Analyses on the Status
of the Atlantic Menhaden Stock

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Table of Contents

1.   Introduction

The purpose of this report is to provide updated analyses on the current status of the Atlantic menhaden stock.   Prior to the adoption of Amendment 1 to the Atlantic Menhaden Fishery Management Plan of the Atlantic States Marine Fisheries Commission (ASMFC), the NOAA 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. This report is modified from Vaughan et al. (2001), and serves as our primary documentation on the current status of Atlantic menhaden, and focuses on the new benchmarks with their respective targets and thresholds identified in Amendment 1.

1.1. Management.   Estimates of 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. 2002). 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). An alternative approach is being tested that uses a forward-projection, age-structured model (implemented in AD Model Builder software) (Appendix A). That approach allows for calibration with the coastwide juvenile abundance index developed in Section 6. That approach also has the potential to incorporate the effects of predators on the Atlantic menhaden population.

1.2. Organization of Report. This report 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 development of the catch-at-age matrix for this fishery. In section 3, the catch-at-age matrix representing the bait fishery is developed. In section 4, the Murphy VPA analysis is applied to the combined reduction and bait (1985-2001) catch matrix, and estimates of population numbers and fishing mortality rates by age and year are obtained**.** Section 5 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 conditioned on either the Ricker or the Beverton-Holt models. In section 6, potential state-specific juvenile abundance indices are updated and used for developing a coastwide index. In section 7, various biological reference points are re-estimated for comparison with last year's estimates, F-based (rate of removal) and SSB-based (availability of spawners) benchmarks, and schematic fishery control rule plots are shown based on benchmarks from Amendment 1. Finally, a brief summary is given in section 8. Two appendices provide: A) preliminary application of a forward-projection, age-structured model, and B) estimates of historical catches of Atlantic menhaden from Chesapeake Bay.

2.   Reduction Fishery Data (1940-2001)

As noted in Ahrenholz et al. (1987) some fishing for Atlantic menhaden has occurred since colonial times, but the reduction fishery 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. Reduction landings rose in 2001 to 233,700 t. 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).

An approximate linear relationship was found between landings (L) and nominal fishing effort (E) for 1940-2001 (Fig. 2.2; $R^2 = 0.58$):

$$L = 0.148 * E + 157.4 + \varepsilon,$$

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. The number of reduction plants along the U.S. Atlantic coast has declined from more than 20 during the late 1950s to 2 plants in 2001 (Table 2.1). Only 2 plants (North Carolina and Virginia) are expected to operate during 2002. 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 2001. Only 12 vessels are expected to be active in the reduction fishery during 2002 fishing year (Population Dynamics Team 2002).

A major change in the industry took place following the 1997 fishing season, when the two reduction plants operating in Reedville, VA, consolidated, which significantly reduced effort and overall production capacity. 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. Estimates of catches from Chesapeake Bay (as opposed to landings at Reedville, VA) are described in Appendix B.

2.2. Sampling Intensity. The NOAA Center for Coastal Fisheries and Habitat Research (Beaufort Laboratory) has conducted coastwide biological sampling of Atlantic menhaden for length and weight at age at the reduction plants 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 low, although the results of Chester (1984) suggest otherwise.

2.3. Mean Weight at Age. Weighted mean weight of menhaden in the reduction fishery are estimated annually. The weightings used were based on the landings in numbers at age by season and area. 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 estimates by a variety of approaches of the large spawning stock biomass estimated during that period.

2.4. Development of Catch Matrix. Detailed sampling of the reduction fishery permits landings in biomass to be converted to landings in numbers at age. For each port-week-area caught, biostatistical sampling provides an estimate of mean weight and age distribution of fish caught. Hence, dividing landings for that port-week-area caught by the mean weight of fish allows the numbers of fish landed to be estimated. The age proportion then allows numbers at age to be estimated. Adjustments in these estimates (using Captain's Daily Fishing Reports, CDFR's) are made to account for potential bias resulting from "topping off" by vessels returning to Chesapeake Bay from outside and taking a final set before offloading (Chester 1984, Smith 1999). Developing the catch matrix at the port-week-area caught level of stratification provides for considerably greater precision than is typical for most assessments. In fact, stratification on an annual basis by fishery is often used for many stock assessments. We consider the catch-at-age matrix for Atlantic menhaden to be one of the most accurate and precise catch matrices available 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 are able to follow cohorts through ages out to at least age 6.

Table 2.1. Years of activity for individual menhaden reduction plants along the U.S. Atlantic coast.

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
2002									+			+																								2	12

4

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), 1955-2001.

Year	Sample size (n)	Landings (millions of fish)	Landings (1000 t)	Sampling 'Intensity' (C/100n)
1955	16136	3118.4	641.4	3975.0
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	1071.6
1970	8435	1403.0	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	5390.2
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	5610	2052.5	297.6	5304.8
1993	5318	1594.0	320.6	6028.6
1994	4708	1492.0	260.0	5522.5
1995	4606	1643.3	339.9	7379.5
1996	4218	1091.9	292.9	6944.1
1997	4115	995.9	259.1	6296.5
1998	3808	1007.5	245.9	6457.5
1999	3600	1056.3	171.2	4755.6
2000	2940	657.4	167.2	5687.1
2001	3913	669.2	233.7	5972.4

Table 2.3.   Estimated landings of Atlantic menhaden in numbers by age (in millions) and weight of total landings (in thousands of metric tons), 1955-2001. (Estimates for 2001 are preliminary).

Year	0	1	2	3	4	5	6-8	Total Numbers	Total Weight
1955	761.0	674.2	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	1635.4	72.1	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	0.3	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	7.9	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	0.2	0.0	868.2	161.6
1970	21.4	870.9	473.9	32.6	4.0	0.1	0.0	1403.0	259.4
1971	72.9	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	1739.6	379.7	16.3	5.8	0.9	3175.7	382.4
1983	964.4	517.2	2293.1	114.4	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	1075.9	1224.6	44.1	35.6	6.3	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	1157.7	301.4	69.8	7.1	0.6	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	38.0	10.7	2.2	3166.6	381.4
1992	399.7	727.2	795.4	66.1	51.3	10.9	1.9	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	1492.0	260.0
1995	56.8	533.7	671.9	309.1	67.5	4.4	0.0	1643.3	339.9
1996	33.7	209.1	679.1	139.0	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	171.2
2000	77.8	114.2	340.6	111.9	11.1	1.9	0.0	657.4	167.2
2001	23.0	43.5	369.5	217.6	14.9	0.7	0.0	669.2	233.7

Table 2.4. Coherency of Atlantic menhaden catch-at-age matrix as measure by pairwise correlations of landings at age for 1955-2001 (Table 2.3). For each age, the Pearson correlation coefficient is shown in the first row, and the probability of exceeding this coefficient under the null hypothesis (significance) that the coefficient equals zero is in the second row.

Age	1	2	3	4	5	6
1	1	0.614	0.754	0.793	0.771	0.376
	0	0.0001	0.0001	0.0001	0.0001	0.0143
2	-	1	0.532	0.477	0.552	0.242
		0	0.0001	0.0009	0.0001	0.1175
3	-	-	1	0.916	0.703	0.369
			0	0.0001	0.0001	0.0138
4	-	-	-	1	0.745	0.579
				0	0.0001	0.0001
5	-	-	-	-	1	0.827
					0	0.0001
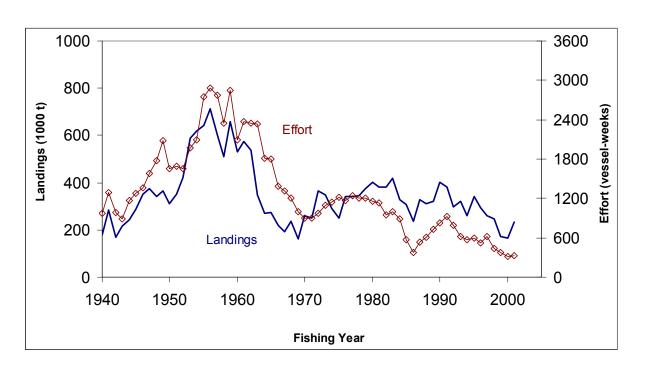
Figure 2.1. **Atlantic menhaden landings and nominal effort, 1940-2001.**
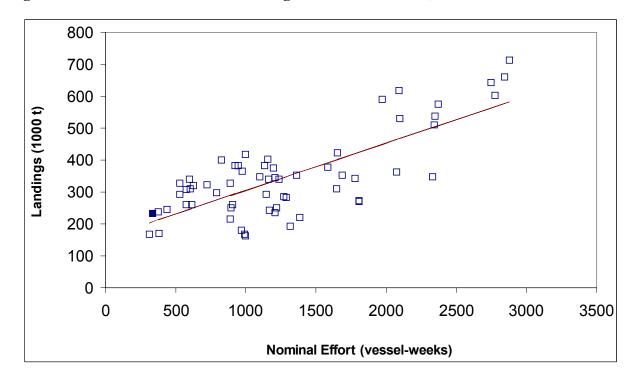
Figure 2.2. **Atlantic menhaden landings versus nominal effort, 1940-2001 (Year 2001 is represented by solid square).**
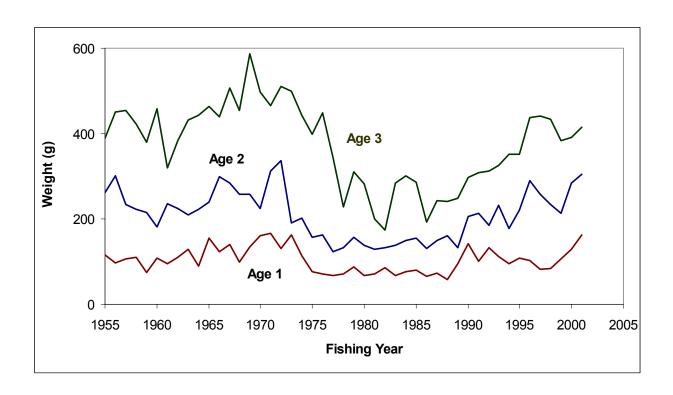
Figure 2.3. **Mean weight at age (g) for Atlantic menhaden, 1955-2001.**

3.   Development of Bait Fishery Catch Matrix (1985-2001)

3.1. Bait Landings. 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. Atlantic coast. Prior to that study, the general assumption had been that bait landings were approximately 5% of the reduction fleet landings. The exception to this assumption would be during the period 1955-1962 period of high landings, when bait landings were probably much smaller as a percentage. Bait landings are available from 1985-2001, with only a few exceptions. Since 1985, no estimates are available from New Hampshire during 1985-1986, so the mean bait landings for 1987-1989 are substituted for these years. Also, no estimates of bait landings were available from MA for 2000-2001, so the mean bait landings for 1997-1999 were substituted for these years.   Based on these data, bait landings were 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 recent years, the relative importance of the bait fishery has increased further, averaging about 15% for the last four years (1998-2001). However, estimates prior to 1998 may be biased low, because of improved acquisition of landings data from the bait fishery in Virginia and elsewhere.

3.2. Bait Biostatistical Sampling. Sampling of the bait fishery for size and age gradually increased during the 1990s, especially since 1994 with sampling 'intensity' falling below 200 t per 100 sampled fish (Table 3.1). Although the sampling 'intensity' is considerably better for the bait fishery than for the reduction fishery by this measure, this results from the relatively small landings of the bait fishery. However, sampling should be adequate to characterize the age distribution of the removals by the bait fishery. Because of the limited age composition data from the bait fishery, bait landings were separated into three geographic regions (New England; Middle Atlantic including Chesapeake Bay; and South Atlantic). For the New England region (CT and north), four years of bait size-at-age data were available (1989, 1994-1996; n = 272). These data were pooled for the four years to estimate a single mean weight of fish and age composition representative of this region for 1985-2001. The mean weight of fish was used to convert landings in tons to landings in numbers for each year, and the age composition was used to estimate catch-in-numbers at age for the New England region. For the Middle Atlantic region (VA through NY), bait size-at-age data were available for 1992-2001 (n = 4,355). Similar to the New England region, these data were used to obtain landings in numbers at age for the Middle Atlantic region. The calculations for pooled data were done for 1985-1993; but with better sampling for 1994-2001 (n > 100), annual calculations were done for these years. Finally, for the South Atlantic region (FL through NC), bait data were available from 1989-2001 (n = 810). Data were pooled into two time periods (1989-1996 and 1997-2001), otherwise calculations were similar to the other regions to estimate numbers at age for the South Atlantic region. Calculations based on the earlier time period were applied to 1985-1996. Estimated numbers at age for the bait fishery were then combined across the three geographic regions for the period 1985-2001 (Table 3.2), and then combined with catch-at-age estimates from the reduction fishery (Table 2.3) to create a combined Atlantic menhaden catch-at-age matrix (Table 3.3).

Table 3.1. Comparison of landings (1000 t) by the bait and reduction fisheries for Atlantic menhaden. Biostatistical sample size of aged bait fish and sampling 'intensity' (catch in t per 100 fish sampled) are also provided.

Year	Reduction Fishery, 1000 t	Bait Fishery, 1000 t (% total)	Total Reduction and Bait, 1000 t	Bait Fishery Sample size (n)	Bait Fishery Sampling 'Intensity' (C/100n)
1985	306.7	26.7 (8.0)	333.4	0	N/A
1986	238.0	28.0 (10.5)	266.0	0	N/A
1987	327.0	30.6 (8.6)	357.6	0	N/A
1988	309.3	36.2 (10.5)	345.5	0	N/A
1989	322.0	31.0 (8.8)	353.0	40	882.4
1990	401.2	30.7 (7.1)	431.9	10	4318.8
1991	381.4	36.2 (8.7)	417.6	80	522.0
1992	297.6	38.7 (11.5)	336.3	120	280.3
1993	320.6	34.7 (9.9)	355.3	170	209.0
1994	260.0	28.1 (9.8)	288.1	570	50.5
1995	339.9	31.2 (8.4)	371.1	400	92.8
1996	292.9	23.3 (7.4)	316.2	410	77.1
1997	259.1	25.7 (9.0)	284.8	440	64.7
1998	245.9	39.2 (13.7)	285.1	750	38.0
1999	171.2	36.1 (17.4)	207.3	679	30.5
2000	167.2	34.9 (17.3)	202.1	729	27.7
2001	233.7	36.2 (13.4)	269.9	1089	24.8

Table 3.2. Catch in numbers at age for the Atlantic menhaden bait landings (in millions of fish).

Year	0	1	2	3	4	5	6	Total
1985	0.4	12.8	29.8	28.2	13.5	1.3	0.3	86.1
1986	0.3	12.8	24.6	31.9	18.0	1.1	0.3	89.0
1987	0.3	13.7	28.2	34.4	18.8	1.3	0.3	97.0
1988	0.3	15.0	29.0	42.2	24.4	1.4	0.3	112.8
1989	0.4	18.1	35.4	33.0	16.6	1.4	0.3	105.1
1990	0.4	20.7	36.2	32.8	17.1	1.3	0.3	108.8
1991	0.4	18.0	35.9	40.1	21.4	1.6	0.3	117.7
1992	0.5	17.3	39.2	42.2	21.5	1.8	0.4	122.8
1993	0.4	12.4	32.0	38.5	19.8	1.6	0.3	105.0
1994	0.2	14.6	22.2	29.6	19.6	2.8	0.2	89.2
1995	0.1	25.5	31.1	37.8	19.4	0.1	0.0	114.2
1996	0.0	2.7	37.4	20.4	5.0	0.2	0.0	65.7
1997	0.0	4.7	32.3	25.5	11.8	3.0	0.6	77.9
1998	2.5	4.2	37.9	30.9	23.1	4.0	0.7	103.4
1999	0.2	4.0	57.7	32.9	17.0	2.3	0.4	114.6
2000	0.3	13.3	59.0	21.3	10.8	1.4	0.3	106.5
2001	0.1	2.6	29.4	49.3	8.0	0.9	0.3	90.5

Table 3.3. Catch in numbers at age for the Atlantic menhaden combined reduction and bait landings (in millions of fish).

Year	0	1	2	3	4	5	6	Total
1985	637.6	1088.7	1254.4	72.2	49.1	7.5	1.9	3111.4
1986	98.7	237.0	1547.8	81.0	28.4	7.2	1.3	2001.4
1987	43.2	518.4	1615.8	186.3	43.9	3.5	1.0	2412.2
1988	339.2	297.7	1186.7	343.6	94.2	8.5	0.9	2270.7
1989	150.1	1172.6	1194.0	141.3	64.0	13.0	0.5	2735.6
1990	308.5	153.5	1589.4	141.7	59.2	13.6	0.7	2266.7
1991	882.2	1051.9	982.0	294.1	59.3	12.3	2.5	3284.3
1992	400.1	744.5	834.6	108.3	72.8	12.7	2.3	2175.2
1993	68.3	391.4	1015.1	187.4	30.7	5.5	0.6	1699.0
1994	88.8	289.1	911.0	194.6	86.9	10.4	0.4	1581.2
1995	56.9	559.1	703.0	347.0	87.0	4.5	0.0	1757.4
1996	33.8	211.8	716.5	159.3	34.0	2.2	0.0	1157.7
1997	25.2	251.6	456.9	263.0	63.4	12.0	1.8	1073.8
1998	75.4	189.2	578.5	157.2	96.1	13.0	1.5	1110.9
1999	194.1	305.1	508.5	114.8	42.0	5.5	0.8	1170.8
2000	78.1	127.4	399.7	133.2	21.9	3.3	0.3	763.9
2001	23.1	46.1	398.9	266.9	22.9	1.5	0.3	759.7

4.   Results of Murphy VPA (1955-2001)

The Murphy (1965) virtual population analysis (VPA) is applied to catch in numbers at age separately by cohort. The starting instantaneous fishing mortality rate, F, on the oldest age for each complete cohort is obtained from the catch curve applied to that cohort for ages 2-6. Separable VPA (SVPA, Clay 1990) is applied to some recent period of time to initialize the Murphy VPA for the incomplete cohorts in the recent years. The period of time is based on varying runs of the SVPA to find that which minimizes the model coefficient of variation (CV) (in this case, 1997-2001). Estimates of F from the SVPA provide starting F's for the oldest ages of the incomplete cohorts (those that are less that age 7 in 2001).

4.1. Exploitation and Fishing Mortality Rates. Temporal trends in exploitation for juveniles (age 0) have been highly variable, depending on availability and weather (Fig. 4.1). Generally, 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 (ages 1-8) generally have declined over the period 1965 through 2001 (the slope is statistically significant less than 0 at the level of $\alpha = 0.0001$, n = 37), with high values occurring during the mid-1960s when stock size was low. This decline in exploitation rate is consistent across all ages 1-8, including declines in exploitation on age-1 menhaden ($\alpha = 0.0001$) and age-2 menhaden ($\alpha = 0.0001$), and slightly less, but still significant, declines in exploitation on age 3-8 menhaden ($\alpha = 0.0085$).

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 population number at age (Fig. 4.2). The pattern over time of full F is similar to the exploitation rates ($u = FA/Z$), with values exceeding 2.0 occurring during 1965 and 1972-1975. The preliminary estimate for the most recent year (F = 1.0) is largely driven by the catch curve for the most recent years. The historical time period 1955-2001 produced a median F of 1.3 with interquartile range between 1.1 and 1.6. The preliminary estimate of fishing mortality rate for 2001 of 1.0 is slightly below the 25th percentile of the historical estimates.

4.2. 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. 4.3). Static SPR for Atlantic menhaden is calculated based on such an index of egg production, and provides lower estimates of static SPR than those estimates based on mature female biomass. This variable is plotted with its median (6.2%) and interquartile range (3.4% to 10.5%). Although highly variable, generally higher values (above 75th percentile) are associated with two temporal periods (4 out of 7 years between 1955-1961 and 8 out of 12 years between 1990-2001). Higher SPR values are associated with lower exploitation regardless of stock size. The preliminary estimate for static SPR in 2001 was 12.6%, above the 75th percentile (10.5%).

14

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 1955-2001 (22.9% in 1960). In 1960, exploitation was low due to the size of the 1958 year class as age-2 menhaden, the first fully recruited age in the reduction fishery. As referred to above, estimates of static SPR between 10% and 20% occurred in 1955, 1958, 1961, and nine out of the last twelve years, including 2000 and 2001. The estimate for 2000 (16.3%) was the second highest estimate for the historical period (exceeded only by the estimate of 22.9% in 1960). Atlantic menhaden have demonstrated remarkable resilience during the period 1963 to 1989, with SPR varying between 1% and 9%. As discussed in the next section (4.3) on spawning stock biomass (SSB), SSB was very low during most of the late 1960s and early 1970s, with higher SSB subsequently.

4.3. Recruits to Age 1 and Spawning Stock Biomass. Annual estimates of recruits to age 1 (Fig. 4.4) and spawning stock biomass (Fig. 4.5) 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 4.1. Estimates of population size at age 0 should be interpreted with care, because natural mortality at this age is poorly known (and probably underestimated as indicated by the recent research funded by ASMFC by Dr. Lance Garrison, NOAA Fisheries, Southeast Fisheries Science Center, Miami, FL). Also, population size at age 1 in the current year is poorly estimated by this approach. Historical trends in recruits to age-1 Atlantic menhaden are plotted with their median (3.3 billion) and interquartile range (2.1 to 4.5 billion) (Fig. 4.4). 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 generally low recruitment since 1996. However, recruitment to age 1 in 1999 (1998 year class) is an improvement at 2.4 billion fish. Estimates of recruits to age 1 for 1996-1998 and 2000 were below the 25th percentile of 2.1 billion menhaden. The preliminary estimate for recruits to age 1 in 2001 was 0.5 billion, the lowest on record. However, the most recent estimate of recruitment has the greatest uncertainty, and that this estimate for 2001 is likely to change considerably as more data from the 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 (56,400 t) and interquartile range (31,300 to 94,400 t) (Fig. 4.5). The largest values of SSB were present during the late 1950s and early 1960s (generally above the 75th percentile for 1955-1962, except for the 1958 year class which produced the most recruits to age 1). This high SSB resulted primarily from two historically large year classes (1951 and 1958). Estimates of SSB from 1965 until 1978 were generally below the 25th percentile. Since 1978, an estimate of

SSB below the 25th percentile occurred only in 1986, and is probably an artifact of the economic conditions that resulted in an industry decision that year not to fish by one plant in Reedville, VA. For those years when estimates of spawning stock biomass are above the 75th percentile (i.e., 1955-1957, 1959-1962, 1993, 1995, 1997, and 2001), 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, 1973-1977, and 1986), the spawning stock biomass can be considered depleted. The preliminary estimate for spawning stock biomass in 2001 was 104,500 t, above the 75th percentiles.

Table 4.1.   **Estimated population size of Atlantic menhaden in numbers by age (in millions) from Murphy Virtual Population Analysis, 1955-2001 Estimates of population size at age 0 should be interpreted with care, because natural mortality at this age is poorly known. Also, population size at age 1 in the current year is similarly poorly estimated by this approach.**

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	5970.1	6648.1	2197.0	368.8	111.4	23.0	2.0	0.0	0.0
1981	9385.1	4688.3	3082.0	306.7	66.6	18.7	3.8	0.2	0.0
1982	3448.5	6438.0	2440.7	591.8	30.6	7.2	0.8	1.5	0.1
1983	6165.1	2652.0	3382.4	261.9	91.6	7.0	0.4	0.1	0.7
1984	8072.8	4065.9	1285.9	440.3	78.9	22.2	0.8	0.1	0.1
1985	6661.5	5296.5	1792.3	153.8	75.6	12.4	2.8	0.1	0.0
1986	4687.1	4751.7	2524.5	207.3	42.6	11.3	2.2	0.5	0.1
1987	4278.1	3655.0	2843.0	440.1	69.6	5.8	1.8	0.4	0.3
1988	7429.3	3377.6	1923.2	584.4	136.9	11.2	1.1	0.4	0.3
1989	4489.6	5630.3	1918.7	329.8	112.1	16.9	0.9	0.2	0.1
1990	5158.0	3451.1	2672.2	322.1	101.4	22.8	1.2	0.2	0.1
1991	5768.2	3844.0	2079.4	499.7	96.2	19.7	4.2	0.2	0.1
1992	4797.1	3822.2	1630.6	572.1	95.7	16.5	3.3	0.9	0.1
1993	3269.4	3474.4	1853.2	401.3	279.9	7.4	1.2	0.8	0.2
1994	4220.7	2549.9	1907.4	408.4	112.0	11.4	0.6	0.3	0.5
1995	2319.0	3291.3	1398.1	516.9	111.0	7.6	0.1	0.1	0.2
1996	2338.7	1801.2	1659.9	353.5	69.6	7.1	1.5	0.0	0.1
1997	2214.2	1837.4	981.9	506.3	102.8	18.3	2.8	0.9	0.0
1998	3070.3	1745.7	973.9	275.0	121.8	17.7	2.7	0.4	0.6
1999	1897.5	2384.4	964.2	182.7	55.9	7.4	1.6	0.6	0.3
2000	728.0	1342.4	1280.5	226.5	30.0	4.6	0.6	0.5	0.4
2001	885.4	511.8	755.6	505.6	43.4	2.9	0.5	0.1	0.3
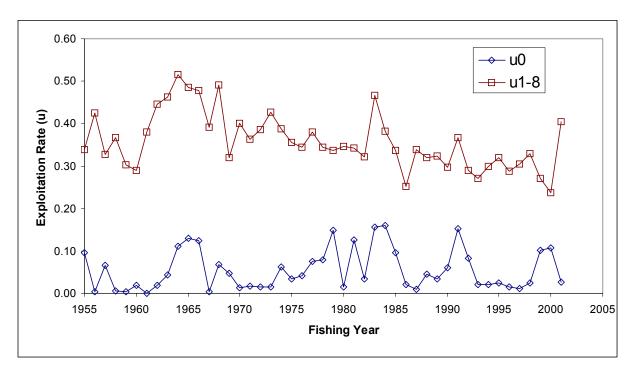
Figure 4.1.   Exploitation rate (u) for age 0 and age 1-8 Atlantic menhaden, 1955-2001.
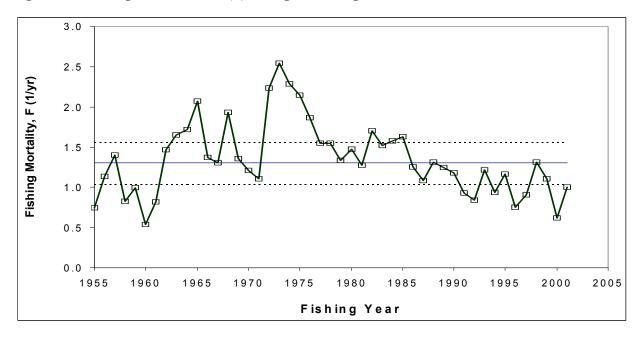
Figure 4.2.   Annual estimates of fishing mortality rates, F, averaged over fully recruited ages (ages 2-8, weighted by population number at age) with median and interquartile range.
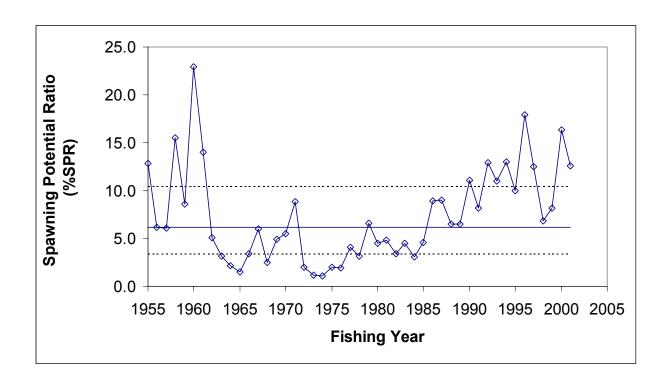
Figure 4.3. Annual estimates of static SPR for Atlantic menhaden with median and interquartile range.
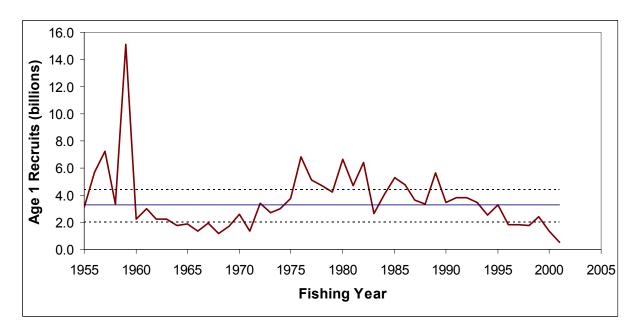
Figure 4.4. Estimates of recruits to age-1 Atlantic menhaden with median and interquartile range.

19
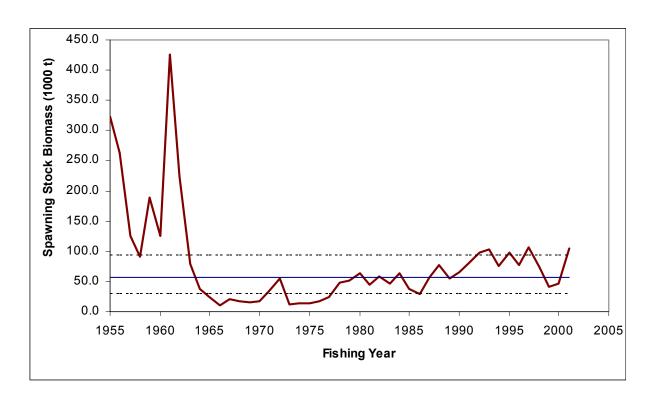
Figure 4.5. Estimates of spawning stock biomass (SSB, age 3-8) of Atlantic menhaden with median and interquartile range.

5.   Spawner-Recruit Relationships and Survival Indices

5.1. Survival Indices as Function of Spawning Stock Biomass. This section provides the results of a ongoing 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 the combined reduction and bait landings. The dependency of spawning stock on the first age of spawning (age 3) is highly variable (Fig. 5.1), but generally high percentages for age 3 contribution occurred during the mid-1960s through mid-1970s, and most recently in 2001. Low percentages (e.g., below 50%) occurred mostly during the late 1950s and early 1960s. Since 1963, low values were obtained in 1985 at 51.8%, 1993 at 49.7% and 1998 at 52.4%.

Conditional probabilities are presented in Table 5.1 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 25th percentile) has about a 42% chance of producing low recruitment, a 33% chance of producing a moderate recruitment, and 25% 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 favors high recruitment over low recruitment (0.30:0.22); while high spawning stock biomass is equally likely to produce low recruitment as high recruitment (0.18:0.18). This simple analysis suggests the need to maintain spawning stock biomass at least above approximately the 25th percentile (31,300 t) when using the long-term data series.

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 1955-2000 by:

$$\textbf{S}_\textbf{O} = \textbf{R}_\textbf{1}/\textbf{SSB}.$$

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. 5.2). A particularly high level for the index of survival is noted during the mid-1970s when the menhaden stock was rebuilding. Only in the last few years has survival declined to levels estimated during the 1950s and early 1960s (with the exception of the 1958 yearclass).

5.2. Ricker Spawner-Recruit Curve. Despite weak dependency of recruits to age 1 on spawning stock biomass for Atlantic menhaden (e.g., Ahrenholz et al. 1987, Vaughan and Smith 1988), the spawner-recruit data can be fit to the Ricker (1975) spawner-recruit curve (Fig. 5.3). Parameter estimates for the Ricker curve:

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

21

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): α = 0.107 (0.022) and β = 0.0083 (0.0019). Similarly, estimates for the data set, with the 1958 year class excluded, are (asymptotic standard error in parentheses): α = 0.101 (0.018) and β = 0.0087 (0.0018). For the full data set, spawning stock that produces theoretical maximum recruitment occurs at P = 1/β, or 120,700 t. The maximum recruits to age-1 menhaden that would be produced by this spawning stock is 4.8 billion age-1 fish. 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 often 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 28,000 t. This value is above the value of the current threshold value for Atlantic menhaden (20,570 t), and well below recent estimated values of spawning stock biomass (the last time a value lower than SSB producing one-half maximum recruitment was in 1977 at 23,800 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 $S_O = S_E$):

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

Estimates of relative survival suggest that the period from 1955 through 2000 was very noisy (in a statistical sense) with two periods of particular interest (Fig. 5.4). 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) 1993-2000. 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.

5.3. Beverton-Holt Spawner-Recruit Curve. The spawner-recruit data also can be fit to the Beverton-Holt (Ricker 1975) spawner recruit curve (Fig. 5.3). Parameter estimates for the Beverton-Holt curve:

$$R = P/(\alpha P + \beta)$$

where R is recruits (as billions of age-1 menhaden) 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): $\alpha = 0.251$ (0.040) and $\beta = 1.080$ (1.474). 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 4.0 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. 5.5). The period from 1973-1988 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) 1993-2000. 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.

5.4. Statistical Properties. The statistical properties of recruits to age-1 Atlantic menhaden are summarized for different ranges of spawning stock biomass (Table 5.2). 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 91,260 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 5.1. **Conditional probabilities of recruitment to age 1 from spawning stock biomass based on interquartile stratifications for 1955-2001.**

Spawning Stock Biomass[a]	Recruits to Age 1[a]		
	Low (< 2.1)	Moderate (2.1 - 4.5)	High (>4.5)
Low (< 31.3)	0.417	0.333	0.250
Moderate (31.3 - 94.4)	0.217	0.478	0.304
High (> 94.4)	0.182	0.636	0.182

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

Table 5.2. **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) | | | Percentiles | |
	n	Mean	Median	25th	75th
All	46	3.6	3.3	1.9	4.7
Greater than:					
20,570[a]	38	3.7	3.4	2.2	4.7
28,000[b]	35	3.8	3.4	2.2	4.7
31,320[c]	34	3.8	3.4	2.2	4.7
37,400[d]	33	3.8	3.3	2.2	4.7
56,450[e]	22	3.9	3.2	2.2	4.7
91,260[f]	12	4.2	2.8	2.2	4.6
94,370[g]	11	3.2	2.5	2.2	3.5
Less than:					
20,570[a]	8	3.3	2.8	1.8	4.4
28,000[b]	11	3.0	2.6	1.4	4.7
31,320[c]	12	3.1	2.8	1.5	4.2
37,400[d]	13	3.1	3.0	1.7	3.7
56,450[e]	24	3.3	3.4	1.8	4.5
91,260[f]	34	3.4	3.4	1.9	4.7
94,370[g]	35	3.7	3.4	1.9	4.7

[a] Threshold (warning) level SSB from Amendment 1.
[b] SSB that produces one-half maximum R_1 (Ricker model).
[c] Twenty-fifth percentile for historical SSB for period 1955-2001.
[d] Target level of SSB from Amendment 1.
[e] Median (50th percentile) of historical SSB for period 1955-2001.
[f] Minimum SSB during period of historically high levels of SSB (1955-1962) that produced maximum recruitment (1958 yearclass).
[f] Seventy-fifth percentile of historical SSB for period 1955-2001.
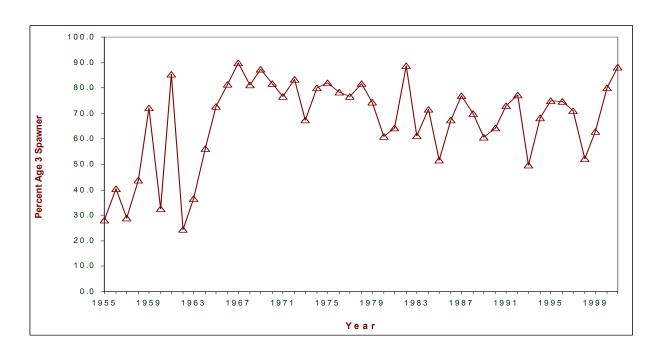
Figure 5.1. Contribution to spawning stock (as eggs) by age 3 Atlantic menhaden.
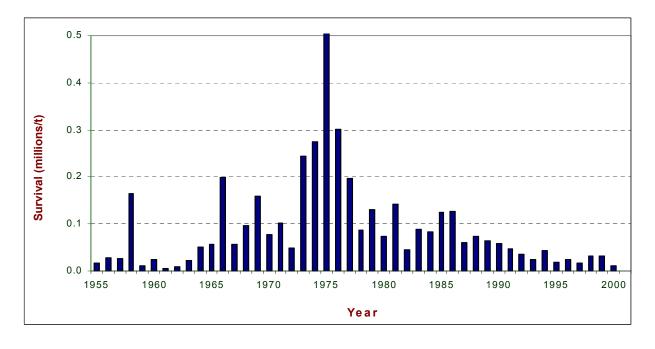
Figure 5.2. Observed survival (millions of recruits to age 1 per metric ton spawning biomass) of Atlantic menhaden.

26
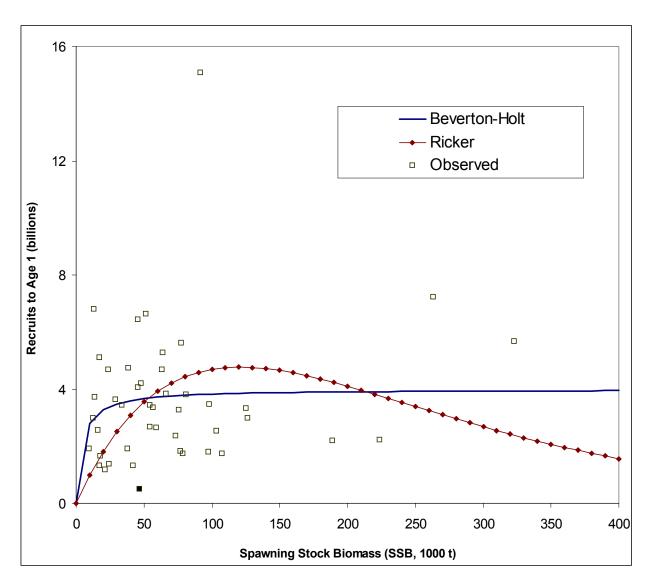
Figure 5.3. Observed, Ricker and Beverton-Holt model estimates of age 1 Atlantic menhaden.
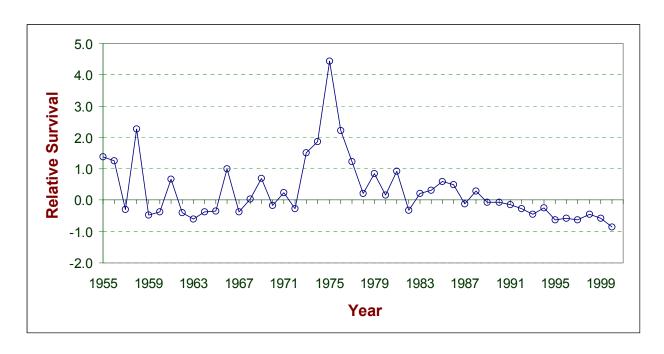
Figure 5.4. Relative survival to age-1 Atlantic menhaden from the Ricker model.
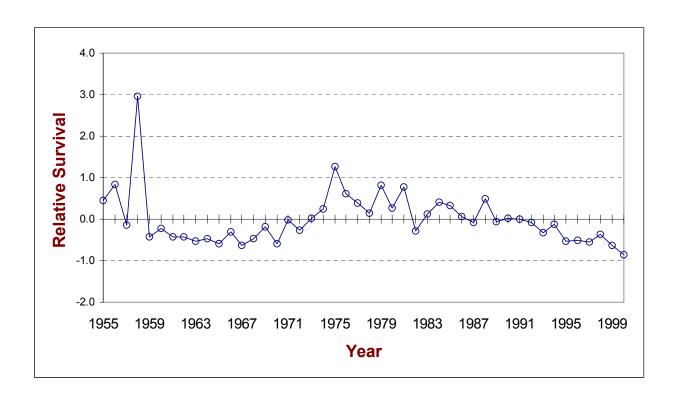
Figure 5.5. Relative survival to age-1 Atlantic menhaden from the Beverton-Holt model.

6. Potential Indices of Juvenile Abundance (Age 0)

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 have shown more congruence between these indices and lagged age 1 recruits from the Murphy VPA. We continue to develop these indices, and where possible, to better separate out age 1 and older menhaden from juveniles (age 0). We continue to explore the utility of the coastwide index as a means of calibrating recruitment in the forward-projection, age-structured model (Appendix A). For consistency, the results below are mostly based on arithmetic means, rather than geometric, although little difference in trends was noted between the two approaches. Exceptions are pointed out below.

6.1. 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 1989-2001 during three seasons: Spring (April-May), Summer (June-August), and Fall (September-October). General linear models (GLM) based on ln(CPUE+1) have been developed for each season. Size frequency data, combined with 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, 1972-2001), 2) striped bass nursery trawl index in Albemarle Sound (July-October, 1982-2001), 3) Pamlico Sound trawl survey index (including Pamlico and Neuse Rivers; June and September, 1987-2001), and 4) estuarine trawl survey index (statewide; May-June, 1987-2001). 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

29

compared with 1-year lagged standardized recruits to age 1 (based on Murphy VPA on reduction and bait data) (Fig. 6.1).

6.2. 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 1959-2001. Among other fish species, juvenile Atlantic menhaden catch-per-unit effort (CPUE) has been made available. A general linear model GLM based on ln(CPUE+1) was used to develop on index (a factor was used to represent 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. Indices for other Middle Atlantic states are currently unavailable.

An index of juvenile Atlantic menhaden for tributaries to the Virginia portion of Chesapeake Bay (1968-1973 and 1980-2001) 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. 6.2).

6.3. Southern New England States (CT-RI). Connecticut DEP provided indices from their fall trawl survey (1984-2001), and Connecticut River Alosid survey (1987-2001). 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 (1990-2001) and a trawl survey of Rhode Island coastal waters (1979-2001). 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. 6.2).

6.4. 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. 6.3). 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 (2001). 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 lagged recruits to age 1 (both the Maryland and the coastwide indices were statistically significant at $\alpha = 0.0001$), with somewhat less, but still significant correlation, with the Rhode Island index at about $\alpha = 0.05$. Only marginally significant correlations ($\alpha \sim 0.1$) were found for both Virginia and Connecticut indices with recruits to age 1. Note that in the early years (1959-1971) the coastwide index is the same as the Maryland.

Inter-correlations among the indices are for the purpose of testing for coastwide coherency. The Maryland was significantly correlate with the Virginia seine index ($\alpha = 0.009$) and with the combined North Carolina indices ($\alpha = 0.03$). A marginally significant correlation was found between the Maryland index and the combined Connecticut indices ($\alpha = 0.12$). Not surprisingly, the coastwide juvenile abundance index was highly correlated with North Carolina, and Chesapeake Bay (MD and VA) indices (all at $\alpha = 0.0001$), but not with any of the other indices ($\alpha > 0.22$).

The most recent values of these indices, as well as four VPA variables (calculated by Murphy VPA), are compared with their median and interquartile range (Table 6.1). Estimated F in 2001 is below its historical 25th percentile, while estimated SSB in 2001 is above its 75th percentile. However, estimated recruitment to age 1 in 2001 is well below its 25th percentiles. However, we re-iterate that estimation of recruitment in the terminal year from a VPA is the *least precise* estimate.

For the juvenile abundance indices, the Virginia index continues to be below its 25th percentile, while the SEAMAP age-1 and Connecticut indices are approximately at their 25th percentiles. The Maryland index is between its 25th and 50th (median) percentiles. The North Carolina index is between its 50th and 75th percentile, while SEAMAP age-2 and Rhode Island indices are above their 75th percentiles. The value of the coastwide index is at approximately its median historical value.

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 6.1. Current conditions for VPA-generated indices and juvenile abundance indices compared to long-term median and interquartile range. Values for 2001 that fall within the interquartile range should be not be considered different from the long-term median (50th percentile).

Variable	n	2001	25th	50th	75th
Population-Based (VPA) Variables (Murphy):					
Full F (2+)	47	1.0	1.1	1.3	1.6
R_1 (billions)	47	0.5	2.1	3.3	4.5
SSB (1000 t)	47	104.5	31.3	56.4	94.4
SPR (%)	47	11.3	3.4	6.2	10.5
Standardized Juvenile Abundance Indices for:					
SEAMAP (Age 1)	13	-0.72	-0.72	-0.12	0.69
" (Age 2)	13	0.95	-0.61	0.14	0.44
NC Combined	30	0.23	-0.83	0.09	0.43
VA Seine	28	-0.73	-0.64	-0.43	0.26
MD Seine	43	-0.67	-0.69	-0.40	0.31
CT Combined	18	-0.62	-0.62	-0.42	0.30
RI Combined	23	-0.03	-0.30	-0.29	-0.22
Coastwide	43	-0.29	-0.79	-0.29	0.34

Figure 6.1. Comparison of standardized indices for Atlantic menhaden from U.S. south Atlantic states with standardized lagged recruits to age 1.

Figure 6.2. Comparison of standardized indices for Atlantic menhaden from U.S. Middle Atlantic and Southern New England states with standardized lagged recruits to age 1.
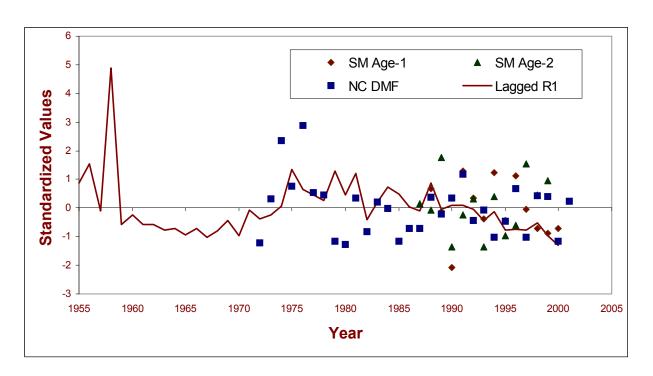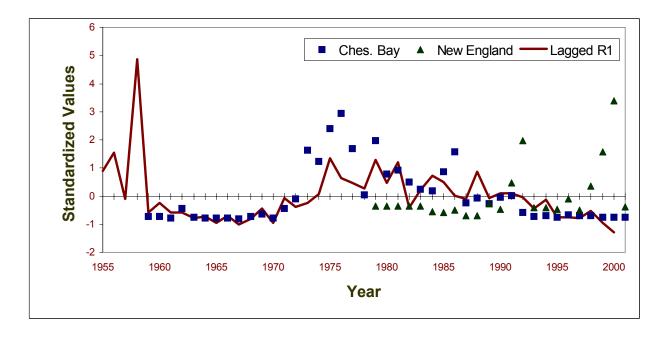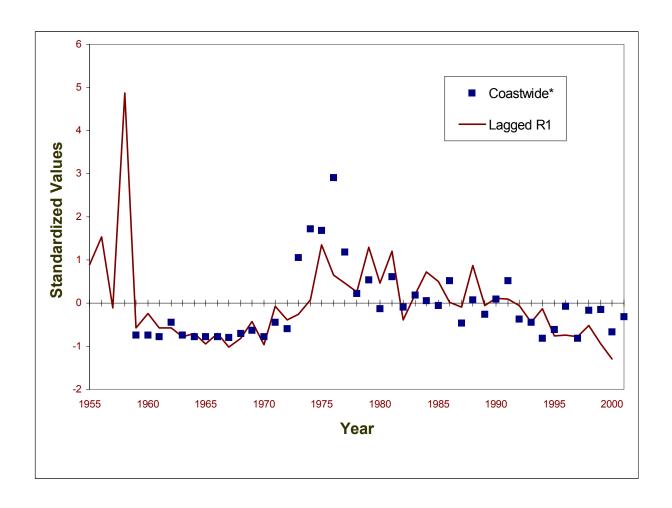
Figure 6.3. Comparison of standardized index for Atlantic menhaden from the coastwide index with standardized lagged recruits to age 1.

7.   Benchmarks and Control Rules

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. 7.1 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.

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 population in numbers). Spawning stock biomass (SSB) is calculated from one-half the weight of menhaden ages 3 and older in the population.

7.1. 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, the rate of fishing prevents the stock from replenishing itself. When the rate of fishing exceeds the threshold, then overfishing is said to occur. Under Amendment 1, the target and threshold for full F are 1.04 and 1.33, respectively. Potential values for targets and thresholds presented in earlier analyses were obtained from a variety of approaches, including: 1) historical performance (25th, 50th and 75th 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 7.1 based on Murphy VPA. A general decline was noted earlier (Section 2.4) in exploitation rate from 1965 to the present.. The estimate of full F (1.0) in the terminal year (2001) is below its historical 25th percentile (1.1).

Estimates of yield per recruit were calculated from estimates of partial recruitment

(selectivity) for 1997-2001 using the method of Ricker (1975) (Fig. 7.2). 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 1.1, while $F_{0.1}$ occurs at a full F of about 0.5 for Atlantic menhaden with partial recruitment based on the period 1997-2001 (Table 7.1).

Estimates of spawning stock biomass per recruit (static SPR) were estimated using the partial recruitment (selectivity) for 1997-2001 using the method of Gabriel et al. (1989) (Fig. 7.2). 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 1.6, F_{10} occurs at an full F of about 1.1, and F_{20} at about 0.7 (Table 7.1).

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. 7.2 unadjusted for SSB/R at F=0). Median SSB/R for the historical Atlantic menhaden data was 17.3 expressed as metric tons per million recruits. The corresponding F from the SSB/R curve generated for the partial recruitment (selectivity) during 1997-2001 was estimated at about 1.1 (and equivalent to a static SPR of about 10%).

Estimates of F-based benchmarks from spawner-recruit models are more problematic. Parameter fits to the Ricker and Beverton-Holt S/R models are described in Sections 5.2 and 5.3. 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 1997-2001 (1.02 from Murphy VPA) ranging from 0.0 to about 2.0. Bifurcation was noted over the whole range in F. While long-term MSY is maximized at the maximum F (F=2.0) for the range used, SSB is maximized at the minimum F (F=0.0).

7.2. SSB-based Benchmarks.

SSB-based benchmarks are used to judge whether the spawning stock is too low. When the spawning stock biomass falls below the threshold, then the spawning stock biomass is said to be depleted. The concern then becomes whether there is sufficient spawning stock biomass to produce adequate recruitment for the long-term viability of the stock. 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 2001 (47 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 1990-2001). 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 7.1 for the Murphy VPA. SSB reached a recent high in 1997, decayed from that level, but increased significantly in 2001 (largely driven by good recruitment to age 1 in 1999). The recent estimate of SSB (104,500 t) is above its 75th percentile (94,400 t).

To obtain a SSB for YPR benchmarks, the SSB/R equivalent to the F-based benchmark is obtained first (Table 7.1). 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 (3.3 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 7.1.

Additionally, a potential threshold for SSB would be that suggested by Myers et al. (1994; discussed in Sections 5.2 and 5.3) using SSB that produces ½max{R_1} (28,000 t for the Ricker model based on Murphy VPA).

7.3. 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).   Through the efforts of AMAC, and now the Menhaden Technical Committee, data available from the bait fishery have been deemed to be of sufficient quality to incorporate them into the stock assessment. The inclusion of removals by all fisheries in the analysis is comparable to all other stock assessments conducted for the U.S. commissions and councils. Estimates for current (2001) levels of F (F_{2001}

= 1.0) and SSB (SSB_{2001} = 104,500 t) are such that current F is at its target and current SSB is well above its target (see solid square in Fig. 7.3).

Ideally, benchmarks for F-based and SSB-based reference variables should be based on an underlying population dynamics model (e.g., Ricker or Beverton-Holt spawner recruit models). However, these models apply poorly to historical Atlantic menhaden data as noted in Sections 5.2 and 5.3. Hence, the benchmarks in Amendment 1 are proxies developed from historical spawner and recruit data and selectivity associated with removals by the reduction fishery (i.e., the reduction catch matrix). Modification of these benchmarks resulting from the addition of bait removals (e.g., reduction and bait catch matrix) can be justified as follows for the two benchmarks. A significant change in the selectivity would imply different total removals for the same fully-recruited F, while an increase in historical removals would imply that historical spawning stock biomass was higher than previously thought.

Last year the Atlantic Menhaden Technical Committee recommended inclusion of the bait catch matrix with the reduction catch matrix (Vaughan et al. 2001). Preliminary analyses of the bait data, when combined with the reduction catch matrix, had suggested a significant change in selectivity from the earlier analyses based simply on the reduction catch matrix. This year, we have done a more complete and detailed analysis of the bait data to estimate an improved bait catch matrix. Based on this new analysis, we observed only minor variations in selectivity as estimated by separable VPA (SVPA) for 1990-2001 applied to the reduction catch matrix only and to the combined reduction and bait catch matrix (Fig. 7.4). Hence we recommend no change in the current F-based benchmarks from Amendment 1 (target = 1.04 and threshold = 1.33).

However, the combined reduction and bait catch matrix has resulted in historically higher estimates of SSB, especially for the period 1985-2001, than those obtained from just the reduction catch matrix. Because SSB-based benchmarks represent absolute values (and not a rate as do F-based benchmarks), we recommend that the SSB-based benchmarks be updated based on the same proxy methodology in Amendment 1 (target equals median SSB/R_1 times median R_1; threshold equals [1-M] times target, where M = 0.45). A potential target estimate can be found at the bottom of the far right column (Table 7.1; 57,200 t), with a corresponding threshold equal to 31,500 t (0.55*57,200 t).
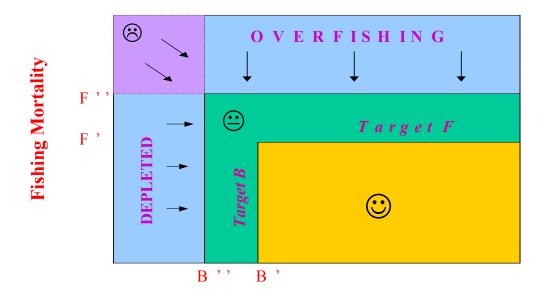
Preliminary analysis of Atlantic menhaden was made using a forward-projecting, age-structured model fitted with AD Model Builder software (Appendix A). Data from the combined reduction and bait fisheries catch matrix for Atlantic menhaden were compiled along with a coastwide juvenile abundance index (Section 6) for input into a forward-projecting, age-structured population model. Estimates of full F, static SPR, recruits to age 1, and spawning biomass (SSB) from the model are shown in Fig. A.1 and Fig. A.2. In particular, this model suggests good recruitment to age 1 in the recent year (1999-2000), with poor recruitment indicated for 2001. The highest estimates of static SPR are obtained for the last two years (2000-2001). As with the Murphy VPA, estimating recruitment in the current year is always problematic. Plots on fishery control rules (full F and SSB) are shown in Fig. A.3. Even with

38

uncertainty represented in estimates of current F and SSB, current conditions of the Atlantic menhaden stock fall in the "good zone"; that is, F is below its target and SSB is above its target. Furthermore, the trend in the most recent years has been downwards for F and upwards for SSB.

Table 7.1. **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 1997-2001 pattern.**

| Approach | Biological Reference Points | | |
	F (1/yr)	SSB/R (t/million)	SSB[a] (1000 t)
Historical Performance (1955-2001):			
25th %	1.1	-	31.3
50th %	1.3	-	56.4
75th %	1.6	-	94.4
Yield per Recruit:			
$F_{0.1}$	0.5	51.6	169.8
F_{max}	1.1	16.2	39.1
Static SPR (in biomass):			
5%	1.6	8.5	28.0
10%	1.1	17.0	56.1
20%	0.7	34.0	112.1
Replacement (SSB/R):			
50th %	1.1	17.3	57.2

[a] Multiply SSB/R by median recruits to age 1 (3.3 billion) to obtain SSB, except for historical performance.

Spawning Stock Biomass

Figure 7.1. Schematic fisheries control law (modified from Mace et al. 1996).
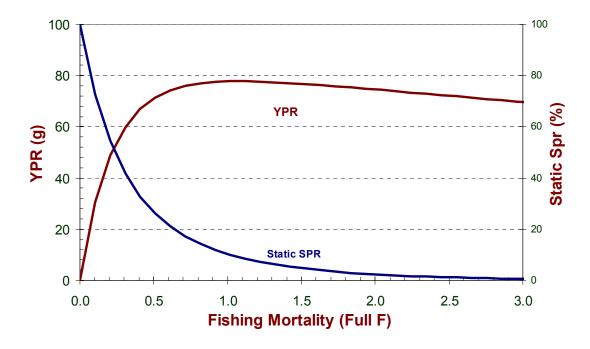
Figure 7.2. YPR and static SPR for Atlantic menhaden based on selectivity for 1997-2001.
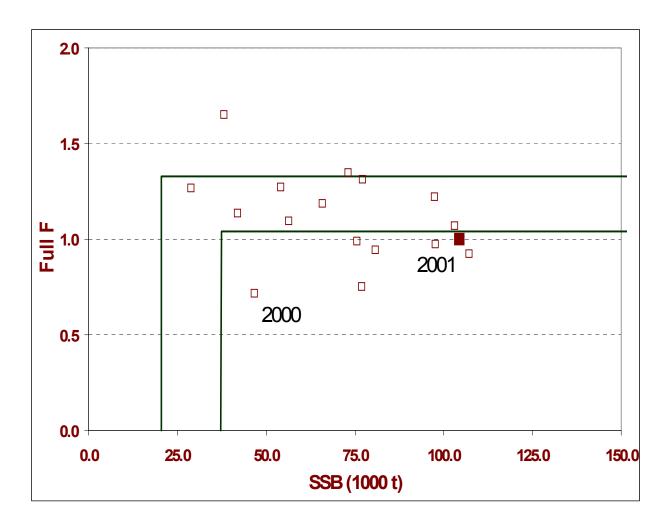
Figure 7.3. **F and SSB from current assessment for Atlantic menhaden with benchmarks from Amendment 1 (solid square represents 2001).**

Figure 7.4. Effect of adding bait catch matrix to reduction catch matrix on selectivity from SVPA on period 1990-2001. Selectivity based on reduction catch matrix only labeled by final year from previous analyses (Vaughan et al. 2000, 2001).

8. Summary

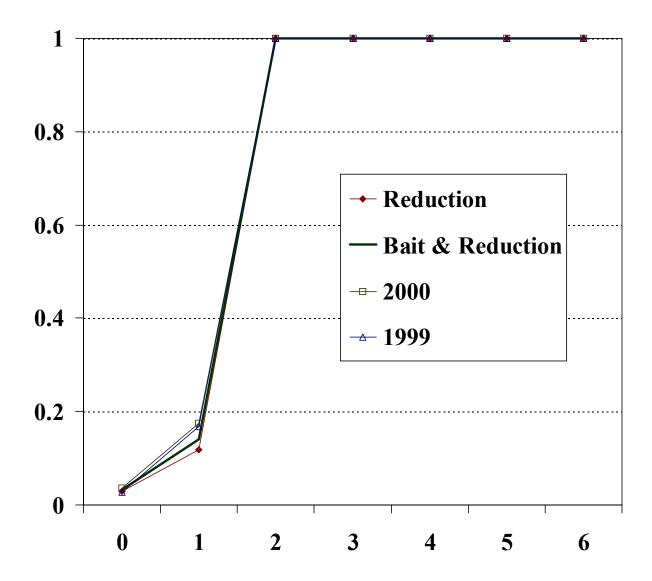**8.1. Data and Research Needs.** State participation in providing more reliable landings data and the continuation and expansion of biostatistical sampling are needed for the menhaden bait fisheries along the Atlantic coast. Exploration of the unreported catch of Atlantic menhaden in other fisheries (e.g., south Atlantic shrimp trawl fisheries) would be worthwhile. Development of the menhaden indices from 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. Virtual population analyses have tended to be unstable when calibrated against a single age class (e.g., lagged age-1 recruits). The forward-projection age-structured model approach (as implemented with AD Model Builder) produces stable results when calibrated with only a lagged juvenile abundance index. This approach can be modified relatively easily to include the effects of various predators on menhaden (simply require availability of appropriate data). 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 research to identify causes of low menhaden recruitment in recent years would be useful.

8.2. Management Objectives. Following the recent period of poor recruitment to age 1 (below 2 billion for 1996-1998; Fig. 4.4) based on the Murphy VPA approach, we note the decay of the SSB from recent high levels to below the historical median in 1999-2000. Concern about recent poor recruitment has been supported by our investigation of state-based juvenile abundance indices (especially in the Chesapeake Bay) and development of a coastwide index (Section 6). However, the coastwide index value for 2001 was close to the long term historical median. Lower values of SSB follow from declining recruitment to age 1 with a two year lag, when they enter the spawning stock. Recruitment for Atlantic menhaden appears to be largely controlled by environmental conditions and not from lack of spawning stock biomass (Section 5). However, our initial estimate for spawning stock biomass (SSB) in 2001 is above the 75th percentile of historical SSB (and about 3 times the target given in Amendment 1). An even higher estimate of SSB in 2001 was obtained from our alternate approach (Appendix A). The problem clearly is not lack of SSB, but apparently one or more factors in the environment causing poor recruitment. This poor recruitment appears to be primarily centered within Chesapeake Bay (Section 6).

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.

9.   References

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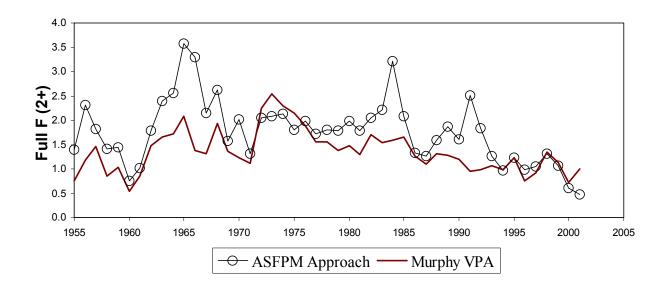
APPENDICES

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

Data from the reduction (1955-2001) and bait (1985-2001) 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 using a logistic function for the reduction fishery and a double logistic function (dome-shaped) for the bait fishery. For both fisheries, selectivity was assumed constant for all years.

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, which loosely follows a Ricker stock-recruit function, and a set of deviation parameters, constrained to follow a lognormal distribution. The numbers-at-age for all years in the model (1955-2001) 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. Female spawning biomass was computed as the product of 0.5*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 160 parameters, which 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 1% and 15% coefficient of variation (CV) for the reduction and bait fisheries, respectively. The CPUE index was assumed to have a CV of 15% and modeled with a lognormal likelihood function. Estimates of F, SPR, R_1 and SSB from the model are shown in Figs. A.1 and A.2. Corresponding estimates from the Murphy VPA are superimposed with this approach in Fig. A.1 and A,2. Recent status of Atlantic menhaden (1985-2001) are plotted relative to Amendment 1 benchmarks in Fig. A.3. A parallel run loosely constrained to a Beverton-Holt recruit function was made with almost identical results relative to F, R_1 and SSB.
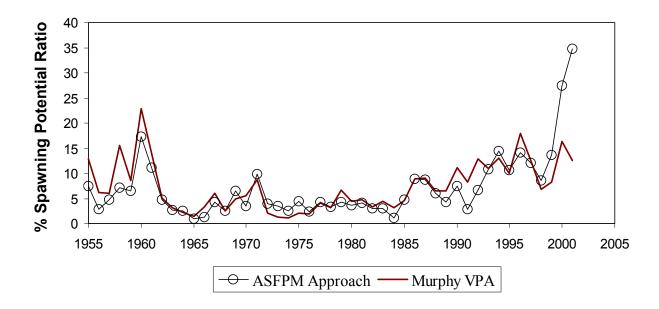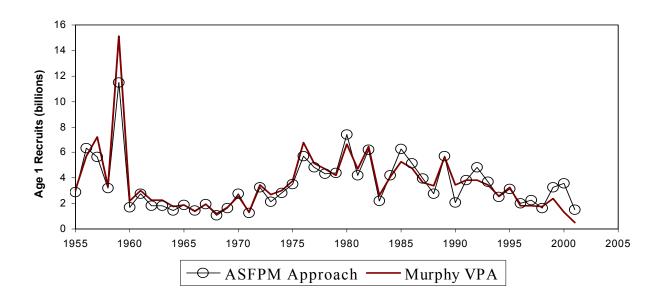
Figure A.1. Fishing mortality and % static potential ratio (SPR) time series estimates for Atlantic menhaden from the age-structured, forward-projection population model (ASFPM, compared with Murphy VPA results in Section 4).

Figure A.2. **Recruitment to age 1 and spawning stock biomass time series estimates for Atlantic menhaden from the age-structured, forward-projection population model (ASFPM, compared with Murphy VPA results in Section 4).**
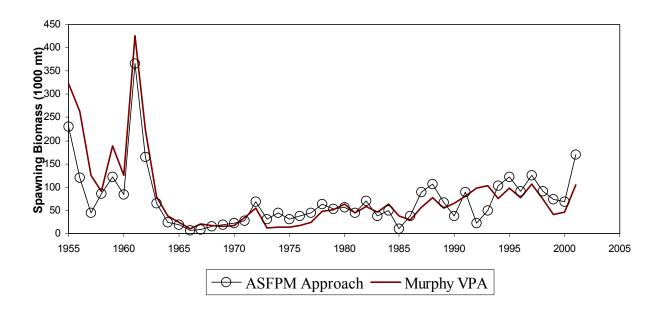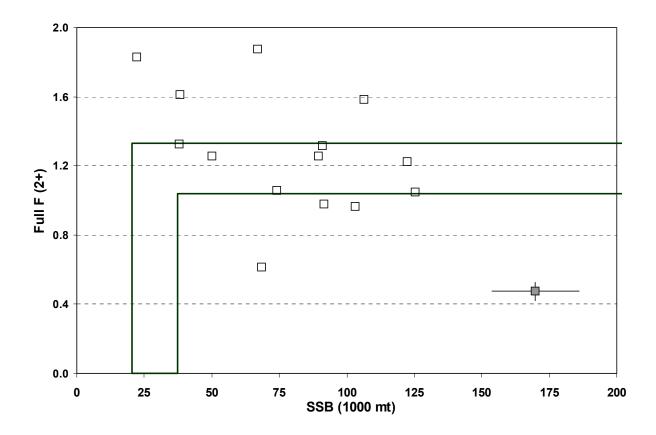
Figure A.3. Recent estimates of full F (2+) and spawning stock biomass (1985-2001) with management thresholds marked as solid heavy lines. Year 2001 point is shaded and marked with ~67% confidence interval lines (±1 standard deviation).

Appendix B: Estimating Reduction Landings from Chesapeake Bay

Because of recent concerns about the availability of forage fish for striped bass in 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 1997-2001. 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, 1955-2001. Biostatistical sampling, which provides location of final set, are available from all ports. An estimate of the portion of landings by port can be made from these data by assuming that the 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"; that is, where 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 these circumstances.

The second approach applies a no-intercept linear regression to obtain estimates of landings within the Bay based on a comparison of estimates from CDFRs with estimates from the biostatistical approach. This approach assumes that there is a constant bias (ratio) over time. The resultant estimates from this regression would then be unbiased relative to the "topping off" problem. Estimates from the CDFRs, biostatistical approach, and regression approach are summarized in Table B.1. Percentages of total coastwide reduction landings caught in Chesapeake Bay are shown in Fig. B.1.

Table B.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 Coastwide Reduction Landings
1955	58103		49330	644408
1956	78218		66408	715542
1957	32465		27563	604813
1958	76612		65044	512390
1959	49118		41702	662168
1960	41483		35219	532237
1961	65483		55596	579148
1962	47533		40356	540129
1963	30207		25646	348439
1964	6776		5753	270404
1965	82071		69679	274602
1966	74094		62907	220686
1967	52925		44934	194393
1968	73303		62235	235863
1969	36464		30958	162333
1970	105768		89799	259391
1971	143402		121750	250350
1972	209873		178185	365882
1973	181655		154227	346906
1974	127584		108321	292204
1975	100330		85181	250208
1976	138757		117806	340538
1977	154403		131090	341163
1978	142544		121021	344080
1979	123134		104542	375745
1980	208663		177157	401530
1981	36976		31393	381309
1982	171465		145576	382460
1983	177303		150532	418634
1984	115766		98287	326296
1985	167449	127200	142166	306665
1986	146414	141400	124307	238001
1987	206747	177400	175530	326912
1988	167147	155900	141910	309293
1989	183398	156000	155707	322014
1990	178071	149500	151184	401159
1991	188472	161800	160015	381413
1992	181909	135700	154443	297631
1993	197931	168500	168046	283498
1994	151328	125900	128479	297082
1995	201519	147400	171092	339927
1996	179685	147800	152554	292924
1997	160220	153297	136028	259140
1998	159334	144547	135276	245920
1999	123645	120315	104976	171315
2000	95310	81035	80919	167253
2001	147039	127389	124838	233769
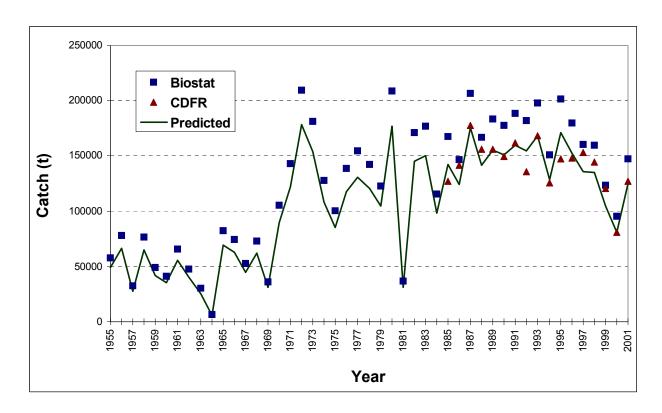
Figure B.1. Estimates of landings of Atlantic menhaden from Chesapeake Bay as percent of total landings from three estimation procedures: biostatistical, CDFR, and regression prediction.