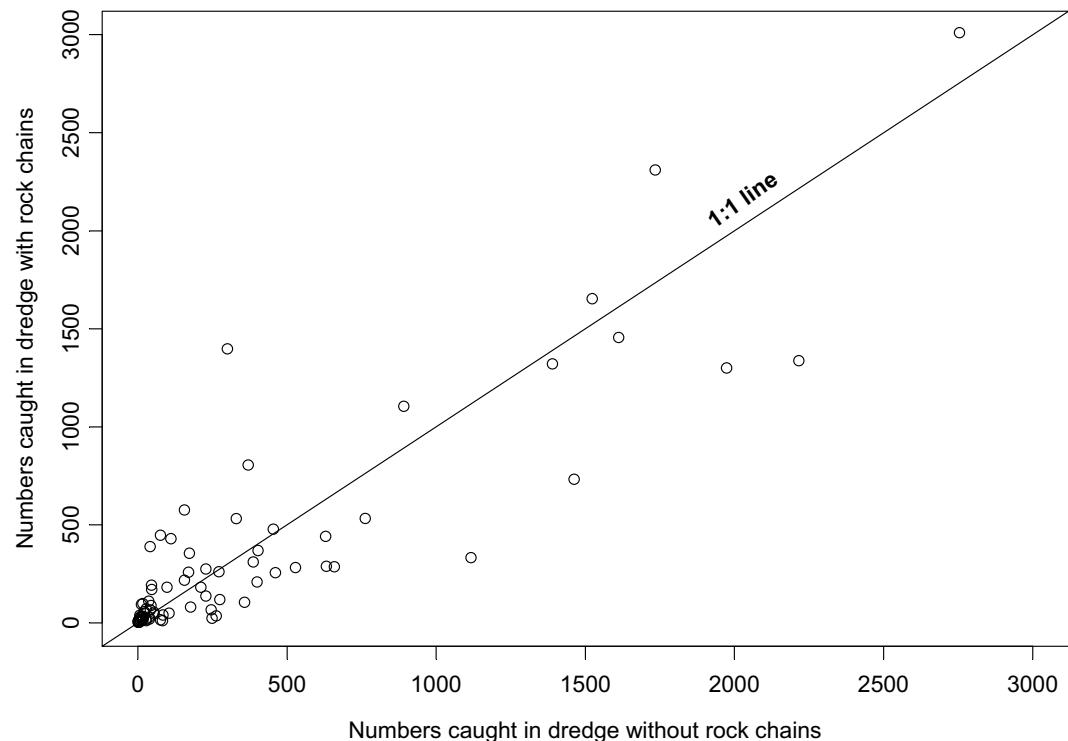
APPENDIX B9 Figure 1. Location of 79 Paired Tows between the Rock Chain and the Standard Dredge



APPENDIX B9 Figure 2. A Sample of the Distribution of Large Rocks on a Typical Scallop Survey



APPENDIX B9 Figure 3. Raw catches over all years for both dredge types.



APPENDIX B9 Figure 4. Catches from dredge with and without rock chains; 1:1 line added for reference.

## **APPENDIX B10: Technical documentation for the CASA Length Structured Stock Assessment Model<sup>12</sup>**

The stock assessment model described here is based on Sullivan et al.'s (1990) CASA model<sup>13</sup> with a number of additional features. Many aspects are similar to aspects of the Stock Synthesis Model (Methot 2000) although CASA assumes a single set of life history characteristics within a single stock area. CASA is entirely length-based with population dynamic calculations in terms of the number of individuals in each length group during each year. Age is largely irrelevant in model calculations although "effective age" (years since recruitment to the model) calculations have been implemented experimentally. Unlike many other length-based stock assessment approaches, CASA is a dynamic, non-equilibrium model based on a forward simulation approach. CASA incorporates a very wide range of data with parameter estimation based on maximum likelihood. CASA can incorporate prior information and constraints on parameters such as survey catchability in a quasi-Bayesian fashion. The implementation described here was programmed in AD-Model Builder (Otter Research Ltd.).<sup>14</sup>

### **Population dynamics**

Time steps in the model are years, which are also used to tabulate catch and other data. Recruitment occurs at the beginning of each time step. If time steps are years, then instantaneous rates have units  $y^{-1}$ . The number of years in the model  $n_y$  is flexible and can be changed easily (e.g. for retrospective analyses) by making a single change to the input data file. Millimeters are the units for length data. Length-weight relationships should generally convert millimeters to grams. The units for catch and biomass are usually metric tones. Model input data include a scalar that is used to convert the units for length-weight parameters (e.g. grams) to the units of the biomass estimates and landings data (e.g. mt).

The definition of length groups (or length "bins") is a key element in the CASA model and length-structured stock assessment modeling in general. Length bins are identified in CASA by their lower bound. Calculations requiring information about length (e.g. length-weight) use the mid-length  $\ell_j$  of each bin. The user specifies the first length included in model calculations ( $L_{min}$ ) and the size of length bins ( $L_{bin}$ ). Based on these specifications, the model determines the number of length bins to be used in modeling as  $n_L = 1 + \text{int}[(L_\infty - L_{min})/L_{bin}]$ , where  $L_\infty$  is maximum asymptotic size based on a von Bertalanffy growth curve supplied by the user and  $\text{int}[x]$  is the integer part of  $x$ . The last length bin in the model is always a "plus-group" containing individuals  $L_\infty$  and larger. Specifications for length data used in tuning the model are entirely separate (see below).

### **Growth**

Although age is not considered, Von Bertalanffy growth models are implicit in several of the configurations of the CASA model. The growth parameter  $L_\infty$  is not estimable because it

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<sup>12</sup> Documentation last updated on May 11, 2007 as file CASA-Appendix-NC-describe57.doc.

<sup>13</sup> Original programming in AD-Model Builder by G. Scott Boomer and Patrick J. Sullivan (Cornell University), who bear no responsibility for errors in the current implementation.

<sup>14</sup> AD-Model Builder can be used to calculate variances for any estimated or calculated quantity in a stock assessment model, based on the Hessian matrix with "exact" derivatives and the delta method. Experience with other models (e.g. Overholtz et al., 2004) suggests that variances estimates from AD-Model Builder, which consider the variance of all model parameters, are similar to variances calculated by the common method of bootstrapping survey abundance data.

is used in defining length bins prior to the parameter estimation phase and in determining the largest “plus-group”.<sup>15</sup> The von Bertalanffy growth parameter  $t_0$  is not estimable because it is irrelevant in length-based models that predict growth during a year based on the von Bertalanffy growth parameter  $K$ ,  $L_\infty$  and size at the beginning of the year.

At the beginning of the year, scallops in each size group grow (or not) based on terms in the growth transition matrix  $P(b,a)$  which measures the probability that a surviving individual that starts in bin  $a$  will grow to bin  $b$  by the beginning of the next year (columns index initial size and rows index subsequent size). Growth probabilities do not include any adjustments for mortality. In the CASA model, growth occurs immediately at the beginning of each year and the model assumes that no growth occurs during the year.

Growth probabilities depend on growth increments because:

$$L_2 = L_1 + \iota$$

where  $L_1$  is the starting length,  $L_2$  is length after one year of growth and  $\iota$  is the growth increment. When growth increments are based on parametric probability distributions (e.g. gamma distributions following Sullivan et al. 1990), probability calculations assume that individuals start at the middle of their original length bin  $\ell_a$ , and then grow to sizes that cover the whole range of each possible subsequent size bin. Thus:

$$P(b,a) = \int_{j=\ell_b - L_{bin}/2}^{\ell_b + L_{bin}/2} P(j | \ell_a) \partial j = \mathbb{N}(\ell_b + L_{bin}/2 | \ell_a) - \mathbb{N}(\ell_b - L_{bin}/2 | \ell_a)$$

where  $P(j | \ell_a)$  is the probability of increment  $j$  for an individual originally in bin  $a$  (at mid-length  $\ell_a$ ).  $\mathbb{N}(a | \ell_a)$  is the size-specific cumulative distribution function for growth increments. In parametric growth model calculations, cumulative distributions for growth increments are computed by numerical integration based on Simpson’s rule (Press et al., 1990) and a user-specified number of steps per bin. The user can change the number of steps to balance the accuracy of the calculation against time required for growth calculations.

Growth probabilities  $P(b,a)$  are calculated in CASA by one of four options. Option 1 is similar to Sullivan et al.’s (1990) approach in that growth probabilities are calculated by numerical integration assuming that increments follow parametric gamma distributions. The gamma distributions for growth increments are initial size dependent and are specified in terms of mean increments and CV’s. Mean increments  $\bar{\iota}_a$  are from the von Bertalanffy growth curve:

$$\bar{\iota}_a = (L_\infty - \ell_a)(1 - e^{-K})$$

where  $K=e^\chi$  is the von Bertalanffy growth coefficient and  $\chi$  is an estimable parameter.<sup>16</sup> Under Option 1, CVs are a log-linear function of length:

$$CV_L = e^{\kappa + \lambda L}$$

---

<sup>15</sup> “Estimable” means a potentially estimable parameter that is specified as a variable that may be estimated in the CASA computer program. In practice, estimability depends on the available data and other factors. It may be necessary to fix certain parameters at assumed fix values or to use constraints of prior distributions for parameters that are difficult to estimate, particularly if data are limited.

<sup>16</sup> Most intrinsically positive or intrinsically negative parameters are estimated in log scale to ensure estimates do not change sign, and to enhance statistical properties of estimates.

where  $\kappa$  and  $\gamma$  are estimable parameters. Sullivan et al. 1990 assumed constant CV's for growth. This implementation of the CASA model includes the special case of constant CV's when  $\lambda=0$ .

Option 2 is nonparametric and constructs a transition matrix directly from size-specific annual growth data (i.e. data records consisting of starting length, length after one year and number of observations). Under Option 2:

$$P(b|a) = \frac{n(b|a)}{\sum_{j=a}^{n_L} n(j|a)}$$

where  $n(b|a)$  is the number of individuals that started at size  $a$  and grew to size  $b$  after one year.

Under option 3, mean increments are from the von Bertalanffy growth curve as in option 1, but with length-specific CVs (and other model parameters) estimated in the model based on growth increments and other data (see below for goodness of fit calculations). Under option 3, the von Bertalanffy growth parameter  $K$ , which describes mean growth, and parameters for variance in growth ( $\kappa$  and  $\gamma$ ) are estimable. Option 4 uses a constant, user-specified transition matrix provided as data to the model.

Growth calculations based on assumed gamma distributions (Sullivan et al. 1990) might be unrealistic for some species because the gamma distribution predicts growth increments of zero to infinity. Therefore, with options 1-3, the user may specify minimum and maximum growth increments for each size. Probabilities from truncated gamma distributions for growth increments between the minimum and maximum values are normalized to sum to one before use in population dynamics calculations. Size bins outside those specified are ignored in all model calculations.

### **Abundance, recruitment and mortality**

Population abundance in each length bin during the first year of the model is:

$$N_{1,L} = N_1 \pi_{1,L}$$

where  $L$  is the size bin, and  $\pi_{1,L}$  is the initial population length composition expressed as

proportions so that  $\sum_{L=1}^{n_L} \pi_L = 1$ .  $N_1 = e^\eta$  is total abundance at the beginning of the first modeled

year and  $\eta$  is an estimable parameter. It is not necessary to estimate recruitment in the first year because recruitment is implicit in the product of  $N_1$  and  $\pi_L$ . The current implementation of CASA takes the initial population length composition as data supplied by the user.

Abundance at length in years after the first is calculated:

$$\vec{N}_{y+1} = P(\vec{N}_y \circ \vec{S}_y) + \vec{R}_{y+1}$$

where  $\vec{N}_y$  is a vector (length  $n_L$ ) of abundance in each length bin during year  $y$ ,  $P$  is the matrix  $(n_L \times n_L)$  of growth probabilities  $P(b|a)$ ,  $\vec{S}_y$  is a vector of length-specific survival fractions for year  $y$ ,  $\circ$  is for the element-wise product, and  $\vec{R}_y$  is a vector holding length-specific abundance of new recruits at the beginning of year  $y$ .

Survival fractions are:

$$S_{y,L} = e^{-Z_{y,L}} = e^{-(M_{y,L} + F_{y,L} + I_{y,L})}$$

where  $Z_{y,L}$  is the total instantaneous mortality rate and  $M_{y,L}$  is the instantaneous rate for natural mortality (see below). Length-specific fishing mortality rates are  $F_{y,L} = F_y s_{y,L}$  where  $s_{y,L}$  is the size-specific selectivity<sup>17</sup> for fishing in year  $y$  (scaled to a maximum of one at fully recruited size groups),  $F_y$  is the fishing mortality rate on fully selected individuals. Fully recruited fishing mortality rates are  $F_y = e^{\phi + \delta_y}$  where  $\phi$  is an estimable parameter for the log of the geometric mean of fishing mortality in all years, and  $\delta_y$  is an estimable “dev” parameter.<sup>18</sup> The instantaneous rate for “incidental” mortality ( $I_{y,L}$ ) accounts for mortality due to contact with the fishing gear that does not result in any catch on deck (see below).<sup>19</sup> The degree of variability in dev parameters for fishing mortality, natural mortality and for other variables can be controlled using variance constraints described below.

Natural mortality rates  $M_{y,L} = u_L e^{\zeta + \xi_y}$  may vary from year to year and by length. Variability among length groups is based on a user-specified vector  $\vec{u}$  that describes the relative natural mortality rate for each length group in the model. The user supplies a value for each length group which the model rescales so that the average of all of the values is one (i.e.  $\vec{u}$  is set by the user and cannot be estimated). Temporal variability in natural mortality rates are modeled in the same manner as temporal variability in fishing mortality. In particular,  $\zeta$  is an estimable parameter measuring the mean log natural mortality rate during all years and  $\xi_y$  is an estimable year-specific dev parameter. Several approaches are available for estimating natural mortality parameters (i.e. natural mortality covariates and surveys that measure numbers of dead individuals, see below).

Incidental mortality  $I_{y,L} = F_y u_L i$  is the product of fully recruited fishing mortality ( $F_y$ , a proxy for effective fishing effort, although nominal fishing effort might be a better predictor of incidental mortality), relative incidental mortality at length ( $u_L$ ) and a scaling parameter  $i$ , which is supplied by the user and not estimable in the model. Mortality at length is supplied by the user as a vector ( $\vec{u}$ ) containing a value for each length group in the model. The model rescales the relative mortality vector so that the mean of the series is one.

Given abundance in each length group, natural mortality, and fishing mortality, predicted fishery catch-at-length in numbers is:

$$C_{y,L} = \frac{F_{y,L} (1 - e^{-Z_{y,L}}) N_{L,y}}{Z_{y,L}}$$

Total catch number during each year is  $C_y = \sum_{j=1}^{n_L} C_{y,L}$ . Catch data (in weight, numbers or as length composition data) are understood to include landings ( $L_y$ ) and discards ( $d_y$ ) but to exclude losses to incidental mortality (i.e.  $C_y = L_y + d_y$ ).

Discard data are supplied by the user in the form of discarded biomass in each year or a discard rate for each year (or a combination of biomass levels and rates). It is important to remember that discard rates in CASA are defined the ratio of discards to landings ( $d/L$ ). The user may also specify a mortal discard fraction between zero and one if not discards are expected to die. If the discard fraction is less than one, then the discarded biomass and

<sup>17</sup> In this context, “selectivity” describes the combined effects of all factors that affect length composition of catch or landings. These factors include gear selectivity, spatial overlap of the fishery and population, size-specific targeting, size-specific discard, etc.

<sup>18</sup> Dev parameters are a special data type for estimable parameters in AD-Model Builder. Each set of dev parameters (e.g. for all recruitments in the model) is constrained to sum to zero. Because of the constraint, the sums  $\phi + \delta_y$  involving  $n_y+1$  terms amount to only  $n_y$  parameters.

<sup>19</sup> . See the section on per recruit modeling below for formulas used to relate catch, landings and incidental mortality.

discard rates in the model are reduced correspondingly. See the section on per recruit modeling below for formulas used to relate catch, landings and incidental mortality.

Recruitment (the sum of new recruits in all length bins) at the beginning of each year after the first is calculated:

$$R_y = e^{\rho + \gamma_y}$$

where  $\rho$  is an estimable parameter that measures the geometric mean recruitment and the  $\gamma_y$  are estimable dev parameters that measure interannual variability in recruitment. As with natural mortality devs, a variance constraint can be used to help estimate recruitment deviations (see below).

Proportions of recruits in each length group are calculated based on a beta distribution  $B(w,r)$  over the first  $n_r$  length bins that is constrained to be unimodal.<sup>20</sup> Proportions of new recruits in each size group are the same from year to year. Beta distribution coefficients must be larger than one for the shape of the distribution to be unimodal. Therefore,  $w=1+e^\omega$  and  $r=1+e^\rho$ , where  $\omega$  and  $\rho$  are estimable parameters. It is probably better to calculate the parameters in this manner than as bounded parameters because there is likely to be less distortion of the Hessian for  $w$  and  $r$  values close to one and parameter estimation is likely to be more efficient.

Surplus production during each year of the model can be computed approximately from biomass and catch estimates (Jacobson et al., 2002):

$$P_t = B_{t+1} - B_t + \delta C_t$$

where  $\delta$  is a correction factor that adjusts catch weight to population weight at the beginning of the next year by accounting for mortality and growth. The adjustment factor depends strongly on the rates for growth and natural mortality and only weakly on the natural mortality rate. In the absence of a direct estimate, useful calculations can be carried out assuming  $\delta=1$ . In future versions of the CASA model, surplus production will be more accurately calculated by projecting populations at the beginning of the year forward one year assuming only natural mortality. **[NOTE: surplus production calculations are being updated and were not available for the 2007 sea scallop stock assessment.]**

#### *Population summary variables*

Population summary variables described above are calculated for the entire stock (all length groups) and two user specified ranges of length bins. One set of bins is typically used for “stock” statistics that may, for example, exclude the smallest size groups. The other set of bins is typically used for exploitable sizes that may be vulnerable to the fishery. Several statistics are calculated for the beginning (January 1) and middle (July 1) of the year.

Estimated total abundance at the beginning of the year is the sum of abundance at length  $N_{y,L}$  at the beginning of the year. Average annual abundance is:

$$\bar{N}_{y,L} = N_{y,L} \frac{1 - e^{-Z_{y,L}}}{Z_{y,L}}$$

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<sup>20</sup> Standard beta distributions used to describe recruit size distributions and in priors are often constrained to be unimodal in the CASA model. Beta distributions  $B(w,r)$  with mean  $\mu = w/w+r$  and variance  $\sigma^2 = wr/[(w+r)^2(w+r+1)]$  are unimodal when  $w > 1$  and  $r > 1$ . See [http://en.wikipedia.org/wiki/Beta\\_distribution](http://en.wikipedia.org/wiki/Beta_distribution) for more information.

CASA assumes that weight-at-length relationships for the stock (on January 1) and the fishery may differ and that mean fishery weight-at-length may change interannually. For example, total stock biomass is:

$$B_y = \sum_{L=1}^{n_L} N_{y,L} w_L$$

where  $w_L$  is weight at length for the population on January 1 computed at the midpoint of each length bin using the length-weight relationship for the fishery specified by the user. Total catch weight is:

$$W_y = (1 + \omega_y) \sum_{L=1}^{n_L} C_{y,L} w'_L$$

where  $w'_L$  is weight at length in the fishery and  $\omega_y$  is an annual anomaly input by the user to describe changes in fishery length weight that may occur from year to year due, for example, to changes in seasonal distribution of fishing. Model input data include a scalar that is used to convert the units for length-weight parameters (e.g. grams) to the units of the biomass estimates and landings data (e.g. mt).

$F_y$  estimates for two years are comparable only if the fishery selectivity in the model was the same in both years. A set of simpler exploitation indices may be more useful when fishery selectivity changes over time. For example:

$$U_y = \frac{C_y}{\sum_{j=x}^{n_L} \tilde{N}_{y,L}}$$

where  $x$  is a user-specified length bin (e.g. just below the first bin that is fully selected during all fishery selectivity periods) and the term  $\tilde{N}$  is predicted abundance at the middle (July 1<sup>st</sup>) of the year. Similar statistics are calculated based on stock and catch weights and for January 1<sup>st</sup> was well as July 1<sup>st</sup>. Exploitation indices from different years with different selectivity patterns may be readily comparable if  $x$  is chosen carefully.

Spawner abundance in each year is ( $T_y$ ) is computed:

$$T_y = \sum_{L=1}^{n_L} N_{y,L} e^{-\tau Z_y} g_L$$

where  $0 \leq \tau \leq 1$  is the fraction of the year elapsed before spawning occurs (supplied by the user). Maturity at length ( $g_L$ ) is from an ascending logistic curve:

$$g_L = \frac{1}{1 + e^{a - bL}}$$

with parameters  $a$  and  $b$  supplied by the user.

Spawner biomass or egg production ( $S_y$ ) in each year is computed:

$$S_y = \sum_{L=1}^{n_L} T_{y,L} x_L$$

where:

$$x_L = cL^v$$

Using parameters ( $c$  and  $v$ ) for fecundity- or body weight at size supplied by the user.

## Fishery and survey selectivity

The current implementation of CASA includes six options for calculating fishery and survey selectivity patterns. Fishery selectivity may differ among “fishery periods” defined by the user. Selectivity patterns that depend on length are calculated using lengths at the mid-point of each bin ( $\ell$ ). After initial calculations (described below), selectivity curves are rescaled to a maximum value of one.

Option 1 is a flat with  $s_L=1$  for all length bins. Option 2 is an ascending logistic curve:

$$s_{y,\ell} = \frac{1}{1 + e^{A_y - B_y \ell}}$$

Option 3 is an ascending logistic curve with a minimum asymptotic minimum size for small size bins on the left.

$$s_{y,\ell} = \left( \frac{1}{1 + e^{A_y - B_y \ell}} \right) (1 - D_y) + D_y$$

Option 4 is a descending logistic curve:

$$s_{y,\ell} = 1 - \frac{1}{1 + e^{A_y - B_y \ell}}$$

Option 5 is a descending logistic curve with a minimum asymptotic minimum size for large size bins on the right:

$$s_{y,\ell} = \left( 1 - \frac{1}{1 + e^{A_y - B_y \ell}} \right) (1 - D_y) + D_y$$

Option 6 is a double logistic curve used to represent “domed-shape” selectivity patterns with highest selectivity on intermediate size groups:

$$s_{y,\ell} = \left( \frac{1}{1 + e^{A_y - B_y \ell}} \right) \left( 1 - \frac{1}{1 + e^{D_y - G_y \ell}} \right)$$

The coefficients for selectivity curves  $A_y$ ,  $B_y$ ,  $D_y$  and  $G_y$  carry subscripts for time because they may vary between fishery selectivity periods defined by the user. All options are parameterized so that the coefficients  $A_y$ ,  $B_y$ ,  $D_y$  and  $G_y$  are positive. Under options 3 and 5,  $D_y$  is a proportion that must lie between 0 and 1. All selectivity curves are rescaled to a maximum value of one before used in further calculations.

Depending on the option, estimable selectivity parameters may include  $\alpha$ ,  $\beta$ ,  $\delta$  and  $\gamma$ . For options 2, 4 and 6,  $A_y = e^{\alpha_y}$ ,  $B_y = e^{\beta_y}$ ,  $D_y = e^{\delta_y}$  and  $G_y = e^{\gamma_y}$ . Options 3 and 5 use the same conventions for  $A_y$  and  $B_y$ , however, the coefficient  $D_y$  is a proportion estimated as a logit-transformed parameter (i.e.  $\delta_y = \ln[D_y/(1-D_y)]$ ) so that:

$$D_y = \frac{e^{\delta_y}}{1 + e^{\delta_y}}$$

The user can choose, independently of all other parameters, to either estimate each fishery selectivity parameter or to keep it at its initial value. Under Option 2, for example, the user can estimate the intercept  $\alpha_y$ , while keep the slope  $\beta_y$  at its initial value.

## Per recruit recruit modeling

A complete per recruit output table is generated in all model runs that can be used for evaluating the shape of YPR and SBR curves, including the existence of particular reference points. The output table summarizes a wide range of per recruit information in terms of fully recruited fishing mortality  $F$  and a number of exploitation indices ( $U$ ) specified by the user. Per recruit calculations in CASA use the same population model and code as all other model

calculations under conditions identical to the last year in the model. It is a standard length-based approach except that discard and incidental mortality are accommodated in all calculations.

In per recruit calculations, fishing mortality rates and associated yield estimates are understood to include landings and discard mortality, but to exclude incidental mortality. Thus, landings per recruit is:

$$L = \frac{C}{(1 + \Delta)}$$

where  $C$  is total catch (yield) per recruit and  $\Delta$  is the ratio of discards  $D$  to landings in the last year of the model. Discards per recruit are calculated:

$$D = \Delta L$$

Losses due to incidental mortality ( $G$ ) are calculated:

$$\begin{aligned} G &= \frac{I(1 - e^{-Z})B}{Z} \\ &= IK \end{aligned}$$

where  $I = F u$  is the incidental mortality rate,  $u$  is a user-specified multiplier (see above) and  $B$  is stock biomass per recruit. Note that  $C=FK$  so that  $K=C/F$ . Then,

$$\begin{aligned} G &= \frac{FuC}{F} \\ G &= uC \end{aligned}$$

In addition to generating a per recruit output table, the model will estimate key ( $F_{\%SBR}$ ,  $F_{max}$  and  $F_{0.1}$ ) per recruit model reference points as parameters. For example,

$$F_{\%SBR} = e^{\theta_j}$$

where  $F_{\%SBR}$  is the fishing mortality reference point that provides a user specified percentage of maximum SBR.  $\theta_j$  is the model parameter for the  $j^{th}$  reference point.

Per recruit reference points are time consuming to estimate and it is usually better to estimate them after other more important population dynamics parameters are estimated. Phase of estimation can be controlled individually for %SBR,  $F_{max}$  and  $F_{0.1}$  so that per recruit calculations can be delayed as long as possible. If the phase is set to zero or a negative integer, then the reference point will not be estimated. As described below, estimation of  $F_{max}$  always entails an additional phase of estimation. For example, if the phase specified for  $F_{max}$  is 2, then the parameter will be estimated initially in phase 2 and finalized the last phase (phase  $\geq 3$ ). This is done so that the estimate from phase 2 can be used as an initial value in a slightly different goodness of fit calculation during the final phase.

Per recruit reference points should have no effect on other model estimates. Residuals (calculated – target) for %SBR,  $F_{0.1}$  and  $F_{max}$  reference points should always be very close to zero. Problems may arise, however, if reference points (particularly  $F_{max}$ ) fall on the upper bound for fishing mortality. In such cases, the model will warn the user and advise that the offending reference points should not be estimated. *It is good practice to run CASA with reference point calculations turned on and then off to see if biomass and fishing mortality estimates change.*

The user specifies the number of estimates required and the target %SBR level for each. For example, the target levels for four %SBR reference points might be 0.2, 0.3, 0.4 and 0.5

to estimate  $F_{20\%}$ ,  $F_{30\%}$ ,  $F_{40\%}$  and  $F_{50\%}$ . The user has the option of estimating  $F_{max}$  and/or  $F_{0.1}$  as model parameters also but it is not necessary to supply target values.

## Tuning and goodness of fit

There are two steps in calculating the negative log likelihood (NLL) used to measure how well the model fits each type of data. The first step is to calculate the predicted values for data. The second step is to calculate the NLL of the data given the predicted value. The overall goodness of fit measure for the model is the weighted sum of NLL values for each type of data and each constraint:

$$\Lambda = \sum \lambda_j L_j$$

where  $\lambda_j$  is a weighting factor for data set  $j$  (usually  $\lambda_j=1$ , see below), and  $L_j$  is the NLL for the data set. The NLL for a particular data is itself is usually a weighted sum:

$$L_j = \sum_{i=1}^{n_j} \psi_{j,i} L_{j,i}$$

where  $n_j$  is the number of observations,  $\psi_{j,i}$  is an observation-specific weight (usually  $\psi_{j,i}=1$ , see below), and  $L_{j,i}$  is the NLL for a single observation.

Maximum likelihood approaches reduce the need to specify *ad-hoc* weighting factors ( $\lambda$  and  $\phi$ ) for data sets or single observations, because weights can often be taken from the data (e.g. using CVs routinely calculated for bottom trawl survey abundance indices) or estimated internally along with other parameters. In addition, robust maximum likelihood approaches (see below) may be preferable to simply down-weighting an observation or data set. However, despite subjectivity and theoretical arguments against use of *ad-hoc* weights, it is often useful in practical work to manipulate weighting factors, if only for sensitivity analysis or to turn an observation off entirely. Observation specific weighting factors are available for most types of data in the CASA model.

### *Missing data*

Availability of data is an important consideration in deciding how to structure a stock assessment model. The possibility of obtaining reliable estimates will depend on the availability of sufficient data. However, NLL calculations and the general structure of the CASA model are such that missing data can usually be accommodated automatically. With the exception of catch data (which must be supplied for each year, even if catch was zero), the model calculates that NLL for each datum that is available. No NLL calculations are made for data that are not available and missing data do not generally hinder model calculations.

### *Likelihood kernels*

Log likelihood calculations in the current implementation of the CASA model use log likelihood “kernels” or “concentrated likelihoods” that omit constants. The constants can be omitted because they do not affect slope of the NLL surface, final point estimates for parameters or asymptotic variance estimates.

For data with normally distributed measurement errors, the complete NLL for one observation is:

$$L = \ln(\sigma) + \ln(\sqrt{2\pi}) + 0.5 \left( \frac{x-u}{\sigma} \right)^2$$

The constant  $\ln(\sqrt{2\pi})$  can always be omitted. If the standard deviation is known or assumed known, then  $\ln(\sigma)$  can be omitted as well because it is a constant that does not affect derivatives. In such cases, the concentrated NLL is:

$$L = 0.5 \left( \frac{x - \mu}{\sigma} \right)^2$$

If there are  $N$  observations with possible different variances (known or assumed known) and possibly different expected values:

$$L = 0.5 \sum_{i=1}^N \left( \frac{x_i - \mu_i}{\sigma_i} \right)^2$$

If the standard deviation for a normally distributed quantity is not known and is estimated (implicitly or explicitly) by the model, then one of two equivalent calculations is used. Both approaches assume that all observations have the same variance and standard deviation. The first approach is used when all observations have the same weight in the NLL:

$$L = 0.5N \ln \left[ \sum_{i=1}^N (x_i - u)^2 \right]$$

The second approach is equivalent but used when the weights for each observation ( $w_i$ ) may differ:

$$L = \sum_{i=1}^N w_i \left[ \ln(\sigma) + 0.5 \left( \frac{x_i - u}{\sigma} \right)^2 \right]$$

In the latter case, the maximum likelihood estimator:

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^N (x_i - \hat{x})^2}{N}}$$

(where  $\hat{x}$  is the average or predicted value from the model) is used explicitly for  $\sigma$ . The maximum likelihood estimator is biased by  $N/(N-d_f)$  where  $d_f$  is degrees of freedom for the model. The bias may be significant for small sample sizes, which are common in stock assessment modeling, but  $d_f$  is usually unknown.

If data  $x$  have lognormal measurement errors, then  $\ln(x)$  is normal and  $L$  is calculated as above. In some cases it is necessary to correct for bias in converting arithmetic scale means to log scale means (and *vice-versa*) because  $\bar{x} = e^{\bar{\chi} + \sigma^2/2}$  where  $\chi = \ln(x)$ . It is often convenient to convert arithmetic scale CVs for lognormal variables to log scale standard deviations using  $\sigma = \sqrt{\ln(1 + CV^2)}$ .

For data with multinomial measurement errors, the likelihood kernel is:

$$L = n \sum_{i=1}^n p_i \ln(\theta_i) - K$$

where  $n$  is the known or assumed number of observations (the “effective” sample size),  $p_i$  is the proportion of observations in bin  $i$ , and  $\theta_i$  is the model’s estimate of the probability of an observation in the bin. The constant  $K$  is used for convenience to make  $L$  easier to interpret. It measures the lowest value of  $L$  that could be achieved if the data fit matched the model’s expectations exactly:

$$K = n \sum_{i=1}^n p_i \ln(p_i)$$

For data  $x$  that have measurement errors with expected values of zero from a gamma distribution:

$$L = (\gamma - 1) \ln \left( \frac{x}{\beta} \right) - \frac{x}{\beta} - \ln(\beta)$$

where  $\beta > 0$  and  $\gamma > 0$  are gamma distribution parameters in the model. For data that lie between zero and one with measurement errors from a beta distribution:

$$L = (p-1)\ln(x) + (q-1)\ln(1-x)$$

where  $p > 0$  and  $q > 0$  are parameters in the model.

In CASA model calculations, distributions are usually described in terms of the mean and CV. Normal, gamma and beta distribution parameters can be calculated mean and CV by the method of moments.<sup>21</sup> Means, CV's and distributional parameters may, depending on the situation, be estimated in the model or specified by the user.

### Robust methods

Goodness of fit for survey data may be calculated using a “robust” maximum likelihood method instead of the standard method that assumes lognormal measurement errors. The robust method may be useful when survey data are noisy or include outliers.

Robust likelihood calculations in CASA assume that measurement errors are from a Student’s  $t$  distribution with user-specified degrees of freedom  $d_f$ . Degrees of freedom are specified independently for each observation so that robust calculations can be carried out for as many (or as few) cases as required. The  $t$  distribution is similar to the normal distribution for  $d_f \geq 30$ . As  $d_f$  is reduced, the tails of the  $t$  distribution become fatter so that outliers have higher probability and less effect on model estimates. If  $d_f = 0$ , then measurement errors are assumed in the model to be normally distributed.

The first step in robust NLL calculations is to standardize the measurement error residual  $t = (x - \bar{x})/\sigma$  based on the mean and standard deviation. Then:

$$L = \ln\left(1 + \frac{t^2}{d_f}\right) \left(1 - \frac{1-d_f}{2}\right) - \frac{\ln(d_f)}{2}$$

### *Catch weight data*

Catch data (landings plus discards) are assumed to have normally distributed measurement errors with a user specified CV. The standard deviation for catch weight in a particular year is  $\sigma_y = \kappa \hat{C}_y$  where “ $\hat{\cdot}$ ” indicates that the variable is a model estimate and errors in catch are assumed to be normally distributed. The standardized residual used in computing NLL for a single catch observation and in making residual plots is  $r_y = (\hat{C}_y - \hat{C}_y)/\sigma_y$ .

### Specification of landings, discards, catch

Landings, discard and catch data are in units of weight and are for a single or “composite” fishery in the current version of the CASA model. The estimated fishery selectivity is assumed to apply to the discards so that, in effect, the length composition of catch, landings and discards are the same.

<sup>21</sup> Parameters for standard beta distributions  $B(w,r)$  with mean  $\mu = w/(w+r)$  and variance

$\sigma^2 = wr/[(w+r)^2(w+r+1)]$  are calculated from user-specified means and variances by the method of moments. In particular,  $w = \mu[\mu(1-\mu)/\sigma^2 - 1]$  and  $r = (1-\mu)[\mu(1-\mu)/\sigma^2 - 1]$ . Not all combinations of  $\mu$  and  $\sigma^2$  are feasible. In general, a beta distribution exists for combinations of  $\mu$  and  $\sigma^2$  if  $0 < \mu < 1$  and  $0 < \sigma^2 < \mu(1-\mu)$ . Thus, for a user-specified mean  $\mu$  between zero and one, the largest feasible variance is  $\sigma^2 < \mu(1-\mu)$ . These conditions are used in the model to check user-specified values for  $\mu$  and  $\sigma^2$ . See [http://en.wikipedia.org/wiki/Beta\\_distribution](http://en.wikipedia.org/wiki/Beta_distribution) for more information.

Discards are from external estimates ( $d_t$ ) supplied by the user. If  $d_t \geq 0$ , then the estimates are treated as the ratio of discard to landed catch so that:

$$D_t = L_t \Delta_t$$

where  $\Delta_t = D_t/L_t$  is the ratio of discard and landings (a.k.a.  $d/K$  ratios) for each year. If  $d_t < 0$  then the data are treated as discard in units of weight:

$$D_t = \text{abs}(d_t).$$

In either case, total catch is the sum of discards and landed catch ( $C_t = L_t + D_t$ ). It is possible to use discards in weight  $d_t < 0$  for some years and discard as proportions  $d_t > 0$  for other years in the same model run.

If catches are estimated (see below) so that the estimated catch  $\hat{C}_t$  does not necessarily equal observed landings plus discard, then estimated landings are computed:

$$\hat{L}_t = \frac{\hat{C}_t}{1 + \Delta_t}$$

Estimated discards are:

$$\hat{D}_t = \Delta_t \hat{L}_t.$$

Note that  $\hat{C}_t = \hat{L}_t + \hat{D}_t$  as would be expected.

#### *Fishery length composition data*

Data describing numbers or relative numbers of individuals at length in catch data (fishery catch-at-length) are modeled as multinomial proportions  $c_{y,L}$ :

$$c_{y,L} = \frac{C_{y,L}}{\sum_{j=1}^{n_L} C_{y,j}}$$

The NLL for the observed proportions in each year is computed based on the kernel for the multinomial distribution, the model's estimate of proportional catch-at-length ( $\hat{c}_Y$ ) and an estimate of effective sample size  ${}^c N_Y$  supplied by the user. Care is required in specifying effective sample sizes, because catch-at-length data typically carry substantially less information than would be expected based on the number of individuals measured. Typical conventions make  ${}^c N_Y \leq 200$  (Fournier and Archibald, 1982) or set  ${}^c N_Y$  equal to the number of trips or tows sampled (Pennington et al., 2002). Effective sample sizes are sometimes chosen based on goodness of fits in preliminary model runs (Methot, 2000; Butler et al., 2003).

#### **Survey index data**

In CASA model calculations, “survey indices” are data from any source that reflect relative proportional changes in an underlying population state variable. In the current version, surveys may measure stock abundance at a particular point in time (e.g. when a survey was carried out), stock biomass at a particular point in time, or numbers of animals that die of natural mortality during a user-specified period. For example, the first option is useful for bottom trawl surveys that record numbers of individuals, the second option is useful for bottom trawl surveys that record total weight, and the third option is useful for survey data that track trends in numbers of animals that died due to natural mortality (e.g. survey data for sea scallop “clappers”). Survey data that measure trends in numbers dead due to natural mortality can be useful in modeling time trends in natural mortality. In principle, the model will estimate model natural mortality and other parameters so that predicted numbers dead and the index data match in either relative or absolute terms.

In the current implementation of the CASA model, survey indices are assumed to be linear indices of abundance or biomass so that changes in the index (apart from measurement error) are assumed due to proportional changes in the population. Nonlinear commercial catch rate data are handled separately (see below). Survey index and fishery length composition data are handled separately from trend data (see below). Survey data may or may not have corresponding length composition information.

In general, survey index data give one number that summarizes some aspect of the population over a wide range of length bins. Selectivity parameters measure the relative contribution of each length bin to the index. Options and procedures for estimating survey selectivity patterns are the same as for fishery selectivity patterns, but survey selectivity patterns are not allowed to change over time.

NLL calculations for survey indices use predicted values calculated:

$$\hat{I}_{k,y} = q_k A_{k,y}$$

where  $q_k$  is a scaling factor for survey index  $k$ , and  $A_{k,y}$  is stock available to the survey. Scaling factors are calculated  $q_s = e^{\varpi_s}$  where  $\varpi_s$  is estimable and survey-specific.

Available stock for surveys measuring trends in abundance or biomass is calculated:

$$A_{k,y} = \sum_{L=1}^{n_L} s_{k,L} N_{y,L} e^{-Z_{y,L} \tau_{k,y}}$$

where  $s_{k,L}$  is size-specific selectivity of the survey,  $\tau_{k,y} = J_{k,y}/365$ ,  $J_{k,y}$  is the Julian date of the survey in year  $y$ , and  $e^{-Z_{y,L} \tau_{k,y}}$  is a correction for mortality prior to the survey. Available biomass is calculated in the same way except that body weights  $w_L$  are included in the product on the right hand side.

Available stock for indices that track numbers dead by natural mortality is:

$$A_{k,y} = \sum_{L=1}^{n_L} s_{k,L} \tilde{M}_{y,L} \bar{N}_{y,L}$$

where  $\bar{N}_{y,L}$  is average abundance during the user-specified period of availability and  $\tilde{M}_{y,L}$  is the instantaneous rate of natural mortality for the period of availability. Average abundance during the period of availability is:

$$\bar{N}_{y,L} = \frac{\tilde{N}_{y,L} (1 - e^{-\tilde{Z}_{y,L}})}{\tilde{Z}_{y,L}}$$

where  $\tilde{N}_{y,L} = N_{y,L} e^{-Z_{y,L}}$  is abundance at elapsed time of year  $\Delta = \tau_{k,y} - \nu_k$ ,  $\nu_k = j_k / 365$ , and  $j_k$  is the user-specified duration in days for the period of availability. The instantaneous rates for total  $\tilde{Z}_{y,L} = Z_{y,L} (\tau_{k,y} - \nu_k)$  and natural  $\tilde{M}_{y,L} = M_{y,L} (\tau_{k,y} - \nu_k)$  mortality are also adjusted to correspond to the period of availability. In using this approach, the user should be aware that the length based selectivity estimated by the model for the dead animal survey ( $s_{k,L}$ ) is conditional on the assumed pattern of length-specific natural mortality ( $\bar{u}$ ) which was specified as data in the input file.

NLL calculations for survey index data assume that log scale measurement errors are either normally distributed (default approach) or from a  $t$  distribution (robust estimation approach). In either case, log scale measurement errors are assumed to have mean zero and log scale standard errors either estimated internally by the model or calculated from the arithmetic CVs supplied with the survey data.

The standardized residual used in computing NLL for one survey index observation is  $r_{k,y} = \ln(I_{k,y} / \hat{I}_{k,y}) / \sigma_{k,y}$  where  $I_{k,y}$  is the observation. The standard deviations  $\sigma_{k,y}$  will vary

among surveys and years if CVs are used to specify the variance of measurement errors. Otherwise a single standard deviation is estimated internally for the survey as a whole.

### **Survey length composition data**

Length bins for fishery and survey length composition data are flexible and the flexibility affects goodness of fit calculations in ways that may be important to consider. The user specifies the starting size (bottom of first bin) and number of bins used for each type of fishery and survey length composition. The input data for each length composition record identifies the first/last length bins to be used and whether they are plus groups that should include all smaller/larger length groups in the data and population model when calculating goodness of fit. Goodness of fit calculations are carried out over the range of lengths specified by the user. Thus length data in the input file may contain data for size bins that are ignored in goodness of fit calculations. As described above, the starting size and bin size for the population model are specified separately. In the ideal and simplest case, the minimum size and same length bins are used for the population and for all length data. However, as described below, length specifications in data and the population model may differ.

Care is required in some cases because the implicit definitions of plus groups in the model and data may differ. If the first bin used for length data is a plus group, then the first bin will contain the sum of length data from the corresponding and smaller bins of the original length composition record. However, the first bin in the population model is never a plus group. Thus, predicted values for a plus group will contain the sum of the corresponding and smaller bins in the population. The observed and predicted values will not be perfectly comparable if the starting sizes for the data and population model differ. Similarly, if the last bin in the length data is a plus group, it will contain original length composition data for the corresponding and all larger bins. Predicted values for a plus group in the population will be the sum for the corresponding bin and all larger size groups in the population, implicitly including sizes  $> L_{\infty}$ . The two definitions of the plus group will differ and goodness of fit calculation may be impaired if the original length composition data does not include all of the large individuals in samples.

In the current version of the CASA model, the size of length composition bins must be  $\geq L_{bin}$  in the population model (this constraint will be removed in later versions). Ideally, the size of data length bins is the same or a multiple of the size of length bins in the population. However, this is not required and the model will prorate the predicted population composition for each bin into adjacent data bins when calculating goodness of fit. With a 30-34 mm population bin and 22-31 and 32-41 mm population bins, for example, the predicted proportion in the population bin would be prorated so that 2/5 was assigned to the first data bin and 3/5 was assigned to the second data bin. This proration approach is problematic when it is used to prorate the plus group in the population model into two data bins because it assumes that abundance is uniform over lengths within the population group. The distribution of lengths in a real population might be far from uniform between the assumed upper and lower bounds of the plus group.

The first bin in each length composition data record must be  $\geq L_{min}$  which is the smallest size group in the population model. If the last data bin is a plus group, then the *lower* bound of the last data bin must be  $\leq$  the upper bound of the last population bin. Otherwise, if the last data bin is not a plus group, the *upper* bound of the last data bin must be  $\leq$  the upper bound of the population bin.

NLL calculations for survey length composition data are similar to calculations for fishery length composition data. Surveys index data may measure trends in stock abundance or biomass but survey length composition data are always for numbers (not weight) of individuals in each length group. Survey length composition data represent a sample from the true stock which is modified by survey selectivity, sampling errors and, if applicable, errors in recording length data. For example, with errors in length measurements, individuals

belonging to length bin  $j$ , are mistakenly assigned to adjacent length bins  $j-2, j-1, j+1$  or  $j+2$  with some specified probability. Well-tested methods for dealing with errors in length data can be applied if some information about the distribution of the errors is available (e.g. Methot 2000).

Prior to any other calculations, observed survey length composition data are converted to multinomial proportions:

$$i_{k,y,L} = \frac{n_{k,y,L}}{\sum_{j=L_{k,y}^{first}}^{L_{k,y}^{last}} n_{k,y,j}}$$

where  $n_{k,y,j}$  is an original datum and  $i_{k,y,L}$  is the corresponding proportion. As described above, the user specifies the first  $L_{k,y}^{first}$  and last  $L_{k,y}^{last}$  length groups to be used in calculating goodness of fit for each length composition and specifies whether the largest and smallest groups should be treated as “plus” groups that contain all smaller or larger individuals.

Using notation for goodness of fit survey index data (see above), predicted length compositions for surveys that track abundance or biomass are calculated:

$$A_{k,y,L} = \frac{s_{k,L} N_{y,L} e^{-Z_{y,j}\tau_{k,y}}}{\sum_{L=L_{k,y}^{first}}^{L_{k,y}^{last}} s_{k,j} N_{y,j} e^{-Z_{y,j}\tau_{k,y}}}$$

Predicted length compositions for surveys that track numbers of individuals killed by natural mortality are calculated:

$$A_{k,y} = \frac{s_{k,L} \tilde{M}_{y,L} \bar{N}_{y,L}}{\sum_{L=L_{k,y}^{first}}^{L_{k,y}^{last}} s_{k,L} \tilde{M}_{y,L} \bar{N}_{y,L}}$$

Considering the possibility of structured measurement errors, the expected length composition  $\vec{A}'_{k,y}$  for survey catches is:

$$\vec{A}'_{k,y} = \vec{A}_{k,y} E_k$$

where  $E_k$  is an error matrix that simulates errors in collecting length data by mapping true length bins in the model to observed length bins in the data.

The error matrix  $E_k$  has  $n_L$  rows (one for each true length bin) and  $n_L$  columns (one for each possible observed length bin). For example, row  $k$  and column  $j$  of the error matrix gives the conditional probability  $P(k|j)$  of being assigned to bin  $k$ , given that an individual actually belongs to bin  $j$ . More generally, column  $j$  gives the probabilities that an individual actually belonging to length bin  $j$  will be recorded as being in length bins  $j-2, j-1, j, j+1, j+2$  and so on. The columns of  $E_k$  add to one to account for all possible outcomes in assigning individuals to observed length bins.  $E_k$  is the identity matrix if there are no structured measurement errors.

In CASA, the probabilities in the error matrix are computed from a normal distribution with mean zero and  $CV = e^{\pi_k}$ , where  $\pi_k$  is an estimable parameter. The normal distribution is truncated to cover a user-specified number of observed bins (e.g. 3 bins on either side of the true length bin).

The NLL for observed proportions at length in each survey and year is computed with the kernel for a multinomial distribution, the model's estimate of proportional survey catch-at-length ( $\hat{i}_{k,y,L}$ ) and the effective sample size ' $N_y$ ' supplied by the user. Residuals are not used in computing NLL for length composition data but are available for use in checking model fit.

### Residuals for goodness of fit to length data

Three types of residuals are calculated automatically for all of the length composition data used in the model and are written to a special output file that can be used to make residual plots and other diagnostics. The output file contains one record for set of length composition data and length bin used in goodness of fit calculations. Each record contains the name of the survey, survey id number, length, length bin id number, observed proportion, predicted proportion and three types of residuals (simple, Pearson and deviance).

For length composition type  $t$ , in year  $y$  and length  $L$ , the simple residual is

$$r_{t,y,L} = p_{t,y,L} - \hat{p}_{t,y,L}$$

where  $p_{t,y,L}$  and  $\hat{p}_{t,y,L}$  are observed and predicted proportions at length. The Pearson residual is

$$\rho_{t,y,L} = \frac{r_{t,y,L}}{\hat{p}(1-\hat{p})/N_{t,y,L}}$$

where the denominator is the expected standard deviation given the predicted proportion and the effective sample size used in goodness of fit calculations. The deviance residual is basically the contribution of the length composition observation to the total likelihood:

$$\delta_{t,y,L} = \text{sign}(r_{t,y,L})' N_{t,y,L} [p_{r,y,L} \ln(\hat{p}_{r,y,L}) - p_{r,y,L} \ln(p_{r,y,L})]$$

Note that the deviance residual is zero if the observed and predicted proportions match exactly and that the deviance and simple residuals have the same sign.

### Effective sample size for length composition data

Effective sample sizes that are specified by the user are used in goodness of fit calculations for survey and fishery length composition data. A post-hoc estimate of effective sample size can be calculated based on goodness of fit in a model run (Methot 1989). Consider the variance of residuals for a single set of length composition data with  $N$  bins used in calculations. The variance of the sum based on the multinomial distribution is:

$$\sigma^2 = \sum_{j=1}^N \left[ \frac{\hat{p}_j(1-\hat{p}_j)}{\varphi} \right]$$

where  $\varphi$  is the effective sample size for the multinomial and  $\bar{p}_j$  is the predicted proportion in the  $j^{\text{th}}$  bin from the model run. Solve for  $\varphi$  to get:

$$\varphi = \frac{\sum_{j=1}^N [\hat{p}_j(1-\hat{p}_j)]}{\sigma^2}$$

The variance of the sum of residuals can also be calculated:

$$\sigma^2 = \sum_{j=1}^N (p_j - \hat{p}_j)^2$$

This formula is approximate because it ignores the traditional correction for bias. Substitute the third expression into the second to get:

$$\varphi = \frac{\sum_{j=1}^N [\hat{p}_j (1 - \hat{p}_j)]}{\sum_{k=1}^N (p_j - \hat{p}_j)^2}$$

which can be calculated based on model outputs. The assumed and effective sample sizes will be similar in a reasonable model when the assumed sample sizes are approximately correct. Effective sample size calculations can be used iteratively to manually adjust input values to reasonable levels (Methot 1989).

### Variance constraints on dev parameters

Variability in dev parameters (e.g. for natural mortality, recruitment or fishing mortality) can be limited using variance constraints that assume the deviations are either independent or that they are autocorrelated and follow a random walk. When a variance constraint for independent deviations is activated, the model calculates the NLL for each log scale residual  $\gamma_y / \sigma_\gamma$ , where  $\gamma_y$  is a dev parameter and  $\sigma$  is a log-scale standard deviation. If the user supplies a positive value for the arithmetic scale CV, then the NLL is calculated assuming the variance is known. Otherwise, the user-supplied CV is ignored and the NLL is calculated with the standard deviation estimated internally. Calculations for autocorrelated deviations are the same except that the residuals are  $(\gamma_y - \gamma_{y-1}) / \sigma_\gamma$  and the number of residuals is one less than the number of dev parameters.

### LPUE data

Commercial landings per unit of fishing effort (LPUE) data are modeled in the current implementation of the CASA model as a linear function of average biomass available to the fishery, and as a nonlinear function of average available abundance. The nonlinear relationship with abundance is meant to reflect limitations in “shucking” capacity for sea scallops.<sup>22</sup> Briefly, tows with large numbers of scallops require more time to sort and shuck and therefore reduce LPUE from fishing trips when abundance is high. The effect is exaggerated when the catch is composed of relatively small individuals. In other words, at any given level of stock biomass, LPUE is reduced as the number of individuals in the catch increases or, equivalently, as the mean size of individuals in the catch is reduced.

Average available abundance in LPUE calculations is:

$${}^a\bar{N}_y = \sum_{L=1}^{n_L} s_{y,L} \bar{N}_{y,L}$$

and average available biomass is:

$${}^a\bar{B}_y = \sum_{L=1}^{n_L} s_{y,L} w_L^f \bar{N}_{y,L}$$

where the weights at length  $w_L^f$  are for the fishery rather than the population. Predicted values for LPUE data are calculated:

$$\hat{L}_y = \frac{{}^a\bar{B}_y \eta}{\sqrt{\varphi^2 + {}^a\bar{N}_y^2}}$$

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<sup>22</sup> D. Hart, National Marine Fisheries Service, Northeast Fisheries Science Center, Woods Hole, MA, pers. comm.

Measurement errors in LPUE data are assumed normally distributed with standard deviations  $\sigma_y = CV_y \hat{L}_y$ . Standardized residuals are  $r_y = (L_y - \hat{L}_y)/\sigma_y$ .

#### *Per recruit (SBR and YPR) reference points*

The user specifies a target %SBR value for each reference point that is estimated. Goodness of fit is calculated as the sum of squared differences between the target %SBR and %SBR calculated based on the reference point parameter. Except in pathological situations, it is always possible to estimate %SBR reference point parameters so that the target and calculated %SBR levels match exactly. Reference point parameters should have no effect on other model estimates and the residual (calculated – target %SBR) should always be very close to zero.

Goodness of fit for  $F_{0,1}$  estimates is calculated in a manner similar to %SBR reference points. Goodness of fit is calculated as the squared difference between the slope of the yield curve at the estimate and one-tenth of the slope at the origin. Slopes are computed numerically using central differences if possible or one-sided (right hand) differences if necessary.

$F_{max}$  is estimated differently in preliminary and final phases. In preliminary phases, goodness of fit for  $F_{max}$  is calculated as  $(1/Y)^2$ , where  $Y$  is yield per recruit at the current estimate of  $F_{max}$ . In other words, yield per recruit is maximized by finding the parameter estimate that minimizes its inverse. This preliminary approach is very robust and will find  $F_{max}$  if it exists. However, it involves a non-zero residual  $(1/Y)$  that interferes with calculation of variances and might affect other model estimates. In final phases, goodness of fit for  $F_{max}$  is calculated as  $(d^2)$  where  $d$  is the slope of the yield per recruit curve at  $F_{max}$ . The two approaches give the same estimates of  $F_{max}$  but the goodness of fit approach used in the final phases has a residual of zero (so that other model estimates are not affected) and gives more reasonable variance estimates. The latter goodness of fit calculation is not used during initial phases because the estimates of  $F_{max}$  tend to “drift down” the right hand side of the yield curve in the direction of decreasing slope. Thus, the goodness of fit calculation used in final phases works well only when the initial estimate of  $F_{max}$  is very close to the best estimate.

Per recruit reference points should have little or no effect on other model estimates. Problems may arise, however, if reference points (particularly  $F_{max}$ ) fall on the upper bound for fishing mortality. In such cases, the model will warn the user and advise that the offending reference points should not be estimated. *It is good practice to run CASA with and without reference point calculations to ensure that reference points do not affect other model estimates including abundance, recruitments and fishing mortality rates.*

#### **Growth data**

Growth data in CASA consist of records giving initial length, length after one year of growth, and number of corresponding observations. Growth data may be used to help estimate growth parameters that determine the growth matrix  $P$ . The first step is to convert the data for each starting length to proportions:

$$P(b,a) = \frac{n(b,a)}{\sum_{j=n_L-b+1}^{n_L} n(j,a)}$$

where  $n(b,a)$  is the number of individuals starting at size  $a$  that grew to size  $b$  after one year. The NLL is computed assuming that observed proportions  $p(a|b)$  at each starting size are a sample from a multinomial distribution with probabilities given by the corresponding column in the models estimated growth matrix  $P$ . The user must specify an effective sample size  $N_j$  based, for example, on the number of observations in each bin or the number of individuals contributing data to each bin. Observations outside bin ranges specified by the

user are ignored. Standardized residuals for plotting are computed based on the variance for proportions.

### **Survey gear efficiency data**

Survey gear efficiency for towed trawls and dredges is the probability of capture for individuals anywhere in the water column or sediments along the path swept by the trawl. Ideally, the area surveyed and the distribution of the stock coincides so that:

$$I_{k,y} = q_k B_{k,y}$$

$$q_k = \frac{a_k e_k u_k}{A}$$

$$e_k = \frac{A q_k}{a_k u_k}$$

$$K_t = \frac{A}{a_k u_k}$$

$$e_k = K_t q_t$$

where  $I_{k,y}$  is a survey observation in units equivalent to biomass (or numerical) density (e.g. kg per standard tow),  $B_{k,y}$  is the biomass (or abundance) available to the survey,  $A$  is the area of the stock,  $a_k$  is the area swept during one tow,  $0 < e_k \leq 1$  is efficiency of the survey gear, and  $u_k$  is a constant that adjusts for different units.

Efficiency estimates from studies outside the CASA model may be used as prior information in CASA. The user supplies the mean and CV for the prior estimate of efficiency, along with estimates of  $A_k$ ,  $a_k$  and  $u_k$ . At each iteration of the model, the gear efficiency implied by the current estimate of  $q_k$  is computed. The model then calculates the NLL of the implied efficiency estimate assuming it was sampled from a unimodal beta distribution with the user-specified mean and CV.

If efficiency estimates are used as prior information (if the likelihood weight  $\lambda > 0$ ), then it is very important to make sure that units and values for the survey data ( $I$ ), biomass or abundance ( $B$ ), stock area ( $A$ ), area per tow ( $a$ ), and adjustments for units ( $u$ ) are correct (see Example 1). The units for biomass are generally the same as the units for catch data. In some cases, incorrect specifications will lead to implied efficiency estimates that are  $\leq 0$  or  $\geq 1$  which have zero probability based on a standard beta distribution used in the prior. The program will terminate if  $e \leq 0$ . If  $e \geq 1$  during an iteration, then  $e$  is set to a value slightly less than one and a penalty is added to the objective function. In some cases, incorrect specifications will generate a cryptic error that may have a substantial impact on estimates.

Implied efficiency estimates are useful as a model diagnostic even if very little prior information is available because some model fits may imply unrealistic levels of implied efficiency. The trick is to down weight the prior information (e.g.  $\lambda=1e^{-6}$ ) so that the implied efficiency estimate has very little effect on model results as long as  $0 < e < 1$ . Depending on the situation, model runs with  $e$  near a bound indicate that estimates may be implausible. In addition, it may be useful to use a beta distribution for the prior that is nearly a uniform distribution by specifying a prior mean of 0.5 and variance slightly less than  $1/12=0.083333$ .

Care should be taken in using prior information from field studies designed to estimate survey gear efficiency. Field studies usually estimate efficiency with respect to individuals on the same ground (e.g. by sampling the same grounds exhaustively or with two types of gear). It seems reasonable to use an independent efficiency estimate and the corresponding survey index to estimate abundance in the area surveyed. However, stock assessment models are usually applied to the entire stock, which is probably distributed over a larger area than the area covered by the survey. Thus the simple abundance calculation based on efficiency and

the survey index will be biased low for the stock as a whole. In effect, efficiency estimates from field studies tend to be biased high as estimates of efficiency relative to the entire stock.

### **Maximum fishing mortality rate**

Stock assessment models occasionally estimate absurdly high fishing mortality rates because abundance estimates are too small. The NLL component used to prevent this potential problem is:

$$L = \lambda \sum_{t=0}^N (d_t^2 + q_t^2)$$

where:

$$d_t = \begin{cases} F_t - \Phi & \text{if } F_t > \Phi \\ 0 & \text{otherwise} \end{cases}$$

and

$$q_t = \begin{cases} \ln(F_t / \Phi) & \text{if } F_t > \Phi \\ 0 & \text{otherwise} \end{cases}$$

with the user-specified threshold value  $\Phi$  set larger than the largest value of  $F_t$  that might possibly be expected (e.g.  $\Phi=3$ ). The weighting factor  $\lambda$  is normally set to a large value (e.g. 1000).

## APPENDIX B11: Forecasting methodology (SAMS model)

The model presented here is a modified version of the SAMS (Scallop Area Management Simulator) model used to project abundances and landings as an aid to managers since 1999. Subareas were chosen to coincide with current management. Thus, Georges Bank was divided into three open areas (South Channel, Northern Edge and Peak, and Southeast Part), the three access portions of the groundfish closures, and the three no access portions of these areas. The Mid-Atlantic was subdivided into six areas: Virginia Beach, Delmarva, the Elephant Trunk Closed Area, the Hudson Canyon South Access Area, New York Bight, and Long Island.

### Methods

The model follows, for each area  $i$  and time  $t$ , population vectors  $\mathbf{p}(i,t) = (p_1, p_2, \dots, p_n)$ , where  $p_j$  represents the density of scallops in the  $j$ th size class in area  $i$  at time  $t$ . The model uses a difference equation approach, where time is partitioned into discrete time steps  $t_1, t_2, \dots$ , with a time step of length  $\Delta t = t_{k+1} - t_k$ . The landings vector  $\mathbf{h}(i,t_k)$  represents the catch at each size class in the  $i$ th region and  $k$ th time step. It is calculated as:

$$h(i, t_k) = [I - \exp(\Delta t H(i, t_k))] p(i, t_k),$$

where  $I$  is the identity matrix and  $H$  is a diagonal matrix whose  $j$ th diagonal entry  $h_{jj}$  is given by:

$$h_{jj} = 1/(1 + \exp(s_0 - s_1 * s))$$

where  $SH$  is the shell height of the mid-point of the size-class. The parameters  $s_0$  and  $s_1$  are derived in Appendix V.

The landings  $L(i, t_k)$  for the  $i$ th region and  $k$ th time step are calculated using the dot product of landings vector  $\mathbf{h}(i, t_k)$  with the vector  $\mathbf{m}(i)$  representing the vector of meat weights at shell height for the  $i$ th region:

$$L(i, t_k) = A_i \mathbf{h}(i, t_k) \bullet \mathbf{m}(i) / (w e_i)$$

where  $e_i$  represents the dredge efficiency in the  $i$ th region, and  $w$  is the tow path area of the survey dredge (estimated as 8/6076 nm<sup>2</sup>).

Even in the areas not under special area management, fishing mortalities tend to not be spatially uniform for poorly mobile stocks such as sea scallops (Hart 2001). Fishing mortalities in open areas were determined by a simple “fleet dynamics model” that estimates fishing mortalities in open areas based on area-specific exploitable biomasses, and so that the overall DAS or open-area  $F$  matches the target. Based on these ideas, the fishing mortality  $F_i$  in the  $i$ th region is modeled as:

$$\mathbf{F}_i = \mathbf{k}^* \mathbf{f}_i^* \mathbf{B}_i$$

where  $B_i$  is the exploitable biomass in the  $i$ th region,  $f_i$  is an area-specific adjustment factor to take into account preferences for certain fishing grounds (due to lower costs, shorter steam times, ease of fishing, habitual preferences, etc.), and  $k$  is a constant adjusted so that the total DAS or fishing mortality meets its target. For these simulations,  $f_i = 1$  for all areas.

Scallops of shell height less than a minimum size  $s_d$  are assumed to be discarded, and suffer a discard mortality rate of  $d$ . Discard mortality was estimated in NEFSC (2004) to be

20%. There is also evidence that some scallops not actually landed may suffer mortality due to incidental damage from the dredge. Let  $F_L$  be the landed fishing mortality rate and  $F_I$  be the rate of incidental mortality. For Georges Bank, which is a mix of sandy and hard bottom, we used  $F_I = 0.15F_L$ . For the Mid-Atlantic (almost all sand), we estimated  $F_I = 0.04F_L$ .

Growth in each subarea was specified by a growth transition matrix  $G$ , based on area-specific growth increment data (see Appendix III).

Recruitment was modeled stochastically, and was assumed to be log-normal in each subarea. The mean, variance and covariance of the recruitment in a subarea was set to be equal to that observed in the historical time-series between 1979-2006 (Mid-Atlantic) and 1982-2006 (Georges Bank). New recruits enter the smallest nine size bins in proportions (1/7,1/7,1/7,1/7,1/7,4/35,3/35,2/35,1/35) at a rate  $r_i$  depending on the subarea  $i$ , and stochastically on the year. Area-specific recruitment rates are given in Table 1. These simulations assume that recruitment is a stationary process, i.e., no stock-recruitment relationship is assumed (NEFSC 2004). At the current high biomass levels, it is likely that any stock-recruitment relationship would have asymptoted, so that this assumption is reasonable provided that biomass remain at or above the target level.

The population dynamics of the scallops in the present model can be summarized in the equation:

$$p(i, t_{k+1}) = \rho_i + G \exp(-M\Delta t H) p(i, t_k),$$

where  $\rho_i$  is a random variable representing recruitment in the  $i$ th area. The population and harvest vectors are converted into biomass by using the shell-height meat-weight relationship:

$$W = \exp[a + b \ln(s)],$$

where  $W$  is the meat weight of a scallop of shell height  $s$ . For calculating biomass, the shell height of a size class was taken as its midpoint. A summary of model parameters is given in Table 2.

Commercial landing rates (LPUE) were estimated using an empirical function based on the observed relationship between annual landing rates, expressed as number caught per day (NLPUE) and survey exploitable numbers per tow. At low biomass levels, NLPUE increases roughly linearly with survey abundance. However, at high abundance levels, the catch rate of the gear will exceed that which can be shucked by a seven-man crew. This is similar to the situation in predator/prey theory, where a predator's consumption rate is limited by the time required to handle and consume its prey (Holling 1959). The original Holling Type-II predator-prey model assumes that handling and foraging occur sequentially. It predicts that the per-capita predation rate  $R$  will be a function of prey abundance  $N$  according to a Monod functional response:

$$R = \frac{\alpha N}{\beta + N},$$

where  $\alpha$  and  $\beta$  are constants. In the scallop fishery, however, some handling (shucking) can occur while foraging (fishing), though at a reduced rate because the captain and one or two crew members need to break off shucking to steer the vessel during towing and to handle the gear during haulback. The fact that a considerable amount of handling can occur at the same time as foraging means that the functional response of a scallop vessel will saturate quicker than that predicted by the above equation. To account for this, a modified Holling Type-II model was used, so that the landings (in numbers of scallops) per unit effort (DAS)  $L$  (the predation rate, i.e., NLPUE) will depend on scallop (prey) exploitable numbers  $N$  according to the formula:

$$L = \frac{\alpha N}{\sqrt{\beta^2 + N^2}}. \quad (*)$$

The parameters  $\alpha$  and  $\beta$  to this model were fit to the observed fleet-wide LPUE vs. exploitable biomass relationship during the years 1994-2004 (previous years were not used because of the change from port interviews to logbook reporting). The number of scallops that can be shucked should be nearly independent of size provided that the scallops being shucked are smaller than about a 20 count. The time to shuck a large scallop will go up modestly with size. To model this, if the mean meat weight of the scallops caught,  $g$ , in an area is more than 20 g, the parameters  $\alpha$  and  $\beta$  in (\*) are reduced by a factor  $\sqrt{20/g}$ . This means, for example, that a crew could shuck fewer 10 count scallops per hour than 20 count scallops in terms of numbers, but more in terms of weight.

An estimate of the fishing mortality imposed in an area by a single DAS of fishing in that area can be obtained from the formula  $F_{\text{DAS}} = L_a/N_a$ , where  $L_a$  is the NLPUE in that area obtained as above, and  $N_a$  is the exploitable abundance (expressed as absolute numbers of scallops) in that area. This allows for conversion between units of DAS and fishing mortality.

Initial conditions for the population vector  $\mathbf{p}(i,t)$  were estimated using the 2006 NMFS research vessel sea scallop survey, with dredge efficiency chosen so as to match the 2006 CASA biomass estimates. The initial conditions from the 2006 survey were bootstrapped using the bootstrap model of Smith (1997), so that each simulation run had both its own stochastically determined bootstrapped initial conditions, as well as stochastic recruitment stream.

APPENDIX B11 Table 1 – Mean and covariance of area specific log-transformed recruitment

<b>Mid-Atlantic</b>	HC	VB	ET	DMV	NYB	LI			
<i>Means</i>	4.14	3.88	4.41	4.01	3.39	3.14			
<i>Covariance Matrix</i>									
HC	1.48	0.54	1.14	0.97	0.93	0.65			
VB	0.54	2.04	0.58	1.32	0.06	-0.20			
ET	1.14	0.58	1.96	1.20	0.75	0.74			
DMV	0.97	1.32	1.20	1.84	0.70	0.34			
NYB	0.93	0.06	0.75	0.70	1.17	0.81			
LI	0.65	-0.20	0.74	0.34	0.81	0.98			
<b>Georges Bank</b>	CL1-NA	CL1-Acc	CL2-NA	CL2-Acc	NLS-NA	NLS-Acc	Sch	NEP	SEP
<i>Means</i>	3.67	3.51	2.87	3.34	-2.15	3.41	4.62	3.16	2.38
<i>Covariance Matrix</i>									
CL1-NA	2.92	0.03	0.34	0.32	-1.03	-0.45	0.75	-0.22	-0.47
CL1-Acc	0.03	1.83	0.94	0.77	2.24	0.58	0.61	0.52	0.38
CL2-NA	0.34	0.94	1.98	0.89	-0.40	0.27	0.53	0.33	0.34
CL2-Acc	0.32	0.77	0.89	2.63	2.22	1.34	0.76	1.00	0.77
NLS-NA	-1.03	2.24	-0.40	2.22	11.03	1.22	0.18	2.09	2.52
NLS-Acc	-0.45	0.58	0.27	1.34	1.22	5.07	0.25	0.72	0.39
Sch	0.75	0.61	0.53	0.76	0.18	0.25	1.27	0.20	0.01
NEP	-0.22	0.52	0.33	1.00	2.09	0.72	0.20	0.82	0.57
SEP	-0.47	0.38	0.34	0.77	2.52	0.39	0.01	0.57	1.42

APPENDIX B11 Table 2. Model parameters

Parameter	Description	Value
$\Delta t$	Simulation time step	1 y
$M$	Natural mortality rate	0.1 $y^{-1}$
$A$	Shell height/meat wt parameter	-10.70 (GB), -12.01 (MA)
$B$	Shell height/meat wt parameter	2.94 (GB), 3.22 (MA)
$s_0$	Logistic selectivity parameter	9.692
$s_1$	Logistic selectivity parameter	0.1016
$s_d$	Cull size	90 mm
$D$	Mortality of discards	0.2
$E$	Dredge efficiency	0.311 (GB), 0.394 (MA)
$\alpha$	LPUE/biomass relationship	43183
$\beta$	LPUE/biomass relationship	30626

## APPENDIX B12: Simulator testing of CASA and rescaled $F$ models

We conducted simulation testing to detect potential bugs, check accuracy and assess robustness of the CASA, rescaled  $F$ , and Beverton and Holt (1956) stock assessment models for sea scallops. CASA is a new and relatively complex stock assessment approach for sea scallops that uses a wide range of data, involves a number of assumptions, and estimates fishing mortality, abundance, biomass and other population characteristics by maximum likelihood (Appendix B10). The rescaled  $F$  model is a very simple approach used in previous sea scallop assessments (NEFSC 2004) that estimates fishing mortality based on survey data shell height composition, landings data and some information about growth and natural mortality. The Beverton-Holt (1956) model is a simple, equilibrium approach often used for “data poor” stocks. It uses survey size (e.g., shell height) composition data to estimate fishing mortality.

### *Software*

Four independently coded programs were used in testing: a simulator program, the CASA and rescaled  $F$ /Beverton-Holt estimation programs, and an interface program to link them. The first program (SAMS model, Appendix B11) simulates a potentially realistic (e.g. spatially structured) population and saves “true” simulated population information (e.g. abundance at size and catch at size without observation errors) for use by the estimation programs.

The interface program links SAMS output to the three assessment models and summarized test results. The interface constructed data files required to run each assessment model with user specified amounts of observation errors in simulated landings, fishing effort, survey records, LPUE observations and survey and fishery length composition data. All models use the same data (same observation errors) in each iteration.

The interface program runs each assessment model with simulated data, and collects and stores biomass, fishing mortality and other estimates from each model. After a specified number of iterations, the interface summarizes information from each model and iteration. Output from the interface program includes tables that compare estimates of biomass and fishing mortality from each model to the “true” values based on a number of statistics that measure model performance.

The statistics used to measure model performance include the CV, %bias (bias/true value), and %RMSE (root mean squared error/true value) for biomass and fishing mortality. CV measures the relative precision of estimates (variability around their mean). The %bias statistic measures the relative difference between the truth and the average estimate. The %RMSE statistic measures relative accuracy, considering both precision and bias. The three measures are related because  $\text{mean squared error } \text{MSE} = \text{bias}^2 + \text{variance}$ .

Simulated landings and survey abundance data were assumed in simulations to be gamma random variables, with mean equal to their true values and a specified variance. Simulated shell height composition data were multinomial random variables based on a user specified number of samples from the true shell height composition. LPUE data were a nonlinear function of stock biomass and abundance calculated from simulated landings and fishing effort data assuming that observation errors for landings and fishing effort were independent

### *Simulations for sea scallops*

Results are presented below for example simulations of particular relevance to this assessment. Similar to patterns in the real scallop fishery, simulations were for 30 years with true fishing mortality starting at a moderate level ( $F = 0.5$ ), increasing to a high level of  $F = 1.0$ ,

and then fell decreasing to a relatively low level ( $F = 0.3$ ) near the end of the simulation. The simulated population assumed some variability in growth among six areas within a single region.

Simulated data ranged from very precise to imprecise. A single survey abundance index with a flat selectivity curve and LPUE data as a nonlinear index of average fishable abundance was available in each simulated year. There were three sets of sets of simulated data with CVs and multinomial sample sizes listed in the table below. The assessment models were all run 20 times for each set of observation errors.

Scenario (magnitude of observation errors)	CV survey & landings data	CV for effort data	Sample size survey and fishery shell height data
Low	10%	2%	800
Medium	20%	2%	400
High	30%	2%	200

Other than observation errors in simulated data, all of the assessment models were generally configured for optimal model performance. In particular, assumptions about natural mortality and growth assumed in modeling were accurate. Size ranges assumed in tabulating survey data for the rescaled  $F$  model and the assumed critical length in Beverton-Holt model were reasonable choices. The growth transition matrix supplied to CASA was the average transition matrix for all area in the simulations. In CASA modeling, assumptions about the survey selectivity pattern (flat) and the general shape of the fishery selectivity pattern (logistic) were correct. There were no changes in fishery selectivity patterns that might have complicated interpretation of results from any of the models.

## Results

For convenience, model performance statistics were averaged over all years for each model and level of observation error (Table 1). In terms of average percent bias, fishing mortality estimates from the rescaled  $F$  model were consistently biased low (-11 %). CASA model fishing mortality estimates were consistently biased high to a modest extent (< 5%). CASA model abundance and biomass estimates were biased high, usually by less than 10%. CASA estimates of landings were relatively unbiased (-0.3 to -2%). More simulations with larger numbers of iterations are required to make definite conclusions, but %bias was not strongly dependent on the magnitude of observation errors.

CASA model  $F$  estimates were most precise (lower CV, Table 1) than estimates from alternative models unless observation errors were high. CVs for CASA model fishing mortality, abundance, biomass and landings estimates increased almost proportionally with CVs for simulated observation errors assumed in survey and landings data.

Results for %RMSE (Table 1) were similar to results for CVs because bias was modest in all cases and changes in accuracy were due primarily to differences in precision.

Comparison of the mean fishing mortality estimates for each year from the three models gives insights into their performance (Figure 1). The negative bias in the rescaled  $F$  mortality estimates was due to underestimation of fishing mortality during years when true fishing mortality rates were highest. The positive bias of the CASA model was due to a consistent overestimation of mortality during the first four years of the simulation. CASA estimated fishing mortalities that were essentially unbiased after the initial years. The strong

oscillations in the Beverton-Holt estimator are due to recruitment variability in the underlying simulation.

In comparing results for individual years, fishing mortality estimates from the rescaled  $F$  seem more variable than from CASA (Figure 2 to 3). In addition, CASA estimates seem to track trends in true fishing mortality better than estimates from other models. CASA estimates appear to track abundance and biomass with a reasonably well (Figure 3 to 4).

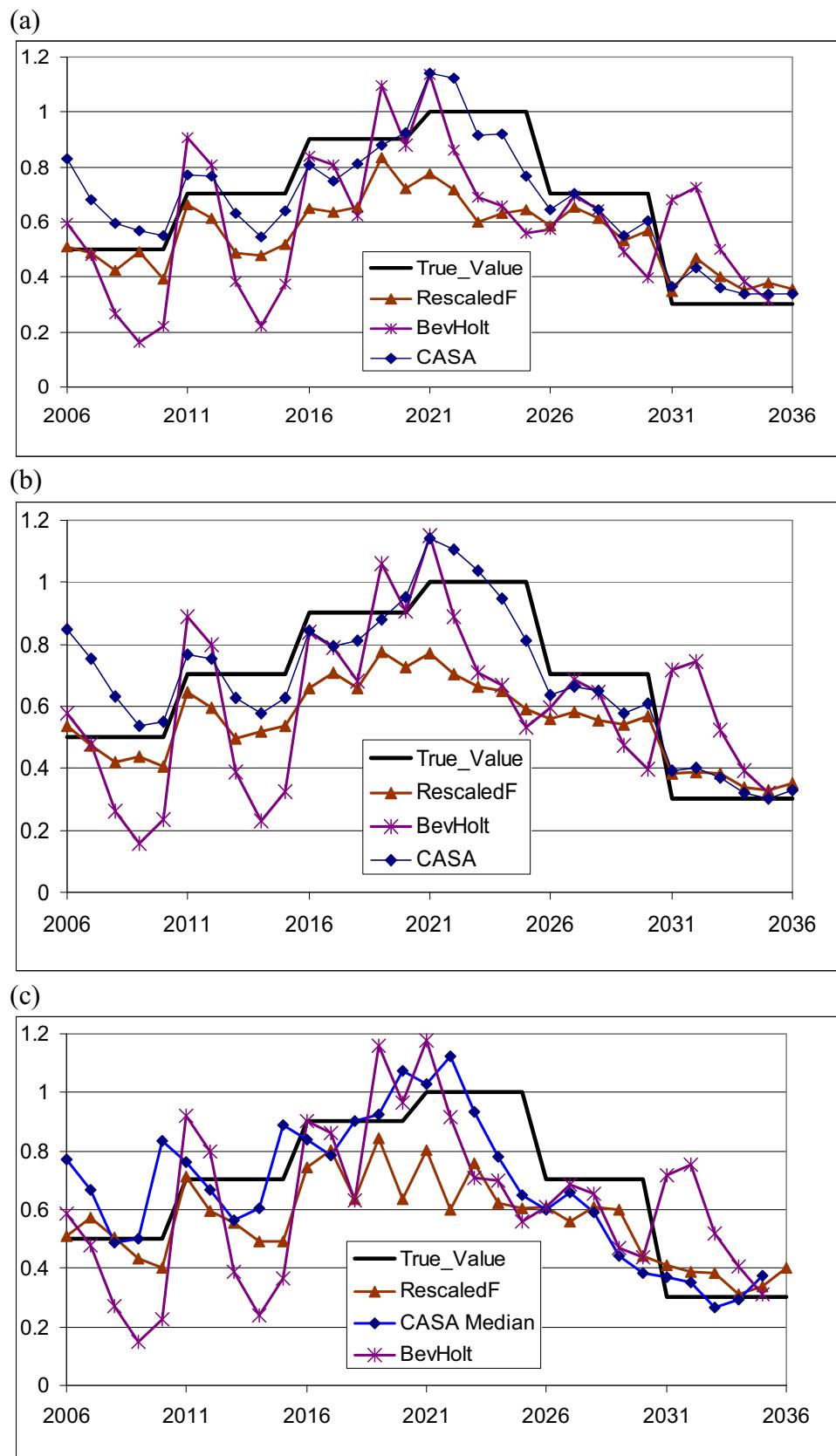
## Conclusions

More testing is required, but simulation tests support use of CASA in this assessment for sea scallops. Results indicate that the CASA model is working properly and estimating abundance and biomass reasonably well. The CASA model generally performed better than the rescaled  $F$  and Beverton-Holt models. With the exception of the first few years, fishing mortality estimates from CASA was nearly unbiased.

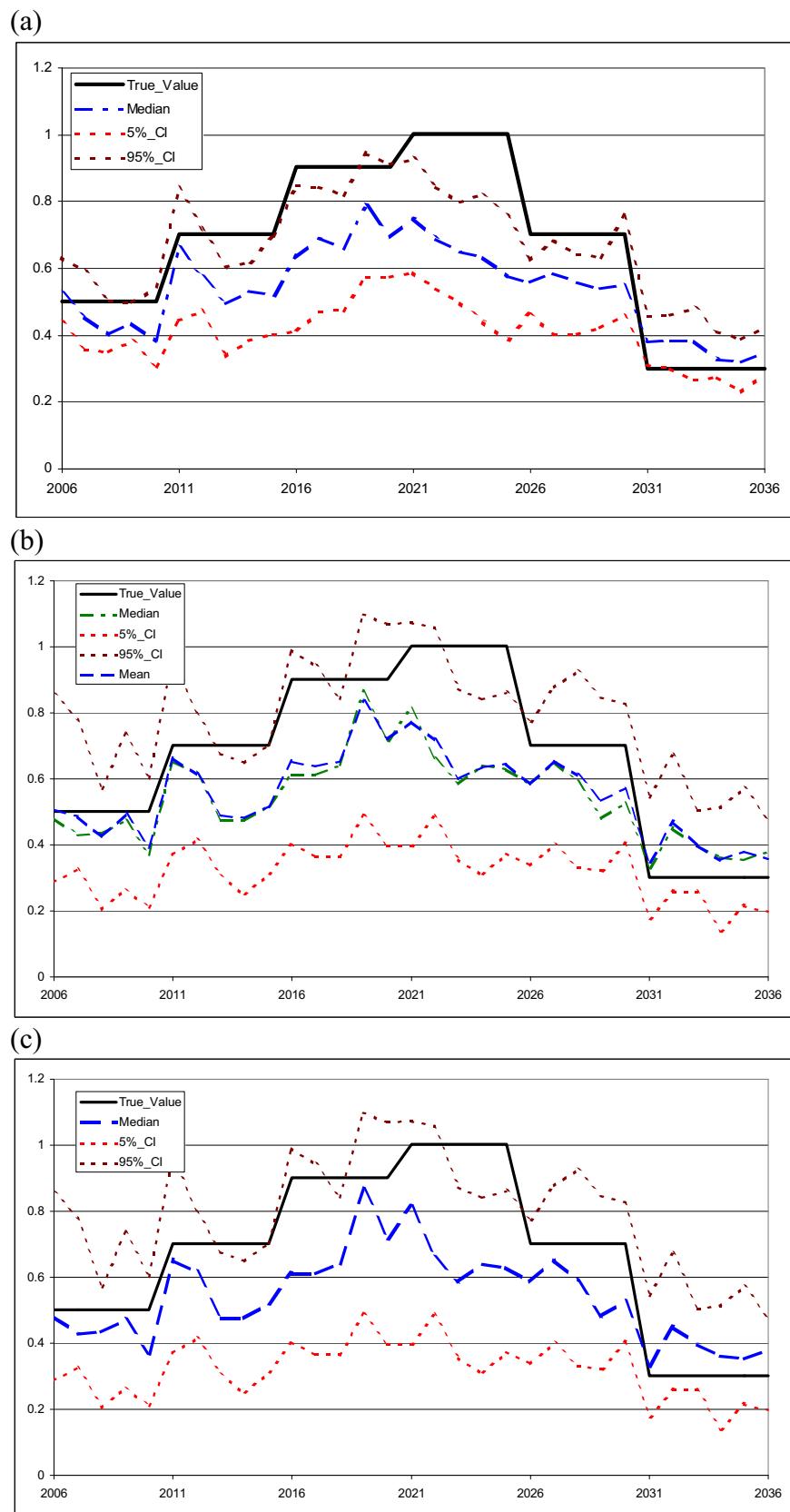
CASA estimates were the most precise and accurate, except at the highest (30%) observation error levels. For sea scallops, low to medium (10-20%) observation errors in survey data are probably more realistic because the dredge and video surveys are relatively precise.

APPENDIX B12 Table 1. Performance measures (%bias, CV and %RMSE) for fishing mortality, abundance, biomass and landings estimates based on simulation testing (20 iterations each). Figures for each model are averages performance measures averaged over 30 simulated years. Performance during individual years may have been better or worse than indicated in the table. The CASA model failed to converge in one iteration with high observation errors. Effects of this run on performance measures for CASA with high levels of observation error were minimized by using medians, instead of means, in the table. When all runs converged, means and medians were similar.

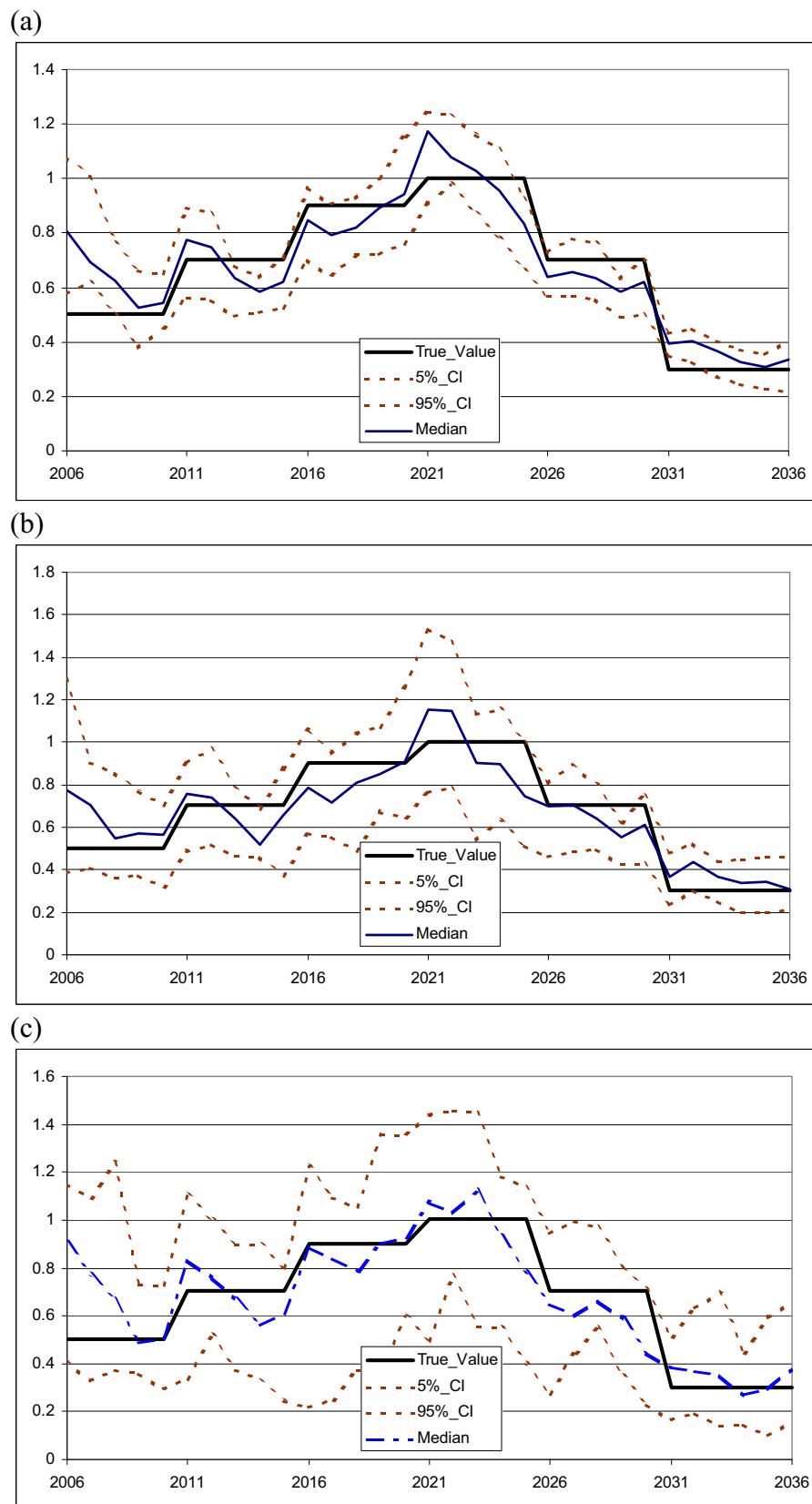
Model / estimate	%Bias			CV			%RMSE		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
	-0.13	-0.11	-0.11	0.15	0.28	0.46	0.26	0.35	0.49
Rescaled F	-0.07	-0.01	0.05	0.11	0.12	0.14	0.23	0.40	0.42
Beverton-Holt F	0.05	0.05	0.03	0.20	0.20	0.30	0.20	0.28	0.32
CASA-F	0.08	0.07	0.12	0.04	0.09	0.49	0.17	0.20	0.58
CASA-Abundance	0.04	0.03	0.07	0.05	0.10	0.57	0.09	0.13	0.61
CASA-Biomass	0.00	0.00	-0.02	0.10	0.20	0.29	0.10	0.20	0.29
CASA-Landings									



APPENDIX B12 Figure 1. Mean annual fishing mortalities for fishing mortality estimates from three models using data with (a) low, (b) medium, and (c) high observation errors.

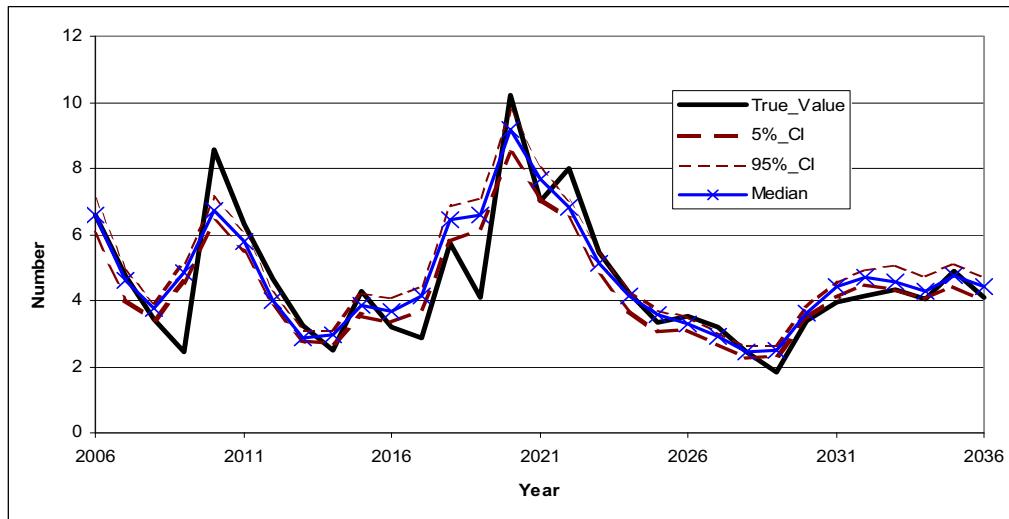


APPENDIX B12 Figure 2. Median, 5<sup>th</sup> and 95<sup>th</sup> percentiles for rescaled  $F$  estimates of annual fishing mortality using data with (a) low, (b) medium, and (c) high observation errors.

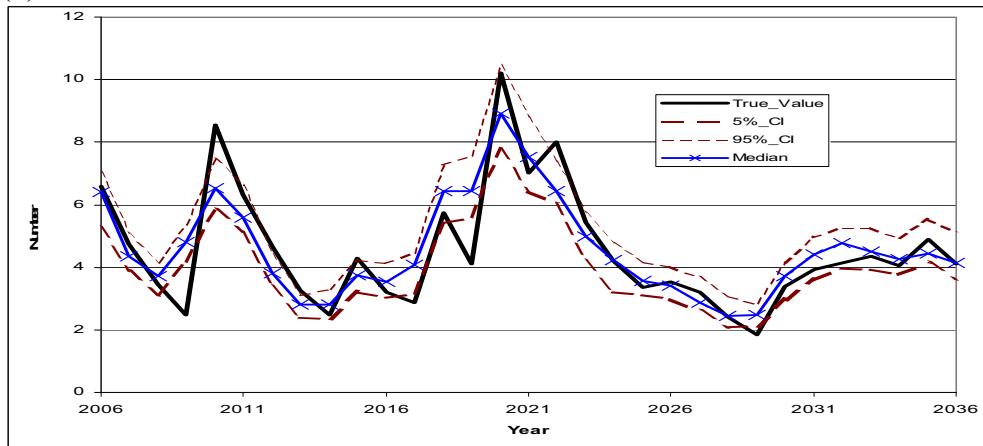


APPENDIX B12 Figure 3. Median, 5<sup>th</sup> and 95<sup>th</sup> percentiles for CASA annual fishing mortality estimates using data with (a) low, (b) medium, and (c) high observation errors.

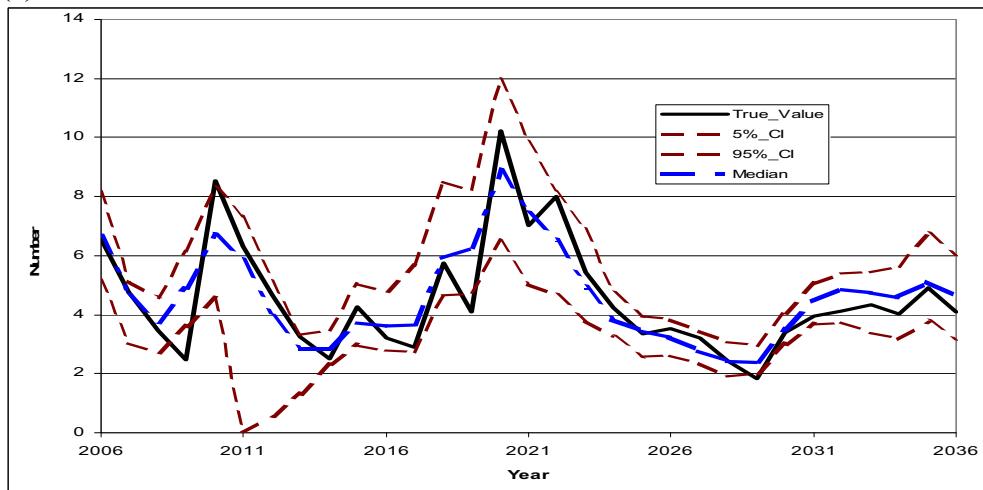
(a)



(b)

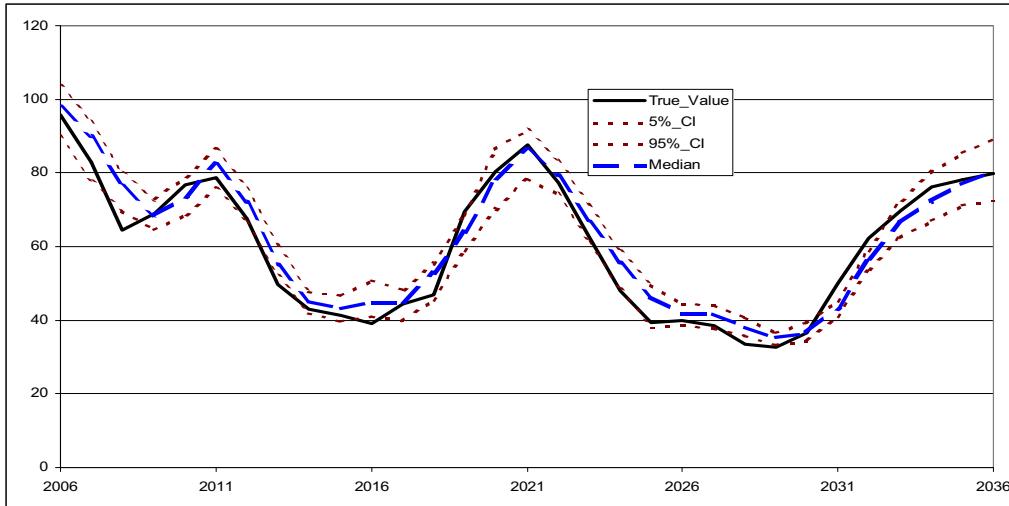


(c)

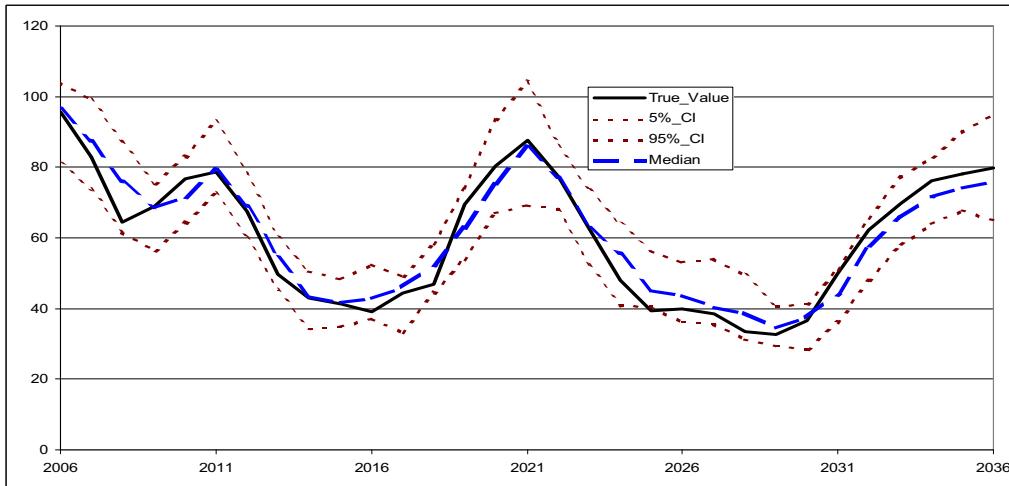


APPENDIX B12 Figure 4. Median, 5<sup>th</sup> and 95<sup>th</sup> percentiles of CASA annual abundance estimates using data with (a) low, (b) medium, and (c) high observation errors.

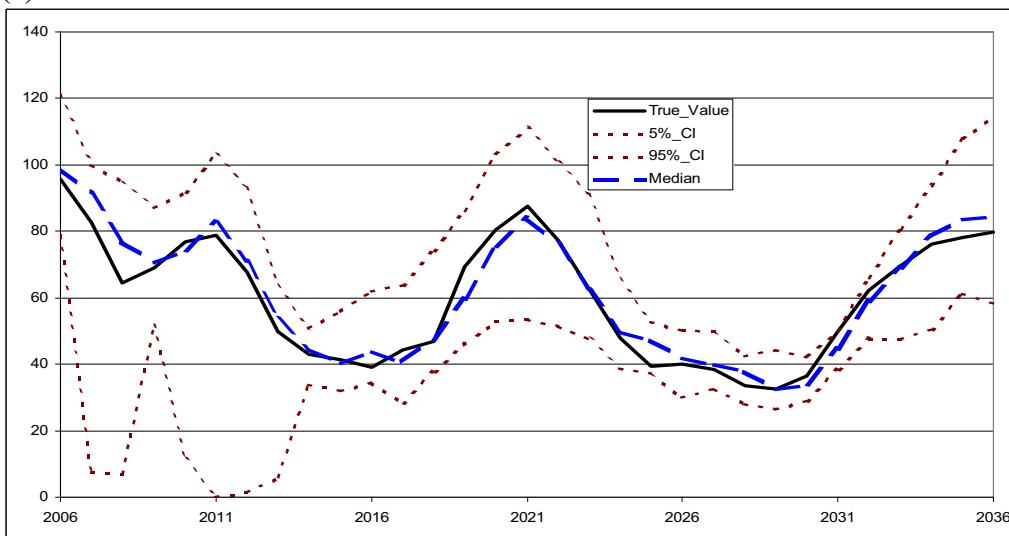
(a)



(b)



(c)



APPENDIX B12 Figure 5. Median, 5<sup>th</sup> and 95<sup>th</sup> percentiles for CASA annual biomass estimates using data with (a) low, (b) medium, and (c) high observation errors.

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