

B. Stock Assessment for Atlantic Sea Scallops
(Placopecten magellanicus)

Consensus Assessment Report

SARC 39

SAW Invertebrate Subcommittee^{1,2}

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1.0 STOCK SUMMARY

This stock assessment is summarized a separate *Assessment Summary* document . This document includes the stock assessment and five appendices that contain important information.

2.0 TERMS OF REFERENCE

(A) Update status of the Georges Bank, Mid-Atlantic and Gulf of Maine sea scallop resources through 2003 using all applicable information, including fishery dependent information and fishery independent surveys (e.g. NEFSC trawl survey, SMAST video survey and others as appropriate). Provide estimates of fishing mortality and stock size. Characterize uncertainty in estimates.

(B) Evaluate stock status relative to current reference points.

(C) Provide short-term projections of stock biomass and catches consistent with target fishing mortality rates

(D) Update estimates of biological reference points (e.g. B-MSY, F-MSY) using revised biological and fisheries data, as appropriate.

(E) Evaluate information provided by various current survey approaches and suggest possible ways to integrate their results.

(F) Continue the development of stock assessment modeling approaches that integrate all appropriate sources of fishery dependent and fishery independent data.

3.0 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 U.S. 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. U. S. landings during 2003 exceeded 25,000 MT (meats), a new record, and 2003 U.S. ex-vessel sea scallop revenues were over \$226 million making the sea scallop fishery the second most valuable in the northeastern United States. Unusually strong recruitment in the Mid-Atlantic Bight area in recent years has been one contributor to the landings; recruitment in the Mid-Atlantic area during the last six years (1998-2003) was over an order of magnitude higher than the six-year period at the start of the survey time series (1979-1984). Increased yield-per-recruit due to effort reduction measures has also contributed to the high landings. The mean meat weight of a landed scallop is now over 20g, compared to under 14g a decade ago.

Area closures have had a strong influence on sea scallop population dynamics. Roughly one-half of the productive scallop grounds on Georges Bank and Nantucket Shoals have been closed for most of the time since December 1994. Scallop abundance and biomass has built up in

these closed areas; currently over 80% of the sea scallop biomass in the U.S. portion of Georges Bank is in areas closed to fishing. Portions of Georges Bank closed areas were temporarily opened for limited scallop fishing during 1999-2001, and a regular rotation of openings is planned to begin during the summer of 2004. While there are no indefinite closures in the Mid-Atlantic, two areas were closed for three years starting in 1998 in order to allow small scallops in these areas to grow to more optimal sizes before they are harvested. A new rotational closure is planned to go into effect in the Mid-Atlantic starting in 2004.

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. In Georges Bank and the Mid-Atlantic, most are harvested at depths between 30 and 100 m, while the bulk of the landings from the Gulf of Maine are from near-shore relatively shallow waters (< 40 m). Sea scallops filter-feed on phytoplankton, microzooplankton, and detritus particles. Sexes are separate with external fertilization, and larvae are planktonic for 4-7 weeks before settling to the bottom. Scallops recruit to the NEFSC survey at about 2 years old (40-70 mm), and to the commercial fishery currently around 4 years old (90-105 mm), though historically most three year olds (70-90 mm) were vulnerable to the commercial fishery.

According to Amendment 10 of the Atlantic Sea Scallop Fishery Management Plan, all scallops in the US EEZ belong to a single stock. However, the U.S. 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 2001). Biologically, the stock is likely composed of smaller regional meta-populations with some movement of larvae from Georges Bank into Southern New England and from Southern New England to the Mid-Atlantic. The main regional components are Georges Bank (including the Great South Channel and Nantucket Shoals) and the Mid-Atlantic Region. NEFSC shellfish survey strata are helpful in defining regional components of the sea scallop stock for assessment work (Fig. B3-1). However, relatively small, but imprecisely known, amounts of sea scallop biomass occur in areas outside regularly surveyed NEFSC shellfish strata. Landings from other regions have been relatively small (Table B3-1). Abundance and fishing mortality estimates for Georges Bank and the Mid-Atlantic are estimated separately in this assessment and then combined to characterize the condition of the stock as a whole.

Age and growth

Sea scallops grow rapidly during the first few years of life with a 50-80% increase in shell height and quadrupling in meat weight between the ages of 3 and 5 years old (Fig. B3-2). The largest observed sea scallop had a shell height (SH) of about 23 cm (shell height is the longest distance between the umbo and outer margin of a scallop shell; length measurements of scallops throughout this assessment are shell heights), but animals larger than 17 cm are rare in commercial and survey catches.

Sea scallop growth is traditionally modeled using the von Bertalanffy growth equation. Growth parameters for an average scallop used in this stock assessment (see table below) were estimated using shell heights and age data from presumably annual rings patterns in shell samples (Serchuk et al. 1979). Merrill et al. (1966) reported problems with identification of annual rings on the external surface of the valve and proposed ring counts in the resilium (hinge ligament) to age scallops. Age determinations by ring counts conflicted with results from oxygen isotope studies by Krantz (1983) and Krantz et al. (1984). In contrast, Tan et al. (1988) found that isotope studies and ring counts gave consistent ages. All of the isotope studies were based on only a few samples, however.

Analysis of growth in closed areas indicated the possibility that growth in the Georges Bank closed areas might be greater than that predicted by the Serchuk et al. with the growth parameter K in closed areas perhaps higher by about 20% (NEFSC 2001). Increased growth might be due to the closure (e.g., if disturbances caused by fishing gear reduced the growth rate of the scallops), or to a Lee's effect with fast growers fished harder and therefore underrepresented in shell samples. Temporal changes in the growth rate, differences were due to ageing techniques and \ statistical errors are also possible. Additionally, because growth depends on depth (Posgay 1979, Schick et al. 1988, Smith et al. 2001), it is possible that the apparently faster growth reflects the depth distribution of certain dominant year classes. In the Mid-Atlantic, analysis of the growth in closed areas suggests that growth is somewhat slower than predicted by the Serchuk et al. equation (NEFSC 2001).

Von Bertalanffy growth parameters (Serchuk et al. 1979).

| Stock Area | K (y^{-1}) | L_{∞} (mm) |
|--------------|---------------------|-------------------|
| Georges Bank | 0.3374 | 152.46 |
| Mid-Atlantic | 0.2997 | 151.84 |

Maturity and fecundity

Sexual maturity commences at age 2 but scallops younger than 4 years may contribute little to total egg production (MacDonald and Thompson 1985; NEFSC 1993). 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.

Shell height/meat weight relationships

Shell height-meat weight relationships are important because survey data are in numbers of scallops by shell height while landings data are in meat weights. Shell height/meat weight relationships are described by the equation $\ln(W) = \alpha + \beta \ln(L)$, where W is meat weight in grams and L is shell height in mm. Survey samples collected in 1997-1998 (NEFSC 1999) suggested that mean meat weights were smaller than the estimates in Serchuk and Rak (1983) that were

used in previous assessments. NEFSC (2001) combined the Serchuk and Rak (1983) with those of NEFSC (1999) to obtain new “blended” estimates (see table below).

Shell height-meat weight relationships vary seasonally and interannually and are affected by depth, temperature, location and other factors. According to Serchuk and Smolowitz (1989), meat weights are generally lowest during September-December after spawning, highest in the spring (March-May), and intermediate during the summer (June-August) when NEFSC sea scallop surveys are usually conducted and shell height-meat samples were collected. No adjustments were made to shell height-meat weight parameters in this assessment for any of these factors. Rather, the assessment assumes that shell height-meat weight parameters from survey samples taken over the entire stock area during the summer approximate average values for the stock as whole during the entire year during all years.

| | α | β |
|----------------------|----------|---------|
| Georges Bank | | |
| NEFSC (1999) | 11.4403 | 3.0734 |
| Serchuk & Rak (1983) | 11.7656 | 3.1693 |
| NEFSC (2001) | 11.6038 | 3.1221 |
| Mid-Atlantic Bight | | |
| NEFSC (1999) | 12.3405 | 3.2754 |
| Serchuk & Rak (1983) | 12.1628 | 3.2539 |
| NEFSC (2001) | 12.2484 | 3.2641 |

Recruitment

McGarvey et al. (1993) reported a stock-recruit relationship for sea scallops on Georges Bank, but that relationship was driven mostly by a single year class (1978), and thus remains questionable. From 1982-1994, no relationship was observed between spawning stock biomass and recruits two or three years later, possibly because of the low contrast in spawning biomass. Since 1994, there has been a large increase in spawning-stock biomass in Georges Bank, primarily due to area closures. A log-log plot of egg production (including the Canadian portion of Georges Bank) vs. recruits (U.S. portion only, 40-72 mm)/egg production gives insight as to the possibility of a stock-recruitment relationship in sea scallops (Fig B3-3a). A regression line fit to the data with a slope of zero would indicate that recruitment is directly proportional to egg production, whereas a slope of -1 would indicate no relationship between recruitment and egg production. Slopes between 0 and -1 suggest partial compensation, while a slope less than -1 implies over-compensation. Linear regression results for sea scallops on Georges Bank stock had a slope of -0.85 ($R^2 = 0.3$), indicating a slight tendency for increased recruitment at higher spawning biomasses. However, the slope was imprecisely estimated and could not be distinguished statistically from a slope of -1 . Therefore, there is little evidence at this time for a relationship between egg production and recruitment on Georges Bank.

A similar linear regression analysis for the Mid-Atlantic gives a slope of -0.3 (Fig B3-3b), suggesting a relationship between egg production and recruitment and that recent increases

in spawning stock biomass may have induced increases in recruitment. However, the high egg production has all been in the most recent years (especially the last four years available). Besides a stock-recruitment relationship, such a pattern could be caused by autocorrelated environmental factors, where good environmental conditions for recruitment over a period of years induce high spawning biomass.

Besides traditional stock-recruitment relationships, fishing activity might directly affect recruitment success. A number of unproven hypotheses exist. The large area closures on Georges Bank give an excellent opportunity to explore for such effects, as they can be considered a classic controlled (BACI) manipulation. There are several hypotheses about possible mechanisms that might differentially affect recruitment in closed and open areas. High densities of adult scallops might increase the mortality rate of newly settled juvenile spat due to space limitation, competition for food, or cannibalism. It has been suggested that scallop dredging may increase settlement success by clearing the bottom of benthic fauna. These factors would tend to reduce recruitment in closed areas only. In contrast, if small (pre-recruit) scallops suffer incidental fishing mortality, or if adult scallops or other benthic fauna enhance the survival of settling spat by providing good substrate, then observed recruitment might differentially increase in closed areas compared to open areas.

Larval scallops are probably capable of travel over long distances prior to settlement. Therefore, an increase in larval production within closed areas, due to increases in spawning biomass and/or fertilization success (due to the higher densities within closed areas), could result in improved recruitment within both open and closed areas, whereas the localized effects discussed above would differentially affect the open and closed areas.

To test whether closures have any effect on recruitment, numbers of scallops 40-72 mm in the Georges Bank closed areas (Closed Area I, Nantucket Lightship, and the northern part of Closed Area II) were compared to those in the open areas, both before and after the area closures at the end of 1994. Data from the transitional 1995 year and from the southern portion of Closed Area II were excluded; the latter because it was heavily fished in 1999 and 2000 but closed for the rest of the period. A two-way ANOVA was performed on the log-transformed data, with the independent variables being "period" (i.e., either 1982-1994, or 1996-2003) and "region" (i.e., either currently open areas, or the closed areas). A stock-recruitment relationship caused by an increase in larvae released in the closed areas would be indicated by a "period" effect. Any of the proposed differential effects on post-larval survival between open and closed areas would appear as an interaction term between period and region. Mean recruitment in the open and closed areas was similar, indicating no "region" effect ($p = 0.95$). While recruitment post-closure was higher, the difference was not significant ($p = 0.37$), so that it is inconclusive whether or not the closures have increased recruitment. Because there were similar increases in recruitment in the open and closed areas, there was no evidence of an interaction effect ($p = 0.99$). Thus, the data do not give support to the hypotheses that recruitment would differentially increase or decrease in areas closed to fishing.

Natural mortality estimates from survey “clapper” data

The rate of natural mortality is usually assumed to be $M = 0.1 \text{ y}^{-1}$ for scallops with shell heights $> 40 \text{ mm}$ (NEFSC 1999) 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/L , where L is the number of live scallops) and the rate at which clappers separate (S/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 $M/L = S/C$ and:

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

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 y^{-1} . MacDonald and Thompson (1986) found a similar overall natural mortality rate.

Time-series of estimated trends in natural mortality, based on clapper ratios and Merrill and Posgay’s method, for the Mid-Atlantic and Georges Bank are shown in Figure B3-4. Clapper ratios for both areas tend to be lower than in Merrill and Posgay. It is unclear whether this is because mortality has been lower than in previous time, or whether there were differences in the clapper separation rate or catchability between the recent years and during Merrill and Posgay’s study, or because of 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 2001).

4.0 - FISHERIES

The U.S. sea scallop fishery is conducted mainly by about 300 vessels with limited access permits. However, there has been an increase in recent years in landings from vessels with open access general category permits; these are primarily smaller vessels that fish near-shore beds. Principal ports are New Bedford MA, Cape May NJ, and Norfolk VA. Scallop dredges (mostly the offshore New Bedford style) are the principal gear type in all regions (Table B3-1). However, some scallop vessels use otter trawls in the Mid-Atlantic.

Sea scallop fisheries in U.S. EEZ are managed under the Atlantic Sea Scallop Fishery Management Plan (FMP) initially implemented on May 15, 1982. Until 1994, the primary management control was a minimum average meat weight requirement for landings. Fig. B4-1 gives a timeline of all management measures implemented since 1982.

FMP Amendment #4 (NEFMC 1993), implemented in 1994, changed the management strategy from meat count regulation to effort control for the entire U.S. EEZ. Effort controls included incrementally increasing restrictions on days-at-sea (DAS), minimum ring size, and crew limits (Fig. B4-1). In order to comply with the Sustainable Fisheries Act of 1996, 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, Amendment #10, is expected to be implemented during 2004. This amendment formalizes an area management system, with provisions and criteria for new rotational closures, and separate days-at-sea allocations for reopened closed areas and general open areas. A new rotational closure for the area offshore of Delaware Bay will go into effect when Amendment 10 is implemented. Amendment 10 will allow each vessel with a full-time scallop permit 42 days-at-sea in open areas and four trips with trip limits of 18,000 lbs. in the Hudson Canyon South area that had been closed during 1998-2001. Pending approval of Framework 16, restricted access is anticipated in portions of two of the Georges Bank closed areas during 2004. 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. New gear regulations are scheduled to go into effect in September, 2004, which will require a 4" minimum ring size (an increase from 3.5") to improve selectivity, and a minimum 10" twine top (previously 8" in open areas and 10" in reopened closed areas) to reduce flounder bycatch.

Landings and effort history

Major changes in collection of commercial fishing data for northeast U.S. fisheries occurred in June 1994. Prior to 1994, commercial fishing data were collected based on interviews and the dealer "weigh-out" database. This was changed in 1994 to a new mandatory reporting system comprised of dealer reports (DR) and vessel trip reports (VTR). DR data contain 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. The regulatory and reporting changes cause some uncertainty in comparing trends in fishing effort and catch rates before and after 1994.

Commercial landings data in this assessment were based on port interviews and the weigh-out database prior to April 1994, and on the DR and VTR databases after April 1994.

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 U.S. increased substantially after the mid-1940's (Fig. B4-2), with peaks occurring around 1960, 1978, 1990, and in the most recent period (2001-2003). Maximum U.S. landings were 25,107 MT meats in 2003.

U.S. Georges Bank landings peaked during the early 1960's, and around 1980 and 1990 (Table B3-1 and Figure B4-3). Landings in the U.S. portion of Georges Bank declined precipitously during 1993 and remained low through 1998, before rebounding in 1999, due in part to the reopening of Closed Area II. Landings in Georges Bank during 1999-2003 have been fairly steady, averaging almost 5000 MT annually. Until recently, the Mid-Atlantic area had been less productive than Georges Bank, with landings between 1962-1982 averaging less than 1800 MT/year. Since the mid-eighties, an upward trend in both recruitment and landings is evident in the area. Landings during each of the last four years (2000-03) set new records for the region. Landings were over 19,000 MT in 2003.

Gulf of Maine landings peaked at 1614 MT in 1980, and in general made up a small percentage of total landings. Gulf of Maine sea scallop landings during 2003 (254 MT) were less than 1% of the total.

LPUE data (Fig. B4-4) showed a general downward trend during 1979 to the mid-1990s, but increased considerably in the last five years. As already pointed out, trends in LPUE are complicated by changes in collection of fishing effort data in 1994.

Discards and Fishery Selectivity

The NEFSC sea sampling program collects information about lengths and weight of landed and discarded sea scallops from sampled tows (Fig B4-5). Ratios of discard to total catch (by weight) indicate a general increasing trend in scallop discard rates with peaks in 1994, 2000, and 2003. Except for 2003, the number of observed trips was limited, so that the ratio in a given year may be imprecise. The estimated cull size (defined as the greatest shell height for which 50% or more of scallops caught are discarded) has increased in recent years (Fig B4-5), which in large part explains the recent increase in discarding. Small scallops may be discarded because they provide relatively little meat weight for the time spent shucking.

5.0 – SURVEYS AND SELECTIVITY

NEFSC sea scallop surveys were carried out in 1975 and then annually after 1977 to measure abundance, size composition, and recruitment of sea scallops in the Georges Bank (including the Canadian portion during some years), Mid-Atlantic and occasionally other regions. A 2.44 m (8') lined survey dredge 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 1979-1981. Thus, survey data used in this assessment are for 1982-2003 for Georges Bank and 1979-2003 in the Mid-Atlantic.

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. Therefore, as in previous assessments (e.g., NEFSC 2001), survey indices for the period 1990-93 based on data from the *R/V Oregon* were used without adjustment. The Northern Edge and Peak Area of Georges Bank was not surveyed by any vessel in 1989. Abundances in this area in 1989 were estimated by averaging 1988 and 1990 survey data. The 1989 Georges Bank survey data should be used cautiously because of these potential problems.

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 the computing survey trends, only data from the (port) NMFS survey dredge was used. There were 21 comparison stations occupied by both the *F/V Tradition* and the *R/V Albatross IV* and NEFSC (2001) found no statistically significant differences in catch rates between the two vessels after corrections were made for differences in dredge width (NEFSC 2001).

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; Richards 1996; Lai and Hendrickson 1997, Smith 1997) with some extensions described below.

No valid tows were performed during some years for certain strata. In these cases, the survey data from the same stratum from the two adjacent years (when available) were "borrowed" and averaged to fill in the gap in the time series (NEFSC 2001).

Stratum areas and post-stratification

The stratum areas calculated using GIS (Arcview and Arcinfo) and used by NEFSC (2001) were used also for this assessment. Relatively high abundance of sea scallops in closed areas makes it desirable in some cases to post-stratify survey data by splitting NEFSC shellfish strata that cross open/closed area boundaries. In addition, after post-stratification, it is desirable to group strata into regions corresponding to open and closed areas. Finally, in cases where the closed or open portion of an NEFSC survey stratum was very small, it is necessary to combine the small portion with an adjacent stratum to form a new 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, 2001; see Table B5-4 in NEFSC 2001) with a few refinements. Closed Area II region in NEFSC (1999) was broken into two new regions in NEFSC (2001) 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 (Fig B3-1). This allows the assessment to take into account the 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 subsequently observed there during the 2000-2003 NMFS scallop surveys. By contrast, the northern portion of Closed Area II has not been fished since December, 1994.

A new scheme for post-stratifying scallop survey catches in the Nantucket Lightship Closed Area is introduced in this assessment. The new stratum, consists of the northeast corner because recruitment and biomass is considerably greater 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 which can be used in connection with the new stratification scheme to potential increase the accuracy of abundance estimates.

Survey and commercial 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. According to Serchuk and Smolowitz (1980), the liner reduces catchability of scallops greater than 75 mm in shell height (Fig B5-1). Based on data from Serchuk and Smolowitz’s (1980) experiment with lined and unlined, survey dredges NEFSC (1995; 1997) estimated that the selectivity curve for an unlined survey dredge was:

$$w'_h = \frac{1}{1 + \exp(3.7992 - 0.0768h)}$$

where h is shell height in mm. The estimated selectivity curve for a survey dredge with a liner was:

$$w_h = \frac{0.7148 e^{0.9180(0.7148)(x-106.3091)} + e^{0.9180(x-106.3091)}}{e^{0.9180(0.7148)(x-106.3091)} + e^{0.9180(x-106.3091)}} \quad (1)$$

where $x = 160 - h$ (Fig. B5-2).

Original survey catch data for scallops > 40 mm in each tow ($c_{h,t}$ for the number of scallops shell height h in tow t) were adjusted for use throughout this assessment by applying the size-specific selectivity of the lined dredge (w_h). With this adjustment, survey shell height distributions approximate the shell height distribution of the population of scallops sampled by the tow ($p_{h,t}$):

$$p_{h,t} = c_{h,t} / w_h$$

Population shell height estimates and distributions for each tow were partitioned into prerecruit (not vulnerable to commercial dredges) and fully recruited (completely vulnerable to

commercial dredges) classes by applying a commercial dredge selectivity function developed by consensus (NEFSC 1995):

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

where $h_{\min} = 65$ mm and $h_{\text{full}} = 88$ mm (Fig. B5-3).

Re-estimation of gear selectivity parameters

In recent years the method of Millar's (1992) SELECT method has become standard approach for estimation of gear selectivity patterns. SELECT uses a conditional likelihood approach that distinguishes between the relative fishing intensity of a type of gear (p) and the parameters (a and b in the standard logistic curve) that define the size-specific relative probability of capture. SELECT was used in this assessment to verify previous analyses and estimates of selectivity parameters. Excel spreadsheet software for this analysis was from Tokai (1997), obtained from <http://www.stat.auckland.ac.nz/~millar/selectware/> and used for sea scallops after testing based on several data sets.

For a simple comparison of two gear types, the general approach of Millar (1992) is to fit a function to the ratio of catches in gear 1 to the total catch in gear 1 and 2. Using this approach the ratio can be modeled as a multinomial likelihood function. Millar's important contribution to selectivity was to recognize not only proper statistical properties of the conditioned ratio, but also to incorporate the difference in relative fishing intensity (p).

$$\phi(L) = \frac{p r(L)}{(1-p) + p r(L)}$$

The function $r(L)$ represents a general function for the selectivity curve. When a two-parameter logistic curve is employed the modeled proportion becomes

$$\phi(L) = \frac{p r(L)}{(1-p) + p r(L)} = \frac{p \frac{e^{a+bL}}{1 + e^{a+bL}}}{(1-p) + p \frac{e^{a+bL}}{1 + e^{a+bL}}} = \frac{p e^{a+bL}}{(1-p) + e^{a+bL}}$$

The proportion of the catch in each length category can now be modeled as a function of three parameters (p, a, b) and asymptotic variances can be obtained from the Fisher information matrix. Model fit can be evaluated using residual plots and the total deviance statistic. Likelihood ratio tests can be used to compare alternative parameterizations.

Results for the Serchuk and Smolowitz's (1980) experiment suggest that the model in which the split fraction p is estimated fits significantly better than the model with p fixed at 0.5 (Table B5-1). Examination of the deviance residuals and other comparisons confirms the appropriateness of the SELECT model (Fig B5-1). Results show that unlined survey dredge was more efficient than the lined dredge. A factor that converts catches by the unlined dredge into predicted catches for the lined dredge is $p/(1-p) = 0.582/(1-0.582) = 1.392$, which is nearly identical to the rescaling parameter used in SARC 23 where survey catches of scallops greater than 60 mm in lined dredges were divided by 0.7147 (or multiplied by $1/0.7147 = 1.399$) to obtain equivalent catches for unlined dredges. Thus the application of SELECT model supports the adjustment factor that has been applied traditionally to standardize the research vessel dredge survey.

Model fit to data from the F/V Tradition was poor when the fishing intensity parameter p was not estimated (Table B5-1). A likelihood ratio test suggested that improvement in fit was statistically significant when p estimated. For the comparison of raw catches, the estimate $p=0.751$ is close to the value expected based on dredge relative widths of the 8' survey and 15' commercial dredges $0.652=15/(8+15)$. If the commercial dredge and research dredge were equally efficient, then the estimate for p should tend to equal the expected value 0.652. The ratio of these proportions can be used to estimate efficiency of the research dredge relative to the commercial dredge. For this experiment, the ratio was $0.652/0.751 = 0.868$ indicating that the lined dredge is less efficient than the unlined F/V dredge.

As noted in SARC 32, the correction factor for size-based selectivity of lined survey dredges results in good agreement with expectations based on commercial and survey length composition data from side-by-side tows collected during the F/V Tradition experiment. To further evaluate this point, the raw data from the research dredge were adjusted by Eq. 1 and the SELECT model was re-run. The results (Table B5-1) indicate $p=0.683$, which is nearly equivalent to the split predicted on the basis of dredge widths alone (i.e., 0.652). Thus, comparison of research and commercial dredge catches suggest nearly equal efficiency when the research dredge catches are adjusted (Eq.1) for dredge width and selectivity due to the liner in survey gear.

Four inch rings will be required as part of the Amendment 10 regulations starting in September, 2004. A number of side-by-side experiments comparing catches by dredges with 4" rings to catches by tows with 3.5" rings were conducted by the Virginia Institute of Marine Science. Estimated survey dredge catches were approximated by back-calculation from the 3.5" ring data using the above survey dredge selectivity curve. Because of difficulty fitting this data using the SELECT model, it was fit using a weighted (inversely by catch in the 4" ring dredge) least squares model. The estimated logistic selectivity parameters were $a = 9.69$ and $b = 0.102$ (Fig B5-3). The selectivity curve for 4" rings is shifted to the right and tends to increase more gradually with full selectivity not reached until over 120 mm. This is due to an increase in the efficiency of 4" rings compared to 3.5" rings at large sizes. Bourne (1964) found a similar phenomenon when comparing 4" rings to 3" rings.

Scallop density estimates from recent video surveys (Stokesbury 2002; Stokesbury et al. 2004) were used in this assessment to estimate region-specific survey dredge efficiencies by comparing them to the 2003 NFMS survey (NEFSC 2001; Appendix 3). Results from a joint SMAST/NMFS calibration experiment (Appendix 1) showed that video length-frequencies measurements had substantially more measurement error than those from dredge surveys. However, results from the preliminary CASA model for sea scallops (appendices 4-5) indicate that video size-frequencies can provide useful information provided that measurement error is accommodated in the model.

Use of rock chains in NEFSC scallop surveys

Tows on hard-bottom areas (especially in the Great South Channel) tend to catch large rocks, which may cause safety problems and reduce the catchability of scallops. NEFSC proposes to use rock excluders (“rock chains”) on the survey dredge in strata 49-52 in the Great South Channel to reduce these potential problems (Appendix 2).

Estimating survey tow distances and area swept

To estimate the distance of survey tows, an inclinometer sensor has been attached the gooseneck of survey dredges during recent years. The inclinometer records the angle of the gooseneck during the tow. Because of difficulty in interpreting the inclinometer signal in previous assessments (NEFSC 2001), a video camera was attached to a survey dredge. Results from five experimental tows with the video camera during the 2003 scallop survey were used to determine how inclinometer data can be used in surveys to estimate tow distance.

Typical inclinometer traces for tows during 2003 are shown in Figure B5-4. The inclinometer trace at the start of each tow followed essentially the same pattern: a steep decline of the frame to a flat position when it initially settles to the bottom, a sharp upward jerk as the wire tightens, a momentary lowering of the frame as the wire slackens, another sharp jerk upward and then a steady settling of the frame to between 0 and 25 degrees from the bottom as the tow got under way and the gear and ship began to move forward together as one.

Based on the inclinometer data, survey tows were judged to have begun when the frame began to flatten out (become more in parallel with the bottom) beginning at the second upward surge. The vast majority of tows followed this pattern at the outset, but some tows surged only once, or hit the bottom at the right angle and speed and began the tow without significant back-and-forth pulling at the beginning. The start of fishing time for a one-surge tow was when the frame began to settle down from the sharp upward swing. For a no-surge tow, fishing time began after the first steep change in angle representing the gear moving off the ship through the water column and coming in contact with the bottom. The disjointed movements of the ship and the gear at the beginning of the tow were not considered fishing time.

The end of the most tows was indicated by a sudden upward jerk of the frame followed by a few minutes of the gear moving through the water column at a 45 to 55 degree angle, then increasing rapidly as it lifted onto the ship. Some tows showed just a smooth and steady increase

in the angle of the frame as it traveled to the surface. The sudden change in the angle of the frame as the winch started pulling it toward the surface was almost always quite evident, and marked the end of fishing time.

The duration of each tow during the 2003 survey was calculated by plotting the inclinometer angle on the y-axis and time on the x-axis, so it was possible to see exactly when in time each inclinometer change took place. The start and end of the tow were noted using the criteria described above, it was determined at what time these occurred, then the start time was subtracted from the end time to calculate the total time the gear was fishing. To calculate the distance towed, the time towed (in minutes) was multiplied by the average speed-over-ground (SOG) for the tow (in knots), then divided by 60 to get the distance in nautical miles.

Besides using the inclinometer, survey tow distance can be estimated by two other methods. First, the tow time (“towdur”) can be estimated by recording when the lead fisherman believes the tow started and stopped. Area swept can then be calculated by multiplying this towdur by SOG as above. Area swept can also be estimated multiplying towdur by the nominal speed of 3.8 knots.

Mean tow distance estimated using inclinometer data was 1.003 nm (see below) and slightly larger estimates by the other two methods. Linear regression indicated a slight, but statistically significant ($p < 0.001$), decrease in towpath length with depth. The estimated regression line was:

$$\text{Distance} = 1.0407 - 0.00058 \text{ Depth}$$

where the distance is in nautical miles and depth is in meters. For example, the towpath at 40m depth would be about 1.018 nm compared to 0.983 nm at 100m depth.

| | N Tows | Mean | Median | Std.Dev. | SEM |
|------------------------------|---------------|-------------|---------------|-----------------|------------|
| Inclinometer tow distance | 434 | 1.0029 | 1.0007 | 0.0530 | 0.0025 |
| Tow dist from towdur and SOG | 434 | 0.9970 | 0.9936 | 0.0516 | 0.0025 |
| Towdur * 3.8 knots | 432 | 0.9734 | 0.9720 | 0.0350 | 0.0017 |

Appendix 3 summarizes information about scallop dredge efficiency, based on depletion experiments and comparison of video and dredge surveys, with the goal of estimating absolute scallop abundance.

Survey abundance and biomass trends, 1979-2003

Biomass and abundance estimates from 1979-2003 for the Mid-Atlantic Bight and 1982-2003 for Georges Bank are presented in Table B5-2 and Figures B5-5 and B5-6. Only random tows were used except in the post-stratified portion of the Nantucket Lightship Area (the “Asia rip”, see above). Variances for strata with zero means were not considered. Confidence intervals were obtained by bootstrapping (Smith 1997, see Appendix 3).

In the Mid-Atlantic Bight, abundance and biomass appear to be increasing rapidly and are currently at record levels. In Georges Bank, biomass and abundance increased in 1995-2000 after implementation of closures and effort reduction measures. Biomass has been consistently high and at near-record levels since 2000, while abundance has declined from its record level in 2000.

The biomass and abundance indices for closed areas in Georges Bank and the Mid-Atlantic Bight showed notable increases after closure. The increase in biomass was more rapid after the Mid-Atlantic closures that were specifically closed to protect high densities of small scallops. These areas were also chosen because they had histories of strong recruitment. Several additional strong year classes settled in the Hudson Canyon South area after the area was closed that contributed to the increases in abundance and biomass. In contrast, the areas that were closed in Georges Bank were not related to scallop recruitment.

Biomass and abundance in the open areas of both regions have increased since 1999. The increases in the open areas have been greater in the Mid-Atlantic, where the biomass is continuing to increase, largely due to good recruitment the last several years. In contrast, recruitment on Georges Bank has been below average in 2002-2003. Biomass in open area declined during 2002-2003. Increases in the open areas in both stock areas were due to a combination of effort reduction and good recruitment. Effort reduction measures have had some effect despite the fact that area closures tend to displace effort into the open areas.

Survey data maps showing the spatial distribution of sea scallop biomass during 1994 (just before the Georges Bank closed areas were implemented) and the during the most recent 2003 survey (Fig. B5-7). Biomass has increased considerably since 1994 in Georges Bank closed areas (shown in gray) and in the Great South Channel. Mid-Atlantic biomass has also increased substantially since 1994, especially in the Hudson Canyon South area (in gray) that was closed for three years between 1998 and 2001 and in the Delmarva area to the south of the closed area.

6.0 - BIOMASS, POPULATION SIZE, AND FISHING MORTALITY

Unless otherwise noted, the natural mortality rate assumed for sea scallop in this assessment is $M=0.1 \text{ y}^{-1}$ (Merrill and Posgay 1964, and see above). Besides fishing mortality resulting in landings, fishing activity may induce discard mortality and incidental (non-catch or indirect) fishing mortality.

Discard mortality

Discard mortality may have been important for sea scallops in some years (see below) and may be important in some calculations. Small sea scallops (currently less than about 90 mm shell height) may be discarded rather than shucked. Discarded sea scallop 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 due to shell damage.

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% (W. DuPaul, Virginia Institute of Marine Science, School of Marine Science, College of William and Mary, Gloucester Point, VA, pers. comm.). 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.

Incidental fishing 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 work was done 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, it is necessary to know the efficiency e of the dredge (the probability that a fully recruited scallop in the path of a dredge are captured). Denote by c the fraction of scallops that suffer mortality among those which were in the path of the dredge but not caught. The best available information indicates that $c = 0.15-0.2$ (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 dredge efficiency e is 50%, then $F_I = F_L c$. 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), $F_I < 0.05 F_L$.

Non-model based fishing mortality and biomass estimates

Non-model based fishing mortality and biomass estimators based on catch and survey data include catch-biomass, survey-based, equilibrium length-based, and rescaled catch-biomass based approaches. Most were used in the previous assessment (NEFSC 2001).

Catch-biomass method

If survey dredge efficiency e is known, then biomass can be estimated directly from mean meat weights per survey tow:

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

where b_y is mean meat weight per tow from the survey in year y , B_y^* is stock biomass, a is the area (nm^2) swept by a standard tow, and A is the size (nm^2) of the stock area or region. In this assessment, a was assumed to be the area swept by an 8 ft NEFSC survey dredge during a 1 nm tow (see above). The NEFSC scallop survey takes place in the summer which, about mid-year. Therefore B_y^* is approximately equal to mean biomass during the calendar year.

Annual catch-biomass fishing mortality rates cF_y were estimated:

$${}^cF_y = \frac{C_y}{B_y^*}$$

where C_y is the meat weight of scallops killed by fishing during the calendar year (Ricker 1975). Because C_y represents only reported landings, this estimate will be biased low if there were non-reported landings, or if there was non-yield fishing mortality. Additionally, these estimates are biomass-weighted, which tend to be biased low compared to numbers-weighted estimates when there is spatial heterogeneity in fishing mortality (Hart 2001). Because of these factors, and uncertainty in the estimates of dredge efficiency, NEFSC (1999 and 2001) used the catch-biomass estimates as an index (the catch-biomass index, or CBI) of relative trends in fishing mortality. The CBI was estimated here assuming 40% dredge efficiency on Georges Bank and 60% in the Mid-Atlantic.

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.

The first bin for Georges Bank consisted of scallops of 80-100 mm shell height and the second bin consisted of all scallops larger than 100 mm. An 80 mm sea scallop was almost fully

recruited to the fishery (except during the most recent period) and will grow to 100 mm in one year, according to von Bertalanffy growth curves for scallops in the Georges Bank stock area. For the Mid-Atlantic region, where growth has been estimated to be slightly slower, the first bin consisted of 80-98.5 mm scallops and the second bin consisted of scallops larger than 98.5 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 population 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).

Rescaled catch-biomass method

Rescaled catch-biomass estimates are the most accurate for fishing mortality available in this assessment and are intended for use in determining stock status. Following NEFSC (2001), rescaled survey-based estimates were computed:

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

where average catch-biomass ${}^c \bar{F}_y$ and survey-based ${}^s \bar{F}_t$ fishing mortality rates were for a time period containing 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. It gives a smoother trend than the survey fishing mortalities, but does not require assumptions about dredge efficiency and non-yield mortality, and is scaled to be numbers-based. For this assessment, the data for 1979-2003 in the Mid-Atlantic and 1982-2003 in Georges Bank was used to estimate the scaling factor.

Following NEFSC (2001), coefficients of variation (CVs) for rescaled fishing mortality estimates were computed using CVs for the rescaling factor (the mean of the survey-based estimates) and CVs for the catch-biomass estimates. The mean survey-based fishing mortality is:

$$F_{MEAN} = \frac{-1}{n} \sum_{t=0}^{n-1} \ln \frac{P_{t+1}}{R_t + P_t} = \frac{1}{n} [\ln(P_0 + R_0) - \ln P_n + \sum_{t=1}^{n-1} (\ln(R_t + P_t) - \ln(P_t))]$$

The terms inside the right-hand sum covary, with the correlation between $R_t + P_t$ and P_t being about $\rho=0.6$. Because $\text{Var}(\ln(X)) = \text{Var}(X)/E(X)^2$, the variance of F_{MEAN} is:

$$\frac{1}{n^2} \left[\frac{\sigma_{P_0+R_0}^2}{(P_0 + R_0)^2} + \frac{\sigma_{P_n}^2}{P_n^2} + \sum_{t=1}^{n-1} \left(\frac{\sigma_{R_t+P_t}^2}{(R_t + P_t)^2} + \frac{\sigma_{P_t}^2}{P_t^2} - \text{Cov}(R_t + P_t, P_t) \right) \right]$$

where the covariance term was calculated assuming a correlation coefficient of 0.6. Standard errors for the catch-biomass index were computed assuming an estimated CV of 0.1 for the landings together with the CVs from the surveys.

Beverton-Holt length-based estimates

The Beverton-Holt (1956) equilibrium length-based fishing mortality estimator may provide independent information about fishing mortality rates and is given by:

$${}^{BH}F_t = K \frac{L_\infty - l_{m,t}}{l_{m,t} - l_c} - M$$

where $l_{m,t}$ is the mean shell height beyond l_c , taken here to be 90 mm. Because this estimator was derived under an equilibrium assumption, it may not be accurate when, as is typical, the fishery is not in equilibrium. However, it still can give useful information if it is understood how it is affected by non-equilibrium conditions.

Large year classes will cause the Beverton-Holt estimator to be biased high when they first pass the length l_c and will bias it low as the year class ages. Also, this estimator tends to be a lagging indicator of fishing mortality, because the mean size will be a function of not only the present fishing mortality, but that of past years. To partially compensate for these properties, the Beverton-Holt indices were computed as three-year forward moving averages of the original estimators.

Whole-stock estimates

Because of differences in e.g., growth rates, between Georges Bank and the Mid-Atlantic, fishing mortalities were calculated separately in the two areas. The overall status determination however requires a whole-stock estimates of fishing mortality. For this purpose, the Georges Bank and Mid-Atlantic estimates were combined using a number-weighted average, using swept area calculations. Because evidence indicates that dredge efficiency on Georges Bank is lower than in the Mid-Atlantic, the swept-area abundances in the Mid-Atlantic were multiplied by 0.67, roughly corresponding to the estimated ratio of dredge efficiencies between the two areas. Results were only slightly sensitive to the exact value of this dredge efficiency-weighting factor.

Results

All methods give qualitatively similar results (Table B6-1 and Fig B6-1). In Georges Bank, fishing mortality peaked in 1991 and declined drastically after 1993, at first due to a shift

in effort as fishers found better fishing opportunities in the Mid-Atlantic, and then because of the build-up of scallops in the groundfish closed areas. In the Mid-Atlantic, fishing mortality was generally high from 1983-1996, and then declined from 1996-1999, likely due primarily to effort reduction measures, the rotational closures, and to the reopening of portions of the groundfish closed areas in 1999, which drew effort out of the Mid-Atlantic. Fishing mortality has averaged about 0.5 y^{-1} since 1999. Whole-stock fishing mortality rates peaked in 1991 and declined substantially between 1993 and 1998. Fishing mortalities since 1999 have been between 0.22 and 0.3 y^{-1} , with the 2003 estimate at the upper end of the range.

Model-based fishing mortality estimates

A length-based, forward projecting assessment model (CASA) was developed for sea scallops in this assessment. Though not used as the primary assessment tool for this assessment, it is presented for review in Appendices 4 and 5 so that it can be employed in future assessments.

7.0 - BIOLOGICAL REFERENCE POINTS

Because of the lack of well-defined stock-recruitment relationships for sea scallops, the per-recruit reference points F_{MAX} and B_{MAX} are used by managers as proxies for F_{MSY} and B_{MSY} . F_{MAX} is defined as the fishing mortality rate (in units y^{-1}) for fully recruited scallops that generates maximum yield-per-recruit. B_{MAX} for sea scallops is defined in survey units (meat weight in g tow^{-1}) and computed as the product of BPR_{MAX} (biomass per recruit at $F = F_{\text{MAX}}$, from yield-per-recruit analysis) and median numbers of recruits per tow based on NEFSC sea scallop survey data. Biological reference points, fishing mortality rates and biomass estimates used in status determination here are for the entire U.S. scallop stock, whereas region-specific estimates for Georges Bank and the Mid-Atlantic Bight were used previously (NEFSC 2001).

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. However, there are special considerations for sessile 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 fishing mortality that achieves maximum or optimal yield may be less than that indicated by a conventional yield-per-recruit analysis (Hart 2001, 2003).

Length-based yield-per-recruit model

A new model for length-based yield-per-recruit analysis (LBYPR, implemented in Fortran-90) was developed for the previous sea scallop assessment (NEFSC 2001; Hart 2003).

LBYPR gives similar results to age-based yield-per-recruit models for sea scallops (e.g., Applegate et al. 1998; NEFSC 1999) but is more flexible because it does not require any assumptions about age (e.g., the results do not depend on the value for t_0 in the von Bertalanffy growth equation) and it allows selectivity patterns to be modeled naturally and directly as functions of length. In contrast, conventional age-based approaches require assumptions about fishery selectivity at age, and mean weights at age (NEFSC 1999). In the scallop fishery, selectivity actually depends on shell height rather than age. Sea scallops grow quickly and there is likely a wide range of sizes at each age. These factors complicate estimation of mean selectivity and meat weight at age. LBYPR avoids these uncertainties by carrying out calculations based on length, rather than age.

In LBYPR, recruits start at a user specified starting shell height h_0 . Starting shell height is converted to an assumed starting age based on an inverted von Bertalanffy growth model; the results are independent of this assumed starting age. Age is increased in each time step as the model runs, and shell heights are calculated based on age and the von Bertalanffy growth model. Shell heights are converted to meat weights with shell height-meat weight relationships. Parameters important in the LBYPR model (including the assumed rate of natural mortality, von Bertalanffy growth parameters, shell height-meat weight relationships, and fishery selectivity) were set at current best estimates (see above), unless otherwise specified. The main changes in these parameters since NEFSC (2001) are an increase in the cull size from 75 to 90 mm, and new estimations of commercial dredge selectivity for dredges with 3.5" and with 4" rings.

Size-dependent fishing mortality rates for sea scallops in LBYPR were $F(h) = F_0L(h)$, where F_0 is the fully recruited fishing mortality rate, h is shell height, and $L(h)$ is the selectivity of a commercial scallop dredge. $L(h)$ can be chosen on the basis of estimated gear selectivity (see above), or from fishery selectivity (including targeting). Scallops caught in commercial dredges are discarded if their shell height is less than a specified cull size h_d (if $h_{min} < h < h_d$). The mortality rate for discarded scallops is d . All individuals caught in the model with shell heights greater than h_d are assumed to be landed, and are included in total yield. $F_c(h)$ is the size-specific rate at which scallops are landed (i.e. caught and retained). Natural mortality $M(h)$ may depend on shell height.

Let F_0 be the fishing mortality on a full recruit due to landings. Incidental fishing mortality is modeled as iF_0 (i.e., proportional to fully recruited fishing mortality F_0 , and independent of size). $Z(h)$ is the total mortality rate, computed as the sum of natural mortality $M(h)$, discard mortality $dF_c(h)$ ($h < h_d$), and incidental mortality due to fishing iF_0 , and landings $F_c(h)$ with ($h > h_d$).

The fraction of the initial number of recruits remaining t years after the beginning of the simulation is:

$$R(t) = \exp\left(-\int_{a_0}^t Z(\tau)d\tau\right).$$

Total expected yield (Y) and biomass (B) over the lifetime of each recruit are:

$$Y = \int_{a_0}^{a_f} R(t)F_c(h(t))w(h(t))dt$$

$$B = \int_{a_0}^{a_f} R(t)w(h(t))dt$$

where a_f is the end time of the simulation, usually $30 + a_0$. For convenience, a_0 was chosen so that the scallops start the simulation at 40 mm shell height. The integrals were computed numerically with a time step of 0.01 years.

Managers currently use an estimate for F_{MAX} of 0.24. Baseline runs indicate that revised estimates of F_{MAX} are close to 0.24 for 4" rings but are slightly below this figure with 3.5" rings (Table B7-1).

Sensitivity runs indicate that LBYPR results were relative to robust to assumptions about scallop biology and the fishery (Table B7-1). Runs were conducted using the new 3.5" ring logistic selectivity curve, the previous SARC-23 piecewise linear selectivity curve, and the estimated 4" ring selectivity curve. There was little difference in the results between the two 3.5" selectivity patterns, but the 4" rings increased YPR by 4-8% and F_{MAX} by 4-15% over the 3.5" ring runs. Note that the increases with 4" rings are greater when incidental mortality was assumed low. Parameters for faster growth in the Georges Bank stock (as suggested in NEFSC 2001) modestly increase F_{MAX} , Y_{MAX} , and B_{MAX} , while slower growth in the Mid-Atlantic analogously slightly lowers these quantities. Incidental fishing mortality lowers F_{MAX} , due to the assumption that incidental fishing mortality affects pre-recruit and partially recruited scallops. Note, however, that targeting of beds composed mostly of larger scallops (which is occurring in some areas) could alleviate the effects of incidental mortality to some extent.

Natural mortality may be age- or size-dependent (MacDonald and Thompson 1986; NEFSC 2001). To explore this possibility, simulations were performed with $M=0.05 \text{ y}^{-1}$ for shell heights less than 120 mm, and 0.1 y^{-1} for larger sizes. In another run, M was taken to be 0.1 y^{-1} for shell heights less than 120 mm, and 0.2 y^{-1} for larger shell heights. The latter gave $F_{MAX}>0.3 \text{ y}^{-1}$ and in some cases greater than 0.4 y^{-1} . In addition to the runs described above, LBYPR analyses were carried out with no incidental fishing mortality and with 0 or 100% discard mortality, or at a cull size characteristic of previous years ($h_d = 75\text{mm}$). Reference points were also estimated under rotational management (Hart 2003), where areas were closed for 3 years, and then subject to ramped mortality (1.6, 2.0, and 2.4 of the time-averaged F over the 6 year period), corresponding to the recommended policy in Amendment 10 (NEFMC 2003).

8.0 - STATUS DETERMINATION

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 the F_{MSY} proxy 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 (in units y^{-1}) for fully recruited scallops that generates maximum yield-per-recruit (see recent F and F_{MAX} estimates above). The target biomass level is B_{MAX} . B_{MAX} and data for status determinations are cast in units of survey data, i.e. meat weight per tow. Specifically, the biomass reference point B_{MAX} is defined as:

$$B_{MAX} = \text{Median recruitment} \times BPR_{MAX}$$

where BPR_{MAX} is biomass-per-recruit at F_{MAX} , based on a yield-per-recruit analysis.

The current management reference point $F_{MAX} = 0.24 y^{-1}$ in Amendment 10 (NEFMC 2003) is from an age-based Thompson-Bell yield-per-recruit analysis (Applegate et al. 1998). $B_{MAX} = 5.6 \text{ kg/tow}$ in Amendment 10 was estimated using median recruitment from 1982-2002 survey data for the entire resource as.

On the basis of the 2003 NMFS scallop survey results, scallop biomass is about 7.6 kg/tow, well above $B_{MAX} = 5.6 \text{ kg/tow}$, so that sea scallops are not overfished. The rescaled fishing mortality estimate for the combined resource is 0.30 and above the overfishing threshold of $F_{MAX} = 0.24$, so that overfishing is occurring.

9.0 – RESEARCH RECOMMENDATIONS

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.
2. Explore potential for surveying hard bottom areas not currently covered using survey dredges equipped with rock chains.
3. Explore the use of VMS and landings data to characterize condition of the resource on grounds not covered by the survey.
4. Further work is required to better characterize the selectivity of the commercial dredges with 4” rings relative to the standard NEFSC survey dredge.
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.

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.
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.
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 M and growth), measurement errors in data, and characterization of uncertainty. In addition, use of smaller time steps, length groups might be helpful. It may prove possible to apply the model or similar models to smaller geographic areas.
9. There appears to be considerable scope for reducing variability in scallop survey data by changing the allocation of tows to survey strata.
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.
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.

11.0 – LITERATURE CITED

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| Year | Gulf of Maine | | | Georges Bank | | | S. New England | | | Mid-Atlantic Bight | | | Uncl. | Total | | | | | | |
|------|---------------|-------|-------|--------------|-------|-------|----------------|--------|-------|--------------------|-----|--------|-------|-------|--------|--------|--------|-------|--------|--------|
| | trawl | other | sum | dredge | trawl | other | sum | dredge | trawl | other | sum | dredge | trawl | other | sum | trawl | other | sum | | |
| 1964 | 0 | 208 | 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 | 3,974 | 3,974 | | 5 | 5,592 | 5,598 | |
| 1966 | 0 | 102 | 102 | | 0 | 883 | 884 | | 0 | 8 | 8 | | 0 | 4,061 | 4,061 | | 1 | 5,055 | 5,056 | |
| 1967 | 0 | 80 | 80 | | 4 | 1,217 | 1,221 | | 0 | 8 | 8 | | 0 | 1,873 | 1,873 | | 4 | 3,178 | 3,182 | |
| 1968 | 0 | 113 | 113 | | 0 | 993 | 994 | | 0 | 56 | 56 | | 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 | 362 | | 18 | 1,311 | 1,329 | | 0 | 7 | 7 | | 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 | | 317 | 2,972 | 3,288 | | 361 | 5,061 | 5,422 | |
| 1977 | 4 | 254 | 258 | | 27 | 4,709 | 4,736 | | 1 | 10 | 11 | | 27 | 2,564 | 2,591 | | 58 | 7,536 | 7,595 | |
| 1978 | 1 | 0 | 243 | 5,532 | 37 | 0 | 5,569 | 25 | 2 | 0 | 27 | 4,175 | 21 | 0 | 4,196 | 9,974 | 61 | 0 | 10,035 | |
| 1979 | 5 | 1 | 407 | 6,253 | 25 | 7 | 6,285 | 61 | 5 | 0 | 66 | 2,857 | 29 | 1 | 2,888 | 9,572 | 64 | 9 | 9,645 | |
| 1980 | 122 | 3 | 1,614 | 5,382 | 34 | 2 | 5,419 | 130 | 3 | 0 | 133 | 1,966 | 9 | 0 | 1,975 | < 0.01 | 8,968 | 169 | 4 | 9,142 |
| 1981 | 73 | 7 | 1,305 | 7,787 | 56 | 0 | 7,843 | 68 | 1 | 0 | 69 | 726 | 5 | 0 | 731 | 9,806 | 135 | 7 | 9,948 | |
| 1982 | 28 | 5 | 664 | 6,204 | 119 | 0 | 6,322 | 126 | 0 | 0 | 126 | 1,602 | 6 | 2 | 1,610 | 8,562 | 153 | 7 | 8,723 | |
| 1983 | 72 | 7 | 895 | 4,247 | 32 | 4 | 4,284 | 243 | 1 | 0 | 243 | 3,081 | 18 | 10 | 3,109 | 8,386 | 124 | 21 | 8,530 | |
| 1984 | 18 | 10 | 678 | 3,011 | 29 | 3 | 3,043 | 161 | 3 | 0 | 164 | 3,647 | 26 | 2 | 3,675 | 7,470 | 76 | 14 | 7,560 | |
| 1985 | 3 | 10 | 421 | 2,860 | 34 | 0 | 2,894 | 77 | 4 | 0 | 82 | 3,227 | 47 | 1 | 3,276 | 6,572 | 88 | 11 | 6,672 | |
| 1986 | 2 | 6 | 316 | 4,428 | 10 | 0 | 4,438 | 76 | 2 | 0 | 78 | 3,257 | 101 | 0 | 3,359 | 8,068 | 115 | 7 | 8,190 | |
| 1987 | 0 | 9 | 382 | 4,821 | 30 | 0 | 4,851 | 67 | 1 | 0 | 68 | 7,488 | 315 | 1 | 7,803 | 12,749 | 346 | 10 | 13,104 | |
| 1988 | 7 | 13 | 526 | 6,036 | 18 | 0 | 6,054 | 65 | 4 | 0 | 68 | 5,774 | 402 | 2 | 6,178 | 12,381 | 430 | 16 | 12,826 | |
| 1989 | 0 | 44 | 644 | 5,637 | 25 | 0 | 5,661 | 127 | 11 | 0 | 138 | 7,549 | 422 | 2 | 7,973 | 13,913 | 458 | 45 | 14,416 | |
| 1990 | 0 | 28 | 574 | 9,972 | 10 | 0 | 9,982 | 110 | 6 | 0 | 116 | 5,954 | 476 | 4 | 6,435 | 16,581 | 493 | 32 | 17,107 | |
| 1991 | 3 | 75 | 605 | 9,235 | 77 | 0 | 9,311 | 55 | 16 | 0 | 71 | 6,195 | 808 | 9 | 7,011 | 16,012 | 903 | 84 | 16,999 | |
| 1992 | 2 | 45 | 722 | 8,230 | 7 | 0 | 8,238 | 119 | 5 | 0 | 124 | 4,386 | 563 | 5 | 4,955 | 13,411 | 577 | 50 | 14,039 | |
| 1993 | 2 | 32 | 797 | 3,637 | 18 | 0 | 3,655 | 65 | 1 | 0 | 66 | 2,382 | 392 | 3 | 2,778 | 6,848 | 413 | 36 | 7,296 | |
| 1994 | 3 | 3 | 525 | 1,133 | 3 | 1 | 1,137 | 0 | 1 | 0 | 1 | 5,176 | 688 | 9 | 5,872 | 6,827 | 693 | 13 | 7,534 | |
| 1995 | 4 | 238 | 665 | 967 | 15 | 0 | 982 | 35 | 1 | 0 | 36 | 5,408 | 744 | 166 | 6,318 | 6,799 | 762 | 404 | 7,965 | |
| 1996 | 20 | 121 | 773 | 2,040 | 6 | 0 | 2,045 | 74 | 0 | 0 | 74 | 4,335 | 656 | 9 | 4,999 | 7,006 | 682 | 130 | 7,818 | |
| 1997 | 21 | 98 | 699 | 2,317 | 10 | 0 | 2,326 | 69 | 0 | 0 | 69 | 2,442 | 357 | 111 | 2,910 | 5,339 | 387 | 209 | 5,936 | |
| 1998 | 10 | 1 | 455 | 1,990 | 27 | 0 | 2,016 | 95 | 6 | 0 | 102 | 2,359 | 574 | 15 | 2,948 | 44 | 4,792 | 610 | 17 | 5,565 |
| 1999 | 3 | 0 | 280 | 5,151 | 4 | 0 | 5,155 | 46 | 5 | 3 | 54 | 3,646 | 958 | 50 | 4,653 | 4 | 9,074 | 965 | 50 | 10,146 |
| 2000 | 8 | 1 | 191 | 5,412 | 25 | 0 | 5,437 | 84 | 2 | 0 | 86 | 7,707 | 1,142 | 10 | 8,860 | 49 | 13,301 | 1,175 | 11 | 14,623 |
| 2001 | 18 | 29 | 430 | 4,941 | 11 | 0 | 4,952 | 27 | 1 | 2 | 31 | 14,161 | 1,570 | 38 | 15,768 | | 19,485 | 1,599 | 67 | 21,180 |
| 2002 | 7 | 2 | 542 | 5,653 | 40 | 0 | 5,694 | 41 | 3 | 0 | 43 | 16,016 | 1,591 | 5 | 17,612 | | 22,202 | 1,639 | 7 | 23,891 |
| 2003 | 7 | 1 | 254 | 4,908 | 14 | 0 | 4,922 | 84 | 2 | 0 | 85 | 18,189 | 1,470 | 1 | 19,660 | 187 | 23,343 | 1,491 | 1 | 25,107 |
| Mean | 11 | 35 | 547 | 4,674 | 26 | 0 | 4,700 | 84 | 3 | 0 | 88 | 6,090 | 606 | 21 | 6,716 | | 11,324 | 645 | 56 | 12,056 |
| Min | 0 | 0 | 191 | 967 | 3 | 0 | 982 | 0 | 0 | 0 | 1 | 1,602 | 6 | 0 | 1,610 | | 4,792 | 76 | 1 | 5,565 |
| Max | 72 | 238 | 895 | 9,972 | 119 | 4 | 9,982 | 243 | 16 | 3 | 243 | 18,189 | 1,591 | 166 | 19,660 | | 23,343 | 1,639 | 404 | 25,107 |

Table B5-1. Gear selectivity parameter estimates for the Serchuk and Smolowitz (1980) and *F/V Tradition* experiments.

(a) Serchuk and Smolowitz (1980) experiment.

| Parameter | p=0.5 (fixed) | | p estimated | |
|-----------|--------------------|------------|-------------|----------|
| | Value | Std Err. | Value | Std Err. |
| a | -4.8032 | 0.3688 | -4.4453 | 0.2691 |
| b | 0.1019 | 0.0091 | 0.0811 | 0.0066 |
| p | 0.5000 | --- | 0.5815 | 0.0085 |
| L50 | 47.1461 | 0.9742 | 54.804 | 1.4483 |
| IQR | 21.5670 | 1.9202 | 27.089 | 2.1878 |
| Ho | model Deviance | 136.68 | 28.61 | |
| | degrees of freedom | 24 | 23 | |
| | significance | 9.4495E-18 | 0.19358978 | |
| Ho | p=0.5 deviance | --- | 108.07 | |
| | degrees of freedom | --- | 1 | |
| | significance | --- | 2.5945E-25 | |

(b) *F/V Tradition* experiment

| Parameter | Raw Data | | | | Adjusted R/V Data | |
|-----------|--------------------|----------|-------------|----------|-------------------|----------|
| | p=0.5 (fixed) | | p estimated | | p estimated | |
| | Value | Std Err. | Value | Std Err. | Value | Std Err. |
| a | -21.46947 | 0.8356 | -15.3815 | 0.2550 | -15.2401 | 0.2520 |
| b | 0.317893 | 0.0128 | 0.1958 | 0.0035 | 0.1943 | 0.0034 |
| p | 0.5 | 0.0012 | 0.7509 | 0.0012 | 0.6829 | 0.0013 |
| L50 | 67.5367 | 0.2170 | 78.5699 | 0.1648 | 78.4511 | 0.1507 |
| IQR | 6.911827 | 0.2791 | 11.2236 | 0.1994 | 11.3106 | 0.1985 |
| Ho | model Deviance | 47682.5 | 6552.2 | | 8292.5 | |
| | degrees of freedom | 31 | 30 | | 30 | |
| | significance | 0 | 0 | | 0 | |
| Ho | p=0.5 deviance | --- | 41130.26 | | | |
| | degrees of freedom | --- | 1 | | | |
| | significance | --- | 0 | | | |

Table B5-2. Stratified mean sea scallop survey data for Georges Bank, Mid-Atlantic Bight and combined (40+ mm shell height). Calculations include corrections for survey dredge selectivity (NEFSC 1997). Population values were split into recruited and not recruited portions using the piecewise linear commercial dredge selectivity function (NEFSC 1992).

| Year | Num/Tow | CV | Num/Tow | | Biomass g/Tow | CV | Biomass Not | Fully | Mean Meat Weight (G) |
|---------------------------|---------|-----|--------------------------|--------------------|------------------|-----|--------------------|--------------------|----------------------------|
| | | | Num/tow Not Recruited | Fully Recruited | | | Recruited g/Tow | Recruited g/Tow | |
| Georges Bank | | | | | | | | | |
| 1982 | 133 | 37% | 100 | 33 | 869 | 18% | 304 | 565 | 6.6 |
| 1983 | 61 | 21% | 24 | 37 | 720 | 16% | 97 | 623 | 11.9 |
| 1984 | 39 | 11% | 15 | 23 | 544 | 9% | 55 | 490 | 14.0 |
| 1985 | 65 | 14% | 31 | 34 | 706 | 13% | 126 | 579 | 10.8 |
| 1986 | 116 | 13% | 79 | 37 | 917 | 9% | 269 | 648 | 7.9 |
| 1987 | 126 | 15% | 67 | 58 | 1,082 | 13% | 245 | 837 | 8.6 |
| 1988 | 104 | 15% | 56 | 48 | 904 | 12% | 216 | 688 | 8.7 |
| 1989 | 111 | 36% | 56 | 55 | 943 | 33% | 248 | 695 | 8.5 |
| 1990 | 207 | 22% | 129 | 78 | 1,340 | 20% | 475 | 865 | 6.5 |
| 1991 | 251 | 30% | 200 | 51 | 1,246 | 14% | 551 | 695 | 5.0 |
| 1992 | 264 | 38% | 185 | 79 | 1,638 | 29% | 787 | 851 | 6.2 |
| 1993 | 70 | 28% | 47 | 23 | 531 | 17% | 204 | 327 | 7.6 |
| 1994 | 45 | 16% | 20 | 25 | 457 | 13% | 69 | 388 | 10.2 |
| 1995 | 120 | 18% | 92 | 28 | 747 | 13% | 285 | 462 | 6.2 |
| 1996 | 139 | 16% | 70 | 69 | 1,332 | 14% | 256 | 1,076 | 9.6 |
| 1997 | 100 | 13% | 28 | 72 | 1,612 | 14% | 98 | 1,514 | 16.1 |
| 1998 | 317 | 31% | 145 | 172 | 4,000 | 37% | 508 | 3,492 | 12.6 |
| 1999 | 246 | 17% | 67 | 179 | 4,306 | 25% | 158 | 4,148 | 17.5 |
| 2000 | 888 | 30% | 542 | 346 | 8,131 | 21% | 2,243 | 5,888 | 9.2 |
| 2001 | 473 | 13% | 147 | 327 | 7,010 | 14% | 616 | 6,394 | 14.8 |
| 2002 | 397 | 13% | 33 | 364 | 8,051 | 13% | 174 | 7,877 | 20.3 |
| 2003 | 311 | 12% | 61 | 250 | 7,529 | 14% | 231 | 7,299 | 24.2 |
| Mid-Atlantic Bight | | | | | | | | | |
| 1979 | 43 | 9% | 11 | 32 | 728 | 10% | 46 | 681 | 16.9 |
| 1980 | 51 | 12% | 27 | 24 | 615 | 7% | 62 | 553 | 12.1 |
| 1981 | 40 | 17% | 18 | 22 | 488 | 11% | 64 | 423 | 12.3 |
| 1982 | 40 | 11% | 16 | 24 | 508 | 8% | 64 | 444 | 12.8 |
| 1983 | 38 | 9% | 20 | 19 | 472 | 8% | 65 | 407 | 12.3 |
| 1984 | 39 | 10% | 15 | 24 | 454 | 9% | 49 | 406 | 11.8 |
| 1985 | 93 | 13% | 58 | 35 | 734 | 9% | 207 | 528 | 7.9 |
| 1986 | 152 | 8% | 89 | 64 | 1,186 | 7% | 323 | 863 | 7.8 |
| 1987 | 152 | 8% | 94 | 58 | 1,039 | 6% | 276 | 763 | 6.9 |
| 1988 | 179 | 10% | 78 | 101 | 1,683 | 8% | 302 | 1,381 | 9.4 |
| 1989 | 216 | 9% | 129 | 87 | 1,525 | 7% | 462 | 1,063 | 7.1 |
| 1990 | 264 | 22% | 173 | 91 | 1,672 | 17% | 702 | 970 | 6.3 |
| 1991 | 103 | 10% | 48 | 55 | 963 | 10% | 196 | 767 | 9.4 |
| 1992 | 53 | 10% | 24 | 28 | 543 | 7% | 82 | 461 | 10.3 |
| 1993 | 164 | 11% | 138 | 26 | 753 | 8% | 391 | 362 | 4.6 |
| 1994 | 162 | 10% | 95 | 67 | 1,043 | 8% | 326 | 717 | 6.4 |
| 1995 | 218 | 13% | 125 | 94 | 1,547 | 11% | 567 | 980 | 7.1 |
| 1996 | 77 | 8% | 23 | 53 | 773 | 7% | 116 | 657 | 10.1 |
| 1997 | 54 | 12% | 28 | 26 | 533 | 6% | 66 | 467 | 9.8 |
| 1998 | 195 | 17% | 145 | 50 | 1,101 | 15% | 474 | 627 | 5.7 |
| 1999 | 309 | 21% | 173 | 136 | 2,281 | 18% | 640 | 1,641 | 7.4 |
| 2000 | 389 | 14% | 131 | 257 | 4,005 | 13% | 572 | 3,434 | 10.3 |
| 2001 | 398 | 12% | 141 | 257 | 4,519 | 13% | 523 | 3,995 | 11.3 |
| 2002 | 404 | 11% | 112 | 292 | 5,122 | 12% | 399 | 4,723 | 12.7 |
| 2003 | 864 | 15% | 495 | 370 | 7,603 | 9% | 1,297 | 6,306 | 8.8 |

Combined

| | | | | | | | | | |
|------|-----|-----|-----|-----|-------|-----|-------|-------|------|
| 1982 | 83 | 28% | 55 | 28 | 676 | 11% | 176 | 500 | 8.1 |
| 1983 | 49 | 13% | 22 | 27 | 587 | 10% | 80 | 507 | 12.1 |
| 1984 | 39 | 8% | 15 | 24 | 496 | 6% | 51 | 445 | 12.8 |
| 1985 | 80 | 9% | 46 | 35 | 721 | 8% | 169 | 552 | 9.1 |
| 1986 | 135 | 7% | 84 | 51 | 1,061 | 6% | 298 | 763 | 7.8 |
| 1987 | 140 | 8% | 82 | 58 | 1,059 | 7% | 262 | 798 | 7.6 |
| 1988 | 144 | 8% | 68 | 77 | 1,320 | 6% | 262 | 1,058 | 9.2 |
| 1989 | 167 | 13% | 95 | 72 | 1,254 | 12% | 363 | 892 | 7.5 |
| 1990 | 237 | 16% | 153 | 85 | 1,517 | 13% | 596 | 921 | 6.4 |
| 1991 | 172 | 21% | 119 | 53 | 1,095 | 9% | 361 | 734 | 6.4 |
| 1992 | 151 | 31% | 99 | 52 | 1,053 | 21% | 410 | 643 | 7.0 |
| 1993 | 120 | 11% | 96 | 24 | 650 | 8% | 304 | 346 | 5.4 |
| 1994 | 108 | 9% | 60 | 48 | 770 | 7% | 206 | 564 | 7.2 |
| 1995 | 173 | 10% | 110 | 63 | 1,175 | 9% | 436 | 739 | 6.9 |
| 1996 | 106 | 11% | 45 | 61 | 1,033 | 9% | 181 | 852 | 10.3 |
| 1997 | 76 | 9% | 28 | 48 | 1,035 | 10% | 81 | 954 | 14.9 |
| 1998 | 251 | 20% | 145 | 107 | 2,451 | 29% | 490 | 1,961 | 10.5 |
| 1999 | 268 | 14% | 124 | 144 | 1,978 | 16% | 416 | 1,562 | 11.1 |
| 2000 | 621 | 21% | 323 | 299 | 5,926 | 14% | 1,350 | 4,576 | 10.0 |
| 2001 | 433 | 9% | 144 | 290 | 5,678 | 10% | 566 | 5,112 | 13.3 |
| 2002 | 401 | 8% | 75 | 326 | 6,485 | 9% | 294 | 6,192 | 16.2 |
| 2003 | 607 | 12% | 293 | 314 | 7,569 | 8% | 801 | 6,768 | 12.5 |

Table B6-1. Fishing mortality estimates.

| Georges Bank | | | | | | | | | | | | | | |
|---------------------|---------------|--------------|----------------|-------------|-----------------|----------------|--------------|-----------|-------------|-----------|------------------|-----------|-------------|---------------|
| | 80-100 | 100+ | SurveyF | CV | Landings | MinEBms | Ebms | CV | CBI | CV | RescaledF | CV | BH-F | MovAvg |
| 1982 | 14.77 | 11.40 | | | 6448 | 3124 | 7811 | 0.12 | 0.83 | 0.15 | 1.44 | 0.16 | 0.50 | 0.53 |
| 1983 | 22.18 | 12.03 | 0.68 | | 4527 | 3443 | 8608 | 0.10 | 0.53 | 0.14 | 0.92 | 0.15 | 0.70 | 0.57 |
| 1984 | 10.52 | 11.25 | 1.01 | | 3207 | 2707 | 6767 | 0.10 | 0.47 | 0.14 | 0.82 | 0.14 | 0.38 | 0.49 |
| 1985 | 17.13 | 12.48 | 0.46 | | 2976 | 3204 | 8011 | 0.14 | 0.37 | 0.17 | 0.65 | 0.18 | 0.61 | 0.68 |
| 1986 | 15.21 | 14.85 | 0.59 | | 4516 | 3585 | 8964 | 0.09 | 0.50 | 0.13 | 0.88 | 0.14 | 0.48 | 0.78 |
| 1987 | 35.75 | 14.82 | 0.61 | | 4919 | 4631 | 11578 | 0.13 | 0.42 | 0.16 | 0.74 | 0.17 | 0.95 | 1.04 |
| 1988 | 27.79 | 12.84 | 1.27 | | 6123 | 3806 | 9515 | 0.10 | 0.64 | 0.14 | 1.12 | 0.14 | 0.89 | 1.32 |
| 1989 | 35.57 | 10.20 | 1.28 | | 5799 | 3842 | 9605 | 0.32 | 0.60 | 0.34 | 1.05 | 0.34 | 1.29 | 1.33 |
| 1990 | 53.88 | 8.84 | 1.54 | | 10098 | 4785 | 11962 | 0.22 | 0.84 | 0.24 | 1.47 | 0.24 | 1.78 | 1.27 |
| 1991 | 26.89 | 12.04 | 1.55 | | 9382 | 3844 | 9611 | 0.09 | 0.98 | 0.14 | 1.70 | 0.14 | 0.92 | 0.88 |
| 1992 | 32.37 | 11.29 | 1.14 | | 8362 | 4708 | 11770 | 0.17 | 0.71 | 0.19 | 1.24 | 0.20 | 1.10 | 0.87 |
| 1993 | 8.72 | 7.15 | 1.71 | | 3721 | 1806 | 4514 | 0.10 | 0.82 | 0.14 | 1.43 | 0.14 | 0.63 | 0.68 |
| 1994 | 16.4 | 7.2 | 0.69 | | 1138 | 2145 | 5363 | 0.12 | 0.21 | 0.16 | 0.37 | 0.16 | 0.87 | 0.72 |
| 1995 | 10.9 | 12.1 | 0.57 | | 1018 | 2554 | 6385 | 0.12 | 0.16 | 0.15 | 0.28 | 0.16 | 0.54 | 0.54 |
| 1996 | 37.86 | 23.50 | -0.12 | | 2120 | 5950 | 14874 | 0.14 | 0.14 | 0.17 | 0.25 | 0.18 | 0.74 | 0.48 |
| 1997 | 24.94 | 44.45 | 0.22 | | 2395 | 8370 | 20926 | 0.14 | 0.11 | 0.17 | 0.20 | 0.18 | 0.36 | 0.33 |
| 1998 | 66.74 | 91.99 | -0.38 | | 2118 | 19308 | 48271 | 0.39 | 0.04 | 0.40 | 0.08 | 0.40 | 0.34 | 0.33 |
| 1999 | 59.25 | 84.69 | 0.53 | | 5209 | 22937 | 57342 | 0.31 | 0.09 | 0.32 | 0.16 | 0.33 | 0.28 | 0.35 |
| 2000 | 133.52 | 135.59 | -0.04 | | 4569 | 32560 | 81401 | 0.20 | 0.06 | 0.23 | 0.10 | 0.23 | 0.36 | 0.38 |
| 2001 | 151.48 | 154.86 | 0.45 | | 4955 | 35358 | 88396 | 0.15 | 0.06 | 0.18 | 0.10 | 0.19 | 0.41 | 0.28 |
| 2002 | 145.32 | 215.07 | 0.25 | | 5249 | 43561 | 108903 | 0.13 | 0.05 | 0.17 | 0.08 | 0.17 | 0.35 | |
| 2003 | 33.77 | 207.89 | 0.45 | | 5048 | 40360 | 100901 | 0.13 | 0.05 | 0.17 | 0.09 | 0.17 | 0.08 | |
| <i>Mean8203</i> | <i>44.59</i> | <i>50.75</i> | <i>0.69</i> | <i>0.04</i> | <i>4723</i> | | <i>29158</i> | | <i>0.40</i> | | <i>0.69</i> | | <i>0.66</i> | |

Mid-Atlantic Fishing Mortality Estimates

| | 80-98.5 | 98.5+ | SurveyF | CV | Landings | MinEBms | EBms | CV | CBI | CV | RescaledF | CV | BH-F | MovAvg |
|-----------------|-------------|-------------|-------------|-------------|-------------|---------|--------------|------|-------------|------|-------------|------|-------------|--------|
| 1979 | 10.9 | 19.1 | | | 2888 | 4326 | 7210 | 0.10 | 0.67 | 0.14 | 0.64 | 0.15 | 0.38 | 0.39 |
| 1980 | 7.0 | 16.2 | 0.52 | | 1975 | 3512 | 5854 | 0.07 | 0.56 | 0.12 | 0.54 | 0.12 | 0.33 | 0.45 |
| 1981 | 9.0 | 10.1 | 0.73 | | 731 | 2686 | 4476 | 0.10 | 0.27 | 0.14 | 0.26 | 0.14 | 0.47 | 0.46 |
| 1982 | 11.3 | 10.6 | 0.49 | | 1610 | 2819 | 4698 | 0.08 | 0.57 | 0.13 | 0.55 | 0.13 | 0.55 | 0.55 |
| 1983 | 6.4 | 10.8 | 0.61 | | 3109 | 2582 | 4304 | 0.08 | 1.20 | 0.13 | 1.16 | 0.13 | 0.36 | 0.61 |
| 1984 | 14.8 | 8.2 | 0.64 | | 3675 | 2577 | 4295 | 0.09 | 1.43 | 0.13 | 1.37 | 0.13 | 0.73 | 0.85 |
| 1985 | 16.9 | 11.8 | 0.57 | | 3276 | 3351 | 5584 | 0.07 | 0.98 | 0.12 | 0.94 | 0.12 | 0.75 | 0.99 |
| 1986 | 40.0 | 15.9 | 0.49 | | 3359 | 5480 | 9133 | 0.07 | 0.61 | 0.12 | 0.59 | 0.12 | 1.06 | 1.10 |
| 1987 | 40.1 | 13.6 | 1.31 | | 7803 | 4842 | 8071 | 0.06 | 1.61 | 0.12 | 1.55 | 0.12 | 1.16 | 1.16 |
| 1988 | 66.4 | 24.8 | 0.67 | | 6178 | 8768 | 14613 | 0.07 | 0.70 | 0.12 | 0.68 | 0.12 | 1.10 | 1.24 |
| 1989 | 53.5 | 16.2 | 1.63 | | 7973 | 6748 | 11247 | 0.07 | 1.18 | 0.12 | 1.13 | 0.12 | 1.22 | 1.21 |
| 1990 | 49.7 | 11.7 | 1.69 | | 6435 | 6161 | 10268 | 0.10 | 1.04 | 0.14 | 1.00 | 0.14 | 1.41 | 1.05 |
| 1991 | 33.5 | 14.8 | 1.32 | | 7011 | 4872 | 8120 | 0.11 | 1.44 | 0.15 | 1.38 | 0.15 | 1.01 | 0.85 |
| 1992 | 15.3 | 10.9 | 1.39 | | 4955 | 2928 | 4880 | 0.07 | 1.69 | 0.12 | 1.62 | 0.12 | 0.73 | 1.13 |
| 1993 | 12.9 | 7.5 | 1.14 | | 2794 | 2300 | 3833 | 0.07 | 1.22 | 0.12 | 1.17 | 0.12 | 0.83 | 1.38 |
| 1994 | 44.5 | 7.6 | 0.89 | | 5872 | 4552 | 7587 | 0.08 | 1.29 | 0.13 | 1.24 | 0.13 | 1.84 | 1.58 |
| 1995 | 50.0 | 13.2 | 1.27 | | 6318 | 6224 | 10373 | 0.09 | 1.02 | 0.13 | 0.97 | 0.13 | 1.48 | 1.17 |
| 1996 | 39.5 | 10.1 | 1.73 | | 4999 | 4168 | 6947 | 0.06 | 1.20 | 0.12 | 1.15 | 0.12 | 1.43 | 1.04 |
| 1997 | 12.6 | 13.2 | 1.23 | | 2910 | 2967 | 4944 | 0.06 | 0.98 | 0.11 | 0.94 | 0.11 | 0.61 | 1.00 |
| 1998 | 28.9 | 11.0 | 0.75 | | 2948 | 3980 | 6633 | 0.14 | 0.74 | 0.17 | 0.71 | 0.17 | 1.10 | 1.16 |
| 1999 | 87.7 | 26.9 | 0.30 | | 4653 | 10418 | 17363 | 0.15 | 0.45 | 0.18 | 0.43 | 0.18 | 1.30 | 1.05 |
| 2000 | 169.9 | 69.9 | 0.39 | | 9691 | 21800 | 36334 | 0.13 | 0.44 | 0.16 | 0.43 | 0.16 | 1.09 | 0.86 |
| 2001 | 129.5 | 114.1 | 0.64 | | 15812 | 25365 | 42274 | 0.14 | 0.62 | 0.17 | 0.60 | 0.17 | 0.76 | 0.69 |
| 2002 | 147.2 | 137.2 | 0.47 | | 17233 | 29985 | 49976 | 0.12 | 0.57 | 0.16 | 0.55 | 0.16 | 0.72 | |
| 2003 | 158.8 | 188.2 | 0.31 | | 19822 | 40033 | 66721 | 0.09 | 0.50 | 0.14 | 0.48 | 0.14 | 0.60 | |
| <i>Mean7903</i> | <i>50.3</i> | <i>31.7</i> | <i>0.88</i> | <i>0.02</i> | <i>6161</i> | | <i>14229</i> | | <i>0.92</i> | | <i>0.88</i> | | <i>0.92</i> | |

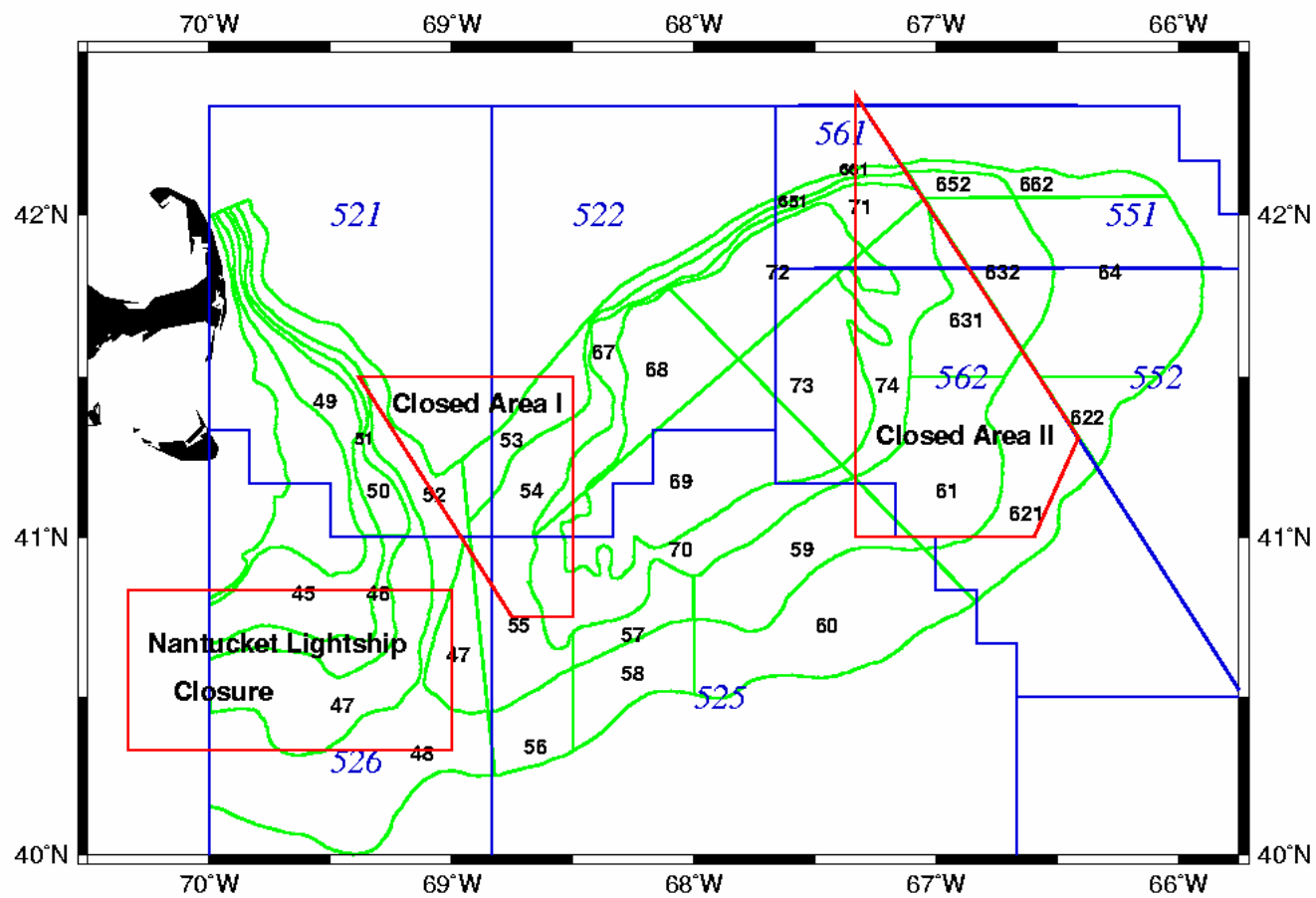
Combined Fishing Mortality Estimates (Number weighted)

| | SurveyF | Landings | Ebms | CBI | RescaledF | CV | BH-F | MovAvg |
|-----------------|----------------|-----------------|--------------|------------|------------------|-----------|-------------|---------------|
| 1982 | | 8058 | 12509 | 0.64 | 1.10 | 0.08 | 0.52 | 0.56 |
| 1983 | 0.66 | 7636 | 12912 | 0.59 | 0.99 | 0.07 | 0.60 | 0.61 |
| 1984 | 0.83 | 6882 | 11062 | 0.62 | 1.09 | 0.07 | 0.55 | 0.69 |
| 1985 | 0.51 | 6252 | 13595 | 0.46 | 0.78 | 0.08 | 0.67 | 0.85 |
| 1986 | 0.53 | 7875 | 18096 | 0.44 | 0.70 | 0.07 | 0.83 | 0.97 |
| 1987 | 0.94 | 12722 | 19648 | 0.65 | 1.13 | 0.08 | 1.05 | 1.11 |
| 1988 | 0.89 | 12301 | 24127 | 0.51 | 0.84 | 0.07 | 1.02 | 1.29 |
| 1989 | 1.48 | 13772 | 20851 | 0.66 | 1.10 | 0.14 | 1.25 | 1.27 |
| 1990 | 1.61 | 16533 | 22230 | 0.74 | 1.25 | 0.11 | 1.61 | 1.19 |
| 1991 | 1.44 | 16393 | 17731 | 0.92 | 1.55 | 0.07 | 0.96 | 0.90 |
| 1992 | 1.20 | 13317 | 16650 | 0.80 | 1.32 | 0.09 | 1.02 | 1.10 |
| 1993 | 1.43 | 6515 | 8347 | 0.78 | 1.30 | 0.07 | 0.73 | 1.17 |
| 1994 | 0.83 | 7010 | 12950 | 0.54 | 0.97 | 0.08 | 1.55 | 1.26 |
| 1995 | 1.09 | 7336 | 16758 | 0.44 | 0.80 | 0.08 | 1.25 | 0.88 |
| 1996 | 0.55 | 7119 | 21820 | 0.33 | 0.58 | 0.08 | 0.99 | 0.62 |
| 1997 | 0.43 | 5305 | 25870 | 0.21 | 0.35 | 0.08 | 0.41 | 0.52 |
| 1998 | -0.20 | 5066 | 54904 | 0.09 | 0.18 | 0.17 | 0.46 | 0.60 |
| 1999 | 0.43 | 9862 | 74705 | 0.13 | 0.27 | 0.14 | 0.70 | 0.62 |
| 2000 | 0.12 | 14260 | 117735 | 0.12 | 0.22 | 0.11 | 0.64 | 0.56 |
| 2001 | 0.52 | 20767 | 130670 | 0.16 | 0.28 | 0.09 | 0.54 | 0.47 |
| 2002 | 0.34 | 22482 | 158878 | 0.14 | 0.26 | 0.09 | 0.49 | |
| 2003 | 0.38 | 24870 | 167622 | 0.15 | 0.30 | 0.08 | 0.36 | |
| <i>Mean8203</i> | <i>0.76</i> | | <i>44530</i> | | <i>0.79</i> | | <i>0.83</i> | |

Table B7-1 Length-based yield-per-recruit analysis results

| Stock | L_{inf} | K | a | b | M | h_d | d | i | rings | F_{max} | Y_{max} | B_{max} | Comments |
|-----------|---------------|---------------|-----------------|---------------|------------|-----------|------------|--------------|----------------|--------------|--------------|--------------|------------------------------------|
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 90 | 0.2 | 0.225 | 3.5-log | 0.189 | 13.58 | 95.54 | Standard 3.5" ring run |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 90 | 0.2 | 0 | 3.5-log | 0.215 | 17.59 | 90.02 | No incidental mortality |
| GB | 152.46 | 0.4 | -11.6038 | 3.1221 | 0.1 | 90 | 0.2 | 0.225 | 3.5-log | 0.202 | 15.11 | 98.44 | Fast growth |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 75 | 0.2 | 0.225 | 3.5-log | 0.178 | 13.24 | 94.69 | Cull size prior to 1999 |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.05/0.1 | 90 | 0.2 | 0.225 | 3.5-log | 0.184 | 16.15 | 116.08 | M increases at 120 mm |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1/0.2 | 90 | 0.2 | 0.225 | 3.5-log | 0.282 | 10.97 | 55.40 | M increases at 120 mm |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 90 | 0 | 0.225 | 3.5-log | 0.202 | 14.08 | 93.41 | No discard mortality |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 90 | 1 | 0.225 | 3.5-log | 0.147 | 11.99 | 107.53 | 100% discard mortality |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 90 | 0.2 | 0.225 | 3.5-pl | 0.196 | 13.82 | 94.42 | SARC-23 selectivity curve |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 90 | 0.2 | 0.225 | 4 | 0.214 | 14.14 | 95.90 | Standard 4" ring run |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 90 | 0.2 | 0 | 4 | 0.275 | 19.15 | 85.30 | No incidental mortality |
| GB | 152.46 | 0.4 | -11.6038 | 3.1221 | 0.1 | 90 | 0.2 | 0.225 | 4 | 0.227 | 15.73 | 98.40 | Fast growth |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 75 | 0.2 | 0.225 | 4 | 0.208 | 14.05 | 96.53 | Cull size typical prior to 1999 |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.05/0.1 | 90 | 0.2 | 0.225 | 4 | 0.208 | 16.86 | 115.85 | M increases at 120 mm |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1/0.2 | 90 | 0.2 | 0.225 | 4 | 0.325 | 11.45 | 57.14 | M increases at 120 mm |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 90 | 0 | 0.225 | 4 | 0.214 | 14.23 | 96.49 | No discard mortality |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 90 | 1 | 0.225 | 4 | 0.202 | 13.79 | 98.57 | 100% discard mortality |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 90 | 0.2 | 0.225 | 4 | 0.227 | 14.29 | 93.78 | Rotation - 3 closed then ramped fc |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 75 | 0.2 | 0.225 | fishery | 0.184 | 13.45 | 93.38 | Fishery Selectivity 79-99 |
| GB | 152.46 | 0.3374 | -11.6038 | 3.1221 | 0.1 | 85 | 0.2 | 0.225 | fishery | 0.214 | 14.27 | 94.03 | Fishery Selectivity 00-03 |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | 90 | 0.2 | 0.04 | 3.5-log | 0.198 | 15.99 | 92.91 | Standard 3.5" ring run |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | 90 | 0.2 | 0 | 3.5-log | 0.200 | 16.85 | 93.07 | No incidental mortality |
| MA | 151.84 | 0.23 | -12.2484 | 3.2641 | 0.1 | 90 | 0.2 | 0.04 | 3.5-log | 0.182 | 13.20 | 86.31 | Slow growth |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | 75 | 0.2 | 0.04 | 3.5-log | 0.177 | 15.30 | 93.60 | Cull size prior to 1999 |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.05/0.1 | 90 | 0.2 | 0.04 | 3.5-log | 0.192 | 19.44 | 114.40 | M increases at 120 mm |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1/0.2 | 90 | 0.2 | 0.04 | 3.5-log | 0.302 | 13.19 | 54.07 | M increases at 120 mm |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | 90 | 0 | 0.04 | 3.5-log | 0.224 | 16.84 | 87.28 | No discard mortality |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | 90 | 1 | 0.04 | 3.5-log | 0.140 | 13.57 | 108.78 | 100% discard mortality |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | 90 | 0.2 | 0.04 | 3.5-pl | 0.208 | 16.40 | 90.87 | SARC-23 selectivity curve |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | 90 | 0.2 | 0.04 | 4 | 0.244 | 17.29 | 90.44 | Standard 4" ring run |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | 90 | 0.2 | 0 | 4 | 0.265 | 18.43 | 86.58 | No incidental mortality |
| MA | 151.84 | 0.23 | -12.2484 | 3.2641 | 0.1 | 90 | 0.2 | 0.04 | 4 | 0.234 | 14.36 | 83.89 | Slow growth |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | 75 | 0.2 | 0.04 | 4 | 0.234 | 17.05 | 91.24 | Cull size typical prior to 1999 |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.05/0.1 | 90 | 0.2 | 0.04 | 4 | 0.239 | 21.07 | 110.43 | M increases at 120 mm |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1/0.2 | 90 | 0.2 | 0.04 | 4 | 0.406 | 14.59 | 53.06 | M increases at 120 mm |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | 90 | 0.2 | 0.04 | 4 | 0.265 | 17.48 | 87.74 | Rotation - 3 closed then ramped fc |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | N/A | N/A | 0.04 | fishery | 0.198 | 16.11 | 91.25 | Fishery Selectivity 79-98 |
| MA | 151.84 | 0.2997 | -12.2484 | 3.2641 | 0.1 | N/A | N/A | 0.04 | fishery | 0.260 | 17.67 | 88.77 | Fishery Selectivity 01-03 |

Figure B3-1. NEFSC Scallop Survey Maps with Closed Areas
(a) Georges Bank



(b) Mid-Atlantic Bight

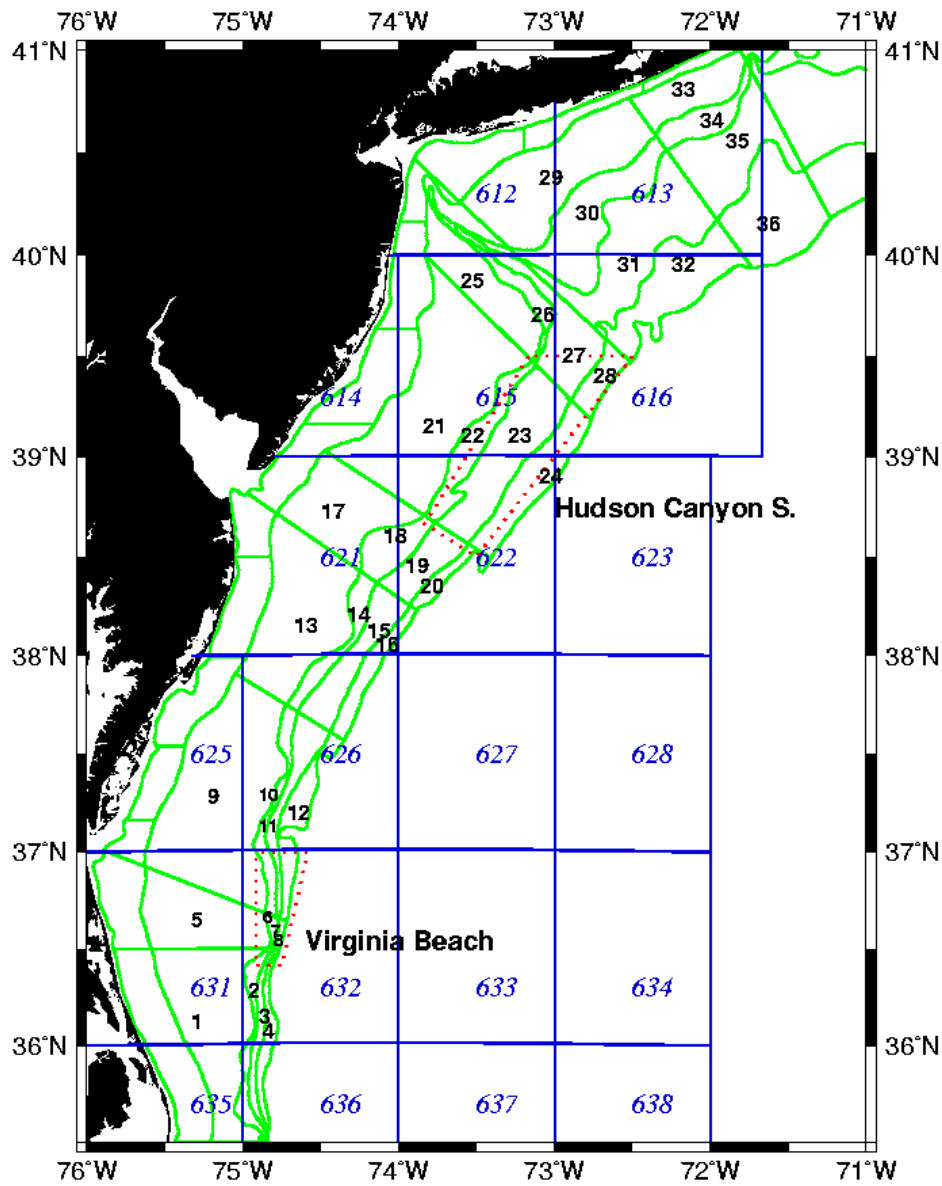


Figure B3-2. Growth in shell height and meat weights of a scallop that started at 40 mm shell height, using the standard growth and shell height/meat weight parameters for Georges Bank.

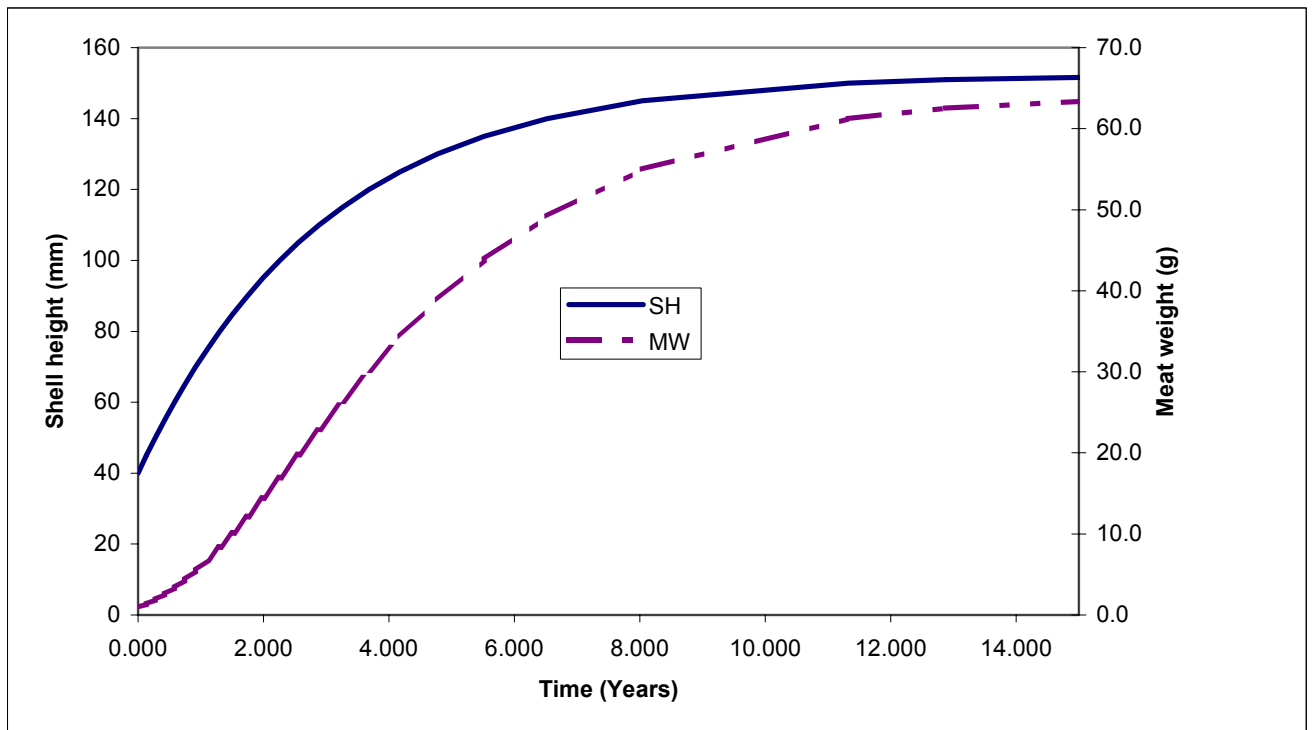
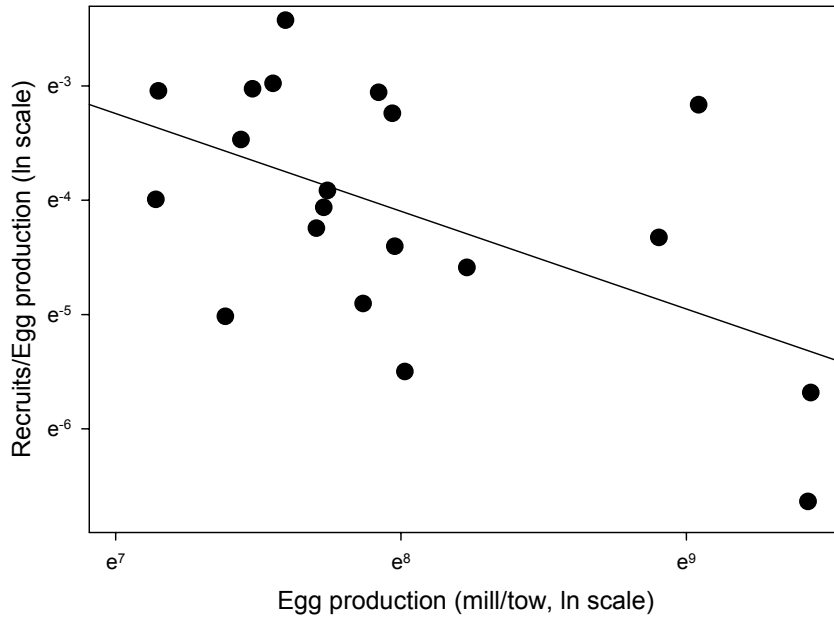


Figure B3-3. Stock-recruitment relationships.
(a) Georges Bank



(b) Mid-Atlantic Bight

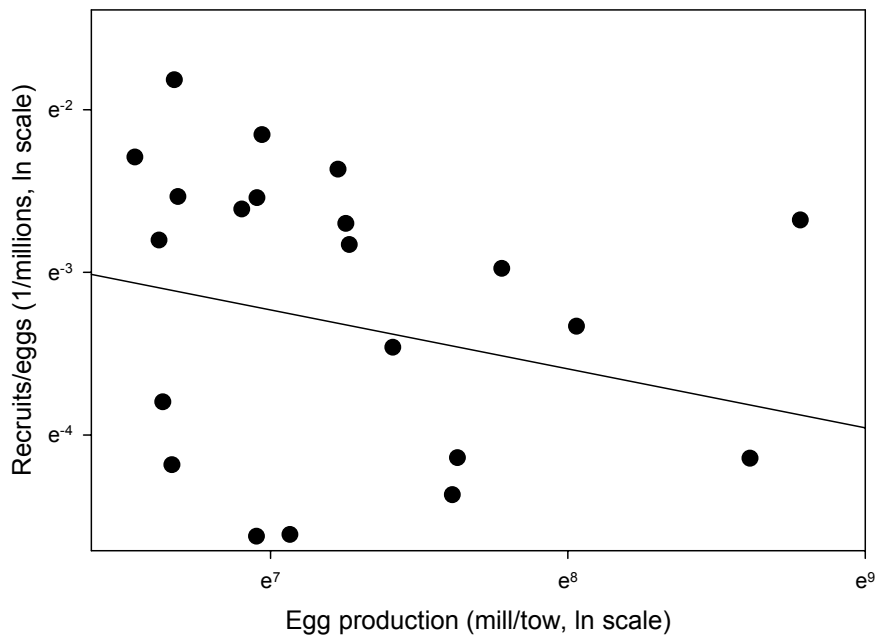


Figure B3-4. Natural mortality as estimated by clapper ratios, assuming the clapper separation rate given by Merrill and Posgay (1964).

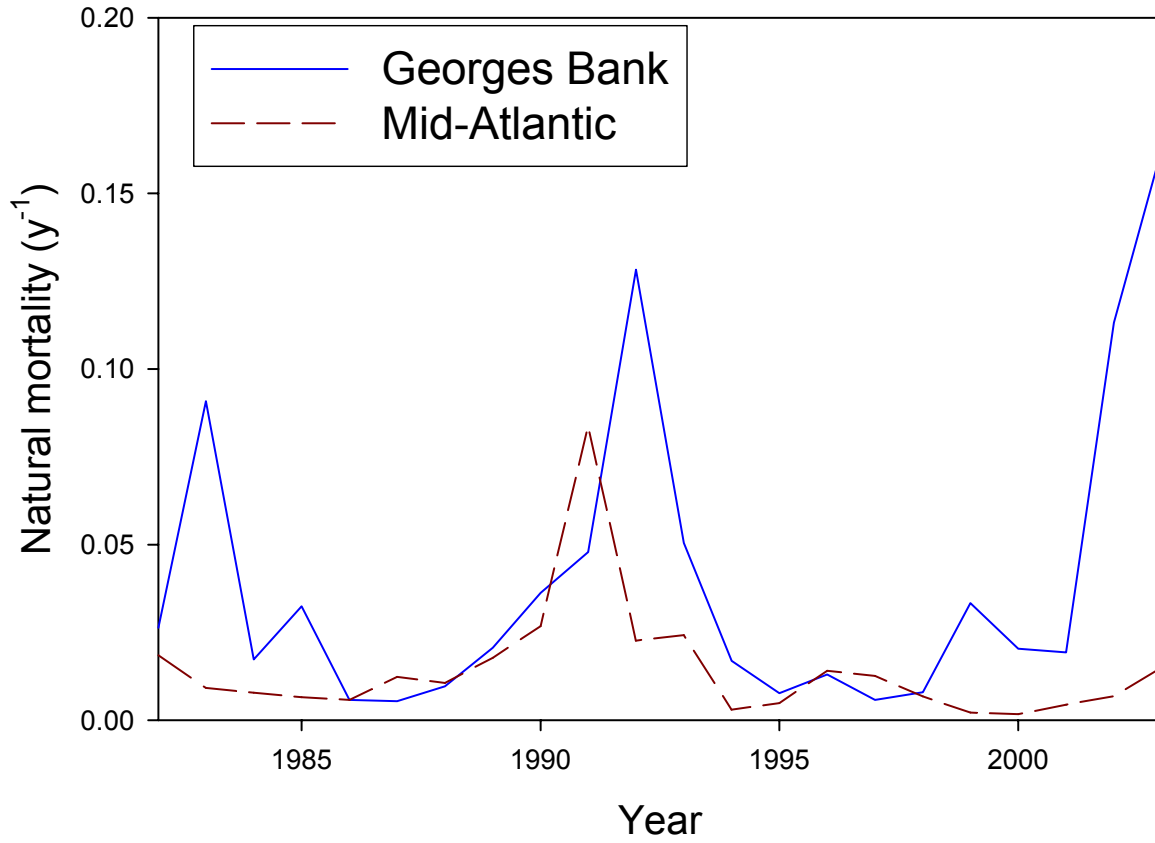


Figure B4-2. Long-term scallop landings (MT meats) in NAFO areas 5 and 6 (U.S. and Canada Georges Bank)

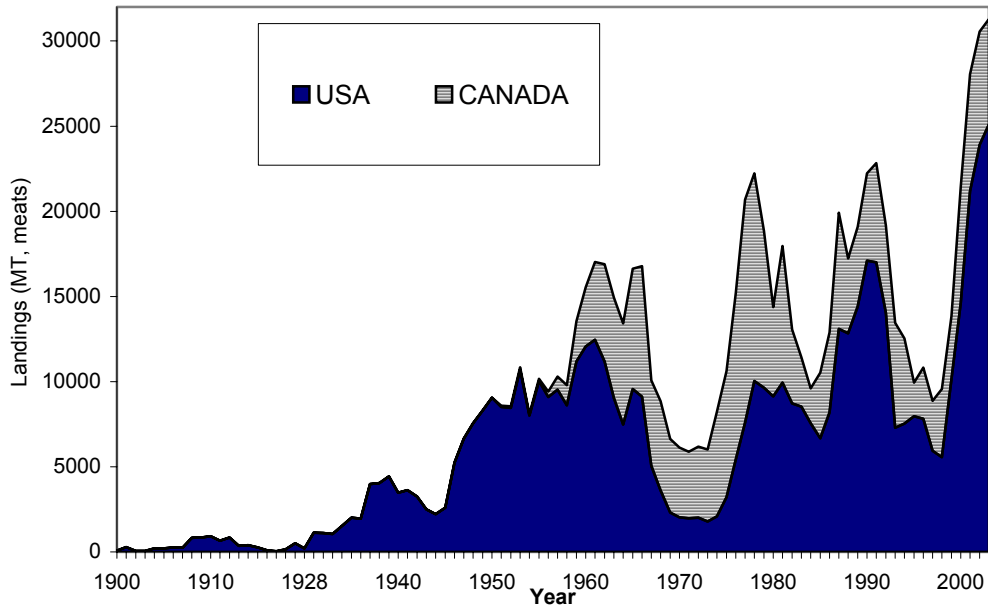


Figure B4-3. U.S. landings by region, 1964-2003.

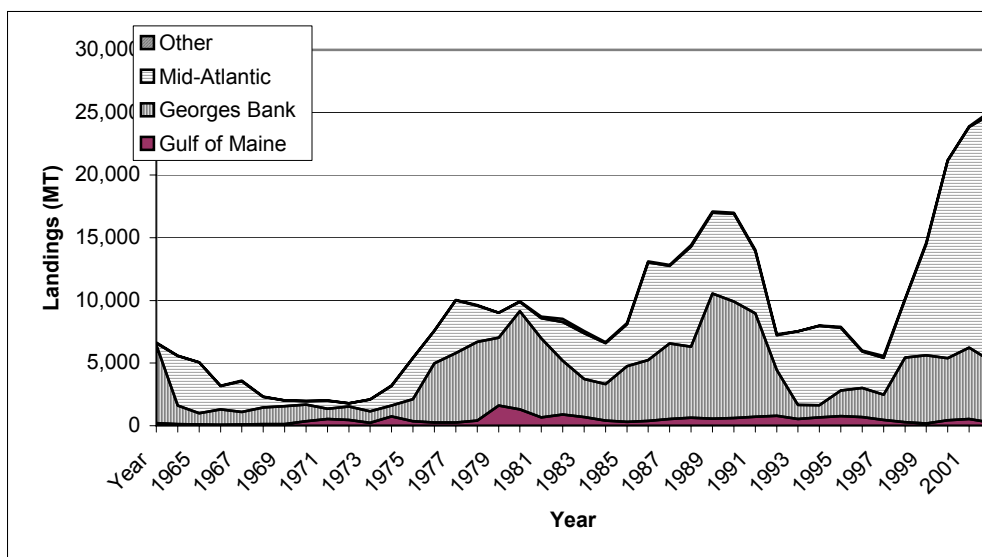


Figure B4-4. Landings-per-unit effort (lbs meats per day absent) for Georges Bank and the Mid-Atlantic Bight.

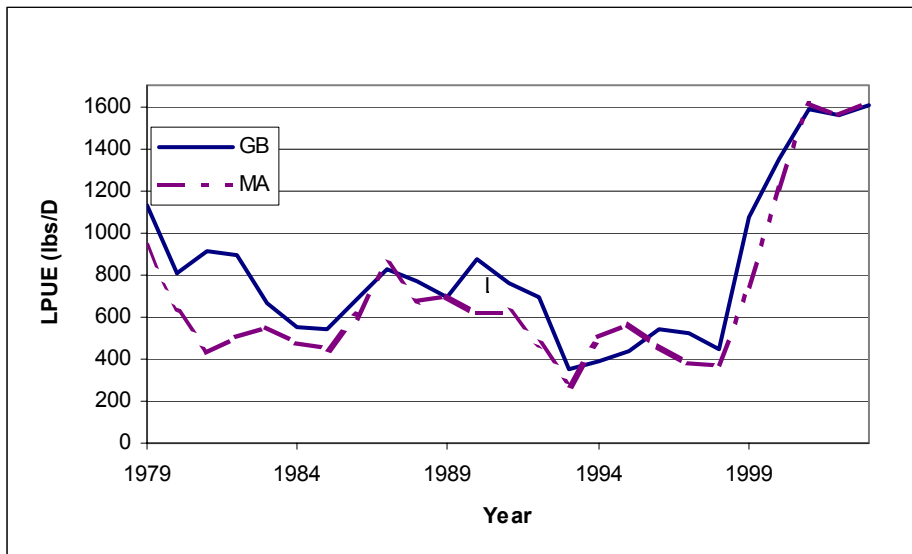


Figure B4-5. Cull sizes (the point of 50% retention) and discarded to kept ratios (by weight) for observed scallop trips (excluding closed area access trips).

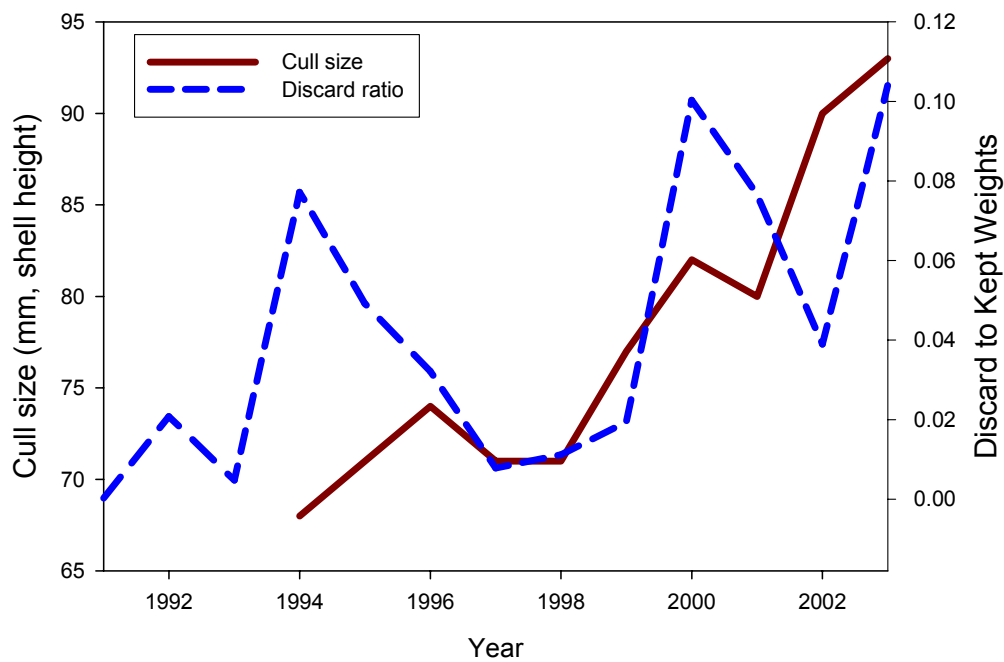


Fig. B5-1. Comparison of observed and predicted shell height frequencies for lined and unlined dredges with 2.0 inch rings from the Serchuck and Smolowitz (1980) experiments. Input data shown in top panel; model comparisons in bottom panel.

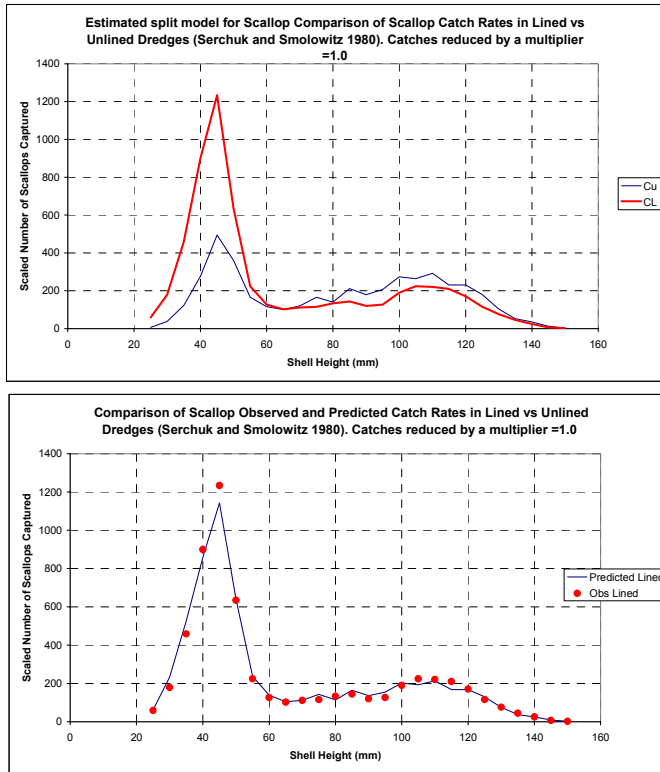


Figure B5-2. Estimated selectivity of the lined survey dredge.

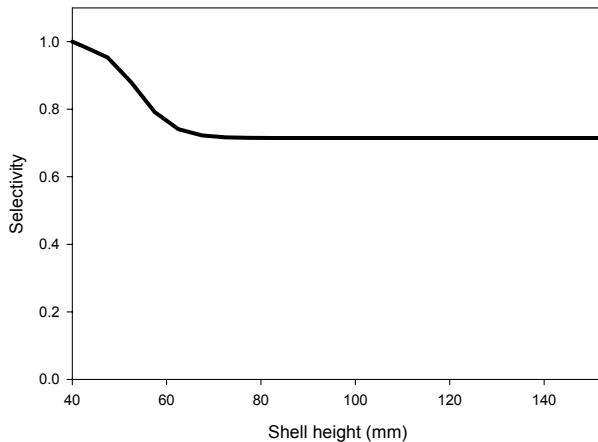


Figure B5-3. Estimated selectivity of commercial scallop dredges with 3.5” and 4” rings. The solid line is the 3.5” ring dredge selectivity from SARC-23, the dashed-dotted line is the estimated selectivity from the F/V Tradition experiment, and the long dashed line is the estimated 4” ring selectivity.

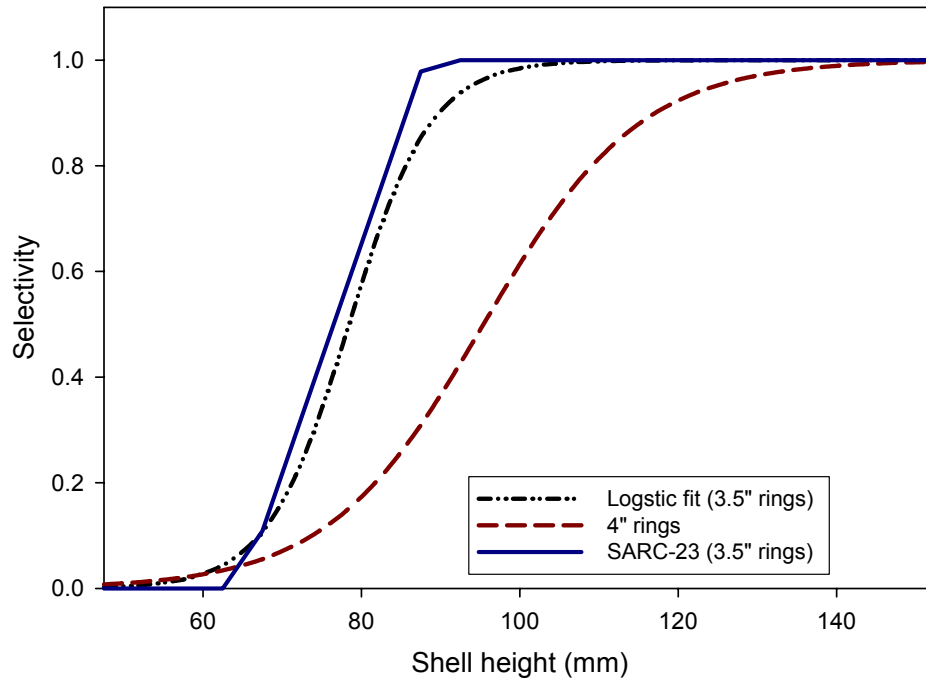


Figure B5-4. Typical inclinometer traces from 15 minute tows in the 2003 NMFS scallop survey.

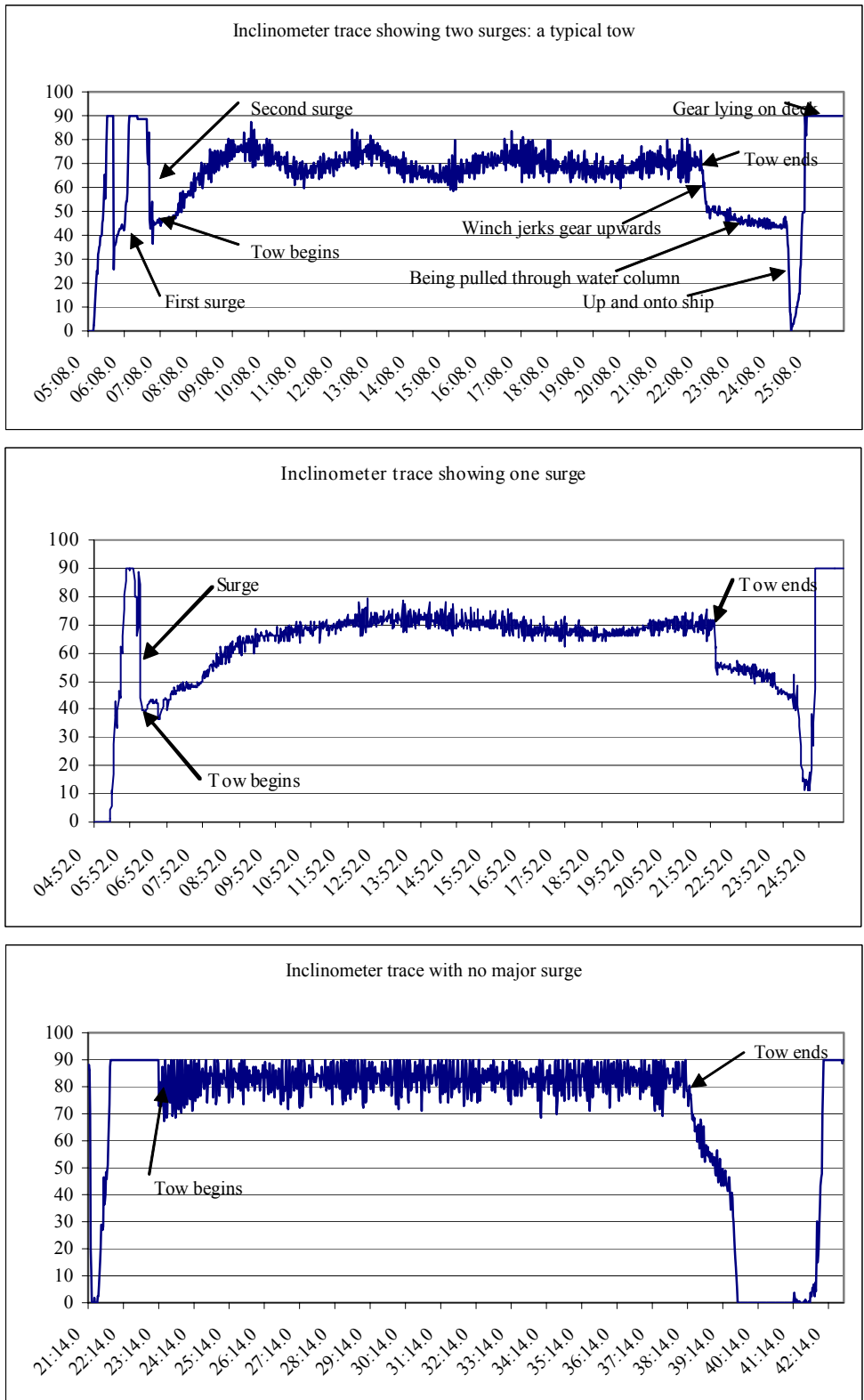
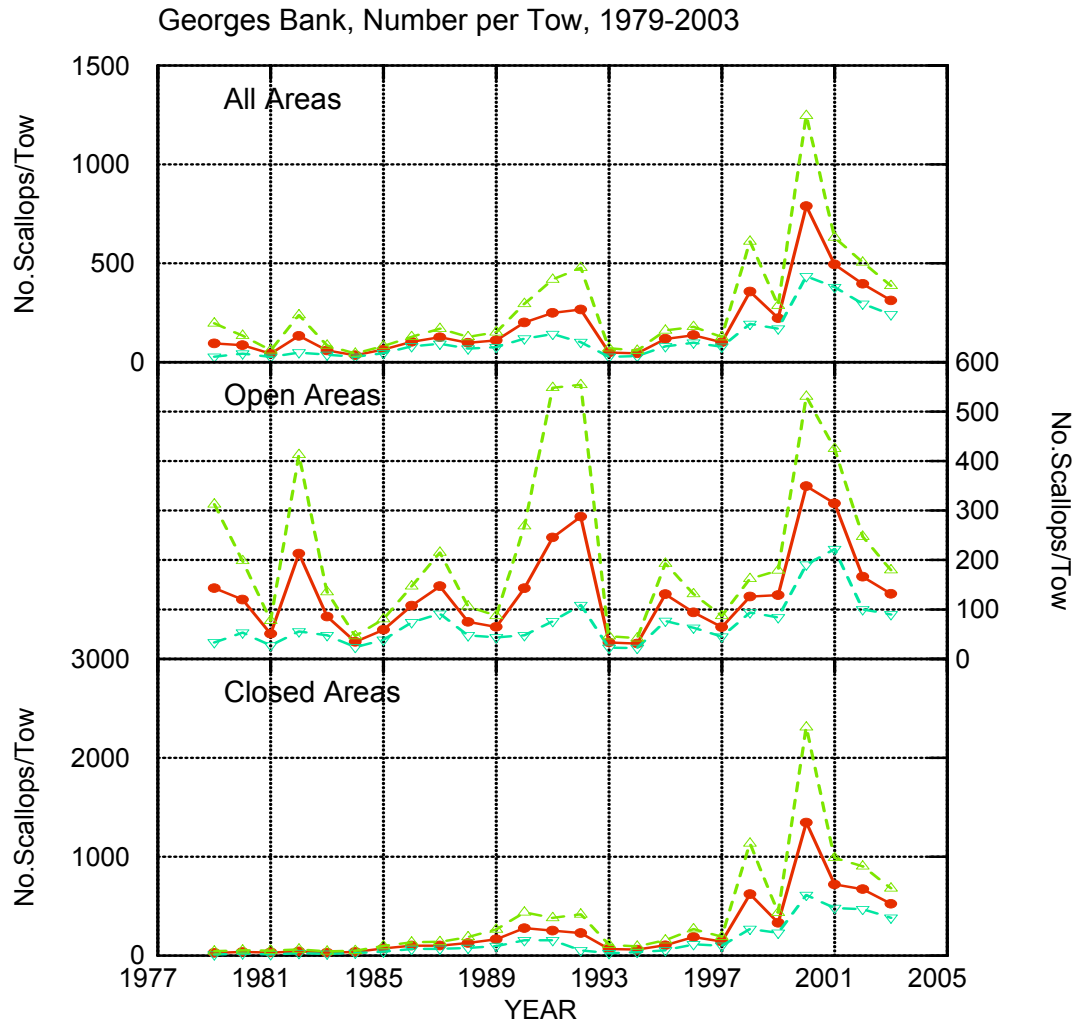


Figure B5-5. Stratified mean sea scallop abundance (>40 mm) in Georges Bank and the Mid-Atlantic, overall, and open and closed, with bootstrapped confidence intervals. Note the changes in scales for the graphs.

(a)



(b)

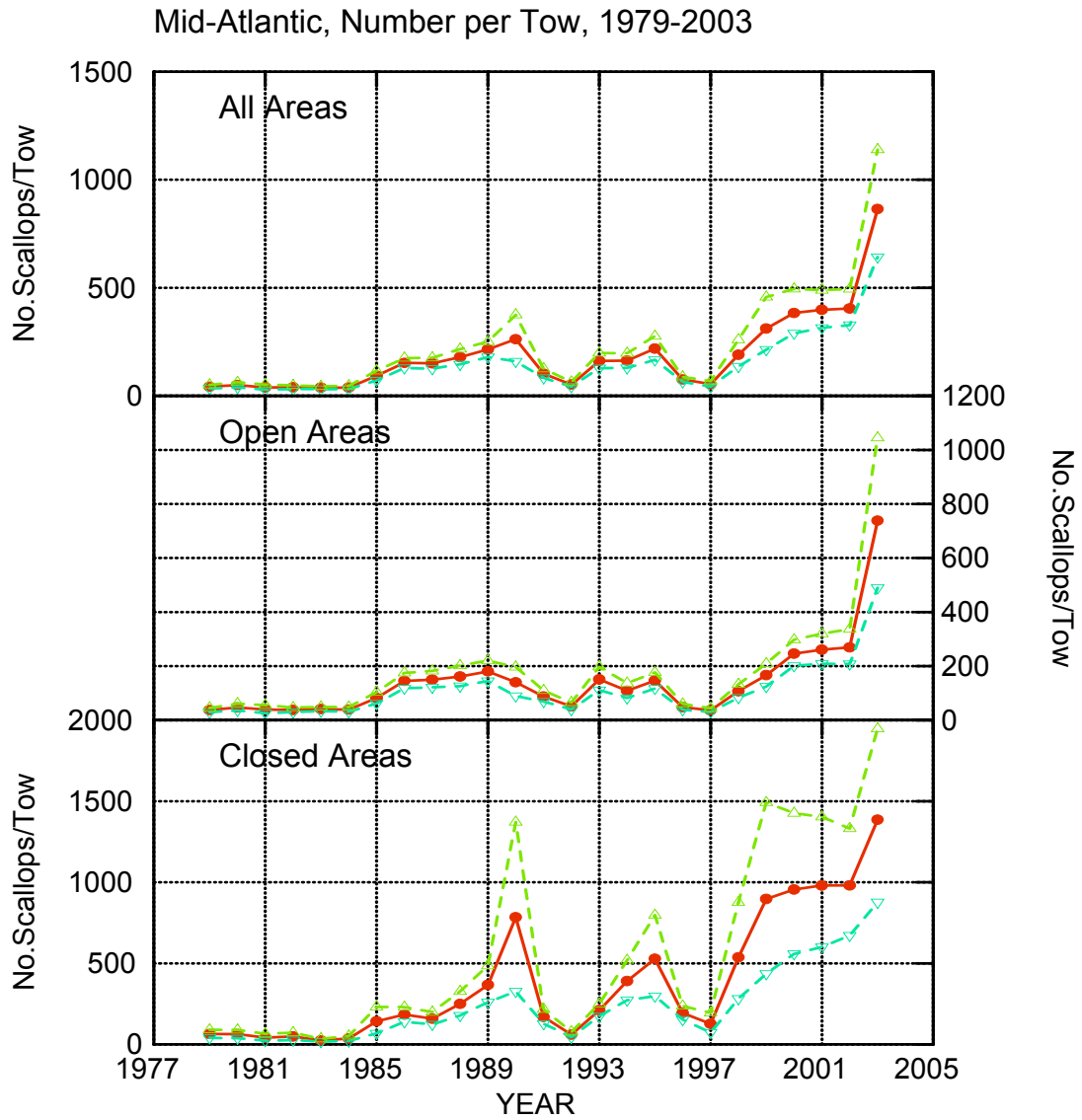
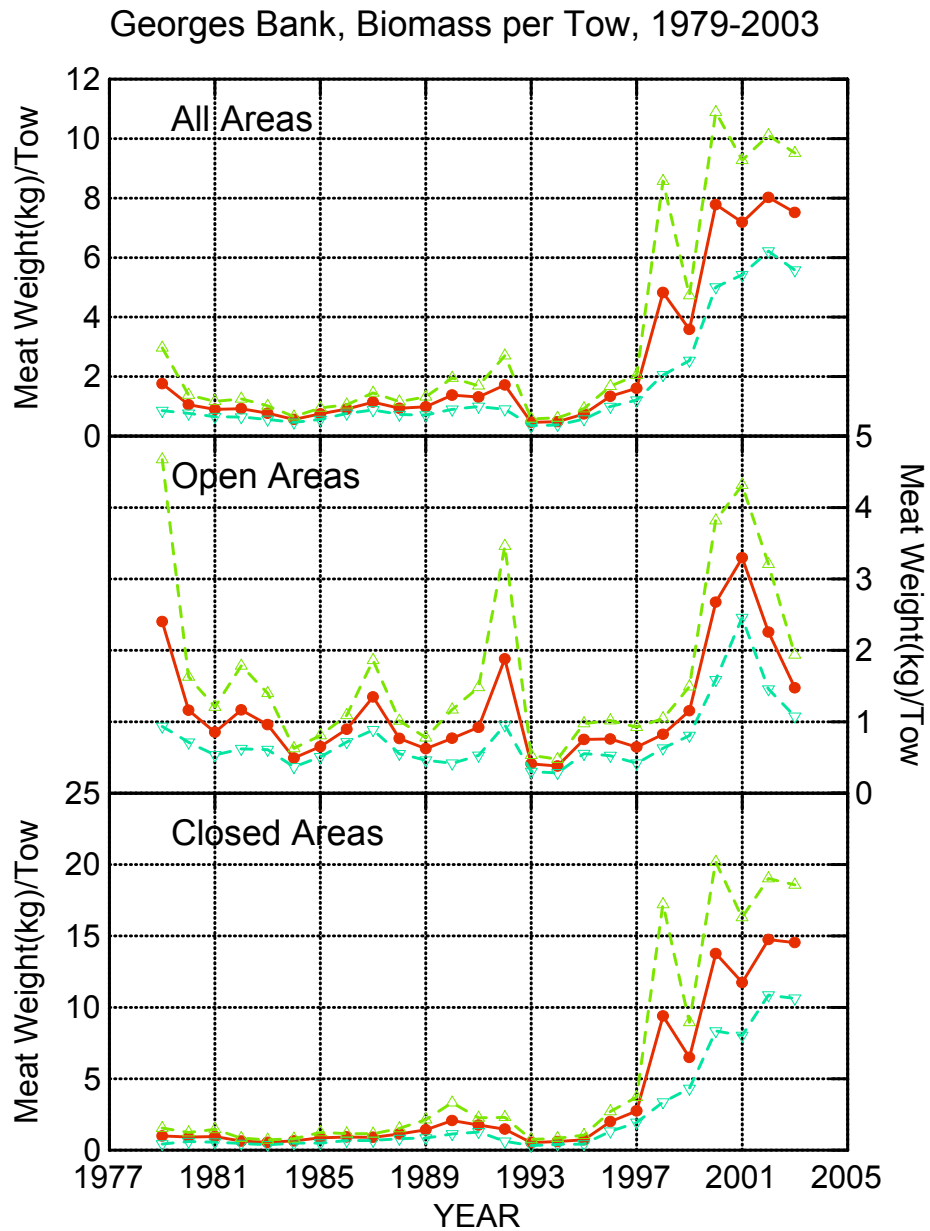


Figure B5-6. Stratified mean sea scallop biomass in Georges Bank and the Mid-Atlantic, overall, and open and closed, with bootstrapped confidence intervals. Note the changes in scales for the graphs.

(a)



(b)

Mid-Atlantic, Biomass per Tow, 1979-2003

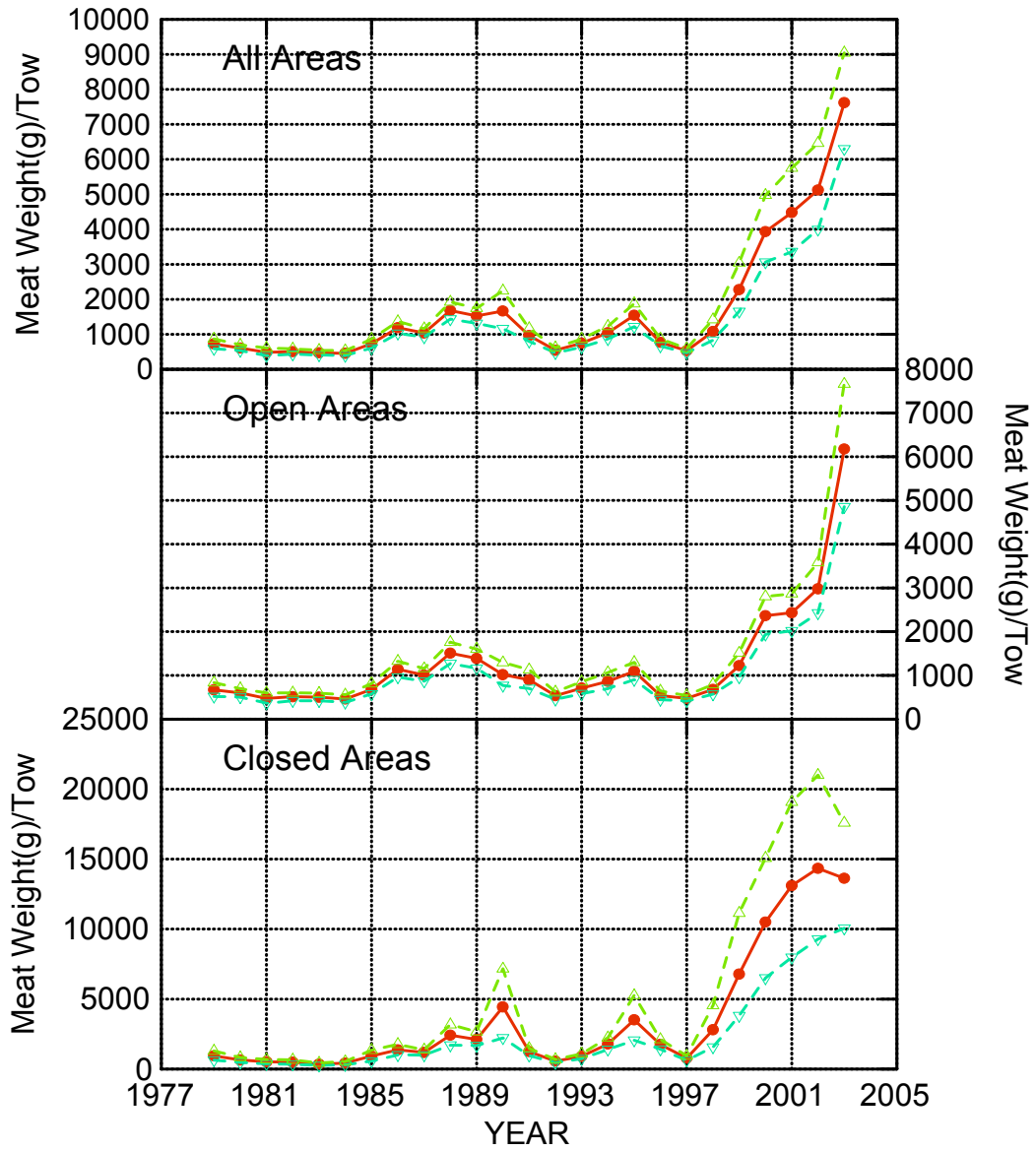
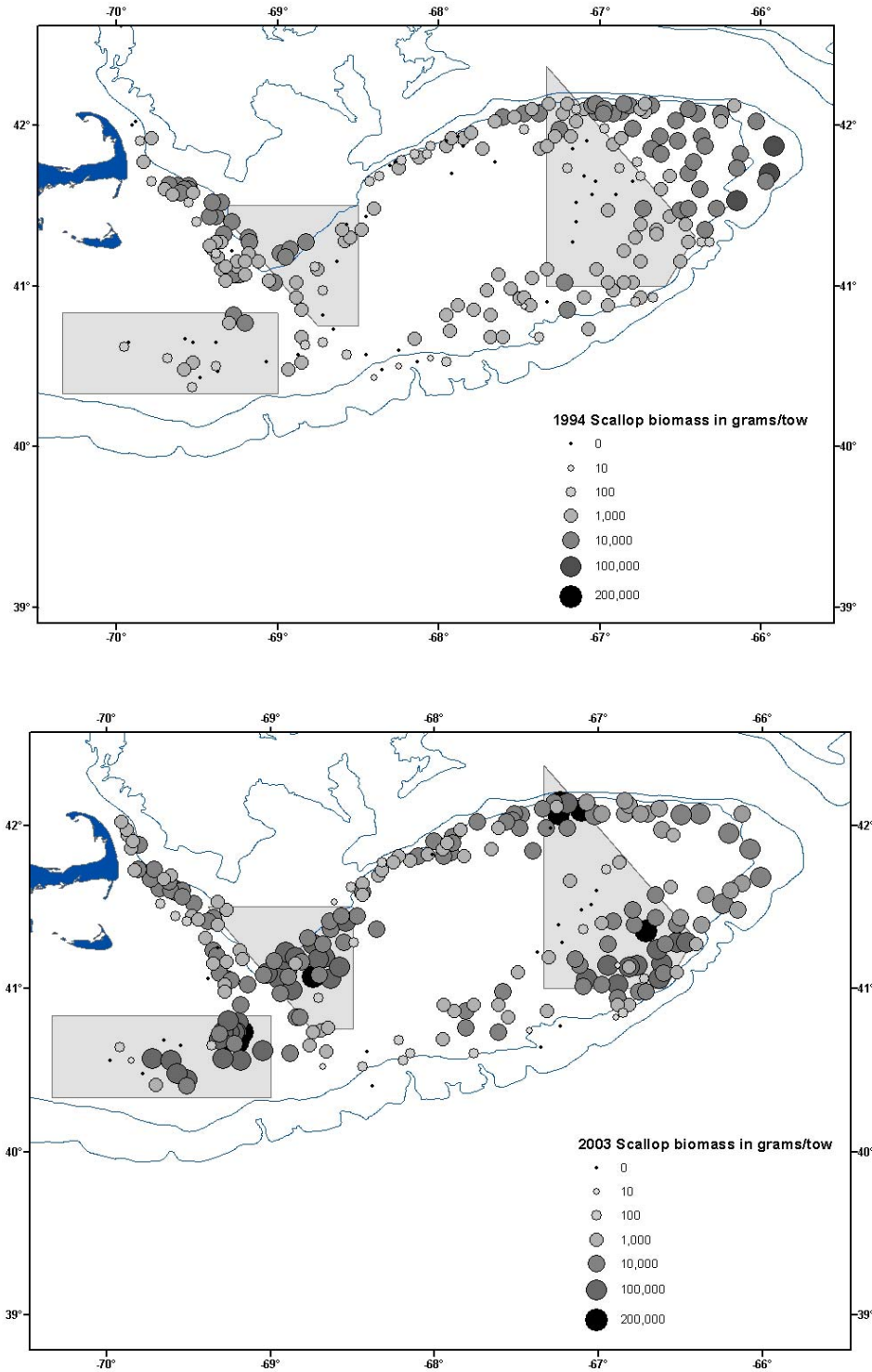


Figure B5-7. Comparison of biomass distributions on Georges Bank and the Mid-Atlantic in 1994 and 2003.

(a) Georges Bank



(b) Mid-Atlantic.

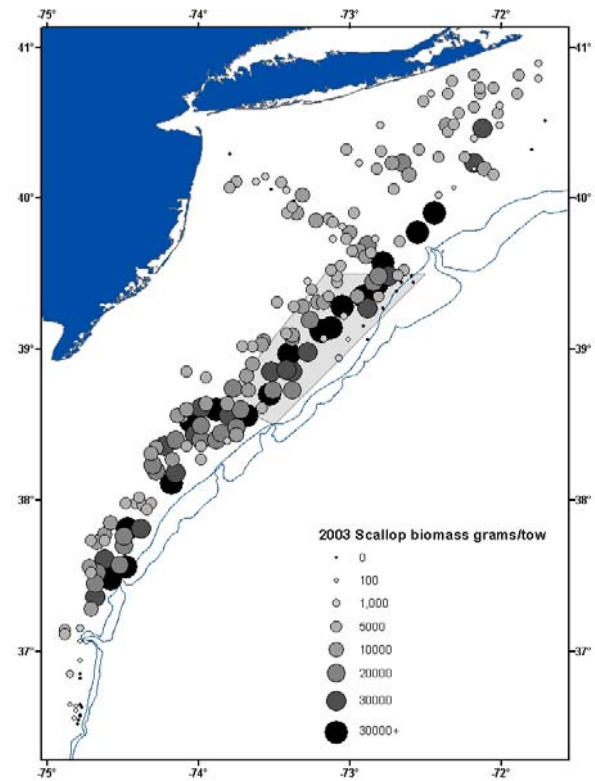
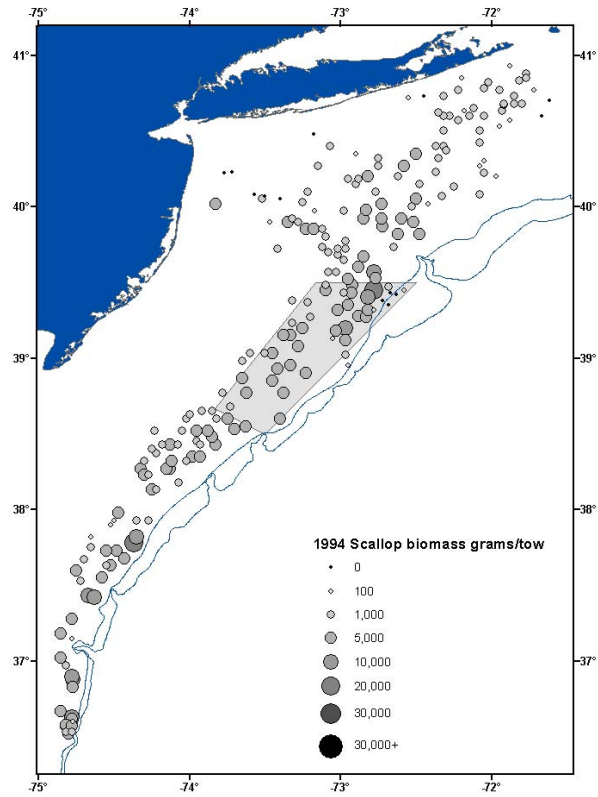
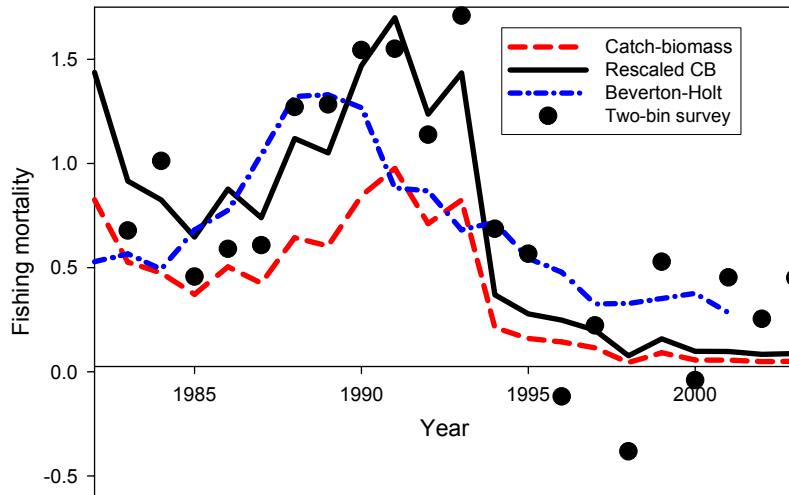
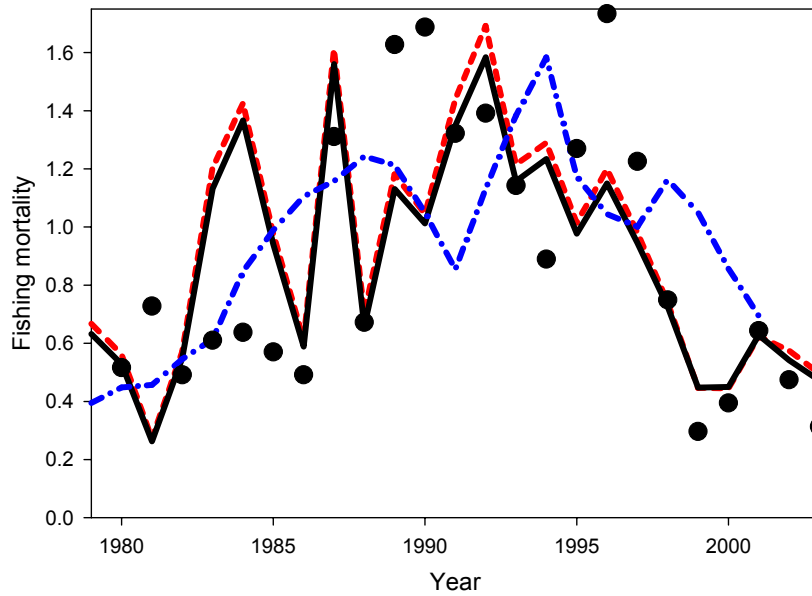


Figure B6-1. Estimates of fishing mortality (Two-bin survey, catch-biomass, rescaled catch-biomass, and Beverton-Holt) for Georges Bank, Mid-Atlantic, and combined.

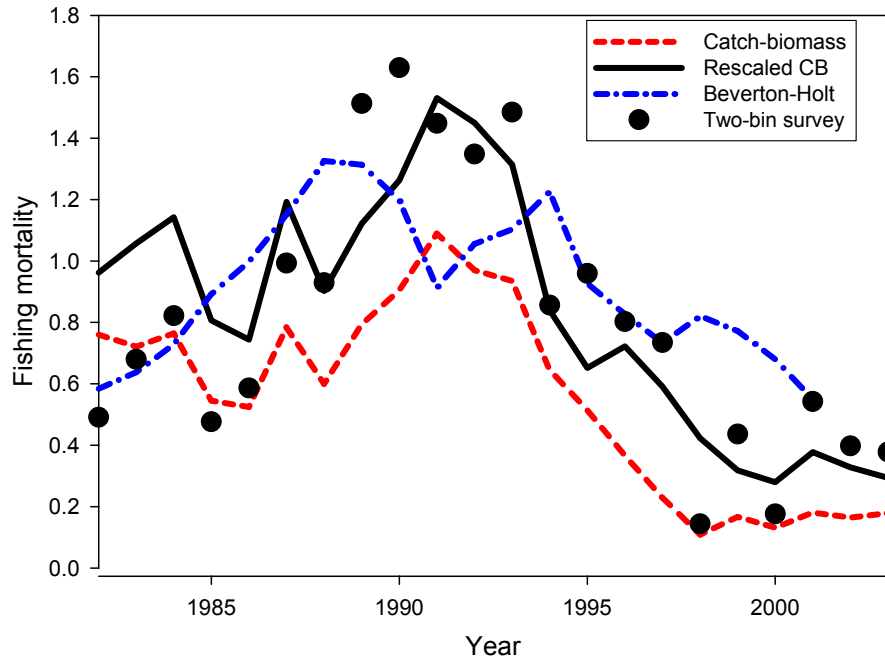
(a) Georges Bank



(b) Mid-Atlantic



(c) Overall



APPENDIX 1. MEASUREMENT ERRORS IN SHELL HEIGHT MEASUREMENTS FROM VIDEO AND DREDGE SURVEYS

The School of Marine Science and Technology (SMAST) at the University of Massachusetts, Dartmouth and the Northeast Fisheries Science Center (NEFSC) carried out collaborative experiments during February 2004 to characterize potential measurement errors in sea scallop shell height data collected during video and dredge surveys. Measurement errors are present to varying degrees in all types of survey data and it is important to know if they are large enough to affect stock assessment results and fisheries management advice. Data sets with measurement errors may provide information not elsewhere available and it is usually possible to accommodate measurement errors, once they are quantified, using modern stock assessment modeling techniques. For example, SMAST video data are valuable because they likely sample scallops over a broad range of lengths (80+ mm) with high and constant efficiency. The NEFSC survey dredge, for example, has lower efficiency for large scallops that must be accommodated when using dredge survey data. Even large measurement errors may be tolerated if large quantities of data can be collected inexpensively. In any case, decisions about how to interpret and use data are easier to make once the nature of any measurement errors is determined.

Shell height data are an important element in stock assessment work for sea scallops because shell heights are converted to meat weights that are used to calculate stock biomass. Meat weight increases as a cubic function of shell height so that doubling the shell height of a sea scallop would, for example, increase its meat weight by about 8-fold. Thus, relatively small errors in shell height data might result in significant under- or over estimation of stock biomass. Moreover, maximum shell height and shell height composition data are used to estimate growth and mortality parameters used in estimating stock status and in calculating biological reference points used by managers.

The SMAST/NMFS study was designed to measure two types of measurement errors: 1) errors that systematically bias shell height data so that measurements are consistently lower or higher than actual shell height, and 2) random measurement errors that increase the variability of shell height measurements making them higher or lower than the actual shell height without affecting the mean. Both types of errors are potentially important. The former tend to bias stock biomass estimates. Effects of the latter are more complex. Random errors obscure information about growth and recruitment strength in shell height composition data, by shifting scallops from modal shell height groups to adjacent shell height groups (i.e. by “smoothing” the length composition). Large random measurement errors may artificially increase the apparent abundance of very large or small scallops. The rapidly increasing nature of shell height-meat weight relationships in scallops means that a 10% increase in shell height generates a change in meat weight that is larger than the decrease in meat weight from a 10% decrease in shell height. Consequently, biomass estimates will be biased with symmetrical (equal positive and negative) random errors in shell heights data.

The purpose of the collaborative SMAST/NEFSC experiments was to estimate measurement errors in shell height data collected routinely in video surveys and using measurement boards which have been used since the late 1970's to collect shell height from scallops taken during NEFSC dredge surveys. For experiments, video and measuring board shell height measurements were compared with accurate shell height measurements made using scientific calipers. Caliper measurements are least affected by measurement errors and were used as a presumably accurate "standard" in data analysis. SMAST and NEFSC staff carried out all of the experimental work at the SMAST facility in New Bedford, analyzed the data, and prepared this report collaboratively.

Materials and Methods

Shell height of a sea scallop is the longest distance between the umbo and the shell margin. The NEFSC scallop survey (Serchuk and Wigley, 1986) uses a measuring board to record shell heights to the nearest 5 mm interval. For example, a scallop with shell height = 54.7 mm falls into the 50.0-54.9 mm shell height group and, in the absence of any measurement errors, would be recorded as 52.5 mm in the NEFSC scallop survey. Measurement boards used in experiments were standard equipment actually used on scallop surveys. During surveys, a number of technicians measure scallops using different measurement boards (each scallop is measured once). All scallops are measured unless the tow is unusually large, in which case all scallops in a large random subsample are measured. These procedures reduce errors in characterizing shell height composition for survey catches due to subsampling. Errors may depend on the height of the technician to the extent that the technician's eye will be higher above the board.

Scallops are placed on measuring boards with the umbo resting on the bottom of the board and ventral valve (bottom shell) down (towards the board). Technicians sit with the board in the middle of their field of view and a tally device is used to record the number of scallops in each 5 mm interval. Measurement errors may occur because the ventral valve of scallop shells is rounded and the technician looks down at the shell margin (which lies above the board) towards the measurement marks. The shell may roll somewhat against the board. The technician may record a shell height observation using the wrong shell size group.

SMAST conducted video surveys during 1999-2003 using methods described by Stokesbury et al. (2002) and Stokesbury et al. (2004). Briefly, a video camera mounted at the top of a steel pyramid-shape frame gives a 2.8 m² image of the sea floor (in calculations, the assumed area is increased to 3.235 m² to compensate for "edge" effects). Video survey stations are arrayed in a systematic pattern along the coast and four images are collected at each station. After the first image is collected, for example, the pyramid is raised so that the sea floor can no longer be viewed, the vessel is allowed to drift for approximately 50 m, and then the pyramid is lowered again to collect the second image. After the pyramid touches bottom, the field of view is allowed to clear before a video image is captured for analysis.

Images of the sea floor are recorded on a high resolution S-VHS tape. The time, depth, number of scallops observed, and latitude and longitude from differential GPS are recorded for each image. Video survey gear includes an additional smaller camera mounted lower and on the side of the pyramid that is useful for identifying and counting small specimens. Experimental results for the small camera are not presented here because the large camera is used to obtain data most immediately useful for stock assessment work.

VHS video survey images (Appendix Figure 1-1) are replayed in the laboratory where a digitized image with each scallop uniquely identified is created using Image Pro Plus[®] software. A technician placed the computer cursor on the umbo and the outer margin of each shell so that Image Pro calculated and the distance between the two points. Shell height data from video measurements are recorded to the nearest mm.

Measurement errors in video shell height measurements may arise from a variety of factors. The maximum resolution of the video system is 3 mm due to pixel size so that, for example, a 100 mm scallop measured properly might be recorded as being 99 or 102 mm. There may be errors in cursor placement during the measurement process. Irregularities on the bottom and the angle of the scallop with respect to the camera may contribute to measurement errors.

Scallop shell height data from video images are affected by the distance between the scallop and the center of the sampling frame because specimens further from the middle are also further from the camera. Other factors, such as lens curvature and resolution of video equipment, also appear important. Correction factors to adjust for distance from the middle of the sampling frame have been developed but are currently uncertain. Moreover, it is theoretically possible to make adjustments for bias but it is probably not possible to use correction factors to remove random errors from shell height data (a more promising approach is to include measurement errors in models fit to the data). For example Stokesbury et al. (2002) used a “step” correction factor and Stokesbury et al. (2004) used the “curve” correction factor:

$$c = sh \sqrt{\frac{(x)^2 + (y)^2}{(y)^2}}$$

where:

c = corrected shell height (mm)

sh = original shell height (mm)

y = vertical camera height from the base of the sampling pyramid

x = distance from the center of the quadrant (mm).

Results for video data with and without the curve correction factor are presented in this report.

Damaged shell margins due to the survey dredge; previous encounters with commercial gear, and benthic predators may all cause measurement errors in shell height data from measurement boards, video gear and calipers. However, these factors had little

effect on experimental data where the goal was to measure the shell heights (including broken edges) by various methods using the same scallops or scallop shells.

Measuring board and video shell heights for the same scallop or group of scallops collected by different technicians were treated as independent observations in this analysis because the data from both surveys used in stock assessment modeling are single measurements from one technician. It should be possible to use the experimental data to quantify the component of variance in shell height data due to differences among technicians in both surveys. Some results of this analysis are relevant but the topic is outside the scope of this report.

Experiment I (live scallops)

Live scallops ($n=393$, caliper shell heights 56-141 mm) were collected by fishing vessels during early February, taken to the laboratory and then divided in a haphazard fashion into ten groups with 24-61 individuals per group. Each group was held until needed in laboratory tanks filled with seawater inside mesh bags labeled 1-10 for identification. Scallops from one group at a time were placed haphazardly on sand and gravel spread under the video equipment in a large tank filled with seawater (sand and gravel were used to mimic some types of natural irregularities in the sea floor). Shell height data were collected from the video images using standard video survey procedures with four shell height measurements made independently for each specimen by four different persons. In addition to video measurements, all of the scallops in each group were individually measured once with calipers by one technician and once independently by each of three technicians using different measuring boards.

Mean shell height and shell height composition information for each type of measurement, as well as scatter plots and linear regression were used to characterize bias and random errors. It was not possible to evaluate measurement errors for individual scallops in Experiment 1 because individual scallops in the experiment were not uniquely identified. It was possible to estimate bias as, for example, the mean shell height for board measurements minus the mean shell height for caliper measurements.

Experiment 2 (numbered scallops shells)

In the second experiment, the dorsal valve (top shell) of 172 individual scallop shells (caliper shell heights 39-192 mm) was marked with unique labels so that video, measurement board, and caliper shell heights could be compared for each individual shell. Labels were inside (under) the valve to prevent identification by technicians while measurements were taken. For video measurements, the shells were placed haphazardly on sand and gravel at the bottom of a tank filled with seawater. Two technicians (rather than four as in Experiment 1) were available for collecting measuring board shell height data during the second experiment.

Results

Experiment 1 (live scallops)

Shell height measurements by measuring boards all had a slight negative bias (-0.4 to -0.9 mm, Appendix Table 1-1). Video measurements without the curve correction factor had a usually negative bias (-1.4 to 0.5 mm) while video measurements with the correction factor showed relatively high positive bias (3.3 to 5.4 mm).

Shell heights from measuring boards were relatively precise (Appendix Figure 1-2). Combining individual board and caliper measurements for all groups, the standard error of residuals around the regression line $\ln(SH_{board}) = \alpha \ln(SH_{video})$ was 0.017 ($\alpha=0.998$, $R^2=0.99$). Assuming a multiplicative model with constant CV, these results indicate that the CV for measurement errors in board shell height data is about 1.7%. This technique was not applied to video data because it was not possible to link individual video and caliper shell height measurements for live scallops.

Experiment 2 (numbered scallops shells)

Measurement errors for individually identified scallop shells in Experiment 2 were characterized by computing the mean and standard deviation of shell height differences for each shell (e.g. video shell height minus caliper shell height), and with Bland-Altman plots (Bland and Altman 1986; Bland and Altman 1995). Bland-Altman plots are designed to avoid spurious conclusions in comparing data with measurement errors to a relatively precise standard.

As in Experiment 1, results for uniquely labeled shells showed a small negative bias for measuring boards (Appendix Table 1-2). Video measurements without the curve correction had a substantial negative bias (-5.8 to -4.0 mm). Video measurements with the curve correction factors had an intermediate positive bias (0.4 to 2.4 mm). Bland-Altman plots confirm these patterns and suggest that the standard deviation of random measurement errors probably increases with shell size (Appendix Figure 1-3). Increasing standard deviations indicate that random measurement errors for one technician may be multiplicative with a constant CV that is independent of shell size (rather than a constant standard deviation). Differences in results for live scallops in Experiment 1 and scallop shells in Experiment 2 were due to a much wider and more even range of lengths for shells in Experiment 2.

The CV for random measurement errors in each set of shell height data was estimated by applying normal measurement errors to caliper data and choosing the CV value that gave the best fit to the observed data (e.g. for video measurements by one technician, Appendix Figure 1-4). Assuming random errors had constant CV's and using curve corrected data, CVs for random measurement errors ranged 0.023 to 0.025 (average 0.024) for measuring boards and 0.053 to 0.084 (average 0.072) for video measurements by different technicians.

Discussion

Shell height data from video (without curve corrections) and measurement boards involve measurement errors that cause a negligible negative bias. Random measurement errors were smaller in shell height data from measuring boards. Based on live scallops, the CV for random errors with measurement boards averaged 0.024. For a 100 mm sea scallop, the 95% probability interval for measurement errors with measurement boards would be -4.8 to 4.8 mm. The proportion of shell height measurements assigned to an incorrect 5 mm shell height group with measurement boards would be roughly $2 * P(z < -2.5/2.4) = 30\%$ where $P(z)$ is the cumulative probability for z from a standard normal distribution. Very few random measurement errors (about $2 * P(z < -7/1.7) = 0.18\%$) would be large enough to place a shell in shell height groups beyond those just above and below the true shell height group.

CVs for random measurement errors in video shell height data averaged 7.2 mm. For a 100 mm scallop, the 95% probability interval for random measurement errors is wider (-14.4 to 14.4 mm for a shell height of 100 mm). Roughly 73% of shells would be assigned to the wrong 5 mm shell height group using video shell height measurements. A relatively large proportion (30%) would be assigned to shell height groups beyond the first groups above and below the true shell height group.

The SMAST/NEFSC experiments could be used to help characterize the relationship between lengths of scallops and scallop shells on the bottom of the tank and lengths in experimental video survey data. However, sampling by dredges was not included in experiments. Therefore, potential differences between the shell height distributions of scallops on the bottom of the ocean and scallops in dredge survey catches due to size specific selectivity patterns were not addressed. Similarly, measurement errors from the video may be smaller under controlled conditions in a tank than in the field.

It would be useful to conduct additional experiments with a large number of individually marked live scallops with higher proportions at small and large sizes. An even distribution of shell heights for live scallops is important because bias with and without curve correction factors differed between Experiment 1 and Experiment 2 because of differences in size composition of live scallops and shells. Data used here were sufficient to characterize measurement errors in broad terms but at least one additional experiment (preferably with individually marked live scallops) is required if more precise estimates of measurement error are required. In future experiments, it might be worthwhile to evaluate differences in shell height measurement errors due to different individuals collecting measuring board and video data.

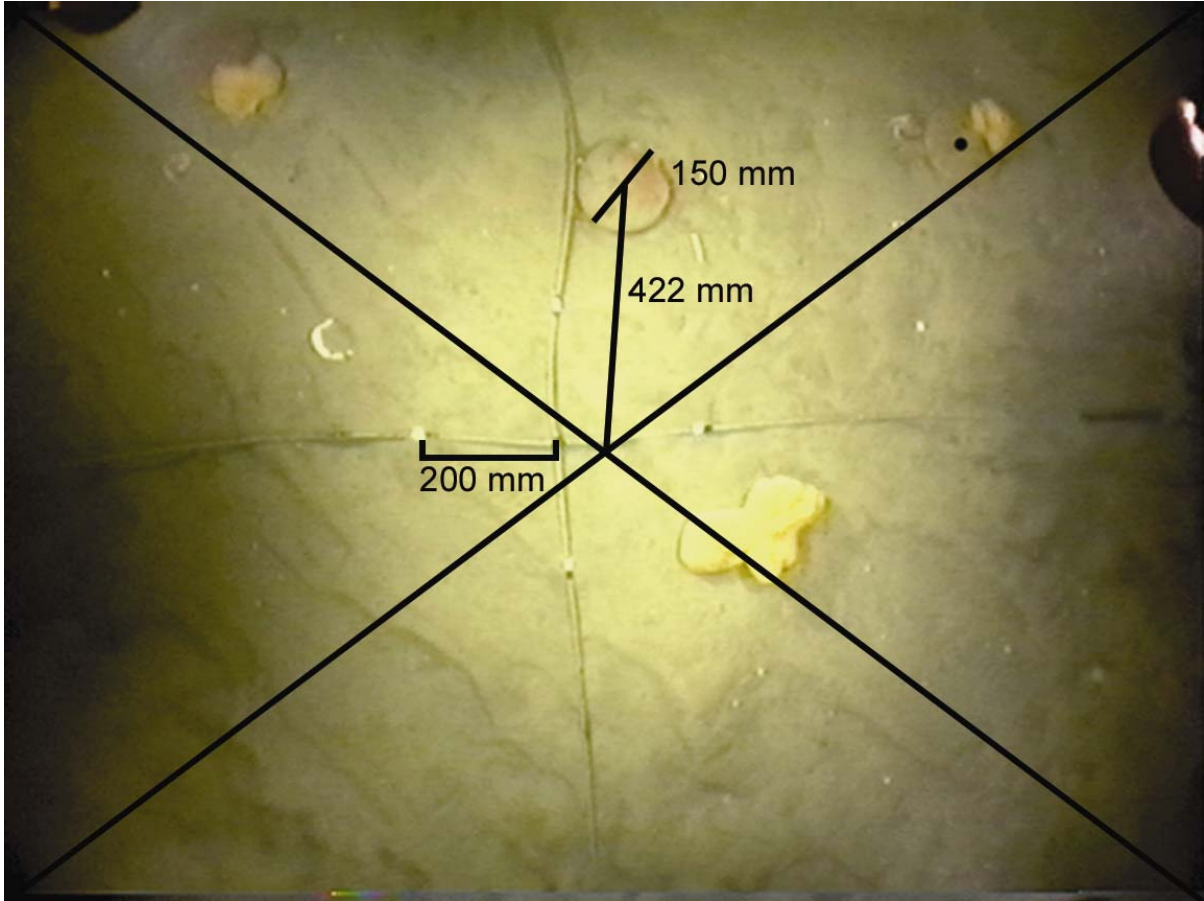
Appendix Table 1-1. Mean shell heights (mm) and bias estimates (in mm relative to caliper measurements, e.g. the mean for measuring board one minus the mean of caliper measurements) for live scallops in experiment 1. Means for all groups combined are the simple average of the means for each group.

| Group | Board 1 | Board 2 | Board 3 | Video Data Without Correction Factor | | | | Video Data With Correction Factor | | | | Calipers | N |
|----------|---------|---------|---------|--------------------------------------|--------------|--------------|--------------|-----------------------------------|--------------|--------------|--------------|----------|-----|
| | | | | Technician 1 | Technician 2 | Technician 3 | Technician 4 | Technician 1 | Technician 2 | Technician 3 | Technician 4 | | |
| 1 | 102.9 | 103.5 | 102.5 | 101.7 | 100.9 | 102.3 | 102.6 | 106.5 | 105.6 | 107.3 | 107.4 | 103.7 | 45 |
| 2 | 98.3 | 98.5 | 97.9 | 95.6 | 98.2 | 97.7 | 96.9 | 101.1 | 104.1 | 103.5 | 102.5 | 98.8 | 36 |
| 3 | 97.0 | 97.3 | 96.4 | 95.2 | 96.7 | 96.4 | 93.4 | 100.2 | 102.2 | 101.6 | 98.7 | 97.8 | 54 |
| 4 | 103.3 | 103.5 | 103.1 | 104.6 | 105.2 | 105.2 | 104.3 | 108.1 | 109.0 | 109.0 | 107.8 | 103.1 | 26 |
| 5 | 95.7 | 95.7 | 95.0 | 95.2 | 96.0 | 96.1 | 93.4 | 99.6 | 100.4 | 100.5 | 97.6 | 96.2 | 44 |
| 6 | 100.1 | 100.1 | 99.7 | 102.6 | 103.2 | 103.7 | 100.2 | 106.3 | 107.6 | 107.6 | 103.8 | 100.6 | 25 |
| 7 | 97.3 | 97.9 | 96.9 | 95.9 | 96.7 | 99.7 | 93.8 | 101.5 | 102.3 | 105.3 | 98.7 | 98.8 | 25 |
| 8 | 101.3 | 101.6 | 101.1 | 104.5 | 101.2 | 103.8 | 101.2 | 110.2 | 106.8 | 109.4 | 106.7 | 101.9 | 28 |
| 9 | 102.8 | 103.6 | 104.2 | 105.2 | 103.6 | 104.6 | 103.5 | 109.9 | 108.3 | 109.3 | 108.0 | 103.9 | 50 |
| 10 | 97.9 | 97.8 | 97.6 | 99.2 | 97.4 | 98.6 | 100.1 | 104.2 | 102.4 | 103.6 | 105.3 | 98.5 | 60 |
| Averages | 99.7 | 99.9 | 99.4 | 100.0 | 99.9 | 100.8 | 99.0 | 104.8 | 104.9 | 105.7 | 103.6 | 100.3 | 393 |
| Bias | -0.7 | -0.4 | -0.9 | -0.4 | -0.4 | 0.5 | -1.4 | 4.4 | 4.5 | 5.4 | 3.3 | | |

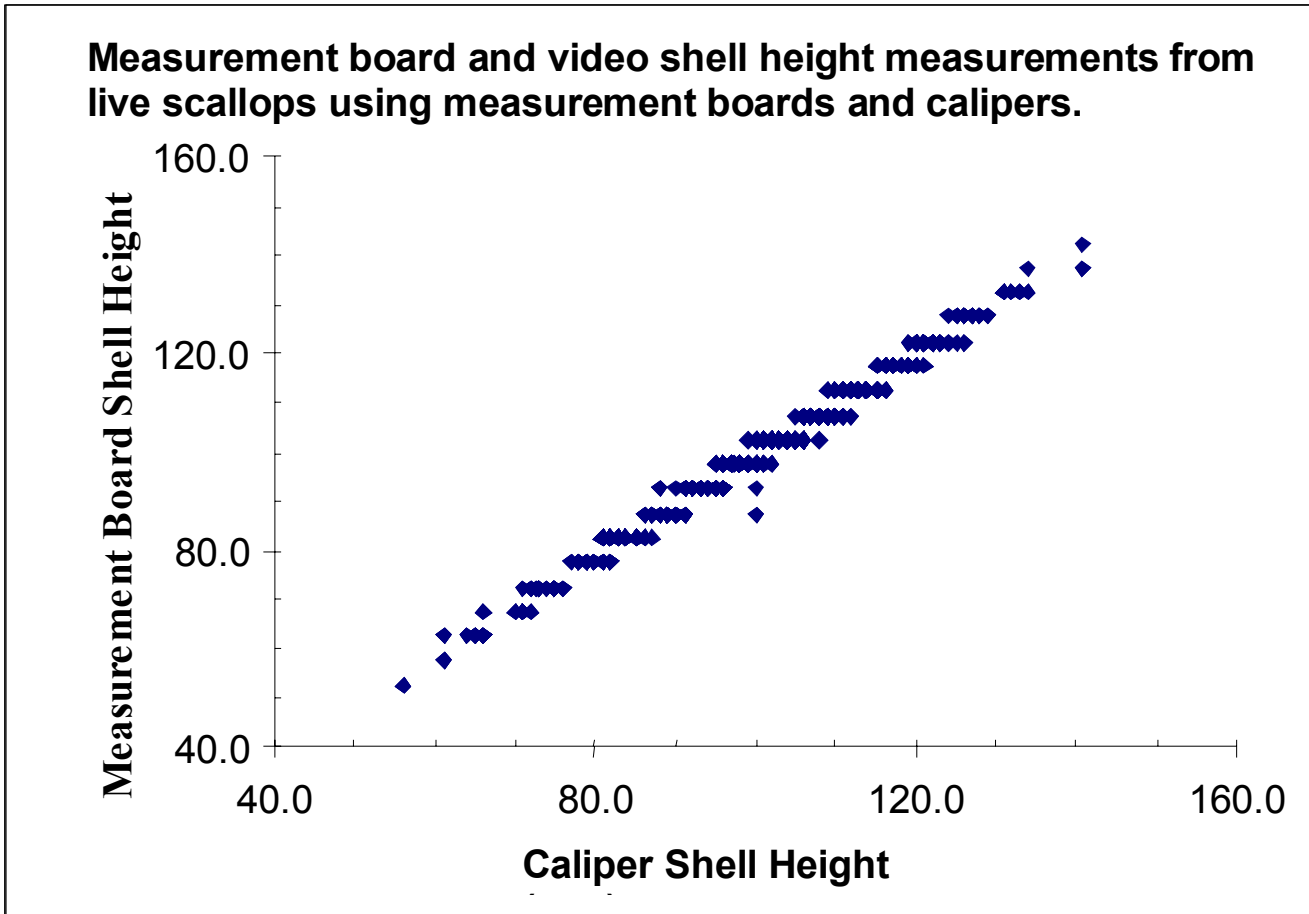
Appendix Table 1-2. Means and standard deviations (mm) for differences (e.g. measuring board – caliper) in shell height measurements from individually labeled scallop shells. Differences between measurements by different technicians (1-4 for video data; 1-2 for measuring boards) and caliper shell heights. Results are shown for video shell heights with and without a correction factor.

| Technique, technician and correction | Mean Difference (mm) | SD (mm) |
|---|-----------------------------|----------------|
| Video 1 no curve correction | -4.0 | 5.7 |
| Video 1 with curve correction | 2.3 | 5.8 |
| Video 2 no curve correction | -4.3 | 7.0 |
| Video 2 with correction | 2.0 | 7.2 |
| Video 3 no curve correction | -4.0 | 5.5 |
| Video 3 with correction | 2.4 | 5.7 |
| Video 4 no curve correction | -5.8 | 6.0 |
| Video 4 with correction | 0.4 | 5.9 |
| Measuring board 1 | -0.9 | 1.7 |
| Measuring board 2 | -0.4 | 1.6 |

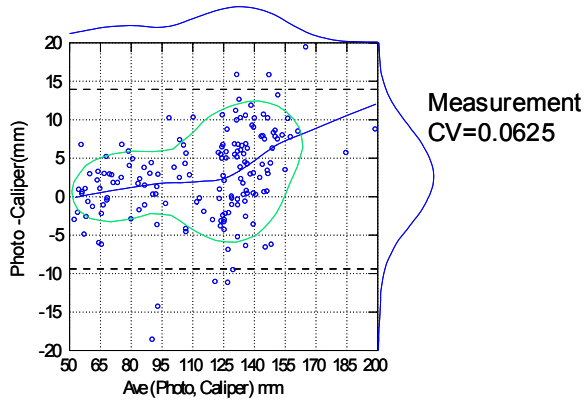
Appendix Figure 1-1. Digitized SMAST video survey image.



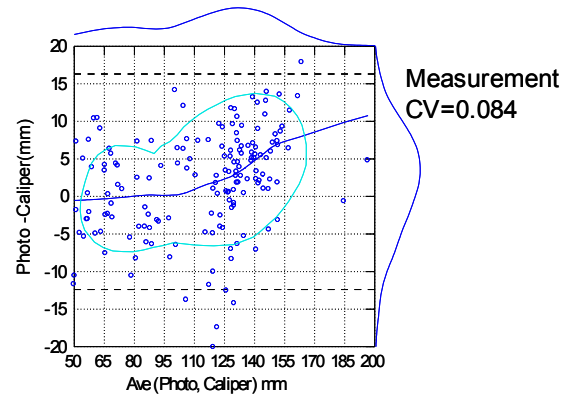
Appendix Figure 1-2.



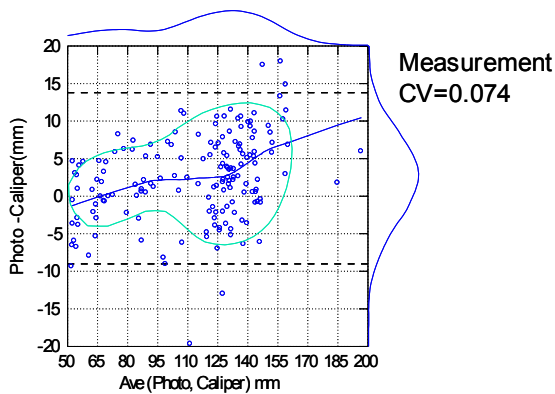
Bland-Altman Plot: Caliper vs Curve Video: Observer M1



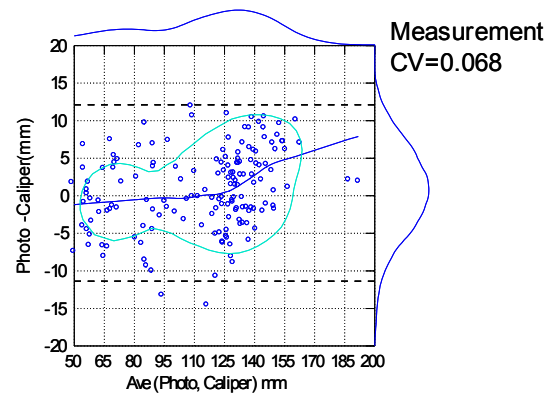
Bland-Altman Plot: Caliper vs Curve Video: Observer M2



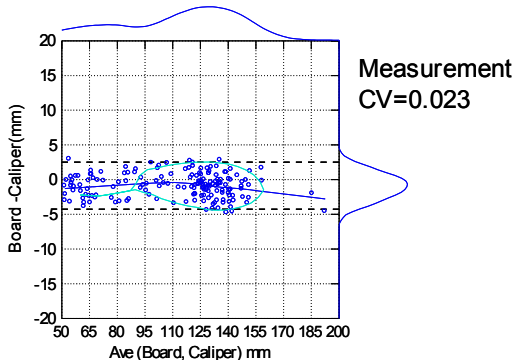
Bland-Altman Plot: Caliper vs Curve Video: Observer M3



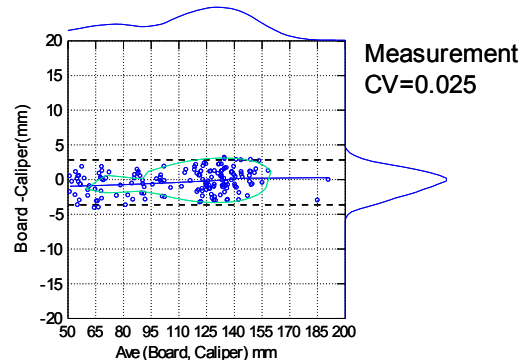
Bland-Altman Plot: Caliper vs Curve Video: Observer M4



Bland-Altman Plot: Caliper vs Board: Observer M5

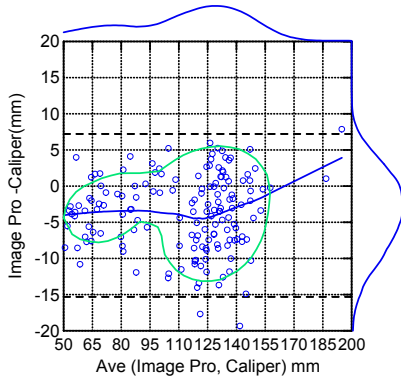


Bland-Altman Plot: Caliper vs Board: Observer M6

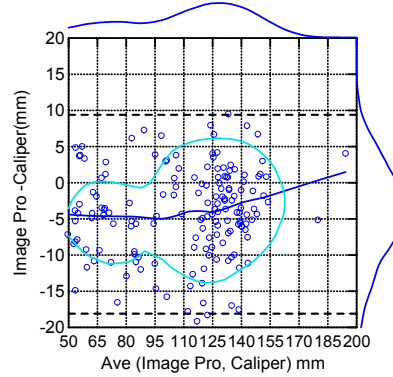


Appendix Figure 1-3. Bland-Altman plots for video and measuring board shell height (mm) measurements by different technicians using caliper measurements as an accurate standard. There were four technicians for video data and two technicians for measuring board data. Video data include curve corrections that worsen bias but have little effect on variance. The y-axis in each plot represents the difference between the measurement and standard. The x-axis gives the mean of the measurement and standard. The dashed bounds represent \pm two standard deviations of the differences. A lowess smooth (tension=0.5) line in each plot shows trends in bias related to shell size. The marginal distributions of the x and y-axes are shown probability distributions estimated using nonparametric kernel smoothers. The area enclosed by the smooth curves is a nonparametric kernel estimate for a 70% confidence region on the bivariate distribution of the data. CV's for random measurement errors were estimated by adding measurement error (assuming a constant CV) to the caliper data to achieve best fit to the measurements.

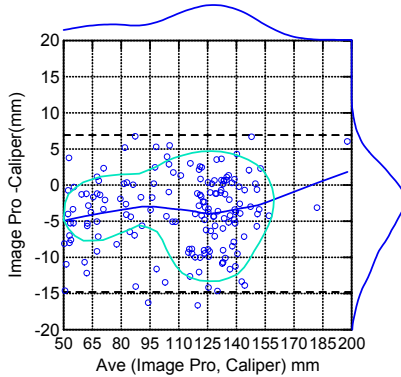
Bland-Altman Plot: Caliper vs Image Pro: Observer M1



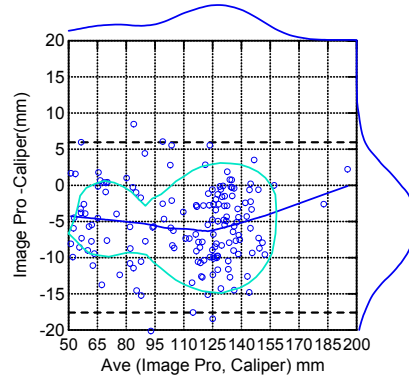
Bland-Altman Plot: Caliper vs Image Pro: Observer M2



Bland-Altman Plot: Caliper vs Image Pro: Observer M3



Bland-Altman Plot: Caliper vs Image Pro: Observer M4



Appendix Figure 1-4. Bland-Altman plots for video shell height (mm) measurements (with no correction factor) by different technicians using caliper measurements as an accurate standard. Axes, etc. as in Appendix Figure 1-3.

APPENDIX 2. NEFSC PROPOSAL FOR ROCK CHAINS IN SCALLOP SURVEYS

Rock chains limit the size of rocks entering the NEFSC scallop survey gear and may increase safety for staff processing catches during the survey. NEFSC is considering using rock chains on all tows in certain rocky strata to improve safety, reduce damage to gear, and to save time. Results from a paired-tow experiment comparing the performance of the NMFS survey scallop dredge with and without rock chains on soft and rocky bottom types were reviewed to determine: 1) the strength of the statistical evidence for an effect of rock chains on sea scallop catch rates, particularly in rocky strata; 2) adequacy of potential correction factors for adjusting historical catch rates in rocky strata to equivalent catches with rock chains; and 3) tentative plans to continue collecting rock chain data.

Each station was assigned to a habitat type (either hard/rocky or soft/sandy) before the experiment based on historical survey data. Possible differences between catch rates for scallops for gear with and without rock chains were tested using a paired t-test with log-transformed catches. Data used in the test were the differences between log-transformed catches with and without rock chains at each station. For the hard bottom analysis, one of the tows by the gear with rock chains caught no scallops so the constant 1.0 was added to the catches from all tows before being the data were log transformed. The data were tested for normality to justify using the paired t-test. For all three sampling sites (pooled, hard, and soft) the log transformed values and the log-transformed values with the constant added were not significantly different from normal (Appendix Table 2-1).

Results for rocky habitats were most important because of plans to use rock chains in rocky areas. The paired t-test for rocky habitat with the constant added was significant (p value = 0.009) with a mean difference of 0.444 in the log scale and a standard deviation of 1.02. The 95% confidence interval was 0.770 to 0.119. Transformation of the mean to the original scale gave $\exp(0.444)=1.56$ which suggests that rock chain catches average 56% larger than non-rock chain catches at the same site. This simple calculation ignores bias induced by exponentiation of lognormal random variables. Using an approximate bias correction, the conversion factor is $1.56 * \exp[(1.02)^2/2] = 2.62$ (Appendix Table 2-2.).

The practice of adding a constant before log transformation may effect results and there is little guidance concerning what the value of the constant should be. The data for rocky habitats were reanalyzed without the constant after removing the station where one tow had no catch. The paired t-test was still significant ($p=0.005$). The mean log scale difference was 0.506 with a standard deviation of 1.06. Back transforming and applying the bias correction factor gives $1.66 * \exp[(1.058)^2/2] = 2.90$ (Appendix Table 2-2).

The simple bias correction factor used above is approximate and meant for large sample sizes. An “exact” correction factor (Smith 1988) gave similar results (2.84).

The mean catch in the standard dredge is 256.7 (var= 189,438.4) and 337.2 (var = 280,968.2) in the rock chain dredge. An alternative non-parametric test (Wilcoxon's rank sum test) on arithmetic catches (no log transformation or constant) and omitting the station with a zero tow was conducted for rocky habitat because of uncertainty about the normality of the data and potential effects of adding a constant (Appendix Figure 2-1). The nonparametric test was significant ($p=0.029$) suggesting a difference in catch between the two dredge types

The Invertebrate Subcommittee commended NEFSC survey staff on their work but noted the variability in potential correction factors and recommended that collection of more data from paired samples on hard bottom sites. Calculation and use of calibration constants with appropriate bias corrections can be deferred until the sample size for the experiment is increased and reviewed.

Preliminary results suggested that the performance of gear without rock chains might become increasingly impeded as more large rocks enter the gear (Appendix Figure 2-2). As the number of large rocks in the standard dredge increases, the log difference between the dredges increase. The effects of this problem on the above analyses should be investigated.

Appendix Table 2-1.

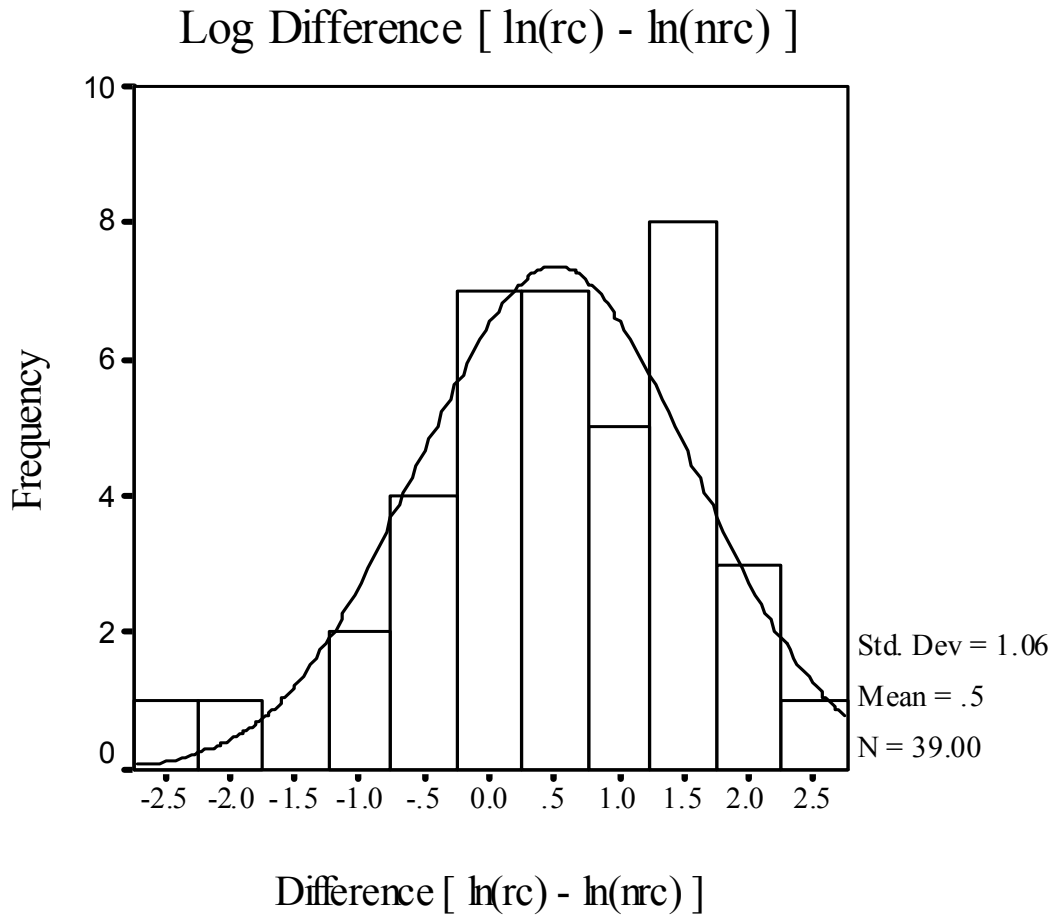
| Test of Normality (Kolmogorov-Smirnov Test ^a) | | | | |
|---|---------|-------|----|-----------|
| Habitat | Trans. | Sig. | Df | Statistic |
| Pooled | ln(x+1) | 0.20* | 68 | 0.07 |
| | ln(x) | 0.20* | 61 | 0.07 |
| Hard | ln(x+1) | 0.20* | 40 | 0.10 |
| | ln(x) | 0.20* | 39 | 0.09 |
| Soft | ln(x+1) | 0.06 | 28 | 0.16 |
| | ln(x) | 0.20* | 22 | 0.12 |
| *. This is the lower bound of the true sign. | | | | |
| a. Lilliefors Significance Correction | | | | |

Appendix Table 2-2.

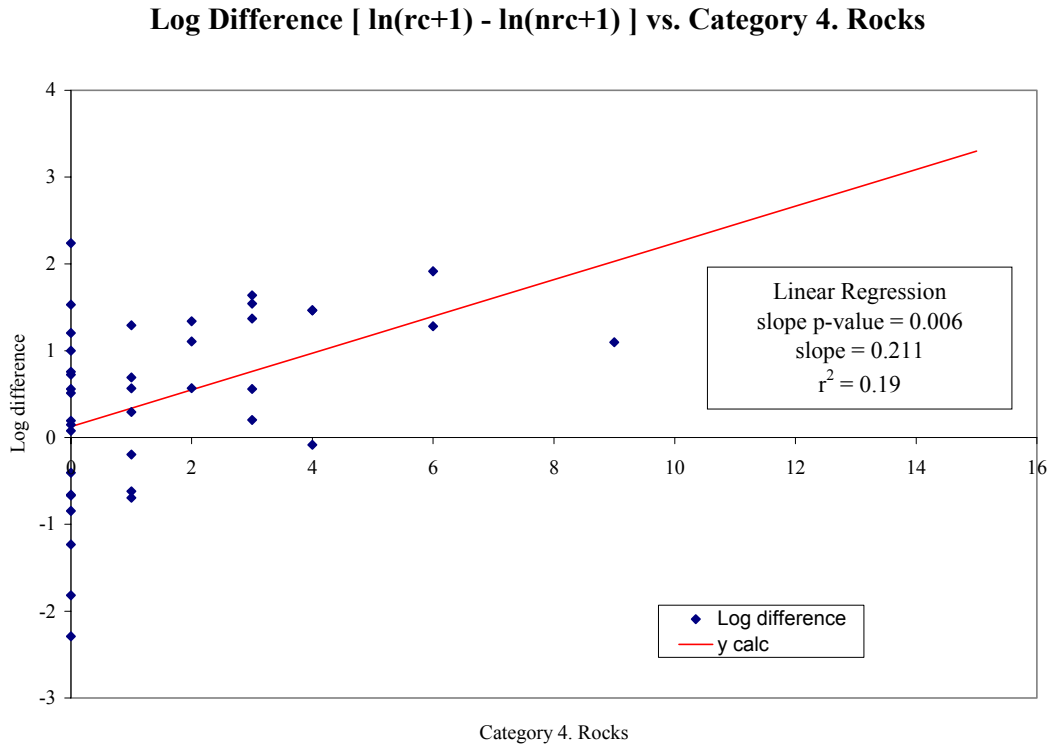
| Paired T-test, sample pairs = 40, ln(x+1) | | |
|---|------|------|
| | | Exp. |
| Mean | 0.44 | 1.56 |
| S.D. | 1.02 | |
| C.I. Lower | 0.12 | 1.13 |
| C.I. Upper | 0.77 | 2.16 |
| Bias Correction $\exp(S.D.^2/2)$ | | 1.68 |
| Calibration Factor (bias * exp(Mean)) | | 2.62 |

| Paired T-test, sample pairs = 39, ln(x) | | |
|---|------|------|
| Approximate | | |
| | | Exp. |
| Mean | 0.51 | 1.66 |
| S.D. | 1.06 | |
| C.I. Lower | 0.16 | 1.18 |
| C.I. Upper | 0.85 | 2.34 |
| Bias Correction $\exp(S.D.^2/2)$ | | 1.75 |
| Calibration Factor (bias * exp(Mean)) | | 2.90 |

Appendix Figure 2-1. Distribution of differences between log survey catches with and without rock chains.



Appendix Figure 2-2. Difference in log survey catches with and without rock chains as a quantity of large (Category 4) rocks in the tow without rock chains.



APPENDIX 3. EFFICIENCY ESTIMATES FOR THE NEFSC SURVEY DREDGE

The ratio densities from the NEFSC scallop dredge and SMAST video surveys were used to estimate absolute NEFSC scallop dredge efficiency assuming that the detection probability of scallops in the video survey was 100%. This ratio can be examined at levels of spatial resolution ranging from tow level estimates (10^{-3} km²) to population level (10^4 km²). Fine scale spatial comparisons were not possible because of insufficient data. Analysis at wide spatial scales may mask important regional variations in dredge efficiency associated with bottom type and depth. For this analysis, dredge efficiency was examined on the scale of subareas of about 10^2 to 10^3 km². Data from video and dredge surveys were post-stratified into subareas occupied by both surveys. Bootstrap methods were used to estimate precision of efficiency estimates for each subarea.

To identify subareas with maximum overlap between video and dredge surveys, waters along the coast were subdivided into 8 discrete subareas (Appendix Table 3-1). Within each subarea, NMFS shellfish strata boundaries were used to partition the video observations into corresponding sets. Strata with greater than 80% video coverage were included in subareas and calculations. Scallops less than 80 mm shell height were excluded from the analysis because the probability of detection in the video survey is lower and the selectivity of the NEFSC survey dredge differs for scallops smaller than 80 mm.

On average, the distance between video stations was 3 nm so that the area of each quadrant is 9 nm². The sum of video quadrants within a NMFS stratum was used to measure the effective stratum size for the post-stratified video survey. For example, NMFS stratum 11 is 213.5 nm² (Appendix Table 3-2). Ten dredge samples were taken in this stratum and 24 video stations were visited. The estimated stratum size for the video survey in this case was $24 * 9 = 216$ nm².

Each survey type was then analyzed as a stratified random design. For the dredge survey this simply meant estimation of density for a smaller number of original strata. For the video survey this process implies that the video estimates can be considered (approximately) as a random sample within an arbitrary new boundary (D'Orazio 2003; Thompson 2002, p. 135; Gunderson 1995; Hilborn and Walters 1992).

Bootstrap estimation methods (Smith 1997) and SPlus software provided by Stephen J. Smith (Department of Fisheries and Oceans, Bedford Institute of Oceanography, Halifax Nova Scotia) were used to estimate the sampling distributions of scallop densities and dredge efficiency for each subarea. A total of 2500 bootstrap densities were computed for each survey and subarea combination and used to compute sampling distributions for density and efficiency estimates. Sampling distributions for efficiency estimates were approximated by dividing each bootstrap density value for the dredge survey by a corresponding bootstrap density value for the video survey. Results were summarized by percentiles (Appendix Table 3-3).

Efficiency estimates compared favorably with estimates by Gedamke et al. (in press) and previous stock assessments (NEFSC 2001). Survey dredge efficiency estimates (medians of bootstrap sampling distributions) were generally higher in the Mid-Atlantic region with estimates of 38% in the Delmarva region, 63% in the New York Bight, and 51% in the Hudson Canyon closed area. On Georges Bank, dredge efficiency in Closed Areas I and II were 55% and 40%, respectively. The low efficiency found in the Nantucket Lightship estimate may be due to insufficient overlap in the western portion of the Nantucket Lightship Area, and the exclusion of non-random tows in the high-density northeast portion of the area. Pooled estimates of dredge efficiency for the entire Mid-Atlantic and Georges Bank areas were 46% and 33%. Note, however, that the lack of overlap in certain areas (e.g., the New York Bight, Nantucket Lightship Closed Area, and the Southeast Part) may cause the combined estimates to be biased, because some areas were covered more completely than others. The combined estimate for Closed Area I and II on Georges Bank was 45%.

Importance of considering efficiency in comparing survey results

Analysis of the SMAST video (Stokesbury et al., 2004) and NEFSC scallop survey (minimum swept-area) results for 2003 demonstrated shortcomings in direct comparison of simple abundance and biomass estimates. Comparisons may be misleading without accommodation for differences in survey gear efficiency, area surveyed, size composition and, for biomass estimates, length-weight relationships. Of these, survey gear efficiency is the most important factor for computations of biomass. In this analysis, sensitivity estimates (number per square meter) from two surveys are a proxy for differences in gear efficiency because, other things equal, surveys with the same gear efficiency should give the same density estimates. Results for simple biomass calculations are summarized here because naïve comparison of biomass estimates is most problematic.

Estimates of total scallop biomass (in meat weight) from a survey can be expressed as a function of the average density, the survey domain (or total area), the size frequency of individuals, and the relationship between shell height and meat-weight. For a survey distributed over L strata with scallops in J shell-height intervals, the simple biomass estimate B_{TOT} is

$$B_{TOT} = \sum_{h=1}^L d_h A_h \sum_{j=1}^J f_{j,h} MW_{j,h}$$

where:

d_h = average density within stratum h (affected by gear efficiency)

A_h = area of stratum h

$f_{j,h}$ = proportion of individuals of size j within stratum h

$MW_{j,h}$ = average meat weight of individuals of shell height j in stratum h .

This general equation can be expanded further by substituting the relationship between shell height and meat weight as

$$MW_{j,h} = \alpha_h SH_j^{\beta_h}$$

where α_h and β_h represent stratum-specific parameters for the shell height-meat weight relationship. The general equation can now be written as

$$B_{TOT} = \sum_{h=1}^L d_h A_h \sum_{j=1}^J f_{j,h} \alpha_h SH_j^{\beta_h}$$

The terms inside the second summation represent the average weight of scallops within a stratum. Differences in average weight can arise from differences in the size frequency distribution as well as from the shell height-meat weight relationship. This distinction is important because of measurement errors in shell height measurements from video surveys and differences in procedures for estimating shell height-meat weight relationships.

Following Keyfitz (1968, p. 189), the “decomposition of observed changes” method was used to measure discrepancies that arise in naïve comparisons that do not account for the factors listed above. To measure the effect of differences in shell height-meat weight relationships, for example, one can calculate the percent change in either SMAST video (Stokesbury et al. 2004) or NEFSC scallop survey (minimum swept area) estimates when shell height-meat weight parameters are used from the other survey. Effects due to differences in more than one factor can be evaluated in an analogous manner.

Results show that the estimate of survey gear efficiency is the most important factor when estimating biomass from the 2003 NEFSC survey. If dredge efficiency were assumed to be 100%, the biomass implied by the SMAST video (Stokesbury et al. 2004) survey changed by -53% when the minimum swept area density from the NEFSC scallop survey was substituted, and the minimum swept area biomass from the NEFSC scallop survey increased by +115% when density from the video survey was substituted. This indicates that dredge efficiency is less than 100% in the dredge survey, consistent with other dredge efficiency studies (e.g., NEFSC 2001; Gedamke et al. in press) and results in this stock assessment. Substituting shell height composition decreased SMAST estimated biomass by 12% and increased NEFSC estimated biomass by 17%. Substituting shell height/meat weight parameters increased the SMAST estimate by 8% and decreased the NMFS estimate by 7%.

Appendix Table 3-1 Summary of sampling effort by stratum and group for dredge and video surveys for 2003 used to estimate efficiency of the NEFSC survey dredge.

| SMAST video survey data: | | | | | | | | | |
|--------------------------|---------|-----|-----|-----|----|-----|----|----|-------------|
| Count of Photo Station | Subarea | | | | | | | | Grand Total |
| NMFS Strata | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Grand Total |
| 10 | 12 | | | | | | | | 12 |
| 11 | 24 | | | | | | | | 24 |
| 14 | 19 | | | | | | | | 19 |
| 15 | 42 | | | | | | | | 42 |
| 18 | 24 | | | | | | | | 24 |
| 19 | 27 | | | | | | | | 27 |
| 22 | 16 | | 19 | | | | | | 35 |
| 23 | | | 79 | | | | | | 79 |
| 24 | | | 28 | | | | | | 28 |
| 27 | | | 15 | | | | | | 15 |
| 30 | | 70 | | | | | | | 70 |
| 31 | | 91 | | | | | | | 91 |
| 34 | | 24 | | | | | | | 24 |
| 46 | | | | | | | | 16 | 16 |
| 47 | | | | 26 | | | | 56 | 82 |
| 49 | | | | 27 | | | | | 27 |
| 50 | | | | 18 | | | | | 18 |
| 51 | | | | 11 | | | | | 11 |
| 52 | | | | 28 | 10 | | | | 38 |
| 53 | | | | | 22 | | | | 22 |
| 54 | | | | 8 | 25 | | | | 33 |
| 55 | | | | 25 | 15 | | | | 40 |
| 61 | | | | | | 64 | | | 64 |
| 71 | | | | | | | 7 | | 7 |
| 621 | | | | | | 39 | | | 39 |
| 651 | | | | | | | 10 | | 10 |
| 661 | | | | | | 3 | 10 | | 13 |
| Grand Total | 164 | 185 | 141 | 143 | 72 | 106 | 27 | 72 | 910 |

| NEFSC dredge survey data: | | | | | | | | | |
|---------------------------|-------|----|----|----|----|----|----|----|-------------|
| Count of Station | Group | | | | | | | | Grand Total |
| 2-3 digit stratum | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Grand Total |
| 10 | 6 | | | | | | | | 6 |
| 11 | 10 | | | | | | | | 10 |
| 14 | 10 | | | | | | | | 10 |
| 15 | 12 | | | | | | | | 12 |
| 18 | 9 | | | | | | | | 9 |
| 19 | 10 | | | | | | | | 10 |
| 22 | 4 | | 6 | | | | | | 10 |
| 23 | | | 20 | | | | | | 20 |
| 24 | | | 5 | | | | | | 5 |
| 27 | | | 8 | | | | | | 8 |
| 30 | | 9 | | | | | | | 9 |
| 31 | | 16 | | | | | | | 16 |
| 34 | | 6 | | | | | | | 6 |
| 46 | | | | | | | | 5 | 5 |
| 47 | | | | 3 | | | | 10 | 13 |
| 49 | | | | 9 | | | | | 9 |
| 50 | | | | 14 | | | | | 14 |
| 51 | | | | 10 | | | | | 10 |
| 52 | | | | 10 | 4 | | | | 14 |
| 53 | | | | | 11 | | | | 11 |
| 54 | | | | 4 | 9 | | | | 13 |
| 55 | | | | 7 | 3 | | | | 10 |
| 61 | | | | | | 16 | | | 16 |
| 71 | | | | | | | 4 | | 4 |
| 621 | | | | | | 13 | | | 13 |
| 651 | | | | | | | 10 | | 10 |
| 661 | | | | | | 3 | 9 | | 12 |
| Grand Total | 61 | 31 | 39 | 57 | 27 | 32 | 23 | 15 | 285 |

Appendix Table 3-2. Summary of subarea definitions and stratum sizes for comparisons of SMAST video survey and NMFS dredge survey efficiency estimates.

| Subarea | Region | Open or Closed Area? | NMFS Strata | Photo Survey Sample Information | | Dredge Survey Sample Information | |
|---------|--------|---------------------------------|-------------|---------------------------------|------------------------------|----------------------------------|------------------------------|
| | | | | Area Sampled (nm ²) | Number of Potential Stations | Area Sampled (nm ²) | Number of Potential Stations |
| 1 | MAB | OPEN | 10 | 108 | 28,625,623 | 124.1247421 | 99,234 |
| 1 | MAB | OPEN | 11 | 216 | 57,251,247 | 213.46 | 170,653 |
| 1 | MAB | OPEN | 14 | 171 | 45,323,904 | 206.16 | 164,818 |
| 1 | MAB | OPEN | 15 | 378 | 100,189,682 | 387.77 | 310,014 |
| 1 | MAB | OPEN | 18 | 216 | 57,251,247 | 236.59 | 189,148 |
| 1 | MAB | OPEN | 19 | 243 | 64,407,652 | 242.59 | 193,944 |
| 1 | MAB | OPEN | 22 | 144 | 38,167,498 | 139.00 | 111,124 |
| 2 | MAB | OPEN | 30 | 630 | 166,982,803 | 668.68 | 534,592 |
| 2 | MAB | OPEN | 31 | 819 | 217,077,643 | 933.55 | 746,352 |
| 2 | MAB | OPEN | 34 | 216 | 57,251,247 | 208.02 | 166,305 |
| 3 | MAB | HCCA | 22 | 171 | 45,323,904 | 175.61 | 140,395 |
| 3 | MAB | HCCA | 23 | 711 | 188,452,020 | 749.31 | 599,053 |
| 3 | MAB | HCCA | 24 | 252 | 66,793,121 | 270.45 | 216,217 |
| 3 | MAB | HCCA | 27 | 135 | 35,782,029 | 137.34 | 109,800 |
| 4 | GBK | OPEN | 47 | 234 | 62,022,184 | 250.60 | 200,346 |
| 4 | GBK | OPEN | 49 | 243 | 64,407,652 | 223.02 | 178,297 |
| 4 | GBK | OPEN | 50 | 162 | 42,938,435 | 156.41 | 125,049 |
| 4 | GBK | OPEN | 51 | 99 | 26,240,155 | 113.73 | 90,924 |
| 4 | GBK | OPEN | 52 | 252 | 66,793,121 | 238.79 | 190,903 |
| 4 | GBK | OPEN | 54 | 72 | 19,083,749 | 73.26 | 58,567 |
| 4 | GBK | OPEN | 55 | 225 | 59,636,715 | 252.26 | 201,677 |
| 5 | GBK | Closed Area I | 52 | 90 | 23,854,686 | 108.72 | 86,921 |
| 5 | GBK | Closed Area I | 53 | 198 | 52,480,309 | 204.76 | 163,697 |
| 5 | GBK | Closed Area I | 54 | 225 | 59,636,715 | 222.58 | 177,947 |
| 5 | GBK | Closed Area I | 55 | 135 | 35,782,029 | 137.10 | 109,607 |
| 6 | GBK | Closed Area II | 61 | 576 | 152,669,991 | 632.53 | 505,691 |
| 6 | GBK | Closed Area II | 621 | 351 | 93,033,276 | 361.29 | 288,840 |
| 6 | GBK | Closed Area II | 661 | 27 | 7,156,406 | 12.35 | 9,872 |
| 7 | GBK | OPEN | 71 | 63 | 16,698,280 | 73.13 | 58,462 |
| 7 | GBK | OPEN | 651 | 90 | 23,854,686 | 88.00 | 70,353 |
| 7 | GBK | OPEN | 661 | 90 | 23,854,686 | 104.82 | 83,803 |
| 8 | GBK | Nantucket Lightship Closed Area | 46 | 144 | 38,167,498 | 136.19 | 108,884 |
| 8 | GBK | Nantucket Lightship Closed Area | 47 | 504 | 133,586,242 | 544.39 | 435,226 |
| 8a | GBK | NLSA--Access Area in 2000 | 46 & 47 | | | 147.09 | 117,595 |

Appendix Table 3-3. Summary of video and dredge survey density and efficiency estimates for scallops greater than 80 mm shell height in the dredge survey.

| Subarea | Region | Sub Area | Open or Closed Area? | Density (#/m ²) or ratio | Percentile | | | | | | |
|---------|--------|-------------------------|----------------------|--|------------|-------|-------|-------|-------|-------|-------|
| | | | | | 5% | 10% | 25% | 50% | 75% | 90% | 95% |
| 1 | MAB | DMV | OPEN | Video | 0.243 | 0.254 | 0.271 | 0.291 | 0.312 | 0.332 | 0.345 |
| | | | | Dredge | 0.087 | 0.092 | 0.101 | 0.110 | 0.121 | 0.130 | 0.135 |
| | | | | Ratio | 0.281 | 0.304 | 0.339 | 0.380 | 0.423 | 0.468 | 0.493 |
| 2 | MAB | NYB | OPEN | Video | 0.044 | 0.047 | 0.054 | 0.075 | 0.093 | 0.112 | 0.129 |
| | | | | Dredge | 0.023 | 0.027 | 0.035 | 0.046 | 0.058 | 0.071 | 0.076 |
| | | | | Ratio | 0.252 | 0.318 | 0.438 | 0.625 | 0.882 | 1.143 | 1.336 |
| 3 | MAB | HCCA | CLOSED | Video | 0.206 | 0.216 | 0.234 | 0.253 | 0.273 | 0.291 | 0.302 |
| | | | | Dredge | 0.091 | 0.098 | 0.112 | 0.128 | 0.145 | 0.159 | 0.167 |
| | | | | Ratio | 0.346 | 0.377 | 0.438 | 0.507 | 0.586 | 0.661 | 0.709 |
| 4 | GBK | Sch | OPEN | Video | 0.038 | 0.042 | 0.047 | 0.054 | 0.062 | 0.070 | 0.075 |
| | | | | Dredge | 0.011 | 0.011 | 0.013 | 0.015 | 0.017 | 0.018 | 0.019 |
| | | | | Ratio | 0.169 | 0.187 | 0.224 | 0.269 | 0.323 | 0.379 | 0.416 |
| 5 | GBK | CA1 | CLOSED | Video | 0.091 | 0.105 | 0.128 | 0.157 | 0.186 | 0.214 | 0.234 |
| | | | | Dredge | 0.053 | 0.060 | 0.072 | 0.085 | 0.101 | 0.116 | 0.124 |
| | | | | Ratio | 0.295 | 0.340 | 0.428 | 0.549 | 0.705 | 0.903 | 1.078 |
| 6 | GBK | CA2 | CLOSED | Video | 0.199 | 0.218 | 0.246 | 0.283 | 0.326 | 0.366 | 0.394 |
| | | | | Dredge | 0.064 | 0.074 | 0.092 | 0.115 | 0.141 | 0.164 | 0.178 |
| | | | | Ratio | 0.211 | 0.245 | 0.312 | 0.403 | 0.512 | 0.638 | 0.711 |
| 7 | GBK | NEP | OPEN | Video | 0.026 | 0.030 | 0.042 | 0.055 | 0.066 | 0.079 | 0.086 |
| | | | | Dredge | 0.007 | 0.008 | 0.010 | 0.012 | 0.014 | 0.016 | 0.017 |
| | | | | Ratio | 0.121 | 0.139 | 0.179 | 0.241 | 0.315 | 0.412 | 0.496 |
| 8 | GBK | NLSA?? | CLOSED | Video | 0.181 | 0.201 | 0.234 | 0.272 | 0.316 | 0.356 | 0.381 |
| | | | | Dredge | 0.020 | 0.024 | 0.031 | 0.040 | 0.049 | 0.057 | 0.062 |
| | | | | Ratio | 0.067 | 0.082 | 0.111 | 0.147 | 0.186 | 0.234 | 0.265 |
| 9 | MAB | All | ALL | Video | 0.174 | 0.179 | 0.188 | 0.199 | 0.210 | 0.221 | 0.229 |
| | | | | Dredge | 0.075 | 0.079 | 0.084 | 0.091 | 0.098 | 0.105 | 0.109 |
| | | | | Ratio | 0.363 | 0.384 | 0.417 | 0.456 | 0.502 | 0.549 | 0.576 |
| 10 | GBK | All | BOTH | Video | 0.138 | 0.145 | 0.155 | 0.169 | 0.183 | 0.196 | 0.204 |
| | | | | Dredge | 0.042 | 0.045 | 0.050 | 0.056 | 0.063 | 0.069 | 0.073 |
| | | | | Ratio | 0.236 | 0.255 | 0.291 | 0.332 | 0.378 | 0.428 | 0.462 |
| 11 | GBK | All Open | | Video | 0.040 | 0.043 | 0.048 | 0.055 | 0.062 | 0.068 | 0.072 |
| | | | | Dredge | 0.010 | 0.011 | 0.012 | 0.014 | 0.016 | 0.017 | 0.018 |
| | | | | Ratio | 0.174 | 0.188 | 0.217 | 0.258 | 0.305 | 0.353 | 0.386 |
| 12 | GBK | All Closed | CLOSED | Video | 0.196 | 0.207 | 0.225 | 0.248 | 0.270 | 0.292 | 0.304 |
| | | | | Dredge | 0.059 | 0.063 | 0.071 | 0.081 | 0.090 | 0.099 | 0.105 |
| | | | | Ratio | 0.225 | 0.244 | 0.278 | 0.329 | 0.380 | 0.429 | 0.466 |
| 12a | GBK | Closed Areas 1 and 2 | Closed | Video | 0.176 | 0.187 | 0.208 | 0.233 | 0.259 | 0.285 | 0.299 |
| | | | | Dredge | 0.072 | 0.078 | 0.090 | 0.104 | 0.119 | 0.134 | 0.144 |
| | | | | Ratio | 0.283 | 0.315 | 0.374 | 0.450 | 0.535 | 0.626 | 0.674 |

APPENDIX 4. PRELIMINARY CASA MODELS FOR SEA SCALLOPS

CASA model results are for use by reviewers in evaluating CASA as a primary analytical tool for the next sea scallop stock assessment. At meetings during 2004, the Invertebrate Subcommittee opted to use methods from NEFSC (2001) to evaluate the official status of sea scallops for the 2004 stock assessment; results described in this appendix are therefore not intended by the Subcommittee for use by managers. The Subcommittee also decided, however, that the CASA modeling approach had considerable merit, provided information not otherwise available, and that it could be used as a primary stock assessment method in the next stock assessment if reviews and subsequent testing proved favorable.

To facilitate review work, this appendix describes CASA models and example results for sea scallops in the Mid-Atlantic Bight (MAB) and Georges Bank (GBK) regions.³ In the interests of space, results for MAB sea scallops are emphasized. More data were available for MAB and the fishery in GBK is a bit more complicated (due to extensive closed areas during recent years where fishing is periodically allowed), but results were basically similar. See Appendix 5 for a general and technical description of the model.

Model structure

Length bins in the models for both regions were 20-155 mm in 5 mm increments. The 155 mm bin includes the best available estimates of L for both stocks (NEFSC 2001). Von Bertalanffy K values and length-weight parameters were fixed at the best available estimates for both regions (NEFSC 2001). The natural mortality rate M was assumed to be 0.1 y^{-1} . Based on examination of survey length composition data, scallops were assumed to recruit into the first 13 size bins (20-84.9 mm, see below) with probabilities for each bin from region-specific beta distributions (beta distribution parameters estimated in the model).

Growth probabilities were from gamma distributions with parameters estimated in the models for each region using length increment data from shells collected during the 2001 NEFSC scallop survey from the GBK and MAB regions. Minimum and maximum growth increments were specified based on a visual examination of the data (Appendix Table 4-1). In retrospect, higher values of maximum growth increments should have been used and minimum and maximum values should have been specified more carefully. Growth matrices estimated in the model for both areas were similar and seemed reasonable (Appendix Table 4-2). Length based selectivity in the NEFSC scallop survey was assumed fixed at the best available estimates, although selectivity parameters for the NEFSC scallop survey were estimated in some sensitivity analysis runs. Selectivity parameters for the commercial fishery and for other surveys in the MAB region were estimated in the models.

³ See Appendix 5 for a technical description of the CASA model.

Mid-Atlantic Bight

Model runs for MAB sea scallops during 1979-2004 used a very wide range of data (Appendix Table 4-3). The last year in the analysis was 2004 because data from the NEFSC winter bottom trawl survey during 2004 was available and because information about scallop abundance and length composition during early 2004 should improve estimates for 2003. However, estimates for 2004 were based little information and are not presented. Landings in 2004 were assumed equal in calculations to the mean during 2001-2003.

Based on information about recent developments in the fishery and availability of fishery length composition data, the CASA model was configured to estimate ascending logistic selectivity curves for the MAB fishery during three periods: 1979-1998, 1999-2000 and 2001-2004. The latter two fishery periods correspond to years with closed areas in the MAB region when well-recognized changes in the fishery occurred. The fishery period 1979-1998 covered many changes in the fishery but too little fishery length composition data were available to estimate additional selectivity patterns.

Data from the sea scallop survey were supplemented by winter, spring and fall trawl survey data in the MAB. The winter survey uses a flounder trawl that is similar to those used by commercial scallop trawl vessels, while the spring and fall surveys use gear that is not optimal for catching scallops. Because the trawl surveys are mainly intended to survey finfish, they need to be employed cautiously in scallop assessments.

Double-logistic selectivity curves were estimated for MAB sea scallops in bottom trawl surveys. Double logistic selectivity curves are potentially dome shaped (highest selectivity at intermediate sizes) to accommodate the possibility that bottom trawls are less efficient for small and large scallops (Rudders et al., 2000). Double logistic curves tend to collapse towards ordinary logistic curves when there is no support for a domed selectivity pattern in the fishery length composition data.

Results

Trial runs with a preliminary version of the model for MAB sea scallops showed no evidence of retrospective bias in biomass or fishing mortality estimates (Appendix Figure 4-1). The Working Group's final "basecase" run converged readily with a full rank Hessian matrix (Appendix Table 4-4). CV's for fishing mortality and abundance were plausible and of reasonably magnitude indicating good model performance. Subjectively, and in comparison to experience with other stocks, the data for MAB sea scallop seemed consistent and relatively easy to model.

Fit to survey index information was good although residuals plots for the NEFSC winter bottom trawl survey showed a temporal pattern that may be related to the overall abundance level (Appendix Figures 4-2 to 4-5). Survey selectivity patterns seemed reasonable with domed patterns for bottom trawl surveys and relatively high selectivity for small scallops in the winter bottom trawl survey (which uses ground gear designed to

catch flatfish that is probably relatively efficient for small scallops). Selectivity patterns were similar for the fall and spring bottom trawl surveys, which used the same gear in most years (Appendix Figure 4-6).

The NEFSC survey dredge efficiency estimate from the model fit was similar to the distribution of bootstrap estimates from an external analysis of SMAST video survey data and NEFSC survey data for scallops 80+ mm on the same grounds (Appendix Figure 4-6). Sensitivity analysis (not shown) indicated that the external efficiency estimates had almost no effect on abundance or fishing mortality estimates for MAB. Fit to LPUE and catch data was generally good, although predicted catches were substantially higher than catch data during 1989-1991 and 1995 (Appendix Figures 4-7 to 4-8) as the model tried to explain conflicting evidence in the catch and most of the survey abundance trends.

Fit to fishery and survey length composition data for MAB sea scallops was generally good (Appendix Figure 4-9). The estimated CV for errors in assigning lengths to scallops in the SMAST video survey was 7.6%. With 100 mm scallops, for example, a CV of 7.6% implies a 95% probability interval for assigned lengths of roughly 85-115 mm, or six length bins in the CASA model. The CASA model estimate for the measurement error CV was similar to estimates from a calibration experiment carried out by SMAST and NEFSC using survey video equipment in a tank with scallops and scallop shells of known size (Appendix 1).

In terms of population dynamics (Appendix Figure 4-10), CASA model runs showed widely recognized recent increases in abundance during recent years. Recruitment in 2003 was estimated imprecisely (CV 56%) but was apparently at record levels. Fishing mortality and exploitation levels were similar to rescaled- F estimates used for status determination in this assessment and were correlated with trends in fishing effort data (Appendix Figure 4-10). Based on model estimates, catch biomass generally equaled or exceeded surplus production until 1997 (Appendix Figure 4-11).

Model estimates show recent increases in mean weight (Appendix Figure 4-11) and stock abundance with more scallops at larger sizes and increases in numbers at all sizes (Appendix Figure 4-12). Estimates reflect changes in fishery length composition towards larger scallops during recent years (Appendix Figure 4-13). Estimated length composition of new recruits was reasonable in comparison to average length compositions from the NEFSC survey during 1979-2003 (Appendix Figure 4-14).

The very high fishing mortality estimate for MAB sea scallops during 1995 was likely exaggerated due to conflicting information in the fishery and survey data during those years. Sensitivity analysis (not shown) showed that reducing the assumed CV for catch measurement errors reduced F and the residual for catch data in 1995, while reducing goodness of fit to LPUE and most of the survey time series.

Likelihood profile analysis

A preliminary model for MAB was fit while fixing the model's estimate of efficiency for the NEFSC scallop survey dredge to a wide range of feasible values. The lower boundary of the range for efficiency ($e=0.2$) implies that the survey dredge captures 20% of the scallops in its path. The upper boundary implies that the dredge captures 100% of the scallops in its path. In comparison, the basecase run for MAB sea scallops estimated an efficiency of 0.59. Estimated fishing mortality increases and estimated abundance decreases at higher values of assumed efficiency.

Profile analysis results showed that the commercial fishery data (catch weight and LPUE) fit best at relatively high values ($e=0.7-0.8$) for survey dredge efficiency. With the exception of trends in the winter bottom trawl survey, survey data fit best at relatively low values ($e=0.2-0.5$) for survey dredge efficiency. Trend and length composition data from the scallop survey fit best at efficiency levels ($e=0.5-0.6$) near the basecase estimate of $e=0.59$. In considering profile analysis results for MAB sea scallops, it may be important to remember that selectivity parameters for the scallop survey were fixed at estimates obtained outside the model, while selectivity parameters for other surveys and the commercial fishery were estimated without constraint. Data from the scallop survey would likely fit well over a broader range of efficiency values if the corresponding selectivity parameters had been estimated in the model.

Sensitivity analyses

A preliminary model for MAB was used to perform a limited number of sensitivity analyses. The model was not able to estimate plausible values for the natural mortality rate M or von Bertalanffy growth parameter K . Scenarios in which NEFSC scallop survey selectivity parameters were estimated seemed to provide plausible results with implied efficiencies ranging 0.46-0.48. Preliminary runs that excluded bottom trawl survey trend and length composition data also seemed to provide plausible results.

Georges Bank

The CASA model for sea scallops in the Georges Bank was similar to the model for sea scallops in the Mid-Atlantic Bight except that trawl survey data were not used due to problems with the catchability of scallops in trawls in MAB, and that the time series starts in 1982 rather than 1979. Data used for GBK included commercial catch and length composition, LPUE and NEFSC scallop survey trend and length composition data. The condition of the fishery in Georges Bank differs from MAB, due to higher peak fishing mortality rates and the dynamics of the closed areas established in late-1994, and fished substantially afterward only during 1999-2000.

Four fishery periods were used in modeling GBK sea scallops to accommodate implementation of closed areas and periodic fishing in closed areas. An ascending logistic selectivity pattern was assumed for the commercial fishery during the first period (1979-1995) prior to the closed areas. A double-logistic selectivity curve (potentially

domed) was assumed during the second period (1996-1998) when large scallops were accumulating in closed areas where they were protected from the fishery. The domed selectivity pattern mimics the action of the fishery operating in open areas and taking primarily intermediate-size scallops. A second double logistic selectivity curve was estimated for the third period (1999-2000) when substantial fishing occurred in closed areas. Finally, a third double logistic selectivity curve was estimated for the fourth period when closed areas again protected large scallops.

Results

Goodness of fit and residual patterns for GBK sea scallops was generally similar to results for MAB. The estimated efficiency of the NEFSC scallop survey dredge was lower for GBK ($e=0.42$) than for MAB, presumably due to rocky ground on Georges Bank.

Abundance and mortality estimates were similar to rescaled-F estimates used for status determination in this assessment, and were correlated with trends in fishing effort data (Appendix Figure 4-15). Fishery selectivity estimates were plausible with ascending logistic selectivity patterns during 1979-1995 when all scallops were available to the fishery, and 1999-2000 when portions of the groundfish closed areas were reopened (Appendix Figure 4-16). In contrast, the CASA model estimated domed shaped fishery selectivity patterns for periods (1996-1998 and 2001-2003) when large scallops in the closed areas were protected. Selectivity curves for later years show a shift in the fishery towards larger scallops. The double logistic selectivity curve estimated for 1999-2000 collapsed to an ascending logistic pattern because fishery length composition data for this period include substantial proportions of large scallops.

Simulation analysis

The CASA model for sea scallops was fit to one simulated data set with no measurement errors as a preliminary test of model performance, and as a means of verifying validity of the computer code used to make calculations in CASA. The simulated data were generated in a separate program that is commonly used to simulate effects of different management options.

Population dynamics in the simulator were like those for MAB sea scallops. The simulation model and CASA were alike in general terms, except that shorter time steps were used in the simulator and growth was handled in a simpler, more deterministic fashion. A single fishery period with an ascending logistic fishery selectivity pattern was assumed in both models. Selectivity of the NEFSC scallop survey was fixed at the same values in both models. Despite differences in model structure, CASA was able to reproduce the conditions assumed in generating the simulated data (Appendix Figure 4-17). The simulation results suggest that the CASA model was working properly, though more simulations are necessary to determine the effects of catch and survey errors and misspecified growth on model performance.

| | Bin_22.5 | Bin_27.5 | Bin_32.5 | Bin_37.5 | Bin_42.5 | Bin_47.5 | Bin_52.5 | Bin_57.5 | Bin_62.5 | Bin_67.5 | Bin_72.5 | Bin_77.5 | Bin_82.5 | Bin_87.5 | Bin_92.5 | Bin_97.5 | Bin_102.5 | Bin_107.5 | Bin_112.5 | Bin_117.5 | Bin_122.5 | Bin_127.5 | Bin_132.5 | Bin_137.5 | Bin_142.5 | Bin_147.5 | Bin_152.5 | |
|--------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|--|
| Bin_22.5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_27.5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_32.5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_37.5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_42.5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_47.5 | 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_52.5 | 1 | 9 | 6 | 3 | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_57.5 | | 7 | 40 | 35 | 5 | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_62.5 | | 6 | 47 | 149 | 86 | 5 | | | | | | | | | | | | | | | | | | | | | | |
| Bin_67.5 | | 1 | 37 | 214 | 175 | 17 | 8 | 1 | | | | | | | | | | | | | | | | | | | | |
| Bin_72.5 | | | 8 | 105 | 190 | 54 | 11 | 24 | 8 | | | | | | | | | | | | | | | | | | | |
| Bin_77.5 | | | 2 | 23 | 91 | 70 | 22 | 31 | 61 | 16 | 3 | | | | | | | | | | | | | | | | | |
| Bin_82.5 | | | | 1 | 16 | 49 | 36 | 27 | 105 | 94 | 22 | 4 | | | | | | | | | | | | | | | | |
| Bin_87.5 | | | | | 2 | 9 | 14 | 14 | 69 | 157 | 84 | 40 | 8 | | | | | | | | | | | | | | | |
| Bin_92.5 | | | | | | 3 | 7 | 7 | 28 | 98 | 127 | 77 | 65 | 13 | | | | | | | | | | | | | | |
| Bin_97.5 | | | | | 2 | | | | 5 | 24 | 62 | 80 | 118 | 71 | 8 | 1 | | | | | | | | | | | | |
| Bin_102.5 | | | | | | | | | 4 | 27 | 36 | 52 | 132 | 102 | 19 | | | | | | | | | | | | | |
| Bin_107.5 | | | | | | | | | | 2 | 6 | 13 | 46 | 129 | 117 | 24 | 1 | | | | | | | | | | | |
| Bin_112.5 | | | | | | | | | | | | 2 | 4 | 35 | 76 | 106 | 51 | 2 | | | | | | | | | | |
| Bin_117.5 | | | | | | | | | | | | | 1 | 5 | 12 | 82 | 112 | 50 | 3 | | | | | | | | | |
| Bin_122.5 | | | | | | | | | | | | | | | 1 | 9 | 39 | 92 | 72 | 8 | | | | | | | | |
| Bin_127.5 | | | | | | | | | | | | | | | | 2 | 5 | 21 | 58 | 77 | 3 | | | | | | | |
| Bin_132.5 | | | | | | | | | | | | | | | | | 1 | 10 | 36 | 8 | 6 | | | | | | | |
| Bin_137.5 | | | | | | | | | | | | | | | | | | 1 | 70 | 7 | 6 | 2 | | | | | | |
| Bin_142.5 | | | | | | | | | | | | | | | | | | | 28 | 9 | 6 | 9 | | | | | | |
| Bin_147.5 | | | | | | | | | | | | | | | | | | | 10 | 50 | 4 | 9 | 4 | | | | | |
| Bin_152.5 | | | | | | | | | | | | | | | | | | | | 4 | 41 | 2 | 9 | 32 | 6 | | | |
| N increments | 5 | 23 | 140 | 530 | 567 | 204 | 94 | 104 | 276 | 393 | 327 | 243 | 258 | 267 | 279 | 227 | 223 | 208 | 166 | 144 | 125 | 106 | 89 | 54 | 43 | 27 | 5 | |
| Effective N | 2 | 6 | 35 | 100 | 100 | 51 | 24 | 26 | 69 | 98 | 82 | 61 | 65 | 67 | 70 | 57 | 56 | 52 | 42 | 36 | 31 | 27 | 17 | 14 | 11 | 7 | 3 | |

Appendix Table 4-1. Growth increment data used in the CASA model for sea scallops in the GBK and MAB regions. Columns give the initial length bin and rows give the length bin one year later. Cells below the black area are feasible for each starting length (i.e. growth \geq zero). "N increments" is the number of observations in each row. "Effective N" is the effective number of observations assumed in fitting the CASA model. The effective number of observations was meant to approximate the number of scallops observed in each starting bin. Assuming that the number of increments observed per scallops was about five, the effective number of observations was the number of increments divided by five.

| | Bin_22.5 | Bin_27.5 | Bin_32.5 | Bin_37.5 | Bin_42.5 | Bin_47.5 | Bin_52.5 | Bin_57.5 | Bin_62.5 | Bin_67.5 | Bin_72.5 | Bin_77.5 | Bin_82.5 | Bin_87.5 | Bin_92.5 | Bin_97.5 | Bin_102.5 | Bin_107.5 | Bin_112.5 | Bin_117.5 | Bin_122.5 | Bin_127.5 | Bin_132.5 | Bin_137.5 | Bin_142.5 | Bin_147.5 | Bin_152.5 | | | | |
|--------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|---|--|--|--|
| Bin_22.5 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_27.5 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_32.5 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_37.5 | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_42.5 | 0 | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_47.5 | 0.145808 | 0 | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_52.5 | 0.308495 | 0.811802 | 0.077018 | 0.017455 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_57.5 | 0.307618 | 0.077811 | 0.2438 | 0.124626 | 0.033278 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | |
| Bin_62.5 | 0.174422 | 0.065755 | 0.329143 | 0.30291 | 0.168435 | 0.055223 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | |
| Bin_67.5 | 0.063656 | 0.033306 | 0.239973 | 0.338605 | 0.322072 | 0.213942 | 0.086245 | 0.016956 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | |
| Bin_72.5 | 0 | 0.011327 | 0.110066 | 0.216404 | 0.30368 | 0.328912 | 0.256713 | 0.134985 | 0.032124 | 0 | 0 | | | | | | | | | | | | | | | | | | | | |
| Bin_77.5 | 0 | 0 | 0 | 0 | 0.172534 | 0.265945 | 0.323551 | 0.313741 | 0.180385 | 0.0536 | 0.005506 | 0 | | | | | | | | | | | | | | | | | | | |
| Bin_82.5 | 0 | 0 | 0 | 0 | 0 | 0.135978 | 0.227631 | 0.329827 | 0.330584 | 0.227786 | 0.092409 | 0.011805 | 0 | | | | | | | | | | | | | | | | | | |
| Bin_87.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.10586 | 0.204491 | 0.294328 | 0.335248 | 0.300955 | 0.134347 | 0.0207 | 0 | | | | | | | | | | | | | | | | | |
| Bin_92.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.162578 | 0.256148 | 0.361453 | 0.332145 | 0.184466 | 0.036588 | | | | | | | | | | | | | | | | | |
| Bin_97.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.127217 | 0.239677 | 0.330029 | 0.352102 | 0.239675 | 0.062301 | 0 | | | | | | | | | | | | | | | |
| Bin_102.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.191674 | 0.292756 | 0.358172 | 0.295578 | 0.100748 | 0.001895 | | | | | | | | | | | | | | | |
| Bin_107.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.149976 | 0.251414 | 0.349617 | 0.346718 | 0.16037 | 0.00485 | | | | | | | | | | | | | |
| Bin_112.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.114152 | 0.208442 | 0.327029 | 0.402636 | 0.229942 | 0.011394 | | | | | | | | | | | | |
| Bin_117.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.084062 | 0.166069 | 0.30384 | 0.419868 | 0.314504 | 0.024867 | | | | | | | | | | | |
| Bin_122.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.059436 | 0.131258 | 0.252972 | 0.415712 | 0.410472 | 0.051932 | | | | | | | | | | |
| Bin_127.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.092369 | 0.198091 | 0.386589 | 0.518678 | 0.10021 | | | | | | | | | |
| Bin_132.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.060299 | 0.142735 | 0.336688 | 0.599827 | 0.187147 | | | | | | | | |
| Bin_137.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.035338 | 0.092703 | 0.251757 | 0.641391 | 0.341102 | | | | | | | |
| Bin_142.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.048206 | 0.153561 | 0.593833 | 0.604383 | | | | | | | |
| Bin_147.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.017901 | 0.061764 | 0.387159 | 0.944204 | | | | | | |
| Bin_152.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.003301 | 0.008458 | 0.055796 | 1 | | | | | |
| N increments | 0.999999 | 1 | 1 | 1 | 0.999999 | 1 | 1 | 1 | 0.999999 | 0.999999 | 1 | 1 | 1 | 1.000001 | 1 | 1 | 0.999999 | 1.000001 | 0.999999 | 1.000001 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | |
| Effective N | 2 | 6 | 35 | 100 | 100 | 51 | 24 | 26 | 69 | 98 | 82 | 61 | 65 | 67 | 70 | 57 | 56 | 52 | 42 | 36 | 31 | 27 | 17 | 14 | 11 | 7 | 3 | | | | |

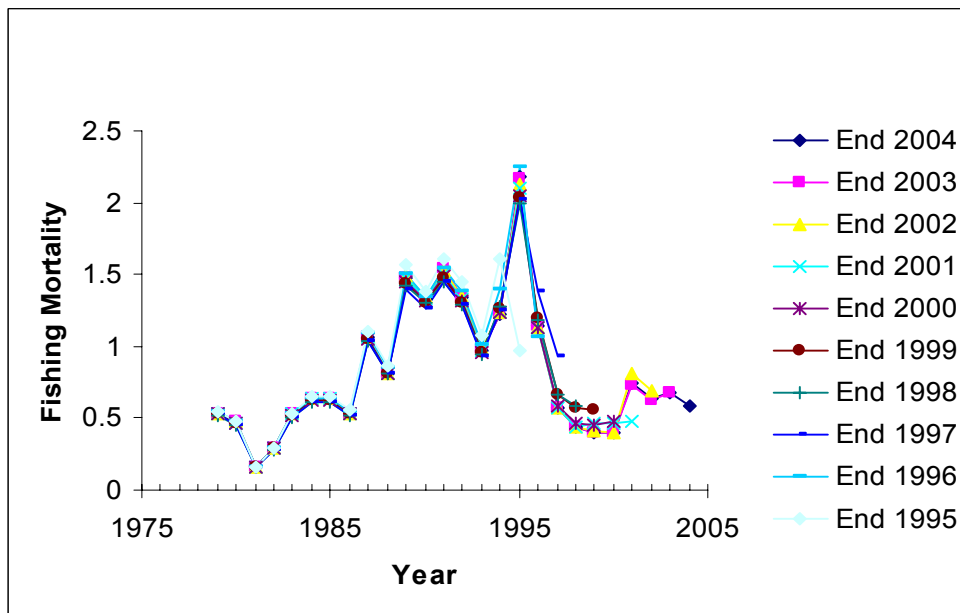
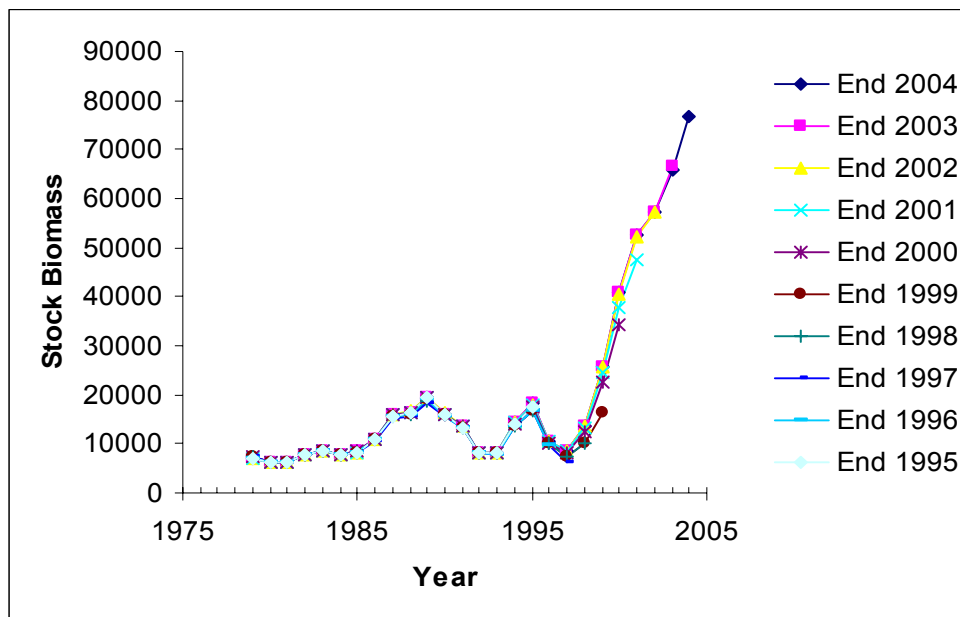
Appendix Table 4-2. Growth probabilities estimated in the CASA model for sea scallops in the MAB region (estimates for GBK were similar). Columns give the initial length bin and rows give the length bin one year later. Cells below the black area are feasible for each starting length (i.e. growth \geq zero). Formatting as in Appendix Table 4-1.

Appendix Table 4-3. Data for MAB sea scallops used in CASA model.

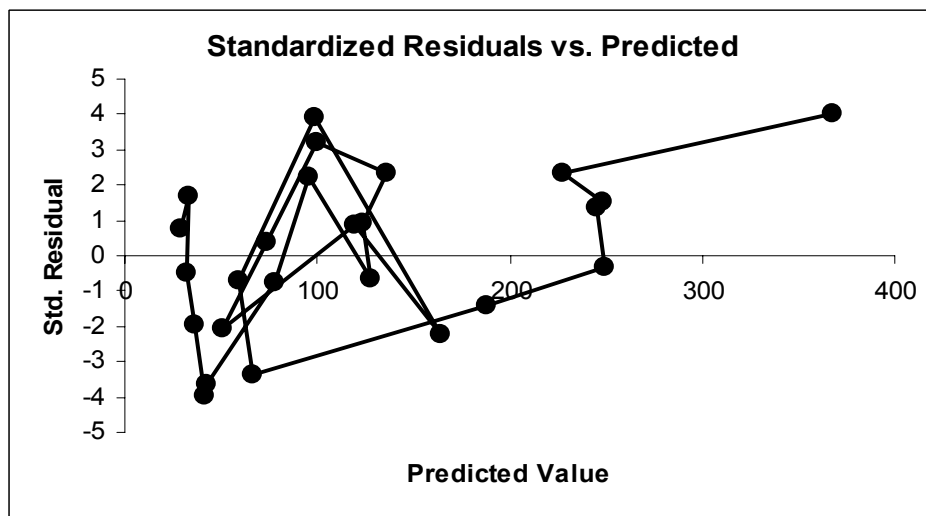
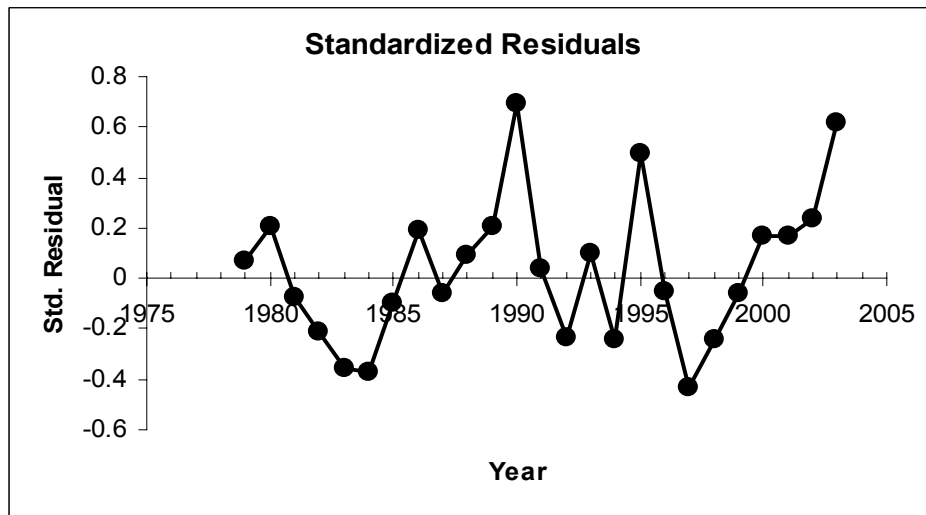
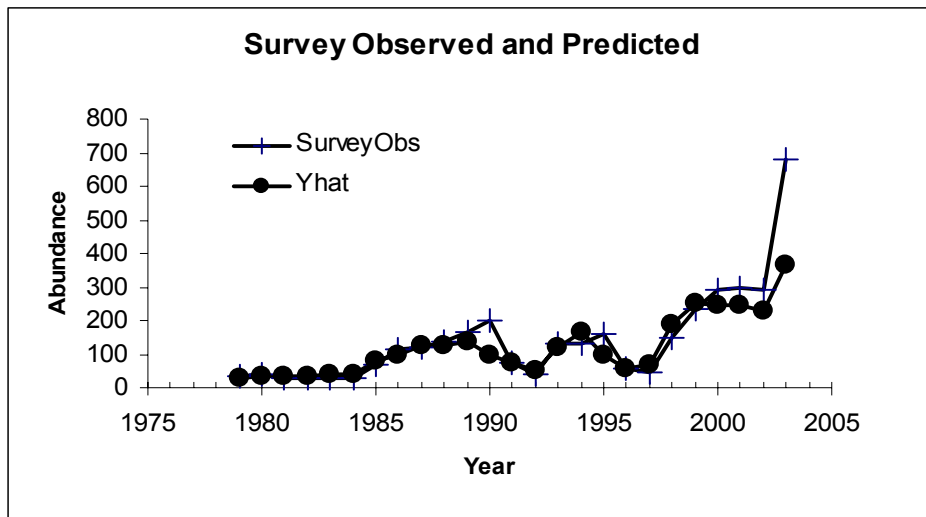
| Data Type | Years in Model | Distribution for Measurement Errors | Comments |
|--|---|---|--|
| Commercial landed weight | 1979-2004 (mean 2001-03 used for 2004) | Normal, CV=10% | MT, not adjusted for discard or incidental mortality |
| Landings per unit effort | 1980-2003 | Normal, CV=25% | MT landed / days absent for large (Type 4) scallop dredge vessels based on port interview and dealer data (1993 and earlier) or VTR logbooks and dealer data (1994 and later). Data for 1979 omitted. |
| Length increments | | | Increment observations from sea scallop shells collected during 2002 sea scallop survey. There were 1,565 increment measurements from MAB and 3,551 measurements from GBK. After preliminary examination data for MAB and GBK were pooled for use in both areas. |
| NEFSC survey dredge efficiency | NA | Beta over 0,1 | Beta prior with the same mean and CV as distribution of bootstrap estimates from SMAST and NEFSC scallop survey densities for sea scallops 80+ mm on same grounds. |
| <i>Survey abundance data</i> | | | |
| NEFSC scallop survey abundance index | 1979-2003 | Log normal, variances from survey CVs | N/tow for sea scallops 40+ mm. Survey selectivity assumed known. |
| NEFSC winter bottom trawl survey abundance index | 1992-2004 | Log normal, variances from survey CVs | N/tow for sea scallops 20+ mm. Logistic survey selectivity estimated. |
| NEFSC fall bottom trawl survey abundance index | 1979-2003 | Log normal, variances from survey CVs | N/tow for sea scallops 40+ mm. Logistic survey selectivity estimated. |
| NEFSC spring bottom trawl survey abundance index | 1979-2003 | Log normal, variances from survey CVs | N/tow for sea scallops 40+ mm. Logistic survey selectivity estimated. |
| SMAST Video Survey | 2003 | NA | Densities for sea scallops 80+ compared to densities in NEFSC scallop survey on same grounds to estimate efficiency of NEFSC scallop survey dredge. |
| <i>Length composition</i> | | | |
| Commercial length composition | 1979-1984; 1995-2003 | Multinomial, effective sample size = 10% N tows sampled | Data for 1979-1984 from port samples; data for 1995-2003 from observer data. |
| NEFSC scallop survey | 1979-2003 | Multinomial, effective sample size = N tows | Sea scallops 40+ mm in 5 mm bins |
| NEFSC winter bottom trawl survey | 1979-2003 | Multinomial, effective sample size = N tows | Sea scallops 20+ mm in 5 mm bins. Data originally by 10 mm bins split into adjacent 5 mm bins. |
| NEFSC fall bottom trawl survey | 1979-2003 | Multinomial, effective sample size = N tows | Sea scallops 40+ mm in 5 mm bins. Data originally by 10 mm bins split into adjacent 5 mm bins. |
| NEFSC spring bottom trawl survey | 1979-2003 | Multinomial, effective sample size = N tows | Sea scallops 40+ mm in 5 mm bins. Data originally by 10 mm bins split into adjacent 5 mm bins. |
| SMAST video survey | 2003 | Multinomial, effective sample size = 34 | Sea scallops 20+ mm in 5 mm bins. Original numbers at length not adjusted for bias. CV for measurement errors estimated in model. |

Appendix Table 4-4. Estimates, standard errors and CVs for parameters estimated in the CASA model for sea scallops in the Mid-Atlantic Bight region.

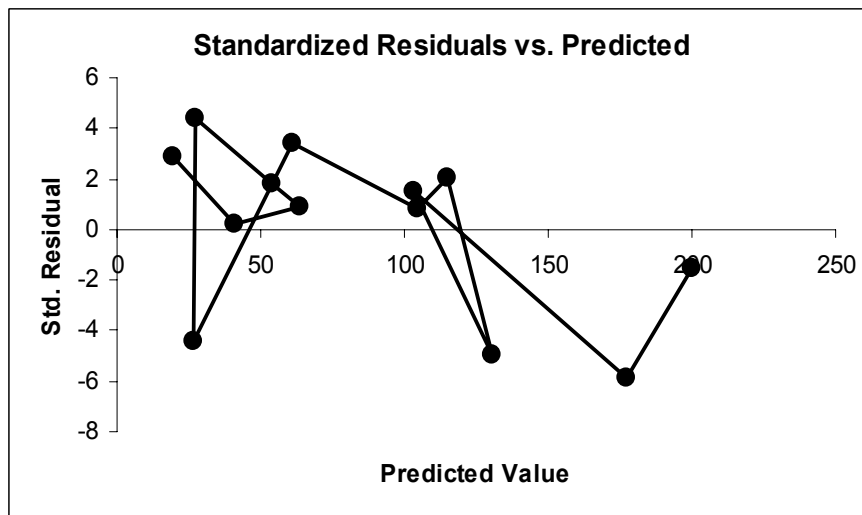
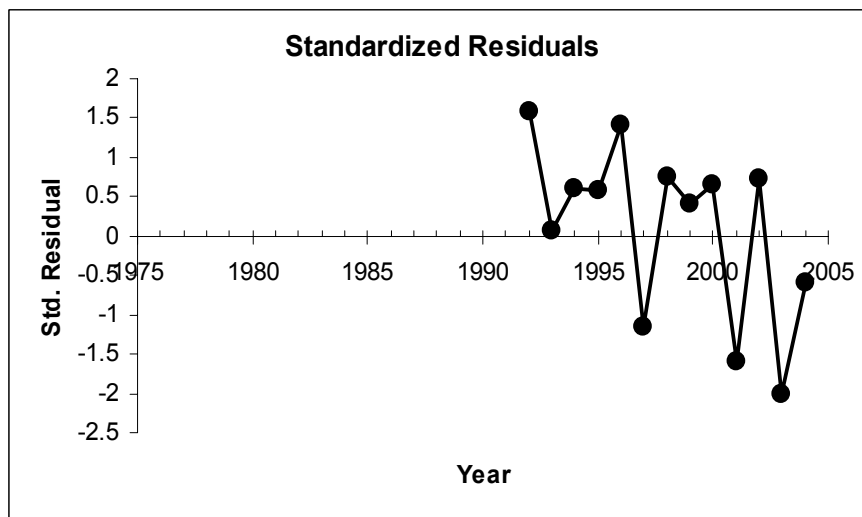
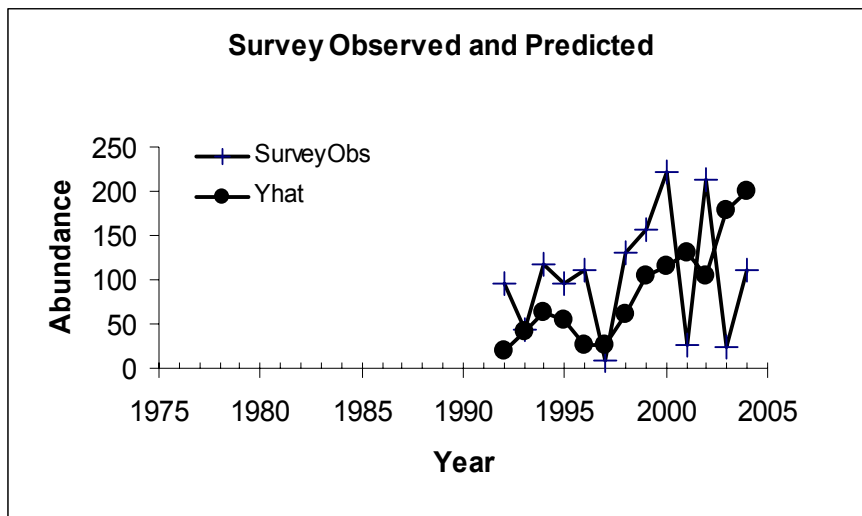
| No. | Description | Estimate | SE | CV | No. | Description | Estimate | SE | CV |
|-----|---|----------|-------|------|-----|--------------------------------|----------|-------|------|
| 1 | Log initial abundance | 19.913 | 0.041 | 0.00 | 44 | Log F dev 1989 | 0.762 | 0.150 | 0.20 |
| 2 | Log beta distribution par new recruits | 1.089 | 0.138 | 0.13 | 45 | Log F dev 1990 | 0.643 | 0.143 | 0.22 |
| 3 | Log beta distribution par new recruits | 1.074 | 0.110 | 0.10 | 46 | Log F dev 1991 | 0.798 | 0.103 | 0.13 |
| 4 | Log mean recruitment | 20.116 | 0.040 | 0.00 | 47 | Log F dev 1992 | 0.655 | 0.097 | 0.15 |
| 5 | Log Q scallop survey | -0.533 | 0.036 | 0.07 | 48 | Log F dev 1993 | 0.319 | 0.130 | 0.41 |
| 6 | Log Q winter BTS | -3.212 | 0.111 | 0.03 | 49 | Log F dev 1994 | 0.539 | 0.137 | 0.25 |
| 7 | Log Q fall BTS | -2.264 | 0.084 | 0.04 | 50 | Log F dev 1995 | 1.148 | 0.103 | 0.09 |
| 8 | Log Q spring BTS | -2.750 | 0.089 | 0.03 | 51 | Log F dev 1996 | 0.503 | 0.098 | 0.19 |
| 9 | Log intercept slx SMAST video survey | 2.210 | 2.022 | 0.92 | 52 | Log F dev 1997 | -0.203 | 0.108 | 0.53 |
| 10 | Log slope slx SMAST video survey | -1.186 | 1.844 | 1.55 | 53 | Log F dev 1998 | -0.479 | 0.108 | 0.23 |
| 11 | Log slope slx winter BTS (ascending) | 1.968 | 0.193 | 0.10 | 54 | Log F dev 1999 | -0.555 | 0.206 | 0.37 |
| 12 | Log intercept slx winter BTS (ascending) | -2.540 | 0.136 | 0.05 | 55 | Log F dev 2000 | -0.559 | 0.189 | 0.34 |
| 13 | Log slope slx winter BTS (descending) | -4.000 | 0.061 | 0.02 | 56 | Log F dev 2001 | 0.037 | 0.187 | 5.05 |
| 14 | Log intercept slx winter BTS (descending) | -3.045 | 0.273 | 0.09 | 57 | Log F dev 2002 | -0.125 | 0.183 | 1.46 |
| 15 | Log slope slx fall BTS (ascending) | 2.127 | 0.058 | 0.03 | 58 | Log F dev 2003 | -0.061 | 0.190 | 3.12 |
| 16 | Log intercept slx fall BTS (ascending) | -2.285 | 0.102 | 0.04 | 59 | Log F dev 2004 | -0.229 | 0.211 | 0.92 |
| 17 | Log slope slx fall BTS (descending) | 2.879 | 0.191 | 0.07 | 60 | Log recruitment dev 1980 | -1.049 | 0.083 | 0.08 |
| 18 | Log intercept slx fall BTS (descending) | -1.793 | 0.168 | 0.09 | 61 | Log recruitment dev 1981 | -1.482 | 0.113 | 0.08 |
| 19 | Log slope slx spring BTS (ascending) | 2.587 | 0.614 | 0.24 | 62 | Log recruitment dev 1982 | -1.370 | 0.122 | 0.09 |
| 20 | Log intercept slx spring BTS (ascending) | -2.393 | 0.085 | 0.04 | 63 | Log recruitment dev 1983 | -1.030 | 0.099 | 0.10 |
| 21 | Log slope slx spring BTS (descending) | 2.703 | 0.093 | 0.03 | 64 | Log recruitment dev 1984 | -1.007 | 0.122 | 0.12 |
| 22 | Log intercept slx spring BTS (descending) | -1.746 | 0.081 | 0.05 | 65 | Log recruitment dev 1985 | 0.224 | 0.092 | 0.41 |
| 23 | Log mean F | -0.363 | 0.047 | 0.13 | 66 | Log recruitment dev 1986 | 0.085 | 0.101 | 1.19 |
| 24 | Log intercept growth CV | -1.922 | 0.012 | 0.01 | 67 | Log recruitment dev 1987 | 0.536 | 0.085 | 0.16 |
| 25 | Slope growth CV | 0.010 | 0.000 | 0.04 | 68 | Log recruitment dev 1988 | 0.205 | 0.113 | 0.55 |
| 26 | Log Q for LPUE | -2.443 | 0.167 | 0.07 | 69 | Log recruitment dev 1989 | 0.670 | 0.090 | 0.13 |
| 27 | Log shape parameter for LPUE | -0.401 | 0.241 | 0.60 | 70 | Log recruitment dev 1990 | -0.061 | 0.115 | 1.90 |
| 28 | Log intercept fishery slx period 1 | 2.543 | 0.072 | 0.03 | 71 | Log recruitment dev 1991 | -1.008 | 0.146 | 0.15 |
| 29 | Log slope fishery slx period 1 | -1.846 | 0.079 | 0.04 | 72 | Log recruitment dev 1992 | -0.915 | 0.119 | 0.13 |
| 30 | Log intercept fishery slx period 2 | 2.629 | 0.290 | 0.11 | 73 | Log recruitment dev 1993 | 0.874 | 0.074 | 0.08 |
| 31 | Log slope fishery slx period 2 | -1.821 | 0.338 | 0.19 | 74 | Log recruitment dev 1994 | 0.812 | 0.089 | 0.11 |
| 32 | Log intercept fishery slx period 3 | 2.747 | 0.205 | 0.07 | 75 | Log recruitment dev 1995 | -0.317 | 0.120 | 0.38 |
| 33 | Log slope fishery slx period 3 | -1.871 | 0.236 | 0.13 | 76 | Log recruitment dev 1996 | -2.047 | 0.236 | 0.12 |
| 34 | Log F dev 1979 | -0.265 | 0.085 | 0.32 | 77 | Log recruitment dev 1997 | -0.136 | 0.093 | 0.69 |
| 35 | Log F dev 1980 | -0.388 | 0.103 | 0.26 | 78 | Log recruitment dev 1998 | 1.272 | 0.075 | 0.06 |
| 36 | Log F dev 1981 | -1.474 | 0.112 | 0.08 | 79 | Log recruitment dev 1999 | 1.125 | 0.088 | 0.08 |
| 37 | Log F dev 1982 | -0.863 | 0.110 | 0.13 | 80 | Log recruitment dev 2000 | 0.671 | 0.113 | 0.17 |
| 38 | Log F dev 1983 | -0.271 | 0.093 | 0.34 | 81 | Log recruitment dev 2001 | 0.728 | 0.110 | 0.15 |
| 39 | Log F dev 1984 | -0.101 | 0.084 | 0.84 | 82 | Log recruitment dev 2002 | 0.387 | 0.146 | 0.38 |
| 40 | Log F dev 1985 | -0.106 | 0.093 | 0.88 | 83 | Log recruitment dev 2003 | 1.999 | 0.112 | 0.06 |
| 41 | Log F dev 1986 | -0.277 | 0.099 | 0.36 | 84 | Log recruitment dev 2004 | 0.833 | 0.531 | 0.64 |
| 42 | Log F dev 1987 | 0.414 | 0.099 | 0.24 | 85 | Logit length error SMAST video | -2.499 | 1.223 | 0.49 |
| 43 | Log F dev 1988 | 0.138 | 0.134 | 0.97 | | | | | |



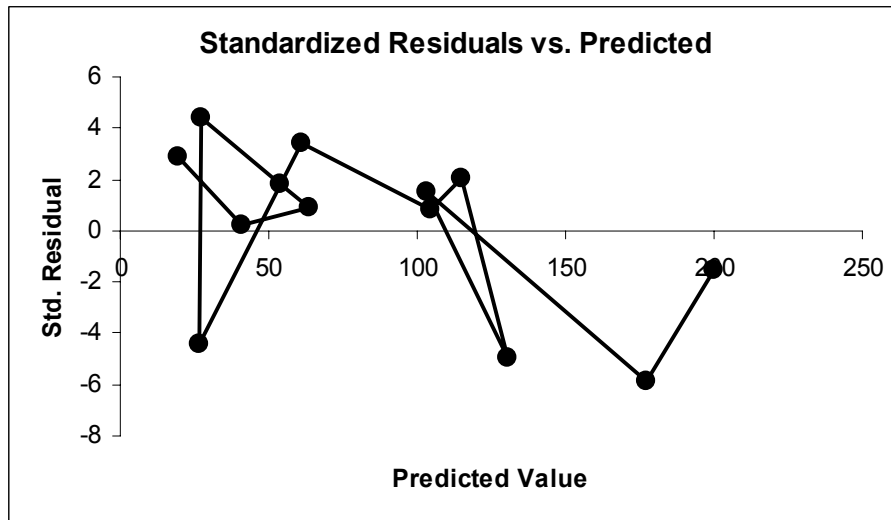
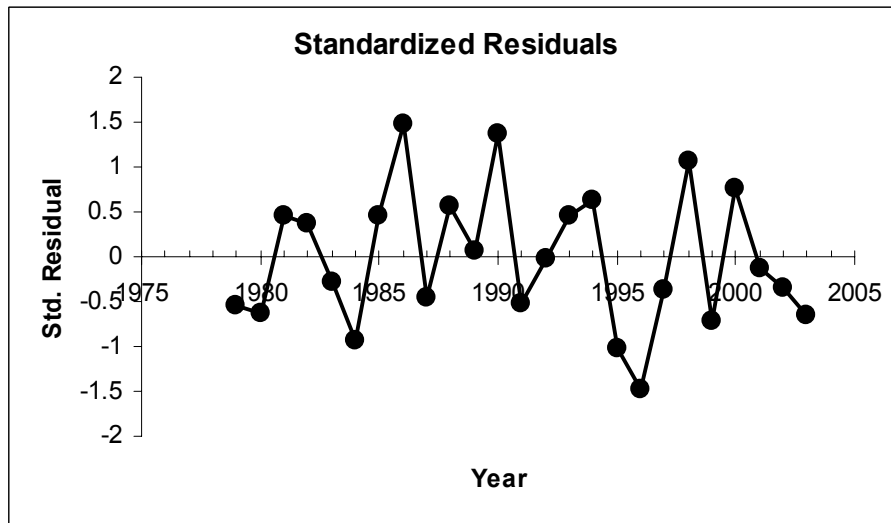
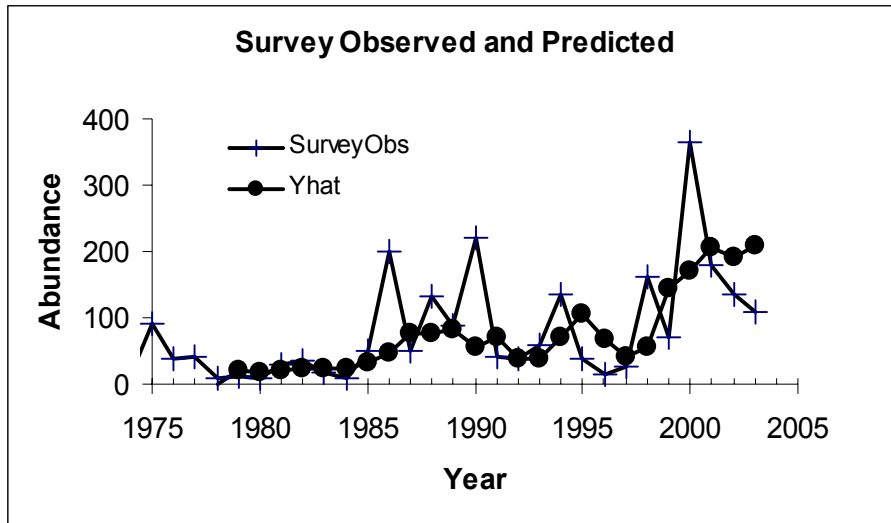
Appendix Figure 4-1. Retrospective analysis for biomass (top) and fishing mortality (bottom) estimates from a preliminary version of the CASA model for MAB sea scallops.



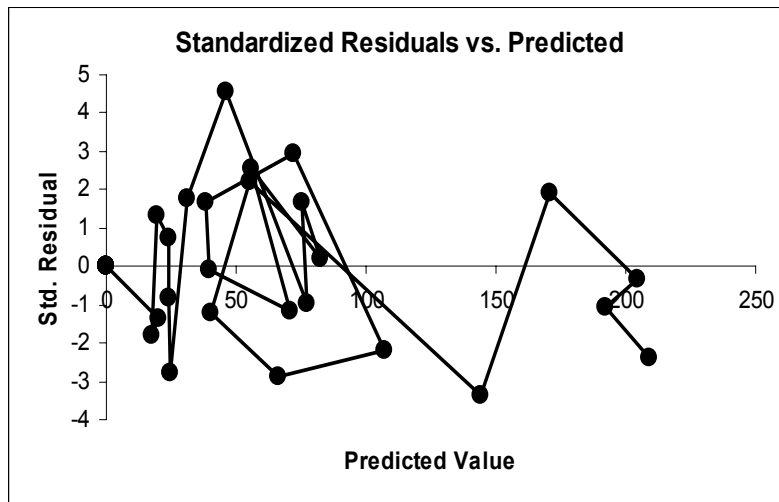
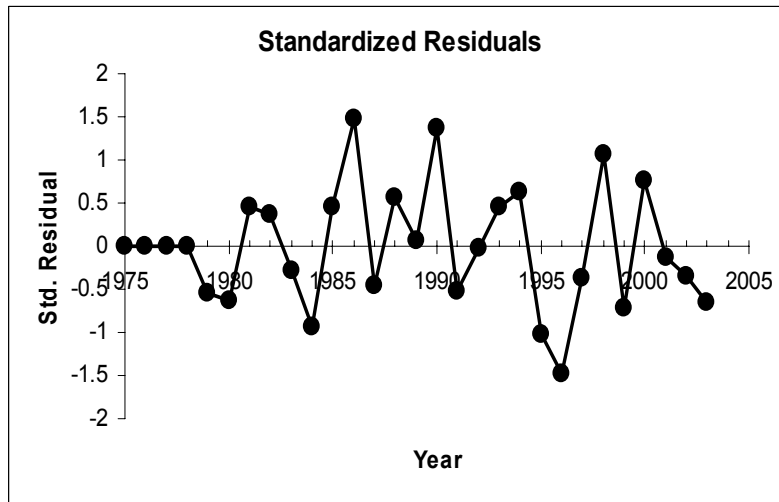
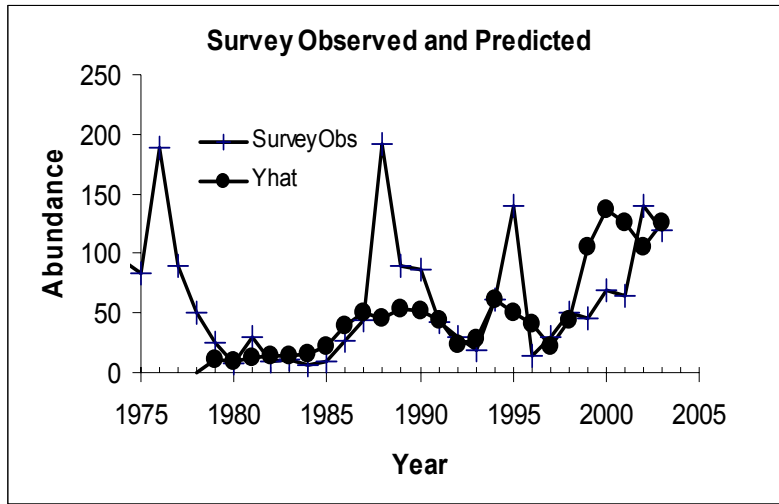
Appendix Figure 4-2. CASA model fit to NEFSC scallop survey data for MAB sea scallops.



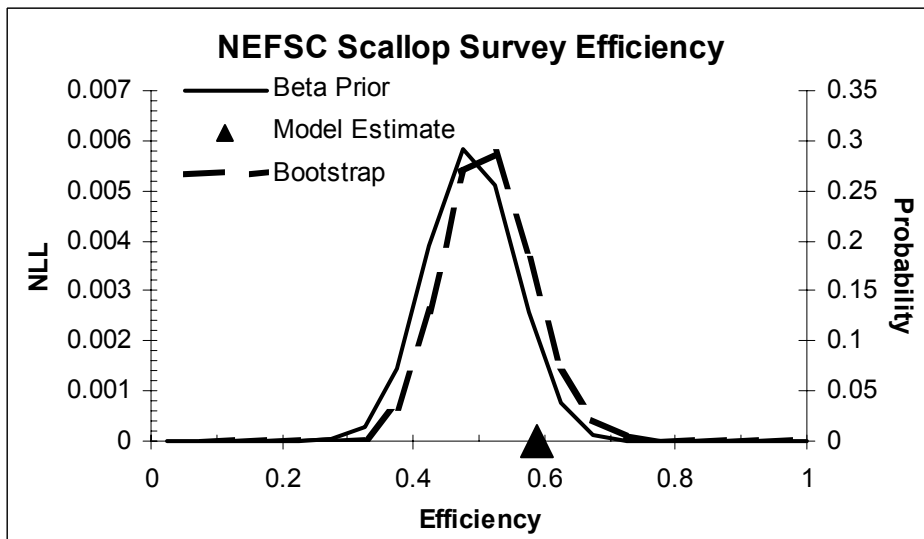
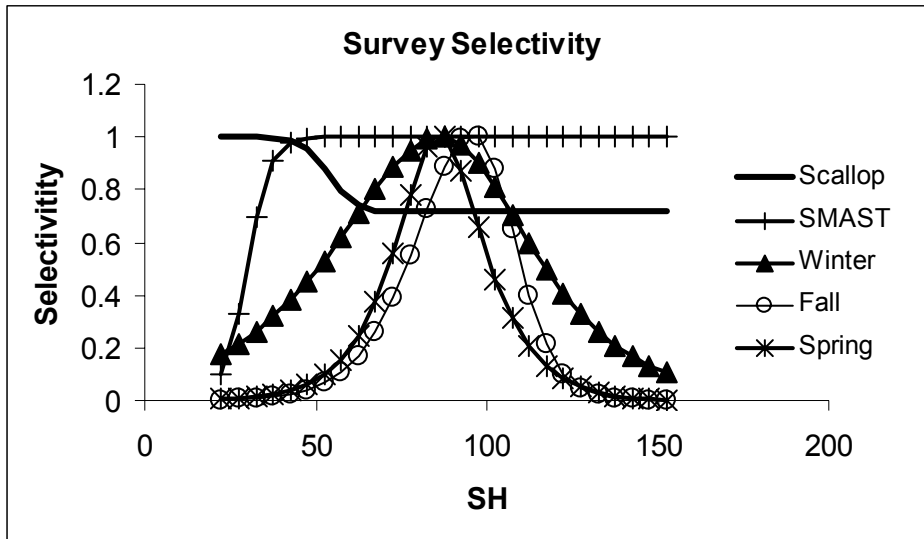
Appendix Figure 4-3. CASA model fit to NEFSC winter bottom trawl survey data for MAB sea scallops.



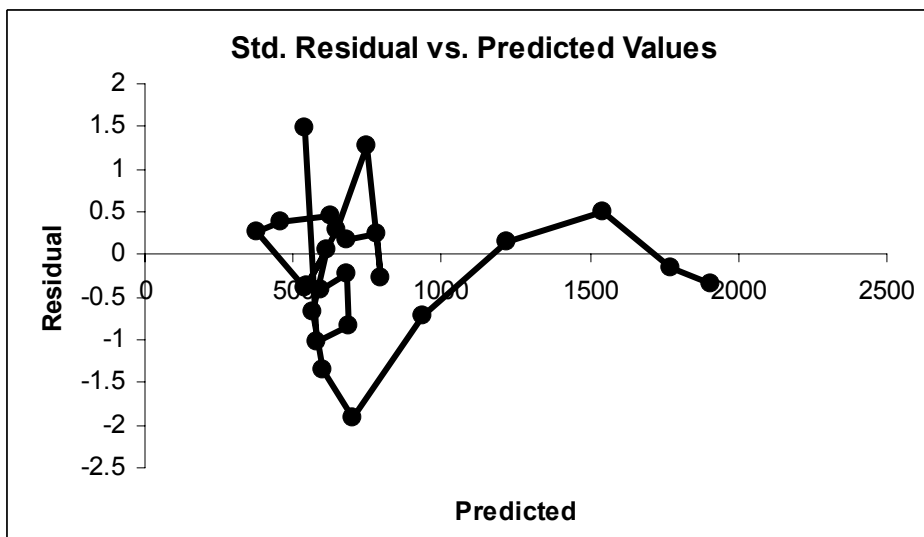
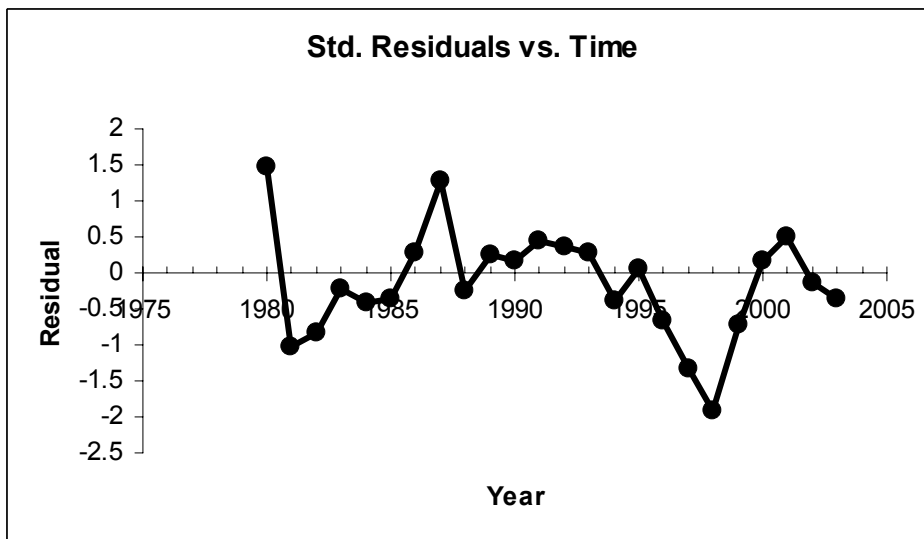
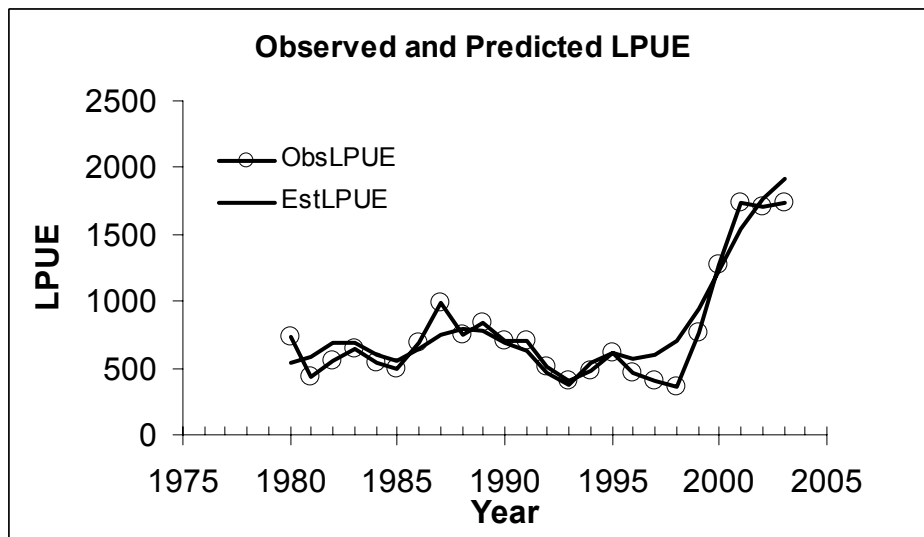
Appendix Figure 4-4. CASA model fit to NEFSC fall bottom trawl survey data for MAB sea scallops.



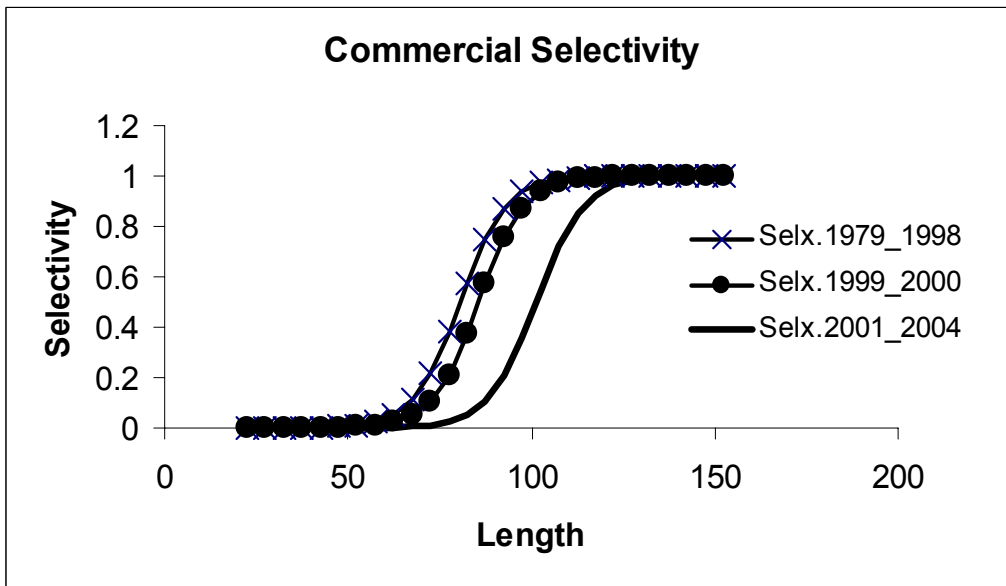
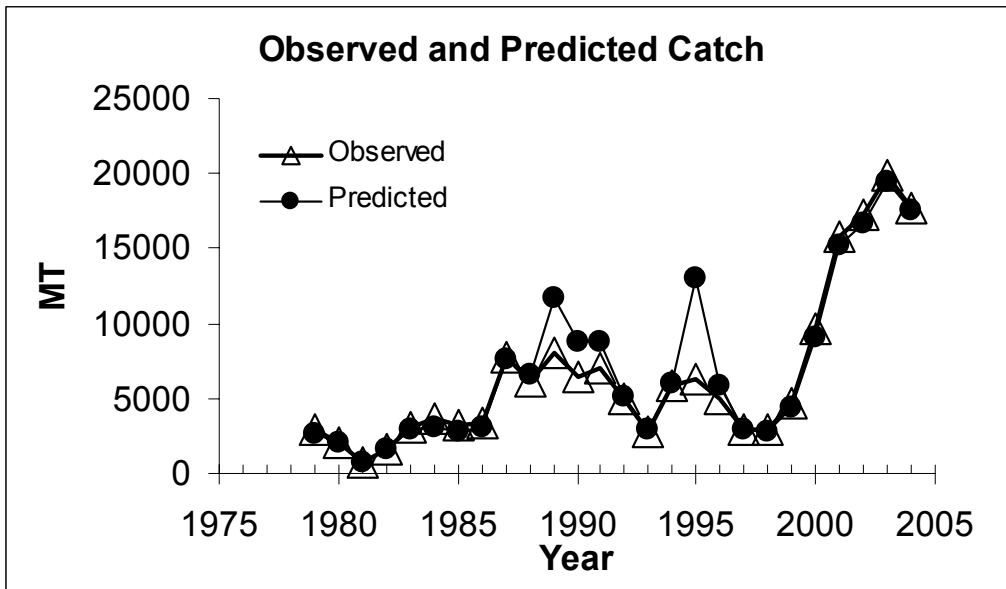
Appendix Figure 4-5. CASA model fit to NEFSC spring bottom trawl survey data for MAB sea scallops.



Appendix Figure 4-6. Survey selectivity patterns and NEFSC survey efficiency estimates for sea scallops in the MAB region.

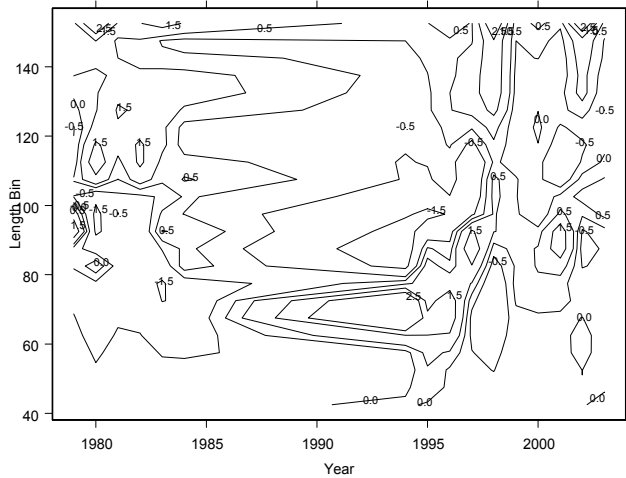


Appendix Figure 4-7. CASA model fit to LPUE data for MAB sea scallops.

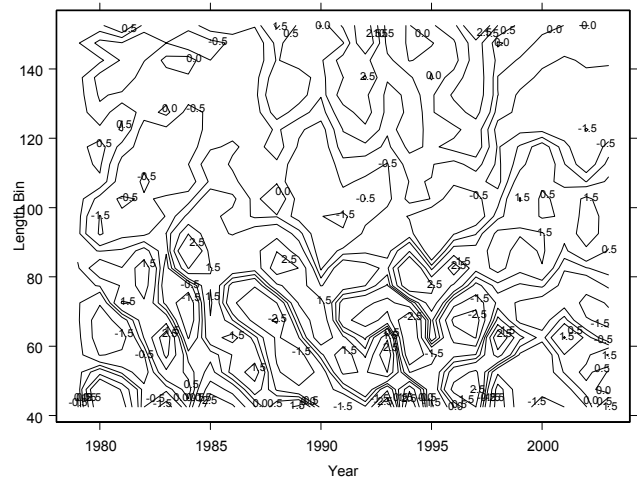


Appendix Figure 4-8. CASA model fit to landings data and estimated fishery selectivity patterns for MAB sea scallops.

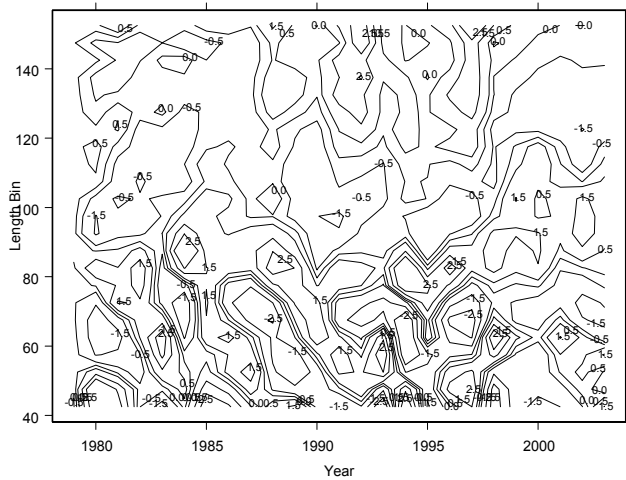
Standardized residuals MAB fishery length composition



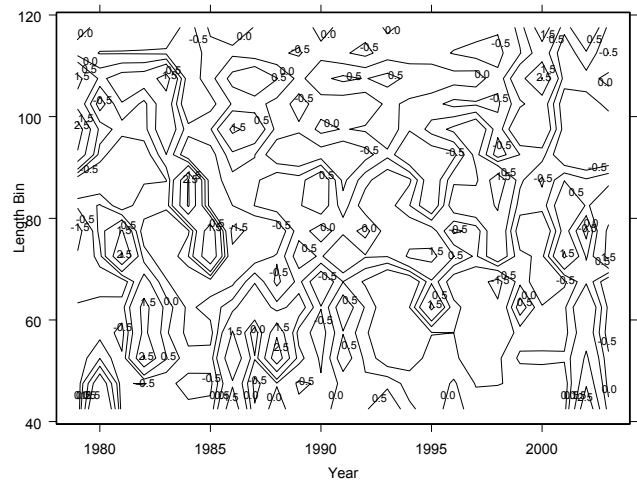
Standardized residuals scallop survey length composition



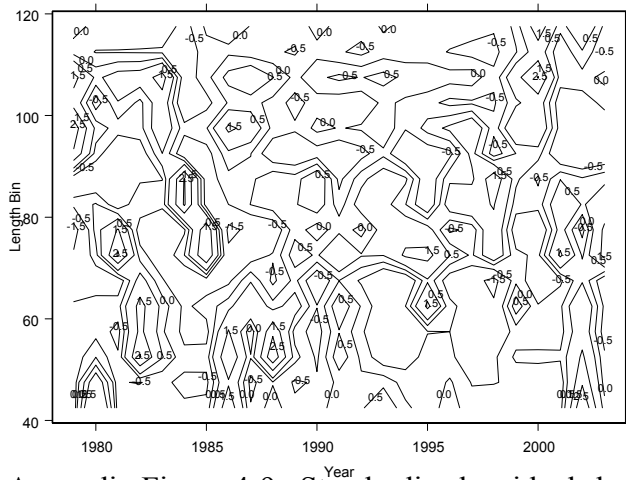
Standardized residuals winter BTS length composition



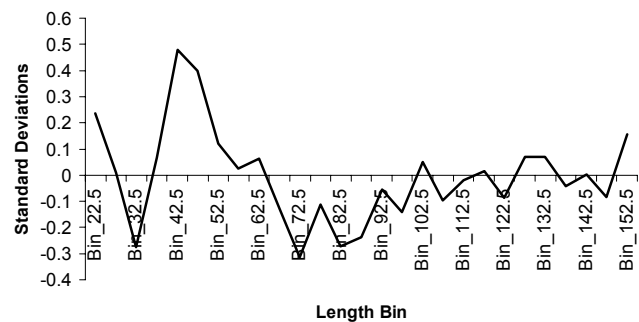
Standardized residuals fall BTS length composition



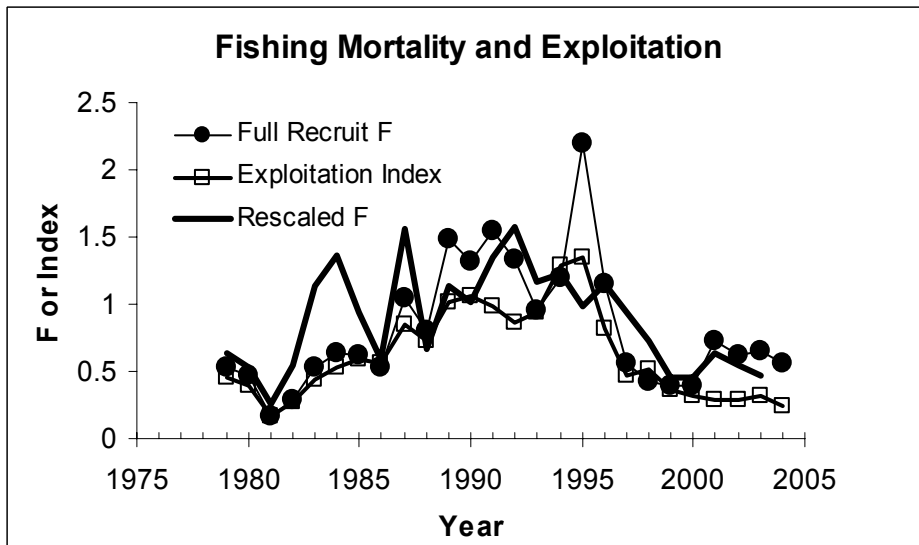
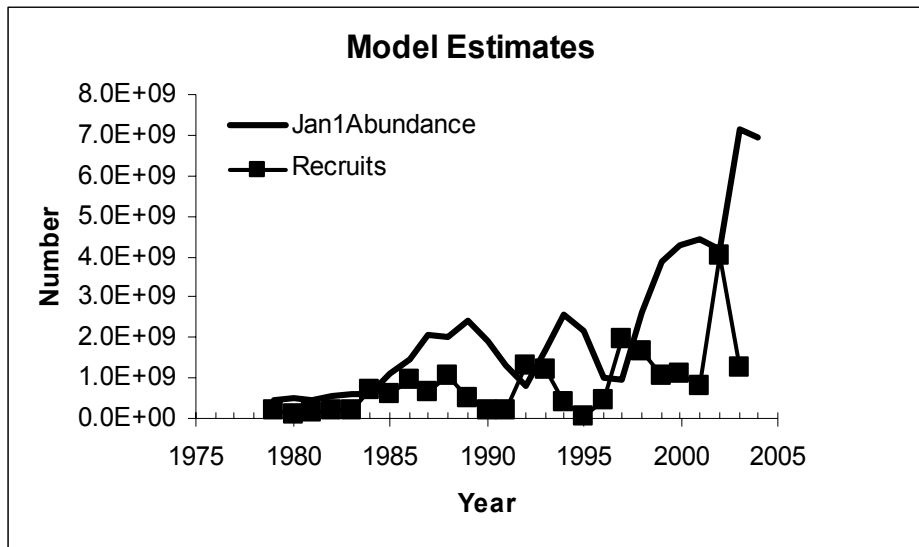
Standardized residuals spring BTS length composition



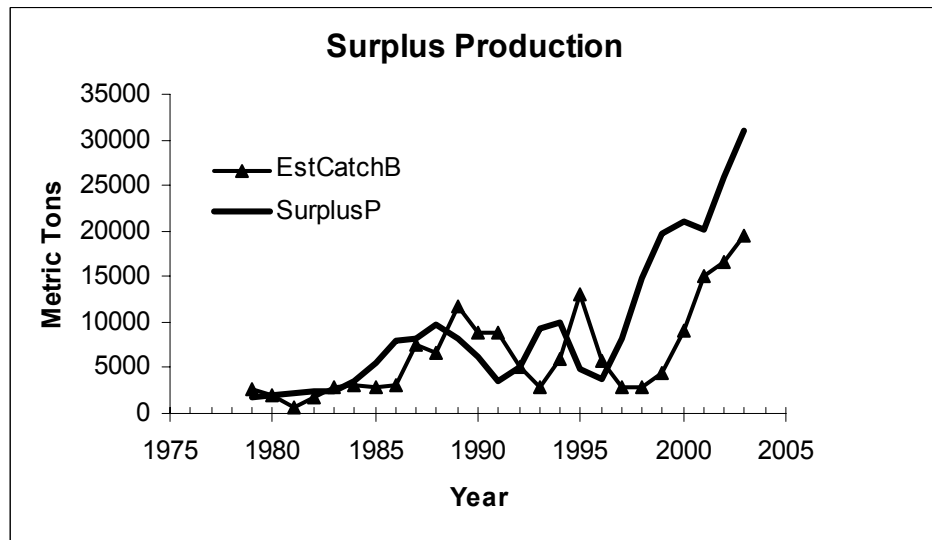
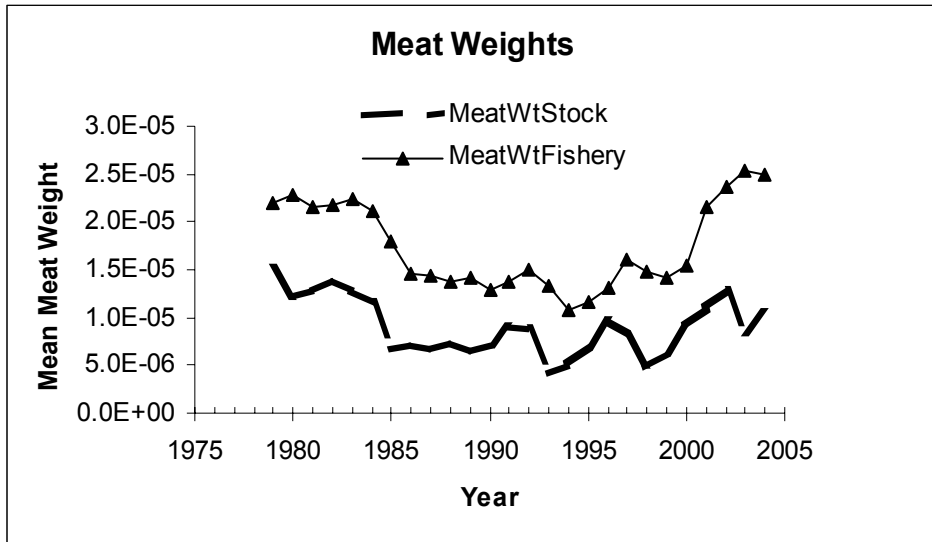
Standardized Residuals 2003 SMAST video survey length composition



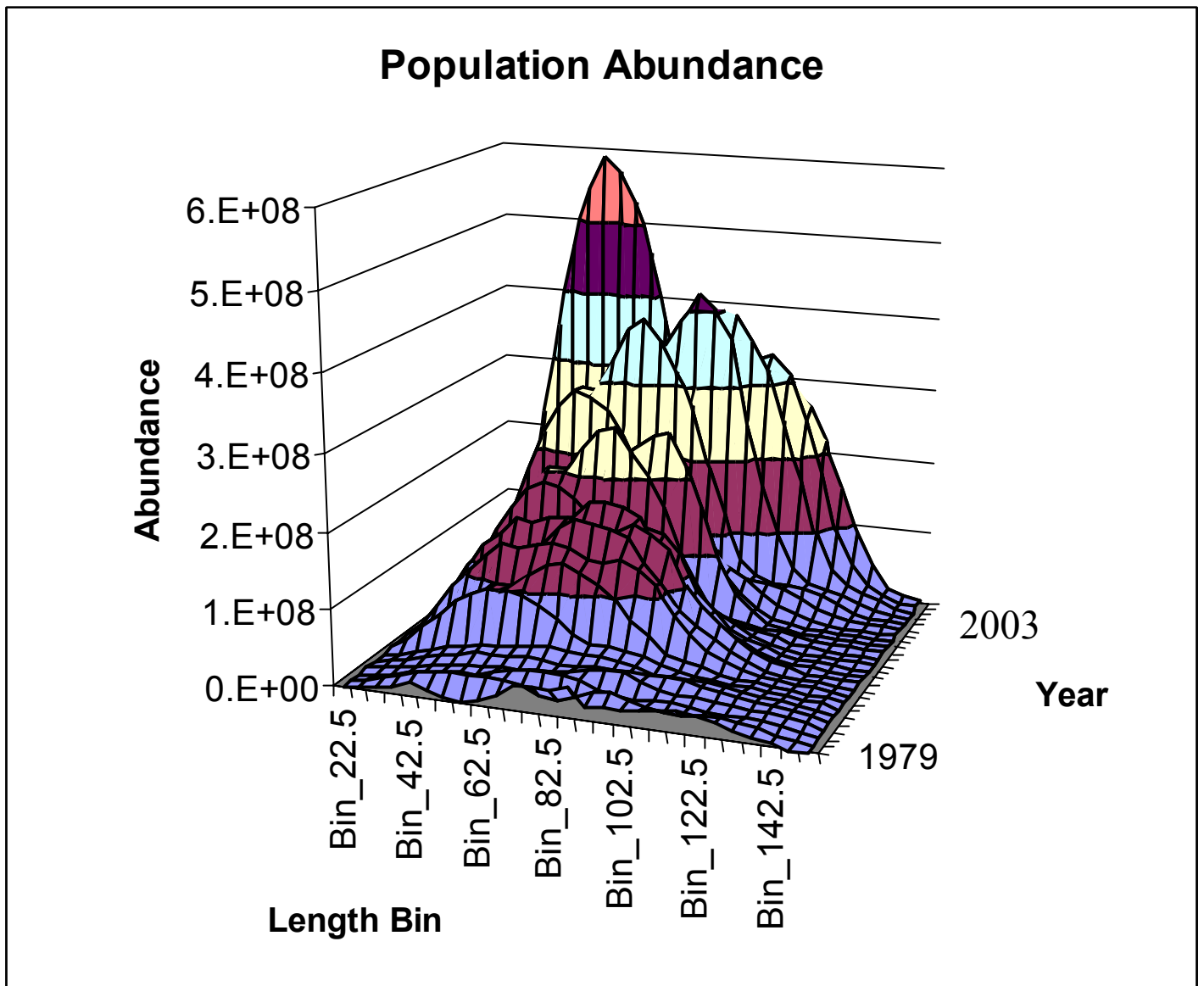
Appendix Figure 4-9. Standardized residuals by year and length bin for MAB sea scallop length composition data. Fishery length composition data were for 1979-1984 and 1994-2003. The apparent residual pattern for fishery data during 1985-1993 is an artifact due to no data.



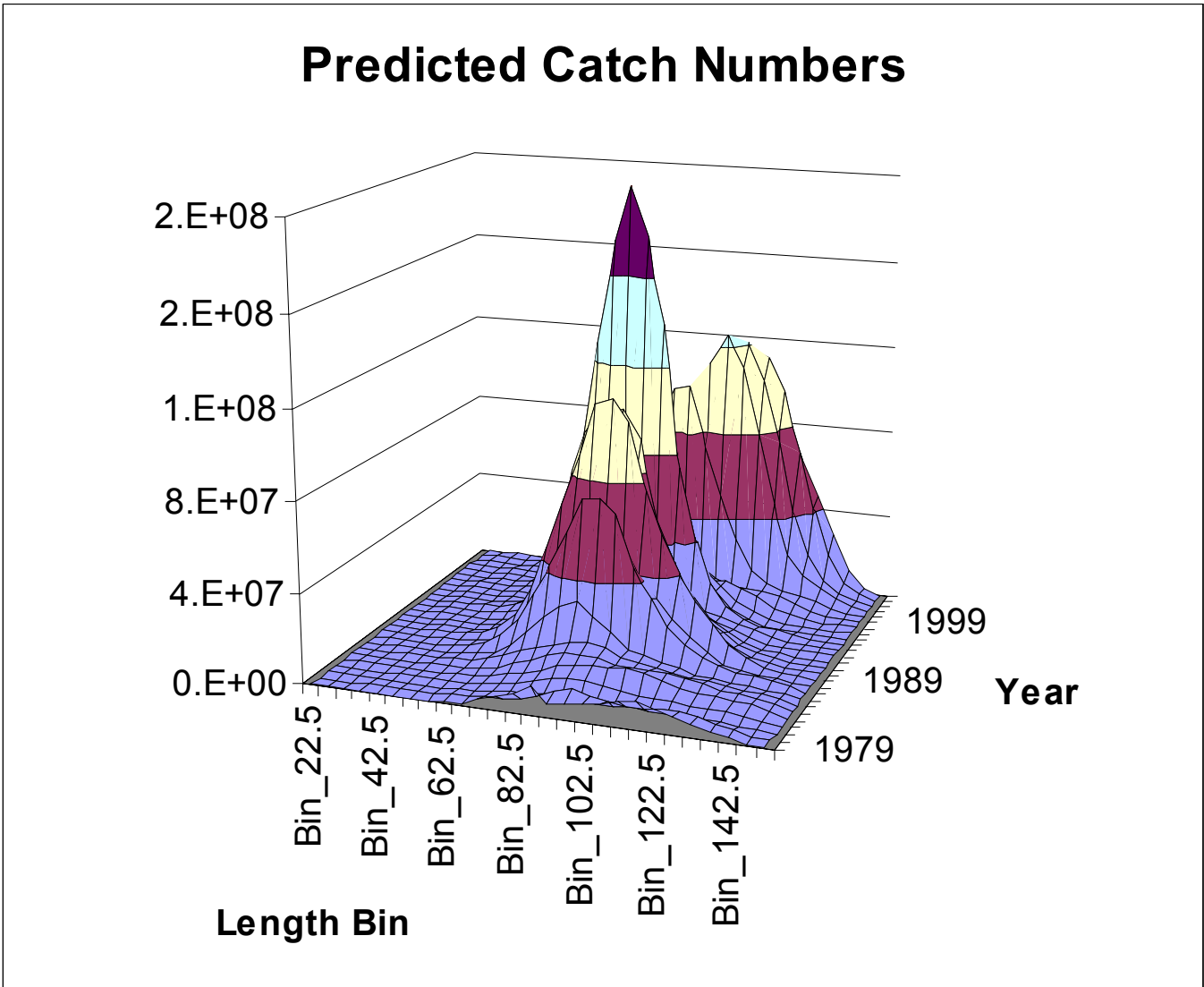
Appendix Figure 4-10. CASA model estimates of abundance, recruitment and fishing mortality for MAB sea scallops. In the lower panel, “Full Recruit F” is for length groups fully selected by the fishery and reflects changes in fishery selectivity, “Exploitation Index” is total catch number divided by abundance of scallops 90+ mm, and “Rescaled F” is for fishing mortality estimates by the method used for status determination.



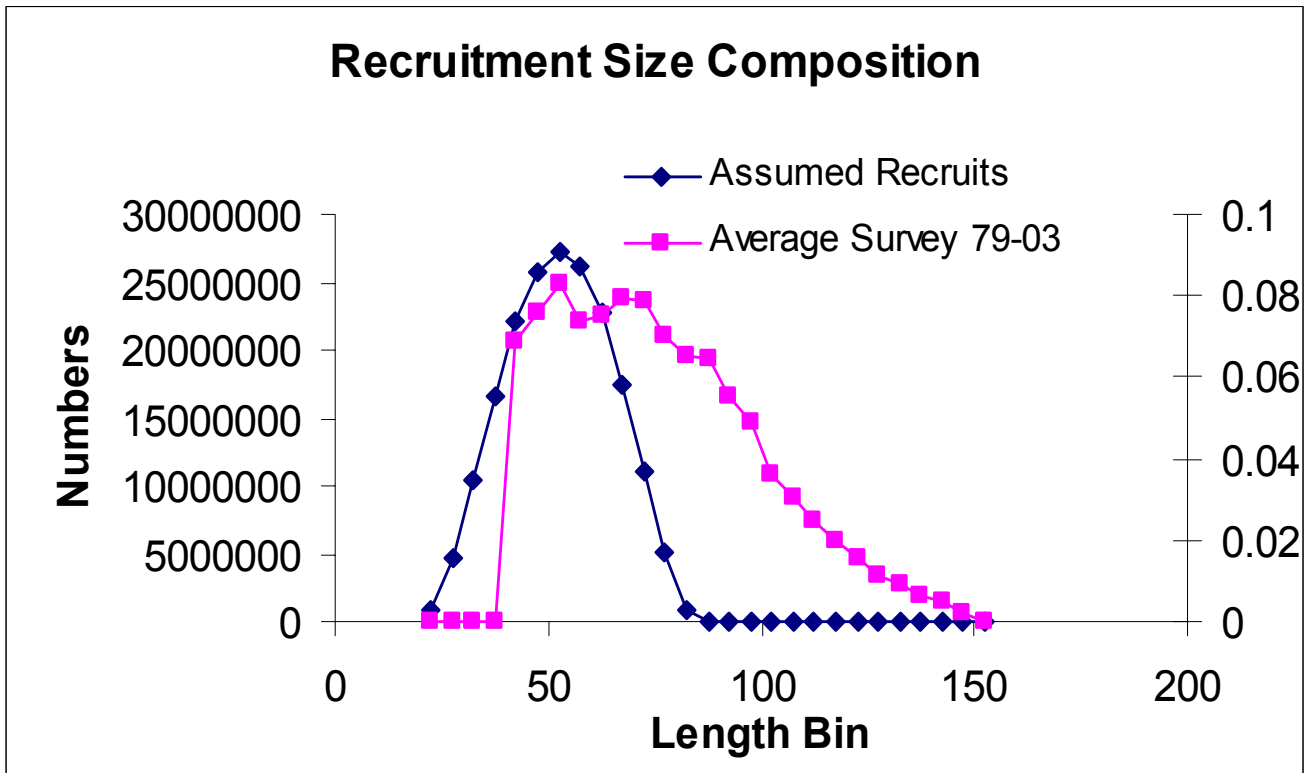
Appendix Figure 4-11. CASA model estimates of mean meat weights in the stock and fishery (top) and surplus production compared to catch of MAB sea scallops.



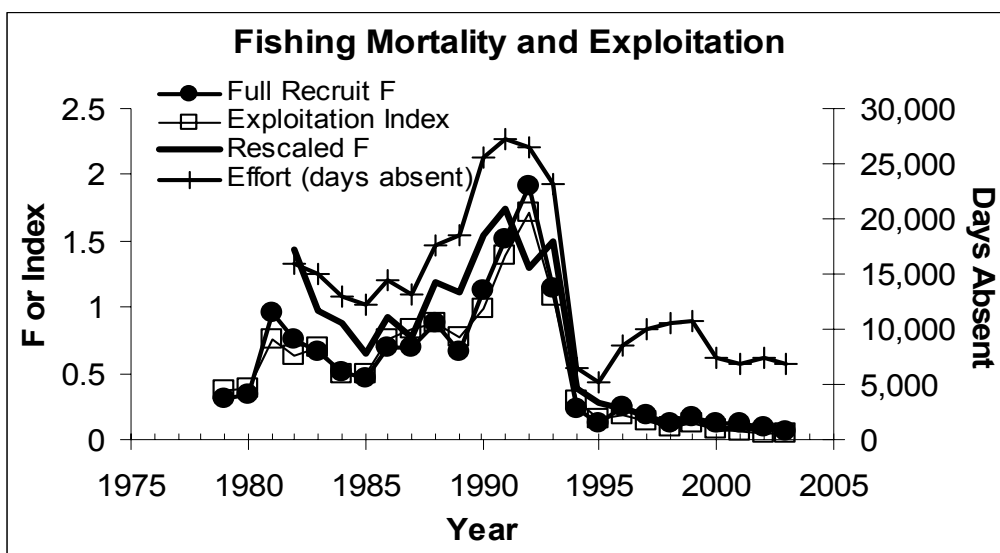
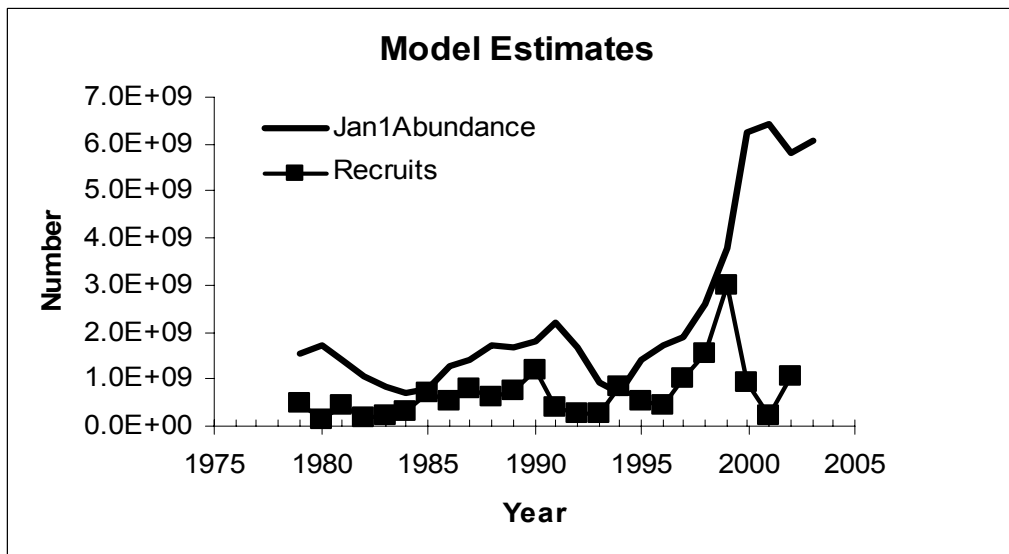
Appendix Figure 4-12. CASA model estimates of abundance at length by year for MAB sea scallops.



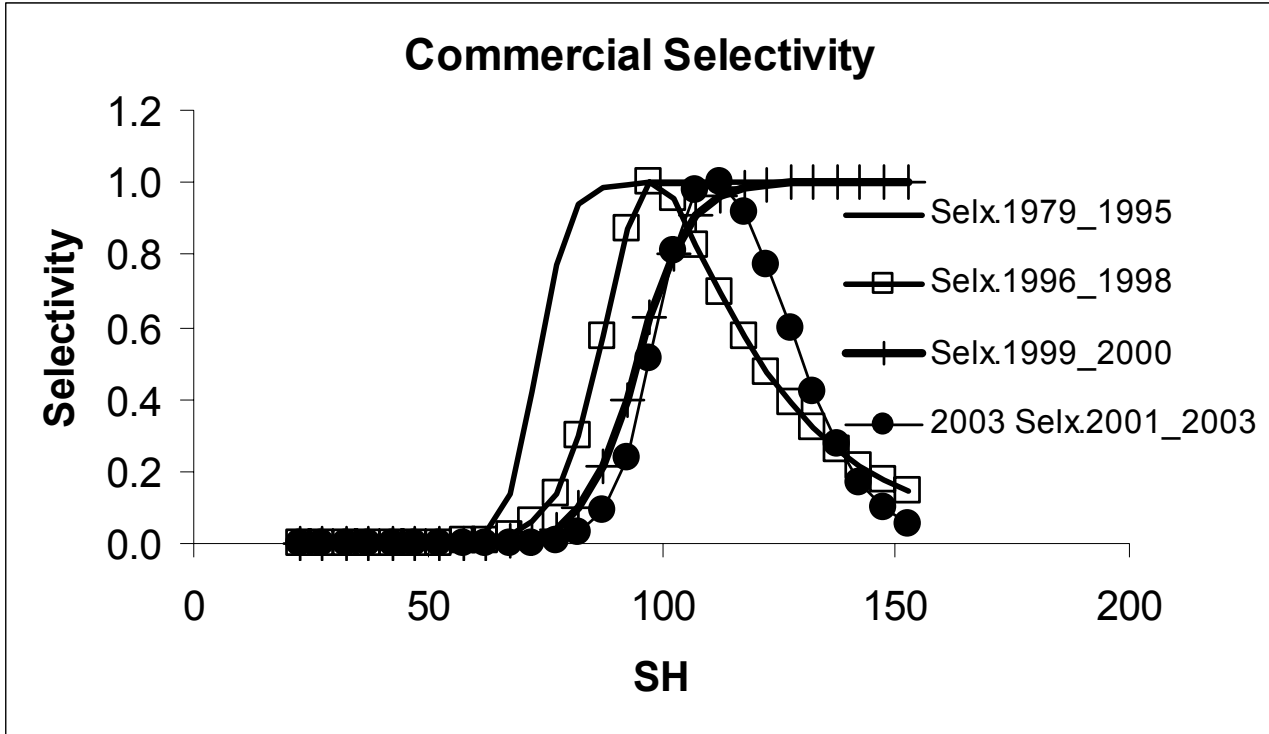
Appendix Figure 4-13. CASA model estimates of catch at length by year for MAB sea scallops.



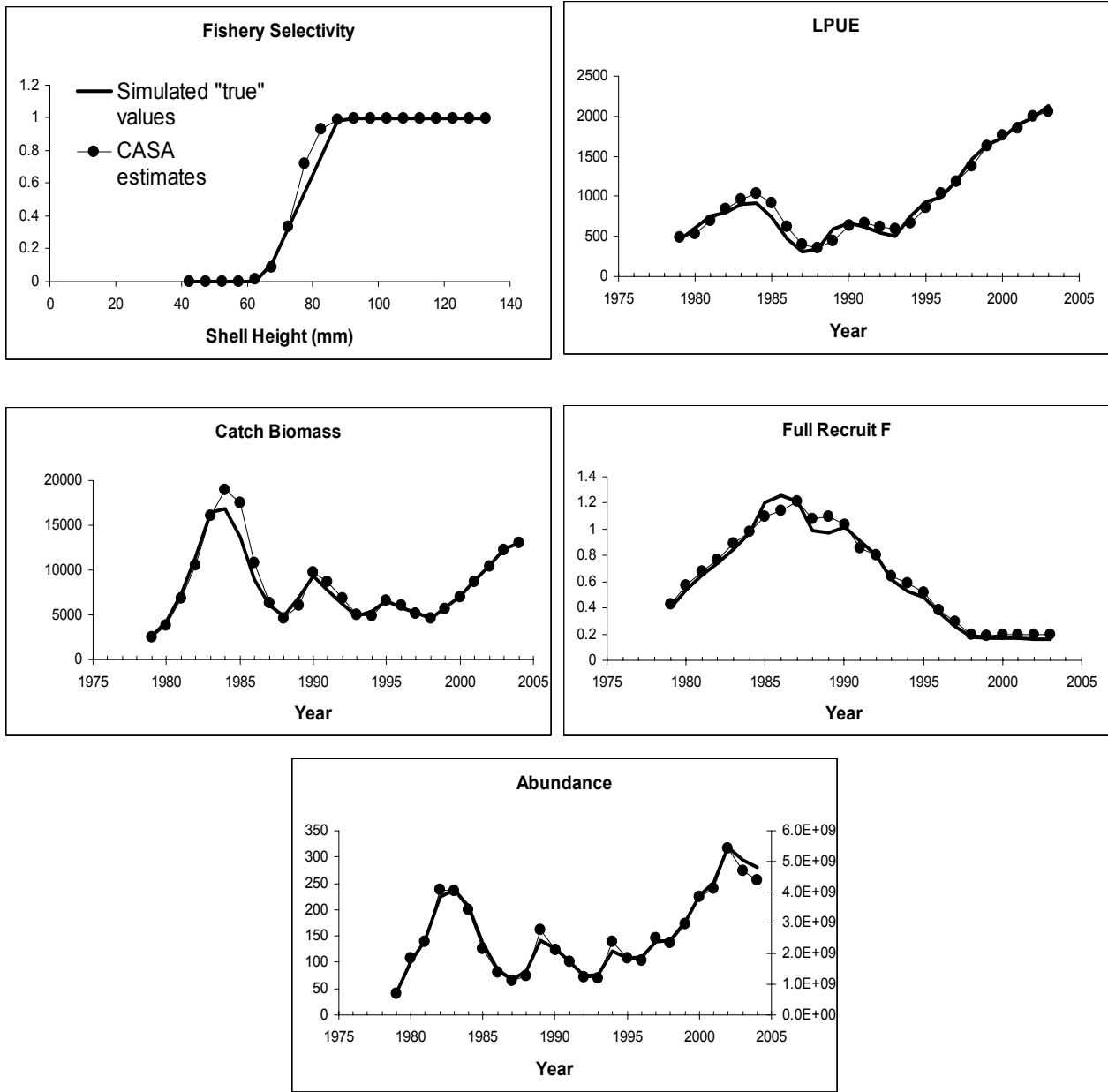
Appendix Figure 4-14. Assumed length composition of new recruits in the CASA model compared to average NEFSC scallop survey length composition data for 1979-2003. The steep ascending limb for the average survey length composition during 1979-2003 is an artifact due to using survey data for scallops larger than 40 mm.



Appendix Figure 4-15. CASA model estimates of abundance, recruitment and fishing mortality for GBK sea scallops. In the lower panel, “Full Recruit F” is for length groups fully selected by the fishery and reflects changes in fishery selectivity, “Exploitation Index” is total catch number divided by abundance of scallops 90+ mm, and “Rescaled F” is for fishing mortality estimates by the method used for status determination. Fishing effort is days absent from port.



Appendix Figure 4-16. Fishery selectivity patterns estimated in the CASA model for GBK sea scallops.



Appendix Figure 4-17. Results of simulation tests.

APPENDIX 5. THE CASA LENGTH STRUCTURED STOCK ASSESSMENT MODEL

The stock assessment model described here is based on Sullivan et al.'s (1990) CASA model.⁴ 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. 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, in the broadest sense, on maximum likelihood. CASA can incorporate prior information about parameters such as survey catchability in a quasi-Bayesian fashion. The implementation described here was programmed in AD-Model Builder (Otter Research Ltd.).⁵

Population dynamics

Time steps in the model are the same as the time periods used to tabulate catch and other data. In principle, the accuracy of calculations improves as time steps in the model become shorter, but data considerations often limit time steps to years. In this description, time steps are referred to as “years” without loss of generality. 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), usually by making a single change to the input data file.

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 by their lower bound. With 10 mm length bins, for example, the 20 mm size bin includes individual 20-29.9 mm. Calculations requiring information about length (e.g. length-weight) use the mid-length ℓ_j of each bin.

In the current implementation, the user must specify the size of length bins (L_{bin}) in the data and model, the minimum size (L_{min}) at the lower bound of the first length bin in the data and model, and the maximum asymptotic length (L). Based on these specifications, the model determines the number (n_L) of length bins to include in modeling. The last bin is a “plus-group” containing individuals L and larger. The number of length groups in catch at length and other data should be $\geq n_L$. Based on user specifications, the program takes care adjusting the original data to the length groups used in the model.

⁴ 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.

⁵ 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.

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_∞ is not estimable because it is used in defining length bins prior to the parameter estimation phase.⁶ 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_∞ and size at the beginning of the year.

At the beginning of the year, scallops in each size group grow (or not) based on growth terms $P(b,a)$ that measure 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 ι is the growth increment. Following Sullivan et al. (1990), and for simplicity, growth probabilities are calculated assuming that all individuals start at the middle of their original length bin ℓ_a , and then grow to sizes that cover the whole range of each possible subsequent size bin. Thus:

$$P(b,a) = \int_{j=\ell_b - L_{bin}/2}^{\ell_b + L_{bin}/2} P(j | \ell_a) \partial j = \aleph(\ell_b + L_{bin}/2 | \ell_a) - \aleph(\ell_b - L_{bin}/2 | \ell_a)$$

where $P(j | \ell_a)$ is the probability of increment j for an individual originally in bin a (at mid-length ℓ_a). $\aleph(a | \ell_a)$ is the initial size-specific cumulative distribution function for growth increments. In CASA, 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 gamma distributions. The gamma distributions for growth increments are starting size-specific

⁶ "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.

and are specified in terms of mean increments and CV's. Mean increments \bar{i}_a are from the von Bertalanffy growth curve:

$$\bar{i}_a = (L_\infty - \ell_a)(1 - e^{-K})$$

where $K=e^\chi$ is the von Bertalanffy growth coefficient and χ is an estimable parameter.⁷ Under Option 1, CVs are a log-linear function of length:

$$CV_L = e^{\kappa + \lambda L}$$

where κ and γ 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 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 (κ and γ) 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.

⁷ 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.

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 η 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 π_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:

$$\vec{N}_{y+1} = P(\vec{N}_y \otimes \vec{S}_y) + \vec{R}_{y+1}$$

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 , \otimes 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:

$$S_{y,L} = e^{-Z_{y,L}} = e^{-(M+F_{y,L})}$$

where $Z_{y,L}$ is the total instantaneous mortality rate. The natural mortality rate $M=e^{\omega}$ (ω estimable) is the same for all length groups in all years. Length-specific fishing mortality rates are $F_{y,L} = F_y s_{y,L}$ where $s_{y,L}$ is the size-specific selectivity for the fishery in year y (scaled to a maximum of one at fully recruited size groups), and F_y is the fishing mortality rate on fully selected individuals.⁸ Fully recruited fishing mortality rates are $F_y = e^{\phi + \delta_y}$ where ϕ is an estimable parameter for the log of the geometric mean of fishing mortality in all years, and δ_y is an estimable “dev” parameter.⁹

Given abundance in each length group, natural mortality, and fishing mortality,

⁸ 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.

⁹ 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.

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 $C_y = \sum_{j=1}^{n_L} C_{y,L}$. Note that, because the catches are in effect assumed to be taken at the beginning of the year, model catches (by weight) will tend to be biased low, especially during years when mostly smaller scallops were taken.

Recruitment (the sum of new recruits in all length bins) at the beginning of each year after the first is calculated based on estimable parameters that measure annual deviations γ_y from the log-scale geometric mean ρ :

$$Ry = e^{\rho + \gamma_y}$$

Proportions of recruits in each length group are calculated based on a standard beta distribution $B(w,r)$ over the first n_r length bins. Proportions of new recruits in each size group are the same from year to year. Beta distribution coefficients must be larger than zero and are calculated $w=e^\omega$ and $r=e^\rho$, where ω and ρ are estimable parameters.

Population summary variables

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:

$$\bar{N}_{y,L} = N_{y,L} \frac{1 - e^{-Z_{y,L}}}{Z_{y,L}}$$

The current implementation of the NC model assumes that weight-at-length is the same for the stock and fishery and a single set of length-weight conversion parameters is used in all calculations. 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 computed at the midpoint of each length bin using the length-weight relationship specified by the user. Total catch weight is:

$$W_y = \sum_{L=1}^{n_L} C_{y,L} w_L$$

F_y estimates for two years are comparable if fishery selectivity in the model was the same in both years. A simpler exploitation index is calculated for use when fishery selectivity changes over time:

$$U_y = \frac{C_y}{\sum_{j=x}^{n_L} N_{y,L}}$$

where x is a user-specified length bin (usually at or below the first bin that is fully selected during all fishery selectivity periods). U_y exploitation indices from different years with different selectivity patterns may be relatively comparable if w is chosen carefully.

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 δ 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 $\delta=1$.

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 (ℓ). 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.

Depending on the option, estimable selectivity parameters may include α , β , δ and γ . 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 α_Y , while keep the slope β_Y at its initial value.

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 λ_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 (λ and ϕ) 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.¹⁰

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:

¹⁰ Likelihood kernels in the present implementation prevent use of AD-Model Builder’s MCMC algorithms for Bayesian statistical approaches.

$$L = 0.5 \left(\frac{x - \mu}{\sigma} \right)^2$$

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 σ . 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 θ_i is the model’s estimate of the probability of an observation in the bin. The constant K is used for convenience to keep L to a manageable number of digits. 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. Means, CV’s and distributional parameters may, depending on the situation, be estimated in the model or specified by the user.

Robust methods

“Robust” maximum likelihood calculations are available for noisy data in the CASA model that might be assumed otherwise to have normally distributed measurement errors. Robust likelihood calculations 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 are reduced, the tails of the t distribution become fatter so that small observations seem more probable (have higher probability) and have 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

In the current version of the CASA model, catch data are for a single or “composite” fishery. The terms “catches” and “landings” are used interchangeably in the current version because discard and non-landed fishery induced mortality are not distinguished. In the current version, total catch and must be specified in units of weight. Ideally, catch data should include all fishery-induced mortality and fishery length composition data (if available) should be represent the size distribution of all individuals that suffered fishery-induced mortality.

Catch data 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 “^” indicates that the variable is a model estimate. The standardized residual used in computing NLL for a single catch observation and in making residual plots is $r_Y = (C_Y - \hat{C}_Y) / \sigma_Y$.

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 cN_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 (Fournier and Archibald, 1982; Pennington et al., 2002). Typical conventions make ${}^cN_Y \leq 200$ or set cN_Y equal to the number of trips or tows sampled. Effective sample sizes are sometimes chosen based on goodness of fits in preliminary model runs (Methot, 2000; Butler et al., 2003).

Standardized residuals are not used in computing NLL fishery length composition data. However, approximate standardized residuals $r_y = (c_{y,L} - \hat{c}_{y,L}) / \sigma_{y,L}$ with standard deviations $\sigma_{y,L} = \sqrt{\hat{c}_{y,L}(1 - \hat{c}_{y,L}) / {}^cN_Y}$ based on the theoretical variance for proportions are computed for use in making residual plots.

Survey index data

In CASA model calculations, “survey indices” are data from any source that reflect relative proportional changes in annual abundance or biomass over time. 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).

In general, survey index data give one number that summarizes relative abundance for a wide range of length bins. Catch at length data from surveys are handled separately (see below). For example, a survey index might consist of stratified mean numbers per tow for all size bins in a bottom trawl survey carried out over a series of years, with one observation of the index per year of sampling.

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 abundance or biomass available to the survey. Scaling factors are calculated $q_s = e^{\varpi_s}$ where ϖ_s is estimable and survey-specific. Available abundance is:

$$A_{k,y} = \sum_{L=first_k}^{last_k} s_{k,L} N_{y,L} e^{-Z_{y,L} \tau_{k,y}}$$

where $s_{k,L}$ is size-specific selectivity of the survey, $\tau_{k,y} = J_{k,y}/365$ where $J_{k,y}$ is the mean Julian date of the survey, and $e^{-Z_{y,L} \tau_{k,y}}$ is a correction for mortality prior to the survey. 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. Available biomass is calculated in the same way except that body weights w_L are included in the product on the right hand side.

The range of lengths ($first_k \geq 1$ to $last_k \leq n_L$) included in the calculation of $A_{k,y}$ is specified by the user for each survey. In addition, the user specifies whether $first_k$ and $last_k$ are plus-groups meant to contain smaller or larger individuals.

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

NLL calculations for survey length composition data are roughly analogous to calculations for fishery length composition data, except that measurement errors in length data can be modeled explicitly. Survey length composition data represent a sample from the true population length composition which is modified by survey selectivity, sampling errors (due to having a limited number of tows) and, if applicable, errors in recording length data (i.e. errors in observations to size bins). For example, with errors in length measurements, individuals belonging to length bin j , might be mistakenly assigned to adjacent length bins $j-2$, $j-1$, $j+1$ or $j+2$. 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).

Survey length composition data are treated as multinomial proportions calculated:

$$i_{k,y,L} = \frac{n_{k,y,L}}{\sum_{j=first_k}^{last_k} n_{k,y,j}}$$

The model's estimate of length composition for the population available to the survey is:

$$A_{k,y,L} = \frac{s_{k,L} N_{y,L} e^{-Z_{y,j} \tau_{k,y}}}{\sum_{j=first_k}^{last_k} s_{k,j} N_{y,j} e^{-Z_{y,j} \tau_{k,y}}}$$

The expected length composition $\vec{A}'_{k,y}$ for survey catches, including length measurement errors is:

$$\vec{A}'_{k,y} = \vec{A}_{k,y} \mathbf{E}_k$$

where \mathbf{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 \mathbf{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.

In CASA, the probabilities in the error matrix are computed from a normal distribution with mean zero and $CV = e^{\pi_k}$, where π_k is an estimable parameter. The normal distribution is truncated to cover a user-specified number of observed bins.

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 an estimate of effective sample size ${}^l N_y$ supplied by the user. Standardized residuals for residual plots are computed as for fishery length composition data.

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.¹¹ 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:

$${}^a \bar{B}_y = \sum_{L=1}^{n_L} s_{y,L} w_L \bar{N}_{y,L}$$

Predicted values for LPUE data are calculated:

$$\hat{L}_y = \frac{{}^a \bar{B}_y \eta}{\sqrt{\phi^2 + {}^a \bar{N}_y^2}}$$

Measurement errors in LPUE data are assumed normally distributed with standard deviations $\sigma_y = CV_y \hat{L}_y$. Standardized residuals are $r_y = (L_y - \hat{L}_y) / \sigma_y$.

¹¹ D. Hart, National Marine Fisheries Service, Northeast Fisheries Science Center, Woods Hole, MA, pers. comm.

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 *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 $^P N_j$ 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 coincide so that:

$$\begin{aligned} I_{k,y} &= q_k A_{k,y} \\ q_k &= \frac{A e_k}{a_k} \\ e_k &= \frac{a_k q_k}{A_k} \end{aligned}$$

where A is the area of the stock, a_k is the area swept during one tow and $0 < e_k \leq 1$ is efficiency of the survey gear. 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 and a_k . Then, 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 beta distribution with the user-specified mean and CV. Alternatively, in Bayesian jargon, the prior probability of the implied efficiency estimate is computed and added to the overall objective function.

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.

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:

$$L = \lambda \sum_{t=0}^N (d_t^2 + q^2)$$

where:

$$d_t = \begin{cases} Ft - \Phi & \text{if } Ft > \Phi \\ 0 & \text{otherwise} \end{cases}$$

and

$$q_t = \begin{cases} \ln(Ft / \Phi) & \text{if } Ft > \Phi \\ 0 & \text{otherwise} \end{cases}$$

with the user-specified threshold value Φ set larger than the largest value of F_t that might possibly be expected (e.g. $\Phi=3$). The weighting factor λ is normally set to a large value (e.g. 1000).