Analyses on the Status of the Atlantic Menhaden Stock

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1. Introduction

The purpose of this report is to provide updated analyses on the current status of the Atlantic menhaden stock. Prior to the recently adopted Amendment 1 to the Atlantic Menhaden Fishery Management Plan of the Atlantic States Marine Fisheries Commission (ASMFC), NOAA Fisheries's Center for Coastal Fisheries and Habitat Research (Beaufort Laboratory) provided the annual trigger report (Vaughan 1994-2000) and a supplemental report (Vaughan and Smith 1998, 1999, 2000) to the Atlantic Menhaden Advisory Committee (AMAC; ASMFC). With adoption of Amendment 1, the six triggers as defined in AMAC (1992) no longer serve as the focus for these analyses. Hence, this report serves as our primary documentation on the current status of Atlantic menhaden, and focus on the new benchmarks with their respective targets and thresholds identified in Amendment 1.

1.1. Management. Estimates of both benchmarks (fishing mortality rate and spawning stock biomass) are obtained from virtual population analysis (VPA). The VPA is used to reconstruct the fish population and fishing mortality rates by age and year, assuming an estimate of natural mortality rate (M). Primary estimation of the benchmarks is based on the Murphy (1965) approach as used in earlier assessments (Vaughan et al. 1986, Vaughan and Smith 1988, Vaughan 1990, Vaughan and Merriner 1991, AMAC 1992, Vaughan 1993, Vaughan et al. 2001). This method does not provide for calibration to fishery independent surveys. In general, VPA estimates have the least accuracy associated with the most recent year in the catch matrix (Cadrin and Vaughan 1997).

1.2. Organization of Report. This report generally follows the outline of earlier supplemental reports (Vaughan and Smith 1998, 1999, 2000), and is designed to provide insight into the historic and current status of the Atlantic menhaden stock. In section 2, a brief summary is provided of the history of the reduction fishery and analyses of stock status (much of which comes from analyses for the benchmarks). In section 3, Murphy VPA analysis on the combined reduction and bait (1985-2000) catch matrix is compared with the Murphy VPA analysis on the reduction catch matrix (from section 2). Section 4 presents an in-depth look at the historical relationship between spawning stock biomass and recruits to age 1, including indices of survival to age-1 recruits based on Ricker and Beverton-Holt models. In section 5, potential juvenile abundance indices are updated and used for developing a coastwide index. In section 6, various biological reference points are re-estimated for comparison with last year's estimates, F-based and SSB-based benchmarks, and schematic fishery control rule plots are shown based on benchmarks from Amendment 1. Finally, a brief summary is given in section 7. Three appendices have been added which provide: A) estimates of historical catches of Atlantic menhaden from Chesapeake Bay, B) preliminary application of AD Model Builder to a forward-projection age-structure model, and C) updated surplus production analysis based on ASPIC.

2. Reduction Fishery Data (1940-2000)

As noted in Ahrenholz et al. (1987) some fishing for Atlantic menhaden has occurred since colonial times, but the purse seine fishery for reduction began in New England about 1850. Landings and nominal effort (vessel-weeks, measured as number of weeks a vessel unloaded during the fishing year) are available since 1940 (Fig. 2.1). Landings rose during the 1940s (from 167,000 to 376,000 t), peaked during the 1950s (high of 712,000 t in 1956), and then declined to low levels during the 1960s (from 576,000 t in 1961 to 162,000 t in 1969). During the 1970s the stock rebuilt (landings rose from 250,000 t in 1971 to 376,000 t in 1979), and then maintained intermediate levels during the 1980s (varying between 238,000 t in 1986 when fish meal prices were extremely low to 418,600 t in 1983). Landings during the 1990s have declined from 401,200 t in 1990 to 167,300 t in 2000. It has been demonstrated, in general, for purse-seine fisheries that catch-per-effort and nominal fishing effort are poor measures of population abundance and fishing mortality, respectively (Clark and Mangel 1979). However, there was an approximate linear relationship between landings (L) and nominal fishing effort (E) for 1940-2000 (Fig. 2.2; $R^2 = 0.58$):

$$L = 0.148 * E + 155.7 + \varepsilon ,$$

where ε is independent, identically distributed as $N(0,\sigma^2)$. Thus, at a rough level, declining nominal effort does equate approximately with declining landings.

2.1. Plants and Vessels. Number of reduction plants along the U.S. East Coast has declined from more than 20 during the late 1950s to 2 plants in 2000 (Table 2.1). Only 2 plants (North Carolina and Virginia) are expected to operate during 2001. Similarly, the number of purse-seine vessels in the reduction fishery have declined from more than 130 vessels during the late 1950s to 12 vessels during 2000. Only 12 vessels are expected to be active in the reduction fishery during 2001 fishing year (Population Dynamics Team 2001).

A major change in the industry took place following the 1997 fishing season which significantly reduced effort and overall production capacity. The two reduction plants operating in Reedville, VA, consolidated. Seven of the 20 vessels operating out of Reedville, VA, were removed from the fleet prior to the 1998 fishing year, and 3 more vessels were removed prior to the 2000 fishing year. Two large vessels continued to be active at the plant located in North Carolina.

2.2. Sampling Intensity. The Center for Coastal Fisheries and Habitat Research (Beaufort Laboratory) has conducted biological sampling of Atlantic menhaden for length and weight at age since 1955, one of the longest and most complete time series of biostatistical fishery data in the nation (Table 2.2). Biological sampling is based on a two-stage cluster design, and it is conducted over the range of the fishery, both temporally and geographically (Chester 1984). Number of fish sampled in the first cluster was reduced during the early 1970s from 20 fish to 10 fish, to increase sampling of the second cluster (number of sets). Given the underlying assumption of virtual population analysis that the catch-at-age matrix is known without error, we do not believe that sample sizes from which the catch at age matrix is developed are inefficiently high. In comparing menhaden sampling intensity to the rule-of-thumb criteria used by the Northeast Fisheries Science Center (e.g., < 200 t/100n), our sampling level might be considered too low, although the results of Chester (1984) suggest otherwise. We consider the catch-at-age matrix for Atlantic menhaden to be one of the most accurate and precise catch matrices used in the U.S. (Table 2.3). An analysis of the coherency of this matrix provides high pair-wise correlations between lagged catch in numbers at age (Table 2.4). Unlike many catch matrices developed for other assessed species, we were able to follow cohorts through ages out to at least age 6.

2.3. Mean Weight at Age. Mean weight at age of individual Atlantic menhaden were generally high during the late 1950s (when stock abundance was high) and the 1960s (when stock abundance declined to low levels) (Fig. 2.3). However during the early 1970s, the mean weight at age declined sharply, and remained low until the late 1980s. Recently, the mean weight at age has risen to levels approaching those of the late 1950s and 1960s. Exceptionally large Atlantic menhaden were encountered in Chesapeake Bay during summer 1996 (one individual was 432 mm FL, weighing 1.55 kg, and aged by scales to be 7 years old) (Smith and O'Bier 1996). The existence of this school of large, old menhaden tends to support the robustness of the spawning stock during the mid-1990s.

2.4. Exploitation and Fishing Mortality Rates. Temporal trends in exploitation for juveniles (age 0) have been highly variable, depending on availability and weather (Fig. 2.4). Recent values have been low. A combination of good recruitment and good winter weather during the late 1970s and early 1980s resulted in high mortality on these young menhaden. Exploitation rates on older fish (ages 1-8) generally have declined over the period 1965 through 2000, with high values occurring during the mid-1960s when stock size was low. This decline in exploitation rate for ages 1-8, statistically significant at α=0.0008, is partly driven by decline in exploitation on age-1 menhaden (α=0.0001), although there are significant declines in exploitation on age-2 (α=0.0017) and age 3-8 menhaden (α=0.0385).

Fishing mortality rates on fully recruited ages (referred to as full F) are calculated as the weighted average of age-specific F's for ages 2-8, weighted by catch in numbers. The pattern over time of full F is similar to the exploitation rates ($u = FA/Z$), with values exceeding 2.0 occurring during 1972-1975 and 1984-1985. The preliminary estimate for the most recent year ($F = 1.1$) is largely driven by the catch curve for the most recent years. The historical time period 1955-2000 produced a median F of 1.4 with interquartile range between 1.1 and 1.7. The preliminary estimate of fishing mortality rate for 2000 of 1.1 is approximately at the 25th percentile.

2.5. Spawning Potential Ratio (Static SPR) as a Measure of Exploitation. Spawning potential ratio (also referred to as maximum spawning potential), is inversely related to fishing mortality rate (Gabriel et al. 1989). Although generally calculated as a ratio of spawning stock biomass per recruit, it is more properly related to an index of egg production (Prager et al. 1987) (Fig. 2.6). Static SPR for Atlantic menhaden is calculated based on such an index of egg production, and provides lower estimates of static SPR than that based on mature female biomass. This variable is plotted with its median (5.5%) and interquartile range (3.1% to 8.2%). Although highly variable, generally higher values (above 75th percentile) are associated with two temporal periods (1955-1961 and 1992-2000). Higher SPR values are generally associated with better stock condition (lower fishing mortality regardless of stock size). The preliminary estimate for static SPR in 2000 was 8.6%, above the 75th percentile (8.2%).

Fishery Management Councils and Commissions have generally adopted values of 20-40% static SPR for definitions of overfishing in their Fishery Management Plans (FMP) which address species that are primarily top predators (generally longer lived fishes with delayed age of first maturity). Estimates of static SPR for the Atlantic menhaden stock have exceeded 20% only once between 1955-1999 (24.1% in 1960). In 1960, F was low due to the size of the 1958 year class as age-2 menhaden, which is the first fully recruited age in the reduction fishery. Estimates of static SPR between 10% and 20% have occurred in 1955, 1958, 1961, and four out of the five years during 1993-1997 (8.2% in 1995). The estimate for 2000 (8.6%) is above the 75th percentile for the historical period. Additionally, Atlantic menhaden have demonstrated that they can produce good to excellent recruitment from much lower values of SPR, especially during the mid to late 1970s and early 1980s when the population was rebuilding (Vaughan and Smith 1998, 1999).

2.6. Recruits to Age 1 and Spawning Stock Biomass. Annual estimates of recruits to age 1 (Fig. 2.7) and spawning stock biomass (Fig. 2.8) are estimated using the Murphy (1965) virtual population analysis approach (Vaughan et al. 1986, Ahrenholz et al. 1987, Vaughan and Smith 1988, Vaughan 1990, 1993). The estimated population numbers at age are summarized in Table 2.5. Historical trends in recruits to age-1 Atlantic menhaden are plotted with their median (3.0 billion) and interquartile range (1.9 to 4.5 billion) (Fig. 2.7). Recruits of Atlantic menhaden to age 1 was high during the late 1950s, with the record recruitment estimated at 15.1 billion recruits in 1959 (from the 1958 year class). Recruitment was generally poor during the 1960s, with values below the 25th percentile for the recruitment time series. High recruitment occurred during the 1970s to levels above the 75th percentile. These values are comparable to the late 1950s (of course, with the exception of the 1958 year class). Moderate to high recruitment occurred during the 1980s, with declining recruitment during the 1990s. Estimates of recruits to age 1 for 1996 through 2000 were below the 25th percentile of 1.9 billion menhaden. The preliminary estimate for recruits to age 1 in 2000 was 0.8 billion, the lowest on record. Recall that the most recent estimate of recruitment has the greatest uncertainty, and that this estimate for 2000 is likely to change considerably as more data from that cohort (age 1 in 2001, age 2 in 2002, etc.) are added to the analysis.

Historical trends in spawning stock biomass (SSB) are plotted with the time series median (39,900 t) and interquartile range (20,900 to 62,900 t) (Fig. 2.8). Extremely large values of SSB were present during the late 1950s and early 1960s, resulting primarily from two very large year classes (1951 and 1958). These values were well above the 75th percentile. Estimates of SSB during the 1960s and most of the 1970s were generally below the median, and occasionally below the 25th percentile. For those year when estimates of spawning stock biomass are above the 75th percentile (i.e., 1994-1995 and 1997), the spawning stock biomass can be considered very healthy. For those years when estimates of spawning stock biomass are below the 25th percentile (i.e., 1965-1970, 1973-1976, and 1985-1986), the spawning stock biomass can be considered depleted. The low estimates of SSB obtained for 1985-1986 are probably an artifact of the economic decision not to fish by one plant in Reedville, VA. The preliminary estimate for spawning stock biomass in 2000 was 33,200 t, between the 25th and 50th percentiles.

Table 2.1. Years of activity for individual menhaden reduction plants.

Year/Plant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	32	33	34	35	36	Total Plants	Number Vessels
1955	+	+	+	+	+	+		+		+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+										23	150
1956	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+											24	149
1957	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+										25	144
1958	+	+	+	+	+			+	+	+	+	+	+	+	+	+	+	+		+	+		+	+	+	+										22	130
1959	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+		+	+		+	+	+	+										23	144
1960	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+		+			+		+											20	115
1961	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+		+			+		+											20	117
1962	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+			+			+		+											19	112
1963	+	+	+	+	+			+	+	+	+	+	+	+	+	+	+	+		+																17	112
1964	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+		+																18	111
1965	+	+		+	+			+		+	+	+	+	+		+	+	+	+	+							+	+								17	84
1966	+	+		+	+		+	+	+	+	+	+	+	+	+	+	+		+	+							+	+	+							20	76
1967		+		+			+	+	+	+	+	+	+	+	+	+	+		+	+							+	+	+							18	64
1968	+	+		+			+			+	+	+	+	+	+	+	+		+	+							+	+	+							17	59
1969	+	+		+			+			+		+	+	+	+	+	+			+							+	+	+							15	51
1970		+					+			+		+	+	+	+	+	+			+			+		+		+	+	+							15	54
1971		+					+			+		+	+	+	+	+	+			+			+		+		+	+								14	51
1972		+					+			+			+	+			+			+			+		+		+	+								11	51
1973		+					+			+			+	+			+			+		+	+		+			+								11	58
1974		+					+			+			+	+			+			+			+		+			+								10	63
1975		+					+			+			+	+			+			+		+	+		+			+		+						12	61
1976		+					+			+			+	+			+			+			+		+			+		+						11	62
1977		+					+			+			+	+			+			+		+	+		+			+		+						12	64
1978		+					+			+			+	+			+			+		+	+		+			+		+						12	53
1979		+					+			+			+	+			+			+		+	+		+			+		+						12	54
1980		+					+			+			+	+			+			+		+	+					+		+						11	51
1981		+					+			+			+	+			+			+		+	+					+		+						11	57
1982							+			+			+	+			+			+		+	+					+		+						10	47
1983							+			+			+	+			+			+			+					+		+						9	41
1984							+			+			+	+						+			+					+		+						8	38
1985							+			+			+							+								+		+						6	24
1986							+			+			+							+								+		+						6	16
1987							+			+			+							+										+	+					6	23
1988							+			+			+																	+	+	+				6	30
1989							+			+			+																		+	+				5	37
1990							+			+			+																		+	+				5	35
1991							+			+			+																		+	+				5	37
1992							+			+			+																		+	+	+	+	+	8	37
1993							+			+			+																		+	+		+	+	7	31
1994							+			+			+																							3	20
1995							+			+			+																							3	20
1996							+			+			+																							3	21
1997							+			+			+																							3	23
1998										+			+																							2	15
1999										+			+																							2	15
2000										+			+																							2	12
2001										+			+																							2	12

Table 2.1. (continued)

Port	Plant	Name	Location
3	1	Atlantic Processing Co.	Amagansett, NY
4	2	J. Howard Smith (Seacoast Products)	Port Monmouth, NJ
4	3	Fish Products Co.	Tuckerton, NJ
8	4	New Jersey Menhaden Products Co.	Wildwood, NJ
0	5	Fish Products Co. (Seacoast Products Co.)	Lewes, DE
0	6	Consolidated Fisheries	Lewes, DE
5	7	AMPRO (Standard Products Co.)	Reedville, VA
5	8	McNeal-Edwards (Standard Products Co.)	Reedville, VA
5	9	Menhaden Co. (Standard Products Co.)	Reedville, VA
5	10	Omega Protein (Zapata Haynie Co.)	Reedville, VA
5	11	Standard Products Co.	White Stone, VA
6	12	Fish Meal Co.	Beaufort, NC
6	13	Beaufort Fisheries, Inc.	Beaufort, NC
6	14	Standard Products Co.	Beaufort, NC
6	15	Standard Products Co.	Morehead City, NC
6	16	Haynie Products, Inc.	Morehead City, NC
7	17	Standard Products Co.	Southport, NC
7	18	Southport Fisheries Menhaden	Southport, NC
9	19	Quinn Menhaden Fisheries, Inc.	Fernandina Beach, FL
9	20	Nassau Oil and Fertilizer Co.	Fernandina Beach, FL
9	21	Mayport Fisheries	Mayport, FL
1	22	Maine Marine Products (Pine State Products)	Portland, ME
2	23	Lipman Marine Products (Gloucester Marine Protein)	Gloucester, MA
2	24	Gloucester Dehydration Co.	Gloucester, MA
11	25	Point Judith By Products Co.	Point Judith, RI
9	26	Quinn Fisheries	Younges Island, SC
5	27	Haynie Products (Cockerall's Ice & Seafood)	Reedville, VA
6	28	Sea and Sound Processing Co.	Beaufort, NC
12	29	Cape Charles Processing Co.	Cape Charles, VA
13	30	Sea Pro, Inc.	Rockland, ME
15	32	Connor Bros.	New Brunswick, Canada
14	33	Riga (IWP)	Maine
14	34	Vares (IWP)	Maine
14	35	Dauriya (IWP)	Maine
15	36	Comeau	Nova Scotia, Canada

Table 2.2. Atlantic menhaden sample size (n), landings in numbers of fish, landings in biomass (C), and sampling intensity (landings in metric tons per 100 fish measured), 1955-2000.

Year	Sample Size (n)	Landings (millions of fish)	Landings (1000 t)	Intensity (C/100n)
1955	16136	3118.4	641.4	3875.0
1956	19875	3564.8	712.1	3582.9
1957	19698	3511.7	602.8	3060.2
1958	15324	2719.2	510.0	3328.1
1959	17960	5353.6	659.1	3669.8
1960	13513	2775.1	529.8	3920.7
1961	13189	2598.3	575.9	4366.5
1962	15733	2099.9	537.7	3417.7
1963	13033	1764.5	346.9	2661.7
1964	10443	1729.1	269.2	2577.8
1965	19550	1519.5	273.4	1398.5
1966	15670	1340.6	219.6	1401.4
1967	15435	984.2	193.5	1253.6
1968	26838	1148.0	234.8	874.9
1969	15081	868.2	161.6	1071.5
1970	8435	1400.5	259.4	3075.3
1971	8269	969.1	250.3	3027.0
1972	6553	1713.9	365.9	5583.7
1973	6353	1843.4	346.9	5460.4
1974	5421	1990.6	292.2	5390.1
1975	7283	2162.3	250.2	3435.4
1976	6725	3283.5	340.5	5063.2
1977	7276	3673.7	341.1	4688.0
1978	7094	3085.2	344.1	4850.6
1979	6366	3870.1	375.7	5901.7
1980	7291	3332.3	401.5	5506.8
1981	9191	3984.0	381.3	4148.6
1982	9066	3175.7	382.4	4218.0
1983	11228	3942.1	418.6	3728.2
1984	11689	3548.0	326.3	2791.5
1985	7700	3025.3	306.7	3983.1
1986	5408	1912.4	238.0	4400.9
1987	7398	2315.2	327.0	4420.1
1988	7339	2158.0	309.3	4214.5
1989	6877	2630.5	322.0	4682.3
1990	7029	2157.9	401.2	5707.8
1991	7690	3166.6	381.4	4959.7
1992	5600	2052.5	297.6	5314.3
1993	5318	1594.0	320.6	6028.6
1994	4708	1492.1	260.0	5522.5
1995	4606	1643.3	339.9	7379.5
1996	4218	1091.9	292.9	6944.0
1997	4115	995.9	259.1	6296.5
1998	3808	1007.5	245.9	6457.5
1999	3600	1056.3	171.3	4758.3
2000	2940	657.4	167.3	5690.5

Table 2.3. Estimated landings of Atlantic menhaden in numbers by age (in millions) and weight of total landings (in thousands of metric tons), 1955-1998. (Estimates for 2000 are preliminary)

Year	0	1	2	3	4	5	6-8	Total Numbers	Total Weight
1955	761.0	674.1	1057.7	267.3	307.2	38.1	13.0	3118.4	641.4
1956	36.4	2073.3	902.7	319.6	44.8	150.7	37.4	3564.8	712.1
1957	299.6	1600.0	1361.8	96.7	70.8	40.5	42.3	3511.7	602.8
1958	106.1	858.2	1635.3	72.0	17.3	15.9	14.4	2719.2	510.0
1959	11.4	4038.7	851.3	388.3	33.4	11.9	18.7	5353.6	659.1
1960	72.2	281.0	2208.6	76.4	102.2	23.8	11.0	2775.1	529.8
1961	0.2	832.4	503.6	1209.6	19.2	29.4	3.9	2598.3	575.9
1962	51.6	514.1	834.5	217.3	423.4	30.8	28.3	2099.9	537.7
1963	96.9	724.2	709.2	122.5	45.0	52.4	14.3	1764.5	346.9
1964	302.6	704.0	605.0	83.5	17.9	7.8	8.3	1729.1	269.2
1965	259.1	745.2	421.4	77.8	12.2	1.8	2.0	1519.5	273.4
1966	349.5	550.8	404.1	31.7	3.9	0.4	0.3	1340.6	219.6
1967	7.0	633.2	265.7	72.8	5.1	0.5	0.0	984.2	193.5
1968	154.3	377.4	539.0	65.7	10.7	1.0	0.1	1148.0	234.8
1969	158.1	372.3	284.3	47.8	5.4	0.1	0.0	868.2	161.6
1970	21.4	870.8	473.9	32.6	4.0	0.1	0.0	1403.0	259.4
1971	72.8	263.3	524.3	88.3	17.8	2.5	0.0	969.1	250.3
1972	50.2	981.3	488.5	173.1	19.1	1.9	0.0	1713.9	365.9
1973	56.0	588.5	1152.9	38.6	7.0	0.3	0.0	1843.4	346.9
1974	315.6	636.7	986.0	48.6	2.5	1.4	0.0	1990.6	292.2
1975	298.6	720.0	1086.5	50.2	6.6	0.2	0.1	2162.3	250.2
1976	274.2	1612.0	1341.1	48.0	8.0	0.3	0.0	3283.5	340.5
1977	484.6	1004.5	2081.8	83.5	17.8	1.4	0.1	3673.7	341.1
1978	457.4	664.1	1670.9	258.1	31.2	3.5	0.0	3085.2	344.1
1979	1492.5	623.1	1603.3	127.9	21.8	1.5	0.1	3870.1	375.7
1980	88.3	1478.1	1458.2	222.7	69.2	14.4	1.4	3332.3	401.5
1981	1187.6	698.7	1811.5	222.2	47.5	15.4	1.3	3984.0	381.3
1982	114.1	919.4	1739.5	379.7	16.3	5.8	0.9	3175.7	382.4
1983	964.4	517.2	2293.1	114.3	47.4	5.0	0.7	3942.1	418.6
1984	1294.2	1024.2	892.1	271.5	50.3	15.2	0.5	3548.0	326.3
1985	637.2	1075.8	1224.6	44.1	35.6	6.2	1.7	3025.3	306.7
1986	98.4	224.2	1523.1	49.1	10.5	6.1	1.1	1912.4	238.0
1987	42.9	504.7	1587.7	151.9	25.2	2.2	0.7	2315.2	327.0
1988	338.8	282.7	1157.6	301.4	69.8	7.1	0.3	2158.0	309.3
1989	149.7	1154.6	1158.5	108.4	47.5	11.6	0.2	2630.5	322.0
1990	308.1	132.8	1553.1	109.0	42.2	12.3	0.4	2157.9	401.2
1991	881.8	1033.9	946.1	254.0	37.9	10.7	2.0	3166.6	381.4
1992	399.6	727.2	795.4	66.1	51.3	10.9	1.4	2052.5	297.6
1993	67.9	379.0	983.1	148.9	10.9	3.9	0.3	1594.0	320.6
1994	88.6	274.5	888.9	165.1	67.2	7.5	0.2	1492.1	260.0
1995	56.8	533.6	671.9	309.1	67.5	4.4	0.0	1643.3	339.9
1996	33.7	209.1	679.1	138.9	29.0	2.0	0.0	1091.9	292.9
1997	25.2	246.9	424.5	237.4	51.6	9.0	1.2	995.9	259.1
1998	72.8	185.0	540.6	126.3	73.0	9.0	0.8	1007.5	245.9
1999	193.9	301.1	450.8	81.8	25.0	3.2	0.4	1056.3	171.3
2000	77.8	114.2	340.6	111.9	11.1	1.9	0.0	657.4	167.3

Table 2.4. Coherency of Atlantic menhaden catch-at-age matrix based on pair-wise correlations, 1955-2000. For each age, the Pearson correlation coefficient is shown in the first row, and the probability of exceeding this coefficient under the null hypothesis that the coefficient equals zero is in the second row.

Age	1	2	3	4	5	6
1	1.0	0.60	0.76	0.79	0.77	0.37
	0.0	0.0001	0.0001	0.0001	0.0001	0.0168
2	-	1.0	0.55	0.47	0.54	0.23
		0.0	0.0001	0.0011	0.0002	0.1348
3	-	-	1.0	0.92	0.70	0.37
			0.0	0.0001	0.0001	0.0154
4	-	-	-	1.0	0.74	0.58
				0.0	0.0001	0.0001
5	-	-	-	-	1.0	0.83
					0.0	0.0001

Table 2.5. Estimated population size of Atlantic menhaden in numbers by age (in millions)from Murphy Virtual Population Analysis, 1955-1998 Estimates of population size at age 0 should be interpreted with care, because natural mortality at this age is poorly known.

Year	0	1	2	3	4	5	6	7	8
1955	7962.2	3091.4	2285.4	619.6	813.4	116.4	32.1	7.3	2.0
1956	9112.6	5680.4	1443.2	644.3	189.1	280.9	44.6	12.3	3.2
1957	4496.7	7243.8	2015.0	239.1	166.0	85.6	64.2	6.9	2.7
1958	19031.2	3324.1	3367.4	265.0	77.7	51.2	23.5	12.9	1.2
1959	2787.9	15103.1	1449.3	893.3	112.8	36.1	20.3	7.9	4.4
1960	3848.3	2216.1	6479.4	278.5	270.5	45.9	13.8	3.6	1.6
1961	2790.7	3008.7	1192.0	2417.1	118.0	93.3	11.1	2.7	0.5
1962	2853.9	2228.3	1269.3	371.7	615.0	60.2	36.7	4.8	1.1
1963	2288.8	2232.9	1018.9	182.5	72.2	75.8	14.9	5.0	0.8
1964	2729.0	1741.2	860.9	120.3	24.5	12.1	9.2	1.7	0.7
1965	1997.5	1910.1	566.4	98.0	14.4	2.3	1.8	0.9	0.1
1966	2810.5	1373.6	641.8	49.6	5.7	0.4	0.2	0.3	0.1
1967	1491.5	1933.5	450.4	104.4	7.7	0.7	0.0	0.0	0.1
1968	2278.0	1184.8	740.7	85.7	12.3	1.1	0.1	0.0	0.0
1969	3397.8	1681.7	462.1	72.4	6.3	0.2	0.0	0.0	0.0
1970	1690.1	2572.3	780.8	79.8	10.3	0.1	0.0	0.0	0.0
1971	4383.0	1330.5	964.0	139.4	25.7	3.4	0.0	0.0	0.0
1972	3426.4	3435.1	642.2	215.0	22.3	3.1	0.3	0.0	0.0
1973	3812.5	2691.5	1425.9	49.6	11.0	0.6	0.6	0.2	0.0
1974	5042.4	2994.4	1255.4	70.2	3.3	1.8	0.1	0.4	0.1
1975	8850.7	3745.2	1410.8	78.4	8.5	0.3	0.1	0.1	0.2
1976	6724.6	6801.3	1823.7	100.8	12.2	0.5	0.0	0.0	0.0
1977	6414.9	5125.1	3076.0	169.4	27.4	1.8	0.1	0.0	0.0
1978	5787.0	4691.0	2480.4	402.9	44.1	4.1	0.1	0.0	0.0
1979	9987.1	4213.8	2469.1	329.9	62.6	4.9	0.1	0.1	0.0
1980	5948.1	6648.1	2197.0	368.8	111.4	23.0	2.0	0.0	0.0
1981	9277.0	4671.0	3082.0	306.7	66.6	18.7	3.8	0.2	0.0
1982	3188.8	6352.2	2429.4	591.8	30.6	7.2	0.8	1.5	0.1
1983	5817.9	2444.5	3328.2	255.6	91.6	7.0	0.4	0.1	0.7
1984	7695.8	3788.6	1153.8	408.8	75.0	22.2	0.8	0.1	0.1
1985	6295.0	4995.5	1616.5	80.5	56.9	10.1	2.8	0.1	0.0
1986	4339.5	4459.5	2342.9	127.8	17.7	9.4	1.7	0.5	0.1
1987	3788.0	3377.2	2666.6	348.6	43.5	3.4	1.4	0.3	0.3
1988	7291.4	2985.6	1757.1	497.4	105.3	8.6	0.5	0.4	0.2
1989	2943.3	5520.8	1678.0	251.0	89.2	14.8	0.4	0.1	0.1
1990	4777.2	2217.0	2477.9	224.0	76.5	20.6	0.9	0.1	0.0
1991	5424.0	3540.1	1308.8	391.3	64.6	16.6	3.8	0.2	0.0
1992	4504.3	3547.8	1452.1	132.0	65.0	12.9	2.6	0.9	0.1
1993	2974.9	3241.1	1692.6	319.9	33.6	5.1	0.6	0.6	0.2
1994	3848.4	2314.9	1768.5	333.2	89.6	12.9	0.4	0.1	0.4
1995	2014.2	2994.1	1260.0	447.2	86.0	7.5	2.5	0.1	0.1
1996	2064.8	1557.8	1490.3	290.7	54.3	5.4	1.4	1.6	0.0
1997	1991.1	1618.7	828.7	427.9	78.7	12.5	1.8	0.9	0.0
1998	1740.9	1567.4	838.1	203.8	92.0	11.4	1.3	0.3	0.6
1999	1259.8	1325.2	853.7	127.7	34.5	5.3	0.7	0.3	0.2
2000	6030.5	833.6	609.3	200.1	19.8	3.5	1.0	0.2	0.2

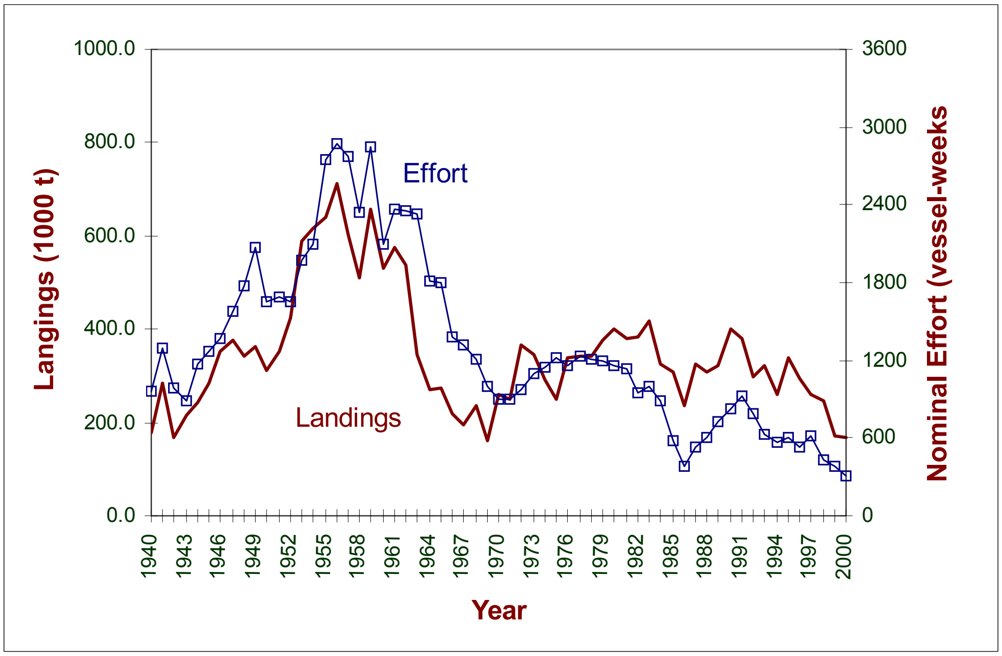

Figure 2.1. Atlantic menhaden landings and nominal effort, 1940-2000.

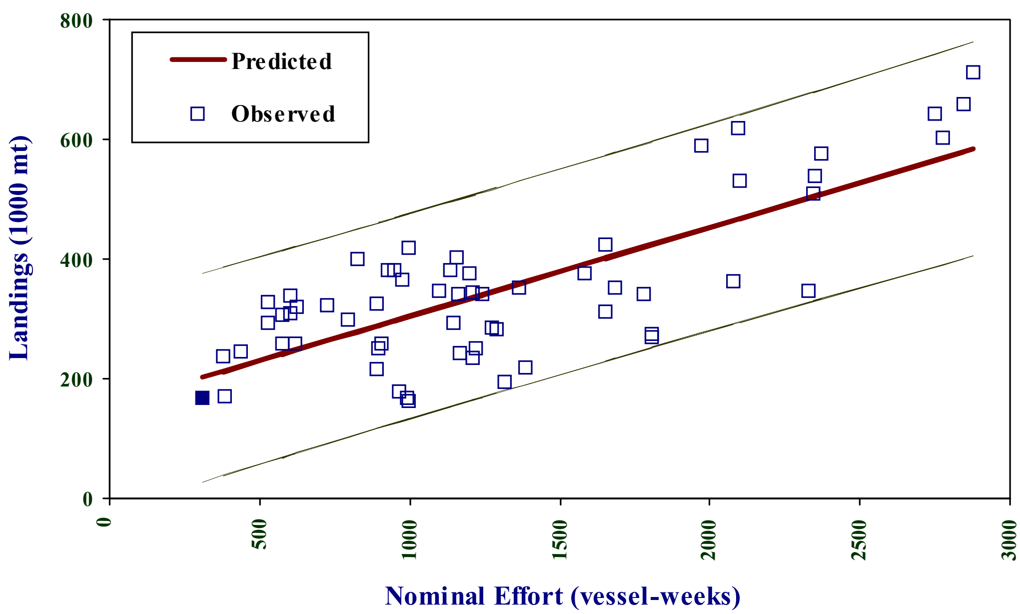

Figure 2.2. Atlantic menhaden landings versus nominal effort, 1940-2000 (Year 2000 is represented by solid square).

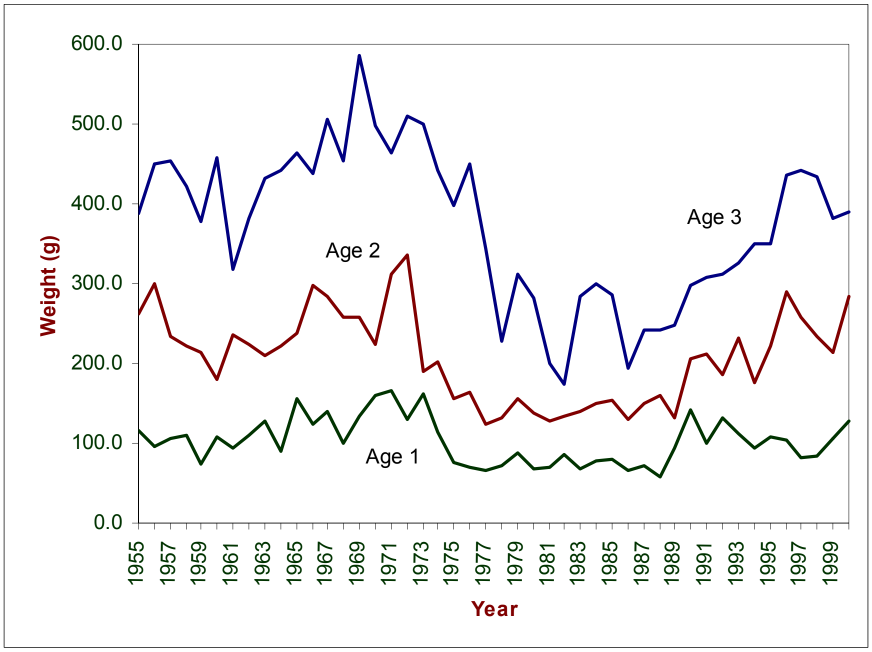

Figure 2.3. Mean weight at age (g) for Atlantic menhaden, 1955-2000.

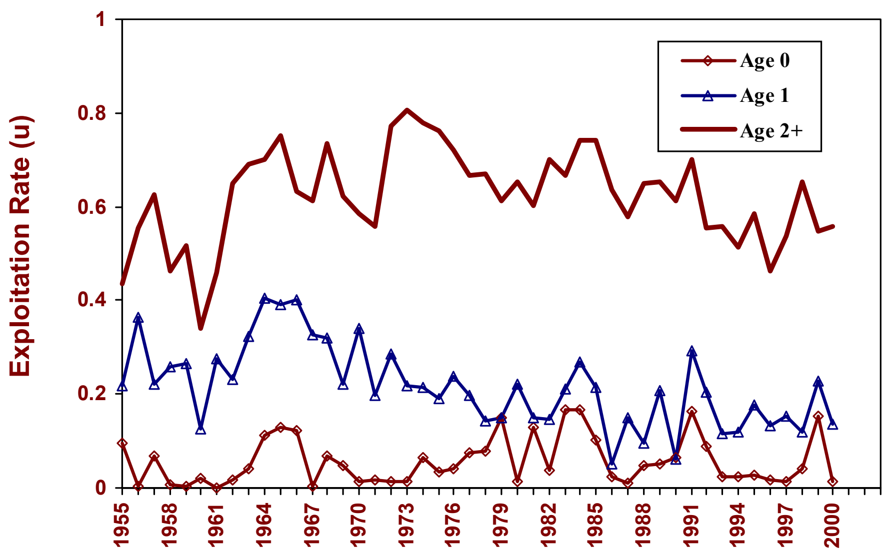

Figure 2.4. Exploitation rate (u) for age 0 and age 1-8 Atlantic menhaden, 1955-2000.

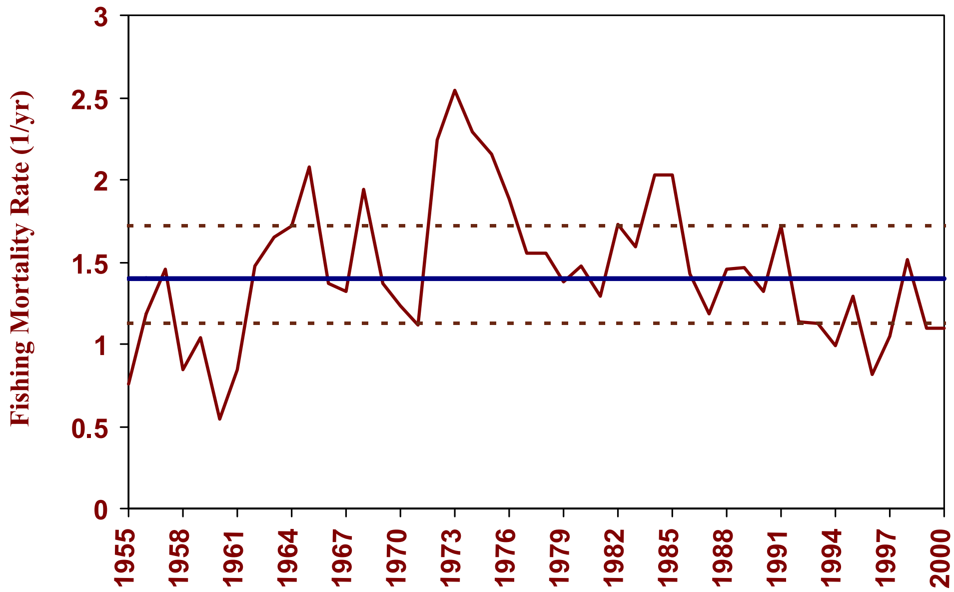

Figure 2.5. Annual estimates of fishing mortality rates, F, averaged over fully recruited ages (2+) and weighted by population numbers at age with median and interquartile range.

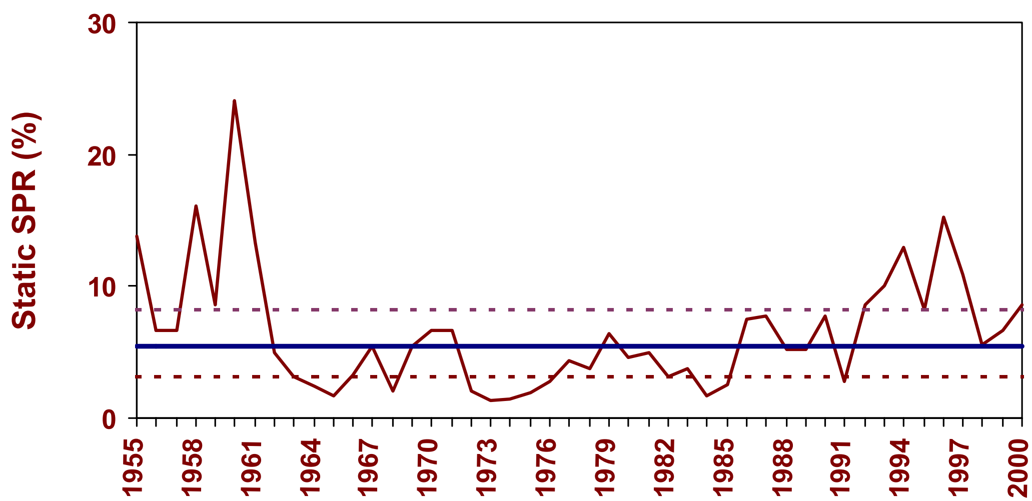

Figure 2.6. Annual estimates of static SPR for Atlantic menhaden with median and interquartile range.

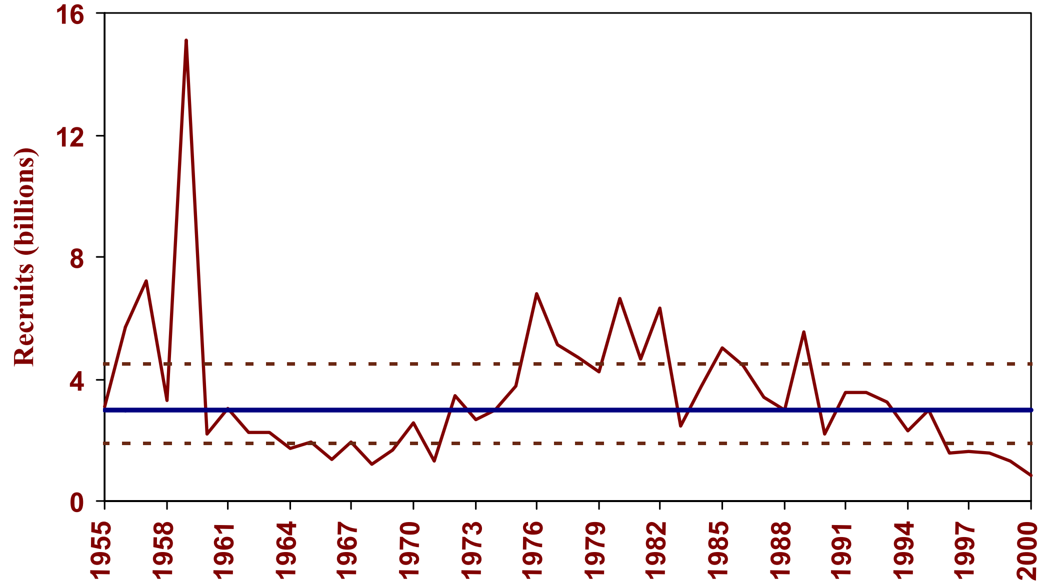

Figure 2.7. Estimates of recruits to age-1 Atlantic menhaden with median and interquartile range.

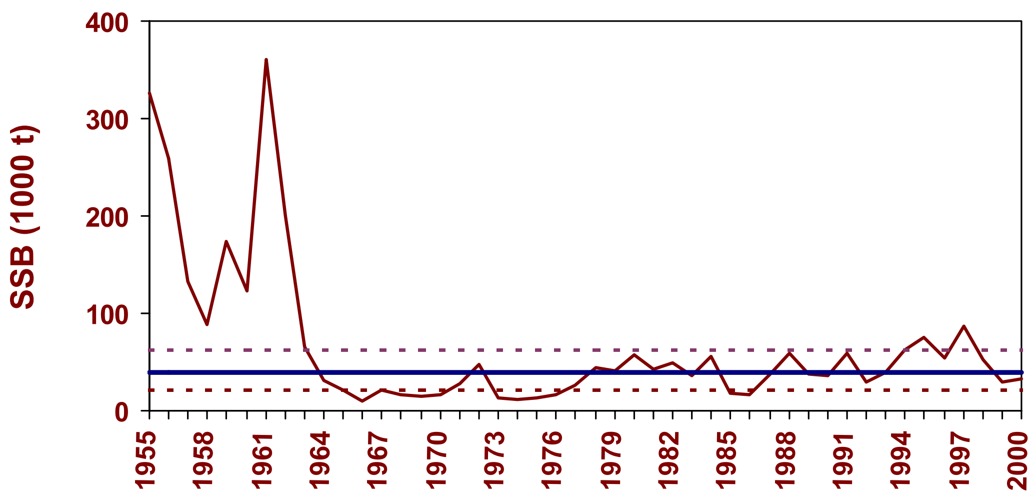

Figure 2.8. Estimates of spawning stock biomass (SSB, age 3-8) of Atlantic menhaden with median and interquartile range.

3. **Bait Fishery Data (1985-2000)**

During the 1990s, the Atlantic Menhaden Advisory Committee (AMAC) began summarizing available data on bait landings and instituted a pilot study to sample Atlantic menhaden landings from the bait fisheries along the U.S. East Coast. Bait landings for 2000 were incomplete, so the mean for 1998-1999 has been substituted for those states lacking estimates for 2000 at the time of this analysis. Bait landings have been estimated generally at or below 10% of the total Atlantic menhaden harvest on an annual basis for the period 1985-1997 (Table 3.1). With the decline in effort and landings by the reduction fishery in the last three years, the relative importance of the bait fishery has increased. However, this view is partially confounded because of improved acquisition of landings data from the bait fishery in Virginia and elsewhere, which was under-represented in prior years.

3.1. Catch-at-Age Matrix. Because of limited age composition data currently available, bait landings were separated into the three geographic areas (New England; Middle Atlantic and Chesapeake Bay including coastal Virginia waters; and South Atlantic). Length frequency distributions and age-length keys for the summer period were developed by area in three year increments from 1989-2000 to convert bait landings to catch in numbers at age. Hence, catch-at-age estimates from the reduction fishery for the period 1985-2000 (Table 3.2) were combined with catch-at-age estimates from the bait fishery (Table 3.3) to create a combined Atlantic menhaden catch-at-age matrix (Table 3.4).

3.2. Murphy VPA Comparison. Comparative applications of the Murphy virtual population analysis (comparable to Section 2) were made with these catch-at-age matrices (with and without bait landings included) for fishing years 1955-1999. The Murphy VPA estimates were compared for three variables: 1) fishing mortality rates (Fig. 3.1), 2) recruits to age 1 (Fig. 3.2), and 3) spawning stock biomass (Fig. 3.3).

Because the bait fishery tends to be on older and larger fish, the combined reduction and bait catch matrix (Table 3.4) implies that more older and larger fish were removed relative to the younger and smaller fish. Hence, inclusion of bait landings suggested lower fishing mortality rates (F=0.6 in 2000 compared to F=1.1 from reduction data only)), slightly higher estimates of recruits to age 1 (R_1=1.2 billion in 2000 compared to R_1=0.8 billion), and significantly higher estimates for spawning stock biomass (SSB=90,100 t in 2000 compared to 33,200 t). Management implications relative to benchmark targets and thresholds will be discussed later in the section on management benchmarks.

Table 3.1. Comparison of landings (1000 t) by the bait and reduction fisheries for Atlantic menhaden. (Preliminary bait data for 2000, average for 1998-1999 used in absence of available estimates.)

Year	Reduction	Bait (%)	Total
1985	306.7	26.7 (8.0)	333.4
1986	238.0	28.0 (10.5)	266.0
1987	326.9	30.6 (8.6)	357.5
1988	309.3	36.3 (10.5)	345.6
1989	322.0	30.9 (8.8)	352.9
1990	401.2	30.7 (7.1)	431.9
1991	381.4	36.2 (8.7)	417.6
1992	297.6	38.7 (11.5)	336.3
1993	320.6	35.1 (9.9)	355.7
1994	260.0	28.1 (9.8)	288.1
1995	339.9	31.1 (8.4)	371.0
1996	291.5	23.3 (7.4)	314.8
1997	259.1	25.6 (9.0)	284.7
1998	245.9	39.1 (13.7)	285.0
1999	171.3	35.9 (17.3)	207.2
2000	167.3	31.8 (16.0)	199.1

Table 3.2. Catch in numbers at age for the Atlantic menhaden reduction landings (in millions). Preliminary values for 2000.

YEAR	N0	N1	N2	N3	N4	N5	N6-8	Total
1985	637.2	1075.9	1224.6	44.1	35.6	6.3	1.7	3025.3
1986	98.4	224.2	1523.1	49.1	10.5	6.1	1.1	1912.4
1987	42.9	504.7	1587.7	151.9	25.2	2.2	0.7	2315.2
1988	338.8	282.7	1157.7	301.4	69.8	7.1	0.6	2158.0
1989	149.7	1154.6	1158.5	108.4	47.5	11.6	0.2	2630.5
1990	308.1	132.8	1553.1	109.0	42.2	12.3	0.4	2157.9
1991	881.8	1033.9	946.1	254.0	37.9	10.7	2.2	3166.6
1992	399.7	727.2	795.4	66.1	51.3	10.9	1.9	2052.5
1993	67.9	379.0	983.1	148.9	10.9	3.9	0.3	1594.0
1994	88.6	274.5	888.9	165.1	67.2	7.5	0.2	1492.0
1995	56.8	533.7	671.9	309.1	67.5	4.4	0.0	1643.3
1996	33.7	209.1	679.1	138.9	29.0	2.0	0.0	1091.9
1997	25.2	246.9	424.5	237.4	51.6	9.0	1.2	995.9
1998	72.8	185.0	540.6	126.3	73.0	9.0	0.8	1007.5
1999	193.9	301.1	450.8	81.8	25.0	3.2	0.4	1056.3
2000	77.7	114.1	340.6	111.9	11.1	1.9	0.0	657.4

Table 3.3. Catch in numbers at age for the Atlantic menhaden bait landings (in millions). Preliminary values for 2000.

YEAR	N0	N1	N2	N3	N4	N5	Total
1985	0.0	7.0	23.8	23.2	21.2	8.0	83.2
1986	0.0	7.8	30.0	24.4	19.1	6.1	87.4
1987	0.0	8.1	30.9	26.8	21.8	7.2	94.8
1988	0.0	9.3	38.1	31.9	24.3	7.3	110.9
1989	0.0	10.6	34.7	26.3	22.8	8.2	102.6
1990	0.0	12.6	40.4	25.5	21.3	7.3	107.1
1991	0.0	10.6	38.3	31.4	25.9	8.8	115.1
1992	0.0	17.8	28.1	32.1	30.2	8.4	116.5
1993	0.0	12.2	22.6	29.3	27.5	7.6	99.2
1994	0.0	17.8	18.8	21.0	24.3	7.6	89.5
1995	0.0	13.6	13.3	42.5	27.2	1.0	97.5
1996	0.0	4.5	4.1	34.9	23.6	0.8	67.9
1997	0.0	13.6	8.6	36.6	24.7	0.9	84.4
1998	0.0	0.3	11.9	34.9	35.6	14.9	97.6
1999	0.0	0.3	11.3	32.0	32.7	13.7	90.0
2000	0.0	0.3	10.9	28.3	28.7	12.1	80.2

Table 3.4. Catch in numbers at age for the Atlantic menhaden combined reduction and bait landings (in millions). Preliminary values for 2000.

YEAR	N0	N1	N2	N3	N4	N5	N6-8	Total
1985	637.2	1082.9	1248.4	67.3	56.8	14.2	1.7	3108.5
1986	98.4	232.0	1553.1	73.5	29.6	12.1	1.1	1999.8
1987	42.9	512.8	1618.6	178.7	46.9	9.4	0.7	2410.0
1988	338.8	292.0	1195.7	333.3	94.1	14.5	0.6	2268.9
1989	149.7	1165.1	1193.3	134.7	70.3	19.8	0.2	2733.2
1990	308.1	145.4	1593.6	134.5	63.4	19.7	0.4	2265.0
1991	881.8	1044.6	984.4	285.4	63.9	19.5	2.2	3281.7
1992	399.7	745.0	823.5	98.1	81.5	19.3	1.9	2168.9
1993	67.9	391.2	1005.6	178.2	38.5	11.5	0.3	1693.2
1994	88.6	292.3	907.6	186.1	91.6	15.1	0.2	1581.6
1995	56.8	547.2	685.2	351.6	94.7	5.3	0.0	1740.8
1996	33.7	213.6	683.2	173.9	52.5	2.9	0.0	1159.8
1997	25.2	260.5	433.1	274.1	76.3	9.8	1.2	1080.3
1998	76.9	185.3	552.4	161.2	108.5	23.9	0.8	1105.0
1999	193.9	301.4	462.1	113.9	57.7	16.9	0.4	1146.3
2000	77.8	114.5	351.5	140.2	39.8	14.0	0.0	737.7

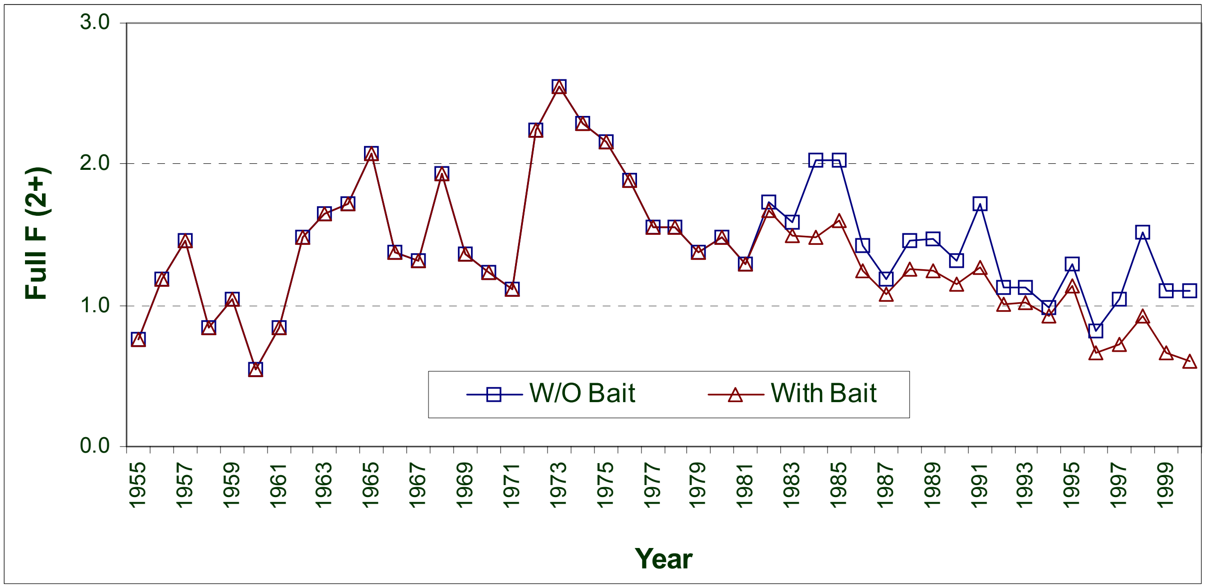

Figure 3.1. Annual estimates of fishing mortality rates (weighted mean over ages 2 and older) from Murphy VPA using Atlantic menhaden catch-at-age with and without bait landings.

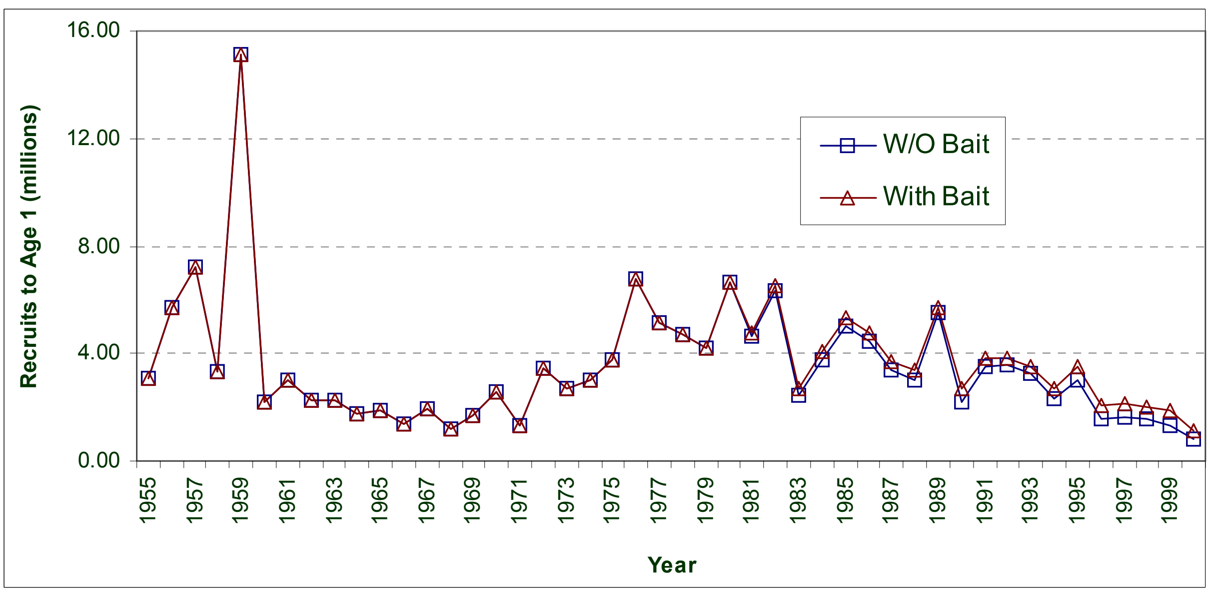

Figure 3.2. Annual estimates of recruits to age 1 from Murphy VPA using Atlantic menhaden catch-at-age with and without bait landings.

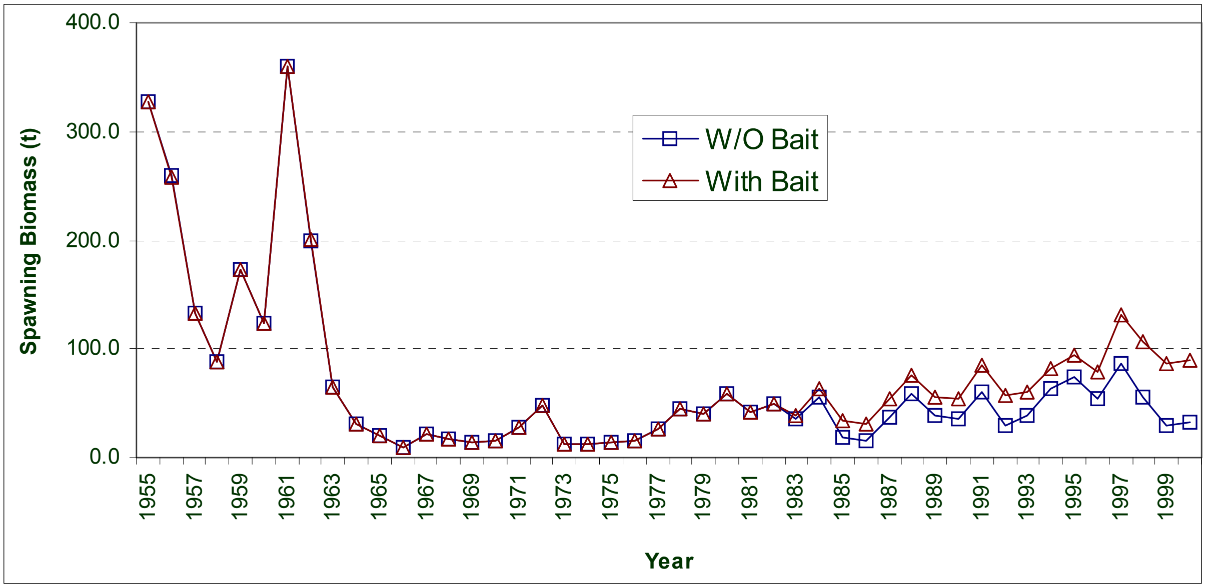

Figure 3.3. **Annual estimates of spawning stock biomass (ages 3-8) from Murphy VPA using Atlantic menhaden catch-at-age with and without bait landings.**

4. Spawner-Recruit Relations and Survival Indices

4.1. Survival Indices as Function of Spawning Stock Biomass. This section provides the results of an investigation of aspects of recruitment to age 1 as it may relate to spawning stock biomass. These analyses are based on the Murphy VPA conducted on combined reduction and bait landings. The dependency of spawning stock on the first age of spawning (age 3) is highly variable (Fig. 4.1), but generally high percentages for age 3 contribution occurred during the mid-1960s through mid-1970s. Low percentages (e.g., below 50%) occurred mostly during the late 1950s and early 1960s, and in 1985. Since 1985, the lowest value was obtained in 1998 (48.7%).

Conditional probabilities are presented in Table 4.1 that relate the historical pattern in recruits to age 1 given the spawning stock biomass that produced them. Low, moderate and high are based on the interquartile range of the historical time series (as in Vaughan 1993). These historical patterns suggest that low spawning stock (below the 25^{th} percentile) has about a 45% chance of producing low recruitment, a 27% chance of producing a moderate recruitment, and 27% chance of producing high recruitment. Thus, there is a bias towards low recruitment when spawning stock biomass is low. Estimates of these conditional probabilities are obtained similarly for moderate and high spawning stock biomass. Note that moderate spawning stock biomass is twice as likely to produce high recruitment than low recruitment (0.13:0.26); while high spawning stock biomass is equally likely to produce low recruitment as high recruitment (0.27:0.27). This analysis suggests the need to maintain spawning stock biomass at least above approximately the 25^{th} percentile for the long-term data series (28,000 t).

Assuming that spawning stock biomass is proportional to eggs produced, we define the index of survival (S_O) as the ratio of recruits to age 1 (R_1) to spawning stock biomass (SSB). Survival from spawning stock biomass to subsequent recruits to age 1 is indexed for 1955-1999 by:

$$\mathbf{S_O = R_1/SSB}.$$

The pattern of survival shows generally low survival during the late 1950s and early 1960s (generally very high SSB), with the exception of the 1958 year class (Fig. 4.2). Particularly high index of survival is noted during the mid-1970s when the menhaden stock was rebuilding. Only in the last few years is low survival again noted on par with the 1950s and early 1960s (with the exception of the 1958 yearclass).

4.2. Ricker Spawner-Recruit Curve. Weak dependency of recruits to age 1 on spawning stock biomass for Atlantic menhaden has been noted (e.g., Ahrenholz et al. 1987, Vaughan and Smith 1988). However, the spawner-recruit data can be fit to the Ricker (1975) spawner recruit curve (Fig. 4.3). Parameter estimates for the Ricker curve:

$$\mathbf{R = \alpha P\{exp(-\beta P)\}}$$

where R (as billions of age-1 menhaden) is recruits and P is spawning stock biomass (as thousands of t of age 3-8 mature females). The parameters α and β are estimated by nonlinear regression techniques. Although the mathematical curve shown has poor explanatory powers, the nonlinear parameter (β) is significantly different from 0 (i.e., the asymptotic 95% confidence interval does not include 0).

Estimates for the full data set are (asymptotic standard error in parentheses): $\alpha = 0.142$ (0.031) and $\beta = 0.0114$ (0.0026). Similarly, estimates for the data set, with the 1958 year class excluded, are (asymptotic standard error in parentheses): $\alpha = 0.209$ (0.043) and $\beta = 0.0189$ (0.0033). For the full data set, spawning stock that produces theoretical maximum recruitment occurs at $P = 1/\beta$, or 88,000 t. However, the maximum recruits to age-1 menhaden that would be produced by this spawning stock is 4.6 billion age-1 recruits. Expected survival (S_E) can be calculated from the predicted R_1 from historical estimates of SSB. Survival during the late 1950s may be low because spawning stock biomass was well above that which produces maximal recruitment based on this model.

Myers et al. (1994) suggest that the spawning stock biomass that produces one-half maximum recruitment may serve as a biological reference point for a stock. Based on the fitted Ricker curve, that value for Atlantic menhaden is estimated at 20,400 t. This value is similar in value to the current threshold value for Atlantic menhaden (20,570 t), and it is still well below recent estimated values of spawning stock biomass (the last time a value lower than either of the above values occurred was in 1976, 15,600 t).

Relative index of survival (S_R) was calculated such that it adjusted observed survival by dividing by predicted survival (based on Ricker spawner-recruit curve) and re-scaling to 0 by subtracting 1 ($S_R = 0$ at $S_O = S_E$):

$$\mathbf{S_R = (S_O/S_E)-1.}$$

Estimates of relative survival suggest that the period from 1955 through 1999 was very noisy (in a statistical sense) with two periods of particular interest (Fig. 4.4). The period from 1973-1977 was characterized by better than expected survival to age 1. There appear to be two periods with an extended duration of worse than expected (negative) relative survival: 1) 1959-1965 and 2) 1993-1999. Because the effect of spawning stock biomass on recruitment has been filtered out of these calculations (assuming Ricker model), environmental conditions such as increased predation (e.g., striped bass), decreased available food, or other physical driving variables (e.g., Ekman transport, river flows, pollutants, etc.) probably contribute to the recent decline in recruitment.

4.3. Beverton-Holt Spawner-Recruit Curve. The spawner-recruit data also can be fit to the Beverton-Holt (Ricker 1975) spawner recruit curve (Fig. 4.3). Parameter estimates for the Beverton-Holt curve:

$$\mathbf{R = P/(\alpha P+\beta)}$$

where R (as billions of age-1 menhaden) is recruits and P is spawning stock biomass (as thousands of t of age 3-8 mature females). The parameters α and β are estimated by nonlinear regression techniques. Again, the mathematical curve shown has poor explanatory powers, and, in addition, the nonlinear parameter (β) is not significantly different from 0 (i.e., the asymptotic 95% confidence interval includes 0).

Estimates for the full data set are (asymptotic standard error in parentheses): $\alpha = 0.247$ (0.039) and $\beta = 0.952$ (1.311). Spawning stock that produces theoretical maximum recruitment occurs at P equal infinity for this model. However, the maximum recruits to age-1 menhaden occurs asymptotically at 4.1 billion age-1 recruits. Expected survival (S_E) can be calculated from the predicted R_1 from historical estimates of SSB. Survival during the late 1950s may be low because spawning stock was above that which produces maximal recruitment.

Again, we consider the suggestion of Myers et al. (1994) that the spawning stock biomass which produces one-half maximum recruitment may serve as a biological reference point (possible trigger warning level) for a stock. Based on the fitted Beverton-Holt curve (all data), the value for Atlantic menhaden is estimated at 5,300 t. This value is well below the current threshold value for Atlantic menhaden (20,570 t), and all historically estimated values.

An index of relative survival (S_{BH}) for the Beverton-Holt model was calculated as for the Ricker model. Estimates of relative survival suggest that the period from 1955 through 1997 was very noisy (in a statistical sense) with two periods of particular interest (Fig. 4.5). The period from 1973-1986 was characterized by better than expected survival to age 1. There appear to be two periods with consecutive years of worse than expected (negative) relative survival: 1) 1959-72 and 2) 1989-2000. Again, because the effect of spawning stock biomass on recruitment has been filtered out of these calculations, environmental conditions such as increased predation (e.g., striped bass), decreased available food, or other physical driving variables (e.g., Ekman transport, river flows, pollutants, etc.) probably contribute to the recent decline in recruitment.

4.4. Statistical Properties. The statistical properties of recruits to age-1 Atlantic menhaden are summarized for different ranges of spawning stock biomass (Table 4.2). In addition to mean values, nonparametric statistics are calculated that are less sensitive to nonnormal (highly skewed) distribution of R_1 due to the remarkable strength of the 1958 year class. These statistics include the median (or 50th percentile), 25th and 75th percentiles. The interquartile range, defined by the 25th and 75th percentiles, is a nonparametric analog to variance. For SSB greater than or equal to a fixed level, the mean value of R_1 shows no trend, but has its largest value at or above a spawning stock biomass of 88,700 t, due primarily to the reduced sample size and increasing effect of the recruits to age 1 in 1959 (1958 year class). There is a suggestion of decreasing median value recruitment (the lowest median value shown is for SSB values in excess of the 75th percentile of the historical time series for SSB). On the other hand, for SSB less than a fixed level, there appears to be an increasing trend in median R_1 with increasing SSB.

Table 4.1. Conditional probabilities of recruitment to age 1 from spawning stock biomass based on interquartile stratifications for 1955-1999 used in population projections.

Spawning Stock Biomass[a]	Recruits to Age 1[a]		
	Low (< 2.1)	Moderate (2.12 - 4.7)	High (>4.7)
Low (< 28.0)	0.454	0.273	0.273
Moderate (28.0 - 88.7)	0.130	0.609	0.261
High (> 88.7)	0.273	0.454	0.273

[a] Recruits to age 1 in billions and spawning stock biomass in thousands of metric tons (t).

Table 4.2. **Statistical properties of recruits to age-1 Atlantic menhaden (R_1, in billions) dependent on the spawning stock biomass (SSB, in t) that produced them.**

Range of SSB (t)	Recruits to Age-1 (billions) n	Mean	Median	Percentiles 25th	75th
All	45	3.7	3.3	2.1	4.7
Greater than:					
20,400[a]	37	3.8	3.4	2.2	4.7
27,500[b]	34	3.9	3.4	2.2	4.7
28,000[c]	34	3.9	3.4	2.2	4.7
50,000[d]	24	3.8	3.2	2.2	4.3
54,500[e]	22	3.8	2.9	2.1	4.7
88,700[f]	11	4.3	2.2	2.1	5.7
Less than:					
20,400	8	3.3	2.8	1.8	4.4
27,500	11	3.0	2.6	1.4	4.7
28,000	11	3.0	2.6	1.4	4.7
50,000	21	3.5	3.4	1.9	4.7
54,540	23	3.5	3.4	1.9	4.7
88,700	34	3.5	3.5	2.1	4.7

[a] SSB that produces one-half maximum R_1 (Ricker for bait).
[b] Threshold level SSB from Amendment 1 (re-estimated for bait).
[c] Twenty-fifth percentile for historical SSB (for bait).
[d] Target level of SSB from Amendment 1 (re-estimated for bait).
[e] Median SSB for period 1955-2000 (for bait).
[f] Seventy-fifth percentile for historical SSB (for bait); and minimum SSB during 1955-62 (period of historically high levels of SSB), but produced maximum recruitment (1958 yearclass).

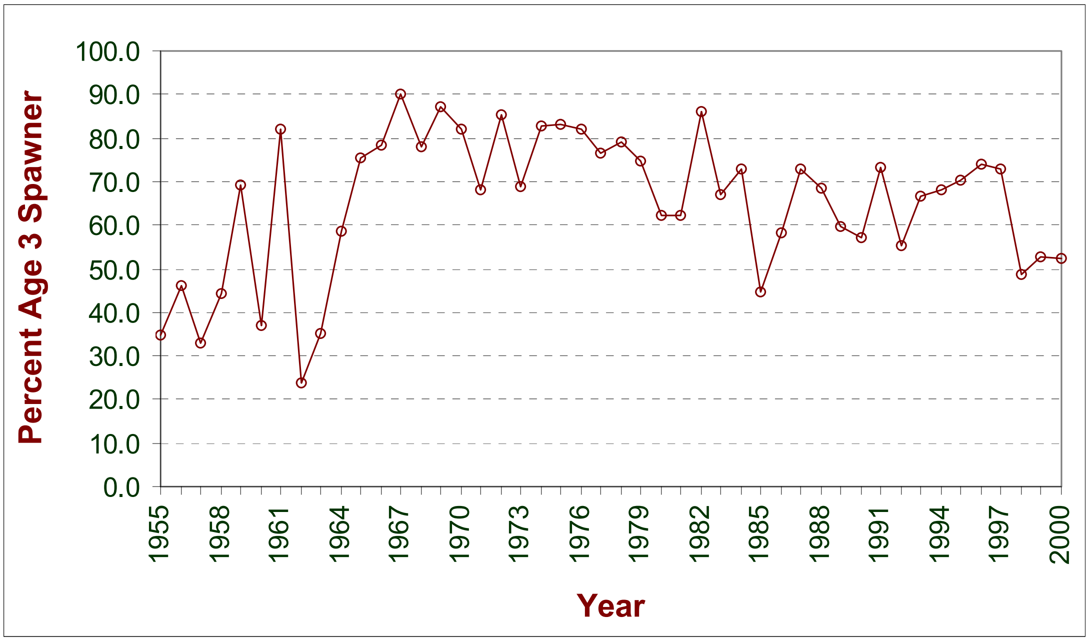

Figure 4.1. Contribution to spawning stock (as eggs) by age 3 Atlantic menhaden.

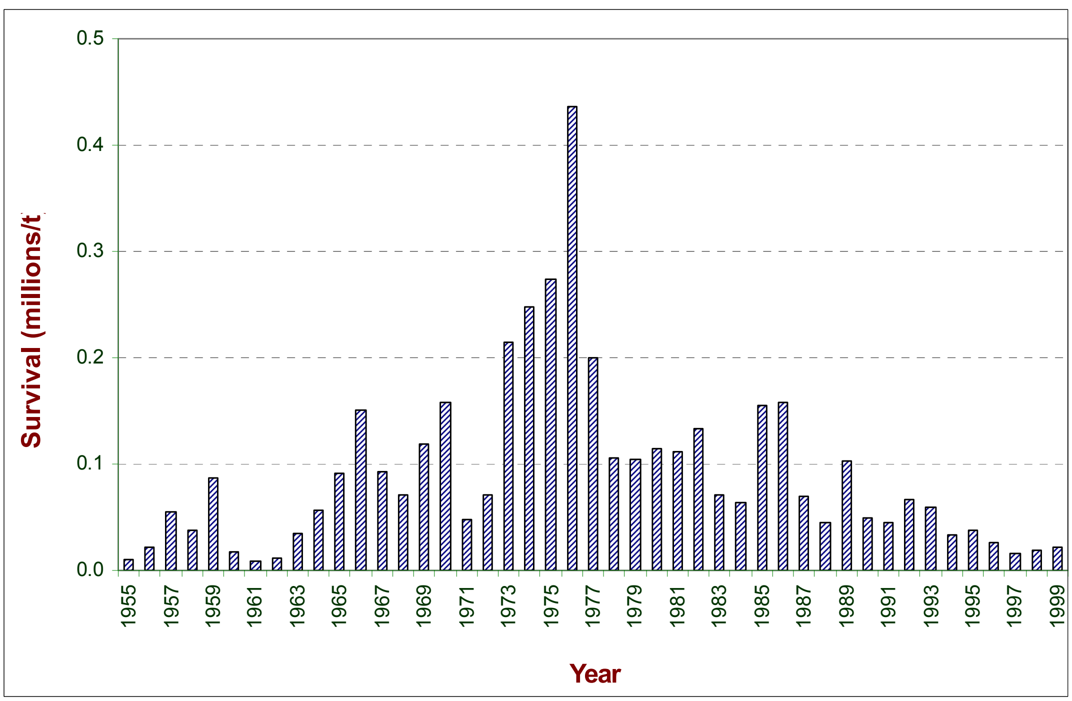

Figure 4.2. Observed survival (millions of recruits to age 1 per metric ton spawning biomass) of Atlantic menhaden.

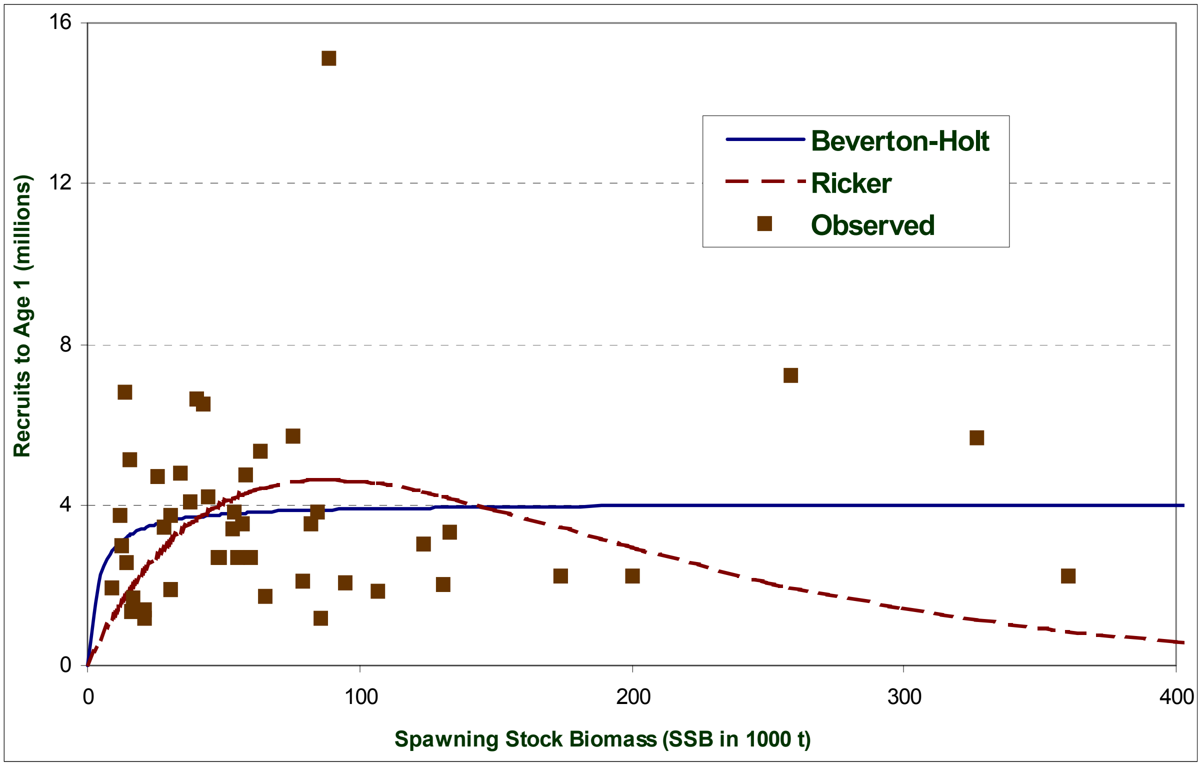

Figure 4.3. Observed, Ricker and Beverton-Holt model estimates of age 1 Atlantic menhaden.

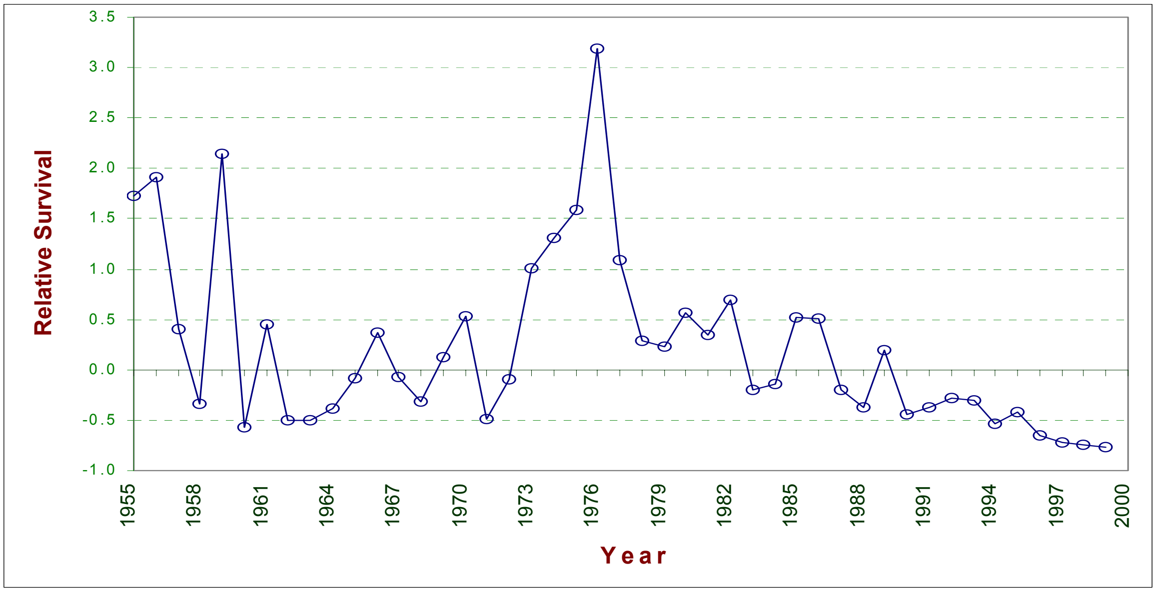

Figure 4.4. Relative survival to age-1 Atlantic menhaden from the Ricker model.

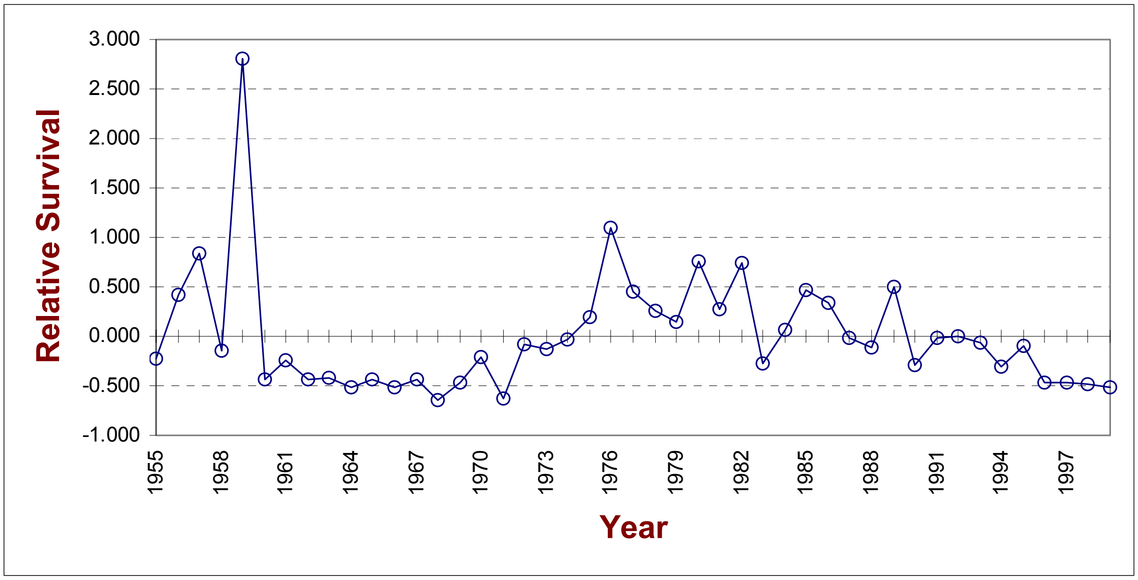

FIGURE 4.5. Relative survival to age-1 Atlantic menhaden from the Beverton-Holt model.

5. Potential Indices of Recruitment to Age 1

Sampling for juvenile Atlantic menhaden by the National Marine Fisheries Service began in 1955, and in the 1970s sampling activities culminated in extensive coastwide trawl surveys conducted through 1978 (Ahrenholz et al. 1989). A four-stream survey (2 streams in North Carolina and 2 streams in Virginia) was continued through 1986. Ahrenholz et al. (1989) found no significant correlations between the relative juvenile abundance estimates and fishery-dependent estimates of year class strength. However, recent investigations with extant data sets suggest there may be some hope! We continue to explore the utility of these indices, and where possible to better separate out age 1 and older menhaden from juveniles (age 0). For consistency, the results below are based on arithmetic means, rather than geometric, although little difference in trends was noted between the two approaches.

5.1. South Atlantic States (FL-NC). Juvenile abundance data from U.S. south Atlantic states include data sets from Florida through North Carolina. Florida DEP provided fishery-independent juvenile menhaden indices collected from the Indian River Lagoon (1991-1997) and Halifax River/Mosquito Lagoon (1993-1997). These indices are based on menhaden species, including both Atlantic and yellowfin menhaden and hybrids. Georgia DNR provided fishery-independent juvenile menhaden indices based on assessment trawl sampling from shrimp bycatch study, 1995-1998. These data sets are of relatively short duration, but will be updated and explored further as the time series increase in duration.

Menhaden data collected by the SEAMAP program have been provided by South Carolina DNR. Trawl sampling was conducted from coastal North Carolina (primarily south of Cape Fear River) to northern Florida for 1989-2000 during three seasons: Spring (April-May), Summer (June-August), and Fall (September-October). Recent use of size frequency data and application of age-length keys from the reduction fishery, suggest that principally age-1 and age-2 menhaden are caught in these samples. Standardized indices for age 1 and age 2 are calculated for the summer and fall seasons (subtracting mean and dividing by standard deviation), and then averaged across seasons for each year.

Four juvenile indices were provided by North Carolina DMF: 1) Alosid seine index in Albemarle Sound (June-October, 1972-2000), 2) striped bass nursery trawl index in Albemarle Sound (July-October, 1982-2000), 3) Pamlico Sound trawl survey index (including Pamlico and Neuse Rivers; June and September, 1987-2000), and 4) estuarine trawl survey index (statewide; May-June, 1987-2000). These indices were standardized, and then averaged across the four indices by year.

The SEAMAP (ages 1 and 2 aligned by yearclass) and combined NC DMF indices are compared with 1-year lagged standardized recruits to age 1 (based on Murphy VPA on reduction and bait data) (Fig. 5.1).

5.2. Middle Atlantic States (Chesapeake Bay). Maryland DNR and the Virginia Institute of Marine Science (VIMS) conduct extensive annual striped bass seine surveys in their respective state waters and tributaries to Chesapeake Bay (primarily June through September) for 1959-2000. Among other fish species, juvenile Atlantic menhaden catch-per-unit effort (CPUE) has recently been made available. Indices were calculated based on arithmetic means for each of the four main regions (Head of Bay, Choptank River, Nanticoke River, and Potomac River) from the Maryland seine survey data for Atlantic menhaden. Standardized indices for each region were calculated, and then averaged across the regions by year.

A similar index of juvenile Atlantic menhaden for tributaries to the Virginia portion of Chesapeake Bay (1968-1973 and 1980-2000) was provided by VIMS based on samples from the lower portion of the rivers where Atlantic menhaden occur.

The Maryland and Virginia indices were re-standardized and combined as a Chesapeake Bay juvenile abundance index, and then compared with 1-year lagged standardized recruits to age 1 (based on Murphy VPA on reduction and bait data) (Fig. 5.2).

5.3. Southern New England States (CT-RI). Connecticut DEP provided indices from their fall trawl survey (1984-1999), and Connecticut River Alosid survey (1987-2000). Standardized indices of each of the Connecticut DEP juvenile abundance indices were calculated, and then averaged for a combined Connecticut index.

Rhode Island F&W provided indices from their juvenile finfish survey of Narragansett Bay (1990-2000) and a trawl survey of Rhode Island coastal waters (1979-2000). These indices were standardized, and averaged to create a combined Rhode Island index.

The re-standardized indices for Connecticut and Rhode Island were then combined, and compared with 1-year lagged standardized recruits to age 1 (based on Murphy VPA on reduction and bait data) (Fig. 5.2).

5.4. Coastwide Comparisons. A coastwide juvenile abundance index was developed for 1959-1999 from re-standardized indices for SEAMAP (age-1 and age-2 menhaden), North Carolina, Chesapeake Bay, and Southern New England (Fig. 5.3). Weightings for each of these regions was 0.15, 0.35, 0.45, and 0.05 (Dr. Dean Ahrenholz, NOAA Beaufort Laboratory, pers. comm.). However, because the SEAMAP indices are for ages 1 and 2, there would be no juvenile value for the latest year (2000). Therefore the SEAMAP indices by age are kept separate and not included in the coastwide index (the above weightings for the remaining three regions are adjusted to add to 1).

Correlations among these juvenile abundance indices and with lagged recruits to age-1 menhaden (based on Murphy VPA on reduction and bait data) were performed. Both the Maryland and coastwide indices were highly correlated with recruits to age 1 (both the Maryland and the coastwide indices at $\alpha = 0.0001$), although marginally significant correlations ($\alpha \sim 0.1$) were found for both SEAMAP (age 1) and Connecticut indices with recruits to age 1. The significance of the correlation for the Virginia index has increased from α = 0.0794 last year to α = 0.1700 with the addition of the index value for 2000. Note that in the early years (1959-1971) the coastwide index is the same as the Maryland index.

Inter-correlations among the indices are for the purpose of testing for coastwide coherency. The Maryland and Virginia seine indices were highly correlated with each other (α = 0.0001). Less significant correlations ($0.01 < \alpha < 0.1$) were found between SEAMAP (age 2) and North Carolina indices (α = 0.0994), SEAMAP (age 1) and Maryland indices (α = 0.0212), and Maryland and Connecticut indices (α = 0.0862).

Not surprisingly, the coastwide juvenile abundance index was highly correlated with North Carolina, and Chesapeake Bay (MD and VA) indices (all at α = 0.0001). The indices for the southern New England states were not significantly correlated with the coastwide indices ($\alpha > 0.18$), which should not be a surprise, since they only represent 5% of the overall weighting. The coastwide index was also not correlated with the SEAMAP indices ($\alpha > 0.37$).

The most recent values of these indices, as well as four VPA variables (calculated by Murphy VPA with and without inclusion of bait fishery data), are compared with their median and interquartile range (Table 5.1). In particular, the estimates of recruitment to age 1 in 2000 are well below their 25th percentiles (whether based on reduction data only or on both reduction and bait data). However, it needs to be re-iterated, that estimation of recruitment in the terminal year from a VPA is the *least precise* estimate. For the juvenile abundance indices, the North Carolina, Virginia and Maryland indices are below their 25th percentile. The SEAMAP indices (ages 1 and 2) are between their median and 75th percentiles, respectively. The southern New England state indices are both above their 75th percentiles. The coastwide index (North Carolina through southern New England) falls just above its 25th percentile.

The interquartile range is an appropriate measure of recent performance relative to historical performance. Hence values outside the interquartile range can be interpreted as low or high relative to their historical performance, while values within the interquartile range are not significantly different from the median value in a statistical sense.

Table 5.1. Current conditions for VPA-generated indices and juvenile abundance indices compared to long-term median and interquartile range. Values for 1999 that fall within the interquartile range should be not be considered different from the long-term median (50th percentile).

Variable	n	2000	25th	50th	75th
Population-Based (VPA) Variables (Murphy on Reduction Only):					
Full F (2+)	46	1.1	1.1	1.4	1.7
R_1 (billions)	46	0.8	1.9	3.0	4.5
SSB (1000 t)	46	33.2	20.9	39.9	62.9
SPR (%)	46	8.6	3.1	5.5	8.2
Population-Based (VPA) Variables (Murphy on Reduction & Bait):					
Full F (2+)	46	0.6	1.0	1.3	1.6
R_1 (billions)	46	1.2	2.1	3.2	4.7
SSB (1000 t)	46	90.1	28.0	54.5	88.7
SPR (%)	46	21.5	3.6	6.5	11.2
Standardized Juvenile Abundance Indices for:					
SEAMAP (Age 1)	12	-0.21	-0.68	-0.33	0.39
(Age 2)	12	-0.13	-0.78	-0.29	0.52
NC Combined	29	-1.10	-0.77	-0.04	0.42
VA Seine	27	-0.77	-0.64	-0.45	0.28
MD Seine	42	-0.92	-0.90	-0.34	0.85
CT Combined	17	0.46	-0.56	-0.43	0.25
RI Combined	22	4.41	-0.27	-0.27	-0.23
Coastwide	42	-0.78	-0.81	-0.17	0.43

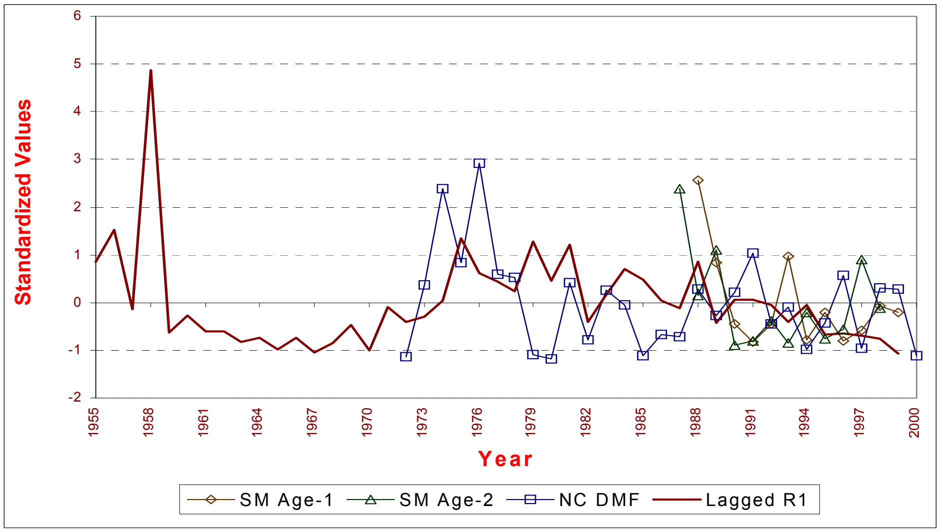

FIGURE 5.1. Comparison of standardized indices for Atlantic menhaden from U.S. south Atlantic states with standardized lagged recruits to age.

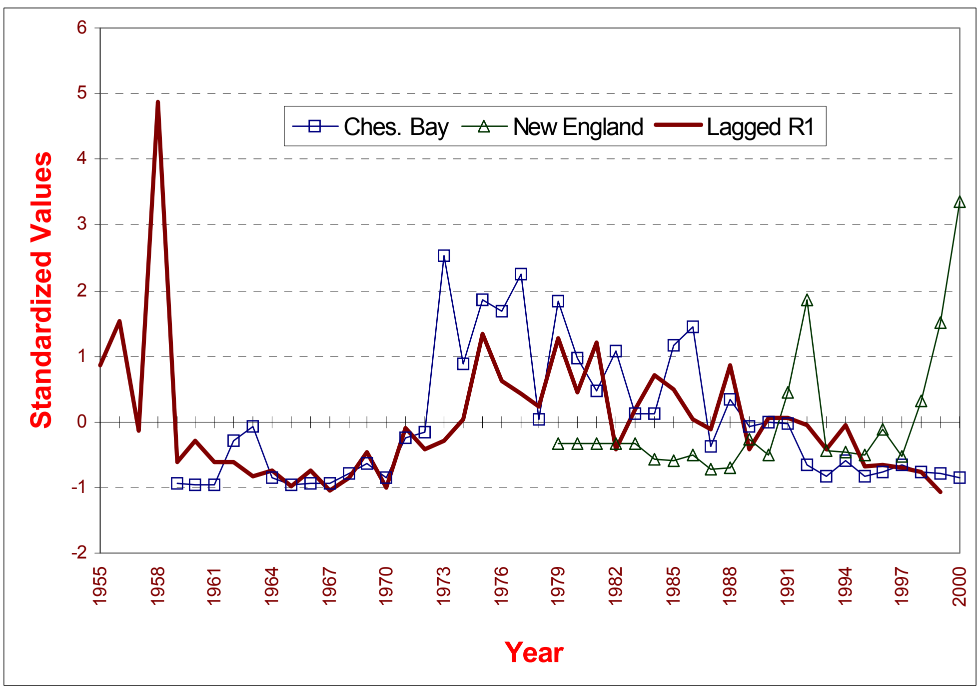

FIGURE 5.2. Comparison of standardized indices for Atlantic menhaden from U.S. Middle Atlantic and Southern New England states with standardized lagged recruits to age.

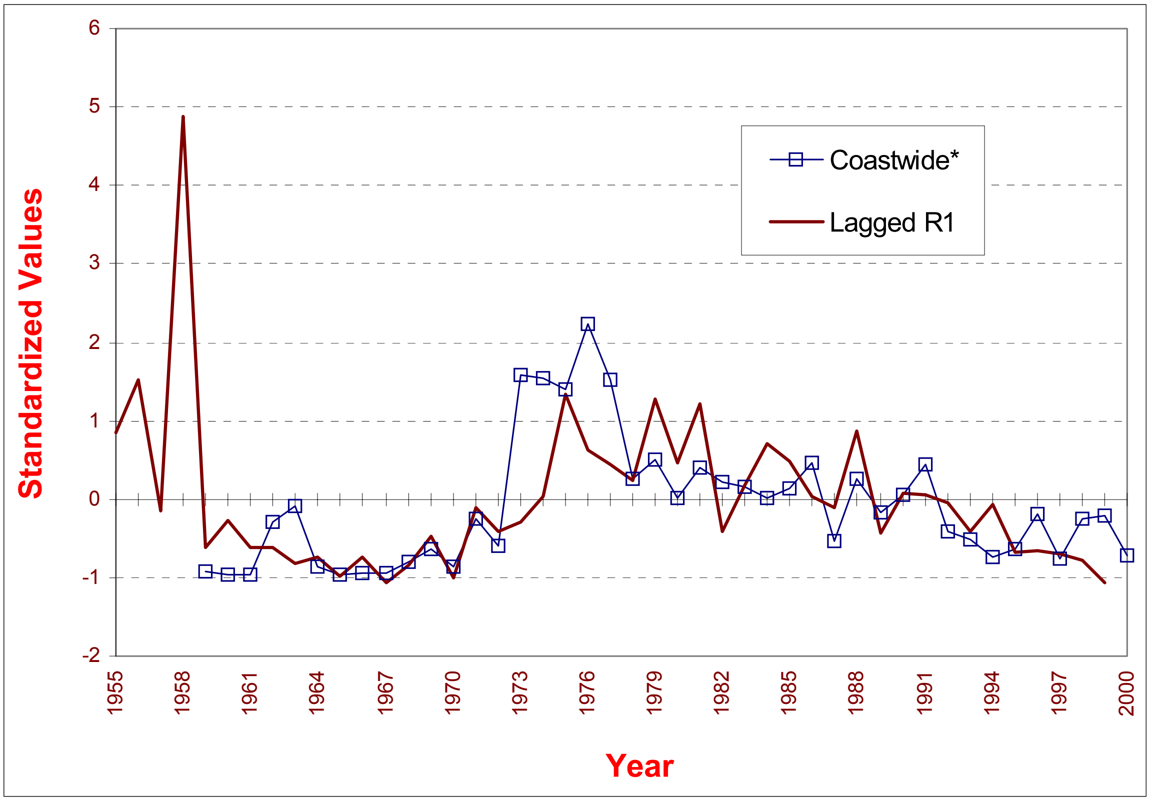

FIGURE 5.3. Comparison of standardized index for Atlantic menhaden from the coastwide index with standardized lagged recruits to age.

6. Biological Reference Points

Under the re-authorization of the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA), benchmarks based on two approaches are described (Restrepo et al. 1998). The schematic in Fig. 6.1 summarizes these approaches as modified from that in the Gulf Council's SPR Management Strategy Committee report (Mace et al. 1996). Fishing mortality is on the vertical axis, and spawning stock biomass on the horizontal axis. F' and B' represent targets, while F" and B" represent thresholds. When spawning stock biomass is below a threshold level, we have purposely used the term depleted, rather than overfished, because fishing may not be the cause of this reduced level of spawning stock biomass. However, it is still the responsibility of management to assist in rebuilding a depleted stock to the target level, regardless of the cause of the decline. Recruitment is not on this schematic, because it is not directly controllable by management actions. Maintenance of spawning stock in the vicinity of the target level is the primary management influence over recruitment. Targets represent desired long term levels, while thresholds represent levels beyond which threatens long term viability of the stock. An alternative modeling approach based on surplus production models (ASPIC) is described in Vaughan et al. (2001).

With the recent approval of Amendment 1 to the Atlantic Menhaden Fishery Management Plan (ASMFC), benchmarks based on the two population variables from the MSFCMA were adopted. Historical values of these variables are estimated from application of virtual population analysis described in section 2. Fishing mortality on the fully recruited ages (full F) is calculated from the weighted average of age-specific estimates of F for ages 2 and older (weighting based on catch in numbers). Spawning stock biomass (SSB) is calculated from one-half the weight of menhaden ages 3 and older in the population. Analyses have been conducted with just reduction data (Section 2) and with the incorporation of bait data (Section 3). Much of the results presented below will be for analyses based on combined reduction and bait data unless stated otherwise. Addition of the bait data implies a change in selectivity and differences in estimated benchmarks from analyses based only on reduction data.

6.1. F-based Benchmarks.

F-based benchmarks are used to judge whether the rate of removal of fish by man's activity is too great; that is, fishing prevents the stock from replenishing itself. When the rate is too high or exceeds a threshold, then overfishing is said to occur. Under Amendment 1, the target and threshold for full F are 1.0 and 1.4, respectively. Potential values for targets and thresholds presented in earlier analyses were obtained from a variety of approaches, including: 1) historical performance (25^{th} , 50^{th} and 75^{th} percentiles), 2) yield per recruit (YPR: F_{max} and $F_{0.1}$), 3) static spawning potential ratio (SPR and F_{med}), and 4) spawner-recruit (S/R).

The time series of data for Atlantic menhaden is one of the longest in the United States, hence consideration of historical performance is a reasonable approach to evaluating the ability of the stock to cope with historical levels of fishing mortality. Levels of performance of F based on percentiles are summarized in Table 6.1 based on Murphy VPA on reduction data only and in Table 6.2 based on reduction and bait data combined. A general decline was noted earlier (Section 2.4) in exploitation rate from 1965 to the present. With reduction data only, the recent estimate of full F (1.1) is approximately at the 25th percentile. With both reduction and bait data, the recent estimate of full F (0.6) is well below the 25th percentile.

Estimates of yield per recruit were calculated from estimates of partial recruitment (selectivity) for 1996-2000 using the method of Ricker (1975) (Fig. 6.2). F_{max} represents the level of fishing mortality that maximizes biomass return to the fishery, while $F_{0.1}$ is based on an economic return argument. $F_{0.1}$ is that level of F which occurs where the slope of the tangent to the yield-per-recruit curve is 10% of that at the origin. F_{max} occurs at a full F (mean F over ages 1-8) of about 0.9 to 1.0, while $F_{0.1}$ occurs at a full F of about 0.5 for Atlantic menhaden with partial recruitment based on the period 1996-2000 (Table 6.1 and 6.2).

Estimates of spawning stock biomass per recruit (static SPR) were estimated using the partial recruitment (selectivity) for 1996-2000 using the method of Gabriel et al. (1989) (Fig. 6.2). This analysis compares spawning stock biomass per recruit calculated for different levels of fishing mortality to spawning stock biomass per recruit calculated with F=0 under an equilibrium (static) assumption. Note that this approach does not calculate the virgin spawning stock biomass, rather a theoretical spawning stock biomass based on the assumption that the life history parameters are unaltered from this 'virgin' state. Biological reference points based on static SPR are given as F subscripted with the level desired for static SPR. Hence, F_{20} refers to the level of F that would produce a theoretical ratio of 20% SPR. Definitions of overfishing (as opposed to overfished or depleted state of the stock) have typically ranged from 20% to 40%, with the higher values associated with long-lived, late-maturing species. For the static SPR approach, F_5 occurs at an full F of about 1.5 to 1.7, F_{10} occurs at an full F of about 1.1, and F_{20} at about 0.7 (Table 6.1 and 6.2).

Another reference point based on spawning stock biomass per recruit is described by Sissenwine and Shepherd (1987). This reference point, F_{med} or F_{rep}, uses the median of plotted R/SSB, and compares the inverse to the theoretical curve of SSB/R (values in Fig. 6.2 unadjusted for SSB/R at F=0). Median SSB/R for the historical Atlantic menhaden data was 15.6 expressed as metric tons per million recruits. The corresponding F from the SSB/R curve generated for the partial recruitment (selectivity) during 1996-2000 was interpolated at 1.1 to 1.3 (and equivalent to a static SPR of 7-9%).

Estimates of F-based benchmarks for spawner-recruit models are more problematic. Parameter fits to the Ricker and Beverton-Holt S/R models are described in Sections 4.2 and 4.3. As noted in those sections, the density-dependent parameter (β) was significantly different from 0 for the Ricker model, but not for the Beverton-Holt model. Therefore, it may be legitimate to proceed with exploring the consequences of an underlying Ricker model, but not with the Beverton-Holt model. May (1976) notes the complex behavior that can arise from simple difference equations (specifically of the form of the Ricker curve). Vaughan et al. (1984) noted that the addition of stress (mortality) on a population regulated by the Ricker curve can alter its dynamics from more complex behavior (i.e., chaotic or bifurcation) to less complex behavior (e.g., stable equilibrium). Based on 100-yr projections using the Ricker model on Atlantic menhaden, complex behavior in spawning stock and recruitment was obtained for multiples of mean F for 1996-2000 (0.72 from reduction and bait data combined) ranging from 0.0 to about 2.0. More stable behavior was obtained for multiples of F starting at about 1.4. Long-term MSY is maximized at about 381,000 t for a multiple F of about 1.5 (F = 1.1), corresponding to SSB of about 165,000 t and mean recruits to age 1 of about 3.6 billion (very similar to the theoretical values for maximum SSB and R obtained in Section 4.2). Usefulness of these estimates is open to debate given the long-term median for F rounds to 1.3, but SSB and R_1 have generally been lower during most of the time series.

6.2. SSB-based Benchmarks.

SSB-based benchmarks are used to judge whether the spawning stock is too low; that is, a depleted stock is too low to replenish itself. When the spawning stock biomass is too low or falls below a threshold, then the stock is said to be depleted. Under Amendment 1, the target and threshold for SSB are 37,400 t and 20,570 t, respectively. As with F-based thresholds, potential values for targets and thresholds presented in earlier analyses were obtained from a variety of approaches, including: 1) historical performance, 2) yield per recruit (YPR), 3) static spawning potential ratio (SPR and F_{med}), and 4) spawner-recruit (S/R).

Estimates of spawning stock biomass are available for 1955 through 2000 (46 years) during which the population has undergone periods of moderate to high recruitment (1955-1959 and 1975-89) and moderate-low recruitment (1960-1974 and 1990-2000). Following periods of low recruitment, spawning stock biomass has declined, and following periods of high recruitment, spawning stock biomass has increased. Levels of performance based on percentiles are summarized in Table 6.1 for the Murphy VPA with reduction catch matrix only and in Table 6.2 for the Murphy VPA with reduction and bait catch matrices combined. In both times series, SSB reached a recent high in 1997 and have decayed somewhat from that level. With reduction data only, the recent estimate of SSB (33,200 t) is between the 25th and 50th percentiles. With both reduction and bait data, the recent estimate of SSB (90,100 t) is above the 75th percentile.

To obtain a SSB for YPR benchmarks, the SSB/R equivalent to the F-based benchmark is obtained first (Table 6.1 and 6.2). The estimate of SSB/R times recruitment gives an estimate of spawning stock biomass. The value used to represent recruitment is the median from the 46-year time series (3.0-3.2 billion). Similarly, SSB for static SPR benchmarks, including the replacement approach of Sissenwine and Shepherd (1987), are obtained in a similar manner. Estimates of SSB for the YPR and static SPR approaches are summarized in Table 6.1 and 6.2..

Additionally, a potential threshold for SSB would be that suggested by Myers et al. (1994; discussed in Sections 4.2 and 4.3) using SSB that produces ½max{R_1} (20,400 t for the Ricker model based on Murphy VPA on reduction and bait catch matrices combined).

6.3. Fishery Control Rules.

Historically, the primary VPA analyses for Atlantic menhaden have used the catch-at-age matrix from the reduction fishery only and using the Murphy (1965) approach (Ahrenholz et al. 1987; Vaughan 1990, 1993; Vaughan and Merriner 1991; Vaughan et al. 1986, 2001; Vaughan and Smith 1988, 1998, 1999, 2000; and ASMFC Amendment 1). Based on this historical precedence, current values for F (F_{2000} = 1.1) and SSB (SSB_{2000} = 33,200 t) fall in the "grey" area between the target and threshold values (see solid square in Fig. 6.3). With the incorporation of the bait removals into the catch-at-age matrix (1985-2000) and application of the same Murphy VPA approach, lower estimates of F (F_{2000} = 0.6) and higher estimates of SSB (SSB_{2000} = 90,100 t) were obtained, in the "good zone" defined by there respective targets for the year 2000 (Fig. 6.4). New benchmarks are estimated that parallel those developed in Amendment 1. This is necessary due to the change in selectivity implied by incorporating bait data into the analysis. Because the original estimate of F-target was based on F_{max} and F-threshold was based on F_{rep}, new estimates of these benchmarks are 0.9 and 1.1, respectively. Similarly, SSB-target was estimated from the SSB per recruit for Frep times median recruitment, and SSB-threshold was calculated from (1-M)*SSB-target (see Restrepo et al. 1998). Following this approach, new estimates of SSB-target (50,000 t) and SSB-threshold (27,500 t) were made.

Preliminary analysis of Atlantic menhaden was made using a forward projecting age-structured model fitted with AD Model Builder software (Appendix B). Data from the reduction (1955-2000) and bait (1985-2000) fisheries for Atlantic menhaden were compiled along with a catch-weighted coastwide CPUE index for input into a forward projecting, age-structured population model. Estimates of full F, recruits to age 1, and spawning biomass (SSB) from the model with and without the bait fishery are shown in Table B.1. In particular, this model suggests improving recruitment in the most recent years (greater with bait data than without). Plots on fishery control rules (full F and SSB) are shown in Fig. B.2. Based on just the reduction data, the current value of full F is above the threshold (overfishing), but the uncertainty is such that F could be below the threshold or even target levels. The current value of SSB is slightly above the threshold, so the uncertainty suggests that there is almost even odds that it is above or below the threshold. However, when bait data are included, full F is clearly below its target (a small probability that it is above the target) and SSB is clearly above its target.

The surplus production approach offers an alternative method for investigating the benchmarks (F and SSB) relative to internally consistent estimates of F_{msy} and B_{msy} (Appendix C). The temporal pattern in F is somewhat different from the age-structured approaches. Although there is agreement that F was high in the 1960s, these estimates drop to a minimum, and then gradually increase over time to a recent high during 1995-1998. Low values ensue for the last two years with the recent reduction in effort. Biomass (ages 0 and older, rather than SSB) follows the same generally trend as SSB from the age-structured models. With younger age groups included, biomass more quickly reflects the poor recruitment during the 1990s, but suggests a recent increase from very low values.

Table 6.1. Biological reference points from Murphy VPA output using reduction data only: a) historical performance (as percentiles), b) yield per recruit ($F_{0.1}$ and F_{max}), and c) static spawning stock per recruit (SPR for 5, 10 and 20%, and replacement, F_{med}). Selectivity for YPR, static SPR, and replacement based on 1996-2000 pattern.

Approach	Biological Reference Points F (1/yr)	 SSB/R (t/million)	 SSB[a] (1000 t)
Historical Performance (1955-2000):			
25^{th} %	1.1	6.7	20.9
50^{th} %	1.4	12.4	39.9
75^{th} %	1.7	34.8	62.9
Yield per Recruit:			
$F_{0.1}$	0.5	50.4	151.2
F_{max}	1.0	19.2	57.6
Static SPR (in biomass):			
5%	1.7	8.5	25.5
10%	1.1	17.0	51.0
20%	0.7	34.0	102.0
Replacement (SSB/R):			
50^{th} %	1.3	12.5	37.5

[a] Multiply SSB/R by median recruits to age 1 (3.0 billion) to obtain SSB, except for historical performance.

Table 6.2. Biological reference points from Murphy VPA output using reduction and bait data: a) historical performance (as percentiles), b) yield per recruit ($F_{0.1}$ and F_{max}), and c) static spawning stock per recruit (SPR for 5, 10 and 20%, and replacement, F_{med}). Selectivity for YPR, static SPR, and replacement based on 1996-2000 pattern.

Approach	Biological Reference Points F (1/yr)	SSB/R (t/million)	SSB[a] (1000 t)
Historical Performance (1955-2000):			
25^{th} %	1.0	8.2	28.0
50^{th} %	1.3	15.6	54.5
75^{th} %	1.6	37.4	88.7
Yield per Recruit:			
$F_{0.1}$	0.5	50.9	162.8
F_{max}	0.9	20.5	65.4
Static SPR (in biomass):			
5%	1.5	8.5	27.2
10%	1.1	17.0	54.4
20%	0.7	34.0	108.8
Replacement (SSB/R):			
50^{th} %	1.1	15.6	50.0

[a] Multiply SSB/R by median recruits to age 1 (3.0 billion) to obtain SSB, except for historical performance.

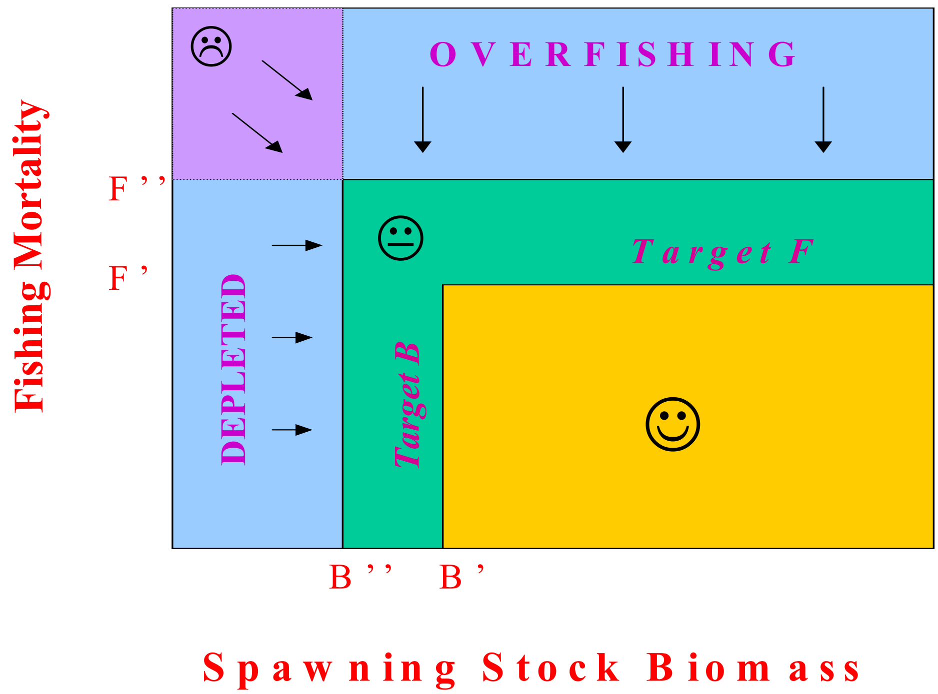

Figure 6.1. Schematic fisheries control law (modified from Mace et al. 1996).

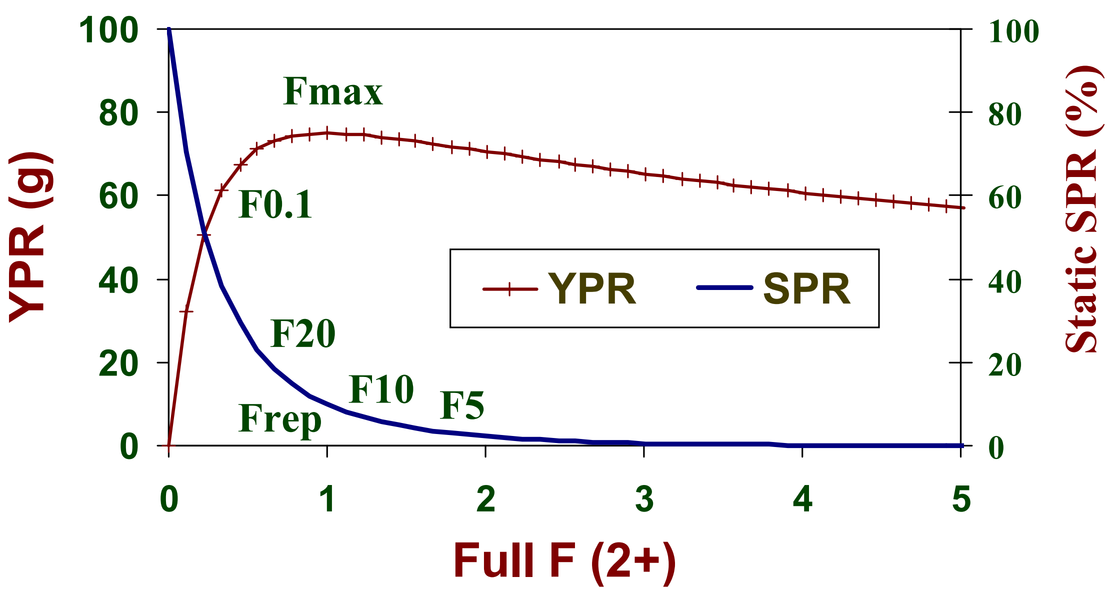

Figure 6.2. YPR and static SPR for Atlantic menhaden.

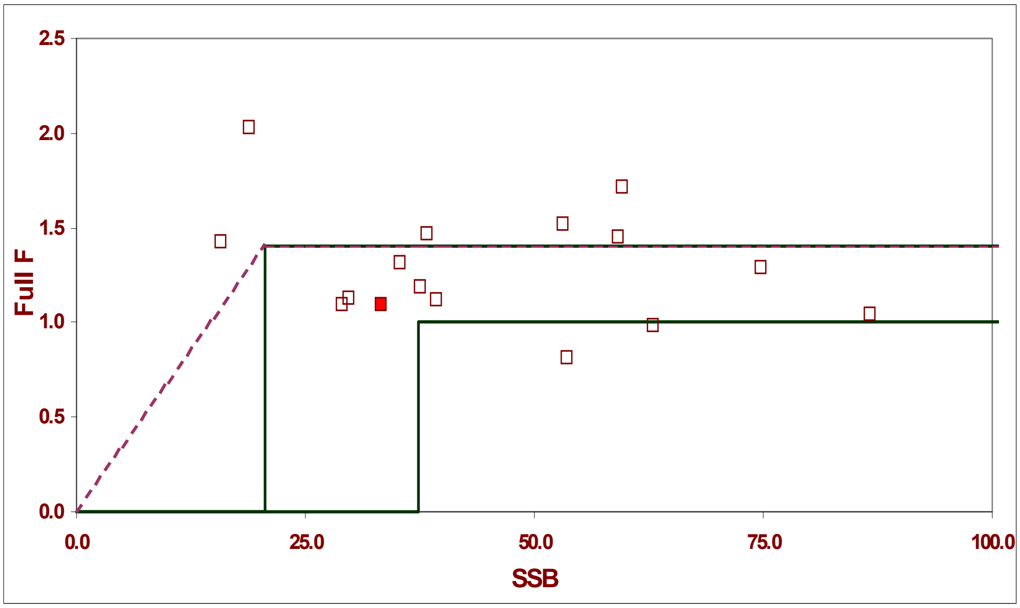

Figure 6.3. F and SSB from standard (reduction fishery only) assessment for Atlantic menhaden with benchmarks from Amendment 1. (Solid square represents 2000)

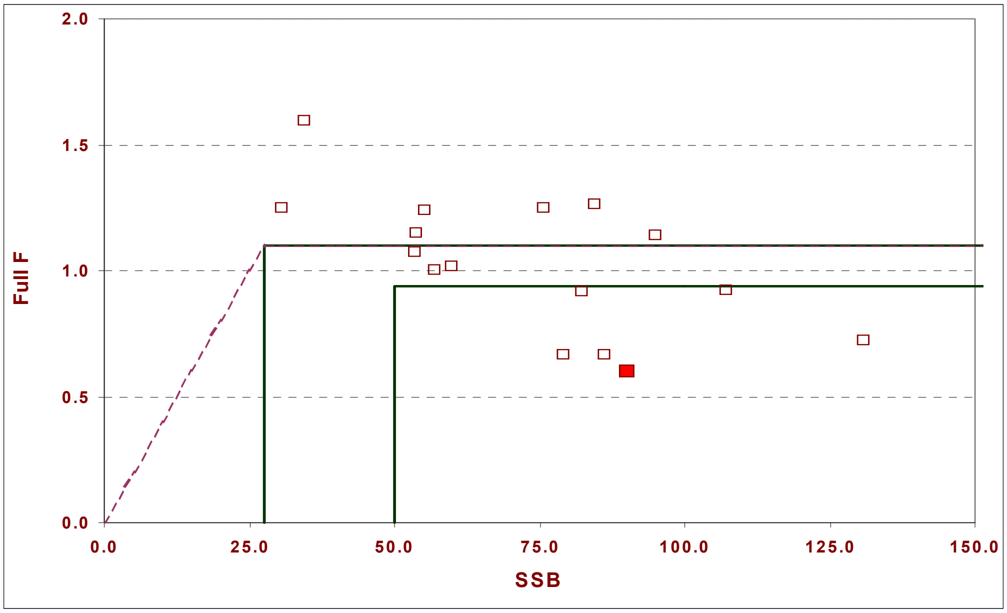

Figure 6.4. F and SSB from assessment with reduction and bait landings for Atlantic menhaden with benchmarks recalculated based on Amendment 1.(Solid square represents 2000)

7. Summary

7.1. Data and Research Needs. More reliable landings data and continuation and expansion of biostatistical sampling are needed for the menhaden bait fishery along the Atlantic coast. Exploration of the unreported catch of Atlantic menhaden in other fisheries (e.g., south Atlantic shrimp trawl fisheries) would be worthwhile. Further exploration of the striped bass seine surveys (both Maryland and Virginia components) and other coastal surveys are being pursued and should continue. Size-specific data from SEAMAP suggests that mostly age-1 and age-2 menhaden are caught in that survey. Other than the VIMS index which is based on age-0 menhaden, the other indices are assumed age 0. However, calibration virtual population analyses have tended to be unstable when tuned against a single age class (e.g., lagged age-1 recruits). Hence, there is a need for a multi-age survey that at least captures the center of the stock (e.g., North Carolina through Delaware). Power plant impingement data may provide one method for obtaining these data. Additional exploration of potential environmental factors and other multi-species interactions (e.g., predator-prey) should be continued. Development of a program to identify causes of low menhaden recruitment in recent years would be useful.

7.2. Management Objectives. Following the recent period of poor recruitment to age 1 (below 2 billion for 1996-2000; Fig. 2.7) based on the Murphy VPA approach applied to reduction data only, we are now seeing the decay of the SSB from recent high levels to below the historical median. The concern about recent poor recruitment is further substantiated by our investigations with state-based juvenile abundance indices and development of a coastwide index (Section 5). Because the decay in SSB is in response to declining recruitment, recruitment for Atlantic menhaden appears to be largely controlled by environmental conditions and not from lack of spawning stock biomass (Section 4). Hence, seeking to increase spawning stock biomass is not likely to improve the situation by itself.

With the addition of bait data to these analyses, the status of F and SSB in 2000 suggest that fishing mortality rate is well below the F-target and SSB is well above the SSB-target (either based on benchmarks from Amendment 1 or on re-calculated benchmarks) (Fig. 3.2 and B.1). However, only slight improvement is noted in recent estimates of recruits to age 1, with the most recent estimates for 1999 and 2000 very low. These estimates typically are poorly estimated from VPA approaches, and possess large uncertainty associated with them. With recent low values for juvenile abundance indices from the Chesapeake Bay, this region appears to be the epicenter for poor survival to age 1.

There is no evidence that the recent low levels of recruitment were caused by overfishing, hence, the primary benefit from reducing fishing effort (hence fishing mortality) would be to reduce the rate at which older Atlantic menhaden are removed from the population to allow time for fortuitous recruitment to occur. Estimates of natural mortality for Atlantic menhaden from extensive tagging studies (Ahrenholz et al. 1987) suggest M is about 0.45, which implies about 36% mortality in the absence of fishing. Much of that tagging work was done during a period when stocks of striped bass and other piscivores were at moderate to low levels.

With increased predation in recent years, e.g., improved populations of striped bass, weakfish, marine mammals, cormorants and other piscivores, M now is probably higher than 0.45. Hence, in the short run some significant reduction in fishing effort may slow the decline in spawning stock biomass. Only the occurrence of one or more moderate to strong recruitment year classes will prevent the continuing deterioration from recent high levels of spawning stock biomass to lower levels.

8. References

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APPENDICES A-C

Appendix A: Estimating Reduction Landings from Chesapeake Bay

Because of recent concerns about the availability of forage fish for striped bass in the Chesapeake Bay, we have developed estimates of the removals of Atlantic menhaden (as opposed to landings) from the Bay proper. Smith (1999) provided such estimates of menhaden catches from Chesapeake Bay for 1985-1996 based on the Captain's Daily Fishing Reports (CDFRs), which we update in this appendix for 1996-2000. In addition we develop two approaches for estimating historical values prior to the availability of CDFRs (1955-1984).

The first approach is based on estimates of landings by port and corresponding biostatistical sampling, 1955-2000. Biostatistical sampling, which provides location of final set, are also available from all ports. An estimate of the portion of landings by port can be made from these data by assuming that final set, and hence sampling, is proportional to location of set (i.e., inside or outside Chesapeake Bay). There has historically been concern about "topping off" in which vessels fishing from Reedville, VA, will make a final set upon returning to the Bay after fishing outside the Bay. This first approach would tend to overestimate the catch from Chesapeake Bay relative to outside the Bay under this condition.

The second approach regresses estimates of landings within the Bay from CDFRs on the estimates from the biostatistical approach (no-intercept linear regression). The resultant estimates from this regression should be unbiased relative to the "topping off" problem. Estimates from the CDFRs, biostatistical approach, and regression approach are summarized in Table A.1. Percentages of total coastwide reduction landings caught in Chesapeake Bay are shown in Fig. A.1.

Table A.1. Estimates of catch (1000 t) of Atlantic menhaden from Chesapeake Bay from biostatistical sampling, Captain's Daily Fishing Reports, and predicted from no-intercept linear regression.

Year	Biostatistical	CDFR	Predicted	Total
1955	57.8		48.7	641.4
1956	77.8		65.6	712.1
1957	32.4		27.3	602.8
1958	76.3		64.2	510.0
1959	48.9		41.2	659.1
1960	41.3		34.8	529.8
1961	65.1		54.9	575.9
1962	47.3		39.9	537.7
1963	30.1		25.3	346.9
1964	6.7		5.7	269.2
1965	81.7		68.8	273.4
1966	73.7		62.1	219.6
1967	52.7		44.4	193.5
1968	73.0		61.5	234.8
1969	36.3		30.6	161.6
1970	105.8		89.1	259.4
1971	143.4		120.8	250.3
1972	209.9		176.8	365.9
1973	181.7		153.0	346.9
1974	127.6		107.5	292.2
1975	100.3		84.5	250.2
1976	138.7		116.9	340.5
1977	154.4		130.1	341.2
1978	142.6		120.1	344.1
1979	123.1		103.7	375.7
1980	208.6		175.8	401.5
1981	37.0		31.1	381.3
1982	171.4		144.4	382.4
1983	177.3		149.3	418.6
1984	115.8		97.5	326.3
1985	167.5	127.3	141.1	306.7
1986	146.4	141.4	123.3	238.0
1987	206.8	177.4	174.2	327.0
1988	167.2	155.9	140.8	309.3
1989	183.4	156.0	154.5	322.0
1990	178.1	149.5	150.0	401.2
1991	188.5	161.8	158.8	381.4
1992	181.9	135.7	153.2	297.6
1993	223.8	168.5	188.6	320.6
1994	132.4	125.9	111.6	260.0
1995	201.5	147.4	169.7	339.9
1996	179.7	147.8	151.4	292.9
1997	160.2	153.3	134.9	259.1
1998	159.3	144.5	134.2	245.9
1999	123.6	120.3	104.1	171.3
2000	95.3	81.0	80.3	167.3

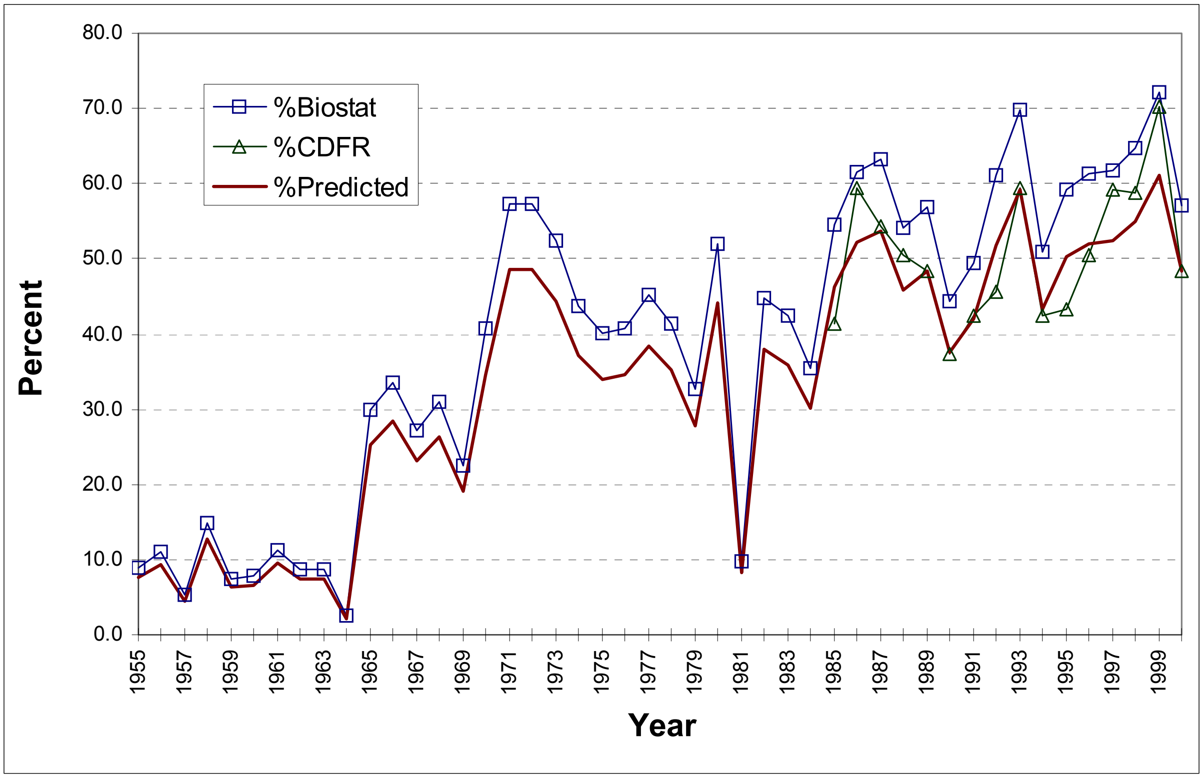

Figure A.1. **Estimates of landings of Atlantic menhaden from Chesapeake Bay as percent of total landings from three estimation procedures: biostatistical, CDFR, and regression prediction.**

Appendix B: Preliminary Analysis of Atlantic Menhaden Using a Forward Projecting Age-structured Model Fitted with the AD Model Builder Software.

Data from the reduction (1955-2000) and bait (1985-2000) fisheries for Atlantic menhaden were compiled along with a catch-weighted coastwide CPUE index for input into a forward projecting, age-structured population model. The model was programmed in the AD Model Builder software, which allows for rapid optimization of hundreds of parameters and provides Delta-method approximations of the standard deviations of model estimates based on the Hessian matrix derived from a quasi-Newton optimization routine.

Natural mortality in the age-structured model was assumed fixed for all years and ages to be 0.45 per year. Fishing mortality followed the separability assumption with a selectivity and full fishing mortality component. Fishing mortality time series for both the reduction and bait fisheries were modeled with a parameter for the average of the time series and a deviation parameter for each year of each fishery, constrained to follow a normal distribution. Selectivity was modeled for each fishery using a logistic function, composed of a slope parameter and an average age at 50% selection parameter (A50). As was done with the fishing mortality time series, a set of A50 deviation parameters were estimated for each year of each fishery. These deviation parameters were also constrained to follow a normal distribution.

In a forward projecting age-structured model, the numbers at the first age (in this case age 0) are parameters of the model. As was done above, the time series was modeled with a mean and set of deviation parameters, constrained to follow a lognormal distribution. The numbers-at-age for all years in the model (1955-2000) is then computed by tracking each cohort's decay from total mortality (F+M). The catch-at-age from the population was estimated using the Baranov catch equation. Estimated landings were computed as the product of catch-at-age and weight-at-age for each year. Spawning biomass was computed as the product of numbers-at-age, maturity-at-age, and spawning weight-at-age. Total biomass was computed as the product of numbers-at-age and weight-at-age. Estimated CPUE was then estimated from the numbers of age 0 recruits multiplied by a catchability parameter.

The model was estimated with 183 and 148 parameters by including and excluding the bait fishery, respectively. The model parameters were estimated in the AD Model Builder software by minimizing the sum of the negative log-likelihood components. Observed catch-at-age was input as percent composition and modeled with a multinomial likelihood function. Observed landings were modeled with a normal likelihood function and assumed to have 5% and 15% coefficient of variation (CV) for the reduction and bait fisheries, respectively. The CPUE index was assumed to have a CV of 25% and modeled with a lognormal likelihood function. Estimates from the model with and without the bait fishery are shown in the following figures.

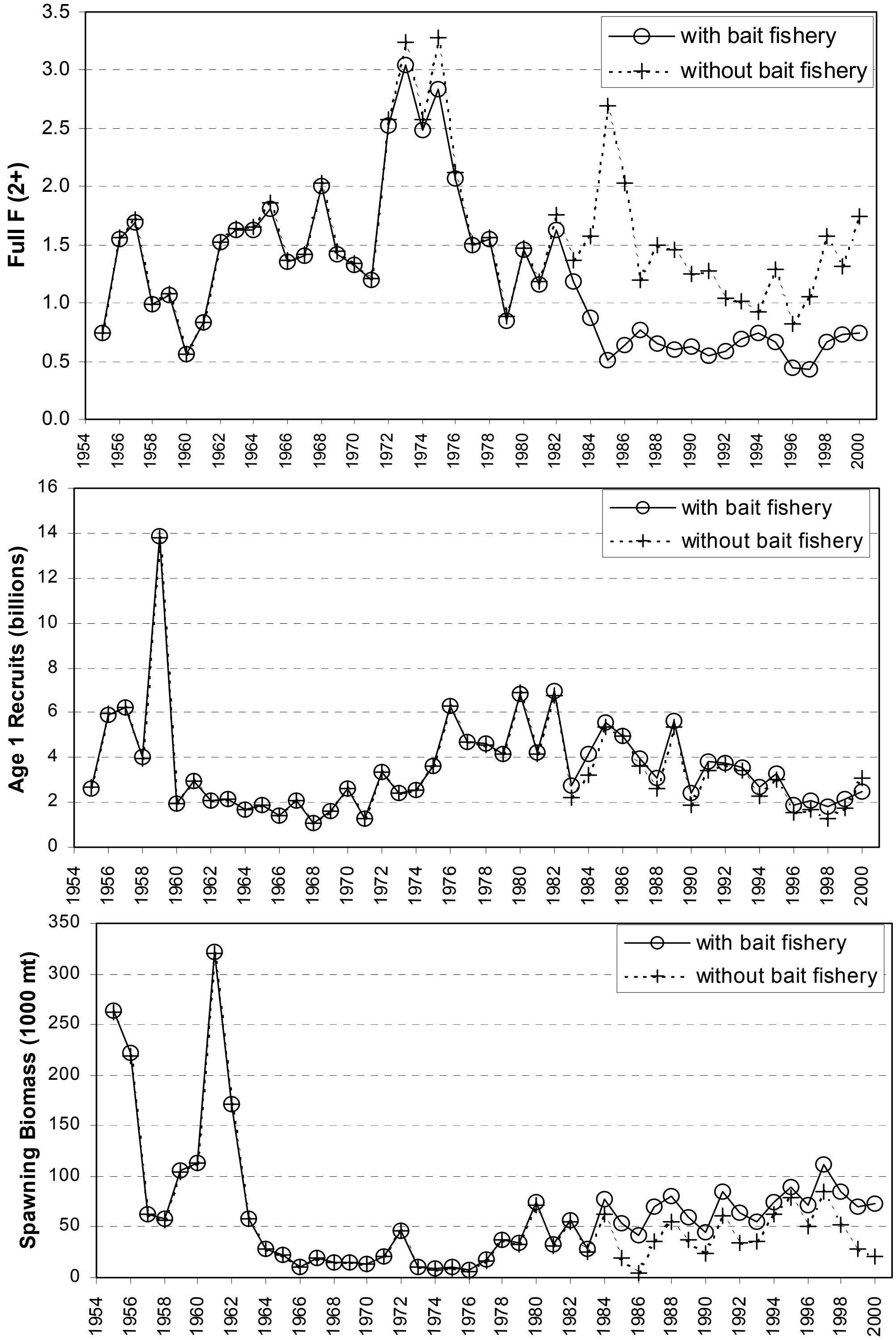

Figure B.1. **Fishing mortality, recruitment, and spawning biomass time series estimates for Atlantic menhaden from the forward projecting age-structured population model.**

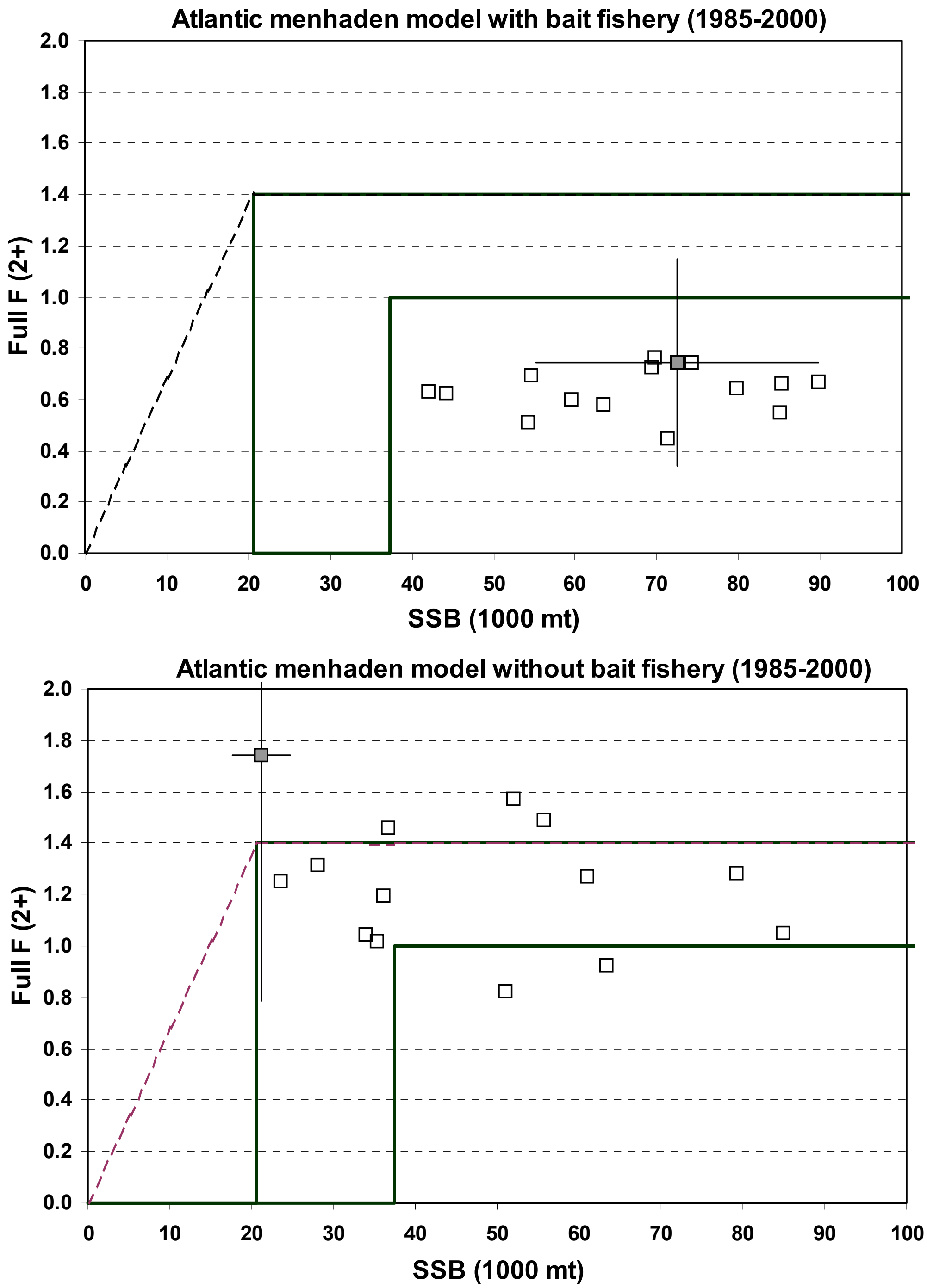

Figure B.2. **Recent estimates of full F (2+) and spawning biomass (1985-2000) with management thresholds marked as solid heavy lines. Year 2000 point is shaded and marked with 95% confidence interval lines.**

Appendix C. Surplus-Production Model

A logistic (Schaefer-form) surplus-production model was applied to data on total annual landings in weight and estimates of stock biomass (ages 0 and older) derived from the VPA based on reduction and bait data combined. Biomass was used rather than fishing effort or CPUE in order to remove effects of density-dependent catchability, a phenomenon well documented in this species (Schaaf 1979). Because absolute biomass estimates were used, the catchability coefficient was fixed at $q = 1$, thus reducing the usual number of estimated parameters by one.

Fitting used an observation-error estimator, conditioned on observed yield and estimated in logarithmic transformation, as implemented by the ASPIC computer program (Prager 1994, 1995). A bootstrap was used to estimate confidence intervals on reference points and estimated population trajectories of biomass B and fishing mortality rate F. The model fit the data reasonably well (Fig. C.1), with R^2 of 74% (computed on non-log-transformed data) between observed and predicted biomass series. The largest discrepancies are in the years of peak abundance centered around 1960, where the production model, most likely because it lacks age structure, is unable to replicate the rapid changes in stock size estimated by age-structured cohort-based models.

Estimates of management-related quantities (Table C.1) and of trajectories of biomass and fishing mortality rate (relative to their respective benchmarks B_{MSY} and F_{MSY}) depict a stock that has been below the benchmark B_{MSY} since about 1960, and fishing mortality rate that has been above F_{MSY} for most of the time period (Fig. C.2). The model used, and thus these estimates, assume that population parameters (carrying capacity and MSY) have remained constant through the time period.

Nonparametric 80% confidence intervals on B and F are quite narrow (Fig. C.2), and we emphasize that they include only one source of uncertainty: fit of the logistic model to the observed data. True uncertainty about the estimates includes model specification error and the statistical error associated with the VPA biomass estimates and is thus much greater. To assess the reasonableness of the assumption $q = 1.0$, we refit the logistic model, estimating q; the resulting estimate was $q = 1.1$, which suggests that the assumption is not in marked conflict with the data or model.

Estimated fishing mortality rates from the production model are lower than those from the cohort models, being 0.19/yr in the year 2000. This difference reflects several factors, but chief among them are that the production model estimates F are in units of proportion of weight per year, not proportion of number, and that the cohort-model estimates are of fully-selected F (peak F), but the production-model estimates are of F across the entire stock biomass, including all ages from zero.

Table C.1. Estimates of three management-related quantities for Atlantic menhaden, estimated by logistic production model. Bias-corrected 80% confidence intervals, derived from bootstrapping, are also given.

Estimated quantity	Point estimate	BC 80% interval
Maximum sustainable yield (MSY)	450 kmt/yr	386–1087
B_{2001}/B_{MSY}	0.58	0.42–0.68
F_{2000}/F_{MSY}	0.82	0.68–1.03

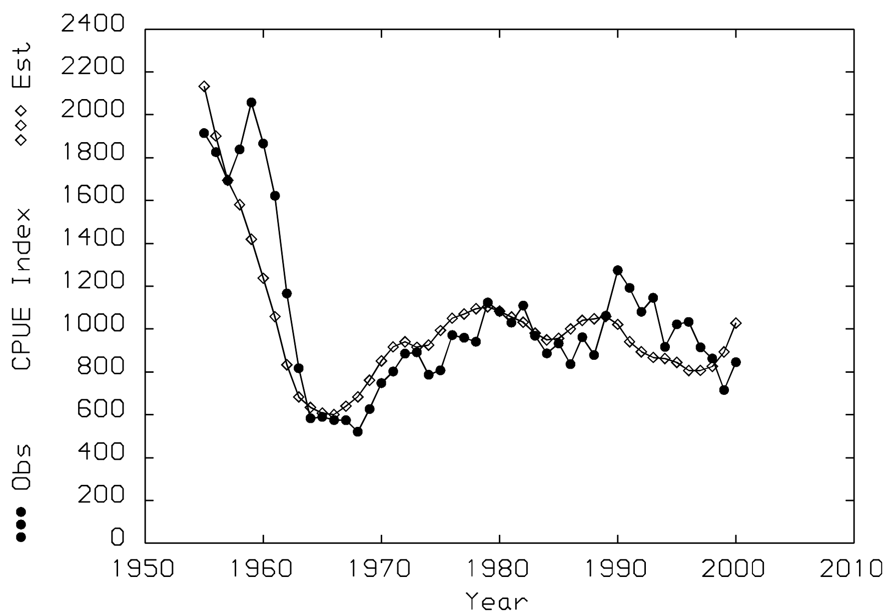

Figure C.1. Fit of surplus-production model to Atlantic menhaden biomass series.

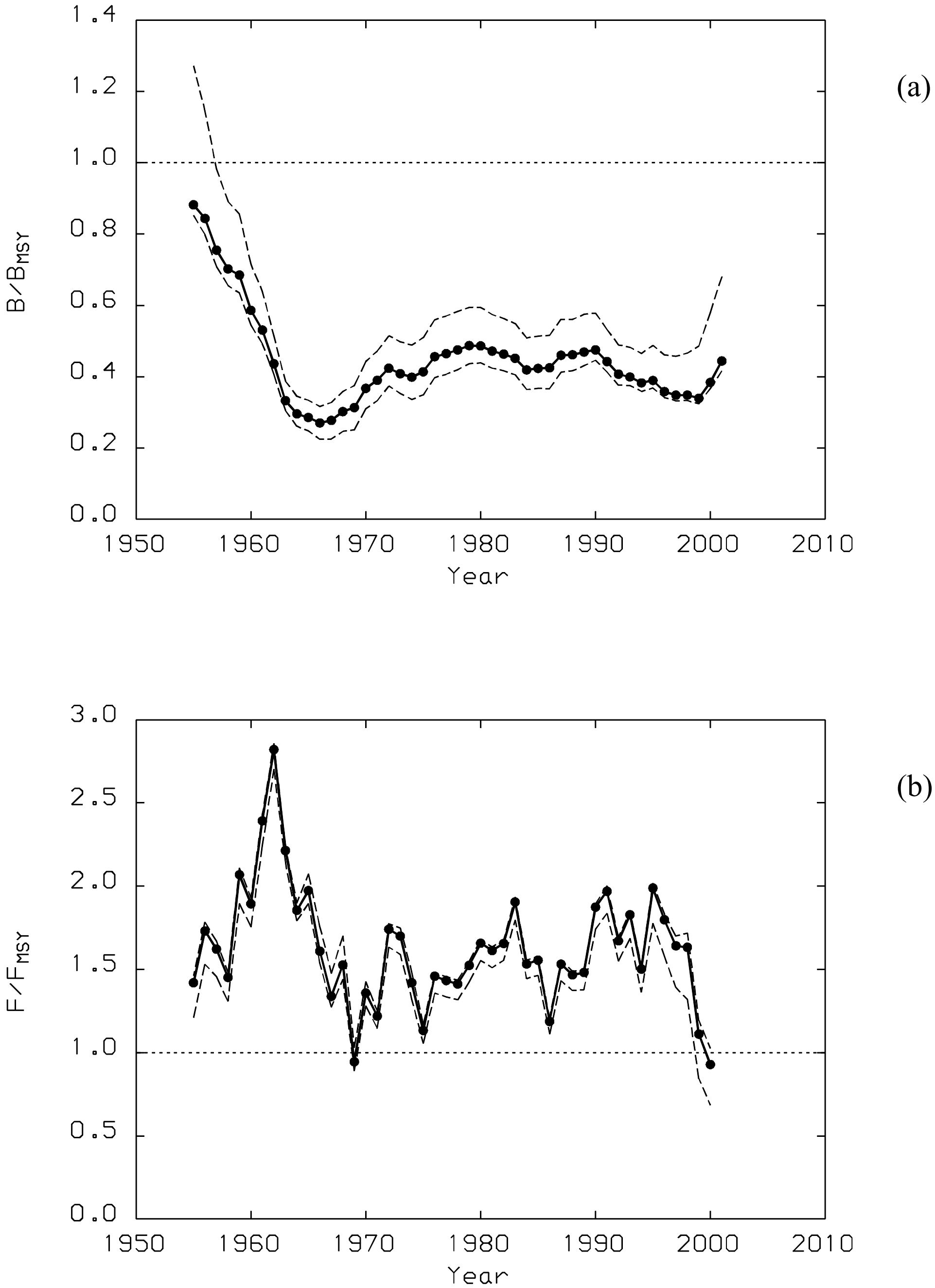

Figure C.2. Production-model estimates for Atlantic menhaden. Trajectories of relative biomass (a) and relative fishing mortality rate (b), both with 80% confidence intervals.