ECOSYSTEM BASED FISHERIES MANAGEMENT FOR CHESAPEAKE BAY

Menhaden Species Team Background and Issue Briefs

The Ecosystem-Based Fisheries Management (EBFM) Project for Chesapeake Bay has been developed and coordinated by Maryland Sea Grant, working in partnership with the scientific community and the region's state and federal agencies (the Virginia Marine Resources Commission, Maryland Department of Natural Resources, Potomac River Fisheries Commission, Atlantic States Marine Fisheries Commission, District of Columbia Department of the Environment, NOAA, and EPA). The EBFM Project targets five key species identified in the Ecosystem Planning for Chesapeake Bay document, including striped bass, menhaden, blue crab, alosines, and oysters. The goals of the EBFM project are to build a sustainable mechanism for addressing ecosystem issues for fisheries within Chesapeake Bay and to develop ecosystem tools for use in ecosystem-based fishery management plans for the five key species (or group of species in the case of alosines). Currently the project involves 85 scientists, managers, and stakeholders from within and beyond the Chesapeake Bay region. For more information on Maryland Sea Grant's Ecosystem-Based Fishery Management Project please visit: www.mdsg.umd.edu/ebfm.

This publication was produced by Maryland Sea Grant.

Ecosystem-Based Fisheries Management for Chesapeake Bay: Menhaden Background and Issue Briefs. 2009. EBFM Menhaden Species Team.

Publication Number
UM-SG-TS-2009-08

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Ecosystem Based Fisheries Management for Chesapeake Bay: Menhaden Background and Issues Briefs

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Published by Maryland Sea Grant
Publication Number UM-SG-TS-2009-08

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Acknowledgments

Support for this project was provided by the U.S. EPA Chesapeake Bay Program, the Maryland Department of Natural Resources, and the Maryland Sea Grant College Program.

Maryland Sea Grant would like to thank the Menhaden Species Team members for their contributions. We also acknowledge and are grateful for the efforts of the many other contributors who provided insights and materials needed for completion of the Ecosystem Issue Briefs.

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MENHADEN BACKGROUND BRIEFS

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Menhaden Species Team

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Maryland Sea Grant and the Menhaden Species Team would also like to thank Doug Lipton, University of Maryland, for his contribution to the Socioeconomics Issue Brief

BACKGROUND

Introduction

Ed Houde, Chair, Menhaden Species Team

Ecosystem-Based Management of Atlantic Menhaden in Chesapeake Bay

The Atlantic menhaden, *Brevoortia tyrannus,* supports the Chesapeake Bay's largest fishery. It also is a key player in the Bay's food web — filtering plankton, cycling and recycling nutrients, and serving as prey for piscivores (Figure 1). Precautionary management that minimizes risk of collapse of the menhaden resource is critical to the wellbeing of the Bay, its fisheries, and water quality. In many ways, menhaden epitomizes arguments in support of ecosystem-based fisheries management (EBFM). The importance of including menhaden in multi-species and EBFM plans for Chesapeake Bay has been recognized for at least a decade (CBP 2000; CBFEAP 2006) and action is now underway to develop an ecosystem-based plan.

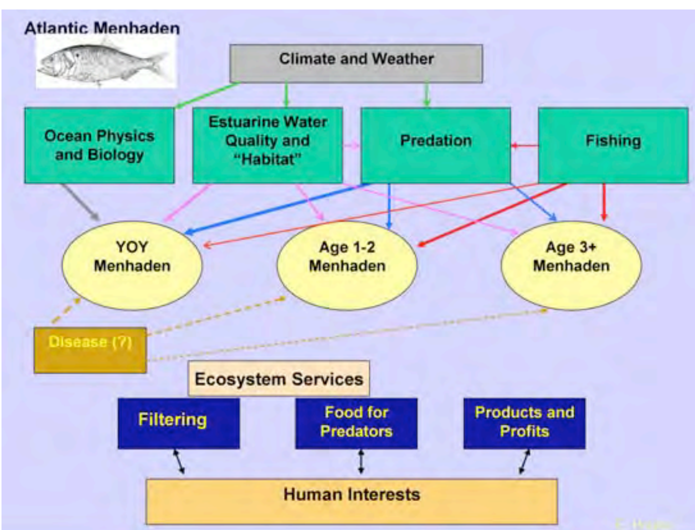

Figure 1. Diagrammatic representation of factors affecting the ecology and dynamics of Atlantic menhaden, including fishing, and a depiction of its role in the Chesapeake Bay ecosystem.

Background and briefing documents included herein provide information on key themes that must be addressed in an EBFM plan for menhaden in Chesapeake Bay. Among these themes, there are two cross-cutting issues that are important for menhaden in Chesapeake Bay: (1) the perception that "localized depletion" characterizes the status of the menhaden resource in the Bay and (2) low recruitment of young-of-the-year menhaden in Chesapeake Bay over the past 15 years. Low abundance of YOY menhaden may now be limiting to predators such as striped bass. The Atlantic States Marine Fisheries Commission (ASMFC) capped the purse-seine, reduction fishery in the Bay at 109,020 tons in 2006, in response to calls for action by a concerned public. In many ways, that action was a precautionary measure to address ecosystem concerns, despite a stock assessment by ASMFC that found the coastwide stock to be neither overfished nor experiencing overfishing.

A precautionary, ecosystem-based management plan that recognizes the historical fishery but also the concerns of diverse stakeholders in the Bay watershed is needed. Briefing documents we prepared address the following issues:

- Background (The Atlantic Menhaden Fishery and Uses of Menhaden, Management, Life History)
- Habitat Suitability (Water Quality, Climate Change, Oceanographic Factors)
- Foodweb (Feeding and Bioenergetics, Predation, Competition)
- Stock Assessment (Exploitation, Recruitment Variability, Diseases/Fish Kills and Connectivity/Regional Abundance)
- Socioeconomics (Services and Products, User Conflicts, Economic Value).

This briefing document will be transmitted fishery managers in the Chesapeake Bay and to the EBFM Quantitative Ecosystem Teams (QETs) who will use information herein to develop reference points appropriate for EBFM of Atlantic menhaden in Chesapeake Bay.

The Atlantic Menhaden Fishery and Uses of Menhaden

Brad Spear, Joe Smith, and Doug Vaughan

History of Menhaden Fishery along the U.S. Atlantic Coast

Some fishing for Atlantic menhaden has occurred since colonial times, but the use of purse-seine gear began in New England by the mid 1800s (Ahrenholz et al. 1987). No longer bound to shore-based seining sites, the purse-seine fishery spread south to the Mid-Atlantic states and the Carolinas by the late 1800s. Purse-seine landings reached their zenith in the 1950s, and peak landings of 712,100 metric tons occurred in 1956 (Figure 2). The Atlantic menhaden fishery has been the largest U.S. fishery on the Atlantic coast for many decades. In the 1950s, over 20 menhaden factories ranged from northern Florida to southern Maine (ASMFC 2004). In the 1960s, the Atlantic menhaden stock contracted geographically, and many of the fish factories north of Chesapeake Bay closed because of a scarcity of fish (Nicholson 1975).

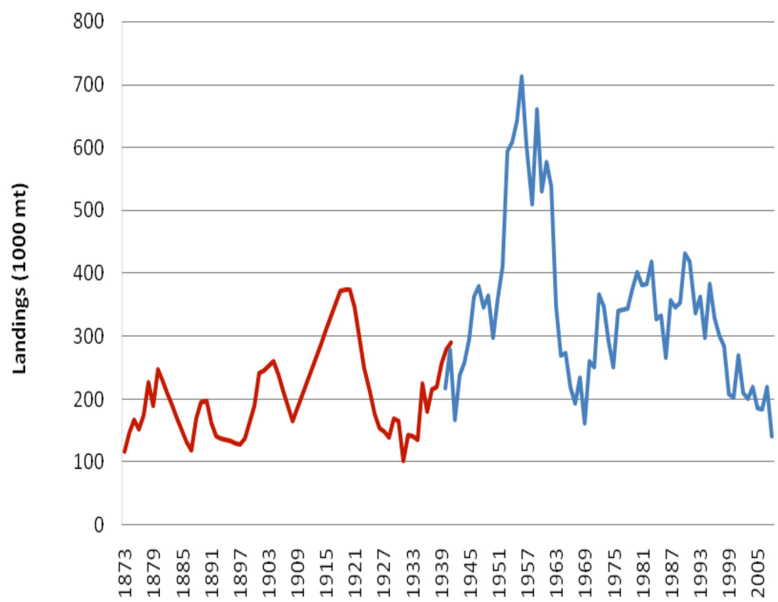

Figure 2. Historical Atlantic menhaden commercial coastwide landings.

During the 1970s and 1980s, the menhaden population began to expand, primarily because of a series of above average year classes entering the fishery. Adult menhaden were again abundant in the northern half of their range, that is, Long Island Sound north to the southern Gulf of Maine. By the mid-1970s, reduction factories in Rhode Island, Massachusetts, and Maine began renewed processing of menhaden. In 1987, a reduction plant in New Brunswick, Canada, processed menhaden harvested in southern Maine that were transported by steamer to Canada.

Beginning in 1988, Maine entered into an Internal Waters Processing venture (IWP) with the Soviet Union which drew up to three foreign factory ships into Maine territorial waters (< 3 miles from the coast). American vessels purse seined the menhaden and unloaded the catch for processing on the factory ships. By 1989 all shore-side reduction plants in New England had closed mainly because of odor abatement issues with local municipalities. A second Canadian plant in Nova Scotia also processed Atlantic menhaden caught in southern Maine in 1992-93. The Russian-Maine IWP and the Canadian plants last processed menhaden during summer 1993.

During the 1990s the Atlantic menhaden stock contracted again (as in the 1960s) mostly due to a series of poor to average year classes recruiting into the fishery. Menhaden again became scarce north of Long Island Sound. After 1993, only three factories remained in the reduction fishery, two factories in Reedville, VA, and one factory in Beaufort, NC. Virginia purse seineres (about 18-20) ranged north to New Jersey and south to Cape Hatteras, NC, while the North Carolina vessels (generally two) fished mostly in North Carolina waters.

A major change in the industry took place following the 1997 fishing season, when the two reduction plants operating in Reedville, VA, consolidated into a single company and a single factory. This consolidation 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, reducing the Virginia fleet to generally 10 vessels from 2000 through 2008. Another major event in the industry occurred in spring 2005 when the fish factory at Beaufort, NC, chose not to operate and later closed. Thus, beginning in 2005 the lone surviving Atlantic menhaden plant has been in Reedville, VA.

Within the geographic range of the current menhaden reduction fleet, Virginia and North Carolina are the only states which permit menhaden reduction purse-seine fishing in their state waters. The Virginia fleet catches Atlantic menhaden off the coasts of Maryland, Delaware, and New Jersey. However, these catches are made beyond three miles from shore in the U.S. EEZ.

As reduction landings have declined in recent years, menhaden landings for bait have become relatively more important to the coastwide total landings of menhaden. Commercial landings of menhaden for bait (e.g., for crab pot and trap fisheries) occur in almost every Atlantic coast state. Historically, information on harvest of menhaden in the bait fisheries was difficult to obtain because of the nature of the fisheries and data collection systems. However, bait landings data have been collected and reported in a more standardized manner since 1985 (Figure 3). Recreational fishermen also catch small quantities of Atlantic menhaden as bait for various game fish, although the extent and magnitude of this harvest has never been well documented.

The Contemporary Fishery for Menhaden in Chesapeake Bay

Since 2005, the lone extant reduction factory for processing Atlantic menhaden on the East coast of the US is owned by Omega Protein, Inc., and is located at Reedville, VA. The Omega Protein plant has a fleet of 10 purse-seine vessels, which range in length from about 160 to 200 ft and in gross tonnage from about 500 to 600 tons. Fully loaded, these vessels, on average, carry about 500 tons of menhaden. In recent years, 60 to 75 percent of the catch and fishing effort by the Reedville fleet is in the Virginia portion of Chesapeake Bay and adjacent Virginia ocean waters.

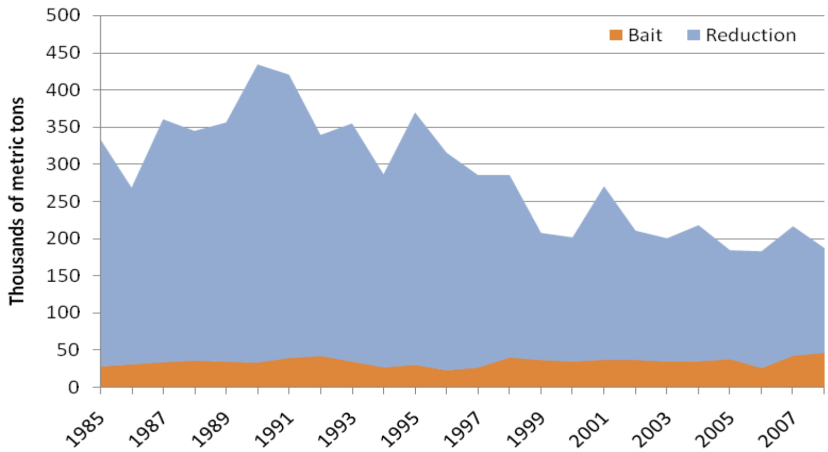

Figure 3. Coastwide landings of Atlantic menhaden for reduction and bait, 1985-2008, in thousands of metric tons.

However, in summer and early fall the Virginia vessels may range as far north as northern New Jersey in search of menhaden. In fall, the fleet may travel south and harvest migratory menhaden schools along the North Carolina Outer Banks. In 2008, landings of Atlantic menhaden for reduction at Reedville amounted to 141,133 metric tons. In recent years (2005-08) landings at Reedville have averaged 154,980 metric tons. Total value of fisheries landings at the port of Reedville for the period — an overwhelming proportion was menhaden for reduction purposes — averaged $26 million (NMFS 2007a, 2007b, and 2008).

Menhaden purse-seine vessels are called ‘steamers’, and carry crews of about 14 men. Each steamer also carries two purse boats which hold the net used to encircle a school of menhaden. Purse-seine nets are about 1,200 feet long and may be up to 10 fathoms deep; in Virginia net meshes can be no smaller than 1-3/4” in stretched length. Airplane spotter pilots locate schools of fish and direct the setting of the net by the purse boat crews via radio. Catches are ‘hardened’ into one corner of the net, then hydraulically pumped into the hold of the steamer. Vessel trips within Chesapeake Bay generally last one or two days. Weather conditions permitting, vessels average four to five ‘sets’ of the net per fishing day. Smith (1999) found that, on average, vessels made at least one set of the net on 76-83% of the available fishing days during May through December.

In Virginia, the purse-seine season for menhaden begins on the first Monday of May and extends through the third Friday of November. After the close of the ‘Bay Season’, Virginia permits purse-seine fishing in its ocean waters until the Friday before Christmas. Virginia menhaden vessels fish only Monday through Friday. Most menhaden fishing activity occurs in the Virginia portion of Chesapeake Bay from early June through mid-October. Smith (1999) found that two statistical reporting areas near Smith Point and the Rappahannock River adjacent to the fish factory at Reedville accounted for about 50% of the catch and effort by the purse-seine fleet within Chesapeake Bay. Purse-seine fishing for menhaden has been prohibited in Maryland waters, including Chesapeake Bay, since 1931.

Each month, the menhaden factory at Reedville reports its daily vessel unloading statistics to the NMFS in Beaufort, NC. Vessels maintain daily logbooks which itemize catch and location information for each purse-seine set; logbook data are supplied to the NMFS at Beaufort on a weekly basis, and are used to monitor the ‘Chesapeake Bay Cap’ [see the Management section below for more information]. The NMFS employs a full-time port agent at Reedville to sample catches dockside throughout the fishing season for age and size composition of the catch.

Reduction Fishery Products

The industrial reduction process for menhaden yields three main products: fish meal, fish oil, and fish solubles. Menhaden meal is a valuable ingredient in poultry, swine, equine, and aquaculture feeds. Historically, most menhaden oil was exported, but in recent years significant amounts are used domestically as edible oils since the Food and Drug Administration in 1997 approved refined menhaden oil for general use in foods in the U.S. Omega Protein, Inc. operates the only marine oil refinery in the USA and produces several grades of refined menhaden oil (www.omegaproteininc.com/products-all.html). Significant and increasing amounts of refined menhaden oil, rich in omega-3 oils, are now incorporated into various human food products.

Atlantic menhaden are also harvested commercially as bait for crab pots, lobster pots, and hook-and-line fisheries. The bait fishery utilizes a wide variety of gear and fishing techniques. While directed harvest comes primarily from small purse seines, pound nets, and gill nets, non-directed harvest, in which menhaden is not the primary target, comes from pound nets, haul seines, and trawls. Landings that come from directed fisheries make up the majority of bait landings. Total landings of menhaden for bait along the U.S. East coast have been relatively stable in recent years, averaging about 37,100 metric tons during 2001-2008 (Figure 3), with peak landings of about 46,700 metric tons in 2008. However, as menhaden landings for reduction have declined, bait landings have become relatively more important. For example, in 2001, total Atlantic menhaden for bait landings amounted to 36,300 metric tons representing 13% of total Atlantic menhaden landings (270,000 metric tons); in 2008 bait landings represented about 25% of total landings (187,800 metric tons). Regional landings of menhaden for bait are dominated by catches in Chesapeake Bay and New Jersey (Figure 4). Combined menhaden-for-bait landings in Maryland, Virginia, and the Potomac River (Chesapeake Bay, Figure 4) amounted to 21,200 mt in 2008, or 45% of the total menhaden-for-bait landings on the U.S. East coast (Figure 4).

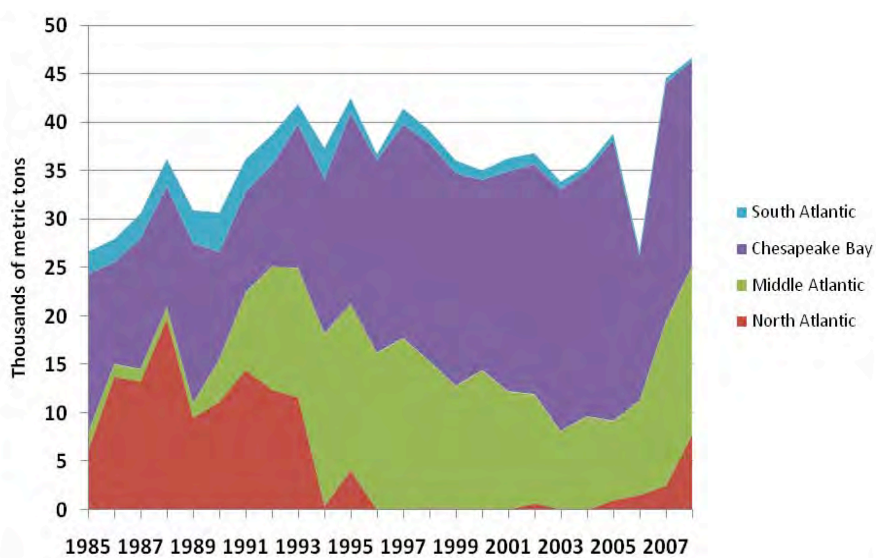

Figure 4. Coastwide landings of Atlantic menhaden for bait, by region, 1985-2008.

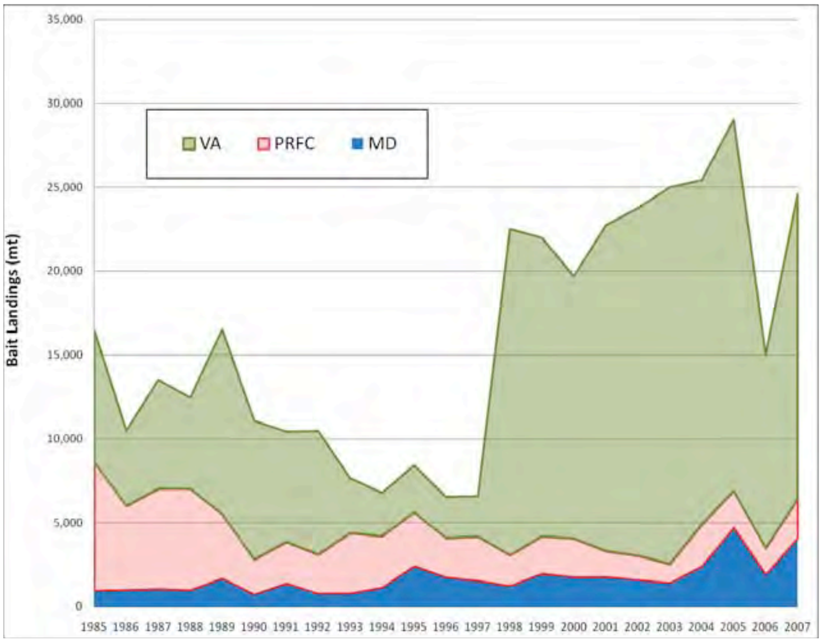

Figure 5. Menhaden-for-bait landings from Chesapeake Bay. Virginia, Maryland, and Potomac River, 1985-2007.

Bait landings of menhaden in Virginia (Figure 5) are dominated by purse-seine gear called ‘snapper rigs’, whose nets are smaller than the gear employed by the larger reduction vessels. ‘Snapper rig’ vessels are also smaller (about 100 ft long) than reduction ‘steamers’, and make fewer sets of the net each fishing day. In recent years, three ‘snapper rig’ vessels have operated from Northern Neck, VA, near Reedville. ‘Snapper rig’ vessels supply daily logbooks to the NMFS at Beaufort, NC from which their daily and annual catches are tabulated. A NMFS port agent also samples ‘snapper rig’ landings for age and size composition of the catch. Bait landings of menhaden in Maryland and the Potomac River are dominated by pound net catches.

Recreational fishermen catch menhaden for bait primarily with cast nets. Anglers use menhaden as a live or “cut” bait for many species of game fishes, such as striped bass, bluefish, and sharks. Ground menhaden is preferred as a “chum” to attract many sport fishes. Quantities of menhaden harvested by sport fishermen are unknown, but thought to be minor compared to landings by the commercial fishery.

User Conflicts
(For more on this topic, see Menhaden Issue Briefs: Socioeconomics)

Conflicts between the menhaden fishery and various user groups have generally been argued over several core issues: fishing operations and distance from shore, by-catch, forage base, water quality, and management. Fishing and distance from shore conflicts are less of an issue in Chesapeake Bay compared to ocean beaches because most fishing effort occurs in the main stem of the Bay. By-catch, that is, harvest of non-target species in purse-seine vessels, is generally relatively small in the Atlantic menhaden fishery. Most by-catch studies, including those in Chesapeake Bay, show incidental catch of non-target species is low (e.g., Austin et al. 1994). Because menhaden occupy a unique position in the Bay’s food web and with the resurgence of the striped bass population in Chesapeake Bay during the 1990’s, numerous entities insist that menhaden be abundant as food for game fish higher in the food chain (e.g., http://www.menhadenmatter.org/ and http://www.savethebait.org/). It is hypothesized that menhaden removals from Chesapeake Bay affect predator growth, well-being, and abundance. The effect of menhaden schools on Bay water quality by their filtering activity and nutrient sequestering and recycling is a complex issue (e.g., Gottlieb 1998), and one not yet fully understood.

Management

Brad Spear and Alexei Sharov

The Atlantic States Marine Fisheries Commission (ASMFC) is responsible for the oversight and of Atlantic menhaden from Maine through the east coast of Florida. The Atlantic Menhaden Management Board (Board) directs management of the species. The ASMFC approved the Interstate Fishery Management Plan (FMP) for Atlantic Menhaden in 1981 (ASMFC 1981). The Interstate FMP has been amended twice to incorporate additional information and address new needs. The 1992 Plan Revision, which replaced the FMP, established the goal "to manage the menhaden fishery in a manner that is biologically, economically, and socially sound" (ASMFC 1992). Since 2001, the current plan, Amendment 1, seeks to manage the fishery in a "biologically, economically, socially, and ecologically sound" way (ASMFC 2001). It has been modified through a series of three addenda (ASMFC 2004, 2005, 2006). Individual states and jurisdictions are required to implement regulations consistent with ASMFC plans. Amendment 1 is enforceable through the Atlantic Coastal Fisheries Cooperative Management Act of 1993 (ACFCMA).

Historical Management

Throughout most of its history, the Atlantic menhaden fishery has been largely unregulated. Prior to approval of the FMP in 1981, management of the fishery was largely left to industry (ASMFC 1981). However, at the time the FMP was passed, Maryland and Virginia were the two most restrictive states along the Atlantic coast. Maryland was the only state to prohibit the use of purse seine nets in its waters, thereby eliminating a commercial reduction fishery. Virginia was the only state to use both a closed season and mesh size limits to regulate the menhaden fishery.

The 1981 FMP did not recommend or require specific management actions, but provided a suite of options should they be needed. After the FMP was implemented, the Atlantic fishery became more important, mainly because the population was recovering and the Gulf of Mexico landings were dropping. However, a combination of further state restriction, imposition of local land use rules, and changing economic conditions resulted in the closure of most reduction plants by the late 1980s (ASMFC 1981). In 1988, the ASMFC concluded that the 1981 FMP had become obsolete and initiated revision of the plan.

The 1992 Plan Revision included a suite of objectives to improve data collection and promote awareness about the fishery and its research needs (ASMFC 1992). Under this revision, the coastwide menhaden program was directed by the Atlantic Menhaden Management Board, which at the time was composed of up to five state directors, up to five industry representatives, and one representative each from the National Marine Fisheries Service and the National Fish

Meal and Oil Association. The 1992 Revision adopted six "management triggers" to annually evaluate the menhaden stock and fishery:

- Landings in weight — recommend action if landings fell below 250,000 metric tons.
- Proportion of age-0 menhaden in landings — recommend action if more than 25% harvested (by number) are age-0 fish.
- Proportion of adults in landings — recommend action if more than 25% harvested (by number) are age 3 and older.
- Recruits to age 1 — recommend action if estimates of age-1 fish dropped below 2 billion.
- Spawning stock biomass (SSB) — recommend action if SSB dropped below 17,000 metric tons.
- Percent maximum spawning potential (%MSP) — recommend action if %MSP dropped below 3%.

The Atlantic Menhaden Advisory Committee (AMAC) comprised of technical and industry representatives annually considered the "management triggers". If one or more was reached or exceeded, and this indicated a problem, the AMAC recommended regulatory action to "the Board." The 'Recruits to age 1 trigger' was reached in several years while the triggers were in place. However, AMAC never recommended regulatory action because SSB was at high levels during those years and AMAC believed reduced recruitment was attributable to environmental factors (as opposed to fishing pressure). Also, there was a retrospective bias associated with the recruitment estimates in which initial low values for recruits in stock assessment models were followed by higher estimates in subsequent years.

Reported landings for the Atlantic menhaden reduction fishery are available back to 1940. Earlier landings were reported, but are less reliable with regard to accuracy. Reported landings for the bait fishery are reliable back to 1985.

Current Management

Directed by "the Board" which is comprised of three representatives from each state, Maine through Florida, the management program in Amendment 1 provides specific biological, social/economic, ecological, and management objectives. Addendum I establishes the biological reference points that are currently in place. Addendum II initiated a five-year research program for Chesapeake Bay aimed at evaluating possible localized depletion. Addendum III instituted a harvest cap for reduction landings from Chesapeake Bay for a five-yr period, 2006-2010.

Stock Assessment (also see Stock Assessment Issues Briefs)

The Atlantic menhaden is believed to be a single coastwide stock. Stock assessment is conducted on the coastwide stock. The current assessment model is unable to determine stock status for geographic areas smaller than coastwide. According to the 2006 assessment, the coastwide stock is not overfished, nor is overfishing occurring.

A menhaden stock assessment is conducted by ASMFC every three years and is peer reviewed at least every six years. Scientists annually evaluate the most recent data against "assessment triggers" that will initiate an assessment in any non-assessment year. While management action might result from a stock assessment, reaching these "assessment triggers" does not automatically require management action. Addendum I (ASMFC 2004) establishes that the following "triggers" are reached when: 1) the catch-per-unit-effort (CPUE) index falls below the 5th percentile for the past 20 years; and 2) the ratio of ages 2-4 to the total catch of all ages falls below the second standard deviation unit over the last 20 years. To date, these "triggers" have never been reached.

Addendum I also establishes biological reference points based on fishing mortality and fecundity that are used to determine if management action should occur. A standard management tool, a "control rule," defines the status of the stock based on fishing mortality and spawning stock biomass (fecundity) in relation to target and threshold values. Below is a chart providing the reference points:

	Population Fecundity	Fishing Mortality Rate
Threshold	13.3 trillion eggs	F = 1.18
Target	26.6 trillion eggs	F = 0.75

Overfishing occurs if the fishing mortality rate exceeds the fishing mortality threshold and would result in the ASMFC Atlantic Menhaden Management Board taking action to reduce fishing mortality. If the fishing mortality rate exceeds the fishing mortality target, the Management Board is not required to take steps to reduce fishing mortality. The stock is considered overfished if fecundity drops below the threshold. If this occurs, the Management Board would take action to increase spawning stock biomass and fecundity. Neither fishing mortality nor the population fecundity thresholds were crossed since the inception of the control rule in 2004 and, therefore, no management actions were taken based on the rule.

Fishery Regulations

There are no coastwide regulations in place to restrict menhaden harvest. Individual states have adopted a suite of regulations for the menhaden reduction and bait fisheries, including gear restrictions and seasonal closures. Through Addendum III, ASMFC set a harvest cap for the purse-seine reduction landings from Chesapeake Bay. Because Maryland has prohibited purse seines in its waters, the only reduction harvest in Chesapeake Bay comes from Virginia waters. Virginia regulates its menhaden reduction and bait fisheries through stretched-mesh minimum size of 1 ¾". Menhaden is the only fishery in Virginia that is regulated directly by the Legislature, not the state's Marine Resources Commission. The Potomac River Fisheries Commission limits entry into its pound net fishery, which accounts for nearly all menhaden landings within its jurisdiction.

The Addendum III reduction fishery harvest cap of 109,020 metric ton for Chesapeake Bay is in place from the 2006 fishing season through 2010. The cap, calculated as five-year average landings from Chesapeake Bay in 2001 -2005, was instituted following concern over localized depletion of menhaden in the Bay expressed by many stakeholders. The addendum allows for harvest underages to be applied to the next year's harvest cap with a maximum cap of 122,740 mt in any given year. Also, any harvest overages are subtracted from the next year's harvest cap. However, landings from the Bay since the cap was established have been well below the cap. One apparent effect of the cap has been an increase in reduction landings in ocean waters from Virginia to New Jersey.

Monitoring and Research

Fishery-independent monitoring of menhaden is conducted in several states' surveys, including striped bass young-of-the-year seine surveys in Virginia and Maryland. Fishery-dependent monitoring is conducted mostly on the reduction fishery. However, as bait landings have increased in recent years, they have become an important source of age and length data. In addition, a fishery-dependent index of abundance was developed from commercial pound net landings and effort in the Potomac River.

Addendum II initiated a research program to evaluate the possibility of localized depletion of menhaden in the Chesapeake Bay. It established four research priority areas that were designated to inform this evaluation:

- Determine menhaden abundance in Chesapeake Bay.
- Determine estimates of removal of menhaden by predators.
- Determine exchange of menhaden between the Bay and coastal systems.
- Determine recruitment to the Bay through larval studies.

Research has been conducted, or is being conducted, in each of the four areas. Most of the funding has been provided by NOAA Chesapeake Bay Office, Maryland Department of Natural Resources, and ASMFC.

Early Life History: Egg/Larval Stage (Ocean)

Ed Houde, Eric Annis, and Cynthia Jones

Menhaden recruitments to Chesapeake Bay, based on YOY survey abundance estimates, vary >20-fold and have been at low levels for nearly two decades. The causes of the variability are not known, but may be associated with variable survival of early life stages in the coastal ocean (eggs and larvae). Alternatively, poor conditions for production and survival in estuarine habitats occupied by juveniles may lead to poor recruitment. Additionally, spawning output, i.e., egg abundance, could be a factor, although spawning stock biomass and, presumably, fecundity and egg production are at reasonably high levels.

Spawning

Most, but not all, eggs are spawned over the continental shelf in the coastal ocean from Florida to the Gulf of Maine. Some spawning also occurs in coastal embayments and estuaries. Spawning in some parts of the Atlantic menhaden's range occurs in every month of the year, usually at temperatures >15 °C (Higham and Nicholson 1964; Reintjes and Pacheco 1966; Reintjes 1969; Ahrenholz 1991). The primary, documented spawning areas are off the Carolinas, inshore of the Gulf Stream, in the South Atlantic Bight. Most spawning in the primary areas is in the winter months. Evidence is accumulating to indicate that a substantial fraction of spawning occurs in fall months in the Mid-Atlantic Bight, from New Jersey to Virginia (SABRE 1999; Warlen et al. 2002; Light and Able 2005). Additionally, spring and summer spawning occurs within estuaries, in coastal embayments, and in near-shore coastal areas. Eggs and newly hatched larvae have been collected from the Chesapeake Bay in spring months (Houde, *unpublished data*). It is probable, although not demonstrated, that individual females spawn many times during the year, over a broad geographic range, exhibiting serial spawning behavior typical of clupeoid fishes. There is evidence that spawning events may occur after strong winds and storms in the South Atlantic Bight, conditions that promote upwelling and potentially high production of food for larval menhaden (Checkley et al. 1999).

Eggs

Eggs are pelagic, ranging from 1.3 to >1.5 mm diameter and resemble eggs of many clupeid fishes (Reintjes 1969; Ahrenholz 1991). The eggs have a narrow perivitelline space and a single small oil globule. Hatching time is approximately 2-3 days at 15-20 °C (Ferraro 1980; Ahrenholz 1991). Egg occurrences in ichthyoplankton surveys have been reported in nearly all months of the year (e.g., MARMAP collections), although they are most common and frequent in fall and winter (Kendall and Reintjes 1975; Judy and Lewis 1983; Morse et al. 1987; Berrien and Sibunka 1999).

Little is known about hatchability and survival rates of eggs in the sea. In the laboratory, where adults have been artificially spawned (e.g., Ferraro 1980; Hettler 1981), eggs survival was low, but best at 15 to 25 °C, with virtually no survival at 10 °C. Eggs are broadly tolerant of salinity. Nothing is reported on predators of menhaden eggs, although it is probable that planktonic predators eat them. Based on observations of other clupeoid, filter-feeding fishes, it is probable that cannibalism occurs, although it is not yet reported for Atlantic menhaden. The relatively short stage duration of eggs (~1.5 to 3 days) (Reintjes 1969; Hettler 1981) suggests that this life stage usually may not be a critical stage in controlling levels of recruitment.

Yolk-Sac Larvae

Newly-hatched larvae range from 3.0-4.5-mm in length. Eyes are unpigmented and the jaws and gut are not fully developed or functional. The elliptical yolk sac is prominent. Menhaden larvae, like all clupeoid larvae, are slim and long-bodied, with a long tubular gut. The yolk-sac larval stage lasts ~3 to 5 days at 15-20 ° C (Reintjes 1969; Powell and Phonlor 1986). Nutrition is supplied by yolk and no exogenous food is required. There are no reports on predators or mortality rates of yolk-sac larvae. Reintjes (1969) suggests that planktonic predators such as salps, chaetotnaths and other fish larvae may be predators.

Early-Feeding Larvae

At ~3 to 5 days after hatching, depending on temperature, and at approximately 5 mm length, larval eyes, jaws and gut become functional, the yolk is absorbed, and exogenous nutrition is required to fuel growth (Reintjes 1969; Powell and Phonlor 1986). Feeding-stage larvae live in the plankton community, primarily on the continental shelf, and shoreward of the Gulf Stream front. Larvae drift and disperse, and are gradually transported shoreward to mouths of estuaries. Reintjes and Pacheco (1966) believed that larvae were 1-3 months old when entering estuaries. Recent estimates based on otolith increment analysis of larval ages at the time of delivery to the mouths of Mid- and South-Atlantic estuaries, including Chesapeake Bay, indicate that these larvae are ~30-100 days post-hatch (Warlen 1994; Warlen et al. 2002; Light and Able 2003; Lozano, *unpublished*).

Early-feeding larvae occur in continental shelf waters that generally are >12 °C. Vertical distributions are variable, but most larvae occur in the mid- to surface layers of the water column (Govoni and Pietrafasa 1994; Hare and Govoni 2005). Upon reaching the mouths of estuaries, most often in the October to April period for Chesapeake Bay and other Mid- and South-Atlantic estuaries, a wide range of temperatures may be encountered. Temperatures at the Chesapeake Bay mouth upon arrival of larvae in the November to April period in years 2005-2008 ranged from ~4 to 14 °C (Houde, *unpublished data*). Temperature tolerances of early-feeding larvae are not defined, but late-stage larvae, upon arrival at estuary mouths, apparently can survive if temperatures are >3 °C (Lewis 1965).

Reported growth rates of Atlantic menhaden larvae range broadly from ~0.3 to 1.0 mm/d (Ahrenholz et al. 1995). In the laboratory, Atlantic menhaden larvae grew at ~0.3 to 0.4 mm/d at 20 °C (Powell and Phonlor 1986). On the continental shelf off North Carolina, larvae reportedly grew at 0.25 to 0.66 mm/d at temperatures of 15 to 20 °C (Maillet and Checkley 1991).

Hatch dates of larvae, based on back-calculated dates from otolith-aging analysis, indicate a wide range of hatch dates of individuals that occur in Delaware and Chesapeake Bays, and in the Carolina Sounds, with birth dates commonly occurring from September to April (Warlen 1994; Warlen et al. 2002; Light and Able 2003; Lozano, *unpublished data*)

MARMAP monitoring survey collections indicate a general progression of menhaden larvae occurrences on the inner shelf that begins in early fall off the New Jersey coast and progresses southerly as winter approaches (Morse et al. 1987; Berrien and Sibunka 1999). In late winter, larvae are primarily found off the Carolinas (Kendall and Reintjes 1975). Drift of larvae and transport to Delaware and Chesapeake Bays may differ seasonally. Most feeding-stage larvae delivered to the Chesapeake Bay in fall and early winter possibly originated from spawning in the Mid-Atlantic Bight, while most larvae in late winter-early spring originated from spawning off the Carolinas (e.g., SABRE reports 1999; Warlen et al. 2002; Light and Able 2003). Except for modeling research that has simulated drift and drift tracks, relatively little is known about bio-physical coupling and interactions that affect dispersal, growth, and survival of feeding-stage larvae in the first 50 days of life.

Menhaden larvae eat zooplankton, mostly crustaceans such as copepods (Reintjes 1969; June and Carlson 1971; Rogers and Van den Avyle 1983). In the laboratory, *Artemia nauplii* and the rotifer *Brachionus plicatilis* are adequate foods for early-feeding larvae. Stomach contents and foods of first-feeding larvae from ichthyoplankton collections apparently are not reported. It is not known if larvae potentially may starve or grow slowly under conditions of low zooplankton concentrations in the sea. Specific predators of feeding-stage menhaden larvae are unreported, although it is probable that pelagic fishes, gelatinous zooplankton, and other pelagic invertebrate predators take their toll.

Mortality rates of feeding-stage larvae in the sea are unreported. In mesocosm experiments (Keller et al. 1990), instantaneous mortality rates ranged from 0.038 to 0.056 d^{-1} (3.7 to 5.4% d^{-1}). These rates may be lower than those in the sea where predators on menhaden larvae presumably are more abundant.

Late-Stage Larvae

Late-stage larvae at time of ingress into estuaries generally are >30 days old and usually range from 14 to 34-mm fork length (Reintjes and Pacheco 1966). In Chesapeake Bay, most ingressing larvae are 40-50 days old. Late-stage larvae peak in abundance at the Bay mouth during late winter when sea temperatures generally are <10 °C (Houde and Secor 2009). The specific mechanisms and explanation of how late-stage larvae enter bays and estuaries are poorly understood, but entry probably depends on a combination of larval behavior, tuned to tides and time of day, and favorable onshore winds and currents. In recent surveys at the Chesapeake Bay mouth, most ingressing larvae occurred above the pycnocline, but there are as yet unexplained shifts in distribution and strong daily variability in spatial occurrences.

Late-stage larvae collected at the Chesapeake Bay mouth from November to April in three survey years ranged from 7 to 40 mm total length. Growth rates ranged from 0.1 to 0.6 mm/d (Houde and Secor 2009), with evidence that rates were declining in larger and older larvae, a probable effect of declining temperature as larvae dispersed from warmer offshore waters to colder inshore waters at the Bay mouth.

Late-stage larvae eat zooplankton. Several species of copepods are reported as dominant prey (June and Carlson 1971; Kjelson et al. 1975). The primary food at the mouth of Chesapeake Bay is calanoid copepods, with barnacle nauplii and marine cladocera also common in the diet[1]. Mortality rates of late-stage, ingressing larvae are not reported and specific predators are not identified, although pelagic fishes, squids, and possibly seabirds could be significant predators on late-stage larvae.

Ecosystem Considerations

Atlantic menhaden has a complex life history (Figure 6). Survival of earliest life stages depends on environmental and hydrographic conditions on the continental shelf. A connectivity pathway is necessary to transport young menhaden to estuaries which serve as juvenile nurseries. Seasonal and interannual variability in weather and hydrography on the shelf could account for variable transport conditions that affect recruitment level (Nelson et al. 1977). Alternatively, environmental variability could act on predators, or on primary production that supports production of zooplankton prey eaten by menhaden larvae, affecting survival and growth of the larvae, and ultimately levels of recruitment. The recent long series of low recruitments in Chesapeake Bay might be related to decadal shifts in regional climate that presently is unfavorable for either larval survival or larval dispersal. It also is possible that longer-term, global climate change will modify hydrographic conditions on the continental shelf ecosystem and could affect early-life ecology and delivery of menhaden to the Chesapeake Bay.

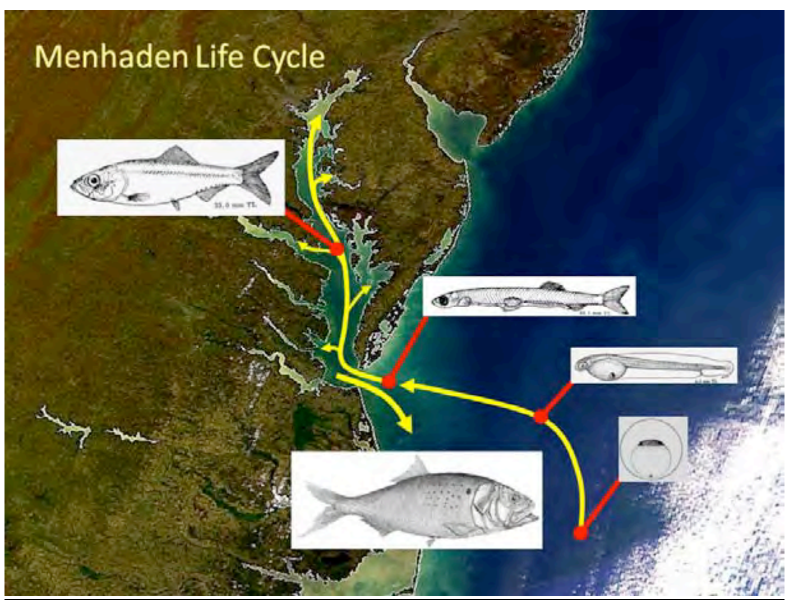

Figure 6. Life cycle of Atlantic menhaden with respect to the Mid-Atlantic region and Chesapeake Bay.

Early Life History and EBFM

Fishing on adult stock, ocean variability, and directed shifts in climate can interact to control or regulate menhaden abundance. Much of the variability in natural mortality and recruitment level is dependent on the dynamics of early life stages. At the ecosystem level, small changes in habitat suitability, climate effects, or predator-prey interactions can translate into order-of-magnitude differences in abundance of menhaden, or can force geographical shifts in spawning sites, nursery locations, and transport pathways of larvae. Fishing mortality affects adult abundance, fecundity, and egg production. In combination with natural environmental variability, fishing also potentially can contribute to temporal and spatial shifts in spawning areas or times that may affect survival probability of eggs and larvae.

Surveys of menhaden eggs and larvae, e.g., the historical NOAA MARMAP and present ECOMON programs, could provide information on present and past distributions and abundances of early life stages, and indications of geographical or temporal shifts. Such knowledge would be useful for development of forecasting models of menhaden recruitments and abundance and, in a broader context, to support EBFM.

Early Life History: Young of the Year (Estuary)

Eric Annis, Ed Houde, and Cynthia Jones

Young of the year (YOY) menhaden experience critical transitions in habitat, morphology and diet during their first year of life. Recruitment and growth during this period are dependent on favorable environmental and water quality conditions in Chesapeake Bay that can influence recruitment to the adult population.

Distribution

Menhaden larvae enter Chesapeake Bay during the winter months and disperse upbay to tributaries and the head of the Bay. The larvae undergo metamorphosis to the juvenile stage between 30-40 mm TL when they assume a body form essentially that of the adult with a significant increase in body depth and weight (June and Carlson 1971; Lewis et al. 1972). The YOY menhaden spend their first summer in the Bay filter-feeding on the phytoplankton rich waters of the estuarine environment. The distribution of menhaden in the mainstem of Chesapeake Bay indicates that the highest abundance of YOY menhaden generally occurs in the upper half of the Bay in June and September (Figure 7) (Houde and Harding 2009). By late summer-early fall, declining water temperatures (below about 24°C) signal a mass migration of most young-of-the-year (10-14 cm fork length) menhaden from creeks and rivers toward the ocean (Friedland and Haas 1988).

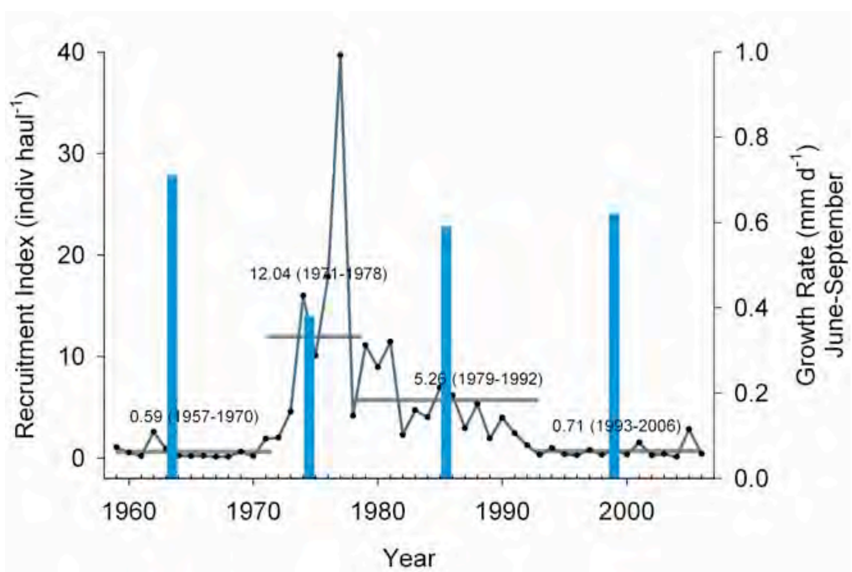

Figure 7. Recruitment index and growth rates of YOY menhaden. Maryland Department of Natural Resources (DNR) survey indices of YOY menhaden abundance. Area-weighted estimates of catch-per-unit effort (line) from summer seine surveys. Bars are mean growth rates for indicated years. Numbers on the figure are the mean recruitment index value for years (in parentheses). (From Houde and Harding 2009.)

Recruitment

Menhaden recruitments, based on YOY survey abundance estimates, vary more than 10-fold in the Chesapeake Bay and have been at low levels for nearly two decades (Figure 8). Indices of menhaden recruitment depicted here include data from the Maryland Department of Natural Resources Striped Bass Seine Survey and both seine and trawl surveys conducted by the Virginia Institute of Marine Science. Shore seines are probably not the best means of surveying this schooling species, may not include preferred habitat, and cannot provide a precise estimate of the density of juvenile menhaden. However, the long time series (50+ years) and consistent sampling make the Chesapeake Bay time series one of the best indices of young-of-the-year recruitment. These surveys, coupled with others from coastal Atlantic states, are presently used by ASFMC in estimating age-0 population abundance in the virtual population analysis model used to manageme the coastwide stock (See Stock Assessment Issues, Recruitment Variability brief).

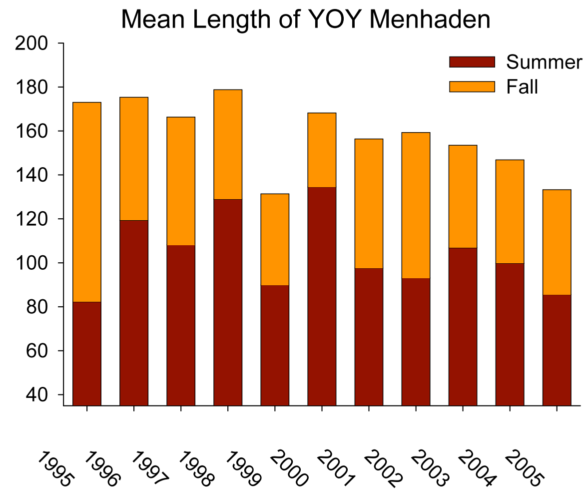

Figure 8. Mean lengths of YOY menhaden in Chesapeake Bay mainstem. Measurements were made on fish collected during TIES[1] and CHESFIMS[2] cruises (1995-2005).

Recruitment was low in the 1960's, increased and peaked in the 1970's, but began a gradual decline through the 1980's. Recruitment since the mid-1990's has remained at low levels similar to those recorded in the 1960's. The relationship between spawning stock biomass and recruitment is highly variable (e.g. Nelson et al. 1977) and does not adequately explain interannual variability in recruitment. More recently, attempts have been made to link variability in recruitment to biotic or abiotic factors with some success. There is evidence that recent recruitments may vary as a function of *chl-a* availability (See Oceanography Issues brief). There is also evidence that recruitment may vary as a function of larger scale climatic changes. Wood (2000) linked recruitment variability to regional climatology and Kimmel et al. (2009) suggested that winter climate patterns leading to drier spring conditions resulted in higher menhaden recruitment. There is a generally negative relationship between recruitment and spring freshwater input into the Bay but it was not statistically significant (See Oceanography Issues brief). Research

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[1] TIES. Trophic Interactions in Estuarine Ecosystems. Midwater trawl surveys, 1995-2000. NSF-funded Land Margin Ecosystem Research, University of Maryland Center for Environmental Science.

[2] CHESFIMS. Chesapeake Bay Fisheries Independent Multispecies Surveys, 2001-2005. Midwater trawl surveys, 2001-2005. NOAA Chesapeake Bay Office-funded program. University of Maryland Center for Environmental Science.

results suggest that biological and environmental conditions contribute to recruitment variability in YOY menhaden in Chesapeake Bay but more research is needed to define the nature of the relationships and the mechanisms driving them.

Trophic Dynamics

YOY menhaden make two important transitions in feeding during their first summer in the Bay. Prior to metamorphosis, larval menhaden feed selectively on zooplankton. Metamorphosis is accompanied by a lengthening of the gill rakers and development of filter-feeding capacity (Friedland et al. 1984; June and Carlson 1971). The YOY menhaden shift to filter feeding on a diet that appears to be largely comprised of phytoplankton although detritus and zooplankton may be important in areas of high relative abundance (Jeffries 1975; Lewis and Peters 1981). Another transition appears to occur between 100-200mm fork length a result of allometric increases in spacing of the gill rakers (Friedland et al. 2006). This likely reduces the filtering efficiency on phytoplankton and implies that zooplankton may become increasingly important in the diet of menhaden at older ages (primarily age-1 and older) both within the Bay and in the coastal ocean.

From a top-down perspective, YOY menhaden serve as a forage fish for numerous piscivorous fishes including striped bass, bluefish, and weakfish (Ahrenholtz 1991). In addition, menhaden may comprise a significant component of avian diets, e.g., ospreys, pelicans and loons. Spitzer 1989; Viverette et al. 2007). As primary consumers, YOY menhaden provide an efficient forage base for transfer of energy from primary production to higher order predators in the Chesapeake ecosystem.

Growth

Young-of-the-year menhaden range widely in size (Ahrenholtz 1991), with lengths varying as a function of density, timing of larval ingress, temperature and *chl-a* availability. Mean growth rates of YOY menhaden in Chesapeake Bay were lowest (0.38 mm d^{-1}) during years of peak YOY recruitment while mean growth rates were highest (0.62 and 0.71 mm d^{-1}) during years of low recruitment (Figure 7). Other growth rates reported for YOY menhaden in Chesapeake Bay have ranged from 0.50 to 0.91 mm d^{-1} (McHugh 1967; Rippetoe 1993).

Variability in menhaden lengths observed in the summer and fall trawl surveys illustrate the range of inter-annual variability during the present period of low recruitment (Figure 8). A bioenergetics model specific to YOY menhaden in Chesapeake Bay effectively captured this variability as a function of *chl-a* levels and water temperature (Annis et al in prep, see Food Web Issues brief).

Young of the Year and EBFM

In addition to spawning stock biomass and numbers of larvae that are transported to the Bay, a suite of environmental and biological conditions contribute to the successful recruitment and growth of YOY menhaden. Transitions in habitat, feeding, and morphology during this period suggest that YOY juveniles represent a critical life phase that can regulate recruitment and adult population abundance. Evidence for bottom-up control of YOY menhaden abundance in

Chesapeake Bay indicates that changes in the quantity and composition of phytoplankton affect growth rates (Houde and Harding 2009) which may affect recruitment to adult populations. The shift in feeding between zooplankton by late-stage larvae to phytoplankton by YOY juveniles indicates that the status of both prey resources may be important metrics to gauge menhaden recruitment. Abundance of predators may provide a strong top-down control over YOY menhaden abundance. And, the overarching effect of local climatology may play an important role in contributing to variability in the recruitment of YOY menhaden in Chesapeake Bay.

Late Life History

Joe Smith and Doug Vaughan

Coastwide Stock

Ahrenholz (1991) pointed out that historically, considerable debate existed with respect to defining stock structure of Atlantic menhaden on the U.S. East coast, with a northern and southern stock hypothesized based on meristics and morphometrics (Sutherland 1963; June 1965). Nicholson (1972) and Dryfoos et al. (1973) argued convincingly, from back-calculated length-frequencies information and tag recoveries, for a single biological population of Atlantic menhaden. Ahrenholz (1991) noted that, although different temporal spawning cohorts of menhaden exist, they appear to mix rapidly as a result of their extensive migratory movements and are virtually inseparable in the commercial fishery. Thus, primarily based on size-frequency information and tagging studies (Nicholson 1972 and 1978; Dryfoos et al. 1973), the Atlantic menhaden resource is believed to consist of a single unit stock or population. Recent genetic studies (Anderson 2007; Lynch 2008) support the single stock hypothesis.

Adult Atlantic menhaden undergo extensive seasonal migrations north and south along the U.S. East coast (ASMFC 2004). Roithmayr (1963) found evidence of this migratory behavior based on the decrease in the number of purse-seine sets north of Cape Cod in September. Also, Reintjes (1969) observed the disappearance of fish in October north of Chesapeake Bay and their appearance off the coast of North Carolina in November. Nicholson (1971) examined latitudinal differences in length-frequency distributions of individual age groups at different times of year and described a cyclic north-south movement with the largest and oldest fish proceeding farthest north such that the population stratifies itself by age and size along the coast during summer. A study of length frequencies at the time of first annulus formation on scales (Nicholson 1972) supported the concept of a north-south migratory movement and also indicated that a great deal of mixing of fish from all areas occurs off the North Carolina coast before fish move northward in spring.

Returns of tagged Atlantic menhaden (Dryfoos et al. 1973; Nicholson 1978) generally confirmed what had been learned from earlier work and added some important details (ASMFC 2004). Adults begin migrating inshore and north in early spring following the end of the major spawning season off the Carolinas during December-February. The oldest and largest fish migrate farthest, reaching southern New England by May and the Gulf of Maine by June. Fish begin migrating south from northern areas to the Carolinas in late fall. Adults that remain in the south Atlantic region during spring and summer migrate south later in the year, reaching northern Florida by fall. During November and December, most of the adult population that summered north of Chesapeake Bay moves south of the Virginia and North Carolina capes.

After winter dispersal along the south Atlantic coast, adults again begin migrating north in early spring.

Chesapeake Bay Component

Atlantic menhaden occur in Chesapeake Bay year-round, but are generally in low numbers during winter (Hildebrand 1963). They are most abundant in the Bay during May through October when they form dense, near-surface schools that are harvested by an industrial purse-seine fishery in Virginian waters (Smith 1999). Age-1 and -2 Atlantic menhaden dominate the commercial catch in the main stem of Chesapeake Bay; age-3+ fish occur in the Bay, but usually account for less than 10% of the catch (Smith et al. 1987). All life history stages of Atlantic menhaden, from larvae to adults, occur in Chesapeake Bay and its tributaries at some point during the calendar year [see Early Life History sections above].

Information on the proportion of the coastal stock of Atlantic menhaden residing in Chesapeake Bay at any point in time is presently unavailable. The absolute abundance of Atlantic menhaden inside Chesapeake Bay is unknown, as are rates of ingress and egress (exchange) to and from the Bay. Indeed, the need for studies on these topics was listed as a priority research need by the ASMFC's Atlantic Menhaden Technical Committee (AMTC 2004).

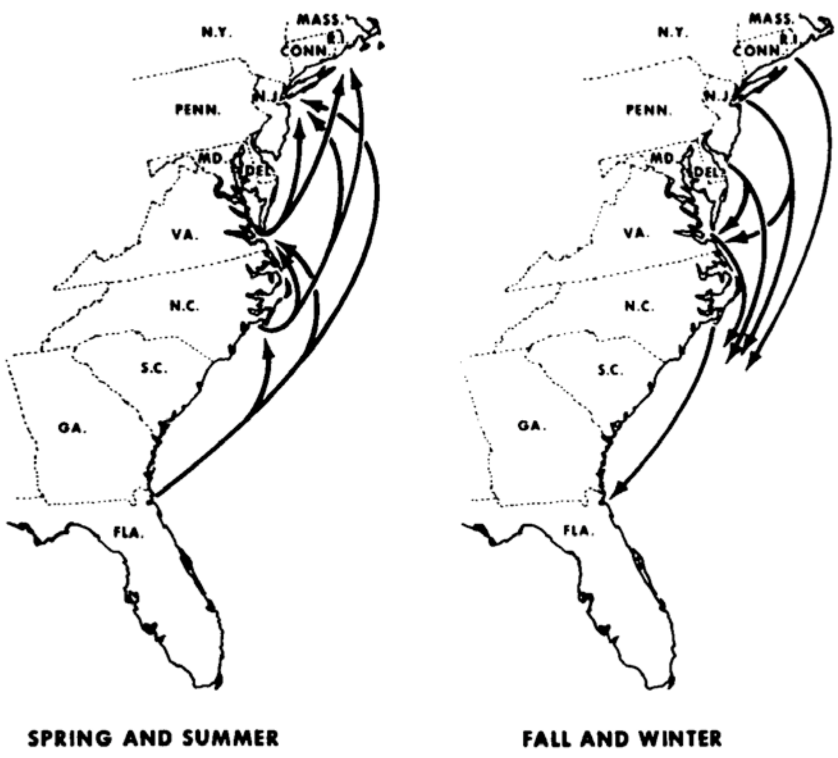

Figure 9. Generalized movements of tagged adult Atlantic menhaden from Dryfoos et al. 1973.

Much of what is known about movements of Atlantic menhaden into and out of Chesapeake Bay and the relationship between components of the coastal population and menhaden in the Bay have been discerned from tagging studies conducted by the NMFS Beaufort, NC Laboratory. Small (about ½ to 1 inch) ferro-magnetic tags were inserted into the body cavities of more than one million menhaden during the 1960s and 1970s (Nicholson 1978). Tag recoveries occurred on magnets strategically located in the menhaden reduction factories along the Atlantic coast.

Based on regional releases and recoveries, Dryfoos et al. (1973) reached several conclusions about movements of fish to and from Chesapeake Bay (Figure 9). Some menhaden tagged in North Carolina in early spring were recovered in Chesapeake Bay as early as May. Some fish tagged in Chesapeake Bay in April and May appeared in New Jersey catches by June; this movement slowed through spring, and there was little movement between these two areas after June. Only a few fish tagged in spring in the Maryland portion of Chesapeake Bay moved northward. Fish from Virginia and Maryland enter the North Carolina fall fishery before the end of November. A total of 34% of the menhaden tagged off Florida in summer were recaptured in Chesapeake Bay the following summer, and 21% of the recoveries of fish released in Chesapeake Bay in 1967 and 1968 occurred off New Jersey and New York one year later.

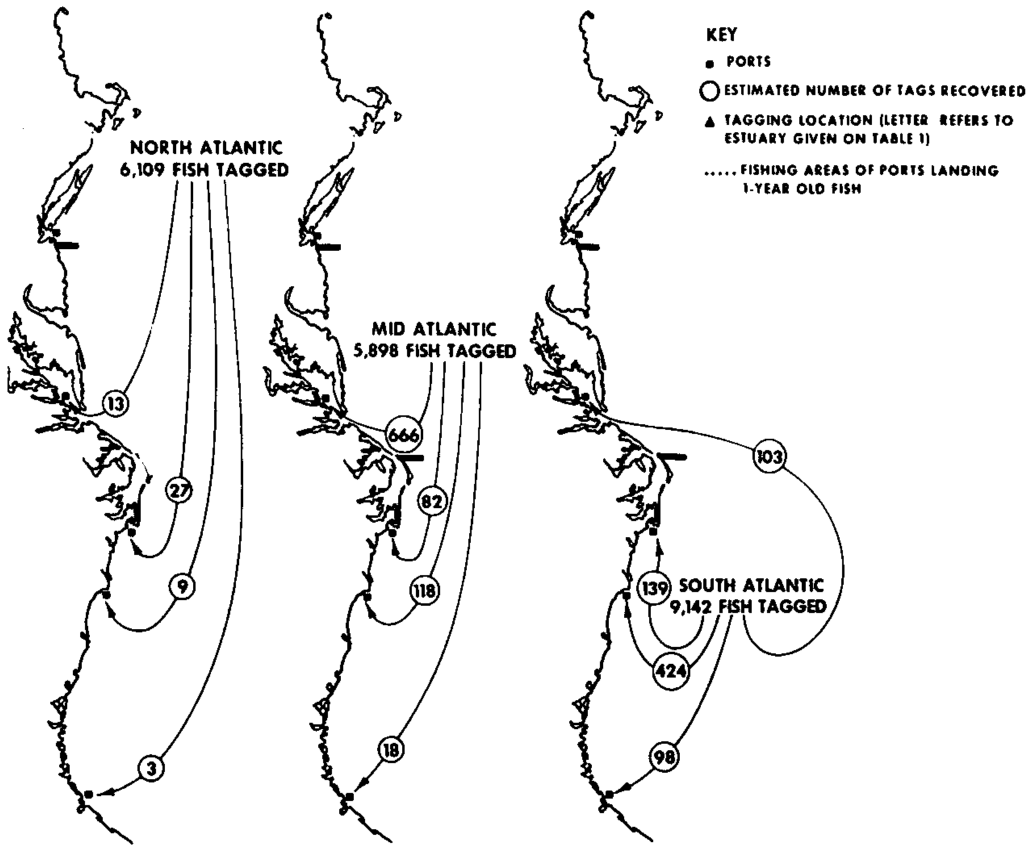

Figure 10. Movements and numbers of tagged juvenile Atlantic menhaden tagged in 1970 and recovered in 1971; from Kroger and Guthrie 1973.

Kroger and Guthrie (1973) analyzed tag recoveries of juvenile Atlantic menhaden (Figure 10). They confirmed that juveniles tagged in Chesapeake Bay move south in fall to below Cape Hatteras, North Carolina, and then redistribute northward along the coast by size as age-1's during the following spring and summer. Large juveniles (up to about 150 mm fork length) tagged in the Mid-Atlantic area tended to be recovered the following year as age-1's in Chesapeake Bay. Large age-1's tended to move farther north and in greater numbers than smaller fish. Kroger and Guthrie reported some movement of age-1 fish from the South Atlantic into Chesapeake Bay through mid-summer.

From these tagging studies some generalities can be drawn about the inter-relationships of the coastal stock of Atlantic menhaden and the Chesapeake Bay component. Juveniles from Chesapeake Bay migrate south below Cape Hatteras in late fall. Large juveniles, up to 150 mm fork length in fall, mostly from the Mid-Atlantic estuaries, migrate into Chesapeake Bay the following spring as age-1 fish. Some fish from Chesapeake Bay in early spring migrate north to New Jersey; presumably most of these are age-2 menhaden as few age-1's appear in commercial catches off New Jersey. Some age-1's from the South Atlantic migrate into Chesapeake Bay through mid-summer.

Although the proportions of age-1 and age-2 Atlantic menhaden in the catch in Chesapeake Bay and vicinity may vary considerably from year-to-year, the mean length and weight of menhaden in the commercial samples in recent years have been fairly consistent, with most of the variability among age-1's. Mean fork length and weight by age of commercial port samples from Chesapeake Bay in recent years (2004-2008) are shown in Tables 1 and 2.

Table 1. Mean fork length in mm of Atlantic menhaden sampled in Chesapeake Bay and vicinity, 2004-2008.

	Mean fork length in mm; (std dev in parentheses)				
Age	**2004**	**2005**	**2006**	**2007**	**2008**
0	137 (7)	126 (10)	139 (9)	150 (7)	137 (11)
1	179 (27)	151 (23)	189 (25)	191 (17)	196 (25)
2	220 (26)	231 (25)	225 (27)	222 (24)	239 (13)
3	270 (25)	266 (23)	270 (19)	271 (18)	267 (16)
4	278 (26)	287 (16)	281 (16)	283 (18)	286 (9)

Table 2. Mean weight in grams of Atlantic menhaden sampled in Chesapeake Bay and vicinity, 2004-2008.

	Mean weight in grams; (std dev in parentheses)				
Age	**2004**	**2005**	**2006**	**2007**	**2008**
0	44 (6)	34 (7)	44 (9)	58 (8)	43 (13)
1	108 (51)	61 (36)	121 (46)	123 (37)	136 (51)
2	195 (71)	221 (72)	204 (76)	189 (60)	234 (42)
3	361 (97)	325 (74)	341 (69)	337 (65)	324 (61)
4	403 (106)	397 (69)	374 (72)	376 (72)	392 (55)

Growth of Atlantic menhaden varies from year-to-year and occurs primarily during the warmer months (AMTC 2006). Growth of juveniles is density dependent (Ahrenholz et al. 1987; ASMFC 2001), i.e., growth rates are accelerated during the first year when juvenile abundance is low and are reduced when juvenile abundance is high [see also Early Life History: Young of the Year Figure 2]. Annual estimates of fork length (mm) at age (yr) in the most recent stock assessment (AMTC 2006) are derived from the von Bertalanffy growth model [$FL = L_\infty(1-exp(-K(age-t_0)))$]. Weight-length relationships are obtained from annual

log_e-transformed regressions of weight (g) on fork length (mm) [log_e W = a+b log_e FL) corrected for transformation bias (root MSE). Parameters from these regressions were averaged for the most recent five years (2001-2005) (Table 3).

Table 3. Annual parameter estimates (2001-2005) of weight-length and length-at-age regressions for biological samples of Atlantic menhaden from the commercial fishery.

	Weight – Length			Von Bertalanffy Model			
	n	a	b	n	L_{inf}	K	t_0
2001	5012	-11.546	3.106	4102	332.64	0.500	-0.473
2002	4370	-11.279	3.065	3654	317.91	0.623	-0.065
2003	3945	-12.031	3.211	3108	346.20	0.418	-0.556
2004	4600	-11.603	3.120	3759	370.20	0.303	-0.609
2005	3940	-11.012	3.007	3102	336.90	0.382	-0.412

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HABITAT

Introduction

Atlantic menhaden has a complex life cycle. Its various life stages occur in waters ranging from the coastal estuaries and inlets to the western margin of the Gulf Stream from central Florida to Nova Scotia (Manooch 1991). Menhaden juveniles occupy the low-salinity upper areas of estuaries, which are their primary nurseries, and migrate to coastal waters as YOY (Friedland et al. 1996; Friedland and Haas 1988). Adult migration is a function of size and age, with the oldest and largest menhaden migrating furthest north (Rogers and Van Den Avyle 1983; Ahrenholz 1991). Spawning occurs primarily on the continental shelf and larval menhaden spawned offshore are transported in response to meteorological and oceanographic processes to estuarine nursery areas along the Atlantic coast (Nelson et al. 1977; Pietrafesa and Janowitz 1988; Quinlan et al. 1999). Depending on their life-history stage, menhaden inhabit from near-freshwater to fully marine salinities. Hildebrand and Schroeder (1928) stated that menhaden were found throughout the year in Chesapeake Bay, although in diminished numbers in the winter. Chesapeake Bay is habitat for Atlantic menhaden larvae, juveniles, and sub-adults. Given the complex life cycle and the variability in habitats occupied by life stages, it is not surprising that menhaden life stages can tolerate and occur within a wide range of hydrographic and environmental conditions.

Oceanographic Factors

Ed Houde, Eric Annis, and Kevin Friedland

Distribution

Atlantic menhaden are distributed in the western Atlantic from the Gulf of Maine to the Florida east coast. Adults occur from the western edge of the Gulf Stream to the coast, including estuaries and coastal bays. Adult menhaden migrate seasonally. Winter concentrations are located on the continental shelf off the Carolinas. Overton et al (2008) also found menhaden in striped bass guts throughout winter off the Virginia Capes. A northerly migration and shift of the population occurs in spring-summer, with adults distributed in coastal waters primarily from the mid-Atlantic to New England. During spring and summer, some adults are found throughout the species' reported range.

Spawning occurs over the adult distributional range, primarily in shelf waters, and, reportedly, mostly in fall to winter months, at sea temperatures >12 °C. Based on eggs and larvae from ichthyoplankton surveys, most spawning in fall-early winter apparently occurs in neritic, shelf waters of the Mid-Atlantic Bight at temperatures of 10 to 20 °C and in salinities ranging from ~25 to 33 (e.g., Kendall and Reintjes 1975: Judy and Lewis 1983; Morse et al. 1987; Berrien and Sibunka 1999). Mid- to late-winter spawning, which may constitute the major portion of annual egg production, occurs primarily off the Carolinas and farther offshore (mostly 20-75 km offshore) at temperatures >15 °C, out to the edge of the Gulf Stream.

Ichthyoplankton surveys conducted since the 1960s provide a good indication of hydrographic conditions associated with spawning by adults and of occurrence of eggs and larvae. Eggs, which have a short stage duration (<3 days to hatch), generally occur where temperatures are >15°C and their seasonal distributions follow the latitudinal shift of the 15° C isotherm. As such, adult occurrence and spawning are prominent in the Long Island-Gulf of Maine region in the June-September period; spawning progresses southward as fall and winter approaches, with late-season spawning (Jan-Mar) centered off the Carolinas (Kendall and Reintjes 1975; Judy and Lewis 1983). Checkley et al. (1988) proposed that spawning and potential for larval survival were tied to storm-generated upwelling events along the Gulf Stream Front. These events provided a cue for spawning and stimulated plankton productivity and shoreward transport of early-life stages that are favorable conditions for larval production and eventual ingress to estuaries.

Hydrography and Circulation Features

Although menhaden are widely distributed along the coast of eastern North America, hydrographic and circulation features provide boundaries for distributions and occurrences and control life-cycle activities. Temperature acts as the primary hydrographic control over seasonal migration patterns, areas of abundance, and reproductive activities. The 10 °C isotherm more or less delineates the boundaries of common occurrence of adult menhaden. Spawning is mostly confined to areas bounded by the 15-20 °C isotherms. The Gulf Stream Front sets a seaward boundary for adult distribution. When found on the continental shelf and in nearshore coastal areas, adults show no obvious preference for salinity.

Currents and circulation features play an important role in cueing reproduction and in controlling dispersal of larval stages, assuring that some larvae are transported to the coastal estuaries and embayments that serve as juvenile nurseries. Most larval menhaden are found shoreward of the Gulf Stream Front (GSF); those sampled in the GSF or seaward of it presumably are rapidly advected northeast and lost to the population, although it is possible that warm-core rings and on-shore streamers could return some larvae to the shelf (Hare and Govoni 2005). There is ample evidence, based on observations and models, that coastward transport of larvae is supported by favorable winds and currents on the shelf (e.g., Checkley et al. 1988; Werner et al., 1999). Models and observations of advective mechanisms at estuary mouths present a less-clear picture of how menhaden larvae move into estuaries, although it is apparent that winds, tides, and larval behavior control the ingress (see below).

Interannual variability in recruitments is believed to be at least partly controlled by variability in oceanographic conditions that affect hydrography, circulation, and possibly biological productivity. Weather and climate patterns are probable drivers of such variability. Wood et al. (2004) demonstrated that prevalence of a late-winter climate pattern designated a "Bermuda-Azores High" that brings dry and warm late-winter weather to the Mid-Atlantic region is associated with high recruitment of Atlantic menhaden. This weather pattern may promote favorable shoreward transport or feeding conditions for early-stage menhaden larvae while on the continental shelf. Alternatively, the pattern could be associated with favorable nursery conditions for late-stage larvae and juveniles upon entering estuarine nurseries.

The remarkable temperature tolerance of larval menhaden is notable in distribution statistics. Larvae have been collected at temperatures from 0 to 25 °C. The low-temperature observations are for late-stage menhaden larvae (usually >20 mm length), in winter that have been advected to the mouths of mid-Atlantic estuaries (e.g., Kendall and Reintjes 1975).

The mechanics and details of larval ingress to estuaries are poorly known, despite numerous studies to describe and explain it. Larval ingress may occur in pulses, supported by wind-generated high-inflow events (Forward et al. 1999b). Wind forcing may play an important role, in combination with entrainment in up-estuary residual flow (Hare et al 2005).

Biological Oceanography

Vertical Distribution of Larvae and Larval Ingress

Larval behavior, tuned and responsive to ocean conditions, insures connectivity between shelf and estuary/embayment ecosystems. Although variable, menhaden larvae in offshore surveys occur mostly in surface layers, above the thermocline or pycnocline (Kendall and Reintjes 1975: Govoni and Pietrafesa 1994). Intermediate and late-stage larvae fill their swimbladder each night by swimming to the sea surface and gulping air (Forward et al. 1993). Observed vertical distribution patterns of larvae in the water column are complex and difficult to interpret. Early-stage larvae apparently do not follow an endogenous tidal rhythm in their vertical migrations. Lab-based studies do suggest a diel vertical migration behavior, but field studies do not confirm it (Forward et al. 1999a).

The mechanism by which late-stage larvae (>20 mm length) accomplish ingress into estuaries also is only partly understood. In a brief, 2.5-d study at the mouth of Chesapeake Bay, Hare et al. (2005) found that up-estuary flux of menhaden larvae depended on wind forcing and residual bottom flow. In ongoing research, the vertical distributions of >20-mm larvae at the Chesapeake Bay mouth are variable and not obviously associated with tide, wind, or diurnal variability, although analysis is still incomplete (Houde, unpublished data[1]). It is probable that ingress is driven by larval behavior in response to environmental, tidal and diurnal cues.

Juveniles and Adults, Associations with Plankton

Young-of-the-year, juvenile menhaden in the estuary feed primarily on phytoplankton. Menhaden juveniles appear to use gradient search behaviors to find plankton food resources in estuaries, resulting in highly patterned distributions within juvenile nursery areas. Considering both physical and biological gradients, gradients associated with phytoplankton control menhaden migration and local movement in estuaries (Friedland et al., 1989, 1996). Though not as clearly defined, the mesoscale distribution of adult gulf menhaden *B. patronus* in the Gulf of Mexico also appears to be conditioned by similar mechanisms and gradient responses to primary production metrics (Kemmerer et al., 1974; Kemmerer, 1980). The association of adult Atlantic menhaden, if any, with phytoplankton on the shelf or in estuaries, is not known.

Primary Production and Recruitment

In recent years, recruitment of YOY menhaden in Chesapeake Bay has been positively correlated with *chl-a* levels. This correlation is strongest when examined with respect to *chl-a* in the months of April, May and June (Figure 1) Houde and Harding 2009). Spring is a critical time period when menhaden larvae transform to juveniles and make a transition from selective zooplankton feeding to filter feeding primarily on phytoplankton (June and Carlson 1971). Variability in primary production at this time of transition could have a significant impact on the success of YOY recruitment. In Chesapeake Bay, the strongest relationship to YOY recruitment was obtained using estimates of annually integrated, euphotic zone *chl-a* which is effectively a measure of standing stock of available phytoplankton. The best relationship between

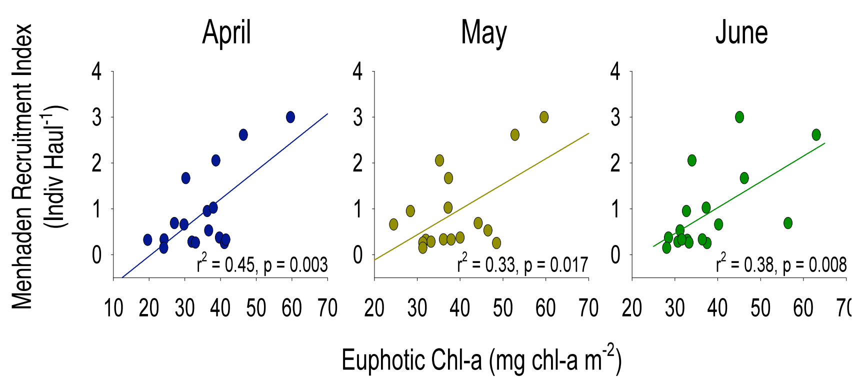

Figure 1. YOY menhaden recruitment in Chesapeake Bay with chl-a *levels in the months of April, May, and June.*

monthly euphotic zone *chl-a* and recruitment was observed in April for years 1995-2005 (Figure 1) is fairly variable and explains only 45% of variability in recruitment. Furthermore, this relationship did not hold up when examined using estimates of *chl-a* hindcast to the 1960's (Annis and Houde unpublished data). Recruitment variability likely depends on a suite of hydrographic and environmental parameters.

Menhaden recruitment may also be influenced by freshwater discharge into Chesapeake Bay. Kimmel et al. (2009) analyzed climatology to identify dry and wet years and found that YOY menhaden recruitment was higher in dry years (p=0.07). The relationship between freshwater river input to Chesapeake Bay and YOY recruitment was negative but weak (p=0.12; Figure 2, Annis and Houde *unpublished data*) as were relationships between YOY menhaden recruitment and variables that respond positively to high freshwater flow, e.g., abundance of the copepod *Eurytemora affinis* and the cladoceran *Bosmina longirostris*. Conversely, recruitment was positively correlated with indicators of low freshwater flow, e.g., increasing Secchi disk depth and abundance of the copepod *Acartia tonsa*.

Eutrophication coupled with stratification of Chesapeake Bay insummer results in hypoxic zones at depths below the pycnocline. While such conditions may not have a large impact on phytoplankton available in the upper water column it may reduce the habitat available to menhaden. Spatially-explicit bioenergetics models predict that low dissolved oxygen levels in summer would lead to decreased menhaden production (Brandt and Mason 2003, Luo et al. 2001). Vertical distribution of menhaden is poorly documented at present so the actual impact of these conditions is unknown.

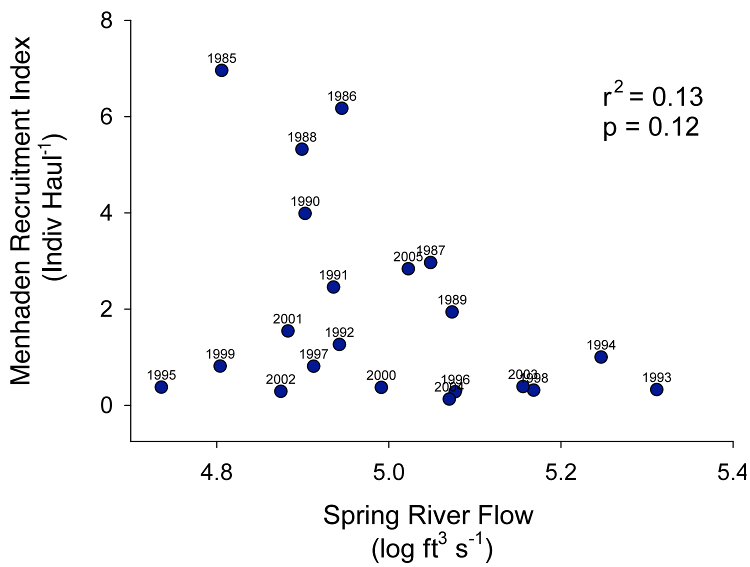

Figure 2. Menhaden recruitment and spring river flow into Chesapeake Bay, 1989-2004.

Issues

1. Interannual variability in continental shelf hydrography and circulation. Spawning patterns and interannual variability in survival, production, and transport/dispersal of menhaden eggs and larvae almost certainly are linked to variability in the physical regime of the extensive offshore spawning and larval nursery areas. Little is documented with respect to how interannual variability in oceanographic conditions affects production of early life stages, the probability of larval ingress to estuarine juvenile nurseries, and the overall variability in recruitment.

Metrics/Indicators

- Temperature, salinity, sea-surface height, upwelling and downwelling indices, other hydrographic and physical features.
- Gulf Stream anomalies, warm- and cold-core rings.
- Relationships between YOY abundance in Chesapeake Bay, or in larval ingress to mouth of Chesapeake Bay, and oceanographic/hydrographic variability.

2. Decadal or longer oceanographic regime shifts and climate effects. Climate-related shifts in dominant oceanographic variables that represent decadal or longer trends can precipitate shifts in spawning areas and temporal patterns, larval production, predominant dispersal pathways, and the distribution of larval ingress patterns on the Atlantic coast. Such trends can translate into shifts in the average level of recruitment, or latitudinal shifts in areas of juvenile production, e.g., a possible explanation for the lower than average recruitments in Chesapeake Bay in the past two decades.

Metrics/Indicators

- Trends in oceanographic/hydrographic variables and ocean climate indices (e.g., North Atlantic Oscillation or regional synoptic climatology).
- Recruitment levels of YOY menhaden in Chesapeake Bay. Shifts in ocean climate trends and probable regime shifts; relationships to recruitment success.
- Trends and variability in freshwater-flow regimes in Chesapeake Bay and factors driving freshwater flow; indices of flow conditions (e.g., synoptic climatology; Palmer drought index).

3. The relationship of plankton production to menhaden production and recruitment. Biological productivity and its seasonal and interannual variability, especially primary production and zooplankton abundance/production where it is critical to support larval menhaden production offshore and in estuarine nurseries (i.e., Chesapeake Bay) where juveniles reside are key factors affecting recruitment. Bottom-up trophodynamics, the temporal-spatial scales and variability over which trophodynamics operate, and the hydrographic and oceanographic conditions that support biological production are poorly understood with respect to larval menhaden production on the continental shelf and YOY juvenile production in estuaries.

Metrics/Indicators

- Seasonal and annual measures of *chl-a* and primary production on the continental shelf and in Chesapeake Bay.
- Measures of zooplankton abundance offshore and in the Bay.

- Correlation and regression statistics to establish relationships between menhaden recruitment/production and measures of plankton productivity.
- Spatial and temporal scales of plankton distributions and productivity.

Water Quality Consideration

Eric Annis, Kevin Friedland, and Jim Uphoff

Effect of Menhaden on Water Quality

The Chesapeake Bay continues to have issues with water quality, which in part has been attributed to declines in populations of filter-feeding animals (Coen et al. 2007). Menhaden is one of the principal filter feeders in the Bay and important aspects of their feeding should be considered in evaluating the impact of menhaden on water quality.

Menhaden diet changes ontogenetically with changes in their morphology. Larval menhaden feed selectively on individual plankton particles such as large phytoplankton and zooplankton (Chipman 1959; June and Carlson 1971). When they transform into juveniles, there is a transition to filter feeding after anatomical changes occur to their branchial baskets and gill rakers (Figure 3) (Friedland et al. 2006). As juveniles and adults, menhaden are omnivorous filter feeders, eating both phytoplankton and zooplankton (Chipman 1959; June and Carlson 1971) and deriving some nutritive value from cellulose in detrital particles that are consumed (Lewis and Peters 1994). Phytoplankton, zooplankton, and detrital particles are removed from the water, potentially having a significant effect on water quality.

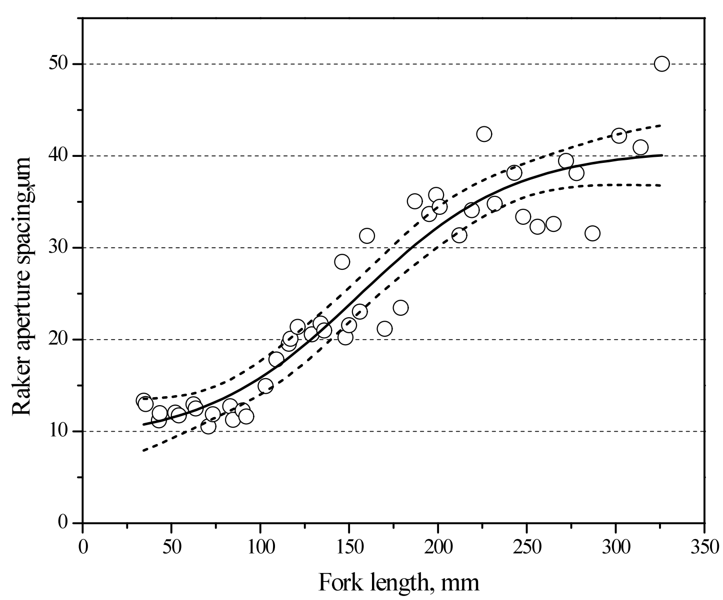

Figure 3. Atlantic menhaden raker aperture spacing versus fish size.

Filtering ability changes ontogenetically in menhaden with change in the structure of the gill rakers. In laboratory experiments on large, adult menhaden (~260 mm fork length, FL), Durbin and Durbin (1975) reported that these large menhaden filtered particles larger than 13 μm diameter. However, the clearing rate data for these fish suggested that significant retention (10% efficiency) did not occur for particles <30 μm in diameter. Moreover, menhaden of that size were highly efficient when filtering zooplankton. In contrast, juvenile menhaden transitioning to adult size (~140 mm FL) were able to retain particles as small as 5-7 μm and had significant retention efficiencies of 7-9 μm sized particles (Friedland et al., 1984). These smaller menhaden (generally <1-yr of age) also filtered some zooplankton, but at a lower efficiency than phytoplankton.

Evidence suggests that certain classes of plankton, such as cyanobacteria, although filtered and removed from the water, pass through the menhaden gut intact (Friedland et al. 2005). Hence, modeling of menhaden grazing impact on phytoplankton and its effects on water quality should account for the possibility that menhaden through its feeding may actually enhance blooms of bluegreen algae by filtering and digesting phytoplankton except for bluegreens, while adding nutrients to the water.

The role of menhaden in providing ecological services that affect water quality is complex and poorly understood. In this regard, Durbin (2007) estimated that menhaden may excrete up to 62% of the nitrogen they ingest, which may promote local phytoplankton growth, a non-intuitive consequence of filtering activity. Gottlieb (1998) modeled age-0 menhaden filtering in Chesapeake Bay. Modeled results were highly variable, but menhaden might consume about 10% of the annual primary productivity in Chesapeake Bay. Durbin (2007) cited a net nitrogen export of about 800 metric tons by migrating menhaden leaving Narragansett Bay. For the similar gulf menhaden, Deegan (1993) calculated that it accounted for annual export of 5-10% of total primary productivity from an estuarine system in Louisiana. In this regard, the distribution of menhaden juveniles is correlated with gradients of plankton biomass, reflecting search behavior of the fish (Friedland et al., 1989; Friedland et al., 1996). Though not as clearly defined, the meso-scale distribution of adult menhaden in the Gulf of Mexico also appears to result from similar mechanisms and behavior (Kemmerer et al., 1974; Kemmerer, 1980).

Issue

1. Water quality in the Chesapeake Bay has changed over time. The plankton community is believed to be responding to nutrient enrichment with a shift in the size spectra to smaller size plankton and a species shift including a shift to more blue-green algae (Marshall et al. 2006). The role of menhaden as filterers is poorly understood. If significant, the enhancement of menhaden abundance could be considered in a strategy of water remediation that relies on management of key organisms in the Bay ecosystem (Gifford et al. 2007).

Metrics/Indicators

– Spatial and Temporal Extent of Turbidity

- Nutrient loading and concentrations in Chesapeake Bay.

- Spatial extent and time series change in water column turbidity.
- Filtering potential of the menhaden population.

– Plankton Community Structure

- Structure of the plankton community with respect to species composition and size spectra.

Effect of Water Quality on Menhaden

Phytoplankton

Phytoplankton comprises the biggest component of the diet of young-of-the-year menhaden (June and Carlson 1971) and there is evidence that recruitment recently has been correlated with phytoplankton standing stock (see Oceanography and Food Web briefs) (Houde and Harding 2009). Further, variability in growth of YOY menhaden is a function of available *chl-a* and temperature (see Food Web brief). Trends and variability in the abundance and composition of phytoplankton in Chesapeake Bay are driven by long-term trends in nutrient dynamics, resultant eutrophication, and fluctuations in climatology (Kemp et al. 2005; Paerl et al. 2006). Phytoplankton abundance increased with nutrient loading in the 1950's and 1960's, but reached a relative plateau since 1970 in most regions of the Bay (Harding 1994; Harding and Perry 1997; Kemp et al. 2005). Phytoplankton biomass is highest in the oligohaline upper Bay, but the increase in phytoplankton in recent decades was most pronounced in the polyhaline region. The oligohaline region has actually experienced a decrease in *chl-a* since 1970 (Kemp et al. 2005).

Composition of phytoplankton, especially size structure, has important implications for menhaden feeding as smaller cells may not be retained as efficiently on their gill rakers (Durbin and Durbin 1975; Friedland et al. 1984), at least for age 1+ menhaden, and some taxonomic groups such as cyanobacteria may pass through the gut undigested (Friedland et al. 2005). Diatoms are the dominant taxonomic group in Chesapeake Bay during the spring and fall while dinoflagellates, cyanobacteria, and cryptophytes are more abundant in the summer (Adolf et al. 2006; Paerl et al. 2006) There has been a general shift over time in composition towards smaller cell sizes and increased abundance of cyanobacteria (Marshall et al.2005; Marshall et al. 2006). At present, little is known about the relative nutritive value of different taxonomic groups of phytoplankton but a bioenergetics model developed for YOY menhaden performed better with total *chl-a* than with *chl-a* from any of the constituent taxonomic groups (see Food Web brief) (Annis et al. *in prep*).

Inter-annual variability in phytoplankton abundance and composition is largely a function of climatology, which controls freshwater discharge. Miller and Harding (2007) examined spring bloom dynamics in Chesapeake Bay with respect to synoptic climatology (1989-2004) and found that the bloom was larger, later, and further down-estuary in warm/wet years. It is probable that climate change will impact bloom temporal dynamics (see section on Climate Change in this Brief). With respect to taxonomic composition, increased freshwater flow from the Susquehanna River results in increased diatom abundance (Adolf et al. 2006; Paerl et al. 2006). Inter-annual variability in phytoplankton abundance in Chesapeake Bay appears to have an impact on menhaden growth and recruitment of YOY menhaden (See Oceanography and Food Web briefs).

Issue

1. Quantity and quality of phytoplankton may affect growth and recruitment of YOY menhaden. While there is evidence to support this observation, additional research is needed to quantify and define relationships.

Metrics/Indicators

- Remote sensing is particularly effective for generating spatially explicit data on phytoplankton blooms and associated environmental factors.

- Climate patterns and Susquehanna River flow provide useful predictive indices for phytoplankton abundance and composition.

- Recruitment levels and growth rates of menhaden in relation to water quality and bloom characteristics provide a measure of habitat suitability.

Zooplankton Composition

Zooplankton is a major constituent in the diet of larval and age 1+ menhaden (Hettler et al. 1997; June and Carlson 1971; Peck 1893). Although long-term trends in eutrophication have impacted phytoplankton and benthic communities, they appear to have had minor effect on zooplankton populations (Kemp et al. 2005). The two dominant copepods in the Bay, *Acartia tonsa* and *Eurytemora affinis*, provide an important link between primary production and fish production (e.g. North and Houde 2003). These copepods show no long-term trend in abundance, but their relative abundance changes as a function of climatological variability and freshwater input to the Bay. *Eurytemora* is positively correlated with high freshwater discharge and *Acartia* thrives in drier years (Kimmel et al. 2006; Kimmel and Roman 2004). Despite the absence of a long-term trend, inter-annual variability in zooplankton could play a significant, but yet to be defined, role in menhaden recruitment and growth. Kimmel et al. (2006) reported a positive correlation between striped bass recruitment and *Eurytemora* abundance while bay anchovy recruitment was negatively correlated. No direct relationship has been established between menhaden recruitment and zooplankton abundance, but higher recruitments appear to be concordant with climatologically drier years (Kimmel et al. 2009).

Menhaden interactions with gelatinous zooplankton are not well studied, but gelatinous zooplanktons are potential competitors with all menhaden life stages. Additionally, jellyfish are potential predators on menhaden early life stages. There is evidence of increased jellyfish abundance in recent years in Chesapeake Bay. Blooms of the ctenophore *Mnemiopsis leidyi* can significantly reduce the abundance of local mesozooplankton populations (Purcell and Decker 2005; Reaugh et al. 2007; Testa et al. 2008), potentially reducing food available for menhaden. Cowan and Houde (1993) projected a maximum prey size of 11.4 mm for *Mnemiopsis* predation on fish larvae. Thus, menhaden larvae entering the mouth of the Bay at a length of 7-38mm (Houde and Secor 2009) may be subject to some direct predation by *Mnemiopsis* although there presently are no data or observations. The scyphozoan, *Chrysoara quinquecirrha*, feeds on ctenophores and may control their abundance (Purcell and Cowan 1995). The scyphozoan also may be a significant potential predator on larval and YOY menhaden (Cowan and Houde 1993). Although jellyfishes are abundant and appear to be an increasing problem in an eutrophic

Chesapeake Bay, there is no program to monitor bay-wide gelatinous zooplankton levels or research to define their probable interactions with menhaden.

Issue

1. Zooplankton populations vary in abundance and taxonomic composition from year to year in response to variable climatic and environmental factors in Chesapeake Bay. Zooplankton is an important component of age 1+ menhaden diet and variability in zooplankton abundance could influence growth of age 1+ menhaden and recruitment of age-0 menhaden because larval and pre-juvenile menhaden consume zooplankton before becoming filter feeders. The potential for future increases in gelatinous zooplankton and their potential effect as competitors and predators on menhaden warrants increased efforts to monitor abundance and evaluate impacts on menhaden. It is noteworthy that the Chesapeake Bay Program terminated its zooplankton monitoring in 2002.

Metrics/Indicators

- Long term trends in zooplankton abundance, taxonomic composition, and distribution, including the gelatinous zooplankton.

- Stomach analysis on juvenile and adult menhaden to establish significance of zooplankton in the diet.

Hydrological Changes and Eutrophication

Nutrient and sediment loads delivered to the Bay increase with increasing stream flow. Annual stream flow may exhibit high inter-annual variability, but little trend has been observed for the tributaries of Chesapeake Bay between 1983 and 2003 (Langland et al 2004). Nutrient and sediment loading continue to present a significant problem for the health of the Chesapeake Bay ecosystem, but some progress has been made in recent years to reduce the amount of phosphorus, nitrogen and sediment reaching the Bay (Chesapeake Bay Program 2009, Langland et al 2004). Phosphorous loading in some Maryland tributaries actually was found to be positively associated with levels of YOY menhaden abundance (Love et al. 2006).

Loss of wetlands may also impact menhaden adversely, especially since wetlands provide a valuable detrital food source for YOY menhaden (Lewis and Peters 1981) and sequester nutrients and contaminants that would otherwise enter the Bay. Despite restoration efforts and achieving nearly 50% of the established restoration goal, total wetland acreage has dropped slightly in the past 5 years (Chesapeake Bay Program, 2008).

Another threat to menhaden and other fishes in Chesapeake Bay is the increase in impervious surfaces in the watershed as a result of human construction activity. Impervious surfaces increase the rate at which nutrients, sediment and contaminants are delivered to tributaries (Clagett 2007), exacerbating eutrophication and expansion of anoxic zones. Dissolved oxygen levels can be negatively associated with percent coverage by impervious surfaces (Uphoff et al. 2009).

Loss of nursery habitat due to hypoxia may have implications for menhaden beyond Chesapeake Bay. Historically, the Bay has been the largest east-coast nursery for YOY menhaden, contributing >65% of recruits to Atlantic Coast menhaden fisheries (Ahrenholz et al. 1989; Vaughan et al. 2001). There is general recognition that hypoxia (Dissolved Oxygen < 2 mg / L) impacts a substantial portion of Chesapeake Bay in summer, has increased in extent during the past 50 years (Figure 4), causes significant ecological harm, and is the target of substantial nutrient management efforts (Breitburg 2002; Hagy et al. 2004; CBFEAP 2006). Hypoxia is most prevalent in summer when menhaden are at high abundance in the Bay, but hypoxic conditions are present at lesser levels during spring and fall (Hagy et al. 2004).

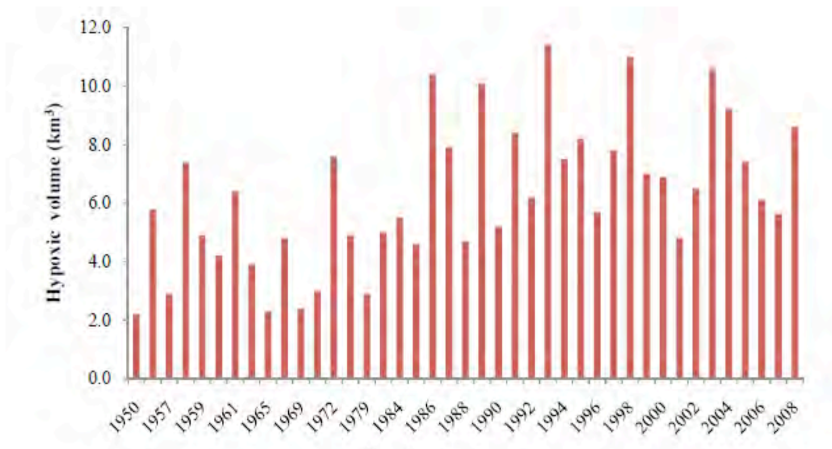

Figure 4. Chesapeake Bay. Estimated hypoxic volume, 1949-2008. (http://sitemaker.umich.edu/scavia/hypoxia_forecasts.)

Atlantic menhaden often suffers mass mortalities during summer months, generally in small coves and heads of creeks where their high demand has exhausted DO (Lippson 1991). Algal and bacterial respiration, often associated with algal blooms in eutrophic systems, is a contributor to DO depletion (Lippson 1991). Habitat loss due to hypoxia in coastal waters is often associated with fish expending energy to avoid DO that reduces growth or may be associated with lethal conditions (Breitburg 2002). However, Breitburg et al. (2009) analyzed nitrogen, hypoxia, and fisheries landings in 30 estuaries and semi-enclosed seas, including Chesapeake Bay, and reported that hypoxia did not generally affect landings, which were closely linked to nitrogen loading rates. Systems with seasonal hypoxia generally had high landings, but local effects (within the hypoxic area) would be of concern to management (Breitburg et al. 2009).

Spatially explicit bioenergetics models predict that low DO levels in summer should lead to decreases in baywide levels of menhaden production (Brandt and Mason 2003; Luo et al. 2001) because only a portion of the Bay volume is available to menhaden. The modeled outcomes are predicated on the assumption that menhaden will use the entire water column in the absence of hypoxia. Vertical distribution of menhaden is not documented so the magnitude of impact from hypoxic conditions is unknown. For striped bass, Constantini et al. (2008) examined the impact of hypoxia in Chesapeake Bay during 1996 and 2000 through a bioenergetics approach. The authors had hypothesized that hypoxic conditions might provide a refuge from predation for prey fishes, including Atlantic menhaden. However, hypoxia was found to have a probable opposite short-term effect because prey fishes avoided hypoxic waters and were more vulnerable to striped bass predation.

Issue

1. Hypoxic volume due to eutrophication has expanded in Chesapeake Bay since the1950s and represents an increasing loss of summer habitat for adult and juvenile menhaden. Turbidity and other water-quality problems are significant in the Bay and may be factors affecting Atlantic menhaden recruitment and production.

Metrics/Indicators

- Annual estimates of volume, location, and extent of hypoxia in Chesapeake Bay are available through the Chesapeake Bay Program.

- Spatially explicit, bioenergetics-based, modeling of growth-rate potential with respect to hypoxia and other water-quality stressors.

- Estimates of nutrient loading and impervious surface coverage.

- Appropriate surveys of menhaden could delineate behavior and distribution of menhaden in the Bay relative to areas of hypoxia and other water-quality stressors.

Historic Habitat Changes in Chesapeake Bay

Cynthia Jones

Atlantic menhaden has a complex life cycle and individual fish are exposed to a wide variety of habitats which are affected by conditions not only in the aqueous environment, but also by associated watershed land-use. Changing habitats and water quality potentially can affect habitat use and productivity of menhaden in the coastal ocean, estuaries, and particularly the Chesapeake Bay. Menhaden's various life stages occur in waters ranging from the coastal estuaries and inlets along the continental shelf to the western margin of the Gulf Stream from southern Florida to Nova Scotia (Manooch 1991; see Life History section for more details). Depending on their life-history stage, menhaden inhabit waters of salinity from near-freshwater to fully marine. Given the complex life cycle and the variability in habitats occupied by life stages, it is not surprising that most life stages can tolerate and occur over a wide range of hydrographic and environmental conditions.

Menhaden provides important ecosystem services to Chesapeake Bay as an herbivorous fish whose diet primarily consists of phytoplankton during the juvenile-and adult stages, and serves as a primary prey for piscivores. As primary consumers, menhaden are impacted by habitat change and, in turn, affect the productivity of secondary consumers that depend on them. The Bay has experienced profound changes due to agricultural land use, other human use and development. These habitat changes can impact menhaden productivity directly and indirectly.

Changing Agricultural Land-use Practices throughout the Watershed

Estuarine habitats in Chesapeake Bay have been altered dramatically since the arrival of European colonists in 1607. Prior to then, Native Americans had only minimal to marginal effects (Miller 2001). Initially, European colonization also had little impact too because the colonists did not clear large land tracts. Before intensive farming led to large-scale forest clearing, forests broke up the impact of winds and reduced effects of precipitation. Even during major storms, river rise was ameliorated and streams ran clear (Silver 2001). However, by the late1700s — after fields had been cleared across the region — colonists noted the first instances of habitat change. By 1930, 60-80% of the watershed was under cultivation and fields were spread with fertilizers and animal waste that dramatically increased nitrogen flux into the Bay (Brush 2009). Although forests began to grow back by the early 1900s, the benefit of reforestation was diminished by the draining of large wetlands on the eastern shore, and by explosive urban and suburban development.

Along with clearing forests, beginning in the 1620's colonists began to construct lumber dams to divert water to power sawmills. Additionally, dams were built to establish reservoirs to provide water for the growing population and to generate power (CBFEAP, 2006). By the 1900s, the effects of dams on anadromous fishes were apparent and governments began to dismantle dams that were no longer useful. However, because dams trap contaminated sediments, removals must be undertaken carefully on a case-by-case basis (Ashley et al. 2006). Dams trap coarser sediment and allow fine-grains to pass downstream. The effect of sediment releases and potential release of pollutants from dam removal has note been evaluated with respect to menhaden or other fishes.

Issues

1. The Chesapeake Bay Program seeks to restore the Bay by protecting and restoring wetlands, while encouraging conservation tillage practices on agricultural lands. Conservation practices and restoration of wetlands, and stream banks and shores are needed to ameliorate runoff and sediment loss from forests, and farmlands.

Indicators/Metrics

- The acreage of wetlands and farmland under conservation tillage in the Chesapeake watershed.
- Status and trends in forest acreage.
- The acreage of stream and riverbank protected from erosion.

Effect on Habitat by Urbanization and Runoff

Perhaps the most significant physical alteration of the Chesapeake Bay watershed in recent decades has been the increase in impervious surfaces, with at least 400,000 hectares projected by 2010 (Brush 2009). These surfaces increase the rate of flow of nutrients, sediment, and contaminants to the Chesapeake Bay (Clagett 2007) and exacerbate eutrophication and expansion of anoxic zones. The probability of bottom waters becoming hypoxic was about 3-times greater when impervious surfaces exceeded 10% than when they were ≤5%. Impervious surfaces have a significant, negative influence on presence of some fishes and blue crabs in mid-channel bottom habitat (Uphoff et al., 2009). Although not studied at present, reduced water quality associated with increases in impervious surfaces could diminish habitat for menhaden or their predators.

Issues

1. Urban and suburban development has been accompanied by dramatic increases in paved surfaces and other impermeable surfaces that have increased runoff to the Chesapeake Bay. New paving materials and methods of road construction, and new types of urban planning that minimize building footprints can decrease runoff.

Indicators/Metrics

- Acreage under impermeable surfaces.
- Measures of water quality and relationships to impermeable surfaces.

Sediment Load and Turbidity

Historically, forest clearing led to changes in sediment loading (Brush 1986). Before 1700 the mean rate of deposition in Chesapeake Bay was 0.05cm/yr, but increased to 0.60 cm/yr after 1750 (Hilgartner and Brush, 2006). Without the buffer provided by trees, shrubs, plants, and wetlands that previously bordered tributaries and the Bay, storm water was unchecked. This resulted in erosion that brought increased sediment into the Bay. Moreover, the dramatic increase in impermeable surfaces has also increased runoff. Impervious surfaces amplify storm water discharges into streams that feed the Bay (Goetz and Jantz 2006). One consequence of these changes is that sediment grain size has changed over time so that very fine sediment predominates now that reduces light penetration. Secchi disk readings have steadily declined since 1985 from just over 2 meters to about 1 meter in 2008 (Greer 2008). Because juvenile menhaden while filter feeding can retain particles as small as 5-7 µm, and to a minor extent particles <5 µm, there is a possibility that menhaden feeding could be compromised (Friedland et al. 1984).

Increased turbidity acts to shade submerged aquatic vegetation (SAV), thus decreasing the extent and composition of SAV beds. Loss of SAV may indirectly affect menhaden by increasing turbidity as a result of increased sediment resuspension (Orth et al., 2006) which in turn can lower phytoplankton productivity. SAV has also been shown to exercise control over ecosystem function through nutrient recycling and linkage to fish productivity (Orth et al., 2006; Hughes et al., 2009), which may impact menhaden abundance, although specific impacts in Chesapeake Bay are not known at present.

Issues

1. Sedimentation rate has increased historically and grain size has decreased recently, adding to the turbidity in the Bay. Although effects on menhaden have not been studied, this issue is potentially important from the perspective of either its direct or indirect effects on menhaden production (see Water Quality section).

Indicators/Metrics

- Measurements of turbidity and grain size of suspended sediment.
- Menhaden distributions and abundance in Chesapeake Bay with respect to turbidity and sediment loads.

Nutrient Loading

Nutrient loads fuel phytoplankton growth and its distribution in Chesapeake Bay (Harding and Perry 1997; Harding et al. 2002). As filter feeders, menhaden depends on the quantity, quality, and distribution of phytoplankton food. The relationship of nutrient loading to menhaden recruitment and productivity is mostly not understood. Love et al. (2006) found a positive relationship between age-0 menhaden recruitment and P loading in Maryland tributaries of the Bay.

Nutrients enter the Bay from point and non-point sources. Point sources include sewage treatment outflow. Major improvements have been achieved in significantly reducing nutrients from point sources (CBFEAP 2006). However, human population in the watershed has doubled since 1950, which has resulted in a 41% increase in paved roads and other impervious surfaces (Stokstad, 2009). Less success has been achieved in reducing nutrients from non-point sources such as agriculture and other, diffuse non-point runoff. Agriculture contributes over 40% of the nitrogen that enters the Bay (Stokstad 2009). Point-source sewage treatment plants contribute only 20%. Ninety percent of the bioavailable N and P enter the Bay in association with runoff from the seven largest storms each year (Pionke et al., 2000). Depending on how storm events and precipitation are altered by climate change (see Climate Change section of this brief), nutrient loads might increase if these events are exacerbated. Increased nutrient loading has led to increased prevalence of harmful algal blooms on the U.S. East Coast (Mulholland et al., 2004). The role of harmful algal blooms and effects on menhaden productivity in Chesapeake Bay are not known.

Issues

1. An important task of the Chesapeake Bay Program has been to reduce nutrient input to the Bay from point and non-point sources. While there have been successes in reducing nutrient loading from point sources, there has been less progress in reducing nutrients from non-point sources. Excessive nutrient loading can contribute to the problem of hypoxia in the Bay and, through this mechanism, could affect menhaden production potential.

Indicators/Metrics

- Nutrient concentrations in Chesapeake Bay and its tributaries.
- Relationships between nutrient loading, phytoplankton production, and menhaden production/wellbeing in the Bay.

Hypoxia and the Dead Zone

The volume of hypoxic water increased in Chesapeake Bay during the 20th century, which potentially limits available habitat, even to pelagic organisms such as Atlantic menhaden. The increased nutrient loading stimulates production of phytoplankton beyond what can be consumed by herbivores. This unused biomass degrades and depletes oxygen from the deeper waters. When dissolved oxygen concentration is reduced to <2.0 mg l^{-1} it creates a “dead zone” that precludes most living organisms and presumably excludes use of these waters by menhaden. Localized hypoxia was first noticed in the Bay in the 1930s (Diaz and Rosenberg 2008). The volume of hypoxic water in summer has increased three-fold since 1950 (Hagy et al. 2004) and is recorded in the sediment record only after European settlement (Cooper and Brush, 1991). Currently, the dead zone in the Bay covers roughly an area of 7.7 to 12.3 km^3 and persists from July to September each year. This is exacerbated in years of high runoff, when more nutrients enter the Bay.

Predators such as striped bass may increase their predation rate if fish prey such as menhaden are concentrated above the oxycline (Costantini et al. 2008). However, it is possible that increased plankton production and turbidity associated with eutrophic systems that have large hypoxic volumes may diminish predation risk by providing a visual refuge for prey (Breitburg et al.

2009). Although there are no directed studies on menhaden, these factors may affect both juveniles and adults in Chesapeake Bay. Notably, Brady et al. (2009) and Tyler et al. (2009) have documented episodic diel hypoxia, even in shallow bays and estuarine tributaries, habitats used by menhaden. In general, pelagic species such as menhaden will experience a habitat squeeze if the cooler, deeper waters of the Bay below the oxycline are unavailable due to anoxia (Diaz and Rosenberg, 2008).

In a study of gulf menhaden in Texas, Thronson and Quigg (2008) found over a 55-year period that menhaden made up 72% of the fish kills, the majority of which were caused by hypoxia. Fish kills in Chesapeake Bay also frequently involve menhaden (see Stock Assessment, Diseases and Fish Kills brief) and these kills are believed to be related to low dissolved oxygen events.

Issues

See Water Quality section in this brief for issues and indicators/metrics.

Changes in Weather and Climate

The impact of decadal and longer-term climate variability and change on fishes and invertebrates is likely to be widespread, including effects in Chesapeake Bay (see section on Climate Change). Effects on menhaden habitat use and productivity are possible. One noteworthy trend is the recent increase in frequency of hurricanes and tropical storms in the Chesapeake region. The number and intensity of hurricanes has followed a long-term periodicity, with a relatively quiet period from 1970-1990, and a recent increase in hurricane activity (Dailey et al. 2009). The immediate and short-term effect of hurricanes has been increased algal biomass, hypoxia of bottom waters, changes in nutrient cycling, changes in fish distribution and catches, and fish disease (Paerl et al. 2006). While potentially important, the relationship of these factors to abundance, and recruitment success of menhaden is unevaluated in Chesapeake Bay.

In addition to long-term climate change, Chesapeake Bay also has experienced shorter-term, decadal fluctuations in weather, shifting between cold-wet and warm-dry periods. Austin (2002) showed that the 1960s were warmer and wetter than the 1970s and 1990s. These shifts can occur suddenly and appear to be related to changes in fish abundance (CBFEAP 2006). Menhaden recruitment success in Chesapeake Bay tends to be relatively high in years when late winter-spring conditions are warm and dry (Wood 2000). The generally low recruitments of YOY menhaden in recent years appear to be constrained by frequent cool and wet, winter-spring conditions that favor recruitment of anadromous spawners, but not offshore-spawning fishes such as menhaden (Kimmel et al. 2009). It is not certain how climate change will affect long-term abundance and productivity of menhaden, as noted in the next section.

Issues

See Issues and Metrics/Indicators below under Climate Change.

Climate Change

Cynthia Jones and Kevin Friedland

Although climate change is a major issue in the scientific community, relatively less is understood about its potential effects on commercial fisheries worldwide (Brander 2007) or along the US East Coast, with little information specific to Atlantic menhaden (but see comments by Cronin et al. 1999). This is especially surprising because of the important role menhaden plays as prey for other resource species and its reproductive strategy as a winter-, shelf-spawning species whose eggs must be transported to inshore nurseries. Menhaden ingress is sensitive to changes in wind patterns and temperatures which are known to be variable and may be influenced by climate change (Quinlan et al. 1999; Austin 2002). Moreover, nursery habitats within bays and estuaries, including Chesapeake Bay, are likely to be transformed by the effects of climate change, in some cases potentially enhancing menhaden productivity and other cases resulting in lower production and recruitment.

The effects of climate change are projected to include: increased water temperatures; sea-level rise; change in precipitation patterns, changes in climate variability that include increased storm and drought events, among other related phenomena. These changes will influence salinity, temperature, and nutrients in Chesapeake Bay (Cronin et al. 1999), which historically has been the primary nursery ground for menhaden along the U.S. East Coast.

Projected Effects of Sea-level Rise Along the U.S. East Coast

Sea levels worldwide rose at least 1.8 mm/yr over the period 1961 to 2003 (Meehl et al. 2007; Day 2004). Moreover, from 1993-2003, sea level rise was estimated at 3.1mm/yr worldwide (Bindoff et al. 2007), indicating that the rate of sea-level rise may be increasing. During the previous 2000 years, a period of relative geological stability, rates averaged 0.0-0.2 mm/yr (IPCC 2007). Model predictions indicate that rates of global sea-level rise may be 4mm/yr by the end of the 21st Century for a total rise of 0.22-0.44 m above present sea level. Although complex and difficult to predict, the predicted rate for the North Atlantic is maximal for the area east-northeast of the U.S. coast (Bindoff et al. 2007).

One effect of sea-level rise is the intrusion of marine waters further into bays and estuaries. For example, salinity is expected to increase in the Chesapeake Bay. Gibson and Najjar, (2000) analyzed 50 years (1949-1998) of salinity observations in the mainstem of the Bay and found a trend of increasing salinity.

For Chesapeake Bay, sea-level rise is not only a product of water expansion and melting glaciers, but also a result of land subsidence. Over the past 1000 years, sea level rise was 0.56 mm/yr while subsidence was 1.6-2.0 mm/yr (Kearney 1996). Thus sea-level rise in the Bay region during 1993-2003 was 3.2 mm/yr, while the decadal rate in the 1990s was very high, more than 1.3 cm per year (Stevenson et al. 2002). This rise in sea level may have already had an impact on the estuarine nursery grounds used by menhaden. For example, the vegetative buffer zones in the form of extensive tidal marshes that can protect against nutrient runoff are being lost with sea level rise (Kemp et al. 2005). Marshes in the middle and lower reaches of Chesapeake and Delaware bays are being degraded due to sea level rise (Kearney et al. 2002) and, as their buffering capacity is lost, more sediment and nutrients can enter the estuary proper. Secondary effects are the loss of submerged macrophytes and increased incidences of harmful algal blooms (discussed below).

Projected Temperature Change along the U.S. East Coast

The projected rise in surface air temperatures by mid-century will be 1.3-1.8 ^{0}C worldwide. Temperatures have already risen by at least 5^{0}C over the past century (IPCC 2007). These figures mask the fact that the variability in temperature rise will be uneven globally with the Arctic experiencing the greatest proportional rise of 5^{0}C by mid-century, and the U.S. East Coast <2^{0}C (Meehl et al. 2007). Correspondingly, water temperatures during the 1960s in Chesapeake Bay were below average; in the 1970s temperatures were variable; but since the 1980s there has been a distinct warming trend above the long-term average (Austin 2002). Wood et al. (2002) noted that within-season temperatures in the Chesapeake region also reflected this increased temperature in over half the months, with warmer winter temperatures and earlier springs. The same pattern of increased temperatures was seen for mid-Atlantic air temperatures (Yarnal 1997), and mid-Atlantic Bight waters (Cronin et al. 2003; Drinkwater 1996). The warming of sea surface temperatures on the continental shelf that has occurred over the past few decades is not without precedent in the historical record of the past century. However, the contemporary warming is more thermally dynamic, being associated with higher annual temperature ranges and more rapid seasonal transitions (Friedland and Hare 2007).

Increased temperatures can affect menhaden in a variety of ways, including: direct effects on ontogeny and growth; changes in the spatial extent of habitat and spawning location; range shifts (such as documented for fishes in the North Sea by Perry et al. 2005); and changes in advection patterns that effect ingress dynamics. Roessig et al. (2004) stated that relatively small increases in temperature can have profound impacts on fish abundance and distribution. Austin (2002) correlated changes in recruitment success of menhaden in Chesapeake Bay to decadal climate changes. These potential effects can be understood in the context of menhaden life history. Atlantic menhaden spawns in waters of 10-20^{0}C, with larvae occurring at temperatures >12^{0}C (see Background brief). Thus, warmer temperatures in the coastal ocean could result in a longer season for spawning and larval growth, if sufficient food is available. Similarly, warmer temperatures offshore would provide a larger habitat to support winter spawning that presently is concentrated in the warmer waters off North Carolina. Kendall and Reintjes (1975) reported that this winter spawning constitutes the majority of egg production. With the rise in sea temperatures, one could predict a northern expansion of the spawning range for menhaden. Moreover, Austin (2002) postulated that changes in wind regimes, in particular wind direction, might alter success of larval transport to bays, hence recruitment success. Together such changes could profoundly affect the synchronization mechanisms between egg production and current patterns that drive advective transport to inshore nurseries.

Increased Climate Variability

A notable outcome of climate change modeling work is the prediction that climate will become more variable (Meehl et al. 2007). Over the short term, climatic variability in the mid-Atlantic Bight is influenced strongly by the North Atlantic Oscillation (Austin 2002). Austin (2002) reviewed climate variability and fish abundances in the Chesapeake Bay ecosystem and described decadal oscillations and regime shifts that impacted fish populations and noted that summer versus winter spawning fishes were differentially favored. Climate change is predicted to influence NAO variability with the result that zonal winds will be enhanced (Rauthe et al. 2004), thus potentially influencing fish abundances.

Climate models predict increased severity of droughts and flood events (Meehl et al. 2007) with uncertain effects on Atlantic menhaden and other organisms in Chesapeake Bay. In his analysis of long-term patterns in the mid-Atlantic Bight, Austin (2002) found that temperatures and precipitation were linked, resulting in a dichotomy between dry cool periods versus warm wet periods. Hence, his analysis suggested that the East Coast may experience wetter weather, on balance. It should be noted that the precipitation forecasts are among the least certain from climate models (Pyke et al. 2008). Years of high river discharge produce increases in nutrient and sediment runoff, which in turn result in changes in phytoplankton populations and turbidity (Austin 2002). Higher periodic runoff has several environmental impacts. For example, since 1985 there has been a significant decrease in Secchi depth readings due to changes in the sediment load and type resulting from changes in runoff and land-use practices (Greer 2008). Storm runoff also contributes to the organic load in estuarine and coastal waters. Increased organic loads stimulate the production of algae, which die and cause hypoxic conditions, particularly in the poorly mixed portion of the Bay. For example, in 2004 Tropical Storm Ivan resulted in a freshwater plume that increased the stratification of the water column in Chesapeake Bay and resulted in a significant oxygen deficit in the more saline bottom waters (CBF report Fall 2004 p:6). Climate change could increase the frequency of such events, which would exacerbate current anoxic conditions already affecting some 250 square miles of the deeper waters of Chesapeake Bay during parts of the year.

The intensity and frequency of major storm events are predicted to increase (Pyke et al. 2008). Recent papers by Christensen et al. (2007) and Meehl et al. (2007) indicate that winter storms will increase and the hurricane season will lengthen. Hurricane events have had long-term effects on east coast estuaries such as Pamlico Sound (Paerl et al. 2000) and Chesapeake Bay due to destruction of sea grass habitats. Effects of hurricanes on menhaden production are not known, but presumably perturbations that impact plankton dynamics in the Bay could have consequences for menhaden feeding and growth.

Effects of Potentially Increased Nutrient and Sediment Flux

Increased temperatures, nutrient enrichment and higher salinities contribute to the presence of harmful algal blooms (HAB) in the bays and estuaries that may be detrimental to fish and, specifically, Atlantic menhaden wellbeing. For example, the toxic heterotrophic dinoflagellate *Pfiesteria piscicida,* which is believed to be a disease vector in menhaden populations (Burkholder and Glasgow 1997), appears to respond positively to increases in hypoxia. Pyke et al. (2008) point out that non-point sources are the greatest contributors to phosphorus loads in the Bay, while sources of nitrogen include both point and non-point sources (Pyke et al. 2008, Schaefer and Alber 2007). Major storms in the Chesapeake Bay watershed area account for the vast majority of the algal-available P in the Bay; it is this source of P that enhances phytoplankton production (Pionke et al. 2000). Non-point sources of nitrogen include atmospheric deposition and riverine input. In Chesapeake Bay, the Susquehanna River supplies the majority of nitrogen (Howarth et al. 2006). This will be influenced by variability in storms and drought events. Again, the changes in precipitation along the U.S. East Coast are less certain in the climate models (Meehl et al. 2007).

A potential result of increased nutrient loads and altered timing of precipitation events is a projected increase in harmful algal blooms in Chesapeake Bay (Pyke et al. 2008). Dinoflagellates, the group which contain a number of harmful species, bloom under conditions of increased nutrients and water-column stratification. The effects of HAB on menhaden are largely unknown. One can assume that menhaden, as a filter feeder, could be strongly impacted, though there is some evidence they are capable of avoiding potentially harmful conditions (Friedland et al. 1989).

Sediment flux will increase with any increase in climate-induced, storm events and precipitation. Sediments profoundly impact ecosystems in bays, estuaries, and coastal waters through the import of nutrients and decreased light penetration (Williams 2004). The decrease in light penetration has already impacted species composition and abundance of submerged aquatic vegetation (SAV). The abundance of SAV in Chesapeake Bay has decreased dramatically over the past century (Moore et al. 2000), and the species composition has changed (Moore and Jarvis 2008). SAV do not constitute an important habitat for menhaden, but grass beds are an important nursery habitat for the young of some menhaden predators.

If climate change results in increased precipitation in the watershed, then the hypoxic area would be expected to grow in spatial extent and duration resulting in a loss of habitat. This could affect menhaden abundance by reducing predator habitat and increasing the potential for interaction between menhaden and their predators (Costantini et al. 2008). Increased nutrient influx associated with higher freshwater flows into the Bay will result in greater temporal and spatial extent of hypoxic zones (Kemp et al. 2005) and will exacerbate hypoxic conditions (Boesch et al. 2001).

Ocean Acidification

The accumulation of atmospheric CO_2 has been known for some time to pose a threat to life in marine waters through direct effects of high gas concentration and through indirect effect of changing the carbonate equilibrium, resulting in lower pH levels. To date, the oceans have absorbed nearly one-third of the anthropogenic carbon emitted to the atmospheric (Sponberg 2007). Although these problems have received recent attention, little research has been directed to understanding effects of CO_2 and acidification on marine fish (Ishimatsu et al. 2008).

Elevated CO_2 could have adverse effects on physiology of Atlantic menhaden, considering observations that are recorded for other marine fishes. Under a high concentration of CO_2, fish growth may be reduced due to increased energetic costs to obtain sufficient O_2 for respiration (Ishimatsu et al. 2008). Hayashi et al. (2004) showed that high CO_2 levels were toxic when compared to the effects of pH reductions in their experiments on adult Japanese flounder (*Para-*

lichthys olivaceus). Similar toxicity to CO_2 was seen in the eggs and larvae of the red sea bream, *Pagrus major* (Kikkawa et al. 2004).

Higher concentrations of CO_2 in seawater lower the pH and dissolves calcium carbonate. The primary effect of these conditions is to interfere with calcification of marine organisms and their osmotic regulation. Specifically, many classes of phytoplankton are expected to experience physiological disruption if ocean carbonate balances are changed (Rost et al. 2008) and this could cause a shift in species composition that disrupts trophic food webs (Doney 2006). In contrast to invertebrates, fishes have been shown to compensate fully for acid-base imbalances by modifying their enzymatic functions (Melzner et al. 2009), at least as adults. Fish cultured from the egg through the yolk-sac larva stage show increased otolith mass at higher concentrations of CO_2 apparently while maintaining normal internal pH (Checkley et al. 2009).

The life cycle and the productivity of menhaden could be affected by ocean acidification in a number of ways, but our most immediate concern would be on stressors that affect early life stages in the open ocean and the impact on menhaden feeding caused by a highly altered community of primary and secondary producers.

Issues

1. Climate change impacts the suitability of juvenile habitats in Chesapeake Bay. Climate change results in shifts in the distribution and productivity of juvenile menhaden nursery habitats. While many of the specific effects of climate change remain speculative, it is probable that increases in temperature, freshwater flow, acidification, and sea-level rise in combination will affect productivity and recruitment of menhaden.

   Indicators/Metrics

   - Thermal conditions, freshwater input, pH, nutrients, salinity.
   - Recruitment patterns and trends.
   - Distribution of juvenile menhaden; plankton abundance and distributions

2. Climate change impacts on early life stages. Climate change may result in shifting oceanographic and hydrographic conditions in the coastal ocean, potentially affecting adult menhaden spawning areas and times. Effects on primary productivity and zooplankton production could compromise larval menhaden feeding and survival. And, dispersal and transport pathways that deliver larvae to the mouth of Chesapeake Bay could shift

   Indicators/Metrics

   - Oceanographic conditions; hydrographic measures; pH, winds, currents.
   - Egg production; temporal and spatial measures.

- Larval abundance, growth, and survival.
- Larval ingress to Chesapeake Bay.

3. Climate change impact on stock productivity. Climate change results in a change in the productivity of Atlantic menhaden habitats and species composition of the plankton. Such changes could occur in the coastal ocean and in the Chesapeake Bay, having effects on all life stages of Atlantic menhaden.

Indicators/Metrics

- Primary production and *chl-a* temporal-spatial variability.
- Satellite, airplane, shipboard, and other time series measures of primary production.
- Environmental, hydrographic and oceanographic variables.
- Growth, survival, and production of menhaden in all life stages.

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FOODWEB

Introduction

Atlantic menhaden plays a key trophic role in estuarine and coastal ecosystems along the east coast of the United States. As juveniles and adults, menhaden filter-feed, consuming phytoplankton and zooplankton, which are utilized to fuel routine metabolism, growth, and reproduction. However, in the larval stage, menhaden eat zooplankton, which are captured as individual particles. Menhaden is an important prey resource for piscivorous predators at all stages of its life history, in habitats ranging from the western edge of the Gulf Stream to freshwater (see Habitat Suitability Issue Briefs for discussion of environment and bioenergetics relationships). The abundance of menhaden suggests that feeding by menhaden and predation on menhaden have significant trophodynamic impacts over its distributional range. The important trophic role of menhaden is highlighted in development of this ecosystem-based management plan and in the recent development of multispecies models (MSVPA-X) that ASMFC has undertaken (ASMFC 2003) , Menhaden's important role in food webs that include major predators in Chesapeake Bay is illustrated in Figure 1. Atlantic menhaden also is a key species in the Ecopath with Ecosim ecosystem and food-web modeling that is being promoted by the Chesapeake Bay Program (Christensen et al. in press).

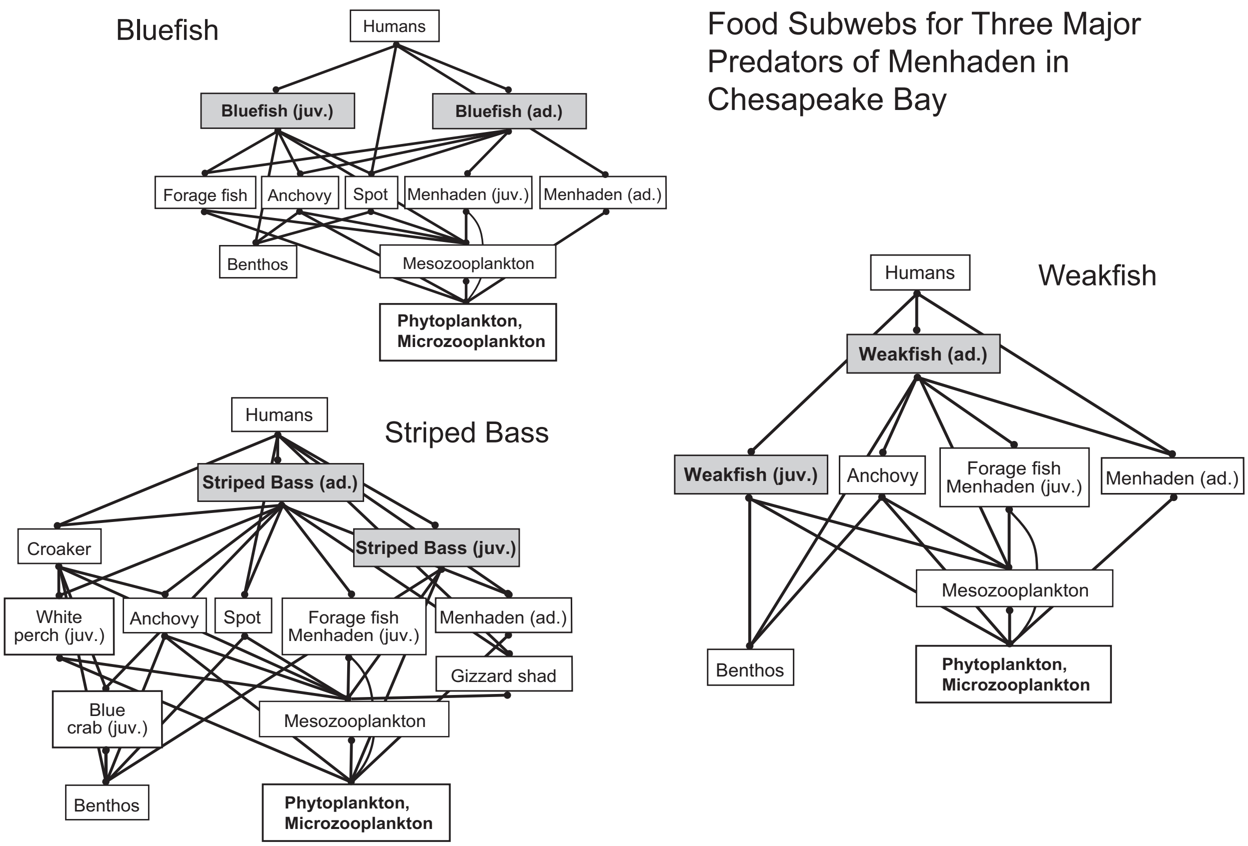

Figure 1. Conceptual models of food subwebs for bluefish, striped bass, and weakfish — three major predators of Atlantic menhaden in Chesapeake Bay. Note the prominent position of menhaden in the subwebs. Modified from figures in CBFEAP (2006).

Foods, Foraging, and Productivity

Eric Annis, Jim Uphoff, and Cynthia Jones

Atlantic menhaden occupies two distinct feeding niches during its lifetime. Menhaden is a size-selective zooplankton feeder as larvae and a filter feeder as juveniles and adults (Rogers and Van Den Ayvle 1989). Juvenile and adult menhaden strain phytoplankton, zooplankton, and detritus on their sieve-like gill rakers (see Habitats brief). Because of menhaden's abundance, rapid growth, and seasonal migrations, the population annually consumes and redistributes large amounts of energy and materials throughout estuaries and continental shelf waters (Rogers and Van Den Ayvle 1989).

Control of marine ecosystems may be strongly directed by plant-herbivore interactions. Atlantic menhaden is the major herbivorous fish on the Atlantic coast (Schaaf 1975) and may contribute significantly to top-down control of the Chesapeake Bay ecosystem. Simulation models indicated that Atlantic menhaden in Narragansett Bay and Chesapeake Bay potentially has substantial effects on zooplankton and phytoplankton populations, and on nutrient dynamics (Durbin and Durbin 1975, 1998; Gottlieb 1998), although more research is needed to confirm these possibilities.

As consumers of phytoplankton menhaden provides an efficient trophic link between primary production and fish production. Juvenile and adult menhaden are filter feeders, consuming not only phytoplankton, but also zooplankton and detritus (June and Carlson 1971; Jeffries 1975; Peters and Schaaf 1981; Lewis and Peters 1994). Phytoplankton is generally believed to be the major food of juvenile and young adult menhaden. The role of zooplankton in the diet becomes more important in older menhaden as gill raker spacings on their filtering apparatus increase in size (Friedland et al. 1984, 2006). The relative importance of each food type varies with ontogeny, region, and in relation to local availability. The role of detritus from vascular plants and other sources in nutrition of juvenile and adult menhaden, and in trophodynamics of estuaries and coastal systems is not resolved. Detritus can be a major constituent of stomach contents in some situations (Jeffries 1975; Peters and Schaaf 1981; Lewis and Peters 1994), but its contribution to nutrition and growth is probably less than that from phyto- and zooplankton.

Like most marine fish larvae, menhaden larvae are zooplankton feeders. Late-stage larvae (~28-35mm), collected after ingress into estuaries, feed selectively on zooplankton, particularly on copepods and notably on the copepod *Acartia tonsa* (June and Carlson 1971; Kjelson et al. 1975). Ingressing larvae, 20-35 mm in length, at the mouth of Chesapeake Bay in the November to April period ate mostly calanoid copepods, supplemented with the marine cladoceran *Pogon* sp. and barnacle nauplii. Feeding incidence and success of ingressing larvae differed significantly among years (Houde et al. 2009)

Filter-feeding capability develops post-metamorphosis and analyses of stomach contents indicate a corresponding transition in diet from predominately zooplankton to phytoplankton between 30 and 50 mm fork length (June and Carlson 1971). Detritus also may comprise a significant proportion of the juvenile diet, especially in proximity to salt marshes where detritus from vascular plants is reported in menhaden stomachs (Lewis and Peters 1981; Lewis and Peters 1984). The retention of small particles by YOY menhaden suggests that nanoplankton and even small amounts of bacteria may be included in the diet (Friedland et al. 1984). Friedland et al. (2006) hypothesized that another feeding transition occurs between 100 mm and 200 mm FL as gill raker spacing becomes wider and presumably less efficient at retaining small phytoplankton. The change in filtering efficiency was documented, showing that 138-mm individuals retained particles in the 5-7 µm range (Friedland et al. 1984) while 257-mm individuals only retained particles >13 µm (Durbin and Durbin 1975).

Mean lengths of YOY menhaden sampled during fall from Chesapeake Bay ranged from 120-180 mm (TIES[1]/CHESFIMS[2] data). Those lengths are within the ontogenetic transition in filtering efficiency and suggest that as YOY menhaden migrate from the Bay in their first winter the proportion of zooplankton in their diet is increasing. However, there is presently no empirical evidence to document this shift in diet. The stomach contents of adult menhaden include a slurried mixture of phytoplankton, zooplankton and detritus (Peck 1893), but quantified estimates of the proportions are not available. Zooplankton undoubtedly plays a critical role in the diet of early-stage larval menhaden on the continental shelf and in late-stage larvae in Chesapeake Bay during their ontogenetic transition to the juvenile stage. Zooplankton also is important in diets of adult menhaden in the coastal ocean and estuaries, although its contribution to diets is temporally and spatially variable.

Spatial considerations in foraging include ontogenetic changes in habitat and changes in prey availability between habitats. Zooplankton abundance and composition may be most important in estuaries and coastal waters where larvae and age 1+ menhaden are found. Phytoplankton is probably most important in estuaries and embayments inhabited by the fast-growing YOY juveniles. Friedland et al. (1989) found that schools of YOY menhaden tracked patches of phytoplankton. Fatty acid analysis of stomach contents of juvenile menhaden suggested that the fraction of zooplankton in diets varied from 1% near salt marshes to 30% in river habitat, and up to 71% in Narragansett Bay (Jeffries 1975), a reflection of the relative abundance of zooplankton in those habitats.

Temporal changes in prey availability and composition may affect menhaden diet. The biomass of phytoplankton in Chesapeake Bay has remained relatively constant since the 1970's (Harding 1994; Paerl et al. 2006). While diatoms still constitute the most abundant taxa of phytoplankton in the Bay (Paerl et al. 2006), there has been a shift in composition towards taxa with smaller cells and cyanobacteria are increasing (Marshall et al. 2005). Smaller cells may be less efficiently retained by filter-feeding menhaden. Cyanobacteria, even if retained, may provide low

[1] TIES. Trophic Interactions in Estuarine Ecosystems. Midwater trawl surveys, 1995-2000. NSF-funded Land Margin Ecosystem Research, University of Maryland Center for Environmental Science.

[2] CHESFIMS. Chesapeake Bay Fisheries Independent Multispecies Surveys, 2001-2005. Midwater trawl surveys, 2001-2005. NOAA Chesapeake Bay Office-funded program. University of Maryland Center for Environmental Science.

nutritive value because they can pass through the digestive tract intact (Friedland et al. 2005). Zooplankton quantity and composition in Chesapeake Bay shows high inter-annual variability but no significant long term trend in the past 30 years, particularly for common and abundant copepods such as *Acartia tonsa* (Kimmel and Roman 2004) (see Habitat/Water Quality briefs). Recently, there has been progress in relating measures of primary productivity to recruitment and growth of YOY menhaden. During the past two decades, there has been a positive correlation between recruitment and euphotic-zone *chl-a* and integrated annual primary production in the Bay (Houde and Harding 2009), suggesting that menhaden populations are controlled in part by bottom-up processes, i.e., quantity of food available. Furthermore, bioenergetics modeling indicates that much of the variability in YOY growth observed in the field can be explained by variability in *chl-a* levels and temperature (Annis et al. in prep). The Annis et al. model, derived from the foraging model of Luo et al. (2001), used measurements of *chl-a* (from the Chesapeake Bay Remote Sensing Program) and water temperature (Chesapeake Bay Program) to develop seasonal growth curves for YOY menhaden in each year for an 11-year time series (1995-2005). The model output was fit to observed menhaden sizes from research cruises in the Bay by adjusting available *chl-a* (Figure 2). The near 1:1 relationship between modeled and observed sizes indicates that the model effectively represents inter-annual variability in growth. To evaluate importance of phytoplankton taxa, the model was run with *chl-a* values partitioned into diatom, dinoflagellate, cyanobacteria, and cryptophyte fractions. Model output was not improved beyond the fit obtained with total *chl-a*, implying that YOY menhaden growth is not dependent on any particular taxonomic group of phytoplankton. Because diatoms were dominant in the Bay's *chl-a* data, it is probable that they are important in supporting menhaden nutrition and growth.

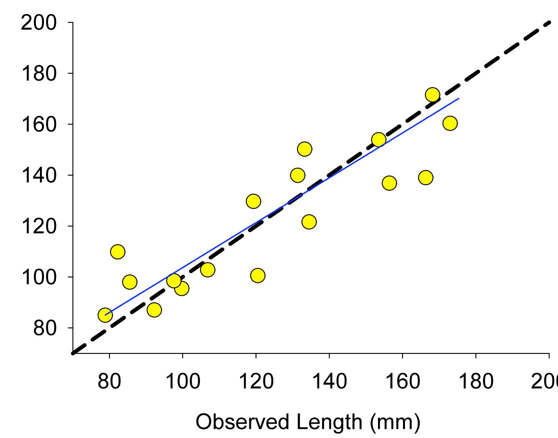

Figure 2. Comparison of modeled menhaden lengths with menhaden lengths observed in the field. Each point represents an average fish length from annual spring and fall field collections and modeled length (growth potential) for the corresponding dates. The dashed line indicates the line of 1:1 correspondence and the blue line is a linear fit to the data points.

Spatially-explicit bioenergetics models have been used to estimate carrying capacity of menhaden in the Bay as well as the reduction of habitat volume and productivity from eutrophication and hypoxia (Brandt and Mason 2003; Luo et al. 2001). The recent validation of bioenergetics-model estimates of growth potential using field data (Annis et al. in prep, Figure 1) indicates that these models have excellent potential to evaluate trophic interactions by menhaden with respect to water quality and plankton productivity on an ecosystem scale.

Issues

Water quality (habitat) and productivity potential (available food) in Chesapeake Bay may vary from year-to-year, decadally, or in longer-term trends that have led to lower recruitment levels of

YOY menhaden. The positive relationship between *chl-a* and YOY menhaden growth suggests that reductions in phytoplankton biomass could negatively affect menhaden growth. Menhaden also might exercise some control over primary production in the Bay if nutrient recycling by these abundant fish is significant in baywide or local situations. Shifts in phytoplankton productivity from climatological changes or successful efforts to mitigate eutrophication in the Bay could affect menhaden growth and productivity and its role as forage in the Bay food web.

Shifts in phytoplankton composition towards smaller phytoplankton and cyanobacteria potentially could reduce nutritional value and quantity of food available to menhaden. The magnitude of change in composition required to negatively impact menhaden feeding is presently unknown.

Menhaden growth and nutrition also may be affected by reduction in zooplankton abundance and shifts in taxa size or dominance resulting from competition with gelatinous zooplankton or changes in trophic status of the Bay. Climate and water-quality changes could cause such shifts.

Metrics

Metrics to gauge the status and importance of Atlantic menhaden foods and foraging include:

- Climatological indices and their relationships to changes in the phytoplankton and zooplankton communities.
- Time-series of zooplankton/phytoplankton abundance or relative abundance (baywide monitoring of zooplankton should resume).
- Zooplankton/phytoplankton monitoring, and remotely sensed *chl-a* data.
- Analysis of stomach contents to document variability in feeding of larval, YOY and adult menhaden.
- Growth rates of YOY menhaden.
- Natural and anthropogenic forcing factors affecting the plankton community composition in terms of size and species, such as nutrient enrichment indices and other pollution indicators.

Predation on Menhaden

Jim Uphoff, Cynthia Jones, and Rae Marie Johnson

Atlantic menhaden is important forage for many fish, bird and mammalian predators along the Atlantic Coast (Rogers and Van Den Ayvle 1989; Munroe and Smith 2000). Within Chesapeake Bay, piscivorous fishes and birds prey upon menhaden and share the menhaden resource with the fishery (Hartman and Brandt 1995; Smith 1999; Walter et al. 2003; Viverette et al. 2007). Menhaden is important prey for striped bass, weakfish, and bluefish in Chesapeake Bay (Hartman and Brandt 1995; Walter et al. 2003) and these piscivores are key elements of the Bay's recreational and commercial fisheries.

Piscivorous fishes are size-selective and gape-limited predators and, as such, consume small prey fishes such as bay anchovy when they initiate piscivory. Juvenile menhaden represent the next step in piscivory as the predators grow to larger size (Juanes 1994; Hartman and Brandt 1995; Uphoff 2003; Walter et al. 2003). A switch early in life from an invertebrate to fish diet by bluefish, weakfish, and striped bass categorizes them as specialized piscivores that exhibit high growth rates, implying the need for forage of appropriate size (Persson and Brönmark 2002).

Diet studies by Walter and Austin (2003) and Overton et al. (2008) reported that large striped bass, >900 mm, could eat fish prey >400 mm, a length approximating that of the largest Atlantic menhaden (Ahrenholz 1991). However, large striped bass also feed on small pelagic prey (e.g., bay anchovy, juvenile clupeids and other small fishes) (Figure 3). Bluefish, a pelagic predator,

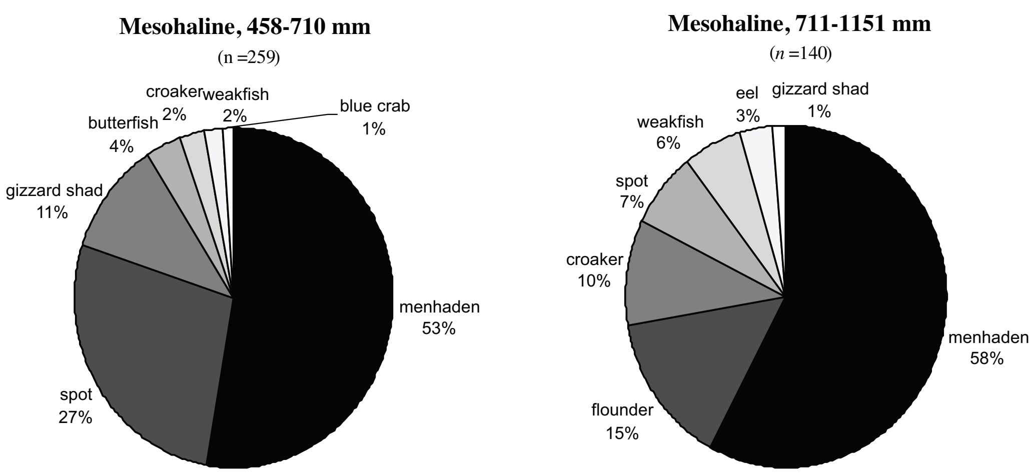

Figure 3. Diets of large striped bass from the mesohaline region of Chesapeake Bay in Fall months (1997-1998). Menhaden comprises >50% of the diet by weight (from Walter and Austin 2003, their Figure 3).

has a large gape relative to its length that is indicative of its ability to consume large as well as small prey fishes (Scharf et al. 2000). Unlike striped bass and bluefish, weakfish does not expand the size range of items in its diet with growth (Scharf et al. 2000) and largely remains a predator on fish in the size range of bay anchovy and small, juvenile menhaden.

Of the three piscivorous fishes important to the Bay, striped bass is most likely to have a large impact on menhaden abundance. Consumption of menhaden and river herrings (alosines) by the recovered striped bass population is potentially high enough to substantially impact abundance of these forage fishes along the Atlantic coast (Hartman 2003; Uphoff 2003; Savoy and Crecco 2004). Potential consumption (a measure of potential, not actual consumption) of age 0-2 Atlantic menhaden by striped bass increased steadily from a small fraction of the coastal commercial landings in 1982 until it exceeded landings after 1994. Potential consumption exceeded estimated menhaden abundance after 1997 (Uphoff 2003). Estimated consumption of menhaden by bluefish along the Atlantic coast in 1995 was approximately 5% of menhaden landings (Buckel et al. 1999). No comparable estimates are available for weakfish, but the limited prey size selection and low population biomass of weakfish suggest a smaller impact on menhaden.

Reduced fishing mortality and higher minimum size limits that restored the coastal striped bass population during the 1980s and 1990s led to more abundant and larger striped bass in Chesapeake Bay, increasing its predatory demand for Atlantic menhaden. Since the late 1990s, stakeholders have hypothesized that an outbreak of lesions and poorly conditioned striped bass in Chesapeake Bay are attributable to poor nutrition, consequences of a shortage of Atlantic menhaden (Uphoff 2003).

Striped bass may prefer Atlantic menhaden, but will prey on other organisms when menhaden are not sufficiently abundant (Overton 2003; ASMFC 2004; Rudershausen et al. 2005). The prey to predator ratio in biomass of age 1+ menhaden (ASMFC 2006) to age 2+ striped bass (NEFSC 2008) fell from an average of 73 in 1982-1987 to an asymptotic low of about 6 after 1996. Potential susceptibility of menhaden to striped bass predation along the Atlantic Coast can be indexed by this ratio (Uphoff 2003). Diet studies on striped bass and weakfish in Chesapeake Bay indicated major shifts in the past decade (Uphoff 2003, 2006). Menhaden became less frequent in diets from the early 1990s to early 2000s and invertebrates became more important (Hartman and Brandt 1995; Griffin and Margraf 2003; Overton 2003; Bonzek et al. 2004). Switching to alternative prey potentially has implications for populations of those prey taxa that had previously been unimportant in striped bass diets (see Striped Bass Food Web Brief).

Since the close of the DDT era in the early 1970s, piscivorous bird populations grew exponentially throughout the tidal reaches of Chesapeake Bay (Viverette et al. 2007). Menhaden historically has been one of their most important prey. The actual or potential consumption of menhaden by bird predators that include the bald eagle and osprey, but also terns, gannet, loons, great blue heron, double-crested cormorant, brown pelican, and some gulls in the Bay watershed, has increased substantially in the past three decades, as has their demand for fish (Figure 4) (Viverette et al. 2007). Predator-prey interactions between piscivorous birds and fish prey have received little attention from wildlife managers (Steinmetz et al. 2003) or fishery managers. And, Chesapeake Bay ecosystem models (e.g. Baird and Ulanowicz 1989; Christensen et al. in press) largely ignore birds. In an ecosystem-based approach, the interaction between birds and

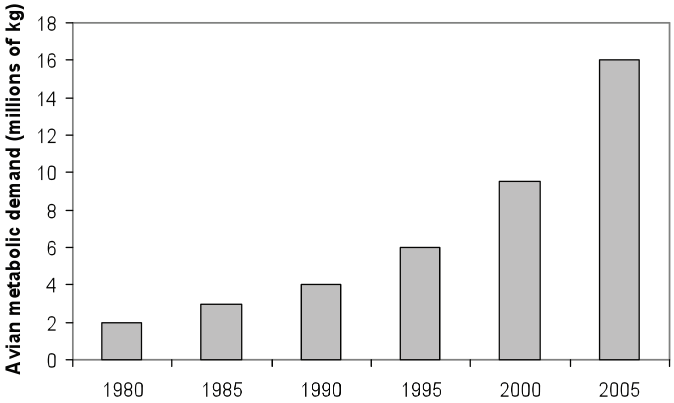

Figure 4. Estimated metabolic demand for fish by piscivorous birds (all species) in Chesapeake Bay (C. Viverette, personal communication, Virginia Commonwealth University, Richmond, VA).

menhaden, and predation mortality attributable to the birds, must be considered and quantified to the extent possible.

Diet studies have been conducted on osprey. Menhaden is a major component of the diet of coastal osprey populations in New England (Poole 1989), coastal New Jersey (Steidl et al. 1991a) and the Delaware Bay (Steidl et al. 1991b). The only published diet study of osprey in Chesapeake Bay, conducted in high-salinity reaches of the lower Bay during the mid-1980s, found that menhaden comprised 75% of nest deliveries (McClean and Byrd 1991).

The double-crested cormorant (*Phalacrocorax auritus*) has increased in abundance throughout the Chesapeake watershed. The first record of breeding in the region occurred in 1978 within the tidal freshwater James River (Blem et al. 1980) and the population then grew rapidly (Watts and Bradshaw 1996). Cormorants are now common in the Bay, but feeding habits are unreported. However, it is probable that cormorants consume menhaden as part of their diets. Research on feeding habits of cormorants in other regions indicate feeding on small individuals (~75-125 mm) of many fish taxa. An adult cormorant can consume substantial amounts of fish, approximately one pound per day (U.S. Fish and Wildlife Service 2009), highlighting the consumption potential of bird predators when they are abundant.

Issues

It is clear that Atlantic menhaden plays a key role in Chesapeake Bay's trophic dynamics and food web, but the role is largely unquantified. Potential demand for menhaden by fish and avian predators, actual consumption of menhaden, inter-annual variability in predation mortality, and the fraction of natural mortality imposed by major predators are not typically estimated but will be important for management of the menhaden resource and also its predators. Predators and the fishery presumably are competing for the menhaden resource.

Ecosystem-based approaches for management of the menhaden resource are dependent on knowledge of trophic interactions. Modeling research, for example biomass dynamic and Ecopath with Ecosim models, now being developed for Chesapeake Bay (Christensen et al. *in press*) have potential to define and quantify implications of different fishing strategies and variable predation pressure for both menhaden and its predators. Although managers recognize the key trophic role of menhaden, an explicit strategy for allocating menhaden among the competing objectives of the fishery and menhaden's services as prey for piscivores has not been developed.

Indicators/Metrics

Prey-Predator Ratios

- Prey-predator ratios can index availability and probable vulnerability of prey to predators and serve as an indicator of expected prey mortality (i.e., *M*, the natural mortality rate, inversely proportional to the ratio).

- Ratios of menhaden to striped bass, expressed as absolute or relative numbers or biomass, as used by Uphoff (2003).

- Ratios of menhaden abundance with respect to combined abundance of major predators.

Predator Stomach Analyses

- Predator feeding success and quantification of consumption of menhaden based on predator stomach analysis.

- Indices of size- and age-specific losses of menhaden to predation.

- Bioenergetics models, developed from predator feeding data, can be used to estimate consumption potential by predators on menhaden in the Bay (e.g., Hartmen and Brandt 1995).

Accounting for Predation and Predation Mortality: Multispecies Reference Points

- A measure of mortality attributable to major predators, based on multispecies models. Multispecies management models must include predators having the greatest impact on target species (Hollowed et al. 2000a, b).

- A multispecies model (MSVPA-X) has been developed by ASMFC for Atlantic menhaden that includes predation mortality attributable to striped bass, bluefish and weakfish. That model has been used to estimate age-varying natural mortality (*M*) in menhaden.

- Other multispecies and ecosystem models are being developed (e.g. Ecopath with Ecosim), or are available, and should be compared with the MSVPA.

Competition

Ed Houde, Eric Annis, Kevin Friedland, and Jim Uphoff

Atlantic menhaden is a pelagic planktivore in all of its life stages. As such, the potential for competitive interactions rests primarily on availability of planktonic food resources. Competition in abundant, schooling menhaden could be a consequence of intra- or inter-specific interactions. While there is evidence that intra-specific competition may be important in controlling or regulating growth and recruitment levels, i.e., density dependence (e.g., Ahrenholz et al. 1989), there is no explicit analysis that documents effects of competition on stock dynamics.

Larval-stage menhaden is a zooplanktivore, consuming copepods and other common plankton organisms. Although undocumented, larvae potentially compete for food resources with other vertebrate and invertebrate planktivores, e.g., jellyfishes, chaetognaths, larval fishes and juvenile/adult planktivorous fishes.

During ontogeny, menhaden becomes a filter-feeder and diets of YOY juveniles consist primarily of small phytoplankton (Friedland et al. 1984). As growth continues, the filtering efficiency gradually shifts such that smaller phytoplankton can no longer be effectively filtered, and zooplankton and detrital food become more important (Durbin and Durbin, 1975). It is also believed that energetic demand is supplemented by direct utilization of detritus (Lewis and Peters, 1994). During the juvenile-adult stages, there is potential for competition by dense schools of filter-feeding menhaden foraging for limited numbers of plankton and detritus particles.

Intra-specific Competition

There is no evidence or knowledge to confirm that competition is important in the larval stage, before menhaden adopt schooling behavior. During YOY juvenile and adult stages, menhaden form large schools that are capable of clearing a substantial fraction of the plankton in a school's path by their filter-feeding behavior (Oviatt et al. 1972; Durbin and Durbin 1998). In Chesapeake Bay, recruitment levels and growth rates of YOY menhaden in the 1988-2004 period were positively correlated with biomass of phytoplankton and integrated annual primary production (Houde and Harding 2009; Houde and Secor 2009). In an analysis of growth patterns since the 1960s, abundance of YOY juveniles and recruitment levels in Chesapeake Bay were inversely correlated with growth rates, suggesting possible resource limitation and density dependence mediated by intra-specific competition (Houde and Harding 2009).

Issues

Growth, productivity, and recruitment level of the menhaden stock in Chesapeake Bay may be limited by available planktonic food resources (quantity and quality) promoting intra-specific competition for food that could limit growth rates and affect size-selective mortality.

Indicators/Metrics

Indicators and metrics that are relevant to detect and evaluate intra-specific competition include:

- Larval and YOY growth rates, and size-at-age variability.
- Indices of prey and food abundance.
- Natural and anthropogenic forcing factors affecting the plankton community composition in terms of size and species, such as nutrient enrichment indices and other pollution indicators.
- Measures of feeding success.
- Juvenile abundance indices of planktivorous fishes.
- Indices of prey availability (e.g., prey per predator).

Inter-specific Competition

Specific competitors of larval-stage Atlantic menhaden on the continental shelf are not known although it is likely that menhaden larvae utilize the same or similar zooplankton prey as other fish larvae and invertebrate carnivores, e.g., jellyfishes and chaetognaths. After ingress into Chesapeake Bay, late-stage larvae may compete with larvae of anadromous and estuarine fishes within the Bay itself, e.g., striped bass, white perch, shads and river herrings, or other planktivorous juvenile and adult fishes, e.g. bay anchovy, silversides, juvenile alosines, gizzard shad.

YOY juveniles and, to an extent, adult Atlantic menhaden are nearly unique among Chesapeake Bay fishes in their capability to filter phytoplankton as their primary food resource. Primary competitors of menhaden may be planktonic invertebrate grazers such as copepods and other small zooplankton species, and also filter-feeding invertebrates such as oysters, mussels, clams, barnacles, and tunicates, e.g., *Molgula* sp. With respect to fishes, menhaden diets in the upper Bay and oligohaline reaches of tributaries may overlap with omnivorous gizzard shad *Dorosoma cepedianum*, which consumes phytoplankton, zooplankton, and detritus (Drenner et al. 1984; Devries et al. 1992; Schaus et al. 2002). Except for bay anchovy *Anchoa mitchilli*, which includes some large diatoms in its diet (Houde and Harding 2008), there are no competing phytoplanktivorous fishes in the mesohaline and polyhaline regions of the Bay.

A substantial but unknown fraction of the diets of YOY juvenile and adult menhaden in Chesapeake Bay consists of zooplankton. That fraction is believed to increase as menhaden grows to lengths >150 mm. There are many organisms sharing coastal and estuarine environments with menhaden that consume zooplankton in their larval, juvenile or adult stages. Among these are two dominant jellyfish species that are major consumers of zooplankton prey in Chesapeake Bay. Fishes and jellyfishes probably compete for zooplankton prey with Atlantic menhaden in a complex web of interactions. The bay anchovy is the most abundant fish in Chesapeake Bay and is primarily a zooplankton consumer (Houde and Zastrow 1991; Houde and Secor 2009). The lobate ctenophore *Mnemiopsis leidyi* is the most abundant jellyfish. It is a major consumer of small plankton organisms, and potentially a major competitor with both Atlantic menhaden and bay anchovy (Purcell 1991; Purcell et al. 2001). The scyphomedusa *Chrysaora quincecirrha* eats zooplankton, thus competing directly with planktivorous fishes, including menhaden. Additionally, the scyphomedusa is a predator on the lobate ctenophore, thus indirectly mediating competition among jellyfishes, Atlantic menhaden and other planktivorous fishes in Chesapeake Bay.

Issues

The primary issue is understanding how Chesapeake Bay productivity, availability of prey, and predators limit the abundance, carrying capacity, and potentially the recruitment of Atlantic menhaden in the Bay. Do planktonic prey resources that are consumed by the diverse community of planktivores limit production, recruitment, and carrying capacity of Atlantic menhaden in Chesapeake Bay?

Indicators/Metrics

Indicators and metrics to evaluate inter-specific competition include:

- Abundances or relative abundances of plankton organisms that serve as prey for consumers, including menhaden.
- Abundances or relative abundances of competitors, including zooplankton grazers (e.g., copepods), jellyfishes, invertebrate filter feeders and pelagic fishes.
- Statistical relationships among key competing organisms and prey.
- Food-web modeling output and predictions.
- Stomach analysis and growth of menhaden (and possibly its competitors).
- Natural and anthropogenic forcing factors affecting the plankton community composition in terms of size and species, such as nutrient enrichment indices and other pollution indicators.

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STOCK ASSESSMENT

Recruitment Variability

Doug Vaughan, Alexei Sharov, and Joe Smith

Recruitment is a function of population fecundity (eggs produced by mature females) and subsequent survival through the early portion of life. Survival through this early portion of life is typically controlled by environmental factors ranging from physical to biological processes. How fecundity is distributed along the coast of the U.S. is related to menhaden annual migration pattern and the maturation and fecundity of adult female menhaden. This information is fundamental to stock assessments. While coastwide migration patterns and maturation schedules are well known, inter-annual variability in migration schedules and in fecundity are less known and potentially could contribute to variability in coastwide and Chesapeake Bay (CB) recruitment success.

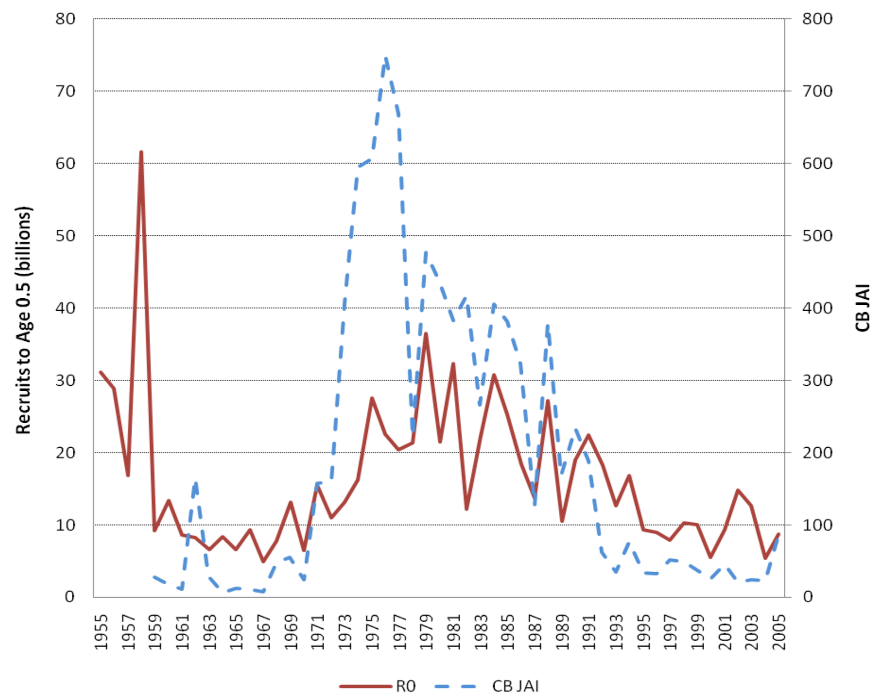

Figure 1. Atlantic menhaden recruitment to age-0.5 (R0) from coastwide model, and Chesapeake Bay juvenile abundance index (CB JAI).

Coastwide estimates of Atlantic menhaden recruitment of juveniles were found to vary by 12-fold during the period 1955-2005 (AMTC 2006). As part of the 2006 assessment, a Chesapeake Bay juvenile abundance index (JAI) was developed from combined Maryland and Virginia seine indices, analyzed using a delta lognormal GLM. This index was found to vary by 113-fold during a somewhat shorter time period (Figure 1). Trends in juvenile abundance (coastwide or within Chesapeake Bay) show a pattern of low recruitment in the 1960s, increasing and high recruitment in the 1970s and 1980s, and declining to low recruitment in the 1990s. Generally low recruitment occurred in the 2000s.

In 2007, the Chesapeake Bay Program adopted an index of Atlantic menhaden recruitment to the Bay based on positive occurrences of Young-of-the-Year (YOY) menhaden in seine hauls in Maryland's portion of the Bay (Maryland striped bass juvenile seine survey data). This index uses the same data as the delta-lognormal- GLM developed by ASMFC (2006), and both indices are strongly correlated with the coastwide age-1 abundance from the ASMFC stock assessments.

Interplay of Spawning, Growth and Migration

A description of menhaden spawning, growth and migration is provided in the Late Life History Brief. The interplay of spawning with geographic location, as mediated by the migration pattern, can result in as many as three seasonal cohorts or spikes in recruitment in the Chesapeake Bay and North Carolina Sounds (Ahrenholz 1991). Because of this interplay between the coastal population and the Chesapeake Bay recruitment component, indices of recruitment of menhaden to Chesapeake Bay do not by themselves represent overall coastwide menhaden recruitment. However, historically the Chesapeake Bay component has contributed a major share of recruits to the coastwide stock. Additionally, the menhaden population stratifies by size latitudinally; larger and older fish are found farther north during the summer months. Thus, any analysis of growth and migration, and its potential contribution to variability in recruitment dynamics, must take this stratification into consideration. Mean abundance, size and age of menhaden in Chesapeake Bay, while not necessarily representative of the stock as a whole, can be important indicators of age structure, growth, recruitment success and production in the Bay. As such, they must be considered when analyzing recruitment variability and developing ecosystem-based approaches for fisheries management in the Bay.

Assessment Spawner-Recruit Models

Factors affecting recruitment to fish stocks in general, and menhaden in particular, can be categorized as either density dependent or density independent. Environmental factors acting on early life stages can control abundance and often are density independent. Density dependence, on the other hand, implies that the current size of the spawning stock can regulate subsequent recruitment and can be described by spawner-recruit models. Stock assessments usually rely on two traditional fisheries models, the Beverton-Holt and the Ricker models, although others are available. The biological implications of the Beverton-Holt and Ricker models are: (1) the Beverton-Holt model assumes recruitment approaches a saturated level as spawning stock increases, with regulation attributed to increasing competition among the young-of-year, (2) the Ricker model assumes that recruitment reaches a maximum level at an intermediate level of spawning stock, and then declines at higher spawning stock due to cannibalism or other negative impact of adult fish on young-of-the-year. Early Atlantic menhaden assessments (e.g., Nelson et al. 1977) favored the Ricker spawner-recruit model, based in part on the argument that filter-feeding menhaden may consume their own eggs. In recent assessments, both Beverton-Holt and Ricker models have been used.

Reproductive capacity of a stock often is modeled using female weight-at-age (spawners in the spawner-recruit model). To the extent that egg production is not linearly related to female weight, indices of egg production (fecundity) are better measures of reproductive output of a stock. This is the case for Atlantic menhaden (Figure 2). Importantly, the relationship for menhaden emphasizes the relative importance of older and larger individuals to population egg production. It can be argued that existing fecundity studies of Atlantic menhaden have under-estimated absolute spawning potential based on debate as to whether menhaden are determinate or indeterminate spawners. Nevertheless, the extant studies of fecundity, conducted on fall or early-winter concentrations of gravid menhaden off the North Carolina coast, are believed to represent the area of probable greatest spawning intensity (Ahrenholz 1991). If growth of recruited menhaden is density-dependent and fecundity is a function of size, there is the potential that a larger, slower-growing year class may produce fewer eggs overall than a smaller, faster-growing year class with individuals of large size.

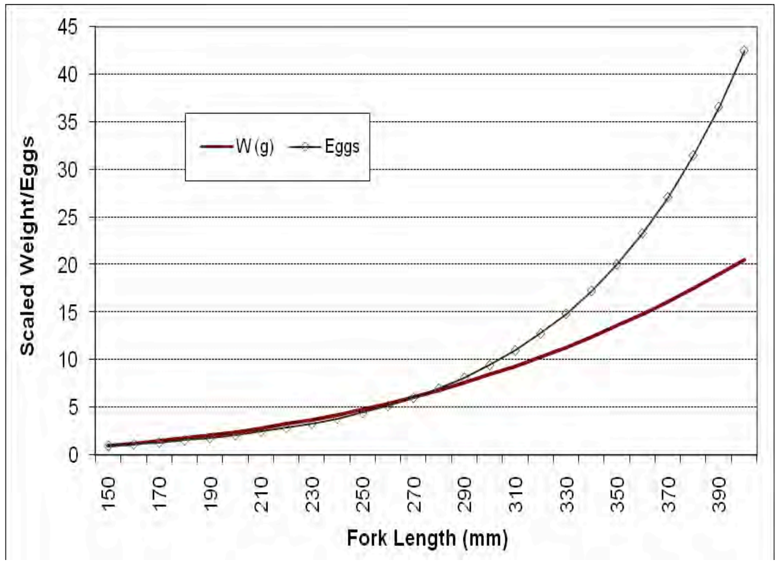

Figure 2. Comparison of weight versus egg production as a function of Atlantic menhaden length.

Typical of many spawner-recruit analyses, an overlayed plot of recruits on adult spawners for Atlantic menhaden demonstrates high variability (poor fit). Myers and Barrowman (1996) warned that, in spite of these poor fits, spawner abundance cannot be ignored in the management of fish populations. To avoid implicitly assuming an underlying spawner-recruit relation for Atlantic menhaden (e.g., Beverton-Holt or Ricker), Vaughan (1993) used a conditional probabilistic approach to forecast coastwide recruitment. Historical estimates of spawners and recruits were each grouped into ranges of low, medium and high based on quartiles ($<25^{th}$, 25^{th}-75^{th}, and $>75^{th}$). This approach suggested that low, medium and high levels of spawners were equally likely to produce low or high coastwide recruitment. This outcome suggested that environmental factors, rather than spawning stock biomass, have primary control over menhaden recruitment. Even when environmental factors exercise the dominant control over recruitment, other factors, e.g., excessive fishing mortality, can reduce spawning biomass and shorten average lifespan, potentially eroding stock productivity and recruitment potential. Declining and poor menhaden recruitment (see Figure 1) occurred during two time periods (1960s and 1990s) when spawning biomass was relatively high and not following an erosion of spawning stock. Compensation for increased removal of spawners by increased egg to pre-recruit survival can occur, but has some upper limit where risk of poor recruitment occurs (Goodyear 1993).

Environmental Factors

Environmental factors that affect recruitment are generally viewed as density independent. These factors include physical processes, for example transport mechanisms, water temperature, dissolved oxygen (DO), freshwater inflow and nutrient loadings. Biological factors, such as amount of food and competition for food, or predation by higher trophic levels which control survival and growth of YOY menhaden prior to recruitment to the fishery, can be either density independent or density dependent.

Physical Processes

Nelson et al. (1977) developed a Ricker spawner-recruit model relating coastwide spawning stock of Atlantic menhaden as number of eggs produced to subsequent recruits. These authors further developed a recruit survival index from the deviations around the Ricker curve, which they then regressed on several environmental parameters. Most significant was zonal Ekman transport, acting as a mechanism for transporting larval menhaden from offshore spawning areas to estuarine nursery grounds. William Schaaf later conducted a retest in the mid-1980s (referred to in Myers (1998). Because one value (1958 year class) had high statistical leverage in the original analysis, the addition of more years diluted the significance of the metric for Ekman transport, thus reducing its statistical significance. Such indices, while valuable in exploratory analysis, often fail in long time series. For example, Myers (1998) reviewed environment-recruitment correlations, finding that "the proportion of published correlations that have been verified upon retest is low."

Wood (2000) investigated synoptic scale climatic forcing of multispecies fish recruitment patterns in Chesapeake Bay. He developed recruitment patterns from five fishery-independent data sets which he then compared to spring climatic variability using a variety of multivariate statistical techniques. He found "that spring conditions in March, brought on by an early appearance of the Azores-Bermuda High, favor recruitment of shelf spawners [i.e., menhaden] while prolonged winter conditions, brought on by relative dominance of the Ohio Valley High, favor spawning success of anadromous fishes." Wood et al. (2004) later fit a modified Ricker model, with days of Azores-Bermuda High in spring months included, and obtained a fairly good fit to the coastwide recruitment time series for Atlantic menhaden. Austin (2002) and Wood and Austin (2009) suggested that a statistically significant regime shift occurred in 1992, when recruitment in anadromous fishes in Chesapeake Bay became favored at the expense of shelf-spawning, estuarine-dependent fishes.

Stone (1976) conducted a series of stepwise regressions on gulf menhaden, *B. patronus,* catch and effort related to a wide range of environmental data (air temperature, water temperature, rainfall, tides, and wind speed and direction). Not unexpectedly, several significant correlations were found including minimum and mean air temperature, maximum water temperature, and wind direction at several locations, resulting in an R^2 value of 0.86. Subsequently Guillory refined much of this work to forecast Louisiana gulf menhaden harvest (Guillory et al. 1983, Guillory 1993). As a congener of gulf menhaden, Atlantic menhaden might be expected to respond to similar environmental factors.

Govoni (1997) demonstrated an inverse relationship between freshwater discharge from the Mississippi River on gulf menhaden recruitment. Subsequent analyses have shown this relationship continues to hold (Vaughan et al. 2000; and subsequent revisiting). This approach was applied to the coastwide recruitment of Atlantic menhaden, using freshwater inflow to Chesapeake Bay from the major rivers in Maryland and Virginia, without obtaining statistically significant results, presumably because the freshwater inflow to Chesapeake Bay does not dominate the coastwide recruitment success of Atlantic menhaden as Mississippi River flow does for gulf menhaden. Although not statistically significant in the Chesapeake Bay, recruitment strength of YOY menhaden in the Bay is negatively correlated with freshwater flow in spring and positively correlated with Secchi depth (Houde and Harding 2009). Overall, recruitment of menhaden to Chesapeake Bay tends to be low in years when late winter-early spring conditions are dominated by climatic patterns characterized by high precipitation and freshwater flow (Kimmel et al. 2009).

Biological Processes

Predation is a process that potentially plays a major role in controlling recruitment level. The role of menhaden in the foodweb is summarized in the Foodweb Issues Brief. Ahrenholz (1991) noted that all life stages of menhaden are potential prey for a variety of predators. Juvenile and adult menhaden are prey to piscivorous fishes (including of course striped bass and bluefish), seabirds and marine mammals. Food and nutrition during the larval and juvenile stages are dependent on amounts and types of available prey and, as such, may serve to control recruitment. As larvae, menhaden eat zooplankton, which are captured as individual particles. As juveniles and adults, menhaden are filter feeders, consuming phytoplankton and zooplankton. Consequently, variability in plankton concentrations in the coastal ocean and in the Chesapeake Bay could affect survival and growth, and be a significant factor controlling or regulating recruitment.

Since 1989, there has been a significant relationship between YOY recruitment of Atlantic menhaden in Chesapeake Bay and annual levels of primary production, especially *chlorophyll-a* biomass (Houde and Harding 2009). Additionally, Love et al. (2006) found a positive correlation between YOY recruitment level and phosphorous loading in Maryland tributaries, suggesting that nutrients and level of primary productivity may be related to menhaden recruitment.

Indices of Juvenile Abundance

Sampling for juvenile Atlantic menhaden by NOAA Fisheries began in 1955 and in the 1970s sampling activities culminated in extensive coastwide trawl surveys conducted through 1978 (Ahrenholz et al. 1989). A four-tributary survey (2 tributaries in North Carolina and 2 in Virginia) was continued through 1986. In those surveys, Ahrenholz et al. (1989) found no significant correlations between the relative juvenile abundance estimates and subsequent fishery-dependent estimates of coastwide year-class strength. In the most recent Atlantic menhaden stock assessment, calibration of the age-structured, forward projection model is based in part on a newly developed coastwide juvenile abundance index. The present coastwide index is based only on state seine-survey indices (ASMFC 2004). These surveys, as recently updated (AMTC 2006), included the North Carolina Alosid seine survey, Virginia Striped Bass seine survey, Maryland Striped Bass seine survey, Connecticut River seine survey, Rhode Island Narragansett Bay seine survey, and New Jersey seine survey.

Initially, catch-per-unit-effort (CPUE) indices for juvenile menhaden were developed from six state seine surveys, using a delta lognormal general linear model. The coastwide index was developed from the state surveys by first combining them within a region (e.g., Virginia and Maryland seine surveys in the Chesapeake Bay region, Figure 1), and then combining them across regions (North Carolina, Chesapeake Bay, New Jersey, and New England) based on regional weightings:

- New England (CT-ME) - 1.8%,
- Middle Atlantic (Coastal MD-NY) - 12.5%,
- Chesapeake Bay (including coastal VA) - 68.8%,
- South Atlantic (FL-NC) - 16.9%.

The heaviest weighting is given to the Chesapeake Bay. These weightings were derived from estuarine and fluvial drainage areas along the Atlantic coast (%EDA), combined with menhaden productivity of streams along the Atlantic coast from data collected in the 1970s by the Beaufort Laboratory (Ahrenholz et al. 1989). The resultant percentage weightings reflect the amount of estuarine area adjusted for relative YOY menhaden production.

The 69% contribution to recruitment from Chesapeake Bay is based in part on the coastwide study of stream productivity in the 1970s reported by Ahrenholz et al. (1989). Although Chesapeake Bay has served and is likely to continue to serve a major role in providing recruits to the coastwide Atlantic menhaden population, other areas can and have provided substantial recruitment. Changing environmental conditions such as global warming could shift the center of menhaden productivity latitudinally. The Chesapeake Bay-specific seine indices for juvenile menhaden abundance provide a clear picture of strong inter-annual variability in abundance of young menhaden within the Bay, although they cannot be relied on as predictors of coastwide recruitment. The present, two-decade period of low recruitment to Chesapeake Bay is an issue of concern and has fueled the debate over menhaden wellbeing, "localized depletion," and management of the fishery in Chesapeake Bay.

Issues

The primary issue concerning recruitment variability is the poor understanding of how environmental factors affect recruitment of young menhaden to the adult stock. These environmental factors include physical and biological processes. Additionally, it is not known how reproductive strength (spawning stock) interacts with environmental factors to regulate recruitment success, either coastwide or in the Chesapeake Bay. Developing metrics and indices applicable to the Chesapeake Bay that describe or predict recruitment variability in the Bay will be a challenge. The issue has coastwide implications because of the heavy weighting given to the recruitment contribution from the Bay to the coastwide stock.

Indicators/Metrics

Metrics and other possible indicators are needed to define and quantify the physical and biological processes discussed above.

- Indices that describe, depict, or summarize physical processes related to climate, weather, and water quality have, to some extent, been investigated but more research is needed.

- Indices based on the foodweb and menhaden food preferences could be developed that attempt to characterize varying YOY abundance and relationships with respect to phytoplankton and zooplankton available.

- Investigations of the effect of predation by three important piscivores (striped bass, bluefish and weakfish) are being conducted as an ongoing project by ASMFC. A peer-reviewed, multi-species virtual population analysis (MSVPA-X) incorporated predation data and developed age-specific estimates of predation mortality on menhaden (NEFSC 2006). Input data were recently updated, and results will be used to improve age-varying and, hopefully, year-varying, natural mortality in a new peer-reviewed stock assessment for Atlantic menhaden. To date, the model has not been used by ASMFC to derive reference points for management of Atlantic menhaden, nor has it been considered with respect to assessment or management of menhaden within Chesapeake Bay.

- A Chesapeake Bay Fisheries Ecosystem Model (CBFEM) has been prepared using the Ecopath with Ecosim (EwE) approach and software (Christensen et al. *in press*). The CBFEM has potential to predict productivity and recruitment of Atlantic menhaden in the Chesapeake Bay. The CBFEM was created in response to a management need in the Chesapeake region for a quantified estimation of trophic pathways to understand how taxa affect one another within the foodweb and how the Bay fisheries impact both target and non-target species. Currently, the EwE model includes 45 functional groups of organisms (including Atlantic menhaden), representing all trophic levels.

- Maryland and Virginia seine indices for juvenile menhaden provide a direct metric of recruitment of menhaden to the Chesapeake Bay, and may be indicative of local environmental problems associated with the Bay or with offshore processes that deliver larvae to the Bay. Historically, the Bay has been the major contributor of recruits to the coastwide adult stock. While YOY recruitment variability in the Bay does not necessarily reflect the status of coastwide recruitment, it is an important element in developing Bay-specific and coastwide management strategies.

- Another suggested metric related to recruitment level is mean size of age-0 menhaden in the reduction fishery within the Bay during fall. Because of density-dependent growth, mean size is expected to be inversely related to YOY abundance during the fall months. The relationships between YOY density-dependent growth and possible compensatory survival and recruitment need to be investigated.

Exploitation

Doug Vaughan, Joe Smith, Alexei Sharov, and Jim Uphoff

The menhaden fishery and its history are described in greater detail in the biological background brief: The Atlantic Menhaden Fishery. In summary, fishing for menhaden has been conducted since colonial times, but the use of purse seines was initiated in New England by the mid-nineteenth century. The purse seine fishery spread south to the Mid-Atlantic States and the Carolinas by the late 1800s. Peak landings of >700,000 tons occurred during the 1950s, apparently supported by several exceptionally large year classes. Currently, one reduction plant with 10 purse seine vessels remains, and is located on Chesapeake Bay near the mouth of the Potomac River at Reedville, VA. There is also a significant bait fishery dominated by so-called snapper rigs (small purse-seine gear) in Virginia, New Jersey, and Rhode Island. Since 2000, total landings of Atlantic menhaden have ranged from 184,000 to 270,000 metric tons, averaging 209,000 metric tons. Of these landings, about 82% are from the reduction fishery and the remaining 18% from the bait fishery.

Biostatistical Sampling of Menhaden

Detailed landings information at the menhaden reduction plants have been reported since 1940 and biostatistical samples of the catches have been continuously collected since 1955. Because the reduction fishery presently is conducted by a single company, much of the data specific to Chesapeake Bay is proprietary and not easily available. As the directed bait fishery for menhaden has grown in recent years, greater emphasis has been placed on acquiring more representative port samples and more accurate landings records from this segment of the fishery. Deck logbooks (Captain's Daily Fishing Reports, or CDFRs) maintained by menhaden reduction vessels have helped to reduce some sampling biases inherent in harvesting menhaden on distant fishing grounds.

Regionally and over the past two decades, the bait harvest in the Chesapeake Bay region has averaged 42% of all coastal bait landings. Menhaden landed for bait are primarily of ages 1, 2 and 3. Since 2000, bait landings in other regions were declining, although they have increased in the last two years (2007-2008). Since 2000, bait landings in the Chesapeake Bay region accounted for 61% of coastal menhaden-for-bait landings, ranging between 14,500 and 29,000 metric tons. Over the same period, landings of menhaden-for-bait in the Mid-Atlantic, South Atlantic, and New England regions accounted for 32%, 2%, and 4% of the total coastwide bait landings, respectively.

Age-composition of catches by the reduction fishery from four geographic areas are estimated annually, 1955 to present. Age distributions by area based on biostatistical sampling of reduction landings since 1990 are compared in Figure 3. Modal age is 2 for all but the New England area, which has a modal age of 3. So- called "peanuts" (age 0) menhaden were landed in substantial amounts only in the South Atlantic area. Age-1s are landed mostly in the South Atlantic and Chesapeake Bay. Age 2 menhaden dominate the reduction fishery landings in Chesapeake Bay. Older menhaden (age 4+) are landed mostly in New England and Mid-Atlantic areas.

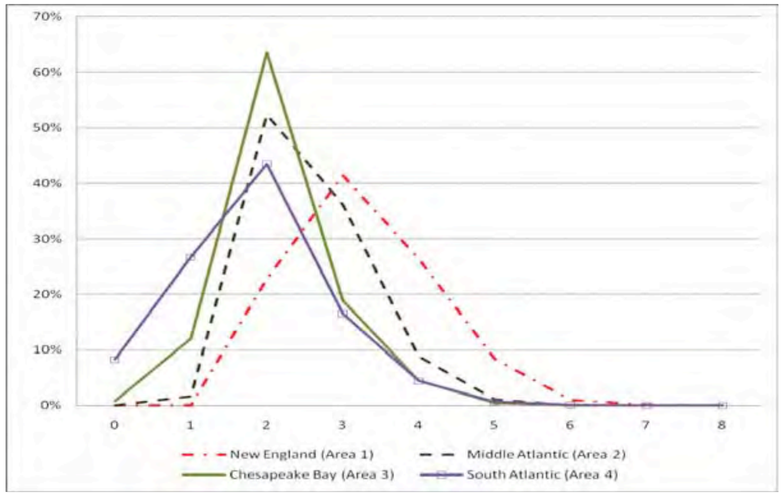

Figure 3. Age-composition of Atlantic menhaden reduction landings from four geographic areas for the period 1990-2006.

Results from Latest Assessment

The latest stock assessment on Atlantic menhaden was conducted in 2006 (AMTC 2006). This assessment was conducted at the stock (coastwide) level, and suggests a general decline in fishing mortality from a peak in 1965, when the menhaden population was very low, to the terminal assessment year (2005) (Figure 4). The stock rebuilt during the 1970s and 1980s, and then declined during the 1990s and early 2000s. The decline in fishing mortality shown here is largely attributable to the consolidation of the reduction industry and closure of plants along the coast for various socio-economic reasons (see Socioeconomics Brief). Fishing effort, as measured in a variety of ways (traditional vessel weeks, trips, or sets), has declined considerably over the last 20+ years.

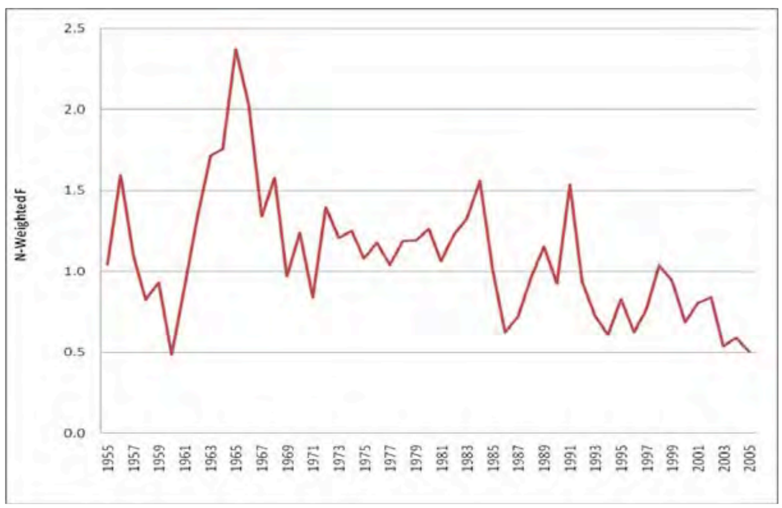

Figure 4. Atlantic menhaden fishing mortality rate (F) from coastwide model, 1955-2005.

Natural mortality (*M*) is not assumed to be constant across ages in the most recent Atlantic menhaden stock assessment. This major improvement allows *M* to vary by age and was first applied to the Atlantic menhaden assessment conducted in 2003 (ASMFC 2004). Age-varying estimates of *M* were developed from the peer-reviewed multi-species virtual population model (MSVPA-X) under development by ASMFC. In this model, menhaden natural mortality is decomposed into background natural mortality (M_1) and that due to predation by three predatory fishes (M_2; striped bass, bluefish, weakfish). Declining natural mortality of menhaden with age is modeled as age-selective mortality generated by predation attributable to these three piscivores. New estimates of year- and age-varying estimates of *M* have been developed for the peer-reviewed coastwide stock assessment currently underway through the SEDAR process (SEDAR is the South East Data Assessment and Review process through NOAA Fisheries Southeast Fisheries Science Center, SEDAR 20 is an assessment and review underway for Atlantic menhaden, www.sefsc.noaa.gov/sedar/). The annually-averaged values in the present stock assessment are:

Age	0	1	2	3	4	5	6
Average	1.066	0.806	0.614	0.521	0.476	0.446	0.425

To date, the MSVPA-X model has not been used explicitly in a process to develop or derive reference points for management of the Atlantic menhaden stock.

Total mortality (*Z*) may be more relevant than fishing mortality (*F*) for a forage species in understanding the current status of the stock. Because $Z = M+F$, *F* and *M* must be considered annually. Thus, age-varying *M*, the natural mortality primarily attributable to inter-annual variability in age-specific predation on menhaden, is treated in a manner comparable to *F*; that is, each age is weighted by the estimated landings in numbers for that age (*N*-weighted). Because the coastwide fisheries for menhaden remove primarily ages 2 and older, these ages are included when computing *N*-weighted *F* and *M* for each year, 1955-2005. The two variables (*Z* and *F/Z*) show similar trends over the assessment period, generally declining since a peak in the mid-1960s (Figure 5) and indicating a general decline in exploitation rate of age 2+ menhaden in the coastwide fishery.

"Localized Depletion"

The argument for "localized depletion" arises from the concern that Atlantic menhaden removals from Chesapeake Bay are excessive and compromise the ability of menhaden to fulfill its ecosystem services, which are its forage and nutrient-cycling roles. Addendum II to Amendment I of the Atlantic Menhaden Fishery Management Plan (ASMFC 2005) defined the potential for "localized depletion" in Chesapeake Bay as a result of concentrated harvest. Not considered in the definition were increased predation and putative changes in water quality that might impact recruitment (see Predation and Water Quality Briefs) and could contribute to "localized depletion." The ASMFC's

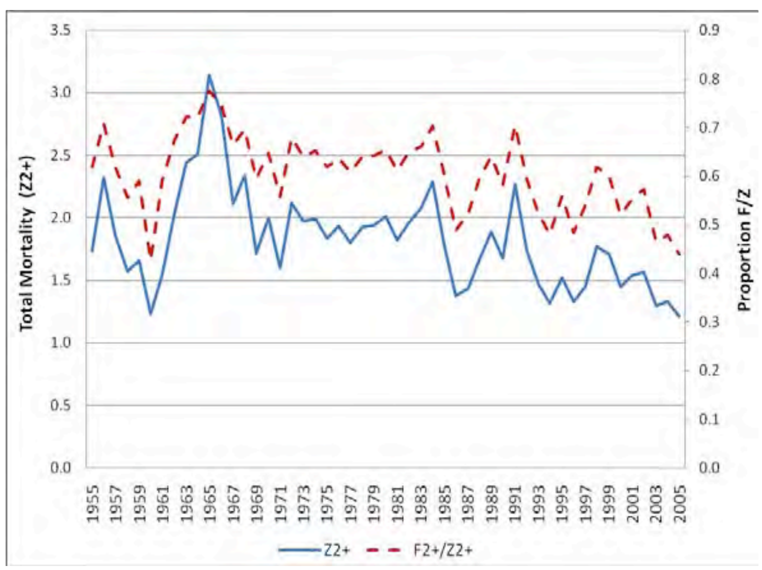

Figure 5. Atlantic menhaden total mortality (Z) and ratio of fishing to total mortality (F/Z) from coastwide assessment, 1955-2005.

Menhaden Technical Committee submitted the following definition for the Atlantic Menhaden Board's consideration following their meeting of 21 September 2007:

> Localized depletion in the Chesapeake Bay is defined as a reduction in menhaden population size or density below the level of abundance that is sufficient to maintain its basic ecological (e.g. forage base, grazer of plankton), economic, and social/cultural functions. It can occur as a result of fishing pressure, environmental conditions, and predation pressures on a limited spatial and temporal scale**.**

This non-quantitative definition provides a general sense of the issue but no metric by which to judge its level or severity. Possible outcomes of "localized depletion" have been suggested, including compromised predator-prey relationships (e.g., resulting in lower quality striped bass and bluefish angling), reduced nutrient cycling, and chronic low recruitment via larval ingress of menhaden to the Chesapeake system (ASMFC 2005).

To understand the potential effects of the harvest of menhaden from within the Chesapeake Bay on the total population, it is important to understand menhaden stock structure along the U.S. Atlantic coast (see Connectivity Brief). There is strong evidence that menhaden is a single migratory stock, and is not composed of discrete populations along the U.S. Atlantic coast. Migration in spring brings age 1+ menhaden north and a portion of the stock into the Chesapeake Bay. Not all migratory schools of menhaden enter the Bay at a single time, but they enter over the course of the spring and summer months. Similarly, migration in the fall and early winter brings age 1+ menhaden south past Chesapeake Bay. Spawning outside the Bay at this time will contribute menhaden larvae that ingress into the Bay. The purse-seine fishery is limited to Virginia waters of Chesapeake Bay during summer and fall. Consequently, not all menhaden are susceptible to capture by the fishery. Still, concentrated fishing in Virginia waters could lead to lower local abundance, at least temporarily, in that part of the Bay.

Because the current stock assessment provides population estimates only at the coastwide level, it is not designed, nor is data currently available, to provide estimates of the menhaden abundance or biomass within Chesapeake Bay. There are estimates of the removals by age of menhaden in the reduction and bait fisheries from within Chesapeake Bay (and coastwide), but exploitation estimates (*F/Z*) are available only for the coastwide stock, and cannot be estimated for the Chesapeake Bay at this time. Trends in abundance of age 1-3 menhaden have been documented in the Potomac River pound net fishery that are believed to be representative of abundances in the river and the mainstem Bay where the reduction fishery operates. But, no estimates of exploitation rate are available for the Bay.

To provide information on "localized depletion" and other issues, a special meeting of the ASMFC Menhaden Technical Committee was held in June 2004 to develop research priorities for menhaden research. The Committee recommended the following four research priorities:

- Determine menhaden abundance in Chesapeake Bay
- Determine estimates of removal of menhaden by predators
- Exchange of menhaden between bay and coastal systems
- Larval Studies (determining recruitment to the Bay)

To address concerns over “localized depletion,” the Atlantic Menhaden Management Board (Board) approved Addendum III to Amendment 1 to the Interstate Fishery Management Plan (FMP) for Atlantic Menhaden in 2006 (ASMFC 2006). Addendum III established a five-year annual cap on reduction fishery landings in the Chesapeake Bay. It based the cap on the mean reduction landings from Chesapeake Bay for the most recent five years (2001-2005). The harvest cap of 109,020 metric tons is in place for 2006 through 2010.

Issues

“Localized depletion” in Chesapeake Bay has not been defined formally or quantified by scientists and managers. Atlantic menhaden in Chesapeake Bay consume and redistribute large amounts of energy and materials throughout Chesapeake Bay and the continental shelf, support major fish and avian predators in the Bay, provide a large share of recruitment to the coastwide population, and constitute its largest fishery. These functions are acknowledged by managers, but have not been indexed or quantified in a manner that transparently defines whether these roles are being met within Chesapeake Bay. An explicit strategy for allocating menhaden among competing sectors in Chesapeake Bay has not been developed. This deficiency is largely because only a portion of the stock is found within Chesapeake Bay, and estimates of standing stock within Chesapeake Bay are unavailable. Consequently, metrics for exploitation that are representative of Chesapeake Bay presently cannot be determined. At the coastwide level, estimates of F and Z are available from stock assessments, and the ratio F/Z can be estimated as well.

Indicators/Metrics

- Indices and estimates of abundance of age 1+ menhaden are needed for Chesapeake Bay.

- The Potomac River pound net catch and effort data provide an index of age 1+ menhaden abundance, but not exploitation rate.

- The ASMFC and Maryland DNR have conducted proof-of-concept research testing LIDAR technology. LIDAR, combined with aerial videography, has the potential to provide, at least, indices of abundance.

- There is a need for more spatially-explicit data to understand relationships between menhaden and their environment within Chesapeake Bay. The Captain’s Daily Fishing Reports (CDFR), collected from the reduction fishery, include purse-seine set information that contains spatial information, especially for the last few years. Biostatistical collections can be related to the final set of a trip when sampled, providing spatially-explicit information on age and size of menhaden caught in the reduction fishery. Limited detailed information presently exists for the bait fishery, but additional data would be an asset.

- Spatially-explicit information is desirable for environmental factors that potentially control menhaden distribution and abundance in the in the Virginia portion of Chesapeake Bay. As suggested in the Recruitment Brief and elsewhere, long-term data sets on water quality and plankton communities exist for the Chesapeake Bay. These could be explored with respect to YOY and adult menhaden distributions.

- Natural mortality rate (*M*) of forage fishes such as menhaden can vary inter-annually, subject to abundance of major predators and their demand for prey. It has been recommended that management of forage species be referenced to total mortality rate, adjusting fishing mortality rate periodically to account for inter-annual variability in predator abundance and the mortality they generate (Collie and Gislason 2001). An annual index of predator abundance and predatory demand, if available for Chesapeake Bay, could be used to consider appropriate levels of fishing effort and landings that would conserve the ecosystem services of menhaden, while providing a reasonably high yield to the fishery.

- The multispecies model (MSVPA-X), referenced above, has been developed for Atlantic menhaden on a coastwide basis and is used to adjust age-specific, natural mortality rates. Expanding the use of such models in spatially-explicit mode and as a means to develop reference points for management is worthy of consideration for the Chesapeake Bay fishery. The lack of abundance estimates for menhaden in the Bay is a constraint on developing this approach.

- ASMFC recently issued a report describing the development and use of reference points (McKown et al. 2008). Their purpose was to provide "a useful and concise guide to ASMFC technical committee members and other fisheries scientists conducting stock assessments in their efforts to determine reliable indicators of stock status." The McKown et al. (2008) guide will be useful for QETs as they work to develop appropriate and relevant reference points for EBFM of menhaden and other species in Chesapeake Bay.

- In the development of management advice, recommendations of Froese (2004) should be kept in mind as we move toward EBFM. These "common sense" rules include allowing every fish at least one replacement spawning, only allowing fish to be harvested at a target size where maximum biomass per year-class occurs, and allowing for sufficient survival of older spawners (Froese 2004).

- Other indicators and reference points may have merit. For example, Patterson (1992) empirically reviewed exploitation and changes in stock biomass of small pelagic fishes and found that *F* levels in excess of $0.67M$ were often associated with stock decline, while *F* below this level was associated with stock stability or recovery. Fishing rates equal to *M* for shoaling pelagic fishes with life-history attributes similar to menhaden were often unsustainable, while those $<0.5M$ allowed for stock rebuilding (Patterson 1992). These recommendations seem to be clear, but questions will arise if this approach is considered when *M* varies with age, as it undoubtedly does in menhaden, and has been accounted for in the ASMFC stock assessment. Also, a decision to delay fishing until older ages, i.e., following the advice of Froese (2004), will reduce *F* on younger fish but may result in higher *F* on older fish in the process of maximizing "biomass per year-class." Despite these technical issues, insights provided by Patterson (1992) can be useful as QETs debate appropriate approaches to develop EBFM reference points.

Disease/Fill Kills

RaeMarie Johnson and Kevin Friedland

Fish Kills — Overview

Reports of fish kills involving Atlantic menhaden (*Brevoortia tyrannus)* have been recorded for over a century. These fish kills have historically been associated with low oxygen levels, however in recent years, fish kills along the eastern seaboard of the United States involving Atlantic menhaden have attracted a more intense interest (for review see Dykstra and Kane 2000). The cause of these fish kills has been the source of much research and debate for over a decade (Burkholder et al. 1992; Kane et al. 1998; Blazer et al. 1999; 2000; Dykstra and Kane 2000; Noga 2000; Law 2001; Glasgow et al. 2001; Vogelbein et al. 2001; Kiryu et al. 2002; Burkholder et al. 2005). Fish kills occurring in the Chesapeake region in the 1970's where Atlantic menhaden exhibited a spinning behavior were shown to be caused by a viral agent (Stephens et al. 1980). Fish kills resulting from skin lesions have been reported in menhaden since 1984 (Levine et al. 1990a) and are identical to other ulcerative diseases seen across the world, and now collectively termed epizootic ulcerative syndrome (EUS).

Dissolved Oxygen

Estuaries, such as those inhabited by menhaden, are often characterized by large fluctuations in dissolved oxygen and are particularly noted for their development of hypoxia (Burnett 1997). For example, in Chesapeake Bay, extensive summer oxygen depletions occur, decreasing the ability of the Bay to support fisheries resources. From June 16 - August 21, 1998, oxygen levels were monitored at a depth of 4m at a site located on the western shore of the Maryland portion of Chesapeake Bay. During this time period, oxygen levels in the Bay fell below 4 mg/L on 81% of the days and below 2 mg/L on 45% of the days. These oxygen depletions can occur rapidly, with levels dropping as much as 6mg/L in 4 hours (Breitburg 1990). Paerl et al. (1998) noted that reported fish kills of menhaden "appeared to reflect the magnitude, area coverage and duration of hypoxia and anoxia events." Menhaden are also known to induce fatal hypoxic events. Oviatt et al. (1972) demonstrated that schools of menhaden can have a marked effect on surrounding waters, including decreased oxygen levels. A large fish kill documented off North Carolina in December of 1997 was attributed to menhaden school-induced low oxygen levels (Smith 1999). Reports of such school-induced hypoxia and resulting fish kills go back to the 1800's.

Lesions

The characteristic and common skin lesions in menhaden are often located near the anus, and appear as deeply penetrating circular lesions with extensive necrosis and tissue loss. These lesions are caused by the fungus *Aphanomyces invadans*. Its oomycete hyphae often penetrate the visceral organs of infected fish and a suite of bacteria and other saprophytic water molds usually co-occur as secondary invaders (Noga and Dykstra 1986; Noga et al. 1988; Levine et al. 1990b; Blazer et al. 2007).

The occurrence of this disease in menhaden has been termed ulcerative mycosis (UM). Lesions such as those described have been reported in menhaden since 1984 (Levine et al. 1990a) and are identical to other ulcerative diseases seen across the world, which are now collectively termed epizootic ulcerative syndrome (EUS). EUS was first recognized in the 1970s in farmed ayu (*Plecoglossus altivelis)* and has since spread across Asia and Europe affecting numerous estuarine species such as snakehead (*Channa striatus*), grey mullet (*Mugil cephalus*), and ayu (Lilley et al. 1998). EUS is caused by *Aphanomyces invadans,* which invades the dermis presenting initially as petechia — minute hemorrhages on the body surface. Once established, the water mold continues to invade, causing small circular lesions that continue to develop into large necrotic ulcers (Lilley et al. 1997).

Other organisms may be involved in ulcer disease, either as primary or secondary invaders. The sporozoan *Kudoa clupeidae* has been reported as present in, and contributing to, lesions in YOY menhaden (Reimschussel et al. 2003). Additionally, mycobacteriosis (*Mycobacterium* spp.), common in striped bass, also reportedly has been isolated from ulcerative lesions in menhaden (Stine et al. 2005).

During 1997, the dinoflagellate *Pfiesteria piscicida* was implicated in several small fish kills, outbreaks of lesions in menhaden, and adverse human health effects in Maryland portions of Chesapeake Bay (Grattan et al. 1998). However, conclusive evidence that *Pfiesteria* is the cause of fish kills and ulcerative lesions on menhaden has not been found (Dykstra and Kane 2000).

Recently, another dinoflagellate, *Karlodinium spp*., has been shown to possess ichthyotoxic properties (Tango and Butler 2006) and is now thought to have played a primary role in fill kills (mostly involving menhaden) in Chesapeake Bay from 1998 to 2002 (Goshorn et al. 2004). Menhaden in fish kills are often seen possessing ulcerative lesions and presence of these lesions has been used in the past as an indicator of the presence of toxic dinoflagellates. This association is still under debate and much research has been conducted concerning the etiology of the lesions seen.

In a review article, Noga (2000) discussed risk factors that have been shown to damage the epithelium and possibly play a role in the development of skin ulcers (defined as the loss of epidermis). These included environmental factors such as hypoxia, ultraviolet radiation, salinity fluctuations, and changes in water temperature, which are common in estuarine environments. Little research has been done on possible relationships between ulcerative mycosis and environmental stressors, but there has been some investigation into relationships between EUS and environmental factors and disease events which appear to be "triggered" or promoted by certain environmental conditions such as temperature, salinity and hypoxia.

The theory that environmental stress can trigger outbreaks of infectious diseases in fish populations (Meyer 1970, Wedemeyer 1970, Snieszko 1974) is based primarily on the coincidence of stress with outbreaks of infectious diseases (Snieszko 1974). There is still much to be learned about the relationship between the stress response of the fish and the subsequent increase in its susceptibility to disease (Pickering and Dunston 1983). At the present time, tolerances to specific stressors are not well defined for most species, including menhaden, even with those stressors that occur singly. This problem is complicated further by the fact that fish populations are normally exposed to many stressors (Wedemeyer and Goodyear 1984).

Issue

The relative magnitude of disease and fish kills with respect to other sources of natural mortality of Atlantic menhaden, coastwide and in Chesapeake Bay, is unknown. Increased mortality of menhaden will have a range of ecological effects including reducing the prey base for striped bass, which may result in increased mycobacteriosis infections in striped bass and increasing the occurrence of algal blooms due to reduced menhaden grazing, leading to eutrophication in our waterways. However, the reduction in menhaden abundance attributable to a disease outbreak would be very difficult to quantify (Vaughan et al. 1986). Vaughan et al. (1986) suggested that "only truly catastrophic reductions in year class abundance (>70%) … are likely to be detected." This results in part from the large annual variability in indices of abundance.

Regardless of the magnitude of disease-related or environmentally-related mortality factors, they remain a concern due to the public health threat with which they are associated. Research is needed to address multiple concerns, including determination of causes of menhaden disease and fish kills, effects of these diseases and fish kills on the menhaden population, and effects of reduced menhaden population size on other species and water quality.

Indicators/Metrics

- The proportion of natural mortality (*M*) due to disease/fish kills events in menhaden will be difficult to ascertain as noted in Vaughan et al. (1986).

- In spite of real concerns about sampling bias and reported lesions, general trends in disease occurrences can give a sense of whether there is a serious problem.

- Natural and anthropogenic forcing factors affecting the occurrence of disease and fish kill conditions, such as nutrient enrichment indices, hypoxia, and other pollution indicators should be identified and monitored.

Connectivity and Regional Abundance

Joe Smith, Alexei Sharov, and Cynthia Jones

Exchange between Ocean and Chesapeake Bay Component

Much of what is known about exchange and connectivity of Atlantic menhaden between the Atlantic Ocean and Chesapeake Bay has been derived from tagging experiments conducted by the NMFS Beaufort Laboratory during the 1960s and 1970s. Nicholson's (1978) seminal paper on movements and population structure of Atlantic menhaden left little doubt that a single population exists on the U.S. East coast, and that menhaden stratify by size and age along the coast during late spring and summer. As menhaden grew older, the number of tag recaptures decreased in southern latitudes and increased in northern latitudes. Nicholson (1978) also provided several qualitative insights on movements into and from Chesapeake Bay. Adults tagged in south Atlantic areas were recovered in subsequent years in the Chesapeake Bay and off New Jersey and New York. Adults tagged in Chesapeake Bay were recovered off New Jersey to New England, while adults tagged off New Jersey were recovered off New Jersey to New England and also in Chesapeake Bay. Nicholson (1978) reported that movements of fish (adults) northward from south of Cape Hatteras, North Carolina, probably ceased in June. However, Kroger and Guthrie (1973) reported some movement of tagged age-1 fish from the South Atlantic into Chesapeake Bay through mid-summer.

Dryfoos et al. (1973) made additional comments about movements of fish to and from Chesapeake Bay, their observations being of a more seasonal nature. Some menhaden tagged in North Carolina in early spring were recovered in Chesapeake Bay as early as May. Some fish tagged in Maryland and Virginia in April and May appeared in New Jersey catches by June; movement slowed through spring, and there was little movement between these two areas after June. Only a few fish tagged in spring in the Maryland portion of Chesapeake Bay moved northward. Fish from the Chesapeake Bay enter the North Carolina fall fishery before the end of November. Recently, genetics research by Anderson (2007) and Lynch (2008) provided additional support for the single stock hypothesis.

Overall, menhaden movements can be summarized as follows. During the warm season (April – October) menhaden are distributed along the coast from Florida to Maine, the larger and older the fish are, the further North they are found. By the end of fall, fish of all ages migrate to the South Atlantic (south of Cape Hatteras) forming a mixed overwintering population. At the end of winter, menhaden begin a northward migration, repopulating coastal areas on their way, including Chesapeake Bay, and stratifying by size and age. Thus, the Chesapeake Bay is repopulated each year by menhaden of variable ages (primarily age-1 through age-3) that were residents of Chesapeake Bay as well as coastal areas south and north of Chesapeake Bay in the previous year. Consequently, the population abundance in Chesapeake Bay in any given year is comprised of fish of various origins, with fish from the South Atlantic and Chesapeake dominating in the Bay's mixed stock. However, little is known about the migration in and out of Chesapeake Bay during summer when intensive fishing by reduction and bait fleets occurs.

Contributions to the Coastwide Stock from Chesapeake Bay

The proportion of juvenile Atlantic menhaden that recruit from major estuarine systems along the U.S. East coast into the coastwide stock is unknown, although the Bay is a major contributor. The coastwide juvenile abundance index used to calibrate the age-structured forward projection model in Atlantic menhaden stock assessments (ASMFC 2004; AMTC 2006) employs state seine-survey indices for YOY menhaden from NC, VA, MD, CT, and RI. Catch-per-unit-effort (CPUE) indices are regionalized, standardized, and then averaged (see Recruitment Variability Brief for regional weightings). The percentages reflect the amount of estuarine area adjusted for relative menhaden production. These results suggest that Chesapeake Bay has contributed on average about 69% of the recruits to the coastal stock. However, estimates of tributary and estuarine productivity (expressed in terms of juvenile menhaden; Ahrenholz et al. 1989) are decades old, and clearly more contemporary estimates of estuarine productivity relative to menhaden recruitment are needed.

Studies at Old Dominion University (C. Jones, unpublished data, Old Dominion University, Norfolk, VA) seek to document the contribution of Chesapeake Bay-derived recruits to the coastal stock. Researchers are in the process of using the distribution of natural chemical tags in otoliths to quantify the contribution of Chesapeake Bay recruits to the total coast-wide population. Otolith chemistry from previous studies of several species has shown that Bay waters impart distinct chemical tags to fish otoliths that can be distinguished from other estuaries (Thorrold et al. 2001).

The ingress of larval Atlantic menhaden to Chesapeake Bay, primarily in late fall to early spring, from spawning by migratory adults in the coastal ocean also serves to link the Chesapeake Bay component to the coastwide stock. In this way, the migration of adults, spawning, juvenile utilization of the Bay as a nursery, and recruitment to the coastwide stock are all connected in critical ways that have implications for management of the menhaden resource.

Mixing among Tributaries within Chesapeake Bay

Otolith chemistry is also being used to show the extent of mixing by YOY menhaden between areas of the Bay and individual tributaries. If individuals mix between the areas and tributaries, they will share the same chemistry. If chemistries differ, then menhaden from areas and tributaries of the Bay have remained separate. Research has shown that otolith chemistries of YOY menhaden are distinct to each tributary and distinguishable between areas of the Bay (C. Jones and J. Schaffler, unpublished data, Old Dominion University, Norfolk, VA). The results indicate that there is little or no mixing by YOY menhaden once in the Bay and that YOY menhaden remain resident in their nursery habitat through the first year of life.

Regional Abundance

Despite the longevity and coastwide nature of the Atlantic menhaden fishery, indices of coastal and regional abundance for adult menhaden are generally unavailable. In fact, developing such indices for Atlantic menhaden has been labeled a high priority research item by the Atlantic Menhaden Technical Committee (AMTC 2004). The usual CPUE indices of relative abundance from purse-seine fisheries often are not reliable because of biases in fisheries that utilize spotter aircraft (Clark and Mangel 1979). The lone Chesapeake Bay index of "adult" menhaden abundance available to assessment scientists has been the Potomac River Pound Net (PRPN) Index (ASMFC 2004; AMTC 2006). A pound net is a stationary fishing gear. The index is the CPUE for each year, which is the annual catch reported by all license holders divided by number of pound net fishing days.

The PRPN time series began in 1964 and is believed to be an index of relative abundance of primarily ages-1-3 menhaden abundance in the Potomac River and Chesapeake Bay. The PRPN Index was used to tune the most recent update of the Atlantic menhaden stock assessment (AMTC 2006). This index value generally declined through the 1980s and 1990s, but appears to have increased since 2000 (Figure 6). The index has potential to be applied as one measure to judge possible "localized depletion" in Chesapeake Bay.

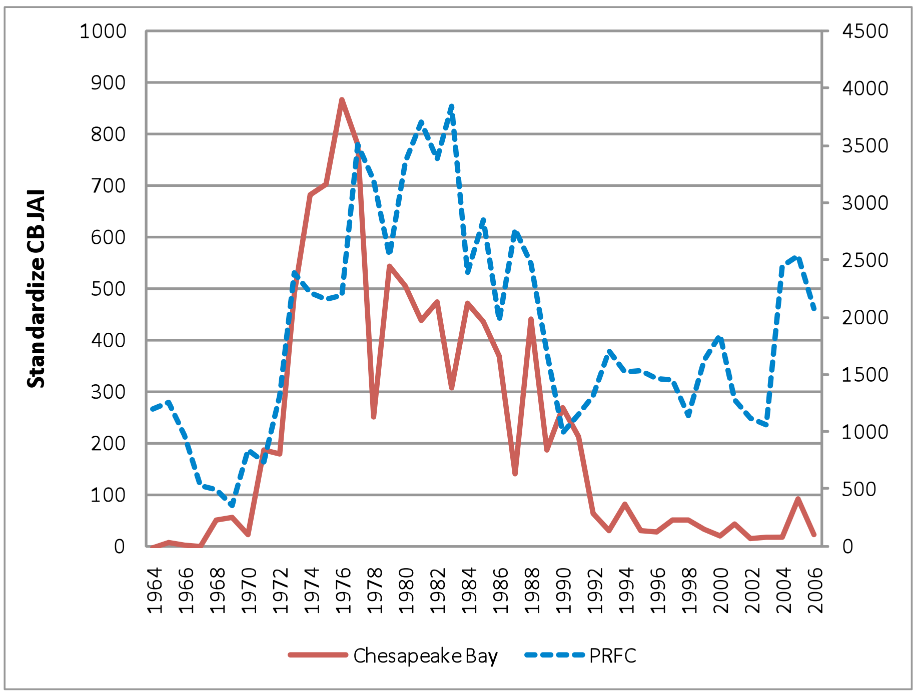

Figure 6. Comparison of standardized Juvenile Abundance Index for Chesapeake Bay from MD and VA seine surveys and Potomac River Fisheries Commission pound net index (C/days fished), updated from most recent Atlantic menhaden stock assessment (ASMFC 2006).

Absolute abundance estimates for Chesapeake Bay are not available, primarily because of migratory movements and lack of immigration and emigration estimates. Testing of LIDAR and video survey methodology to estimate abundance of Atlantic menhaden in Chesapeake Bay is currently underway. While a LIDAR signal is capable of penetrating Chesapeake Bay waters and detecting menhaden schools in the 5-15 m depth range, it has difficulty measuring the depth component of the schools themselves because of the dense packing of schooling menhaden. An airborne video survey is a less expensive alternative, but the survey success is very sensitive to survey conditions (wind, sun glare, cloud cover, and waves) and is likely to produce a relative, rather than absolute, measure of population abundance because of visibility limitations (only schools near the surface can be detected with the video method).

Issues

Understanding connectivity will help to address the "Localized Depletion" issue (see Stock Assessment Brief, Exploitation). The degree of isolation of the Chesapeake Bay component of the coastwide stock and its rate of exchange and replacement with fish from the coastal ocean is at issue. The concern raised by the "localized depletion" argument is that although the coastwide menhaden stock is not depleted, large removals from Chesapeake Bay may have a substantial effect on abundance in the Bay and on the ecosystem services provided by menhaden in the Bay. The extent to which subareas such as Chesapeake Bay are isolated from others (lack of connectivity) will have consequences for the localized impact of fishing. The migratory menhaden stock is highly connected among coastal regions and embayments, including Chesapeake Bay. With respect to "localized depletion," the question reduces to the time-dependence and magnitude of exchange rate of menhaden between Chesapeake Bay and the larger coastal component of stock. The issue is of most concern during the May to November period when the reduction fishery is conducted. The lack of age-specific estimates of menhaden abundance in the Bay is an impediment to understanding connectivity at the regional scale where "localized depletion" is of greatest concern.

A second issue related to connectivity is the nearly 20 years of low recruitment of YOY menhaden to Chesapeake Bay. The coupling between offshore distribution and spawning of adults, and the dispersal and delivery of larvae to Chesapeake Bay is poorly known. Climate-related factors that affect oceanographic variability (See Habitats-Oceanography) and transport pathways leading to the mouths of estuaries, including Chesapeake Bay, may vary inter-annually and decadally. Specific information is lacking on inter-annual variability in spawning locations and times, and on distributions of eggs and larvae. The lack of knowledge of connectedness between spawning adults and ingressing late-stage larvae remains at issue.

Indicators/Metrics

- Indices of abundance are useful metrics for understanding annual trends in production and standing stock of menhaden within Chesapeake Bay. The Maryland and Virginia seine indices for YOY menhaden and Potomac River Pound Net Index for ages 1-3 are examples of available indices.

- Research by Ahrenholz et al. (1989) demonstrated the importance of recruitment from Chesapeake Bay to the coastwide stock in the 1970s.

- Otolith chemistry and elemental signatures may provide information on the contribution of YOY menhaden from Chesapeake Bay to coastwide recruitment. It may be possible to apply chemical techniques to historically preserved menhaden scales or otoliths, if available, to extend this knowledge to the entire time period of the stock assessments (1955-present).

- Estimates are lacking for age-1+ abundance, a critical deficiency in understanding the "localized depletion" problem. It is hoped that a LIDAR study, combined with videography, may provide variability estimates for menhaden standing stock and its distribution in Chesapeake Bay.

- The time-dependence of residency and migrations of menhaden into and out of the Bay are important metrics needed to judge the level and importance of localized depletion. It is not certain that the goals of estimating abundance and migration rates into and out of the Bay will be achieved in the short term. Alternative approaches to estimate the age-specific abundance and movement rates of menhaden in and out of Chesapeake Bay during the fishing season should be considered.

- Larval ingress research may provide estimates of inter-annual variability in abundance of menhaden larvae brought to Chesapeake Bay. Examination and evaluation of historical data on menhaden egg and larvae distributions can contribute to understanding the shifts in spawning areas or times that may result in variability in larval ingress, connectivity to the coastal ocean, and of YOY recruitment in Chesapeake Bay.

- Contemporary research on climate, oceanography, and early-life ecology of menhaden can evaluate variability in connectivity between the coastal ocean and the Bay.

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SOCIOECONOMICS

Ecosystems Services and User Conflicts

Joe Smith and Ed Houde

Role of Menhaden in the Ecosystem

Atlantic menhaden form large, dense schools that are ubiquitous and highly visible in the coastal ocean, embayments, and estuaries from northern Florida to the Gulf of Maine. The menhaden is a major forage species and is consumed by many fish and avian predators. Menhaden is a filter-feeding planktivore and plays a unique ecological role in foodwebs of coastal and estuarine systems on the East coast of the U.S. Juvenile and adult menhaden are obligate filter feeders, straining plankton and other particles from the water column. As such, it is thought that the Atlantic menhaden provides a significant ecosystem service as a top-down controller of algal growth in estuaries (Friedland et al. 1984, 1989, 2006).

Chesapeake Bay represents the center of distribution for Atlantic menhaden on the U.S. East coast. In the Bay, it is the dominant planktivore and also supports the Bay's largest fishery. Although estimates of absolute abundance in the Bay are unavailable, removals from the Bay by the purse-seine fishery attest to menhaden's dominance of fish biomass. From 1985 to 1996, Smith (1999) reported that the fishery removed 149,500 metric tons, on average, annually from the Virginia portion of the Bay. Moreover, median catch per set of a purse seine in the Bay was 18 metric tons. At an average weight of about 200 g (Smith et al. 1987), a single school of Atlantic menhaden may hold upwards of 100,000 individuals. The large purse-seine catches from a relatively restricted region have drawn attention of Bay residents and advocates who are concerned about the health and sustainability of the Bay's resources.

Filtering and Nutrient Cycling

As the dominant planktivore in Chesapeake Bay, menhaden provides an important link in the foodweb of the Bay (see Foodweb brief), providing the ecosystem service of efficiently transforming primary productivity into menhaden biomass, which is consumed by numerous predators. Menhaden provides another ecosystem service through its role in converting and exchanging energy and organic matter by sequestering, cycling, and transporting nutrients within, to, and from Chesapeake Bay (ASMFC 2004a). This important service, while complex and poorly understood, is closely aligned with what is broadly acknowledged as the major problem hindering restoration of Chesapeake Bay, i.e., excessive nutrient loading and eutrophication.

Menhaden may sequester nutrients, removing them from the Bay and thus serving to reduce levels of phytoplankton growth and blooms. However, Durbin (2007) estimated that menhaden may excrete up to 62% of the nitrogen they ingest, which could promote local phytoplankton growth, a non-intuitive consequence of filtering activity. Gottlieb (1998) modeled age-0 menhaden filtering in Chesapeake Bay. Modeled results were highly variable, but menhaden might consume about 10% of the annual primary productivity in the Bay. Durbin (2007) cited an annual net nitrogen export of about 800 metric tons by emigrating menhaden leaving Narragansett Bay. For the similar gulf menhaden, Deegan (1993) calculated that it accounted for annual export of 5-10% of total primary productivity from an estuarine system in Louisiana.

Forage Base for Predators

All life stages of Atlantic menhaden, from eggs to adults, are potential prey for a wide variety of predators (Ahrenholz 1991) (see Foodweb brief). Within Chesapeake Bay, striped bass, bluefish, and weakfish are the dominant fish predators on Atlantic menhaden (Hartman and Brant 1995; Walter and Austin 2003). These three large piscivores are highly sought by recreational anglers and the charter fishing industry. Recreational fishers and environmentalists are advocates for precaution in fishing on menhaden to insure conservation of its ecosystem service as a forage species.

The large shoals and near-surface schooling behavior make menhaden important prey for many waterbirds, such as brown pelican, osprey, double-crested cormorant, great blue heron, common loon, gannet, and terns (Ahrenholz 1991; Spitzer 1989; Viverette et al. 2007; Garman et al. 2008; Blankenship 2009). Waterbird numbers have increased >10-fold in the Chesapeake watershed since 1975, as has their demand for fish prey (Viverette et al. 2007; Garman et al. 2008). This demand increased while YOY menhaden abundance declined and the percentage contribution to bird diets by menhaden also declined, leading many scientists and resource managers to be concerned about the welfare of waterbird populations and calling for precautionary management of the menhaden fishery.

Human Demand Services and Products

Since 2005, the lone extant reduction factory for processing Atlantic menhaden is located on Virginia's Northern Neck at Reedville, near the mouth of the Potomac River (see The Background Fishery and Stock Assessment issues briefs). The fish factory at Reedville is an important local industry and employs about 250 people. Landings of Atlantic menhaden for reduction at Reedville in recent years (2005-08) have averaged 154,980 metric tons (range: 141,100-174,500 mt). In 2007, menhaden landings for reduction in Virginia (174,500 mt) represented 27% of all fisheries landings on the U.S. East coast (NMFS 2008). That year, Reedville ranked second among US ports in terms of total weight of fisheries landings, and 28th in terms of value.

The reduction process for menhaden yields three main products that are used primarily to support livestock production for human consumption: fish meal, fish oil, and fish solubles. Traditionally, menhaden meal has been a valuable ingredient in poultry and swine feeds because of its high protein content, well-balanced amino acid profile and desirable minerals (GSMFC 2002). Information on marketing channels for processed menhaden products is scarce and often proprietary. However, a former Fishery Management Plan for Atlantic menhaden (AMAC, 1992) estimated that during 1986-1990 the three extant menhaden factories in Virginia (2) and North Carolina (1) produced an average of 79,711 short tons of meal and 1.98 million gallons of solubles annually. Approximately 70% of the meal and 67% of the solubles were shipped to destinations in North Carolina, Virginia, and Georgia. Over the past decade, a transformation of the industry has been occurring, with larger quantities of menhaden meal now being milled into aquaculture feeds.

Formulations for catfish, trout, salmon, and shrimp may contain up to 40% fish meal (GSMFC 2002). Environmentalists are concerned that this shift in demand for menhaden and other forage fishes has the potential to spur unsustainable fishing on these resources.

Historically, most menhaden oil was exported to Europe or Canada, where it was refined into cooking oils or margarine-like products for human consumption (ASMFC 2004a). Domestic uses included marine lubricants, plasticizers for rubber products, and additives to alkyd paints and resins. Significant quantities of menhaden oil are now incorporated into aquaculture feeds (http://www.gsmfc.org/menhaden/2002%20Products.shtm). In 1997, the Food and Drug Administration approved refined menhaden oil for general use in foods in the U.S., thus opening new markets and additional demand for the product as edible oil for human consumption. Menhaden oil is rich in omega-3 fatty acids. The fish factory in Reedville recently constructed a refinery to produce human-grade menhaden oil for use as a human-health, diet supplement (Kromhout et al. 1985; Mozaffarian and Rimm 2006).

Virtually all of a menhaden is utilized by the industry. For example, menhaden solubles (the aqueous fraction of the reduction process) traditionally are re-incorporated into fish meal (ASMFC 2004a). Uses of solubles include added ingredients to poultry, swine, and cattle feeds (GSMFC 2002).

In addition to the reduction fishery, there are other elements and interests in menhaden fishing. Atlantic menhaden is harvested commercially as bait for crab pots, lobster pots, and hook-and-line fisheries in almost all U.S. East coastal states (ASMFC 2004a), amounting to 46,674 metric tons in 2008, or 25% of the total Atlantic menhaden landings. Regional landings of menhaden for bait are dominated by harvests in Chesapeake Bay and New Jersey (AMTC 2006) where these landings have increased substantially to >24,000 metric tons over the past decade. Menhaden for bait landings from Chesapeake Bay are primarily, but not entirely, used in the local blue crab pot fishery (ASMFC 2004a). Significant quantities of menhaden are packed and frozen as bait or ground chum for recreational and charter fishermen, thus linking the commercial and recreational fishing industries. The passage of a commercial "net ban" by Florida in 1995 reduced availability of bait and chum in that state, opening new markets for menhaden bait caught in Virginia and the Mid-Atlantic states (ASMFC 2004a). Live menhaden used as bait by anglers are caught with personal cast nets. Although likely to be small, the magnitude of the live menhaden-for-bait harvest is unknown (AMTC 2006).

Conflicts

Purse-seine fishing operations for menhaden are generally highly visible. Vessels are large and up to 200 feet long; purse seines catch tens of thousands of pounds of menhaden per set of the net; and, attendant spotter aircraft often herald the arrival of the fleet. Moreover, vessels often operate at times of peak tourism and waterfront usage. As use of public waters has increased in recent decades, competition for space and resources among menhaden vessels, recreational fishermen, and waterfront property owners has escalated into conflict (ASMFC 1999).

As recent as the mid-1990s, three menhaden reduction factories operated on the US East Coast. Now, the sole surviving menhaden factory on the East Coast is the Reedville, VA plant (since 2005). Although Virginia purse-seine vessels range from the central New Jersey coast to Cape

Lookout, NC, most fishing effort is expended near Reedville, in Virginia waters of Chesapeake Bay. Purse seining has not been allowed in Maryland's waters of Chesapeake Bay since 1931. Virginia regulations allow purse-seining for menhaden in Chesapeake Bay from the first Monday in May to the Friday before Thanksgiving, a period overlapping major months of recreational fishing, boating, and waterfront use.

The regulatory trend of Atlantic coastal states relative to menhaden purse-seining has been one of progressive area closures, often based on societal decisions unrelated to the status of the menhaden resource (AMTC 2006). Many coastal communities did not want menhaden reduction factories. The recreational fishing sector also argued for closures in traditional fishing areas. Since New Jersey closed its state waters in 2003, the menhaden fishery for reduction has become essentially a two-state fishery, with Virginia and North Carolina the only states that allow purse-seining for reduction within the range of the Virginia fleet (the Virginia vessels fish off Maryland, Delaware, and New Jersey in the Atlantic Ocean beyond three miles from shore in the U.S. EEZ where there are no restrictions). The menhaden reduction industry, when referring to these closures, notes that "the box [= fishable areas] is getting smaller and smaller," with ever greater fishing effort concentrated in Chesapeake Bay. In 2008, 77% (n = 2,693) of all purse-seine sets by the reduction fleet were made in the Virginia portion of Chesapeake Bay. Moreover, 50% (n = 1,350) of these sets occurred within two statistical reporting areas adjacent to the Reedville fish factory. Not surprisingly, such fishing effort by large commercial operators in a relatively small portion of Chesapeake Bay has spawned considerable controversy.

Recent conflicts among the menhaden industry, recreational fishing groups, NGOs, and waterfront property owners have been waged over a wide range of issues. Five issues, however, tend to represent the core of many disputes: 1) fishing operations and distance from shore, 2) by-catch, 3) forage base, 4) water quality, and 5) management. Each issue is addressed in the following paragraphs.

Fishing Operations

As human inhabitants have increased in coastal areas (Crossett et al. 2004), traditional waterfront uses such as fish houses, boat yards, and open access shorelines, have yielded to residential/commercial developments, marinas, and privatized shorelines - sometimes referred to as 'waterfront gentrification' (Houlahan 1987). Waterfront property owners often object to menhaden fishing operations on aesthetic principles and fear spills of dead menhaden from a burst net. New Jersey in 2003 (ASMFC 2004a) and Brunswick County, NC, in 2008 prohibited menhaden reduction fishing in their ocean waters out to three miles, ostensibly to separate the two user groups. Off the ocean beaches of Virginia and North Carolina, the nearshore distribution of menhaden is particularly evident. In 2004, the last year the North Carolina menhaden factory operated, 44% of the purse-seine sets in North Carolina occurred one mile or less from shore; 74% were within two miles, and 85% within three miles. In contrast, within Chesapeake Bay during 2008 only 11% of the purse-seine sets occurred within one mile of shore, which is only slightly more than an historical estimate (1985-96) of 8% (Smith 1999).

Virginia regulations prohibit menhaden purse-seining for reduction in tributaries on the Chesapeake Bay's western shore, except for the mouth of the Rappahannock River. Since most menhaden fishing effort in Chesapeake Bay occurs in the Bay's main stem, with 50% (n = 1,335) of the purse-seine sets in 2008 more than three miles from the Bay's shoreline, conflicts involving property owners with respect to menhaden fishing and distance from shore are, surprisingly, less contentious within Chesapeake Bay than along Virginia's ocean beaches outside the Bay.

By-Catch

By-catch, the capture of non-target species in purse-seine sets, has been a controversial issue associated with the menhaden fishery for over a century. Although recreational anglers are concerned that the purse-seine by-catch of recreationally important fishes is high (ASMFC 2004a), by-catch studies (White and Lane 1968; Ganz 1975), some of which date to the early 1800s (Smith 1896), indicate that by-catch of game fish is low and generally less than 1% of the menhaden catch by numbers. The most recent studies of purse-seine by-catch in Chesapeake Bay reported that whether counted by numbers (Austin et al. 1994) or by weight (Kirkley 1995), by-catch of fish and invertebrates was <1% of the total catch. In terms of recreational species, bluefish, weakfish, spot, Atlantic croaker, Spanish mackerel, striped bass, false albacore, and summer flounder occurred in the by-catch; by numbers, bluefish accounted for the largest fraction, approximately 0.0075% of the catch (Austin et al. 1994). In recent years, by-catch issues in Chesapeake Bay have been less of a 'hot-button' issue than previously in the Atlantic menhaden fishery.

Forage Base

Menhaden serve as forage for three major piscivorous fishes in Chesapeake Bay (Hartman and Brandt 1995), namely, striped bass, bluefish, and weakfish. Because menhaden occupies a unique position in the Bay's foodweb, numerous Chesapeake Bay stakeholders and advocates, and especially recreational fishermen, insist that menhaden be abundant as food for game fish (ASMFC 2004a). Indeed, with the resurgence of the striped bass population in Chesapeake Bay during the 1990's, Uphoff (2003) argued that in some years potential coastwide consumption of menhaden by striped bass could exceed commercial harvest. An Expanded Multi-Species Virtual Population Analysis (MSVPA-X; ASMFC 2005), which synthesizes diet, consumption rates, and bioenergentics of predator-prey interactions along the Atlantic coast, indicates age-0 and age-1 Atlantic menhaden is most important in the diets of striped bass and weakfish, while older age classes of menhaden are more important for bluefish. The level of competition for menhaden between predators and the fishery may vary from year to year. The menhaden fleet operates primarily in the main stem of Chesapeake Bay, and a majority of the catch in most years is dominated by age-2 menhaden (Figure 1). Catches of age-0 menhaden are uncommon in the Bay. Fishing mortality (*F*) for Atlantic menhaden has declined (AMTC 2006), and reduction removals from Chesapeake Bay between the 1990s (mean = 145,700 metric tons) and 2000-05 (mean = 104,400 metric tons) declined almost 30%. Annual removals in 2006-2008 (initial years of the Chesapeake Bay 'cap') continued to decline (but are proprietary data) and are considerably less than the 'cap' value of 109,020 metric tons.

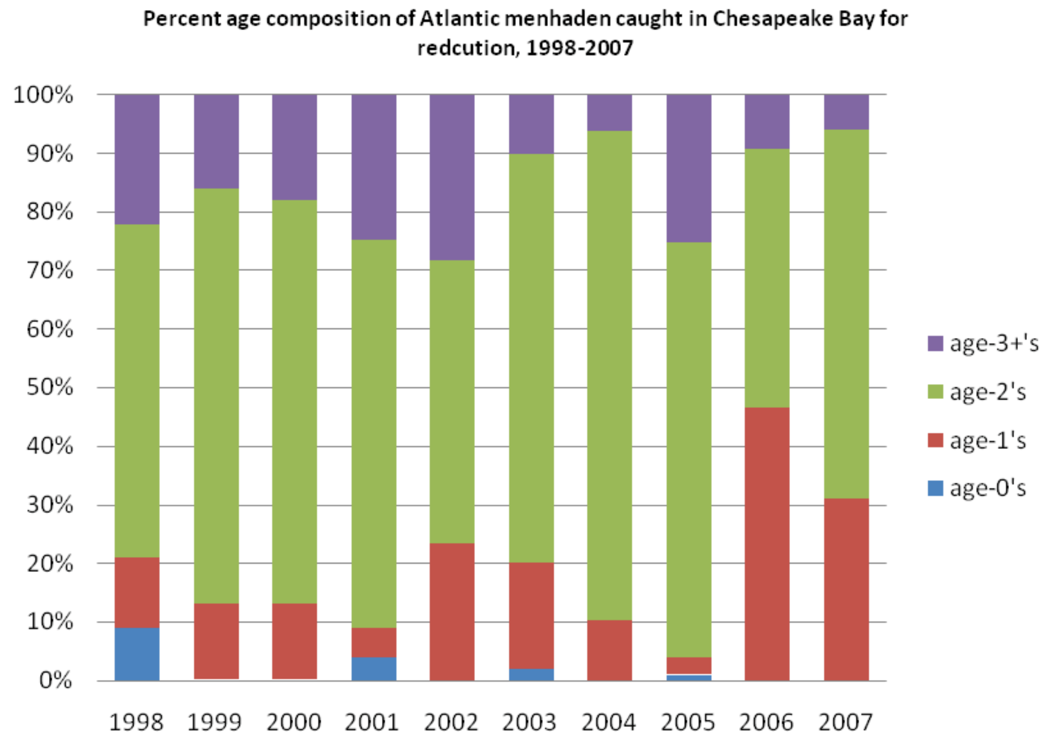

Figure 1. Age composition of Atlantic menhaden (numbers of fish) from the purse-seine reduction fishery in Chesapeake Bay.

Evidence that menhaden removals from Chesapeake Bay have a demonstrable effect on predator growth, condition, or abundance is insufficient at present to draw conclusions. The term 'localized depletion,' used to characterize this perceived condition, has been broadly and vaguely defined (AMTC 2007). The Technical Committee stated:

> Localized depletion in the Chesapeake Bay is defined as a reduction in menhaden population size or density below the level of abundance that is sufficient to maintain its basic ecological (e.g. forage base, grazer of plankton), economic, and social/cultural functions. It can occur as a result of fishing pressure, environmental conditions, and predation pressures on a limited spatial and temporal scale.

Critical to the localized depletion argument and quantifying it are data on absolute abundance of menhaden in Chesapeake Bay and ingress/egress rates of menhaden between the Atlantic Ocean and the Bay, both of which are unavailable. Results of a study in Narragansett Bay >30 years ago by Oviatt (1977) indicated that even when menhaden vessels left Narragansett Bay because schools had become diffuse and difficult to locate, there were sufficient menhaden remaining to serve as forage for bluefish and striped bass.

Water Quality

Recently, some have argued that menhaden can improve estuarine water quality through their filtering activity. To date, there has been neither substantiation nor refutation of the argument that menhaden filtering activity improves water quality. In a popular book, Franklin (2006) became a spokesperson for this argument. In a counter argument, Durbin (2007) noted that concentrations of adult menhaden might actually promote phytoplankton blooms by cropping down zooplankton which graze on phytoplankton and, through excreted nutrient releases (ammonia), precipitate phytoplankton blooms. The Atlantic Menhaden Technical Committee (AMTC 2008a), in addressing this controversy, has acknowledged the complexity and present lack of understanding of the role of menhaden in terms of nutrient dynamics and impacts on estuarine water quality.

Management

Atlantic menhaden is managed as a single coastal population. Menhaden that inhabit the Chesapeake Bay are part of the coastal stock. The most recent stock assessment for Atlantic menhaden states that the coastal stock is not overfished and overfishing is not occurring (AMTC 2006). A recent attempt to develop a spatially-explicit stock assessment model for Chesapeake Bay was unsuccessful (AMTC 2008b) because little or no data exist regarding the temporal or spatial flux of menhaden between Chesapeake Bay and adjacent ocean areas.

There is concern in the management community about low recruitment and perceived low abundance of menhaden in Chesapeake Bay. Recruitment of young menhaden into Chesapeake Bay has been low for >15 years. That concern, and concerns that the fishery might expand in Chesapeake Bay, prompted ASMFC and Virginia to adopt a five-year cap on the reduction fishery's catch of menhaden in the Bay beginning in 2006 (see Stock Assessment Exploitation brief). Critical research to answer questions regarding abundance, localized depletion, recruitment, and other biological issues is being conducted while the harvest cap is in effect. Until recently, there has been little progress towards developing an ecosystem-based management plan for Atlantic menhaden. The effort now underway, sponsored by Maryland Sea Grant, is a definitive step to address this deficiency.

Issues

As use of the Chesapeake Bay watershed has increased in recent decades, conflicts and competition for space, and arguments over allocation of the Atlantic menhaden resource between human, demand-driven services and ecosystem services have increased among the fishing industry, recreational fishermen, and environmental advocates. Five issues (discussed and described above) tend to dominate the arguments: 1) fishing operations and distance from shore, 2) by-catch, 3) forage base, 4) water quality, and 5) management.

Indicators/Metrics

Catch by Distance from Shore

- Daily logbooks called Captains Daily Fishing Reports, or CDFRs (Smith 1999), are completed by menhaden vessel captains, which enumerate individual purse-seine sets listing among other things catch, location, and distance from shore. In-year CDFR data could be monitored for significant changes in the distribution of catches and fishing effort in the Bay and along the coast.

By-Catch

- *By-catch Monitoring.* It has been 16 years since a scientifically-designed survey has been conducted of by-catch in the menhaden purse-seine fishery in Chesapeake Bay (Austin et al. 1994). Most by-catch studies of the menhaden fisheries agree that incidental catch of non-menhaden species is low, at least relative to the large catch of menhaden. Still, it is important to document the by-catch of all non-targeted organisms in the fishery. Should new by-catch research be planned, design should follow that of Austin et al. (1994) and be conducted by observer sampling at sea rather than shore-side enumeration of by-catch in the landings.

Forage Base

- *Abundance of Menhaden in the Bay.* At the heart of the 'menhaden-as-a-forage-base' issue are questions about the absolute abundance of menhaden in Chesapeake Bay and ingress/egress rates between the coastal stock and Chesapeake Bay. Aerial LIDAR technology was recently tested in Chesapeake Bay as a means to estimate abundance. Results to date are inconclusive, primarily because of the Bay's high turbidity, but researchers are hopeful that a combination of LIDAR and high-definition, aerial videography may succeed in leading to estimates of menhaden abundance. Questions concerning movements and exchange of juvenile and adult menhaden between the ocean and Chesapeake Bay, i.e., connectivity, are unresolved, with little or no research being conducted on this topic.

- *Predator Abundances.* Not only estimates of menhaden abundance are at issue. To resolve conflicts over health of the menhaden population and its proportional allocation to the fishery or to conservation needs and ecosystem services, estimates of predator abundance (i.e., forage demand) are required. At the least, annual indices and trends in piscivorous fish and waterbirds are needed. Estimates of consumption by predators of menhaden within Chesapeake Bay also are needed.

- *Fishing Patterns.* The catch-at-age matrix for Atlantic menhaden from Chesapeake Bay has been relatively consistent and stable over the past decade, with age-2 fish dominating landings in most years (Figure 1). Monitoring the catch-at-age matrix for change, i.e., a shift toward harvesting smaller and younger fish (age-0 and small age-1) could signal a shift in fishing patterns and mortality that might be detrimental to the Bay's forage base. Indeed, one of the two annual 'triggers' in ASMFC's Amendment 1 to the Atlantic Menhaden FMP (ASMFC 2004b), which could initiate an out-year stock assessment, measures the ratio of age-2 through age-4 menhaden in coastwide catch relative to the total catch of all ages. This trigger is fired if that ratio falls below the second standard deviation unit over the past 20 years. The second trigger relating to the forage base fires if the CPUE index (coastwide) falls below the 5^{th} percentile for the past 20 years. A similar index, if prescribed for Chesapeake Bay, could signal annual changes in recruited (age 1+) menhaden abundance within the Bay.

Water Quality

- *Menhaden Consumption and Nutrient Recycling.* Gottlieb (1998) modeled and simulated consumption of annual primary productivity by age-0 menhaden in Chesapeake Bay.

Recent research (Houde and Harding 2009) found evidence that YOY recruitment is directly related to phytoplankton biomass and annual integrated primary production in the Bay. Additionally, bioenergetics models (e.g., Luo et al. 2001; Annis et al. *in prep*) can provide information not only on YOY menhaden consumption and carrying capacity, but also predator demand (e.g., Hartman and Brandt 1995). Similar studies on age-1 and age-2 menhaden would expand our understanding of annual consumption rates of larger menhaden and nutrient cycling within the Bay, but would be limited by lack of knowledge on menhaden absolute abundance and on the connectivity/exchange issue.

Note: There is an effort now ongoing by USACE to develop a water quality model for menhaden in Chesapeake Bay.

Management

- *EBFM and Chesapeake Bay.* Atlantic menhaden is managed as a single-species, coast-wide fishery based on a stock assessment by the ASMFC. While there is sensitivity to ecosystem-level concerns, no formal ecosystem-based plan has been developed or implemented. A new, peer-reviewed stock assessment is being conducted in 2009 by ASMFC. That assessment and the Maryland Sea Grant EBFM planning effort now being conducted are likely to change the way menhaden is managed, at least in Chesapeake Bay. The issues of precaution in management and whether present reference points are risk-averse with respect to protecting ecosystem services will be addressed. New reference points may emerge. Concerns of the diverse stakeholders with an interest in the resource and fishery will be addressed as management measures are developed.

- *The 'Cap.'* Year 2009 will be the fourth year of the five-year 'Chesapeake Bay cap' on the Bay's reduction fishery (ASMFC 2006). The cap was ostensibly invoked to prevent expansion of the menhaden fishery in the Bay and to resolve questions of 'localized depletion.' It is uncertain if research funded during the cap's implementation will aid in answering the localized depletion issue. Questions about absolute abundance and ingress/egress in the Bay remain, while an initial attempt at a spatially-explicit assessment model for menhaden in Chesapeake Bay was unsuccessful (AMTC 2008b). It is probable that the new stock assessment now being conducted, like all previous menhaden assessments, will be performed on a coastwide basis. To be effective in addressing ecosystem-level issues in Chesapeake Bay, spatially-explicit indicators, metrics, and reference points that are Bay-specific are needed to address local and regional concerns.

The Regional and National Economic Importance of Menhaden

Doug Lipton

Introduction

Atlantic menhaden is an economically important species. However, that importance manifests itself in a variety of ways, each requiring different measures and analysis. For example, one indicator of its importance is the reported value of menhaden landings; with 2005-08 landings at Reedville, Virginia averaging 154,980 metric tons with an average value of $26 million (NMFS 2007a, 2007b, and 2008). Some would argue that this figure only tells part of the story, as the catching, processing and sale of menhaden-derived products generates economic activity and creates jobs beyond what are directly employed by the industry. Others would argue that landed value tells us very little since it does not account for harvesting costs and we should rather be focusing on the net benefits to producers and consumers resulting from menhaden harvest. A unique factor with menhaden landed value is that most menhaden landed in the region goes to the reduction plant in Reedville, and thus, is incorporated into a production process in a single firm that is vertically integrated (it is involved in both the harvest and processing of the product). The reported price, therefore, is what the company reports it to be, rather than the result of observed transactions between a large number of buyers and sellers as occurs with most other fisheries. Further complicating matters are the interactions of menhaden with other economically important species and with overall water quality issues. The complexity of these issues has led to initiation of a major research project to evaluate them (Kirkley 2006, 2007). Unfortunately, the results of that research are not yet available as these menhaden briefs are released. In this document, we review the major issues related to determining the economic value and importance of menhaden.

Regional Economic Impact of Menhaden Fisheries

The most recent study of economic impacts of Virginia fisheries and menhaden is Kirkley et al. (2005). This study employs input-output analysis to determine the linkages within the regional economy between producers and consumers at all market levels (i.e., fishermen, processors, wholesalers/distributors and final consumers) for the direct sale of the product through the marketing chain, the indirect economic activity that it stimulates in related industries (e.g., equipment manufacturers, packaging, transportation, etc.), and the induced effects due to the spending in unrelated industries by individuals due to the income and profits they make related to the menhaden fishery. Together, this direct, indirect and induced economic activity in the region equals a total economic impact, number of jobs associated with the activity, as well as income. Kirkley (2007) is in the process of refining the data and models used to make these estimates that will provide both an updated and more precise estimate of economic impacts.

Loftus (2006) used Kirkley's spreadsheet model and developed an estimate of the economic impact of the 2004 Virginia menhaden landings. The dockside value of those landings was estimated to be $24.5 million with a total impact on the Virginia economy of $45.2 million. The total impact on income was $26.7 million, and there were 395 full-time equivalent jobs that could be linked to the fishery.

Economic impact analyses are often misinterpreted in reaching policy decisions. For example, if the menhaden fishery were to shut down tomorrow, it would not necessarily lead to a decline in the Virginia economy of $45.2 million. The actual decline may be ameliorated if some of the resources that went into capturing and processing menhaden were reinvested in some other economic-impact generating activity. For example, although some people might find it undesirable, the area now occupied by the menhaden plant could be converted to a waterfront development site. In fact, depending on the nature of the alternative and its reliance on local and regional inputs and resources, it is possible that the alternative activity could have a higher regional impact than menhaden harvesting and processing.

Direct Economic Value of the Menhaden Fishery

The economic impact of menhaden discussed above says nothing about how much better off we are as a result of the menhaden fishery. For that, we must turn to willingness-to-pay measures and consumer and producer surpluses derived from supply and demand estimates. For example, consumer surplus is the difference between the maximum a consumer is willing-to-pay for menhaden (or a product derived from menhaden) and what they actually have to pay based on the market price. If a consumer is willing-to-pay $1.00 more per bottle of 100 omega-3 fish oil capsules derived from menhaden, but only has to pay $0.10 more, that consumer is marginally better off by $0.90. If a million consumers have identical preferences, the aggregate consumer surplus would be $900,000. For the menhaden producer, the producer surplus is the difference between the market revenue from selling a million bottles of menhaden fish oil and the total variable cost (including the opportunity costs of all inputs of production).

Calculation of these producer and consumer surpluses involves estimation of supply and demand for menhaden and may entail data at multiple market levels. To our knowledge, this type of analysis has not been done for menhaden. However, it is possible to make a few qualitative determinations about the menhaden market related to supply and demand, and thus, producer and consumer surplus. With regard to consumer surplus and demand, the more elastic[1] the demand, the smaller the consumer surplus. The more similar substitutes there are for a product, the more elastic the demand will be. On the one hand, there are many substitutes for menhaden fish meal (i.e., fish meal from other fish species, feed made from vegetable products and grains) and fish oil (i.e., oil from other species, flaxseed oil, etc.). On the other hand, fish meal and oil derived from menhaden may be preferred for use in feeds and fish oil capsules due to their favorable amino acid and omega-3 profiles.

Another unique aspect about menhaden that impacts producer surplus is the fact that the Atlantic reduction fishery is prosecuted by a single firm. The concept of a sole owner of a fishery acting

[1] Elasticity is a measure of the percentage change in quantity purchased by consumers relative to a percentage change in price. The more elastic the demand, the greater the reduction in quantity in response to a given change in price.

to optimize the harvest is well-established in the fishery economics literature (e.g. Clark 1976). The sole owner, should have the same incentive as the fishery manager to maximize profits from the fishery, and thus, would not engage in overharvesting or excessive utilization of fishing effort as in the case of an open access fishery. Some difference in the rate of harvest may exist due to the difference between the discount rate that the sole owner applies compared with the fishery manager. In the extreme, a sole owner with an infinite discount rate would overharvest the resource because discounted future harvests would have no value. In an open access fishery, producer surplus may be dissipated by excessive use of effort, whereas, in the sole owner situation, the minimum cost, in theory, will be expended to catch the sustainable harvest, presumably achieving the highest producer surplus possible from the fishery. Observation of the conduct of the Atlantic menhaden fishery suggests that it operates much closer to the efficient sole owner model than an open access fishery.

The Value of Ecosystem Services of Menhaden

In addition to the provisioning services provided by the direct harvest of menhaden for use in the reduction plant or as bait, the complex interactions of menhaden with other economically important species and its overall impact on water quality are also part of the economic importance of menhaden. In these cases, menhaden is an input into production of these ecosystem services and thus derives its value from the value of the ecosystem service. For example, menhaden as a primary forage species might be an input into the production of striped bass recreational fishing value. We have estimates of the benefits of increased catch rates of striped bass from Lipton and Hicks (1999, 2003). So, for example, if the average value of an increase of one striped bass caught per recreational fishing trip in 2009 dollars is $12.80, a fraction of that value increase could be attributed to changes in the menhaden population. The challenge would be to quantify the change in catch rate resulting from the change in menhaden population.

The simple direct relationship between menhaden and striped bass discussed above is not reflective of the complexity of the ecosystem. Sanchirico et al. (2008) undertook a portfolio analysis approach to examine Chesapeake commercial harvests. The portfolio approach takes advantage of statistical relationships in the data on harvests over time to try and determine if species harvests can be managed in a more strategic way to obtain the greatest revenue while minimizing risk. The approach does not attempt to explain or model the complex ecological relationships. While the methodology and data used to calculate optimal portfolios needs refinement, the preliminary results suggested greater harvest revenues with the same level of risk could be obtained from the Chesapeake when harvests of lower trophic level fish such as menhaden were reduced.

Menhaden may also impact water quality. This impact may then result in changes to recreational and commercial fisheries. In fact, the Lipton and Hicks (1999, 2003) studies focused on how changes in dissolved oxygen levels impact recreation, so one would have to relate menhaden abundance to dissolved oxygen level to estimate the change in value. In addition to commercial and recreational fishing, there are other uses of the Bay impacted by water quality that are valued. For example, waterfront housing values have been shown to be affected by water quality, in this case coliform counts in Chesapeake Bay (Leggett and Bockstael 2000). Lipton (2004) used a stated preference survey and found that recreational boaters were willing-to-pay for improvements in Chesapeake Bay water quality.

In addition to these Bay use values that may be influenced by the menhaden resource and its services, citizens in the region may have a preference for different levels of menhaden harvesting, even though there are uncertain scientific connections between menhaden abundance and Chesapeake Bay health. The Kirkley (2007) proposed research will address this aspect of menhaden value via a survey to be mailed out later this year.

An attempt to capture dynamic ecosystem and economic complexity by combining an economic model known as computable general equilibrium (CGE) with a general equilibrium ecosystem model has been applied to fisheries in Alaska (Finoff and Tschirhart 2008). This model focuses on the linkages between commercial fishing for Alaskan pollock and interactions with the tourism industry related to the abundance of Stellar sea lions, killer whales and sea otters. While this approach is data and modeling intensive, it has great potential for capturing the values of a more complete suite of ecosystem services provided by menhaden.

Issues

There are two major indicators of the economic importance of the Atlantic menhaden fishery. The regional economic impact indicator has been calculated and the estimates are currently under refinement to reflect improved data and methodology. While this impact indicator provides important information about the linkages of menhaden to the local and regional economy, the approach specifically excludes the economic importance of menhaden related to non-market transactions. Willingness-to-pay indicators try to estimate the value of menhaden to society for its full suite of ecosystem services, including market-based provisioning services (e.g., reduction fishery, bait, prey for important commercial fisheries), non-market based cultural services (e.g., recreation) and regulating services (e.g., water quality). Estimation of the economic value of menhaden's ecosystem services will require coupling of economic models with ecosystem models.

Indicators/Metrics

- Regional Economic Impacts
    - Regional Economic Output
    - Regional Income
    - Jobs
- Portfolio Performance
    - Distance measures comparing actual portfolio performance to optimal
- Willingness-to-pay
    - Value of recreational fisheries related to menhaden
    - Value of commercial fisheries related to menhaden
    - Community (local, regional) stated preferences for menhaden fishery (survey)

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