B. Stock Assessment for Atlantic Sea Scallops

(Placopecten magellanicus)

Consensus Assessment Report

SARC 39

SAW Invertebrate Subcommittee[1,2]

National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole Laboratory
Woods Hole, MA

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[1] Deborah Hart (National Marine Fisheries Service, Northeast Fisheries Science Center, Woods Hole) led the stock assessment team.

[2] Contributing members of the Invertebrate Subcommittee as follows: Affiliated with the Northeast Fisheries Science Center: Russell Brown, Antoine Chute, Larry Jacobson, Victor Nordahl, Paul Rago and Fred Serchuk; affiliated with the New England Fisheries Management Council: Andrew Applegate; affiliated with the Virginia Institute of Marine Science, College of William and Mary: Bill DuPaul, Dave Rudders and John Walter; affiliated with Rutgers University: Joachim Groger, Grant Law and John Quinlan; affiliated with the School of Marine Science and Technology, University of Massachusetts: Brad Harris, Mike Marino, Jake Nogueira, Kevin Stokesbury and Tu Trong; affiliated with the Woods Hole Oceanographic Institution: Amit Huppert and Hanamunt Singh; affiliated with the Fisheries Survival Fund: Trevor Kenchington and Ron Smolowitz; affiliated with the Department of Fisheries and Oceans, Canada: Stephen Smith; no affiliation listed: Richard Taylor.

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 , 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 $M = 0.1$ y^{-1} for scallops with shell heights > 40 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 ($M \quad L$, where L is the number of live scallops) and the rate at which clappers separate ($S \quad C$, 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 $M \quad L = S \quad C$ and:

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

Merrill and Posgay estimated S=1.58 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 during1979-1981. 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:

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

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):

$$s_h = \begin{cases} 0 & \text{if } h \le h_{\min} \\ \dfrac{h - h_{\min}}{h_{full} - h_{\min}} & \text{if } h_{\min} < h < h_{full} \\ 1 & \text{if } h \ge h_{full} \end{cases}$$

where $h_{min} = 65$ mm and $h_{full} = 88$ 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

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

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 closured 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 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 $c = 0.15\text{-}0.2$ (Caddy 1973), and $c < 0.05$ (Murawski and Serchuk 1989). The ratio R of scallops in the path of the dredge that were caught, to those killed but not caught is:

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

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

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

If, for example, the 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).

<u>Rescaled catch-biomass method</u>

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:

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

where average catch-biomass ${}^{c}\overline{F}_y$ and survey-based ${}^{s}\overline{F}_t$ 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 $\mathrm{Var}(\ln(X)) = \mathrm{Var}(X)/\mathrm{E}(X)^2$, the variance of F_{MEAN} is:

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

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 $\mathrm{BPR}_{\mathrm{MAX}}$ (biomass per recruit at $F= F_{\mathrm{MAX}}$, 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:

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

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 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 that 120 mm, and 0.2 y^{-1} for larger shell heights. The latter gave F_{MAX}>0.3 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 = 75mm). 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:

$$B_{MAX} = \text{Median recruitment} \ \ \mathbf{x} \ \ BPR_{MAX}$$

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). $B_{MAX} = 5.6$ 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 $B_{MAX} = 5.6$ 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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	Gulf of Maine			Georges Bank				S. New England				Mid-Atlantic Bight				Uncl.	Total			
Year	trawl	other	sum	dredge	trawl	other	sum	dredge	trawl	other	sum	dredge	trawl	other	sum	other	dredge	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