

Long-Term Dynamics of U.S. Atlantic Sea Scallop *Placopten magellanicus* Populations

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Abstract.—Biomass and commercial catch rates of Atlantic sea scallops *Placopten magellanicus* in the USA generally declined from the 1960s through the mid-1990s as fishing mortality increased. Sporadic large recruitment events temporarily increased landings but also encouraged higher overall fishing effort and thereby contributed to the long-term declines in resource abundance. In 1994, a number of new management measures were introduced, including a moratorium on new permits, limitations on days at sea, gear and crew restrictions, and year-round closed areas. During 1994–2005, the biomass of sea scallops in the U.S. sector of Georges Bank increased by a factor of about 18, while the biomass of sea scallops in the Middle Atlantic Bight increased by about eight times. These increases were primarily due to the area closures. Biomass in the Georges Bank closed areas was 25 times higher in 2005 than in 1994, and the 2005 level constituted over 80% of the biomass in the U.S. portion of Georges Bank. Substantial increases in sea scallop abundance and biomass also occurred in two of the three areas in the Middle Atlantic Bight that were closed rotationally to sea scallop fishing for 3 years. Mean recruitment on Georges Bank did not significantly increase since the closures there, but very strong recruitment has been observed downstream of one of the mid-Atlantic rotational closures. In the open areas, responses to effort reduction measures were minimal until 1999, but biomass, commercial catch rates, and landings substantially increased during 1999–2005 due to effort controls and increased recruitment in the Middle Atlantic Bight. The recovery of U.S. sea scallop populations demonstrates that the combination of effort controls and area management can rapidly rebuild severely depleted fisheries.

Overfishing is a common problem among the world's fisheries that has caused the depletion of numerous stocks (e.g., Pauly et al. 2002; Rosenberg 2003). Managers of these fisheries face the difficult choice between imposing substantial effort reductions that may cause serious short-term socio-economic disruptions and allowing continued overfishing, thereby sacrificing the long-term social, economic, and ecological benefits that could accrue from rebuilding the stocks. In the mid-1990s, the sea scallop *Placopten magellanicus* resource off the northeastern USA was a typical case of an open-access fishery that had seen a spiral of increasing effort and concomitant decreases in biomass, catch rate, and mean size. A decade later, sea scallop biomass in U.S. waters has increased by an order of magnitude and annual landings have quadrupled. In this article, we will discuss the long-term history of the U.S. sea scallop fishery and the unique way in which the resource was rebuilt.

Atlantic sea scallops occur in the northwestern Atlantic Ocean and range from Cape Hatteras to Newfoundland (Posgay 1957a; Naidu 1991; Black et

al. 1993). Major commercial concentrations of sea scallops in U.S. waters occur on Georges Bank and in the Middle Atlantic Bight on sand and gravel bottoms between 35 and 100 m deep. A small sea scallop fishery also exists in the Gulf of Maine, where sea scallops are generally distributed in shallow, nearshore waters (Smith 1891). Sea scallops in the U.S. exclusive economic zone (EEZ) are fished primarily by means of New Bedford-style offshore scallop dredges; however, a small percentage of mid-Atlantic vessels use otter trawls, and Digby-style dredges and divers are employed off the coast of Maine (Posgay 1957b; Peters 1978; Caddy 1989; Naidu 1991). In most cases, the sea scallops are shucked at sea; only the adductor muscle (meat) is landed, and the remainder is discarded.

Sea scallops can become sexually mature at age 2, but significant production of gametes may not occur before age 4 (MacDonald and Thompson 1986). Sea scallops attain commercial size at about 3.5 years (about 8-cm shell height [SH]) and typically will approach SHs of 15–16 cm and meat weights [MWs] of 50–70 g (Serchuk et al. 1979). Natural mortality (M) for adult sea scallops is low ($M \cong 0.1$; Merrill and Posgay 1964).

In this article, we review and synthesize the population dynamics of sea scallops in U.S. waters

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during the past 60 years. We reconstruct and interpret historical data in light of the recent recovery of sea scallop populations and, in particular, their observed accumulation in areas closed to fishing. Because data were not always collected in a consistent manner, some approximate adjustments were required to compare data from different time periods. Nonetheless, we show that there are long-term relationships among the trends in sea scallop landings, catch rate, stock biomass, size composition, and fishing mortality that can be used to help understand sea scallop population dynamics and to guide the management of this valuable resource.

Methods

The U.S. sea scallop landings and effort data from 1961 to 2004 were obtained from dealer weigh-outs, port interviews (1961–1993), and self-reported vessel logbooks (1994–2004). Resourcewide landings from 1900 to 1960 were obtained from Serchuk et al. (1979). Landings and fishing effort data for Georges Bank from 1944 to 1960 were obtained from Caddy (1975). Canadian Georges Bank landings and effort data originated from Caddy (1975) (1944–1971) and Mohn et al. (1988) (1972–1984). The sea scallop fishery in the Canadian portion of Georges Bank has been managed in recent years by use of a form of individual transferable quotas leading to fleet consolidation, and the remaining vessels typically carry a larger crew than is allowed in the U.S. fishery (Brander and Burke 1995; Peacock et al. 2000). Because the rate at which sea scallops can be landed depends in part on the number of crew, the unit of fishing effort we employ (days fished) is not comparable for the U.S. and Canadian sea scallop fisheries in recent years. For this reason and because we focus on the U.S. fishery only, we did not track Canadian fishing effort after Georges Bank was divided into U.S. and Canadian EEZs in 1984.

To minimize vessel effects when calculating annual commercial landings per unit effort (LPUE), these calculations were based only on class-4 vessels (>150 gross tons) and were computed as the reported landings divided by the days fished (i.e., the time the gear is in the water) by these vessels. Days fished is difficult to infer from the self-reported logbook information available since 1994. For this reason, we estimated days fished for 1994–2004 by multiplying days absent (from the logbooks) by the ratio of days fished to days absent on observed trips. Since few class-4 vessels fished for sea scallops prior to 1966, the pre-1966 LPUE was estimated by calculating the LPUE of all vessels and then adjusting this figure upward by 6.5% (Georges Bank) and 11% (Middle Atlantic Bight), representing the increased catch rate of class-4 vessels compared to smaller vessels during 1966–1975. Even

with adjustments for vessel size, fishing power has increased somewhat over time due to increased engine power, larger gear, and improved navigation equipment. Thus, a long-term decline in LPUE is likely to indicate an even greater decline in fishable biomass.

Sea scallop surveys of the Middle Atlantic Bight and Georges Bank (we include sea scallops in Nantucket Shoals and the Great South Channel as part of the Georges Bank population) have been conducted by the National Marine Fisheries Service (NMFS) annually since 1977 using a stratified random design (Serchuk et al. 1979; Serchuk and Wigley 1986; see Figure 1). In cases where a survey sampling stratum was not surveyed in a given year, the biomass for that stratum and year was taken as the average of the stratum's biomasses in the two adjacent years. Strata that straddle closed-area boundaries were poststratified into open and closed portions. Surveys since 1979 have used a 2.44-m-wide dredge with 5.1-cm-diameter rings and a 4.4-cm-mesh liner; catches were adjusted to account for the selectivity of the liner (NEFSC 2004). Tows were conducted for 15 min at a speed of 7.04 km/h.

The SHs were converted to MWs by equations of the form

$$MW = A \exp[B \log_e(\text{SH}) + C \log_e(\text{depth})].$$

The coefficients A , B , and C were estimated by use of log–log regressions based on SH/MW data at depth collected during the 2001–2004 NMFS sea scallop surveys in July and August ($n = 1,852$ scallops at 273 stations in the Middle Atlantic Bight [$R^2 = 0.90$]; $n = 2,362$ scallops at 318 stations on Georges Bank [$R^2 = 0.88$]). The estimated coefficients (corrected for bias due to the log–log regression; MW in g, SH in mm, and depth in m) are as follows: A is equal to 2.42×10^{-5} for the Middle Atlantic Bight and 1.38×10^{-4} for Georges Bank, B is 3.20 for the Middle Atlantic Bight and 3.01 for Georges Bank, and C is -0.304 for the Middle Atlantic Bight and -0.506 for Georges Bank.

Recruits (to the survey) were defined as those sea scallops with SHs ranging from 40 mm (the smallest size reliably detected in the survey) to those corresponding to 1 year's growth from 40 mm (69 mm in the Middle Atlantic Bight and 72 mm in Georges Bank), as estimated from the von Bertalanffy growth equations of Serchuk et al. (1979). Like the SH/MW relationships, growth in sea scallops is a function of depth (Schick et al. 1988; Smith et al. 2001). However, no quantitative estimates of the effect of growth on depth are available for Georges Bank or mid-Atlantic sea scallops. Because we estimated growth of sea scallop populations aggregated over all depths, employing depth-averaged growth parameters will affect the results only slightly. Recruits roughly correspond to

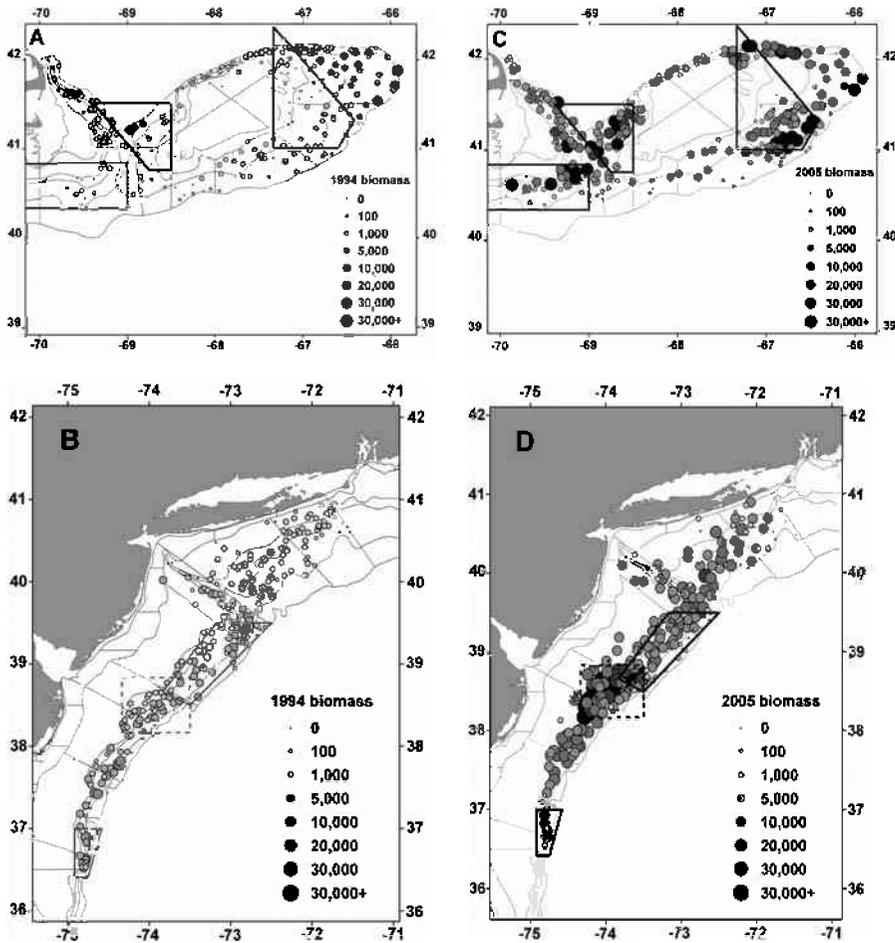


FIGURE 1.—National Marine Fisheries Service sea scallop survey areas, showing strata boundaries (thin lines) and sea scallop biomasses (g/tow) at each station in (A) Georges Bank during 1994, (B) the Middle Atlantic Bight during 1994, (C) Georges Bank during 2005, and (D) the Middle Atlantic Bight during 2005. The Georges Bank closed area and the original two mid-Atlantic rotational closed-area boundaries are indicated by heavy solid lines; the 2004 mid-Atlantic closure boundaries are shown by dashed lines. The three Georges Bank closed areas are (west to east) the Nantucket Lightship Closed Area, Closed Area I, and Closed Area II. The three mid-Atlantic closures are (north to south) the Hudson Canyon South, Elephant Trunk, and Virginia Beach closed areas.

age-2 sea scallops, when they are about 1 year away from being susceptible to commercial gear.

Fishable biomasses were calculated by applying a simple gear selectivity ogive to survey catches (Hart 2003: equation 8). A relative index of fishing mortality, f_r , was calculated by dividing reported annual landings for each region by fishable survey biomass for that region. This “catch/biomass” index should be representative of trends in fishing mortality. To obtain estimates of absolute mortality, we allocated sea scallops over 80 mm (measured in the NMFS survey) into two bins. The first bin represented new recruits in the fishery and was comprised of those sea scallops from 80 mm to 1 year’s growth beyond 80 mm (100

mm in Georges Bank and 98.5 mm in the Middle Atlantic Bight, from the growth curves of Serchuk et al. 1979). All larger scallops were placed in the second bin. The survey-based fishing mortality $F_{s,t}$ between years t and $t + 1$ was estimated as

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

where R_t is the number of sea scallops in the first bin, P_t is the number in the second bin at time t , and M is natural mortality estimated as 0.1 (from Merrill and Posgay 1964). Although highly variable, these estimates of fishing mortality should be unbiased if natural mortality and growth rates are estimated accurately.

The mean of these values over the survey time series, \bar{F}_s , should be a reasonably accurate estimate of the mean fishing mortality during 1982–2004. This estimate was used in the following equation to scale the relative catch/biomass index to produce estimates of fishing mortality that reflected both the trend and scale accurately:

$$F_t = \frac{\bar{F}_s}{\bar{f}} f_t$$

where \bar{f} is the mean of the relative catch/biomass index f_t over the time series.

Surplus production was estimated with the external surplus production methodology of Hilborn (2001) and Jacobson et al. (2002). Following Hilborn (2001), survey biomass estimates (per tow), b_t , were first smoothed by use of the moving average smoother, $\bar{b}_t = \frac{1}{4}b_{t-1} + \frac{1}{2}b_t + \frac{1}{4}b_{t+1}$. Absolute biomass B_t estimates in year t were obtained by expanding the smoothed NMFS survey biomass estimates with the formula

$$B_t = \frac{A}{qa} \bar{b}_t,$$

where q is dredge efficiency (estimated as 0.4 in Georges Bank [Gedamke et al. 2004] and 0.6 in the Middle Atlantic Bight), A is the surveyed area (24,973 km² for Georges Bank, 28,671 km² for the Middle Atlantic Bight), and a is the area swept by the dredge (0.00452 km²). Surplus production S_t can then be calculated as

$$S_t = B_{t+1} - B_t + C_t,$$

where C_t is the fishery removals in year t . In addition to reported landings, C_t needs to include unreported landings and nonyield fishing mortality (discard and/or incidental mortality). We estimated that C_t was 120% of reported landings in Georges Bank and 105% of reported landings in the Middle Atlantic Bight to account for these factors (see Hart 2003).

Results

Long-Term Trends in the U.S. Sea Scallop Fishery

In the late 19th and early 20th century, the sea scallop fishery primarily exploited nearshore beds in the Gulf of Maine, although some trawl fishing for sea scallops may have occurred in the Middle Atlantic Bight (Smith 1891; Merrill 1960). With more powerful vessels and the development of offshore scallop dredges, landings increased as a fishery began developing off Long Island and on Georges Bank in the late 1920s and 1930s (Figure 2; Peters 1978; Serchuk et al. 1979). Landings markedly increased after World War II and then increased more slowly throughout the

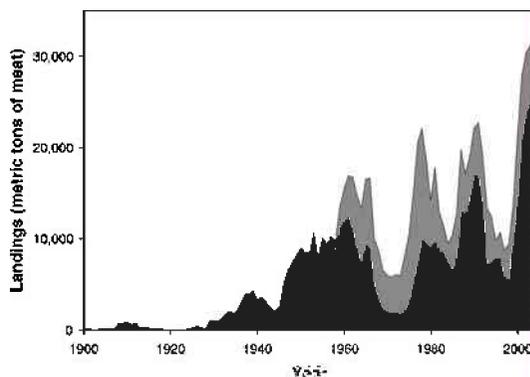


FIGURE 2.—Sea scallop landings from sea scallop grounds in U.S. waters and the Canadian portion of Georges Bank (Northwest Atlantic Fisheries Organization statistical areas 5 and 6). U.S. landings are indicated by the dark portion of the figure, Canadian landings by the light portion.

1950s. Since then, peaks in landings have occurred in the early 1960s, late 1970s, early 1990s, and in the period starting in 2000. Each of these peaks was associated with one or more strong year-classes.

Most of the fishing effort and landings during the early postwar period were concentrated on Georges Bank (Figure 3A). After a rapid increase in fishing effort in the late 1940s, effort increased slowly during the 1950s. A large year-class recruited into the Georges Bank fishery in 1959 (Posgay 1968); as a result, the LPUE increased to a high of about 1.25 metric tons/d in the early 1960s. Likely attracted by the high catch rates, Canadian effort increased during this period. By 1965, the Canadian scallop fleet accounted for the bulk of the effort and landings on Georges Bank, as most U.S. scallopers focused on mid-Atlantic grounds. Another large year-class during the late 1970s again increased LPUE, coinciding with increased U.S. effort on Georges Bank. Biomass (Figure 4A) and LPUE on Georges Bank generally declined from 1977 through the early 1990s, while fishing mortality and effort increased during this period. After the establishment of the U.S.–Canada maritime boundary that partitioned Georges Bank in October 1984 and after several years of good recruitment during the late 1980s, U.S. sea scallop effort on Georges Bank peaked at over 22,000 d fished in 1991, when fishing mortality was about 1.7 per year.

When recruitment declined in 1993–1994, the high fishing mortality quickly reduced biomass and LPUE to their lowest points in the time series (Figures 3A, 4A). This induced many vessels to either leave the fishery or to shift their activity to the mid-Atlantic area, where a strong year-class afforded better fishing opportunities. As a result, effort and fishing mortality

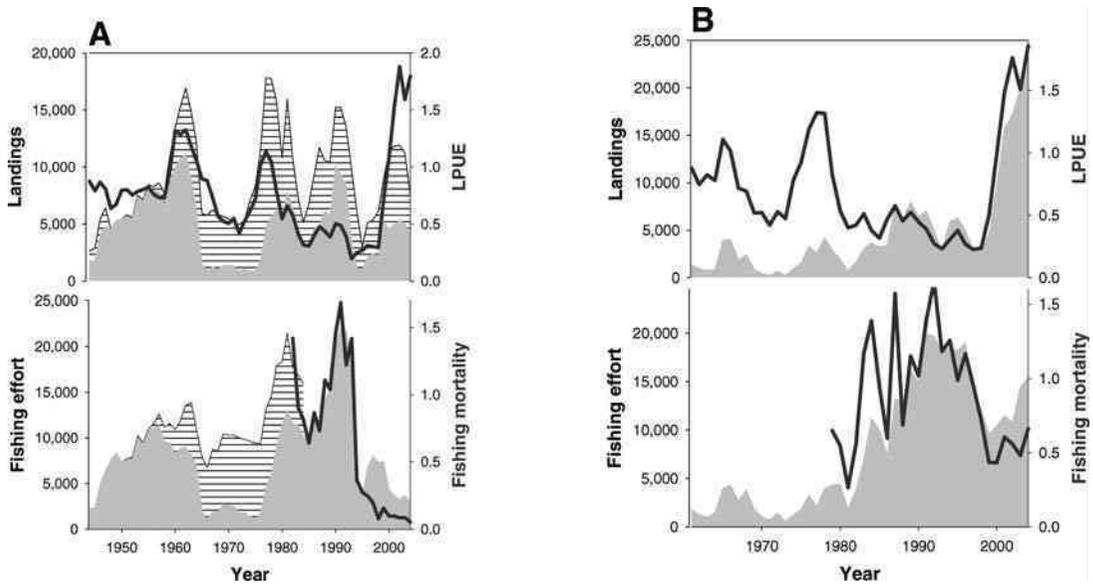


FIGURE 3.—The upper panels show U.S. (solid portions) and Canadian (hatched portions) sea scallop landings (metric tons of meat) and U.S. landings per unit effort (LPUE [metric tons of meat per day fished]; solid lines) in (A) Georges Bank and (B) the Middle Atlantic Bight. The lower panels show U.S. effort (days fished; solid portions), Canadian effort (hatched portions; Georges Bank only), and U.S. fishing mortality (solid lines) for sea scallop fisheries in those same two areas. Note that Canadian effort is only shown for years prior to 1985, when Georges Bank was separated into U.S. and Canadian exclusive economic zones.

on Georges Bank rapidly decreased during 1993–1995. Closure of three large areas in December 1994 (Figure 1) further reduced fishing mortality. Biomass on Georges Bank rapidly increased after that time, and by 2005 it was about 18 times the 1994 value and had exceeded the maximum exhibited during the 1982–1994 preclosure period by a factor of four.

Because sea scallop productivity in the mid-Atlantic area was generally lower than on Georges Bank, fishing effort and landings in this area were relatively low prior to the 1980s (Figure 3B). Landings during the 1950s and early 1960s were fairly stable and averaged about 1,700 metric tons/year (Serchuk et al. 1979). Landings, effort, and commercial catch rates peaked in 1965–1966 due to a strong year-class that attracted many vessels away from Georges Bank (Posgay 1968). Good recruitment also induced increased catch rates and fishing activity in the late 1970s. Fishing effort and mortality increased rapidly after 1981; effort reached a peak of nearly 20,000 d fished in 1991, corresponding to fishing mortality rates well above 1.0 per year. As in Georges Bank, high fishing mortality subsequently induced declines in biomass and LPUE in the Middle Atlantic Bight. Reductions in effort and the rotational closure of two areas from 1998 to 2001 induced a rapid decline in fishing mortality in the Middle Atlantic Bight during

1996–1999. As a result of these measures and strong recruitment, biomass increased by over an order of magnitude during 1997–2005, and marked increases in landings and LPUE were observed during this period.

Effects of Effort Limitations and Area Closures on Sea Scallop Stocks

Between 1982 and 1993, the primary management regulation for U.S. sea scallops was that the mean MW in a trip be above a given minimum value of 11–15 g (usually expressed as an average “meat count” of 30–40 meats/lb [1 lb = 0.454 kg]), depending on the period (Serchuk and Murawski 1997). This regulation only required the mean MW to be about half the weight that would occur at the maximum yield per recruit (Serchuk et al. 1979; Sinclair et al. 1985; Hart 2001) and allowed many sea scallops to be caught before they could contribute significantly to egg production. Thus, these measures were not effective in controlling growth overfishing and possibly also recruitment overfishing (Sinclair et al. 1985; Serchuk and Murawski 1997), and enforcement of this regulation was difficult.

New regulations were enacted in 1994 to limit effort and improve fishery selectivity. Fishing vessels that could demonstrate a history of landing sea scallops were given limited-access permits entitling them to fish for a given number of days at sea each year. The

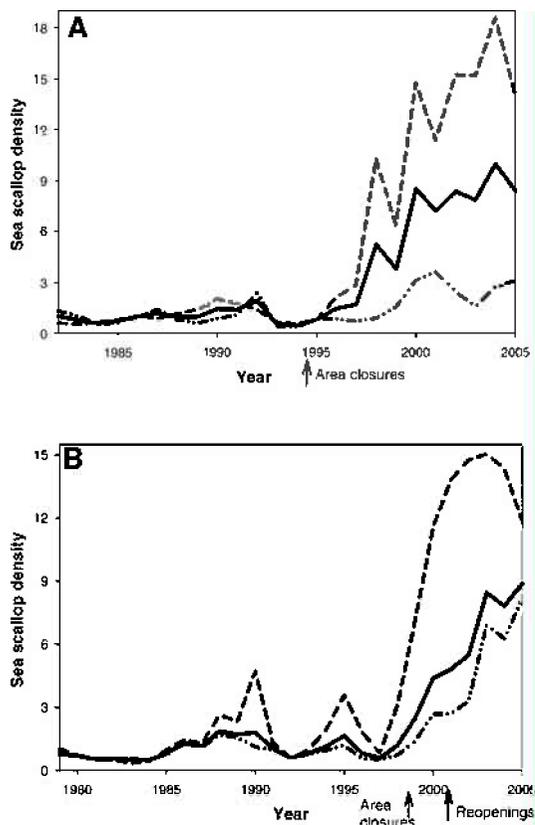


FIGURE 4.—Mean stratified sea scallop density (kg meat/tow) overall (solid lines) and stratified into open (dashed-dotted lines) and closed (dashed lines) areas for (A) the U.S. portion of Georges Bank and (B) the Middle Atlantic Bight. Years when area fishery closures and reopenings began are indicated by arrows.

number of days that a vessel with a full-time sea scallop permit could fish was gradually reduced from 204 d in 1994 to 120 d in 1999–2003. To improve fishery selectivity, the minimum dredge ring size was gradually increased from 76 mm (3 in) in 1994 to 83 mm (3.25 in) in 1995, 89 mm (3.5 in) in 1996, and 102 mm (4 in) in 2004; chafing gear, which reduces the effective selectivity of the rings, was prohibited (Brust et al. 1996). Finally, crew size was limited to seven in order to restrain the number of sea scallops that could be shucked per day; many vessels previously had crews with as many as 13 individuals.

In December 1994, three large portions of Georges Bank were closed to all gear capable of catching groundfish, including scallop dredges (Murawski et al. 2000, 2004; Figure 1). About 52% of the total sea scallop landings from the U.S. portions of Georges Bank during 1982–1993 were obtained from the closed areas. Prior to the closures, biomass levels in the open

and closed areas were similar; therefore, the closures can be regarded as an experimental manipulation wherein the open areas served as a “control” population (Figure 4A). The sea scallop population responded rapidly to the closures: biomass in the closed areas nearly quadrupled in the 2 years between 1994 and 1996 and increased by over nine times in the 4 years between 1994 and 1998. Closed-area biomass doubled again between 1998 and 2000 and has remained roughly constant since then. The increases occurred despite the temporary reopening of portions of the closed areas between June 1999 and January 2001, when approximately 5,000 metric tons of meats were landed from these areas.

Two areas in the Middle Atlantic Bight off the coasts of Virginia (Virginia Beach Closed Area) and New Jersey (Hudson Canyon South Closed Area) were closed to sea scallop fishing for 3 years beginning in April 1998 to help rebuild biomass and to allow the sea scallops there to grow to a larger size before harvest (Figure 1B). The mid-Atlantic closures cannot be regarded as a fully controlled experiment, because these closed areas were chosen specifically as productive sea scallop grounds. In particular, biomass increased in the Hudson Canyon South area in 1990 and 1995 due to strong recruitment, but heavy fishing effort attracted by the high catch rates quickly reduced the biomass to that of the surrounding region (Figure 4B). Another strong year-class in this area that caused biomass to increase again in 1998 was protected by the rotational closures. Growth of this year-class, together with subsequent further strong recruitment, contributed to the rapid increase in biomass in the mid-Atlantic closed areas. A third rotational closure located off of Delaware Bay was implemented in 2004 (Figure 1B).

Open areas in both Georges Bank and the Middle Atlantic Bight showed little response to the effort reduction measures implemented between 1994 and 1998 (Figures 3, 4). For example, the mean open-area biomass in Georges Bank during this time was at about the same level as in the previous 12-year period (1982–1994). Increases in open-area biomass and commercial catch rates only became evident after 1998, and biomass, LPUE, and landings from these areas have been at or near record levels since 2001. Information from observed trips indicates that the percentage of time that the gear was in the water declined considerably during this period (Figure 5A). Catch rates during this period exceeded the shucking capacity of a seven-man crew, so the scallopers needed to spend time shucking their catch before returning their gear to the water. Because a crew can shuck greater weights of meats per hour from larger sea scallops, there was an incentive to target larger individuals. As a result, and

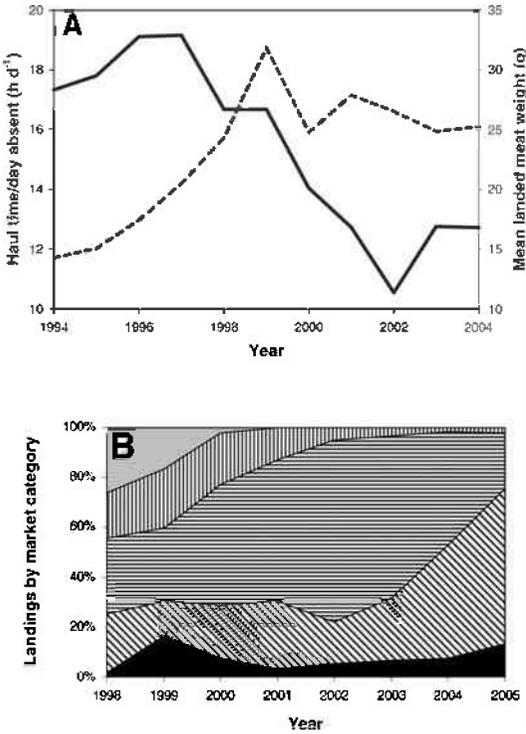


FIGURE 5.—Panel (A) shows the mean total haul time per day absent (solid line) and mean landed sea scallop meat weight (dashed line) on observed open-area sea scallop trips from 1994 to 2004. Panel (B) shows the percentage of sea scallop landings by meat count category from 1998 to 2004. Categories are as follows: under 10 count (>45 g; dark), 10–20 count (23–45 g; diagonal lines), 20–30 count (15–23 g; horizontal lines), 30–40 count (11–15 g; vertical lines), and over 40 count (<11 g; gray).

due to the greater availability of larger sea scallops because of decreased fishing mortality, the weights of landed sea scallops increased substantially after 1998 (Figure 5). Mean landed MWs during the most recent period were about equal to those that occur when yield per recruit is optimized (25–30 g).

Estimated surplus production was generally lower during 1982–1994 than in the more recent years, another indication of overfishing during the earlier period (Figure 6). Mid-Atlantic surplus production has continued to increase with biomass, whereas this quantity in Georges Bank peaked between 1998 and 2000 and has declined in recent years.

In 1994, small peaks indicating age-2 and age-3 year-classes were evident at SHs of about 5 and 8 cm in both the open and closed portions of Georges Bank; due to high exploitation rates, few older sea scallops were present (Figure 7A). Considerable increases in the number and size of sea scallops in the Georges Bank

closed areas were evident in 1998 and 2005, and two strong year-classes were evident in 1998. Little expansion in the size structure was evident in the open portions of Georges Bank in 1998, although a strong age-2 year-class was evident. This and subsequent year-classes were subjected to reduced fishing mortality, so that substantial numbers of them survived to 10–14-cm SHs, as seen in the 2005 size frequencies.

High fishing mortality in the Middle Atlantic Bight through 1998 removed most sea scallops at SHs less than 10 cm (Figure 7B). The large age-2 year-class observed in that year, together with subsequent strong recruitment, was protected in the two original mid-Atlantic closed areas through 2001, which allowed many of these sea scallops to grow to 10–12 cm by that time. After the reopening in 2001, these areas were fished down but still had considerably higher quantities of sea scallops larger than 10 cm than had existed prior to the closures. The length structure in the open portions of the Middle Atlantic Bight also expanded after 1998, and a very large 2001 year-class evident in the 2005 size frequency has been partially protected in the new rotational closure.

The area closures clearly contributed to the rebuilding of sea scallop biomass by allowing the accumulation and growth of sea scallops in these areas. Have these closures also enhanced recruitment? The log-transformed mean of survey recruitment indices (mean \log_e per tow) on Georges Bank since the closure (1996–2003 year-classes) was 4.22, whereas it was 3.96 in the year-classes (1980–1994) observed prior to the closure (Figure 8; the transitional 1995 year-class was excluded from both groups). These differences were not statistically significant (log-transformed two-sample *t*-test: $t = 0.51$, $P = 0.68$). Therefore, while it is possible that the increased egg production due to the closures was a factor in the increased recruitment, the evidence is not conclusive at this time.

Another possible way that the closures could affect recruitment is if trawling and dredging affected the settlement success or survival of juvenile sea scallops. To test for such effects, we compared the sea scallop recruitment (log-transformed) in the groundfish closed areas (excluding the southern portion of Closed Area II, which was heavily fished in 1999) to that of the open portions of Georges Bank, both before and after the closures, by use of a two-way analysis of variance (ANOVA). The two factors in the ANOVA were area (areas open and areas closed to fishing after 1994) and period (1982–1994 prior to the closures, and 1996–2005 after the closures; the 1995 survey year was excluded from both groups). The area effect was not significant ($F = 0.4$, $P = 0.55$), indicating that the long-

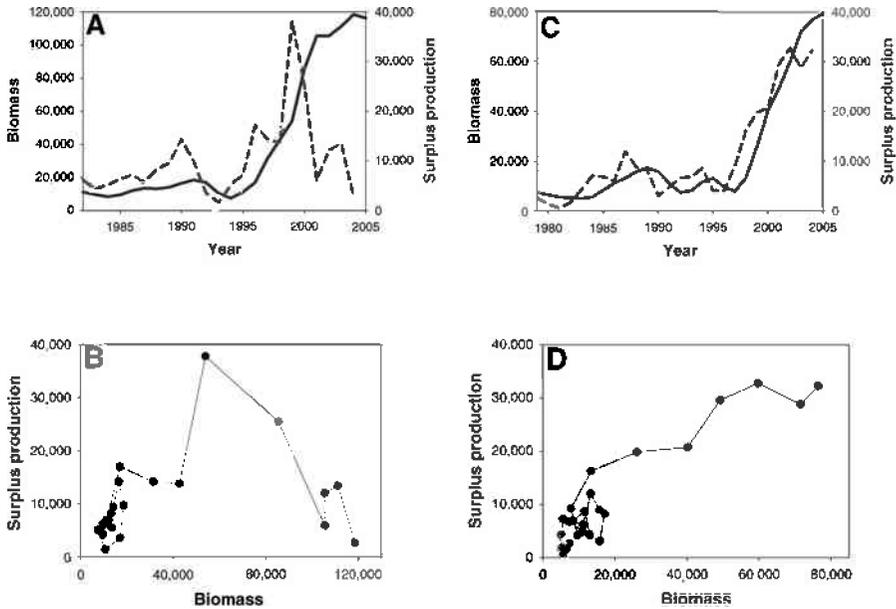


FIGURE 6.—Panels (A) and (C) show the estimated smoothed sea scallop biomass (metric tons of meat; solid lines) and surplus production (metric tons of meat; dashed lines) by year for the U.S. portion of Georges Bank and the Middle Atlantic Bight, respectively. Panels (B) and (D) show estimated surplus production versus biomass (tons of meat) for the same two areas; successive years are connected by lines.

term mean sea scallop recruitment in the closed and open areas was similar. As discussed above, while recruitment was higher after the closure, this increase was not statistically significant ($F = 1.2$, $P = 0.27$). Because recruitment increased similarly in both open and closed areas after the closure, there was no evidence of any interaction between the two factors ($F = 0.2$, $P = 0.63$).

Sea scallop recruitment in the Middle Atlantic Bight was generally poor prior to the 1983 year-class but has been trending upward since then; linear regression on the log-transformed recruitment was significant ($R^2 = 0.49$, $P < 0.001$; Figure 8B). Very strong recruitment was observed in the 2002–2005 NMFS sea scallop surveys (from sea scallops spawned in 2000–2002) in the southern portion of the Hudson Canyon South Closed Area and just to the south (Figures 1B, 6B, 7B). This area was closed rotationally in 2004 to allow growth of the high concentrations of small sea scallops located there; biomass in the new rotational closure was about 53 kg/tow in 2005, considerably higher than the biomass typical even in the groundfish closed areas. Because currents in this region are generally oriented towards the south and slightly inshore (Mountain 2003), the observed recruitment pattern suggests the possibility that the buildup in spawning stock biomass in the Hudson Canyon South Closed Area has enhanced recruitment in areas to the south.

Discussion

The development of the sea scallop fishery fits a pattern seen in many fisheries (e.g., Hilborn and Walters 1992; Pauly et al. 2002). In the first stage, which lasted from the late 19th century to the 1960s, there was gradually increasing exploitation of an underutilized resource. The comparatively long duration of this period was due to the gradual improvements in vessel power, navigational aids, and fishing gear, allowing for utilization of sea scallop beds located further offshore and in rougher bottoms.

The period from the 1970s through the mid-1990s represented the second phase in the fishery, characterized by increasingly severe overfishing. To maintain their economic viability in the face of decreasing catch rates, scallopers increased their fishing power and effort levels, thereby further exacerbating overexploitation of the resource. While strong year-classes temporarily increased catch rates and landings, they also encouraged new entrants into the fishery and upgrades in fishing power for existing vessels. The effects of the increasing effort can be seen not only during periods of relatively poor recruitment but also when recruitment was strong. The period of high catch rates during the 1960s lasted longer than the comparable period during the late 1970s. By the third period of strong recruitment (1990–1992), effort levels were so high that biomass and LPUE increased only

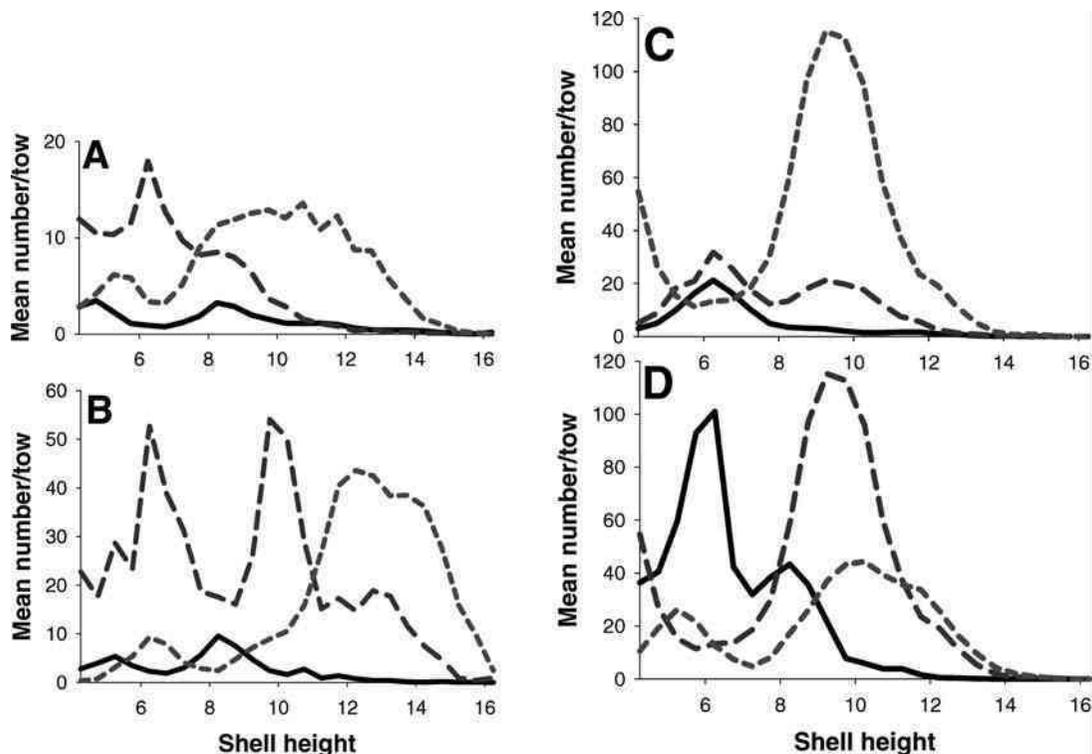


FIGURE 7.—Stratified mean numbers of sea scallops per tow at each shell height (cm), based on the National Marine Fisheries Service sea scallop survey in the open and closed portions of Georges Bank and the Middle Atlantic Bight. Panels (A) and (B) pertain to the open and closed areas, respectively, of Georges Bank in 1994 (solid lines), 1998 (long-dashed lines), and 2005 (short-dashed lines); panels (C) and (D) pertain to the open and closed areas of the Middle Atlantic Bight in 1998 (solid lines), 2001 (long-dashed lines), and 2005 (short-dashed lines).

modestly because sea scallops were being landed soon after they recruited into the fishery.

The four distinct sets of measures that were enacted around 1994 each had a role in the recovery of the sea scallop resource and fishery. Gear restrictions improved selectivity and modestly reduced growth overfishing (Brust et al. 1996). The limited access and effort reduction measures reduced effort and fishing mortality by about 50% and were the most important factors in reducing overfishing in the open portions of the resource. Perhaps the most subtle, although still important, effects were due to the seven-man crew restriction. During the latest period of good recruitment starting in 1999, catch rates exceeded the shucking power of a seven-man crew, thereby reducing the actual fishing time per day at sea, as the crew needed to spend time shucking the catch on deck before they returned the gear into the water. By creating an incentive for scallopers to target larger scallops (since a greater weight of large scallops can be shucked per unit time), the crew size limitation has acted directly to reduce growth overfishing. Moreover,

the crew limitation, together with days-at-sea controls, has prevented fishing mortality in the open areas from increasing substantially as the resource has become more abundant. In contrast, during previous periods of strong recruitment when the fishery had open access, high catch rates encouraged existing vessels to fish more days with larger crew sizes and encouraged new entrants into the fishery, thereby increasing fishing mortality and contributing to the long-term decline in sea scallop biomass and catch rates.

The gear, days-at-sea, and crew regulations and the reopening of closed areas have acted together to alleviate growth overfishing. During the time when the fishery was managed by meat count (1982–1993), scallopers had difficulty maintaining the mean MWs of their landings above the 11–15-g limit. During the most recent period (2000–2005), even without any specific meat count regulation, the mean fisherywide landed MW exceeded 20 g; preliminary information indicates that the mean landed MW in 2005 was about 30 g. A considerable portion of the recent increases in landings

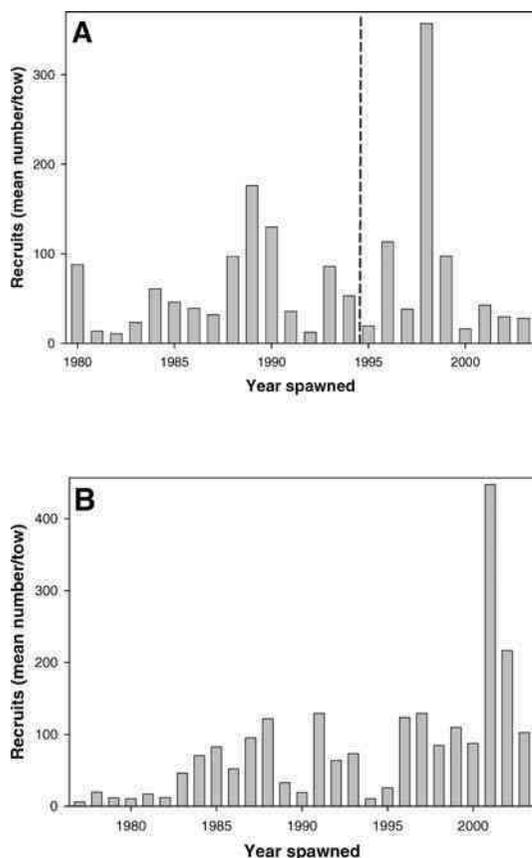


FIGURE 8.—Sea scallop recruitment (mean number of recruits per tow) for (A) the U.S. portion of Georges Bank and (B) the Middle Atlantic Bight, by year spawned. The dashed line in panel (A) divides the year-classes spawned before the area closures from those spawned afterwards.

can be ascribed to the substantial increase in landed MW per scallop, implying improved yield per recruit.

Area closures induced the most striking effects on sea scallop abundance and biomass. Sea scallops have a somewhat unusual amalgamation of life history characteristics: low natural mortality, fast growth rates, and limited mobility. Because only a small percentage of the sea scallops in the closed areas died or emigrated, sea scallops quickly accumulated in these areas. Moreover, because of the sea scallops' rapid growth rate in the first 5 years of life, sea scallop biomass in the closed areas grew even faster than sea scallop numbers. The overall increase in biomass was considerably greater than the biomass that would have occurred if managers had relied only on effort reduction and gear restrictions. In fact, at the same level of effort, rotational closures generally increase biomass over uniform fishing, especially under conditions of overfishing (Hart 2003).

For sedentary species, permanently closed areas can enhance fishery yields only if recruitment outside the closures increases sufficiently to a level that more than compensates for the loss of yields from the closures (Hilborn et al. 2004). In the case of Georges Bank, the postclosure increase in recruitment was nonsignificant, and even if real it was insufficient to fully compensate for the loss of yield from the closed areas, which historically accounted for about half of the sea scallop landings from the U.S. portion of Georges Bank. Thus, while the closed areas may have benefits for other species and for research purposes, it appears that these closures would decrease long-term sea scallop yield if the areas were to remain permanently closed. Indeed, recent U.S. landings on Georges Bank have been near their long-term mean, despite the improvement in selectivity and reduction in fishing mortality. The management plan enacted in 2004 (Amendment 10; NEFMC 2004) implemented rotational scalloping in portions of the closed areas.

In contrast to permanent closures, the mid-Atlantic rotational closures may enhance yields, both by increasing yield per recruit and possibly also recruitment (Hart 2003). Recruitment of sea scallops in the mid-Atlantic area is more likely to be limited by larval supply, because the southwesterly currents allow little opportunity for self-retention of larvae. By contrast, larvae on Georges Bank may be entrained in a gyre, allowing for retention of larvae around the bank and thus allowing for greater larval supply even at lower biomasses.

The possibility has been raised that dredges can induce high levels of incidental fishing mortality, where sea scallops are killed but not captured by the gear (Caddy 1973, 1989; Myers et al. 2000); however, Murawski and Serchuk (1989) observed little evidence for this in the Middle Atlantic Bight. If high incidental fishing mortality existed, then fishing mortality on small pre-recruit sea scallops in fished areas would be substantial and recruitment would therefore differentially increase in areas closed to fishing. Our two-way ANOVA comparing recruitment in closed and open areas gave no evidence for such an effect, suggesting that the level of incidental mortality in sea scallops is relatively small. The ANOVA also indicated that the accumulation of sea scallops in the closed areas has had little or no effect on recruitment success of juveniles settling in these areas.

Surplus production during 1982–1994 was considerably lower than that seen in more recent years. This is consistent with our estimates of fishing mortality and with yield-per-recruit calculations (Hart 2001); at the typical fishing mortalities during 1982–1994, the realized yield per recruit (and hence surplus pro-

duction) was as much as 50% below optimal levels. While the use of external surplus production estimates to estimate maximal sustainable yield (MSY) is subject to some error due to recruitment variability (among other things), annual surplus production during 2000–2004 for the combined resource was over 30,000 metric tons, which suggests that MSY is more than 30,000 metric tons, at least in the most recent environmental regime. This is more than double the mean long-term annual landings, again indicating that overfishing was occurring prior to the most recent period. Surplus production in Georges Bank has declined in recent years due to poor recruitment and because a substantial proportion of the sea scallops in the groundfish closed areas are approaching their maximum size. In contrast, surplus production in the Middle Atlantic Bight has increased substantially during 2000–2004 due to strong recruitment and reduced fishing mortality.

While U.S. sea scallop populations have been rebuilt, there is still considerable overcapacity in the scallop fleet (Kirkley et al. 2002). Regulations in effect between 1999 and 2003 restricted full-time scallop vessels to 120 d at sea with a seven-man crew. Most of these vessels are capable of fishing at least 240 d/year with crews of 11 or more and thus are capable of producing about three times their current fishing power. There has been a gradual reactivation of latent effort as the resource has become restored (Figure 3), and scallopers have found ways to increase the shucking power of a seven-man crew. For these reasons, further days-at-sea reductions may be needed to prevent overfishing. Fleet consolidation, as has occurred in Canada (Brander and Burke 1995; Peacock et al. 2000), could improve the economic efficiency of the U.S. scallop fishery but is opposed by many scallopers, who fear that they will not be part of the reduced fleet.

Recently, it has been suggested that chronically overfished species may not be able to recover to their former levels (Hutchings 2000). The example of the sea scallop fishery shows that at least some species can recover rapidly from a period of severe overfishing when appropriate management measures are taken. The reduction in fishing mortality induced by area closures and effort reduction has increased both biomass and landings to levels not considered imaginable just a decade ago.

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