INVESTIGATING THE RELATIONSHIPS BETWEEN RECRUITMENT INDICES AND ESTIMATES OF ADULT ABUNDANCE FOR STRIPED BASS, WEAKFISH, AND ATLANTIC CROAKER

A Thesis

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of

Master of Science

---

by

Justine R. Woodward

2009

DEDICATION

I dedicate this to the loving memory of my uncle, Donald Bilkey. A man of honor, dignity, and strength, Don fought his battle with cancer courageously and departed from this world on November 29, 2007. In our hearts you will remain always. We love you Don.

TABLE OF CONTENTS

ACKNOWLEDGMENTS

I thank my major professors, Dr. Mary Fabrizio and Dr. Rob Latour, for their insightful suggestions, resourcefulness, and support which helped to bring this work to fruition. I thank my committee members, Dr. John Olney and Dr. Courtney Harris, for their support, guidance, and valuable contributions to this work.

I thank Wendy Lowery, Aimee Halvorson, Ashleigh Rhea, and Hank Brooks for collection of young-of-year weakfish and Atlantic croaker from the VIMS Juvenile Fish Trawl Survey, and for keeping me smiling out on the beautiful waters of Chesapeake Bay. I thank Mandy Hewitt, Branson Williams, and Pat McGrath for collection of young-of-year stripers from the VA Juvenile Striped Bass Seine Survey. I thank Rae Marie Johnson and Melanie Chattin for assistance with ageing otoliths. Other members of the VIMS multi-species monitoring programs that I thank include: Karen Capossela, Jenny Conwell, Mark Henderson, Troy Tuckey, Leonard Machut, Evan McOmber, Jameson Gregg, Deb Parthree, Stefanie Dukes, Durand Ward, and John Olney, Jr..

I thank Chris Bonzek for his expertise and assistance with data analysis and database management. I thank Jim Gartland for his resourcefulness concerning all things ChesMMAP. I thank Dr. John Hoenig for his assistance with data analysis and Andrij Horodysky and Dave Hewitt for their editorial prowess and thoughtful suggestions for this research. I also thank Kelli Wright and Pat Crewe for making my time more enjoyable here at VIMS.

To the following I extend my sincere appreciation for their constant friendship, love, and support: Sally Upton, Abby Lynch, Candi Spier, Amanda Lawless, Kathleen McNamee, Andre Buchheister, Patrick Lynch, Chris Magel, and Dan Dutton.

I am tremendously grateful to Mom, Dad, Natalie, Graeme, Grandma, Grandpa Johnny, and to all the Kiwis for believing in me every step of this journey. I thank my in-laws, especially Caroline and Chase Dixon, for constantly reminding me in their innocent, childlike way of all that I truly desire out of life. And to Wood, my husband, I thank you for your patience, love, and endurance. You have made this journey worthwhile.

LIST OF TABLES

Table Page

CHAPTER 2: Evaluating length as a proxy for age in young-of-year striped bass, weakfish, and Atlantic croaker

LIST OF FIGURES

Figure Page

APPENDIX

ABSTRACT

Establishing the relationships between recruitment indices and estimates of adult abundance using fishery-independent data continues to remain one of the principal challenges faced by fisheries scientists due to the lack of concurrent monitoring programs designed to target different life stages of the same species. In Chesapeake Bay, however, multiple, fishery-independent surveys currently monitor the relative abundance of YOY and adult fishes. Using the available data from these surveys, the relationships between estimates of relative abundance for young-of-year and adults of striped bass (*Morone saxatilis*), weakfish (*Cynoscion regalis*), and Atlantic croaker (*Micropogonias undulatus*) were examined. Year-class strength was reflected in subsequent estimates of age-specific adult abundance; however, the strength of the relationships varied greatly with age. For all three species, the initial lack of significant correlations across all age classes indicated the need for improving the recruitment indices to more appropriately reflect YOY abundance. To ensure that the recruitment indices reflect patterns in abundance of YOY fishes, the following information was examined: assignment of the index period and strata and the distributional assumptions of the YOY catch data. For striped bass, a Bay-wide recruitment index appears to more accurately reflect year-class strength than the individual VA and MD recruitment indices. The recruitment indices for weakfish and Atlantic croaker improved when changes were made to the index period; however, further investigation is necessary to determine how depth influences the distribution and, ultimately, abundance of these two species. Identifying the distribution of the YOY catch data from the VIMS juvenile finfish surveys is also critical for obtaining unbiased recruitment indices. Here, the striped bass and weakfish catch data were gamma distributed; whereas, the Atlantic croaker catch data were lognormally distributed. The application of the delta-lognormal distribution did not improve the recruitment indices for any of the species in this study.

An ageing study was conducted to determine if historically-defined length threshold values accurately distinguish YOY fish from older individuals in present day samples of striped bass, weakfish, and Atlantic croaker collected from the juvenile finfish surveys. The length threshold value for striped bass was determined to be approximately 30 mm too high. Although the current recruitment index for striped bass is not likely influenced by the small number of 1-year olds measured as YOY fish, reducing the length threshold value would ensure that only YOY fish are included in the calculation of the recruitment index. Further research is needed to determine if the length threshold values are appropriate for weakfish. For Atlantic croaker, length threshold values for the early portion of the index period (May, June) were appropriate; whereas, values used for the latter half of the index period (July, August) were too high, allowing for older individuals to be considered YOY based on their length. Consequently, the use of an earlier index period for Atlantic croaker would ensure that older fish are not being considered as YOY fish based upon their length.

CHAPTER 1

INVESTIGATING THE RELATIONSHIPS BETWEEN RECRUITMENT INDICES AND ESTIMATES OF ADULT ABUNDANCE FOR STRIPED BASS, WEAKFISH, AND ATLANTIC CROAKER

INTRODUCTION

Recruitment variability is a characteristic feature of fish populations (Sissenwine 1984); therefore, an important area of research in fisheries ecology involves understanding the processes regulating recruitment variability (Houde 1987; Fogarty *et al.* 1991; Dingsor *et al.* 2007). In general, recruitment refers to the number of individuals that reach a certain stage of the life cycle. Recruitment is often defined as the number of individuals that survive to become juveniles. Variations in recruitment and subsequent adult stock abundance are regulated by density-dependent and density-independent processes. Density-dependence can take the form of compensatory mechanisms such as increased levels of competition and predation at high fish densities (Dingsor *et al.* 2007). Density-independent processes are attributed to environmental factors that can directly or indirectly affect the physiology of fishes. For example, North *et al.* (2005) concluded that variability in abundance of juvenile striped bass (*Morone saxatilis*) in the Maryland portion of Chesapeake Bay may be largely influenced by mean spring discharge and the number of pulsed river flow events. Additionally, variations in recruitment of exploited fish populations are strongly coupled to their life-history strategies (Fogarty *et al.* 1991). For example, fish stocks with higher fecundity exhibit greater recruitment variability relative to other stocks of the same species (Rickman *et al.* 2000).

The stage during which year-class strength is established varies among species. Helle *et al.* (2000) concluded that indices of early juvenile abundance (approximately 3 months of age) for Atlantic cod (*Gadus morhua*) are the earliest reliable indicators of year-class strength. The survival of Atlantic croaker (*Micropogonias undulatus*) to age-1 is regulated by cold-induced overwintering mortality (Norcross 1983; Lankford and Targett 2001). Striped bass recruitment is predominantly controlled at the larval stage but has the potential to be regulated at the juvenile stage due to the effects of changes in instantaneous mortality and growth rates on recruitment to age-1 (Houde 1987). In general, small changes in growth or mortality rates during the early life of fishes (e.g., larval stages) may result in large differences in year-class strength (Houde 1987; Houde 1989).

The potential for year-class strength regulation is the greatest for most species during the larval stage (Houde 1987). When year-class strength is established prior to the juvenile stage, estimates of relative abundance derived from surveys of young-of-year (YOY) fish populations presumably reflect year-class strength. For surveys targeting YOY fishes less than one year of age, year-class strength is assumed to be established prior to capture. To calculate an estimate of relative abundance of YOY fish, or a recruitment index, catch data reflective of a standard set of criteria (e.g. particular sampling locations and time periods) are required. A high recruitment index implies the occurrence of a strong year-class; likewise, a low index implies a weak year-class.

In general, recruitment indices are useful for forecasting trends in future stock abundance (Crecco *et al.* 1983; Bailey and Spring 1992; Helle *et al.* 2000; Axenrot and Hannson 2003; Hare and Able 2007). Goodyear (1985) identified the Maryland striped bass recruitment index as a strong indicator of year-class strength for striped bass in the Maryland portion of Chesapeake Bay based on the ability of the recruitment indices to predict future landings of adults in Maryland commercial catches. Therefore, variations in recruitment can have important implications for management (Fogarty 1993) particularly for species, such as Atlantic salmon (*Salmo salar*), for which a recruitment index based on fry abundance may serve as an early indicator of total smolt production (Crozier and Kennedy 1995).

Patterns in the abundance of YOY fishes tend to be reflected in subsequent adult stages for species such as American shad (*Alosa sapidissima*), striped bass, and Atlantic croaker (Crecco *et al.* 1983; Goodyear 1985; Crozier and Kennedy 1995; Niemela *et al.* 2005; Hare and Able 2007). Previous studies on American shad identified significant correlations between recruitment indices and estimates of virgin females during spawning runs four to six years later (Crecco *et al.* 1983). Due to a lack of fishery-independent data from marine and estuarine ecosystems, most studies have relied upon fishery-dependent data for estimates of adult abundance. For example, Hare and Able (2007) showed that spring YOY abundance of Atlantic croaker was correlated with estimates of adult (age-2) abundance derived from the 2005 stock assessment of Atlantic croaker. Evaluating the relationship between indices of relative abundance at different life stages using only fishery-independent data remains one of the principal challenges faced by fisheries scientists. Fishery-independent data are desirable because they present an unbiased estimate of relative abundance. Yet, research has been limited due to the absence of concurrent monitoring programs designed to independently target various life stages of the same species. In Chesapeake Bay, however, multiple, fishery-independent surveys currently monitor the relative abundance of YOY and adult fishes. Using the available data from these surveys, I examine the relationships between estimates of relative abundance for YOY and adults of striped bass, weakfish (*Cynoscion regalis*), and Atlantic croaker.

CPUE as an index of abundance

Catch-per-unit-effort (CPUE) data can be used as a measure of relative abundance under the assumption of a proportional relationship between CPUE and density. Catch is related to density and effort through the following relationship:

$$C = qE\left(\frac{N}{A}\right) \tag{1}$$

where C is the total catch in numbers, q is the catchability coefficient (generally assumed constant over time and space), or the fraction of the stock captured with one unit of effort, E is the amount of effort, N is abundance in numbers, and A is the area in which the stock occurs (Gulland 1969). The equation is rearranged to obtain the following proportional relationship between CPUE, or catch rate, and density:

$$\frac{C}{E} = CPUE = I = q\left(\frac{N}{A}\right) \tag{2}$$

where I is the index of relative abundance. According to this theory, changes in *CPUE* are proportional to changes in density. This assumption is expected to remain valid as long as q is constant.

Variability in estimates of relative abundance is characteristic of survey data and can be attributed to either measurement or process error. Measurement error, or noise, occurs as a result of within-survey sampling variability; whereas, process error occurs as a result of actual changes in abundance (Pennington 1985; Helser and Hayes 1995). For research surveys using one vessel, measurement error is reduced through standardization of gear, optimal survey design, and appropriate estimation techniques (Chen *et al.* 2004). When a stratified random sampling design is employed, the use of stratification will improve precision when the variance among observations within each stratum is less than the variance of a random sample of observations from the entire sampling area (Hilborn and Walters 1992).

Catch rates, in general, are influenced by the availability and vulnerability of a species and the selectivity of the fishing gear. Availability is defined as the proportion of the stock occupying the survey area (Jennings *et al.* 2001). However, individuals available to the gear may not be equally vulnerable to capture because vulnerability depends on fish behavior. For example, net avoidance, depends on swimming speed which varies across species and sizes within species. On a broader scale, vulnerability depends on the life history characteristics of a species, such as individual growth rate and age at maturity, which collectively determine how populations respond to different levels of exploitation (Jennings *et al.* 2001). Lastly, fishing gear targets and retains specific size or age classes, termed selectivity. Mesh size will control the size of the individuals in the catch by allowing smaller fishes to pass through the mesh while retaining larger fishes incapable of avoiding the net.

Changes in gear efficiency can also influence estimates of relative abundance. Efficiency refers to the fraction of fish that encounter and are retained by the gear. The gear efficiency of a trawl net may change with tidal stage, tow duration, or as the geometry of the gear changes with depth or other factors (Jennings *et al.* 2001, Von Szalay and Somerton 2005). Efficiency of trawl survey gear is assumed constant through time primarily because estimates are difficult to obtain. Although catch rates are influenced by availability, vulnerability, selectivity, and efficiency, it is often impossible to address these factors directly. Efforts must be taken to ensure that the recruitment indices reflect changes in fish density by concentrating on issues such as the temporal and spatial coverage of the surveys and the appropriate methods for dealing with zero catches.

A considerable challenge to analyzing fishery-independent data involves the appropriate way to treat zero catches. The patchy distribution of fishes may cause a large proportion of catches to be acquired in a relatively few number of samples. In this case, the catch data are positively skewed due to the high frequency of zeros or low catches. A commonly used approach is to log transform the data assuming the data came from a log-normal distribution; however, because the log of zero is undefined, a small constant value (e.g. 0.1 or 1) must be added to all catch data prior to transformation. This approach is unsatisfactory because the products, or indices of abundance, may be sensitive to the value of the constant which is usually chosen arbitrarily (Maunder and Punt 2004).

Identifying the distribution of survey catch data is critical for obtaining unbiased recruitment indices. Incorrect distributional assumptions that are made when developing standardized indices of abundance may lead to biased estimates of relative abundance (Terceiro 2003; Ortiz and Arocha 2004). Delta-lognormal distributions have been used to analyze fisheries datasets containing a large proportion of zeros and nonzero values that are log-normally distributed (Pennington 1983; Lo *et al.* 1992; Pennington and Stromme 1998; Ortiz *et al.* 2000; Ortiz and Arocha 2004; Carlson *et al.* 2007). In the past, delta-lognormal models have been applied to standardize commercial catches (Punt *et al.* 2000; Carlson *et al.* 2007); estimate finfish by-catch from commercial fisheries (Ortiz 2000; Ortiz and Arocha 2004) and estimate abundance from survey data

(Pennington 1983; Pennington 1996). Alternatively, delta-gamma models, for which the nonzero values are gamma distributed, have also been used to analyze groundfish survey data (Stefansson 1996; Ye *et al.* 2001). The delta models treat zero and nonzero data separately; consequently, the product of the proportion of zeros and mean of non-zero observations provides an estimate of abundance (Lo *et al.* 1992). The delta-lognormal estimator is not robust to violations of the assumption that non-zero observations are log-normally distributed (Myers and Pepin 1990) implying that the delta-lognormal model should only be applied when the non-zero catch data are clearly log-normally distributed.

Chesapeake Bay Monitoring Programs

Chesapeake Bay is a critical nursery habitat for many recreationally and commercially important fishes. Surveys of fish populations currently operate in both the Virginia and Maryland portions of the Bay to monitor the abundance and distribution of juvenile fishes (Durell and Weeden 2007; Fabrizio and Tuckey 2008; Hewitt *et al.* 2008). The primary objective of the surveys is to estimate the relative abundance of YOY fishes. For economically important species, recruitment indices are derived annually and used as "tuning indices" in stock assessments designed to evaluate stock status.

Initiated in 1955, the VIMS Juvenile Fish Trawl Survey (hereafter referred to as the VIMS trawl survey) monitors the abundance of YOY finfishes on a monthly basis in the James, York, and Rappahannock Rivers (Fabrizio and Tuckey 2008). In 1988, sampling locations expanded to include the lower Chesapeake Bay (Figure 1). Estimates of YOY abundance are calculated annually for selected species. Each species is assumed to be fully recruited to the trawl gear during a 3-4 month window referred to as the 'index period,' and the time of year when this period occurs varies among species. Length threshold values are used to distinguish YOY individuals from older fish. The survey implements a stratified random sampling design such that stratification is based on depth and either latitudinal (Bay) or longitudinal regions (rivers). The number of individuals smaller than the length threshold values and collected during the index period is log-transformed using ln(x +1). Subsequently, means and variances are calculated for each stratum, and stratum means are combined into an overall mean according to the following (Cochran 1977):

$$\bar{y} = \sum_{h=1}^{L} W_h \bar{y}_h \tag{3}$$

where $\bar{y}$ is the overall stratified mean estimate, W_h is the stratum weight (calculated according to stratum surface area), $\bar{y}_h$ is the stratum-specific mean catch-per-tow of the log-transformed values, h is the stratum, and L is the total number of strata. The average catch rate, $\bar{y}$, is back transformed resulting in a geometric mean catch per tow using the following equation:

$$GM_{\bar{y}} = e^{\bar{y}} \tag{4}$$

For all species, the recruitment index is reported as a geometric mean because the survey catch data are currently assumed to be log-normally distributed; however, the validity of this assumption has not been examined since 1990 (Chittenden 1991).

The Virginia Juvenile Striped Bass Seine Survey (hereafter referred to as the VA seine survey) monitors the annual recruitment of striped bass from July to mid-September at fixed stations in the James, York, and Rappahannock Rivers (Figure 2) using a 1.2m x 30.5m minnow seine (Hewitt *et al.* 2008). To investigate possible expansions of the primary habitat for striped bass, the spatial coverage of the VA seine survey was increased in 1989 to include upriver and downriver auxiliary stations in addition to the existing index stations. However, striped bass data collected from the auxiliary stations are not currently incorporated into the calculation of the recruitment index. In the Maryland portion of Chesapeake Bay, the Maryland Department of Natural Resources (MD DNR) Striped Bass Seine Survey has been sampling continuously in the head of Bay region, and in the Potomac, Nanticoke, and Choptank Rivers (Figure 3) since 1954 using the same gear (Durell and Weeden 2007). The overall objective of these seine surveys is to develop annual recruitment indices for YOY striped bass in the Virginia and Maryland portions of Chesapeake Bay. As before, the catch data are assumed to be log-normally distributed, and a logarithmic transformation of ln(x+1) is applied. Consequently, annual indices of abundance are reported as geometric mean catches-per-haul. Under the current protocol for the VA seine survey, the recruitment index is multiplied by a scaling factor of 2.28 to provide an *ad hoc* estimate that is comparable to the arithmetic mean (2.28 is the estimated ratio of the arithmetic mean to the geometric mean, calculated from historical data from the seine survey) (Austin *et al.* 1993). The scaling factor was originally included because of differences in the reported forms of the index, and because the "trigger" used by the fisheries management plan (FMP) for striped bass is based on an arithmetic mean; however, now that both states report the recruitment indices as geometric means, the scaling factor may no longer be necessary.

In addition to recruitment indices, estimates of age-specific adult abundance are necessary for evaluating the status of economically important fishes. Using a large-mesh bottom trawl, the Chesapeake Bay Multi-species Monitoring and Assessment Program

(ChesMMAP) has been monitoring adult fishes in the Virginia and Maryland mainstem portions of Chesapeake Bay (Figure 4) on a bi-monthly basis from March to November since 2002 (Bonzek *et al.* 2007). Information generated from the survey includes: estimates of minimum trawlable abundance, length, weight, age, sex-ratio, and trophic interactions (Bonzek *et al.* 2007). The data provide vital information required for multi-species stock assessments (Bonzek *et al.* 2007).

The ChesMMAP catch data are collected according to a stratified random sampling design where strata are defined by region and depth. Estimates of relative abundance are determined based on the following equation:

$$\overline{N}_h = \frac{\sum_{i=1}^{n} \frac{c_i}{a_i}}{n} \tag{5}$$

where $\overline{N}_h$, is the average catch-per-area in stratum h, c_i is the total catch in tow i, a_i is the product of the average net opening in tow i and the distance towed, and n is the number of tows in stratum h. Stratification is then employed such that:

$$N = \left(\sum_{h=1}^{L} W_h * \overline{N}_h \right) A \tag{6}$$

where N is the overall minimum trawlable abundance, W is the weight of the h^{th} stratum (based on surface area), L is the total number of strata, and A is the total survey area assumed to be 6,000 km^2 for the mainstem of Chesapeake Bay. Because net efficiency is unknown, absolute population size cannot be estimated, and abundance estimates represent 'minimum trawlable abundance,' the minimum number (or biomass) of fish vulnerable to the gear in the sampling area.

Species of Interest

This research will focus on three species captured in high abundances by all finfish monitoring programs in Chesapeake Bay: striped bass, weakfish, and Atlantic croaker (Table 1). Furthermore, these species exhibit different reproductive strategies that influence their distributions and ultimately, abundance. Striped bass spawn in freshwater locations, weakfish are bay and coastal spawners, and Atlantic croaker spawn on the continental shelf. Although striped bass and Atlantic croaker populations continue to remain stable under current management regulations mandated by the Atlantic States Marine Fisheries Commission (ASMFC), weakfish populations are considered depleted with an estimated spawning stock biomass that has declined steadily since 1998 (ASMFC 2006).

Striped bass are anadromous fish belonging to the family Moronidae, and they are native to the east coast of the United States. Spawning in Chesapeake Bay occurs within the freshwater reaches of the tributaries where salinity is less than 1 ppt (McGovern and Olney 1996; North and Houde 2001). Commercial and recreational fisheries for striped bass are supported primarily from Massachusetts to North Carolina with the exception of Connecticut which does not support a commercial fishery (ASMFC 2007). The majority of striped bass removals occurs in Virginia and Maryland waters (including Chesapeake Bay) (Koo 1970; ASMFC 2007). Striped bass experienced a precipitous decline in abundance in the early 1980s followed by a recovery to record levels by the mid-1990s facilitated by moratoria imposed in Chesapeake Bay waters and stringent harvest regulations along the coast (Richards and Rago 1999). The recovery of striped bass is also attributed to characteristics of its life history, including longevity and an extended reproductive lifespan, contributing to the resiliency of populations during periods of poor recruitment (Secor 2000).

Weakfish are members of the family Sciaenidae and migrate annually from offshore overwintering grounds near Cape Hatteras to estuarine and coastal spawning locations along the Atlantic coast (Mercer 1985). Multiple age-0 weakfish cohorts have been identified in the York River (Szedlmayer *et al.* 1990) indicating that weakfish spawn several times from May through August in Chesapeake Bay (Lowerre-Barbieri *et al.* 1996). Weakfish are currently managed as a single stock (ASMFC 2006) despite some evidence of stock structure based on meristic and morphometric studies (Perlmutter *et al.* 1956; Shepherd and Grimes 1983). Using otolith geochemistry as a natural tag, Thorrold *et al.* (2001) concluded that weakfish along the eastern United States appear to exhibit spawning site fidelity to their natal estuary (coastal Georgia, Pamlico Sound, Chesapeake Bay, Delaware Bay, and Peconic Bay) although homing mechanisms in weakfish are not well understood.

Atlantic croaker are demersal sciaenids that are distributed in U.S. waters from New York to Florida and into the Gulf of Mexico (Joseph 1972). The majority of commercial landings occurs between New Jersey and North Carolina with Virginia and North Carolina supporting the most dominant fisheries since 1960 (ASMFC 2006). Adult Atlantic croaker migrate into Chesapeake Bay during spring months and emigrate to overwintering grounds along the continental shelf by late fall (Haven 1959). Spawning occurs as adults emigrate from Chesapeake Bay to the continental shelf (Morse 1980). Atlantic croaker have a protracted spawning season extending from July to February with peak spawning occurring in September (Nixon and Jones 1997), resulting in differential growth rates among YOY fish and large intra-annual variations in length-at-age (Barbieri *et al.* 1994). Atlantic croaker grow rapidly during their first year with lengths at age-1 ranging from 90 to 170 mm (Ross 1988; Miller *et al.* 2003).

JUSTIFICATION AND OBJECTIVES

The information used to develop recruitment indices requires verification to ensure that surveys monitoring YOY fish populations are providing the best available scientific information. Designation of the index period, stratum assignment, and the distributional assumptions used to construct the recruitment indices for these species were last reviewed in the early 1990's (pers. comm. C. Bonzek). In recent years, minimal effort has been directed towards evaluating the information used to construct recruitment indices derived from well-established fishery monitoring programs in Chesapeake Bay. Fishery-independent data on adult abundance are now available; therefore, it is possible to examine the relationships between recruitment indices and estimates of age-specific adult abundance. To date, no attempts have been made to determine if signals in year-class strength are reflected in subsequent estimates of adult abundance using fishery-independent data from Chesapeake Bay for both YOY and adult fishes. Striped bass, weakfish, and Atlantic croaker were selected for this study because they exhibit different reproductive aspects of their life histories which, in turn, influence their temporal and spatial use of Chesapeake Bay and its associated tributaries. I attempted to determine if the recruitment of YOY fishes as measured by the VIMS juvenile finfish surveys is ultimately influenced by the life history of a species. A longitudinal approach was used to examine data for a given cohort, or year class, as it ages to determine if patterns in the recruitment index persist. Strong statistical relationships between recruitment indices and estimates of adult abundance provided support for the current approaches and assumptions for calculating the indices. On the other hand, weak relationships necessitated further investigation (Figure 5). The results of this research were used to determine the most suitable information required for calculating a recruitment index from the juvenile finfish surveys for the selected species. This research was motivated by the following questions:

1) Are patterns in recruitment indices reflected in subsequent estimates of age-specific adult abundance?

2) If not, can the recruitment indices be improved as evidenced by stronger statistical relationships between the recruitment indices and estimates of age-specific adult abundance?

Objectives

1) Evaluate the relationships between recruitment indices and estimates of age-specific adult abundance provided by fishery-independent surveys for striped bass, weakfish, and Atlantic croaker.

2) Investigate the effects of modifications to the recruitment indices with the ultimate goal of developing modified recruitment indices that better reflect abundance of YOY fishes.

METHODS

Objective 1

Simple linear regression models were used to examine the relationships between recruitment indices and age-specific adult abundance derived from Chesapeake Bay finfish monitoring programs (Figure 6). The number of age-classes of adults depended on the oldest age class for which sufficient catch data were determined to be available. Estimates of age-specific abundance from the ChesMMAP survey were assumed to be measured accurately. All analyses were conducted using SAS software (SAS version 9.1, SAS Institute 2002). The model for a simple linear regression is:

$$(I_a)_j = \beta_0 + \beta_1 YOY_{j-a} + \varepsilon_j \qquad (7)$$

where $(I_a)_j$ is the estimate of adult abundance obtained from the ChesMMAP survey for a given age, a, during the j^{th} year, β_0 is the overall mean, β_1 measures the change in $(I_a)_j$ per unit change in YOY_{j-a}, which is the recruitment index for a given year class j-a, and ε_j is the random error associated with the j^{th} year. The following assumptions apply when using linear regression analysis: (i) the observations, $(I_a)_j$, are independent and normally distributed; (ii) ε_j, are independent and normally distributed; (iii) the expected mean value of the error term is 0 and the variance is designated as σ_ε^2; and (iv) variances are homogeneous.

To examine the strength of the relationship between estimates of age-specific adult abundance and the recruitment indices, the Pearson's product-moment correlation coefficient *r,* a derived statistic from simple linear regressions, was determined for each age class and species in the analysis. A statistical test based on the t-distribution was used to test the significance of the correlation coefficient. A sample size of six was used in this study because there are six years of ChesMMAP data available. For n = 6 and 4 (n-2) degrees of freedom, the critical value of *r* in this analysis is t_{crit} = 0.811 at an alpha level of 0.05. Significant, positive correlations provided support for linear relationships between the recruitment indices and estimates of age-specific adult abundance. In this case, variations in the signal of year-class strength were detected during subsequent adult stages.

The lack of a significant correlation for some age classes indicated no discernable linear relationship between the recruitment index and age-specific adult abundance. One potential reason for this is that the recruitment indices may not be representative of underlying abundance. Lack of representation may be caused by the inappropriateness of the information used to derive the recruitment indices such as the index period and stratum assignment or the distributional assumptions of the catch data.

Objective 2

The species-specific information required for deriving recruitment indices was evaluated for striped bass, weakfish, and Atlantic croaker. In situations where significant relationships between the recruitment indices and estimates of adult abundance were not detected, attempts were made to develop modified recruitment indices to improve the relationships. To determine if the current information is still appropriate, I developed modified recruitment indices for striped bass by: 1) combining the VA and MD indices and including data collected from auxiliary stations and 2) examining alternative distributional assumptions. I developed modified recruitment indices for weakfish and Atlantic croaker by: 1) considering catch data associated with different index periods 2) restricting the use of catch data from certain depths and 3) examining alternative distributional assumptions. Lastly, length threshold values used to distinguish YOY individuals from older fish were also evaluated (see Chapter 2). After re-calculating the index, I determined if the modified index provided a better indicator of subsequent adult abundance.

Defining the index period

The current index period used to derive recruitment indices from the VIMS trawl survey remains constant from year to year. However, the temporal and spatial utilization of Chesapeake Bay as a nursery habitat for YOY fishes may vary interannually. These variations may be attributed primarily to environmental drivers, changes in habitat quality, or changes in trophic level interactions, among other factors.

I developed a set of qualitative hypotheses based on the life history characteristics of each species to structure the modified recruitment indices. Currently, an index period of August – October is used for weakfish. I hypothesized that the recruitment index for weakfish would improve if November was included as an index month because YOY weakfish are still captured in relatively high abundance by the VIMS trawl survey in Chesapeake Bay during November. To investigate this, I explored the addition of the month of November to the index period for weakfish (Table 2a). The current index period for Atlantic croaker is May – August. Because year-class strength is established by the spring of the first year due to cold-induced overwintering mortality (Norcross

1983; Lankford and Targett 2001), I hypothesized that an earlier index period, excluding the summer months, may more appropriately reflect abundance of YOY Atlantic croaker (Table 2b) because YOY fish are captured in relatively high abundances during the months of May and June. Therefore, I defined the modified index period to include the months of either April – May or April – June. Subsequently, I re-examined the relationships between the modified recruitment indices and estimates of age-specific abundance to determine if the modified indices provided a better indicator of subsequent adult abundance.

Defining the strata

The current strata used to derive recruitment indices from the VIMS trawl survey do not vary interannually. However, spatial distributions of YOY fishes in Chesapeake Bay may not be constant over time. Because striped bass recruit to tributaries throughout Chesapeake Bay (Olney *et al.* 1991; Rutherford and Houde 1995; Durell and Weeden 2007; Hewitt *et al.* 2008), I hypothesized that a Bay-wide recruitment index, in contrast to state-specific recruitment indices, would provide a better indicator of subsequent adult abundance. The Bay-wide index was derived as the sum of the VA and MD recruitment indices (Table 3). Additionally, the inclusion of YOY striped bass data collected from auxiliary stations was considered to investigate the effects of data collected from these stations on the VA recruitment index. In this study, the scaling factor was not used to calculate the VA striped bass recruitment index.

Previous research has demonstrated that depth, in addition to other environmental variables, may influence the abundance of YOY weakfish in Chesapeake Bay (M.

Fabrizio, unpubl. data). I hypothesized that depth may influence the distribution of YOY weakfish and Atlantic croaker in Chesapeake Bay, and therefore should be considered when developing a recruitment index. YOY weakfish have been shown to exhibit a preference for waters with salinities less than 20 ppt, and YOY Atlantic croaker have been shown to exhibit a preference for waters with salinities less than 18 ppt (Haven 1957). Based on the salinity preferences of these two species, I hypothesized that catch data from the rivers only could be used to develop a recruitment index for weakfish and Atlantic croaker. To determine if the strata that are currently used are defined appropriately for weakfish and Atlantic croaker, I evaluated the influence of depth and river system on the recruitment index for these species (Tables 2a and 2b). For weakfish, and Atlantic croaker, the recruitment indices are based on catch data from all depth strata and all systems, including Chesapeake Bay. Subsequently, I re-examined the relationships between the modified recruitment indices and estimates of age-specific abundance to determine if the modified indices provided a better indicator of subsequent adult abundance. Lastly, because abundance estimates derived from ChesMMAP for weakfish and Atlantic croaker tend to be dominated by catches in VA portions of the Bay, I determined if VA only catches are more appropriate than Bay-wide catches for reporting estimates of age-specific adult abundance for these two species.

Distributional assumptions

A large proportion of zero catches is frequently encountered in fishery-independent catch data, including the VIMS juvenile finfish surveys. Data from the VIMS juvenile finfish surveys are currently assumed to be log-normally distributed. To evaluate the distribution of the catch data from the juvenile finfish surveys, the following candidate distributions were examined based upon their usefulness for modeling fishery-independent catch data (Table 4): normal, Poisson, gamma, negative binomial, and lognormal (Cadigan and Myers 2001; Jiao and Chen 2004). Maximum likelihood was used to fit five different probability density/mass functions to the catch data for each species. An information theoretic approach was then used to select the most appropriate distribution among the candidate set (Burnham and Anderson 2002) for each year (striped bass) or stratum (weakfish, Atlantic croaker). Akaike's Information Criterion (AIC) has been used effectively for identifying the underlying distributions of fisheries data (Dick 2004) and medical data (Lindsey and Jones 1998). However, AIC selects the best of the competing models and does not necessarily identify the true distribution (Burnham and Anderson 2002; Dick 2004).

To allow for sufficient sample sizes for weakfish and Atlantic croaker, the distributions were fitted to stratum-specific catch data that were collapsed across the years 1993-2007. Including the bias correction term for small sample sizes, Akaike's Information Criterion (AIC_c) was calculated as:

$$AIC_c = -2 * \ln(l(\theta)) + 2K + \frac{2K(K+1)}{n-K-1} \tag{8}$$

where $l(\theta)$ is the value of the maximized likelihood from the probability density/mass function of the fitted distribution, K is the number of parameters, and n is the sample size (Burnham and Anderson 2002). Models were compared using ΔAIC_c, where ΔAIC_c is the difference between the AIC_c values for each distribution and the AIC_c value for the distribution with the smallest AIC_c. Distributions with ΔAIC_c values from 0-4 were strongly supported (Burnham and Anderson 2002). Akaike weights were calculated to represent the relative weight of evidence for the i^{th} model given the set of candidate models (Burnham and Anderson 2002). Akaike weights were calculated and reported as:

$$W_i = \frac{\exp\left(-\frac{1}{2}\Delta_i\right)}{\sum_{r=1}^{R}\exp\left(-\frac{1}{2}\Delta_r\right)} \tag{9}$$

where Δ_i is the difference between the AIC_c value for the i^{th} model and the smallest AIC_c value for all models considered, and R is the number of candidate models (Burnham and Anderson 2002). If the results of the AIC_c analysis indicated that the catch data were log-normally distributed, then the geometric mean was confirmed as the appropriate form of the recruitment index. However, if an alternative distribution was selected as the preferred distribution, then the measure of central tendency for the selected distribution was used to calculate the recruitment index (Table 4). Graphical comparisons were also made to examine the patterns in the recruitment indices when the index was expressed in different forms.

To examine the influence of zero catches on the recruitment index calculation, recruitment indices were developed using a delta-lognormal distribution. The delta-lognormal distribution accounts for the proportion of zero and nonzero catches separately. The catch data from the nonzero tows is log-transformed, and the average catch rate is determined. The delta-lognormal estimate of the mean is the product of the two components (Aitchison and Brown 1957):

$$\bar{x} = \hat{p} * \frac{1}{n}\sum_{i=1}^{n_1} x_i \tag{10}$$

where p is the proportion of nonzero tows, n is the total sample size (number of tows, including zero catches), n_1, is the non-zero values, and x_i is the catch data from the nonzero tows. The underlying assumption of this model is that the nonzero values follow a lognormal distribution. AIC_c values were calculated and used to select the most appropriate distribution (Table 4) for the non-zero catches (Burnham and Anderson 2002). For cases in which the positive catch data were lognormally distributed, the delta-lognormal distribution was applied. Estimates of age-specific adult abundance were then regressed against the modified delta-lognormal recruitment indices. Improvement in the relationships between the recruitment indices and estimates of age-specific adult abundance indicated a preference for the delta-lognormal distribution.

RESULTS

Striped Bass

Simple linear regressions were constructed for seven age classes using the original VA and MD recruitment indices. Initially, the abundance data for 3 of 7 age classes (ages 1, 3, and 6) exhibited significant correlations using the VA striped bass recruitment index (Figure 7), and 5 of 7 age classes exhibited significant correlations using the MD striped bass recruitment index (Table 5). Recruitment indices for which abundance at a later age was significant suggest that during years of low recruitment, estimates of age-specific adult abundance will be lower than years when the recruitment index is high. The results signify the reliability of some measurements of striped bass abundance at different life stages by the VIMS finfish surveys.

A recruitment index based on YOY abundance in VA and MD combined (Bay-wide index, *Index* 1) exhibited significant correlations with all age classes of striped bass except age-2 (Table 5). Significant correlations were obtained for 5 of 7 age classes when YOY catch data collected from auxiliary stations were incorporated into the VA recruitment index and were subsequently combined with the MD index. Thus, incorporating YOY catch data from VA auxiliary stations in the recruitment index does not appear to provide a better indicator of subsequent adult abundance relative to the Bay-wide index. Although the majority of catches of adult striped bass are obtained by

ChesMMAP in the MD portion of the Bay, estimates of adult abundance should also be considered on a Bay-wide scale (Table 5).

The distributional assumptions do not appear to directly influence the relationship between the recruitment indices and estimates of age-specific adult abundance for striped bass. Based on graphical comparisons, the patterns observed in the recruitment indices were the same irrespective of the distributional assumptions (Figure 8). The gamma distribution was selected as the preferred distribution for the YOY striped bass catch data (Table 6). The nonzero catch data were log-normally distributed (Table 7), however, the recruitment index developed using a delta-lognormal model did not result in a better indicator of adult abundance as compared to the original VA index or the recruitment index assuming a gamma distribution because significant correlations were obtained for only 2 of 7 age classes (Table 5). Therefore, modeling the zero and nonzero catches separately appears to be unnecessary for the purposes of calculating a recruitment index for striped bass from the VA seine survey.

Weakfish

For three age classes of weakfish, age-specific adult abundances were regressed against recruitment indices derived from the VIMS trawl survey. Only 1 of 3 age classes (age 1) exhibited a significant correlation (Table 8; Figure 9). A significant correlation was not detected between age 0 abundance from the ChesMMAP survey and the recruitment index from the VIMS trawl survey potentially as a result of the lack of representativeness of the information used to construct the recruitment index, including the index period, assignment of strata, and the distributional assumptions of the catch data.

With the addition of November to the index period, the modified weakfish recruitment index (*Index* 1) provided a better indicator of subsequent adult abundance. Significant correlations for 2 of 3 age classes (ages 0 and 1) were obtained when the modified recruitment index with the months of August to November and estimates of age-specific abundance from VA only were used (Table 8).

The current strata, including all depths and river systems, used to derive the recruitment index for weakfish appear to be appropriate. To determine if the recruitment index improved when catches of weakfish from the rivers only were used, estimates of age-specific adult abundance were regressed against the modified recruitment index calculated using catch data from the James, York, and Rappahannock Rivers (*Index* 9). No significant positive relationships were detected which indicates the importance of the VA mainstem portion of Chesapeake Bay as habitat for YOY weakfish (Table 8). Because it is unclear from the results how depth may influence the distribution and abundance of YOY weakfish in Chesapeake Bay, all depth strata should be used to develop the recruitment index for this species (Table 8).

The gamma distribution appears to be the most appropriate distribution for the weakfish catch data. For the gamma distribution, AIC_c values were the smallest for 77% of the strata; whereas, the lognormal distribution had the smallest AIC_c values for only 23% of the strata (Table 9). When zero and nonzero catches were modeled separately using the delta-lognormal model, there were no improvements in the relationships between estimates of age-specific adult abundance and the recruitment indices for weakfish. The nonzero catches of YOY weakfish were log-normally distributed (Table 10); however, the adjusted recruitment index calculated using a delta-lognormal model did not provide a better indicator of subsequent adult abundance. A slight decrease in the correlation coefficients for each of the three age classes indicated that the application of the delta-lognormal neither strengthened nor weakened the overall relationships between the recruitment indices and estimates of age-specific adult abundance (Table 8). Therefore, the appropriate weakfish recruitment index is based on the measure of central tendency of the gamma distribution (Table 4).

The strength of the relationships between the recruitment indices and estimates of age-specific adult abundance for weakfish is influenced by the distributional assumptions of the YOY catch data. When the recruitment index was re-estimated assuming the catch data were gamma distributed, the only significant correlation was obtained for 2-yr old fish (Table 8). Additionally, a difference in the pattern of the weakfish recruitment index is observed depending on whether the catch data are assumed to be gamma or log-normally distributed (Figure 10).

Atlantic croaker

For Atlantic croaker, 3 of 7 age classes (ages 1, 2, and 5) exhibited a significant correlation between estimates of age-specific adult abundance and the original recruitment index (Table 11; Figure 11). Five of seven age classes (ages 1-4, and 6) exhibited significant correlations when the index period used to derive the modified recruitment indices included 3 months (April, May, and June) instead of the original 4 months (May, June, July, and August) and estimates of age-specific adult abundance from VA and MD were used (Table 11).

When the index period is modified to include the months April through June, catch data from all depths and systems should be used to derive the recruitment index for Atlantic croaker. Five of the seven age classes (ages 1, 2, 4-6) exhibited significant correlations when catch data collected from depths less than 30 ft (Table 11) and the original index period was used. However, modifying the index (*Index 5*) by redefining the index period (April – June) and using catch data from strata less than or equal to 30 ft does not provide a better indicator of subsequent adult abundance relative to the use of a modified index period (*Index* 1) with depth strata included (Table 11). Based upon the principle of parsimony, the most appropriate index for Atlantic croaker appears to require the use of catch data from April, May, and June as the index period and all depth strata.

The lognormal distribution was selected as the preferred distribution for the YOY Atlantic croaker catch data. The lognormal distribution had the smallest AIC_c values for 66% of the strata; whereas, the gamma distribution had the smallest AIC_c values for 34% of the strata (Table 12). Thus, the geometric mean is appropriate for expressing the recruitment index for Atlantic croaker. When the delta-lognormal distribution was applied to the catch data and the recruitment index was re-estimated, the modified index (*Index* 12) did not provide a better indicator of subsequent adult abundance (Table 11, 13).

DISCUSSION

Recruitment indices as indicators of subsequent adult abundance

The results of this study demonstrate the use of recruitment indices derived from juvenile finfish surveys for striped bass, weakfish, and Atlantic croaker as early indicators of subsequent age-specific adult abundance. Year-class strength was reflected in subsequent estimates of age-specific adult abundance; however, the strength of the relationships between recruitment indices and adult abundances varied greatly with age. The initial lack of significant correlations across all age classes and species indicated the need for exploring and potentially improving the recruitment indices to more appropriately reflect YOY abundance by focusing on the information used to construct the recruitment indices, including the assignment of the index period and strata, and the distributional assumptions of the data. Based on this study, the VIMS juvenile finfish surveys are useful tools for measuring recruitment to the juvenile stage; however, the results emphasize the importance of further investigation of the species-specific information required to derive a reliable recruitment index, particularly for species not examined here. Lognormality is not an appropriate assumption for all catch data and should be investigated on a species-specific basis. Additionally, the application of the delta-lognormal distribution to calculate a recruitment index did not provide a better indicator of subsequent adult abundance for any of the species in this study; therefore, modeling the zero and nonzero catches separately appears to be unnecessary for calculating recruitment indices for striped bass, weakfish, and Atlantic croaker from the juvenile finfish surveys.

Fisheries-dependent data have been the source of estimates of age-specific adult abundance in previous studies (Crecco *et al.* 1983; Goodyear 1985; Hare and Able 2007). However, this study is unique in that survey-based estimates of adult abundance were used. Unlike sampling in small streams (Jordan *et al.* 2008) or closed systems such as lakes, it is difficult to obtain multiple fishery-independent estimates of abundance in open marine and estuarine environments due to the high costs associated with sampling. Multispecies surveys, such as the VIMS finfish surveys, offer a practical means for obtaining estimates of relative abundance. The sampling strategy is designed to accommodate the ecology and distribution of various species without focusing on one species in particular. In general, life history characteristics influence the distribution and abundance of a species. In this study, I selected three species with contrasting reproductive strategies to determine if the surveys perform more favorably for a species with certain reproductive strategy. Although I did not evaluate the performance of the surveys *per se*, I attempted to determine the influence of contrasting life histories, with respect to the temporal and spatial use of the estuaries, on the recruitment of YOY fishes as measured by the VIMS juvenile finfish surveys. Future studies should include a larger number of species that represent different reproductive strategies. The abundance of YOY finfishes in Chesapeake Bay as measured by the VIMS juvenile finfish surveys is also likely influenced by the synergistic effects of other biotic factors, such as predator-prey interactions, and abiotic factors, such as salinity, temperature, and dissolved oxygen.

The main limitation of this study is the availability of only six data points in the regression analyses between the recruitment indices and estimates of adult abundance. Although six data points are sufficient for investigating the nature of the assumed linear relationship between two variables, more data points would be helpful for determining the degree to which a linear function describes the relationship between two variables. Consequently, the methods presented here should be revisited in the future to determine if linear relationships are supported with additional years of data. Another limitation of this study is the fact that estimates of adult abundance from the ChesMMAP survey were assumed to be measured accurately; however, the information used to derive these estimates should also be investigated to ensure that they reflect patterns in actual abundance of adult fishes. Lastly, age-specific fishing mortality for each species was assumed to remain constant through time as supported by the lack of significant management changes for striped bass (ASMFC 2007), weakfish (ASMFC 2006), and Atlantic croaker (ASMFC 2006) during the last several years.

An additional limitation of this study is the small number of age classes examined for weakfish. Only three age classes were examined due to the lack of sufficient sample sizes of adult weakfish older than 2 years from the ChesMMAP survey. No weakfish older than 4 years have been captured by the ChesMMAP survey since 2002 (Bonzek *et al.* 2007) concurrent with considerable declines in stocks as evidenced by commercial and recreational landings (ASMFC 2006). Currently, there is a paucity of information on weakfish population dynamics, and estimated spawning stock biomass has been declining steadily since 1998 (ASMFC 2006). Nevertheless, the findings of this study may be used to guide future research on weakfish to better understand the factors that influence habitat use by YOY fish.

The distributional assumptions of catch data from juvenile finfish research surveys require examination to evaluate the influence of zero observations on the underlying distribution and to ensure that recruitment indices are calculated appropriately for each species. For standardized surveys using the same gear and survey design, zero observations likely occur as a result of the biology and ecology of YOY fishes, such as the absence of a species in a particular area due to unsuitable habitat. My conclusions do not support the results of Chittenden (1991) in which the log transformation was determined appropriate for weakfish abundance data from the VIMS trawl survey. However, I examined distributions that had not been previously considered by Chittenden (1991), including the gamma distribution which I found to be more suitable for the weakfish abundance data.

A Bay-wide recruitment index appears to more accurately reflect year-class strength for Chesapeake Bay striped bass than the state-specific recruitment indices currently used by both VA and MD. The results of this study suggest that recruitment indices could be combined across jurisdictions to more appropriately reflect YOY abundance of striped bass on a Bay-wide scale. Although the VA index exceeds the MD index 57% of the years between 1980 and 2007 (Figure 12), a Bay-wide recruitment index is practical because YOY striped bass recruit to tributaries throughout Chesapeake Bay (Olney *et al.* 1991; Rutherford and Houde 1995; Durell and Weeden 2007; Hewitt *et al.* 2008). The primary contributors to the Atlantic coastal fishery for striped bass are the Chesapeake Bay and Hudson River populations (Berggren and Lieberman 1978; Wirgin *et al.* 1993) with contributions varying among year classes (Van Winkle *et al.* 1988) and through time (Fabrizio 1987). Due to the importance of the contributions of Chesapeake Bay striped bass populations to the coastal fishery, it is imperative that estimates of YOY striped bass are measured accurately for stock assessment purposes.

My results support the notion that year-class strength for striped bass in Chesapeake Bay is established prior to the summer months during which YOY fish are captured by the VA seine survey. Hurst and Conover (1998) failed to detect a significant correlation between abundance of YOY striped bass and age-1 abundance in the Hudson River. They argued that winter severity regulates the recruitment of YOY striped bass to the Hudson River population such that year-class strength is not established until the spring of the first year (Hurst and Conover 1998). Year-class strength of striped bass in Chesapeake Bay is primarily influenced by density-independent factors such as the effects of freshwater pulses on the transport and retention of larvae and post-larvae in the estuarine turbidity maximum (North and Houde 2001; North *et al.* 2005), and the effects of temperature on larval growth rates and stage duration (Rutherford and Houde 1995; Secor and Houde 1995).

For weakfish and Atlantic croaker, changes to the index period resulted in recruitment indices that provided better indicators of subsequent adult abundance. To ensure that the recruitment index reflects the relative abundance of YOY weakfish, the seasonal migration patterns of YOY fish should be accounted for in the index period. Prior to migrating to overwintering grounds off of the coast of North Carolina, YOY weakfish remain in Chesapeake Bay through November (Wilk 1976) as evidenced by historical information and catches from the VIMS trawl survey. Although weakfish generally occupy Chesapeake Bay from April to November (Pearson 1941; Massman *et al.* 1958), November may not have previously been considered an index month because YOY catches tend to be smaller in November than in August-October. Nevertheless, the inclusion of an additional month of YOY catch data into the recruitment index calculation better reflects the relative abundance of YOY weakfish in Chesapeake Bay. This is further supported by the observation of multiple age-0 cohorts in the York River (Szedlmayer *et al.* 1990). Collectively, these studies may indicate the need for incorporating an additional month into the index period. Further research may be necessary to determine if multiple age-0 cohorts are observed in the James and Rappahannock Rivers and the mainstem of Chesapeake Bay. For Atlantic croaker, the recruitment index can be improved by shifting the index period earlier to include catches of YOY fish from April through June. The VIMS trawl survey catches YOY Atlantic croaker year round (Fabrizio and Tuckey 2008), although Chao and Musick (1977) noted that YOY Atlantic croaker are present in the York River in large numbers throughout the year except during June-August.

Habitat-structuring variables and distribution and abundance of juvenile fishes

Several habitat-structuring factors may contribute to variations in the distribution and abundance of juvenile fishes including salinity (Weinstein 1980; Peterson *et al.* 1999, Paperno et al. 2000; Miller *et al.* 2003; Ross 2003), temperature (Norcross 1983; Lankford and Targett 2001), and substrate type (Martin *et al.* 1995; Miller *et al.* 2003). Although juvenile weakfish recruit to all areas of Delaware Bay, the greatest recruitment occurs in areas with salinities less than 20 ppt (Paperno *et al.* 2000). However, Paperno *et* *al.* (2000) observed lower growth rates, smaller lengths-at-age, and lower mortality rates in oligohaline portions of the upper Delaware Bay suggesting a tradeoff between minimizing mortality potentially due to predation and optimizing growth (Lankford and Targett 1994). Miller *et al.* (2003) determined that YOY Atlantic croaker were collected across a wide range of salinities in the deeper waters of Delaware Bay, but were most abundant over muddy areas. In Chesapeake Bay, YOY Atlantic croaker exhibit preference for waters with salinities less than 18 ppt (Haven 1957). The results presented here do not support Haven's findings because the use of a rivers only recruitment index did not improve estimates of subsequent adult abundance. However, it is important to note that the rivers only index may have catch data from stations with salinities slightly higher than 18 ppt particularly in the lower portion of the rivers. Similarly, Ross (2003) concluded that upstream oligohaline habitats provide the optimal environment for YOY Atlantic croaker in Cape Fear and Pamlico Sound, NC based on growth, mortality, and distribution data. Both laboratory and field studies have also identified an inverse relationship between salinity and growth of YOY Atlantic croaker (Peterson *et al.* 1999; Rakocinski *et al.* 2000).

In general, species-specific responses to environmental gradients may result in large-scale (approximately 10km) patterns in the structure of estuarine fish assemblages, whereas habitat associations driven by competition, predator avoidance strategies, and habitat selection may drive smaller scale patterns (Martino and Able 2003). Paperno and Brodie (2004) noted that differences in salinity, temperature, depth, and the influx of juvenile fishes may also result in small-scale differences in fish assemblages found in nursery areas of the St. Sebastian River, Florida. Araujo *et al.* (2006) postulate that habitat partitioning is the result of species-specific responses to environmental gradients which act as a density structuring mechanism for the abundance of Sciaenids in Sepetiba Bay, a tropical embayment of southeastern Brazil. Dissolved oxygen concentrations may also influence the distribution and abundance of YOY weakfish and Atlantic croaker. Tyler and Targett (2007) concluded that juvenile weakfish in a small mesohaline tributary of Delaware Bay exhibit an avoidance threshold of ~2.0 mgO_2l^{-1} and demonstrate short-term changes in distribution associated with variable dissolved oxygen levels. Eby and Crowder (2002) previously reported an avoidance threshold of 2.3 mgO_2l^{-1} for Atlantic croaker. Furthermore, the avoidance threshold may be influenced by the spatial extent of the hypoxia (Eby and Crowder 2002). Similarly, collections of Atlantic croaker have occurred at concentrations of 1-2 mgO_2l^{-1} in the Neuse River Estuary, NC (Bell and Eggleston 2005). High densities of Atlantic croaker have been reported at the offshore edge of the hypoxic region in the northwestern Gulf of Mexico where Atlantic croaker were observed at dissolved oxygen concentrations ranging between 1.6 and 3.7 mgO_2l^{-1} (Craig and Crowder 2005). The results of previous studies designed to investigate the influence of abiotic factors on the abundance of YOY weakfish and Atlantic croaker neither corroborate nor contradict the findings presented here because additional environmental factors, such as dissolved oxygen, temperature, and salinity were not included in this study. Instead, the existing literature indicates the need for considering abiotic factors in future studies designed to evaluate factors influencing the recruitment of fishes to the juvenile stage. This claim is further supported by the hydrodynamic and physico-chemical differences between the Chesapeake Bay and the James, York, and Rappahannock Rivers which likely influence catch rates of YOY fishes. For example, of the three tributaries, the James River is closest in proximity to the mouth of Chesapeake Bay, allowing for higher exchange rates, less stratification, and similar dissolved oxygen levels between shallow (≤30 ft) and deep (>30 ft) stations in most years (Figure 13). The James River is also shallower, in general, than the Rappahannock River which exhibits consistently lower dissolved oxygen levels in deep areas during the summer months (Figure 14). Future studies may be used to elucidate how abiotic factors, such as salinity and dissolved oxygen, influence the distribution, and ultimately, abundance of YOY fishes in Chesapeake Bay.

Among other factors, depth influences the composition of fish communities in an estuarine environment (Loneragan *et al.* 1987; Martino and Able 2003). Haven (1957) determined that YOY Atlantic croaker in the York River are confined to the bottom waters of relatively deep channels with some venturing into adjacent shoal waters and very few near shore. Depth has also been shown to influence the distribution of some Sciaenids, including whitemouth croaker (*Micropogonias fumieri*) and barbel drum (*Ctenosciaena gracilicirrhus*) but not others, such as smooth weakfish (*Cynoscion leiarchus*) and southern kingcroaker (*Menticirrhus americana*), in Sepetiba Bay, Brazil (Araujo *et al.* 2006). In this study, the modified recruitment indices constructed using depths less than or greater than 30 ft did not result in better indicators of subsequent adult abundance for weakfish or Atlantic croaker. Although the results suggest that depth does not need to be accounted for when constructing a recruitment index for these species, this may be due to the way depth was included in this study. Deep and shallow areas were partitioned at 30 ft in accordance with the stratification of the VIMS trawl survey but this level of resolution may have limited the extent to which the influence of depth on abundance could be detected.

Although I did not detect an influence of depth on the distribution and abundance of YOY weakfish and Atlantic croaker, the physical and chemical characteristics of brackish water that vary spatially and temporally with depth in an estuary may, in part, contribute to variations in the distribution and abundance of YOY finfishes in Chesapeake Bay. During index months, catches of YOY weakfish tend to be highest at dissolved oxygen concentrations from 4 to 7 mgO_2l^{-1} (Figure 15), salinities typically less than 20 ppt with catches remaining high at salinities of 25 ppt in some years (Figure 16), and bottom water temperatures between 25 and 28 °C (Figure 17). Similarly, catches of YOY Atlantic croaker during index months tend to be highest at dissolved oxygen concentrations from 4 to 7 mgO_2l^{-1} (Figure 18), salinities typically less than 25 ppt (Figure 19), and bottom water temperatures between 20 and 28 °C (Figures 20).

Model-based abundance estimates

If the abundances of YOY finfishes captured by the VIMS trawl survey are influenced by factors such as temperature, salinity, dissolved oxygen concentrations, tidal stage, and depth, then accounting for these factors in model-based estimates of abundance may improve recruitment indices. Currently, recruitment indices are developed using design-based theory, where abundance estimates are derived from a stratified random design that specifies how observations (i.e. stations) are selected (Smith 1990). In contrast, model-based estimates of abundance are derived according to the statistical model being used (Smith 1990). For instance, recruitment indices could be constructed using generalized linear models (GLMs) to examine the effects of additional environmental covariates on abundance. In GLMs, the distribution of the response variable is not limited to the normal distribution and can include members of the exponential family, such as the gamma distribution (McCullagh and Nelder 1989), which has been demonstrated in this study to be appropriate for the striped bass and weakfish catch data. Incorporating additional explanatory variables into a model-based framework for estimating relative abundance will account for a greater amount of variability that is not due to actual changes in abundance but that arises due to other factors being considered, such as dissolved oxygen or temperature. In addition to other species, GLMs have been used to construct abundance estimates for cod (Smith 1990; Brynjorsdottir and Steffanson 2004); horse mackerel (*Trachurus trachurus*), blue whiting (*Micromesistiums poutassou*), and hake (*Merluccius merluccius*) (Sousa *et al.* 2007), juvenile reef fishes (Mellin *et al.* 2007), and larval fishes (Franco-Gordo *et al.* 2004). Alternatively, generalized additive models (GAMs) may also be useful as an exploratory tool for understanding the relationships between environmental variables and the relative abundance of fishes captured by the VIMS juvenile finfish surveys. Unlike GLMs, GAMs do not assume a linear relationship between the response and predictor variables; therefore, these models can be used to investigate non-linear relationships (Hastie *et al.* 2001). GAMs are modeled as the sum of a function of the predictors; whereas, generalized linear models are modeled as the sum of the linear combination of predictor variables and are constrained to a linear fit (Quinn and Keough 2002). GAMs have been successfully applied to analyze patterns in abundance of pelagic fishes (Peltonen *et al.*

2007), estimate population size of seabirds (Clarke *et al.* 2003), and standardize CPUE data (Maunder and Punt 2004).

Conclusions

Investigating the relationships between estimates of YOY and adult abundance can help determine if recruitment indices reflect abundance of the year class. Although year-class strength was reflected in subsequent estimates of age-specific adult abundance, the results varied by age class indicating the need for continued examination of the assignment of the index period and strata used to calculate recruitment indices for species captured by the VIMS juvenile finfish surveys. Despite the common application of the lognormal assumption, I determined that it is not always appropriate for catch data from the VIMS juvenile fish surveys. The gamma distribution is a more flexible distribution that is a reasonable description of the distribution of the catch data for some species. Other model-based approaches, such as GLMs or GAMs, should also be considered to investigate the influence of environmental variables on YOY abundance estimates. This will ensure that the best available information is used to develop a recruitment index that appropriately reflects abundance of YOY fishes in Chesapeake Bay.

LITERATURE CITED

Aitchison, J., and J.A.C. Brown. 1957. The lognormal distribution. Cambridge University Press. New York, NY.

Araujo, F. G., F. J. da C. Guimaraes, and M. R. da Costa. 2006. Environmental influences on distribution of four Sciaenidae species (Actinopterygii, Perciformes) in a tropical bay at Southeastern Brazil. Revista Brasileira de Zoologia 23(2): 497-508.

ASMFC (Atlantic States Marine Fisheries Commission). 2006. 2006 review of the ASMFC fishery management plan for Atlantic croaker (*Micropogonias undulatus*). ASMFC, Washington, D.C.

ASMFC (Atlantic States Marine Fisheries Commission). 2006. 2006 weakfish stock assessment. ASMFC, Washington, D.C.

ASMFC (Atlantic States Marine Fisheries Commission). 2007. 2007 review of the ASMFC fishery management plan for Atlantic striped bass (*Morone saxatilis*). ASMFC, Washington, D.C.

Austin, H. M., J. A. Colvocoresses, and T. A. Mosca III. 1993. Developing a Chesapeake Bay-wide young-of-the-year striped bass index. Final Report, CBSAC Cooperative Agreement NA16FU0393-01, 59 p.

Axenrot, T., and S. Hannson. 2003. Predicting herring recruitment from young-of-the-year densities, spawning stock biomass, and climate. Limnology and Oceanography 48(4): 1716-1720.

Bailey, K. M., and S. M. Spring. 1992. Comparison of larval, age-0 juvenile and age-2 recruit abundance indices of walleye Pollock, *Theragra chalcogramma*, in the western Gulf of Alaska. ICES Journal of Marine Science 49: 297-304.

Barbieri, L. R., M. E. Chittenden Jr., and C. M. Jones. 1994. Age, growth, and mortality of Atlantic croaker, *Micropogonias undulatus*, in the Chesapeake Bay region, with a discussion of apparent geographic changes in population dynamics. Fishery Bulletin 92:1-12.

Bell, G. W., and D. B. Eggleston. 2005. Species-specific avoidance responses by blue crabs and fish to chronic and episodic hypoxia. Marine Biology 146: 761-770.

Berggren, T. J. and J. T. Lieberman. 1978. Relative contribution of Hudson, Chesapeake, and Roanoke striped bass *Morone saxatilis* stocks to the Atlantic coast fishery. Fishery Bulletin 76(2): 335-342.

Bonzek, C. F., R. J. Latour, and J. Gartland. 2007. Data collection and analysis in support of single and multispecies stock assessments in Chesapeake Bay: the Chesapeake Bay multispecies monitoring and assessment program. Annual report to Virginia Marine Resources Commission and U.S. Fish and Wildlife Service. Project No. F-130-R-1. Virginia Institute of Marine Science, Gloucester Pt. VA. 23062.

Brynjorsdottir, J., and G. Stefannson. 2004. Analysis of cod catch data from Icelandic groundfish surveys using generalized linear models. Fisheries Research 70: 195-208.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multi-model inference: a practical information-theoretic approach. Springer-Verlag, New York, NY.

Cadigan, N. G., and R. A. Myers. 2001. A comparison of gamma and lognormal maximum likelihood estimators in a sequential population analysis. Canadian Journal of Fisheries and Aquatic Sciences 58: 560-567.

Carlson, J. K, J. Osborne, and T. W. Schmidt. 2007. Monitoring the recovery of smalltooth sawfish, *Pristis pectinata*, using standardized relative indices of abundance. Biological Conservation 136(2): 195-202.

Chao, L. N., and J. A. Musick. 1977. Life history, feeding habits, and functional morphology of juvenile sciaenid fishes in the York River Estuary, Virginia. Fishery Bulletin 75(4): 657-702.

Chen, J., M. E. Thompson, and C. Wu. 2004. Estimation of fish abundance indices based on scientific research trawl surveys. Biometrics 60(1): 116-123.

Chittenden, M. E. 1991. Evaluation of spatial/temporal sources of variation in nekton catch and the efficacy of stratified sampling in the Chesapeake Bay. Final Report for CBSAC to Chesapeake Bay Stock Assessment Committee and the National Marine Fisheries Service, NOAA. Virginia Institute of Marine Science, Gloucester Pt. VA. 23062.

Clarke, E. D., L. B. Spear, M. L. McCracken, F. F. C. Marques, D. L. Borchers, S. T. Buckland, D. G. Ainley. 2003. Validating the use of generalized additive models and at-sea surveys to estimate size and temporal trends of seabird populations. Journal of Applied Ecology 40(2): 278-292.

Cochran, W. G. 1977. Sampling techniques. John Wiley & Sons. New York, NY.

Craig, J. K., and L. B. Crowder. 2005. Hypoxia-induced habitat shifts and energetic consequences in Atlantic croaker and brown shrimp on the Gulf of Mexico shelf. Marine Ecology Progress Series 294: 79-94.

Crecco, V., T. Savoy, and L. Gunn. 1983. Daily mortality rates of larval and juvenile American shad (*Alosa sapidissima*) in the Connecticut River with changes in year-class strength. Canadian Journal of Fisheries and Aquatic Sciences 40(10): 1719-1728.

Crozier, W. W., and G. J. A. Kennedy. 1995. Application of a fry (0+) abundance index, based on semi-quantitative electrofishing, to predict Atlantic salmon smolt runs in the River Bush, Northern Ireland. Journal of Fish Biology 47: 107-114.

Dick, E. J. 2004. Beyond 'lognormal versus gamma': discrimination among error distributions for generalized linear models. Fisheries Research 70: 351-366.

Dingsor, G. E., L. Ciannelli, K. S. Chan, G. Ottersen, and N. C. Stenseth. 2007. Density dependence and density independence during the early life stages of four marine fish stocks. Ecology 88(3): 625-634.

Durell, E. Q., and Weedon, C. 2007. Striped Bass Seine Survey Juvenile Index Web Page. http://www.dnr.state.md.us/fisheries/juvindex/index.html. Maryland Department of Natural Resources, Fisheries Service.

Eby, L. A., and L. B. Crowder. 2002. Hypoxia-based habitat compression in the Neuse River estuary: context-dependent shifts in behavioral avoidance thresholds. Canadian Journal of Fisheries and Aquatic Sciences 59: 952-965.

Evans, M., N. Hastings, and B. Peacock. 1993. Statistical distributions second edition. John Wiley & Sons, Inc. New York, NY.

Fabrizio, M. C. 1987. Contribution of Chesapeake Bay and Hudson River stocks of striped bass to Rhode Island coastal waters as estimated by isoelectric focusing of eye lens proteins. Transactions of the American Fisheries Society 116: 588-593.

Fabrizio, M. C., and T. D. Tuckey. 2008. Estimating relative abundance of ecologically important finfish in the Virginia portion of Chesapeake Bay. Annual report to Virginia Marine Resources Commission Project F-104-R-12. Virginia Institute of Marine Science, Gloucester Pt., VA 23062. 84 p.

Fogarty, M. J. 1993. Recruitment in randomly varying environments. ICES Journal of Marine Science 50:247-260.

Fogarty, M. J., M. P. Sissenwine, and E. B. Cohen. 1991. Recruitment variability and the dynamics of exploited marine populations. Trends in Ecology and Evolution 6(8): 241-246.

Franco-Gordo, C., E. Godinez-Dominguez, A. E. Filonov, I. E. Tereshchenko, and J. Freire. 2004. Plankton biomass and larval fish abundance prior to and during the El Nino period of 1997-1998 along the central Pacific coast of Mexico. Progress in Oceanography 63: 99-123.

Goodyear, C. P. 1985. Relationship between reported commercial landings and abundance of young striped bass in Chesapeake Bay, Maryland. Transactions of the American Fisheries Society 114:92-96.

Gulland, J. A. 1969. Manual of methods for fish stock assessment. Part 1. Fish population analysis. FAO (Food and Agriculture Organization of the United Nations) Manuals in Fisheries Science 4, Rome.

Hare, J. A. and K. W. Able. 2007. Mechanistic links between climate and fisheries along the east coast of the United States: explaining population outbursts of Atlantic croaker (*Micropogonias undulatus*). Fisheries Oceanography 16(1): 31-45.

Hastie, T., R. Tibshirani, and J. Friedman. 2001. The elements of statistical learning: data mining, inference, and prediction. Springer-Verlag, New York, NY.

Haven, D. S. 1957. Distribution, growth, and availability of juvenile croaker, *Micropogonias undulatus*, in Virginia. Ecology 38(1): 88-97.

Haven, D. S. 1959. Migration of the croaker, *Micropogonias undulatus*. Copeia: 1959(1): 25-30.

Helle, K., B. Bogstad, C. T. Marshall, K. Michalsen, G. Ottersen, and M. Pennington. 2000. An evaluation of recruitment indices for Arcto-Norwegian cod (*Gadus morhua* L.). Fisheries Research (Amsterdam) 48(1): 55-67.

Helser, T. E. and D. B. Hayes. 1995. Providing quantitative management advice from stock abundance indices based on research surveys. Fishery Bulletin 93: 290-298.

Hewitt, A. H., L. S. Machut, and M. C. Fabrizio. 2008. Estimation of juvenile striped bass relative abundance in the Virginia portion of Chesapeake Bay. Annual Report 2007. Virginia Institute of Marine Science, Gloucester Point, VA, 23062. 28 pp.

Hilborn, R, and C. J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics, and uncertainty. Chapman and Hall, Inc., New York, NY.

Houde, E. D. 1987. Fish early life dynamics and recruitment variability. American Fisheries Society Symposium 2: 17-29.

Houde, E. D. 1989. Subtleties and episodes in the early life histories of fishes. Journal of Fish Biology 35(Supplement A): 29-38.

Hurst, T. P., and D. O. Conover. 1998. Winter mortality of young-of-the-year Hudson River striped bass (*Morone saxatilis*): size-dependent patterns and effects on recruitment. Canadian Journal of Fisheries and Aquatic Sciences 55: 1122-1130.

Jennings, S., M. J. Kaiser, and J. D. Reynolds. 2001. Marine fisheries ecology. Blackwell Publishing, Malden, MA.

Jiao, Y., and Y. Chen. 2004. An application of generalized linear models in production model and sequential population analysis. Fisheries Research 70: 367-376.

Jordan, F., H. L. Jelks, S. A. Bortone, R. M. Dorazio. 2008. Comparison of visual survey and seining methods for estimating abundance of an endangered, benthic stream fish. Environmental Biology of Fishes 81: 313-319.

Joseph, E. B. 1972. The statues of the sciaenid stocks of the middle Atlantic coast. Chesapeake Science 13(2): 87-100.

Koo, T. S. Y. 1970. The striped bass fishery in the Atlantic states. Chesapeake Science 11(2): 73-93.

Lankford, T. E., Jr., and T. E. Targett. 1994. Suitability of estuarine nursery zones for juvenile weakfish (*Cynoscion regalis*): effects of temperature and salinity on feeding, growth and survival. Marine Biology 119: 611-620.

Lankford, T. E., Jr., and T. E. Targett. 2001. Low-temperature tolerance of age-0 Atlantic croakers: recruitment implications for U.S. mid-Atlantic estuaries. Transactions of the American Fisheries Society 130: 236-249.

Lindsey, J. K., and B. Jones. 1998. Choosing among generalized linear models applied to medical data. Statistics in Medicine 17: 59-68.

Lo, N. C., L. D. Jacobson, and J. L. Squire. 1992. Indices of relative abundance from fish spotter data based on delta-lognormal models. Canadian Journal of Fisheries and Aquatic Sciences 49: 2515-2526.

Loneragan, N. R., I. C. Potter, R. C. J. Lenanton, and N. Caputi. 1987. Influence of environmental variables on the fish fauna of the deep waters of a large Australian estuary. Marine Biology 94: 631-641.

Lowerre-Barbieri, S. K., M. E. Chittenden, Jr., and L.R. Barbieri. 1996. The multiple spawning pattern of weakfish in the Chesapeake Bay and Middle Atlantic Bight. Journal of Fish Biology 48: 1139-1163.

Martin, T. J., D. T. Brewer, and S. J. M. Blaber. 1995. Factors affecting distribution and abundance of small demersal fishes in the Gulf of Carpentaria, Australia. Marine and Freshwater Research 46: 909-920.

Martino, E. J., and K. W. Able. 2003. Fish assemblages across the marine to low salinity transition zone of a temperate estuary. Estuarine, Coastal and Shelf Science 56: 969-987.

Massman, W. H., J. P. Whitcomb, and A. L. Pacheco. 1958. Distribution and abundance of gray weakfish in the York River system, Virginia. Transactions of the North American Wildlife Conference 23: 361-369.

Maunder, M. N., and A. E. Punt. 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research 70: 141-159.

McCullagh, P., and J. A. Nelder. 1989. Generalized Linear Models. Chapman and Hall, London.

McGovern, J. C., and J. E. Olney. 1996. Factors affecting survival of early life stages and subsequent recruitment of striped bass on the Pamunkey River, Virginia. Canadian Journal of Fisheries and Aquatic Sciences 53(8): 1713-1726.

Mellin, C., S. Andrefouet, and D. Ponton. 2007. Spatial predictability of juvenile fish species richness and abundance in a coral reef environment. Coral Reefs 26(4): 895-907.

Mercer, L. P. 1985. Fishery Management plan for the weakfish (*Cynoscion regalis*) fishery. North Carolina Department of Natural Resources and Community Development, Division of Marine Fisheries, Special Scientific Report 46, Morehead City, NC.

Miller, M. J., D. M. Nemerson, and K. W. Able. 2003. Seasonal distribution, abundance, and growth of young-of-the-year Atlantic croaker (*Micropogonias undulatus*) in Delaware Bay and adjacent marshes. Fishery Bulletin 101(1): 100-115.

Morse, W.W. 1980. Maturity, spawning, and fecundity of Atlantic croaker, *Micropogonias undulatus*, occurring north of Cape Hatteras, North Carolina. Fishery Bulletin 78:190-195.

Myers, R. A. and P. Pepin. 1990. The robustness of log-normal based estimators of abundance. Biometrics 46: 1185-1192.

Niemela, E., J. Erkinaro, M. Julkunen, and E. Hassinen. 2005. Is juvenile salmon abundance related to subsequent and preceding catches? Perspectives from a long-term monitoring programme. ICES Journal of Marine Science 62: 1617-1629.

Nixon, S.W. and C.M. Jones. 1997. Age and growth of larval and juvenile Atlantic croaker, *Micropogonias undulatus*, from the Middle Atlantic Bight and estuarine waters of Virginia. Fishery Bulletin 95: 773-784.

Norcross, B.L. 1983. Climate scale environmental factors affecting year-class fluctuations of Atlantic croakers (*Micropogonias undulatus*) in the Chesapeake Bay. Doctoral dissertation. The College of William and Mary, Williamsburg, VA.

North, E. W. and E. D. Houde. 2001. Retention of white perch and striped bass larvae: biological-physical interactions in Chesapeake Bay estuarine turbidity maximum. Estuaries 24(5): 756-769.

North, E. W., R. R. Hood, S.-Y. Chao, and L. P. Sanford. 2005. The influence of episodic events on transport of striped bass eggs to the estuarine turbidity maximum nursery area. Estuaries 28(1): 108-123.

Olney, J. E., J. D. Field, and J. C. McGovern. 1991. Striped Bass egg mortality, production, and female biomass in Virginia rivers, 1980-1989. Transactions of the American Fisheries Society 120: 354-367.

Ortiz, M., C. M. Legault, and N. M. Ehrhardt. 2000. An alternative method for estimating bycatch from the U.S. shrimp trawl fishery in the Gulf of Mexico, 1972-1995. Fishery Bulletin 98: 583-599.

Ortiz, M. and F. Arocha. 2004. Alternative error distribution models for standardization of catch rates of non-target species from a pelagic long-line fishery: billfish species in the Venezuelan tuna longline fishery. Fisheries Research 70: 275-297.

Paperno, R., T. E. Targett, and P. A. Grecay. 2000. Spatial and temporal variation in recent growth, overall growth, and mortality of juvenile weakfish (*Cynoscion regalis*) in Chesapeake Bay. Estuaries 23(1): 2000.

Paperno, R., and R. B. Brodie. 2004. Effects of environmental variables upon the spatial and temporal structure of a fish community in a small, freshwater tributary of the Indian River Lagoon, Florida. Estuarine, Coastal and Shelf Science 61: 229-241.

Pearson, J. C. 1941. The young of some marine fishes taken in lower Chesapeake Bay, Virginia with special reference to the gray sea trout *Cynoscion regalis* (Block and Schneider). Fishery Bulletin 50: 79-102.

Peltonen, H., M. Luoto, J-P. Paakkonen, M. Karjalainen, A. Tuomaala, J. Ponni, and M. Viitasalo. 2007. Pelagic fish abundance in relation to regional environmental variation in the Gulf of Finland, northern Baltic Sea. ICES Journal of Marine Science 64(3): 487-495.

Pennington, M. 1983. Efficient estimators of abundance, for fish and plankton surveys. Biometrics 39:281-286.

Pennington, M. 1985. Estimating the relative abundance of fish from a series of trawl surveys. Biometrics 41: 197-202.

Pennington, M. 1996. Estimating the mean and variance from highly skewed marine data. Fishery Bulletin 94(3): 498-505.

Pennington, M. and T. Stromme. 1998. Surveys as a research tool for managing dynamic stocks. Fisheries Research 37: 97-106.

Perlmutter, A., W. S. Miller, and J. C. Poole. 1956. The weakfish (*Cynoscion regalis*) in New York waters. New York Fish and Game Journal 3(1): 1-43.

Peterson, M. S., B. H. Comyns, C. F. Rakocinski, and G. L. Fulling. 1999. Does salinity affect somatic growth in juvenile Atlantic croaker, *Micropogonias undulatus* (Linnaeus)? Journal of Experimental Marine Biology and Ecology 238: 199-207.

Punt, A. E., T. I. Walker, B. L. Taylor, and F. Pribac. 2000. Standardization of catch and effort data in a spatially-structured shark fishery. Fisheries Research 45: 129-145.

Quinn, G. P., and M. J. Keough. 2002. Experimental design and data analysis for biologists. Cambridge University Press. New York, NY.

Rakocinski, C. F., B. H. Comyns, and M. S. Peterson. 2000. Relative environmental fluctuation and the early growth of estuarine fishes: ontogenetic standardization. Transactions of the American Fisheries Society 129: 210-221.

Richards, R.A. and P. J. Rago. 1999. A case history of effective fishery management: Chesapeake Bay striped bass. North American Journal of Fisheries Management 19: 356-375.

Rickman, S. J., N. K. Dulvy, S. Jennings, and J. D. Reynolds. 2000. Recruitment variation related to fecundity in marine fishes. Canadian Journal of Fisheries and Aquatic Sciences 57: 116-124.

Ross, S. W. 1988. Age, growth, and mortality of Atlantic croaker in North Carolina, with comments on population dynamics. Transactions of the American Fisheries Society 117: 461-473.

Ross, S. 2003. The relative value of different estuarine nursery areas in North Carolina for transient juvenile marine fishes. Fishery Bulletin 101: 384-404.

Rutherford, E. S., and E. D. Houde. 1995. The influence of temperature on cohort-specific growth, survival, and recruitment of striped bass, *Morone saxatilis*, in Chesapeake Bay. Fishery Bulletin 93(2): 315-332.

Secor, D. H. 2000. Longevity and resilience of Chesapeake Bay striped bass. ICES Journal of Marine Science 57: 808-815.

Secor, D. H, and E. D. Houde. 1995. Temperature effects on the timing of striped bass egg production, larval viability, and recruitment potential in the Patuxent River (Chesapeake Bay). Estuaries 18(3): 527-544.

Shepherd, G. R. and C. B. Grimes. 1983. Geographic and historic variations in growth of weakfish, *Cynoscion regalis*, in the Middle Atlantic Bight. Fishery Bulletin 81(4): 803-813.

Sissenwine, M. P. 1984. Why do fish populations vary? Pages 59-94 in R. M. May, editor. Exploitation of marine communities. Springer-Verlag. New York, NY.

Smith, S. J. 1990. Use of statistical models for the estimation of abundance from groundfish trawl survey data. Canadian Journal of Fisheries and Aquatic Sciences 47: 894-903.

Sousa, P., R. T. Lemos, M. C. Gomes, and M. Azevedo. 2007. Analysis of horse mackerel, blue whiting, and hake catch data from Portugese surveys (1989-1999) using an integrated GLM approach. Aquatic Living Resources 20(2): 105-116.

Stefansson, G. 1996. Analysis of groundfish survey abundance data: combining the glm and delta approaches. ICES Journal of Marine Science 53: 577-588.

Szedlmayer, S. T., M. P. Weinstein, and J. A. Musick. 1990. Differential growth among cohorts of age-0 weakfish *Cynoscion regalis* in Chesapeake Bay. Fishery Bulletin 88: 745-752.

Terceiro, M. 2003. The statistical properties of recreational catch rate data for some fish stocks off the northeast U.S. coast. Fisheries Bulletin: 101: 653-672.

Thorrold, S. R., C. Latkoczy, P. K. Swart, and C.M. Jones. 2001. Natal homing in a marine fish metapopulation. Science 291: 297-299.

Tyler, R. M., and T. E. Targett. 2007. Juvenile weakfish *Cynoscion regalis* distribution in relation to diel-cycling dissolved oxygen in an estuarine tributary. Marine Ecology Progress Series 333: 257-269.

Van Winkle, W., K. D. Kumar, and D. S. Vaughan. 1988. Relative contributions of the Hudson River and Chesapeake Bay striped bass stocks to the Atlantic coastal population. Pages 255-266 in L. W. Barnthouse, R. J. Klauda, D. S. Vaughan, and R. L. Kendall, eds. Science, law, and Hudson River power plants: a case study in environmental impact assessment. American Fisheries Society, Monograph 4, Bethesda, Maryland.

Von Szalay, P. G., and D. A. Somerton. 2005. The effect of net spread on the capture efficiency of a demersal survey trawl used in the eastern Bering Sea. Fisheries Research 74: 86-95.

Weinstein, M. P, S. L. Weiss, and M. F. Walters. 1980. Multiple determinants of community structure in shallow marsh habitats. Marine Biology 58: 227-243.

Wilk, S. J. 1976. The weakfish- a wide-ranging species. Atl. States Mar. Fish. Com. Mar. Resourc. Atl. Coast Fish. Leaflet 18, 4 p. Atlantic States Marine Fisheries Commission, Washington, D.C.

Wirgin, I., L. Maceda, J. R. Waldman, and R. N. Crittenden. 1993. Use of mitochondrial DNA polymorphisms to estimate the relative contributions of the Hudson River and Chesapeake Bay striped bass stocks to the mixed fishery on the Atlantic coast. Transactions of the American Fisheries Society 122: 669-684.

Ye, Y., M. Al-Husaini, A. Al-Baz. 2001. Use of generalized linear models to analyze catch rates having zero values: the Kuwait drift net fishery. Fisheries Research 53: 151-168.

Table 1. Survey and sampling locations for recruitment indices and estimates of adult abundance for striped bass, weakfish, and Atlantic croaker.

Data Source	***Species***	***Survey***	***Location***
Recruitment Indices	Striped Bass	VA Striped Bass Seine Survey	VA
	Striped Bass	MD Striped Bass Seine Survey	MD
	Weakfish	VIMS Juvenile Fish Trawl Survey	VA
	Atlantic Croaker	VIMS Juvenile Fish Trawl Survey	VA
Adult abundance	Striped Bass Weakfish Atlantic Croaker	ChesMMAP Trawl Survey	VA & MD

Table 2a. Information used to construct the current and modified recruitment indices for weakfish including the index period, depth, system, the source for estimates of adult abundance, and the distribution of the data.

	Index Period	*Depth*	*System*	*Adult Abundance*	*Distribution*
Current Index					
	Aug. – Oct.	All	All	VA, MD	Lognormal
Modified Index					
1	Aug. - Nov.	All	All	VA	Lognormal
2	Aug. - Nov.	All	All	VA, MD	Lognormal
3	Aug. - Oct.	>30ft	All	VA	Lognormal
4	Aug. - Oct.	≤30ft	All	VA, MD	Lognormal
5	Aug. - Nov.	>30ft	All	VA, MD	Lognormal
6	Aug. - Nov.	≤30ft	All	VA	Lognormal
7	Aug. - Oct.	All	All	VA	Lognormal
8	Aug. - Oct.	≤30ft	All	VA	Lognormal
9	Aug. - Oct.	All	Rivers only	VA, MD	Lognormal
10	Aug. - Oct.	All	All	VA, MD	Delta-Lognormal
11	Aug. - Oct.	All	All	VA, MD	Gamma

Table 2b. Information used to construct the current and modified recruitment indices for Atlantic croaker including the index period, depth, system, the source for estimates of adult abundance, and the distribution of the data.

	Index Period	*Depth*	*System*	*Adult Abundance*	*Distribution*
Current Index					
	May. – Aug.	All	All	VA, MD	Lognormal
Modified Index					
1	Apr. - June	All	All	VA, MD	Lognormal
2	Apr. - May	All	All	VA, MD	Lognormal
3	May - Aug.	>30ft	All	VA, MD	Lognormal
4	May - Aug.	≤30ft	All	VA, MD	Lognormal
5	Apr. - June	≤30ft	All	VA, MD	Lognormal
6	Apr. - June	>30ft	All	VA, MD	Lognormal
7	May - Aug.	All	All	VA	Lognormal
8	Apr. - June	All	All	VA	Lognormal
9	May - Aug.	All	Rivers only	VA, MD	Lognormal
10	Apr. - June	All	Rivers only	VA, MD	Lognormal
11	Apr. - June	All	Rivers only	VA	Lognormal
12	May - Aug.	All	All	VA, MD	Delta-Lognormal

Table 3. Information used to construct the current and modified recruitment indices for striped bass including the index period, stations, the source of the recruitment index and estimates of adult abundance, and the distribution of the data.

	Index Period	*Stations*	*Recruitment Index*	*Adult Abundance*	*Distribution*
Current Index					
VA	July – Sept.	Index	VA	VA, MD	Lognormal
MD	July – Sept.	Index	MD	VA, MD	Lognormal
Modified Indices					
1	July – Sept.	Index	VA, MD	VA, MD	Lognormal
2	July – Sept.	Index, Auxiliary	VA	VA, MD	Lognormal
3	July – Sept.	Index, Auxiliary	VA, MD	VA, MD	Lognormal
4	July – Sept.	Index	VA	VA	Lognormal
5	July – Sept.	Index	MD	MD	Lognormal
6	July – Sept.	Index	VA	VA, MD	Delta-Lognormal
7	July – Sept.	Index	VA	VA, MD	Gamma

Table 4. Probability density/mass functions for the five distributions examined in this study (Evans *et al.* 1993) where *E{Y}* is the expected value of the distribution and *Var{Y}* is the variance.

Distribution	*Probability density function*	*Conditions*	*E{Y}*	*Var{Y}*	*Number of parameters*
Normal	$\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(\chi-\mu)^2}{2\sigma^2}\right)$		μ	σ^2	2
Gamma	$(x/b)^{c-1}[\exp(-x/b)]/b\Gamma(c)$	$b>0, c>0$	bc	b^2c	2
Poisson	$\frac{(e^{-\lambda})\lambda^x}{x!}$	$\lambda>0, x=0,1,2,...n$	λ	λ	1
Negative Binomial	$\frac{\Gamma(x+y)}{\Gamma(x)h!}p^x q^y$		$\frac{xq}{p}$	$\frac{xq}{p^2}$	2
Lognormal	$\frac{1}{x\sigma\sqrt{2\pi}}\exp\left\{-\frac{1}{2}\left(\frac{\log x-\mu}{\sigma}\right)^2\right\}$	$-\infty<\mu<\infty, \sigma>, m=\exp\mu$	$m\exp\left(\frac{1}{2}\sigma^2\right)$	$m^2\omega(\omega-1), \omega=\exp(\sigma^2)$	2

Table 5. Pearson correlation coefficients for estimates of age-specific adult abundance regressed against the original and modified recruitment indices for seven age classes of striped bass. Columns 2 and 3 represent the states that provided the catch data for the recruitment index and adult abundance. Column 4 represents the distribution of the YOY catch data. For modified indices 1, 2, and 3, "+" implies an additive function, and "incl. aux" implies that the catch data from auxiliary stations was included in the recruitment index. The survey period for the VA and MD Striped Bass Seine Survey extends from July to mid-September. Correlations were considered significant if $t_{calc} > t_{crit}$, where t_{crit}=0.811. Asterisk indicates significant correlation coefficient, and NA indicates a negative relationship.

Index	*Recruitment Index*	*Adult Abundance*	*Distribution*	*Age 1*	*Age 2*	*Age 3*	*Age 4*	*Age 5*	*Age 6*	*Age 7*
Original (VA)	VA	VA, MD	Lognormal	0.91*	0.74	0.90*	0.74	0.71	0.84*	0.69
Original (MD)	MD	VA, MD	Lognormal	0.91*	0.52	0.67	0.83*	0.86*	0.89*	0.91*
Index 1	**VA + MD**	**VA, MD**	**Lognormal**	**0.98***	**0.67**	**0.84***	**0.84***	**0.88***	**0.92***	**0.86***
Index 2	VA incl. aux	VA, MD	Lognormal	0.94*	0.74	0.89*	0.73	0.74	0.88*	0.75
Index 3	VA + MD, VA incl. aux	VA, MD	Lognormal	0.96*	0.62	0.80	0.83*	0.88*	0.92*	0.88*
Index 4	VA	VA	Lognormal	NA	0.31	0.82*	0.79	0.71	0.61	0.37
Index 5	MD	MD	Lognormal	0.85*	0.53	0.76	0.72	0.93*	0.67	0.91*
Index 6	VA	VA, MD	Delta-Lognormal	0.87*	0.65	0.83*	0.62	0.63	0.79	0.56
Index 7	VA	VA, MD	Gamma	0.97*	0.67	0.85*	0.70	0.78	0.86*	0.68

Table 6. AIC_c values and Akaike weights for five distributions for the YOY striped bass catch data, 1994-2007. *W* represents Akaike weights, and *n* represents the number of hauls.

Year	*n*	*Normal*		***Gamma***		*Poisson*		*Neg. Binomial*		*Lognormal*	
		AIC_c	*W*	$\mathbf{AIC_c}$	***W***	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*
1994	180	1376.74	0.00	**1075.12**	**1.00**	2450.90	0.00	1146.42	0.00	1159.77	0.00
1995	180	1288.70	0.00	**726.88**	**1.00**	2085.94	0.00	952.17	0.00	775.62	0.00
1996	180	1710.13	0.00	**1421.15**	**1.00**	5572.14	0.00	1454.91	0.00	1485.94	0.00
1997	180	1389.18	0.00	**1019.70**	**1.00**	2654.94	0.00	1129.31	0.00	1096.30	0.00
1998	180	1510.38	0.00	**1179.11**	**1.00**	3392.44	0.00	1249.62	0.00	1260.23	0.00
1999	180	1023.61	0.00	**395.05**	**1.00**	1185.00	0.00	723.80	0.00	406.89	0.00
2000	180	1589.91	0.00	**1260.05**	**1.00**	4353.54	0.00	1335.90	0.00	1343.19	0.00
2001	180	1670.51	0.00	**1204.00**	**1.00**	1899.77	0.00	1305.09	0.00	1277.57	0.00
2002	180	1297.56	0.00	**530.13**	**0.96**	2194.81	0.00	858.19	0.00	536.54	0.04
2003	180	1615.95	0.00	**1396.54**	**1.00**	4390.81	0.00	1428.04	0.00	1481.70	0.00
2004	180	1538.85	0.00	**1179.04**	**1.00**	3401.98	0.00	1227.80	0.00	1242.23	0.00
2005	180	1351.35	0.00	**993.51**	**1.00**	2333.62	0.00	1104.76	0.00	1079.99	0.00
2006	180	1300.94	0.00	**1034.22**	**1.00**	2112.35	0.00	1123.90	0.00	1132.29	0.00
2007	180	1501.56	0.00	**1123.86**	**1.00**	3453.96	0.00	1225.48	0.00	1203.88	0.00

Table 7. AIC_c values and Akaike weights of five distributions for the YOY striped bass catch data with zero catches removed, 1994-2007. *W* represents Akaike weights, and *n* represents the number of hauls.

Year	*n*	*Normal*		*Gamma*		*Poisson*		*Neg. Binomial*		**Lognormal**	
		AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	$\mathbf{AIC_c}$	***W***
1994	160	1230.91	0.00	1042.28	0.00	2095.21	0.00	1057.37	0.00	**1024.69**	**1.00**
1995	127	934.13	0.00	762.49	0.00	1440.03	0.00	777.95	0.00	**733.49**	**1.00**
1996	171	1628.39	0.00	1398.04	0.00	5186.53	0.00	1407.91	0.00	**1384.80**	**1.00**
1997	152	1183.87	0.00	1000.61	0.00	2153.13	0.00	1015.70	0.00	**978.11**	**1.00**
1998	161	1358.92	0.00	1149.90	0.00	2927.50	0.00	1162.72	0.00	**1131.90**	**1.00**
1999	105	624.52	0.00	513.33	0.00	708.55	0.00	532.85	0.00	**490.74**	**1.00**
2000	160	1420.28	0.00	1231.08	0.00	3707.87	0.00	1241.66	0.00	**1216.82**	**1.00**
2001	155	1453.35	0.00	1186.02	0.00	4115.04	0.00	1197.40	0.00	**1162.93**	**1.00**
2002	106	800.40	0.00	647.54	0.00	1333.84	0.00	661.28	0.00	**623.98**	**1.00**
2003	170	1528.03	0.00	1362.97	0.22	4001.45	0.00	1371.56	0.00	**1360.48**	**0.78**
2004	167	1435.40	0.00	1153.95	0.00	3112.12	0.00	1169.02	0.00	**1116.11**	**1.00**
2005	150	1136.98	0.00	962.44	0.00	1840.63	0.00	976.31	0.00	**940.56**	**1.00**
2006	154	1116.01	0.00	990.63	0.34	1673.05	0.00	1002.59	0.00	**989.29**	**0.66**
2007	154	1295.32	0.00	1100.73	0.00	2830.27	0.00	1113.14	0.00	**1082.41**	**1.00**

Table 8. Pearson correlation coefficients for estimates of age-specific adult abundance regressed against the original and modified recruitment indices for three age classes of weakfish. Columns 2 and 3 represent the temporal and spatial information used to construct the modified recruitment indices. Specific information includes the index period, or the months used to construct the index, and specified depth. 'All strata' indicates data collected from all strata in the Chesapeake Bay and James, York, and Rappahannock Rivers. Unless otherwise stated, estimates of age-specific adult abundance include data collected from both VA and MD portions of Chesapeake Bay. Correlations were considered significant if t > t_{crit} =0.811. Asterisk indicates significant correlation coefficient, and *na* indicates a negative relationship.

Index	*Index period*	*Depth*	*System*	*Adult Abundance*	*Distribution*	*Age 0*	*Age 1*	*Age 2*
Original	Aug. – Oct.	All	VA, MD	All	Lognormal	0.51	0.85*	0.40
Index 1	**Aug. - Nov.**	**All**	**All**	**VA**	**Lognormal**	**0.83***	**0.91***	**0.56**
Index 2	Aug. - Nov.	All	All	VA, MD	Lognormal	0.71	0.91*	0.49
Index 3	Aug. - Oct.	>30ft	All	VA	Lognormal	na	0.71	na
Index 4	Aug. - Oct.	≤30ft	All	VA, MD	Lognormal	0.80	0.63	0.69
Index 5	Aug. - Nov.	>30ft	All	VA, MD	Lognormal	0.60	0.92*	0.39
Index 6	Aug. - Nov.	≤30ft	All	VA	Lognormal	0.94*	0.73	0.67
Index 7	Aug. - Oct.	All	All	VA	Lognormal	0.51	0.85*	0.39
Index 8	Aug. - Oct.	≤30ft	All	VA	Lognormal	0.66	0.67	0.63
Index 9	Aug. - Oct.	All	Rivers only	VA, MD	Lognormal	na	na	na
Index 10	Aug. - Oct.	All	All	VA, MD	Delta-Lognormal	0.46	0.81*	0.41
Index 11	Aug. - Oct.	All	All	VA, MD	Gamma	0.38	0.62	0.83*

Table 9. AIC_c values and Akaike weights of five distributions for the YOY weakfish catch data. To allow for a sufficient sample estimate, the data were evaluated by stratum from 1993-2007. Zero catches were included in the analysis. *W* represents Akaike weights, and *n* is the sample size.

Stratum	*n*	*Normal*		**Gamma**		*Poisson*		*Neg. Binomial*		*Lognormal*	
		AIC_c	*W*	$\mathbf{AIC_c}$	***W***	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*
1	123	1722.7	0.00	**482.5**	**0.00**	6079.1	0.00	877.9	0.00	430.3	1.00
2	119	1521.5	0.00	**-55.9**	**0.00**	3712.3	0.00	476.2	0.00	-231.4	1.00
3	158	2536.4	0.00	**1018.7**	**0.00**	20059.7	0.00	1456.0	0.00	997.2	1.00
4	120	2111.3	0.00	**891.8**	**0.00**	17753.2	0.00	1232.5	0.00	879.4	1.00
5	119	2016.5	0.00	**836.3**	**0.00**	15030.2	0.00	1138.0	0.00	819.9	1.00
6	120	1455.3	0.00	**-44.2**	**0.00**	3325.8	0.00	470.5	0.00	-204.3	1.00
7	158	2571.4	0.00	**1697.4**	**1.00**	18166.6	0.00	1960.6	0.00	1781.6	0.00
8	120	2093.8	0.00	**1522.3**	**1.00**	16292.2	0.00	1641.8	0.00	1599.8	0.00
9	118	1802.7	0.00	**1147.4**	**1.00**	9773.1	0.00	1345.2	0.00	1202.7	0.00
10	118	1646.7	0.00	**271.4**	**0.00**	5299.8	0.00	721.2	0.00	176.0	1.00
11	158	2426.5	0.00	**2001.8**	**1.00**	13504.9	0.00	2107.1	0.00	2135.1	0.00
12	120	1949.0	0.00	**1695.6**	**1.00**	10831.8	0.00	1746.8	0.00	1809.0	0.00
30	48	623.4	0.00	**40.6**	**0.00**	1630.7	0.00	233.1	0.00	-11.2	1.00
31	48	798.1	0.00	**415.3**	**1.00**	6126.8	0.00	533.0	0.00	426.5	0.00
32	121	1924.6	0.00	**1637.1**	**1.00**	18361.7	0.00	1650.4	0.00	1684.0	0.00
33	84	1304.8	0.00	**989.2**	**1.00**	9933.7	0.00	1042.6	0.00	1038.6	0.00
34	50	806.8	0.00	**653.9**	**1.00**	4950.4	0.00	677.5	0.00	688.5	0.00
35	129	2058.0	0.00	**1744.7**	**1.00**	13440.6	0.00	1781.3	0.00	1835.7	0.00
36	44	763.2	0.00	**623.7**	**0.85**	7709.1	0.00	629.0	0.06	628.1	0.09

Table 9 (cont.)

Stratum	*n*	*Normal*		**Gamma**		*Poisson*		*Neg. Binomial*		*Lognormal*	
		AIC_c	*W*	$\mathbf{AIC_c}$	**W**	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*
37	84	1326.4	0.00	**1111.1**	**0.97**	147295.0	0.00	1118.2	0.03	1129.3	0.00
38	132	2369.0	0.00	**1922.3**	**1.00**	24730.0	0.00	1952.0	0.00	1965.7	0.00
39	72	904.5	0.00	**674.3**	**1.00**	7572.5	0.00	700.4	0.00	691.7	0.00
40	116	2021.1	0.00	**1563.8**	**1.00**	35021.4	0.00	1628.4	0.00	1636.6	0.00
50	40	370.7	0.00	**-33.1**	**0.00**	1143.3	0.00	91.5	0.00	-87.1	1.00
51	40	418.6	0.00	**240.5**	**0.96**	2303.5	0.00	293.8	0.00	246.9	0.04
52	39	484.9	0.00	**402.2**	**1.00**	4694.7	0.00	417.5	0.00	426.8	0.00
53	116	1690.6	0.00	**1421.0**	**1.00**	13789.6	0.00	1479.9	0.00	1517.6	0.00
54	40	480.0	0.00	**225.9**	**0.34**	4706.2	0.00	291.2	0.00	224.5	0.66
55	40	441.5	0.00	**329.2**	**1.00**	2199.2	0.00	349.9	0.00	346.1	0.00
56	41	554.6	0.00	**419.1**	**1.00**	6328.0	0.00	439.7	0.00	439.2	0.00
57	124	2056.8	0.00	**1334.4**	**1.00**	21490.0	0.00	1504.6	0.00	1391.0	0.00
58	41	410.2	0.00	**345.1**	**0.98**	1684.5	0.00	353.6	0.01	358.4	0.00
59	80	927.9	0.00	**751.3**	**1.00**	3122.8	0.00	792.5	0.00	801.7	0.00
60	78	868.5	0.00	**685.8**	**1.00**	4517.1	0.00	716.6	0.00	725.0	0.00
61	39	353.7	0.00	**304.0**	**0.32**	942.6	0.00	306.9	0.07	302.7	0.61
62	151	1980.7	0.00	**1422.8**	**1.00**	9446.1	0.00	1493.2	0.00	1481.1	0.00
70	37	360.3	0.00	**182.8**	**0.91**	1525.7	0.00	248.7	0.00	187.5	0.09
71	115	1576.3	0.00	**873.4**	**1.00**	7783.2	0.00	1055.9	0.00	896.9	0.00
72	41	460.7	0.00	**311.2**	**1.00**	2796.2	0.00	354.5	0.00	327.8	0.00
73	78	801.9	0.00	**675.4**	**1.00**	2827.5	0.00	686.6	0.00	700.2	0.00
74	36	467.7	0.00	**267.5**	**0.84**	5766.8	0.00	303.2	0.00	270.8	0.16
75	87	1416.0	0.00	**724.4**	**0.92**	16610.2	0.00	853.2	0.00	729.2	0.08

Table 9 (cont.)

Stratum	*n*	*Normal*		***Gamma***		*Poisson*		*Neg. Binomial*		*Lognormal*	
		AIC_c	*W*	$\boldsymbol{AIC_c}$	***W***	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*
76	64	951.3	0.00	**767.8**	**0.99**	10103.1	0.00	776.8	0.01	780.5	0.00
77	36	274.9	0.00	**193.3**	**1.00**	529.0	0.00	226.6	0.00	207.6	0.00
78	81	1057.3	0.00	**694.7**	**1.00**	4353.2	0.00	790.5	0.00	728.7	0.00
79	111	1123.2	0.00	**755.9**	**1.00**	3692.3	0.00	859.6	0.00	794.0	0.00
80	40	296.4	0.00	**133.9**	**0.83**	579.5	0.00	213.1	0.00	137.1	0.17
81	107	968.4	0.00	**490.0**	**1.00**	2953.1	0.00	653.9	0.00	503.6	0.00

Table 10. AIC_c values and Akaike weights of five distributions for YOY weakfish catch data with zero catches removed. To allow for a sufficient sample size, the data were evaluated by stratum. *W* represents Akaike weights, and *n* represents the number of tows.

Stratum	*n*	*Normal*		*Gamma*		*Poisson*		*Neg. Binomial*		***Lognormal***	
		AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	$\mathbf{AIC_c}$	**W**
1	65	901.8	0.00	671.8	0.00	3717.5	0.00	680.8	0.00	**641.9**	**1.00**
2	29	430.8	0.00	310.8	0.00	1780.9	0.00	316.0	0.00	**288.9**	**1.00**
3	84	1427.2	0.00	1174.3	0.00	11753.5	0.00	1180.3	0.00	**1163.4**	**1.00**
4	73	1240.6	0.00	1008.7	0.01	10950.4	0.00	1014.4	0.00	**998.5**	**0.99**
5	72	1264.4	0.00	944.8	0.00	10691.5	0.00	951.9	0.00	**907.0**	**1.00**
6	35	416.9	0.00	305.4	0.00	1538.2	0.00	310.0	0.00	**286.1**	**1.00**
7	117	1926.7	0.00	1706.9	0.97	12335.6	0.00	1713.7	0.03	**1720.5**	**0.00**
8	100	1782.7	0.00	1505.3	0.05	13351.4	0.00	1511.2	0.00	**1499.3**	**0.95**
9	85	1349.5	0.00	1164.0	0.76	6785.3	0.00	1170.5	0.03	**1166.7**	**0.21**
10	51	719.0	0.00	525.1	0.00	3041.7	0.00	533.0	0.00	**492.1**	**1.00**
11	144	2140.6	0.00	1949.0	0.95	10935.7	0.00	1955.1	0.05	**1974.1**	**0.00**
12	110	1787.3	0.00	1646.2	0.86	9246.7	0.00	1649.9	0.14	**1663.0**	**0.00**
30	19	233.4	0.00	161.7	0.00	923.1	0.00	164.8	0.00	**148.2**	**1.00**
31	31	504.7	0.00	437.2	0.08	3656.1	0.00	438.4	0.05	**432.5**	**0.87**
32	117	1876.8	0.00	1620.1	0.00	17707.7	0.00	1623.1	0.00	**1607.6**	**1.00**
33	74	1160.2	0.00	973.8	0.01	8584.4	0.00	977.4	0.00	**965.1**	**0.99**
34	46	742.4	0.00	642.2	0.57	4395.7	0.00	644.8	0.15	**643.6**	**0.28**
35	122	1937.5	0.00	1707.3	0.00	12249.4	0.00	1711.4	0.00	**1694.5**	**1.00**

Table 10 (cont.)

Stratum	*n*	*Normal*		*Gamma*		*Poisson*		*Neg. Binomial*		***Lognormal***	
		AIC_c	*W*	*AIC_c*	*W*	*AIC_c*	*W*	*AIC_c*	*W*	**AIC_c**	**W**
36	43	751.1	0.00	620.9	0.02	7570.6	0.00	623.0	0.01	**612.8**	**0.98**
37	84	1302.0	0.00	1102.6	0.00	14380.8	0.00	1104.5	0.00	**1085.5**	**1.00**
38	126	2286.2	0.00	1907.1	0.00	23711.6	0.00	1913.3	0.00	**1883.7**	**1.00**
39	66	837.4	0.00	669.6	0.00	7001.8	0.00	673.0	0.00	**652.5**	**1.00**
40	100	1812.0	0.00	1534.7	0.00	30872.2	0.00	1537.0	0.00	**1517.4**	**1.00**
50	7	78.8	0.00	59.3	0.16	473.9	0.00	60.0	0.11	**56.2**	**0.73**
51	28	299.8	0.00	252.2	0.21	1600.0	0.00	254.1	0.08	**249.7**	**0.71**
52	35	436.8	0.00	391.3	0.54	3974.6	0.00	392.0	0.38	**395.0**	**0.09**
53	104	1504.5	0.00	1372.1	0.70	11255.0	0.00	1373.9	0.28	**1379.2**	**0.02**
54	25	310.6	0.00	246.1	0.01	3314.9	0.00	247.2	0.01	**237.2**	**0.98**
55	35	390.8	0.00	324.6	0.18	1887.2	0.00	326.5	0.07	**321.7**	**0.75**
56	36	493.6	0.00	412.2	0.10	5529.3	0.00	413.0	0.07	**407.9**	**0.83**
57	94	1601.1	0.00	1337.3	0.00	16437.3	0.00	1341.2	0.00	**1317.8**	**1.00**
58	39	390.8	0.00	340.9	0.30	1571.4	0.00	343.2	0.10	**339.5**	**0.60**
59	71	827.0	0.00	731.9	0.22	2619.3	0.00	736.2	0.03	**729.4**	**0.76**
60	70	786.0	0.00	671.2	0.10	3928.5	0.00	674.0	0.03	**666.9**	**0.87**
61	39	353.4	0.00	303.7	0.31	942.5	0.00	306.6	0.07	**302.3**	**0.61**
62	137	1808.7	0.00	1406.5	0.00	8560.0	0.00	1416.2	0.00	**1368.9**	**1.00**
70	22	220.4	0.00	198.4	0.47	815.5	0.00	199.4	0.28	**199.6**	**0.25**
71	92	1173.5	0.00	913.3	0.00	5910.9	0.00	921.5	0.00	**886.7**	**1.00**
72	31	356.2	0.00	310.2	0.37	2001.5	0.00	311.4	0.20	**309.9**	**0.43**
73	77	773.7	0.00	665.9	0.02	2682.5	0.00	670.0	0.00	**658.1**	**0.98**
74	28	370.6	0.00	274.0	0.01	4890.6	0.00	275.6	0.00	**263.5**	**0.99**
75	63	1059.6	0.00	756.0	0.00	13730.4	0.00	760.3	0.00	**722.1**	**1.00**

Table 10 (cont.)

Stratum	*n*	*Normal*		*Gamma*		*Poisson*		*Neg. Binomial*		***Lognormal***	
		AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	$\mathbf{AIC_c}$	**W**
76	62	927.3	0.00	762.9	0.01	9811.4	0.00	765.4	0.00	**754.0**	**0.98**
77	28	215.7	0.00	192.8	0.44	378.1	0.00	195.3	0.13	**192.9**	**0.43**
78	59	850.9	0.00	700.0	0.01	3394.2	0.00	705.8	0.00	**689.5**	**0.99**
79	87	914.7	0.00	761.6	0.00	2903.3	0.00	769.5	0.00	**745.1**	**1.00**
80	22	166.7	0.00	156.3	0.53	268.5	0.00	157.6	0.29	**158.5**	**0.18**
81	70	654.4	0.00	534.3	0.00	1949.1	0.00	540.2	0.00	**522.7**	**1.00**

Table 11. Pearson correlation coefficients for estimates of age-specific adult abundance regressed against the original and modified recruitment indices for seven age classes of Atlantic croaker. Columns 2-4 represent the information used to construct the recruitment indices, including: index period, depth, and system. 'All depths' indicates data collected from all depth strata in the Chesapeake Bay and James, York, and Rappahannock rivers were used. Unless otherwise stated, estimates of age-specific adult abundance include data collected from both VA and MD portions of Chesapeake Bay. Correlations were considered significant if $t > t_{crit} = 0.811$. Asterisk indicates significant correlation coefficient, and *na* indicates a negative relationship. The delta-lognormal distribution was used to develop the modified recruitment index identified as *Index 12*. For all other recruitment indices, the lognormal distribution was used.

Index	*Index period*	*Depth*	*System*	*Adult Abundance*	*Age 0*	*Age 1*	*Age 2*	*Age 3*	*Age 4*	*Age 5*	*Age 6*
Original	May – Aug.	All	All	VA, MD	0.76	0.86*	0.92*	0.73	0.67	0.87*	0.52
Index 1	**Apr. - June**	**All**	**All**	**VA, MD**	**0.60**	**0.94***	**0.95***	**0.89***	**0.99***	**0.68**	**0.91***
Index 2	Apr. - May	All	All	VA, MD	0.54	0.98*	0.95*	0.84*	0.99*	0.70	0.93*
Index 3	May - Aug.	>30ft	All	VA, MD	0.47	0.40	0.66	0.56	na	0.40	na
Index 4	May - Aug.	≤30ft	All	VA, MD	0.75	0.91*	0.89*	0.74	0.94*	0.82*	0.87*
Index 5	Apr. - June	≤30ft	All	VA, MD	0.60	0.93*	0.94*	0.85*	0.99*	0.65	0.91*
Index 6	Apr. - June	>30ft	All	VA, MD	0.27	0.60	0.60	0.74	0.77	0.85*	0.96*
Index 7	May - Aug.	All	All	VA	0.74	0.86*	0.91*	0.75	0.67	0.78	0.60
Index 8	Apr. - June	All	All	VA	0.58	0.94*	0.94*	0.92*	0.99*	0.68	0.90*
Index 9	May - Aug.	All	Rivers only	VA, MD	0.68	0.76	0.78	0.78	0.93*	0.71	0.71
Index 10	Apr. - June	All	Rivers only	VA, MD	0.51	0.94*	0.85*	0.85*	0.97*	0.63	0.69
Index 11	Apr. - June	All	Rivers only	VA	0.51	0.95*	0.83*	0.85*	0.97*	0.66	0.68
Index 12	May - Aug.	All	All	VA, MD	0.72	0.87*	0.90*	0.73	0.77	0.82*	0.65

Table 12. AIC_c values and Akaike weights of five distributions for YOY Atlantic croaker catch data. To allow for a sufficient sample size, the data were evaluated by stratum from 1993-2007. Zero catches were included in the analysis. *W* represents Akaike weights, and *n* represents the number of tows.

Stratum	*n*	*Normal*		*Gamma*		*Poisson*		*Neg. Binomial*		***Lognormal***	
		AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	$\mathbf{AIC_c}$	***W***
1	156	2444.08	0.00	-185.82	0.00	9769.23	0.00	520.68	0.00	**-501.42**	**1.00**
2	155	1229.88	0.00	-727.02	0.00	862.43	0.00	129.58	0.00	**-1255.52**	**1.00**
3	210	3214.76	0.00	-90.84	0.00	18499.62	0.00	791.86	0.00	**-459.34**	**1.00**
4	160	2516.68	0.00	-175.12	0.00	12996.43	0.00	548.88	0.00	**-507.52**	**1.00**
5	155	1923.08	0.00	-67.72	0.00	4582.63	0.00	629.38	0.00	**-283.82**	**1.00**
6	155	1538.28	0.00	-487.92	0.00	2255.43	0.00	271.58	0.00	**-875.22**	**1.00**
7	209	2956.76	0.00	100.16	0.00	12205.62	0.00	976.36	0.00	**-174.44**	**1.00**
8	160	2047.88	0.00	78.78	0.00	5179.33	0.00	774.68	0.00	**-107.42**	**1.00**
9	154	1930.88	0.00	-6.50	0.00	4535.23	0.00	656.18	0.00	**-200.52**	**1.00**
10	154	1243.18	0.00	-765.02	0.00	754.73	0.00	126.78	0.00	**-1305.02**	**1.00**
11	210	2429.16	0.00	-135.84	0.00	5082.32	0.00	820.46	0.00	**-430.74**	**1.00**
12	159	2041.68	0.00	-125.42	0.00	4897.13	0.00	619.98	0.00	**-377.52**	**1.00**
30	80	902.76	0.00	432.26	0.94	3892.25	0.00	596.16	0.00	**437.66**	**0.06**
31	80	1079.56	0.00	432.26	0.00	8105.85	0.00	567.76	0.00	**392.66**	**1.00**
32	175	2203.27	0.00	993.97	0.85	11729.22	0.00	1358.17	0.00	**997.47**	**0.15**
33	120	1528.10	0.00	648.10	0.00	8468.23	0.00	911.00	0.00	**636.30**	**1.00**
34	80	975.76	0.00	759.96	1.00	5473.65	0.00	824.46	0.00	**813.96**	**0.00**
35	186	2503.17	0.00	1578.27	1.00	14305.52	0.00	1841.97	0.00	**1649.77**	**0.00**

Table 12 (cont.)

Stratum	*n*	*Normal*		*Gamma*		*Poisson*		*Neg. Binomial*		***Lognormal***	
		AIC_c	*W*	*AIC_c*	*W*	*AIC_c*	*W*	*AIC_c*	*W*	**AIC_c**	**W**
36	65	970.09	0.00	574.89	1.00	7928.56	0.00	672.39	0.00	**590.19**	**0.00**
37	128	1838.30	0.00	1380.20	1.00	29878.43	0.00	1480.50	0.00	**1452.20**	**0.00**
38	190	3157.06	0.00	1380.16	1.00	36432.02	0.00	2383.66	0.00	**2321.16**	**0.00**
39	97	1236.83	0.00	860.23	1.00	10351.94	0.00	946.83	0.00	**903.23**	**0.00**
40	156	2666.48	0.00	860.18	1.00	40127.63	0.00	1937.58	0.00	**1803.38**	**0.00**
50	48	184.07	0.00	-161.43	0.00	94.39	0.00	31.27	0.00	**-261.93**	**1.00**
51	48	434.87	0.00	9.17	0.00	1230.29	0.00	147.97	0.00	**-35.53**	**1.00**
52	48	292.47	0.00	15.77	0.00	340.39	0.00	152.17	0.00	**-5.83**	**1.00**
53	154	1289.48	0.00	-150.62	0.00	1833.13	0.00	464.08	0.00	**-327.62**	**1.00**
54	48	469.67	0.00	145.27	0.00	1748.09	0.00	245.87	0.00	**132.67**	**1.00**
55	48	512.97	0.00	145.27	0.00	2587.09	0.00	169.07	0.00	**-14.23**	**1.00**
56	49	304.46	0.00	-62.24	0.00	306.19	0.00	121.56	0.00	**-111.94**	**1.00**
57	165	1266.67	0.00	-490.03	0.00	1191.52	0.00	285.37	0.00	**-819.33**	**1.00**
58	47	485.27	0.00	-489.83	1.00	2429.39	0.00	228.27	0.00	**91.27**	**0.00**
59	102	1342.72	0.00	218.02	0.00	6344.24	0.00	552.12	0.00	**139.32**	**1.00**
60	96	727.83	0.00	1.23	0.00	1306.74	0.00	293.73	0.00	**-70.27**	**1.00**
61	47	497.47	0.00	207.37	0.32	2955.79	0.00	305.97	0.00	**205.87**	**0.68**
62	200	2621.56	0.00	789.06	0.00	16115.42	0.00	1316.16	0.00	**714.36**	**1.00**
70	48	479.37	0.00	274.20	0.99	2141.89	0.00	340.77	0.00	**283.37**	**0.01**
71	156	1751.38	0.00	578.58	0.00	5143.93	0.00	1011.98	0.00	**545.48**	**1.00**
72	52	541.74	0.00	99.44	0.00	2198.18	0.00	241.54	0.00	**68.44**	**1.00**
73	103	984.82	0.00	357.32	0.02	2859.44	0.00	568.82	0.00	**349.42**	**0.98**
74	47	432.57	0.00	258.77	1.00	1462.29	0.00	320.37	0.00	**270.17**	**0.00**
75	114	1437.01	0.00	619.21	0.07	6022.14	0.00	858.61	0.00	**613.91**	**0.93**

Table 12 (cont.)

Stratum	*n*	*Normal*		*Gamma*		*Poisson*		*Neg. Binomial*		***Lognormal***	
		AIC_c	*W*	*AIC_c*	*W*	*AIC_c*	*W*	*AIC_c*	*W*	**AIC_c**	**W**
76	88	1008.04	0.00	560.54	1.00	4276.45	0.00	710.94	0.00	**579.94**	**0.00**
77	49	574.96	0.00	560.66	0.00	4030.49	0.00	396.36	0.00	**370.16**	**1.00**
78	109	1532.01	0.00	1152.61	1.00	8613.44	0.00	1232.51	0.00	**1210.21**	**0.00**
79	149	1828.28	0.00	1024.88	1.00	11339.23	0.00	1181.98	0.00	**1038.78**	**0.00**
80	55	579.83	0.00	1025.03	0.00	3002.28	0.00	471.33	0.00	**456.33**	**1.00**
81	136	1215.59	0.00	742.09	1.00	3544.33	0.00	898.59	0.00	**781.19**	**0.00**

Table 13. Akaike weights of five distributions for the YOY weakfish catch data. To allow for a sufficient sample size, the data was evaluated by stratum from 1993-2007. Zero catches were not included in the analysis. *W* represents Akaike weights, and *n* represents the number of tows.

Stratum	*n*	*Normal*		*Gamma*		*Poisson*		*Neg. Binomial*		***Lognormal***	
		AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	$\mathbf{AIC_c}$	***W***
1	23	484.29	0.00	336.38	0.00	4648.11	0.00	339.54	0.00	**314.09**	**1.00**
2	6	72.60	0.00	65.29	0.32	146.47	0.00	66.00	0.22	**64.63**	**0.45**
3	32	665.54	0.00	528.95	0.01	6939.21	0.00	532.16	0.00	**518.61**	**0.99**
4	24	439.49	0.00	357.08	0.09	4345.72	0.00	359.27	0.03	**352.44**	**0.88**
5	31	517.62	0.00	404.64	0.00	1868.39	0.00	409.69	0.00	**388.83**	**1.00**
6	12	161.35	0.00	149.00	0.59	406.71	0.00	150.42	0.29	**152.17**	**0.12**
7	47	836.86	0.00	665.04	0.00	5067.83	0.00	670.51	0.00	**647.81**	**1.00**
8	44	680.85	0.00	521.89	0.00	2392.69	0.00	530.04	0.00	**499.46**	**1.00**
9	37	595.32	0.00	432.61	0.00	2180.29	0.00	439.36	0.00	**404.82**	**1.00**
11	48	645.75	0.00	519.88	0.00	1930.40	0.00	527.69	0.00	**504.73**	**1.00**
12	29	514.16	0.00	395.76	0.00	2015.86	0.00	401.04	0.00	**377.31**	**1.00**
30	44	567.89	0.00	480.57	0.26	2344.36	0.00	484.55	0.04	**478.54**	**0.71**
31	45	663.51	0.00	469.01	0.00	5957.10	0.00	473.07	0.00	**447.79**	**1.00**
32	105	1378.33	0.00	1107.81	0.00	7609.99	0.00	1115.18	0.00	**1079.02**	**1.00**
33	69	935.52	0.00	745.24	0.00	5495.97	0.00	751.61	0.00	**725.34**	**1.00**
34	64	806.97	0.00	733.96	0.63	3995.85	0.00	735.55	0.28	**737.93**	**0.09**
35	133	1892.97	0.00	1602.80	0.01	10289.32	0.00	1611.81	0.00	**1594.37**	**0.99**

Table 13 (cont.)

Stratum	*n*	*Normal*		*Gamma*		*Poisson*		*Neg. Binomial*		***Lognormal***	
		AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	$\mathbf{AIC_c}$	***W***
36	42	730.57	0.00	592.45	0.00	6031.15	0.00	595.81	0.00	**580.07**	**1.00**
37	100	1528.48	0.00	1350.52	0.70	23277.94	0.00	1352.53	0.26	**1356.06**	**0.04**
38	153	2680.59	0.00	2191.23	0.00	30443.08	0.00	2197.04	0.00	**2165.95**	**1.00**
39	78	1011.20	0.00	854.59	0.33	8092.31	0.00	857.73	0.07	**853.34**	**0.61**
40	123	2119.43	0.00	1753.63	0.00	31831.45	0.00	1759.49	0.00	**1735.97**	**1.00**
51	14	146.13	0.00	102.54	0.02	663.73	0.00	104.48	0.00	**93.88**	**0.98**
52	17	119.23	0.00	95.35	0.06	153.78	0.00	98.10	0.01	**89.74**	**0.93**
53	35	343.09	0.00	278.11	0.00	673.16	0.00	283.61	0.00	**267.00**	**1.00**
54	25	260.84	0.00	192.54	0.01	1137.63	0.00	195.18	0.00	**182.16**	**0.99**
55	13	165.97	0.00	121.31	0.05	1324.60	0.00	122.77	0.02	**115.42**	**0.93**
56	10	84.05	0.00	70.26	0.19	108.65	0.00	72.27	0.07	**67.56**	**0.74**
57	17	189.12	0.00	150.09	0.03	356.85	0.00	153.95	0.00	**143.35**	**0.96**
58	19	212.67	0.00	171.61	0.16	1232.22	0.00	172.95	0.08	**168.42**	**0.77**
59	33	550.87	0.00	406.89	0.00	3575.21	0.00	411.30	0.00	**386.72**	**1.00**
60	27	232.60	0.00	188.30	0.04	524.21	0.00	191.23	0.01	**182.21**	**0.94**
61	24	264.66	0.00	237.98	0.45	1385.83	0.00	238.76	0.31	**239.22**	**0.24**
62	94	1345.54	0.00	1030.78	0.00	9873.43	0.00	1039.00	0.00	**991.69**	**1.00**
70	33	337.56	0.00	288.75	0.45	1408.33	0.00	291.10	0.14	**288.91**	**0.41**
71	79	933.79	0.00	765.63	0.00	2823.85	0.00	774.84	0.00	**749.56**	**1.00**
72	20	232.49	0.00	179.11	0.02	1198.58	0.00	181.25	0.01	**170.98**	**0.98**
73	56	573.78	0.00	438.87	0.00	1793.88	0.00	443.90	0.00	**417.62**	**1.00**
74	33	310.36	0.00	269.64	0.31	967.94	0.00	271.99	0.10	**268.36**	**0.59**
75	67	930.57	0.00	704.64	0.00	4207.80	0.00	712.37	0.00	**673.47**	**1.00**

Table 13 (cont.)

Stratum	*n*	*Normal*		*Gamma*		*Poisson*		*Neg. Binomial*		***Lognormal***	
		AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	AIC_c	*W*	$\boldsymbol{AIC_c}$	***W***
76	58	691.58	0.00	592.93	0.26	2747.67	0.00	597.39	0.03	**590.87**	**0.72**
77	41	488.14	0.00	593.03	0.00	3517.17	0.00	366.64	0.00	**350.13**	**1.00**
78	91	1338.20	0.00	1139.85	0.00	7258.50	0.00	1146.02	0.00	**1128.83**	**1.00**
79	114	1461.18	0.00	1058.13	0.00	9632.24	0.00	1068.13	0.00	**994.32**	**1.00**
80	46	488.67	0.00	429.19	0.77	2344.39	0.00	431.98	0.19	**434.91**	**0.04**
81	100	912.52	0.00	761.69	0.00	2525.37	0.00	769.39	0.00	**748.26**	**1.00**

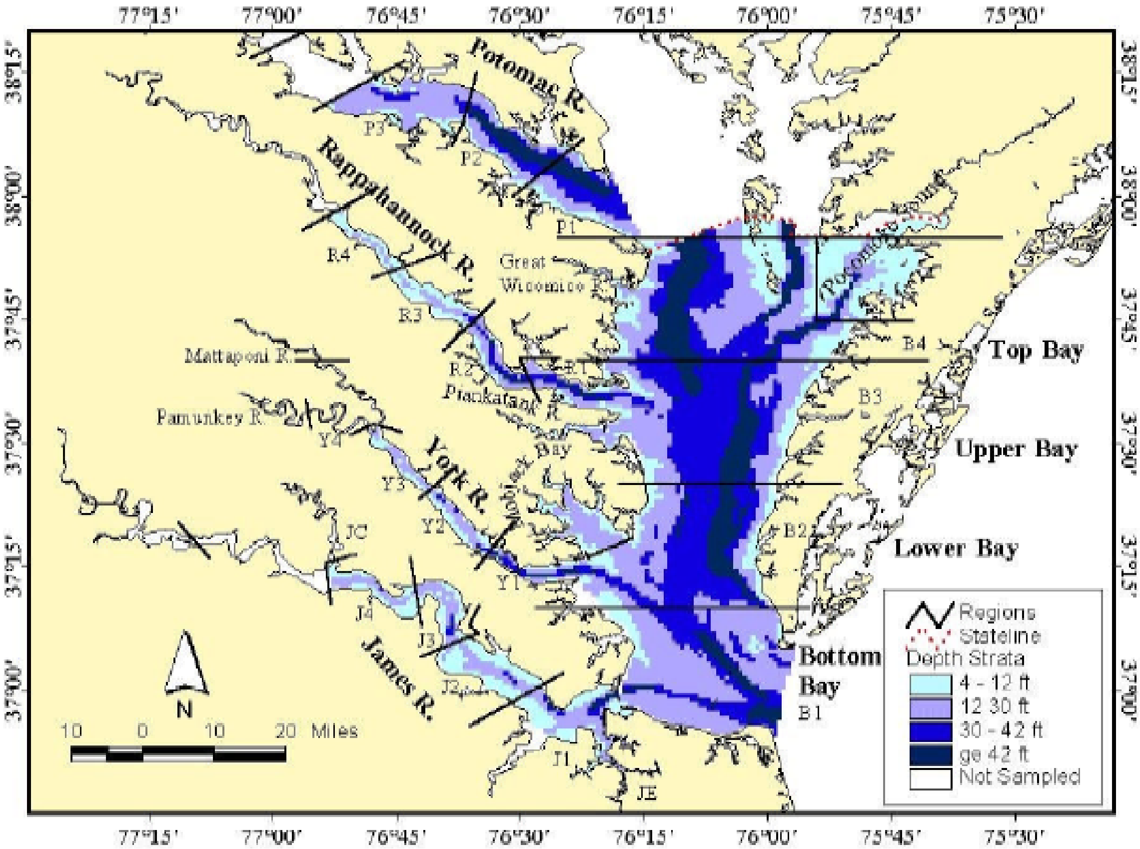


Figure 1. Stratified random sampling design for the VIMS Juvenile Fish Trawl Survey (Fabrizio and Tuckey 2008). The four regions include the James, York, and Rappahannock Rivers, and the mainstem portion of Chesapeake Bay in Virginia.

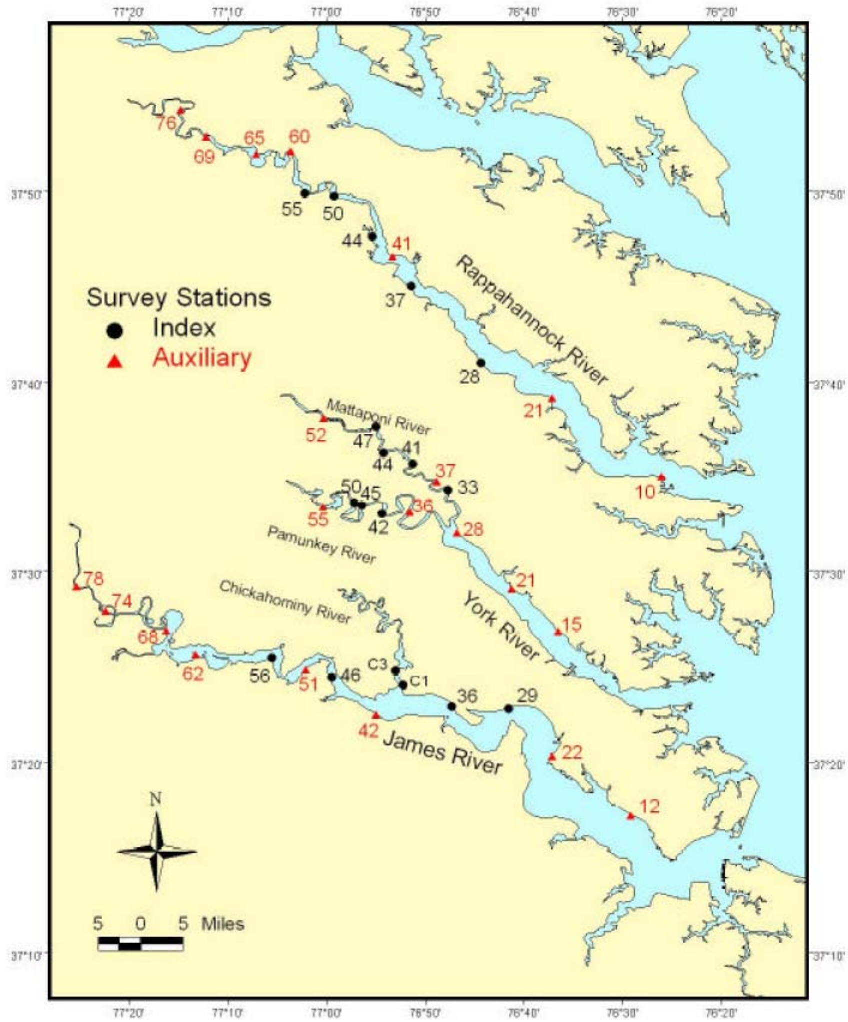


Figure 2. Sampling locations of the VA Juvenile Striped Bass Seine Survey. Data collected from index stations only are used in the striped bass recruitment index. In 1989, auxiliary stations were added to increase the geographic coverage of the survey. Numbers indicate the number of river miles from the mouth of the river (Hewitt *et al.* 2008).

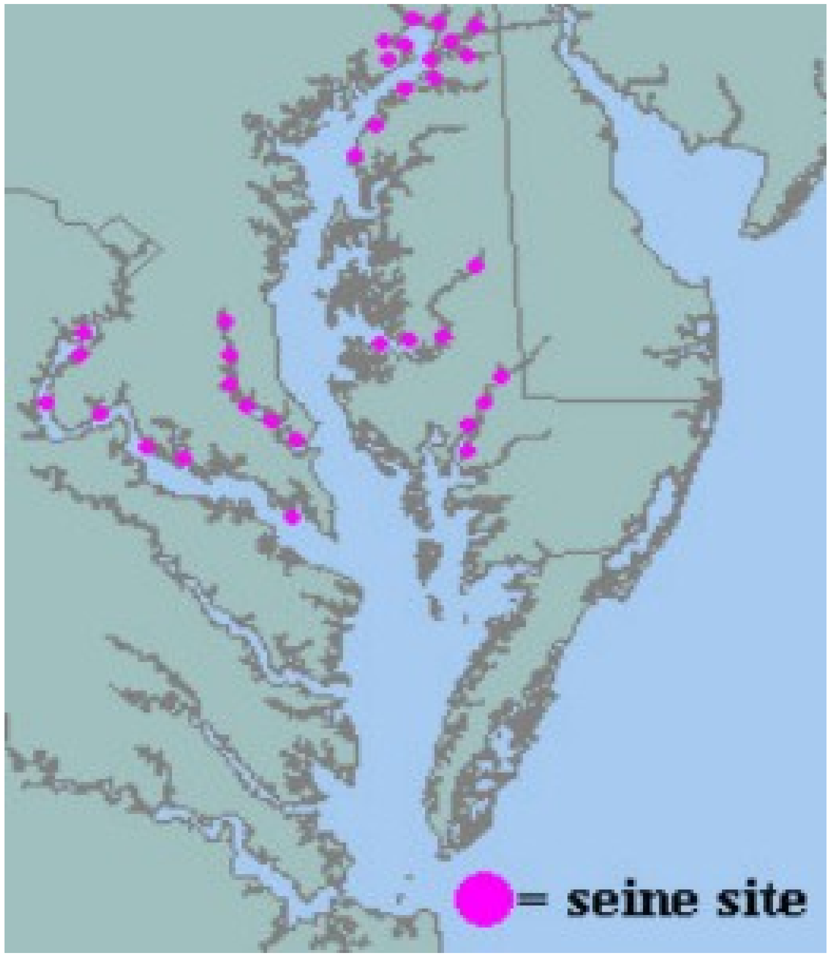


Figure 3. Sampling locations of the MD DNR Juvenile Striped Bass Seine Survey in MD portions of Chesapeake Bay (Durell and Weeden 2007). Sampling occurs in the head of Bay Region and the Potomac, Choptank, and Nanticoke Rivers.

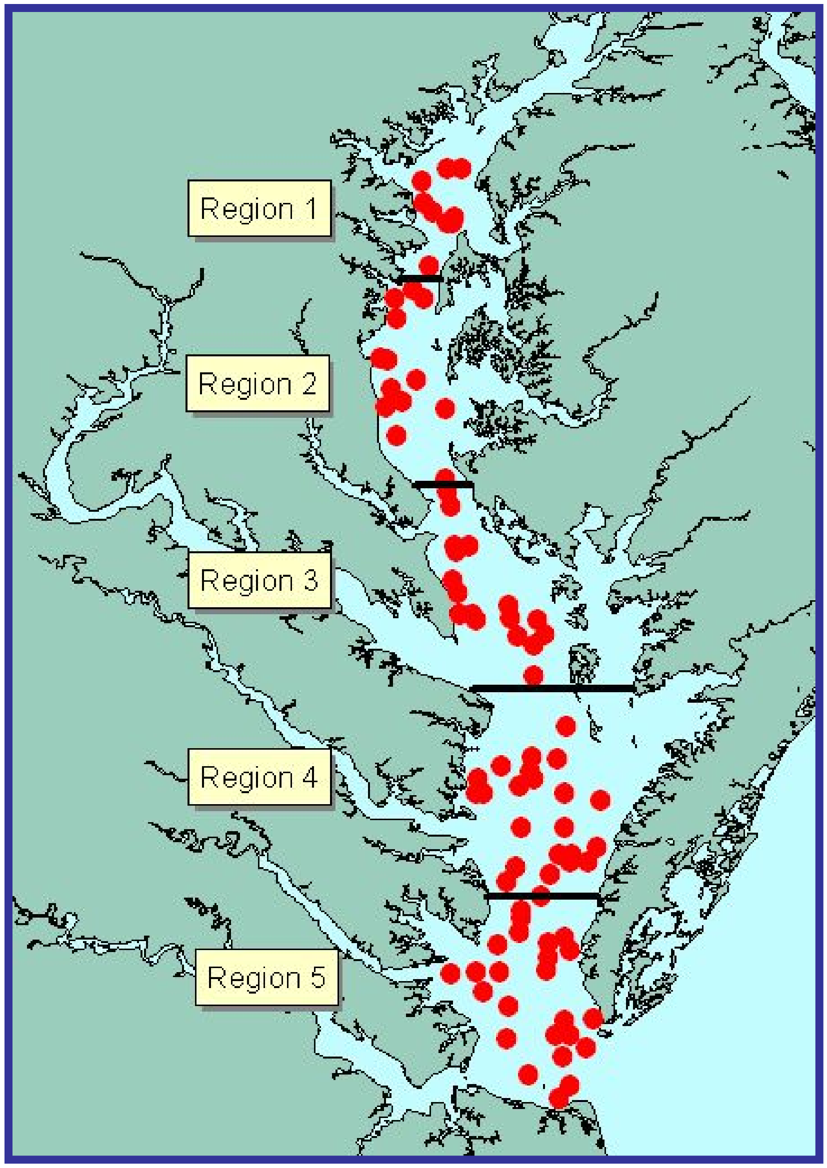


Figure 4. Sampling region for the Chesapeake Bay Multi-species Monitoring and Assessment Program (ChesMMAP). Regions 1-3 are located in Maryland and Regions 4 and 5 are located in Virginia. Example of different sampling locations throughout the Bay indicated by red circles.

PART I

Correlation analysis can be used to investigate the relationship between recruitment indices and estimates of age-specific adult abundance for multiple age classes and species

↓

↓

YES

↓

↓

Patterns in YOY abundance are reflected in ALL subsequent age classes

↓

↓

NO

↓

↓

PART II

Investigate the use of the following alternative information to develop modified recruitment indices to improve the relationship between estimates of age-specific adult abundance and recruitment indices:

1. Index period and strata assignment
2. Distributional assumptions
3. Length threshold values (see Chapter 2)

Figure 5. Conceptual diagram of research. Arrows indicate path followed in the analysis.

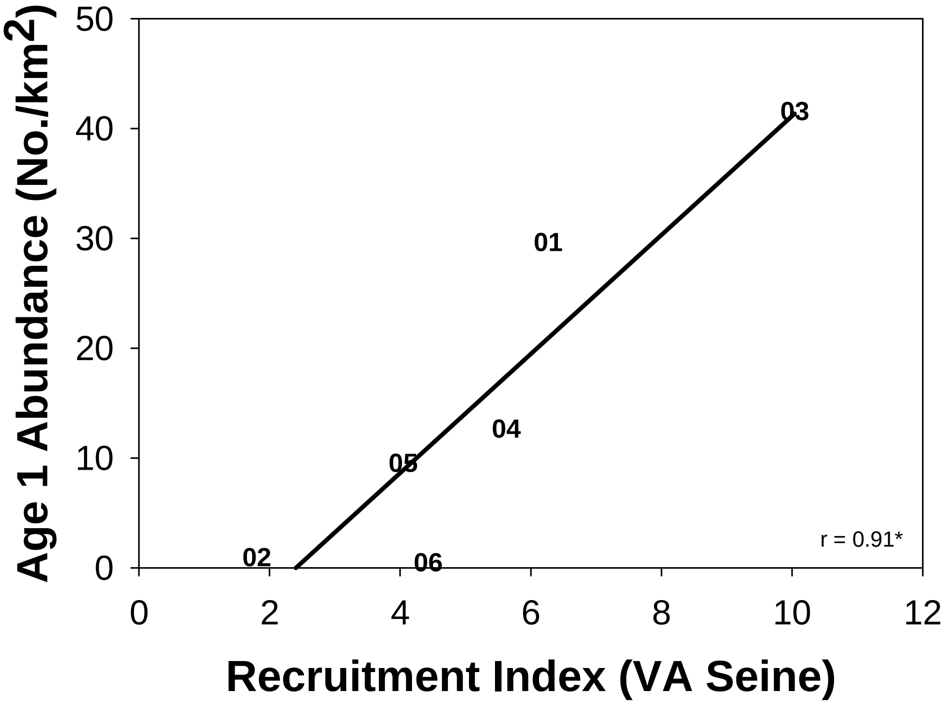


Figure 6. Example of simple linear regression of age-1 abundance of striped bass derived from the ChesMMAP survey regressed against the recruitment index derived from the VA Juvenile Striped Bass Seine Survey. Data points are identified by the year class. For example, to obtain the 05 datapoint, the 2005 year class had a recruitment index value of 3.99; whereas the estimate of age-1 abundance in 2006, was approximately 9.60. A significant correlation exists between age 1 abundance and the recruitment index for striped bass as indicated by the correlation coefficient labeled with an asterisk (r = 0.91*).

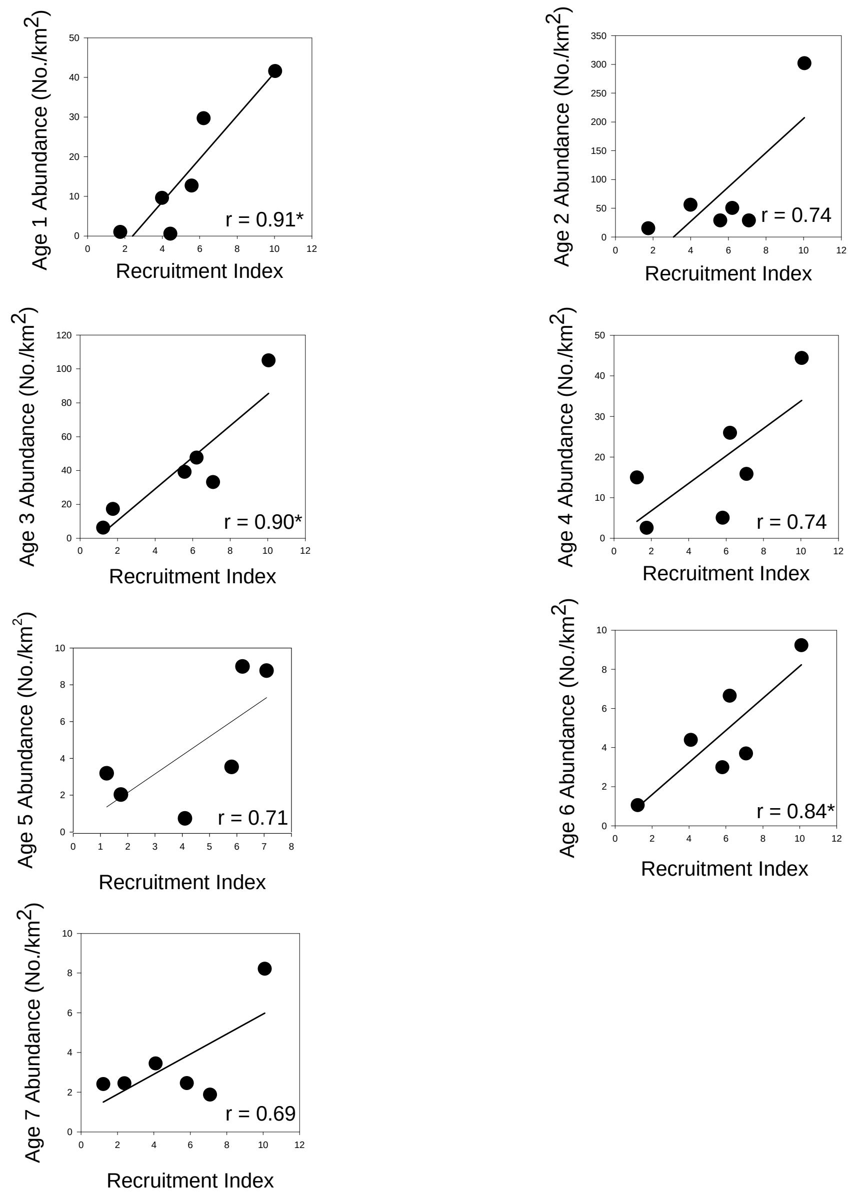


Figure 7. Estimates of age-specific adult abundance regressed against the original striped bass recruitment index derived from the VA Juvenile Striped Bass Seine Survey. Correlation coefficients are shown in the lower right-hand corner. Asterisk indicates a significant correlation (alpha = 0.05) between the two variables.

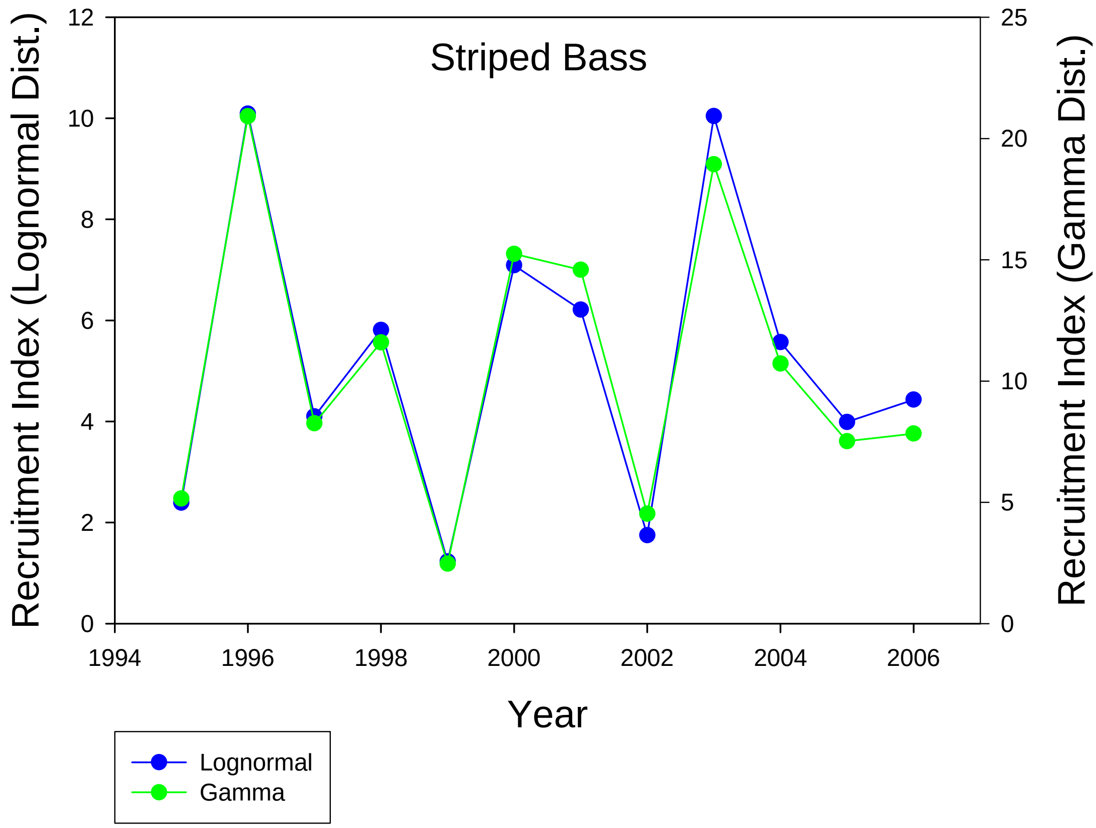


Figure 8. Striped bass recruitment index for 1995 to 2006. The form of the recruitment index depends on the distributional assumptions of the data. Here, the recruitment index is calculated from the means of a lognormal distribution or a gamma distribution.

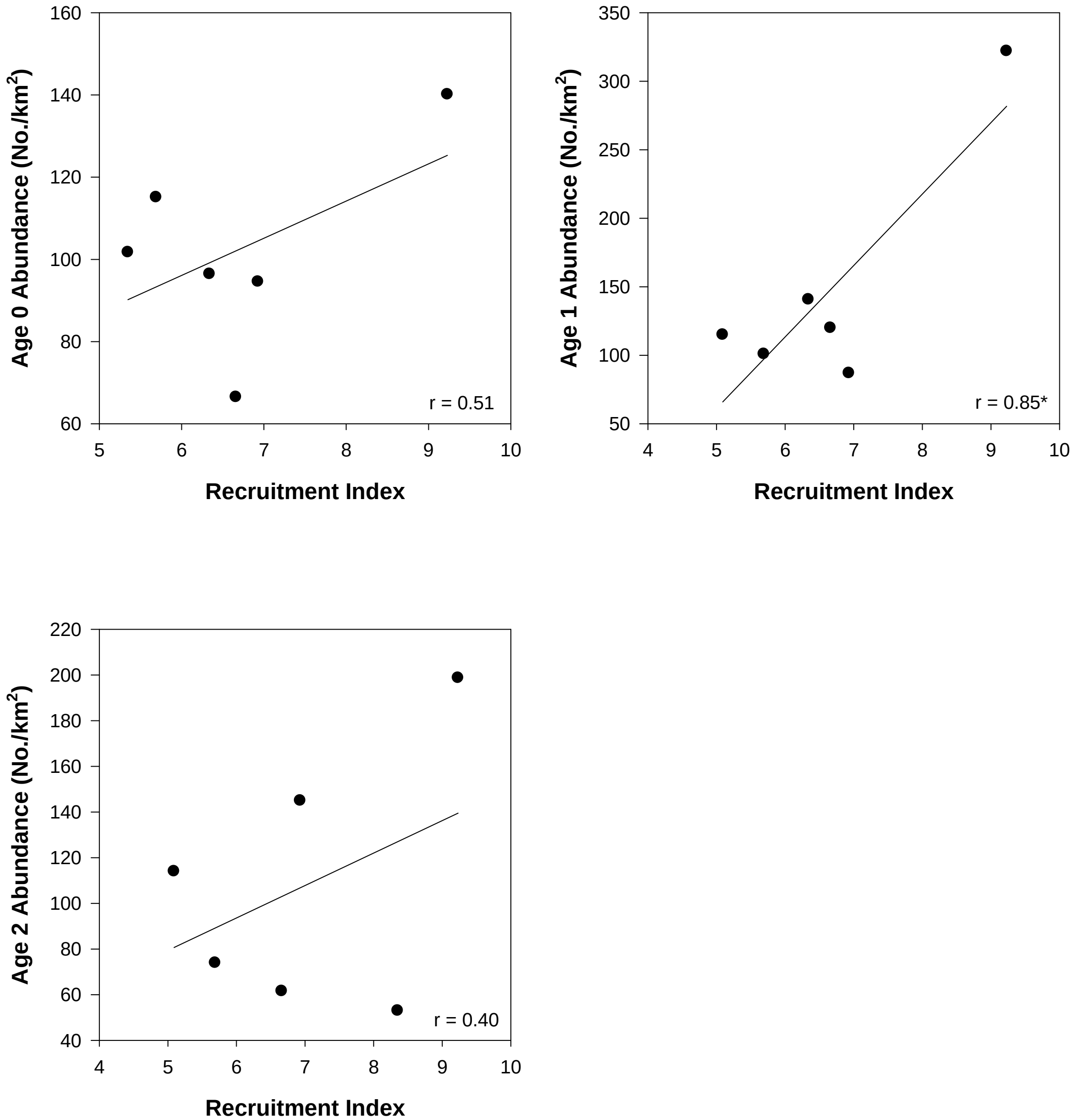


Figure 9. Estimates of age-specific adult abundance regressed against the original weakfish recruitment index derived from the VIMS Juvenile Fish Trawl Survey. Correlation coefficients are shown in the lower right-hand corner. Asterisk indicates a significant correlation (alpha = 0.05) between the two variables.

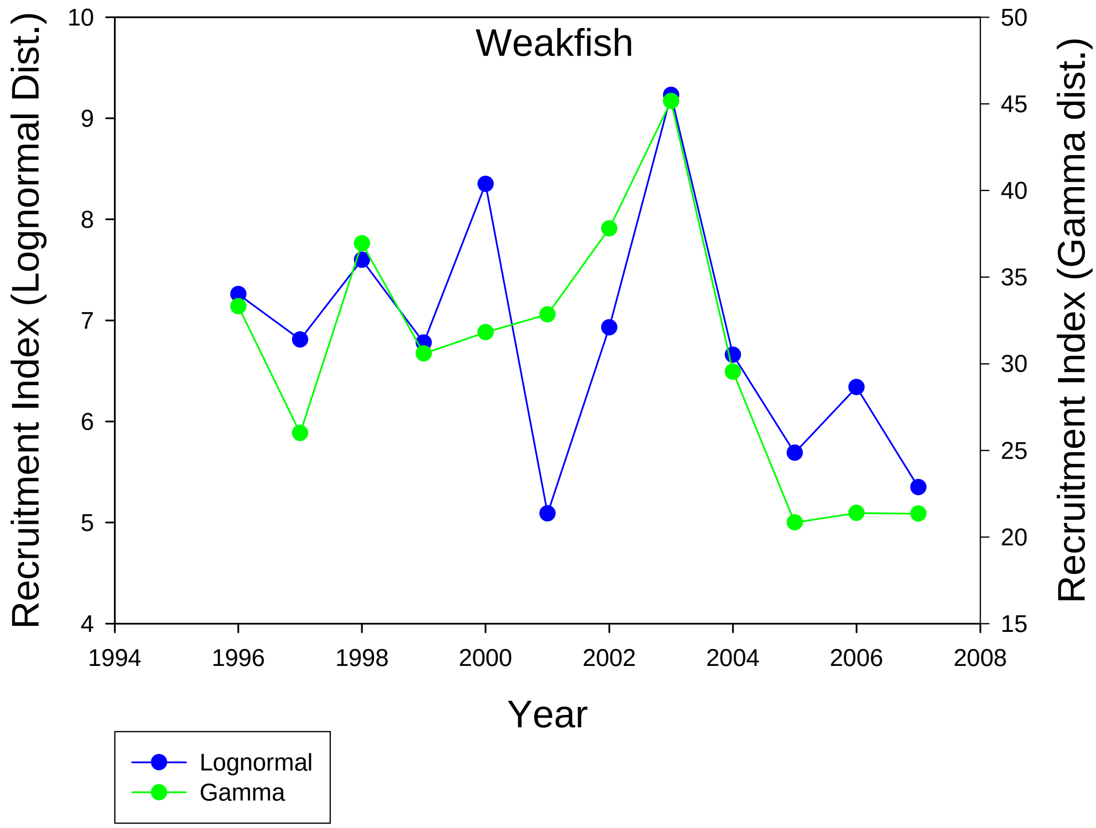


Figure 10. Weakfish recruitment index for the years 1996 through 2007. The form of the recruitment index depends upon the distributional assumptions of the data. Here, the recruitment index is calculated from the means of a lognormal distribution or a gamma distribution. Patterns in the weakfish recruitment index differ depending on the distributional assumptions of the data.

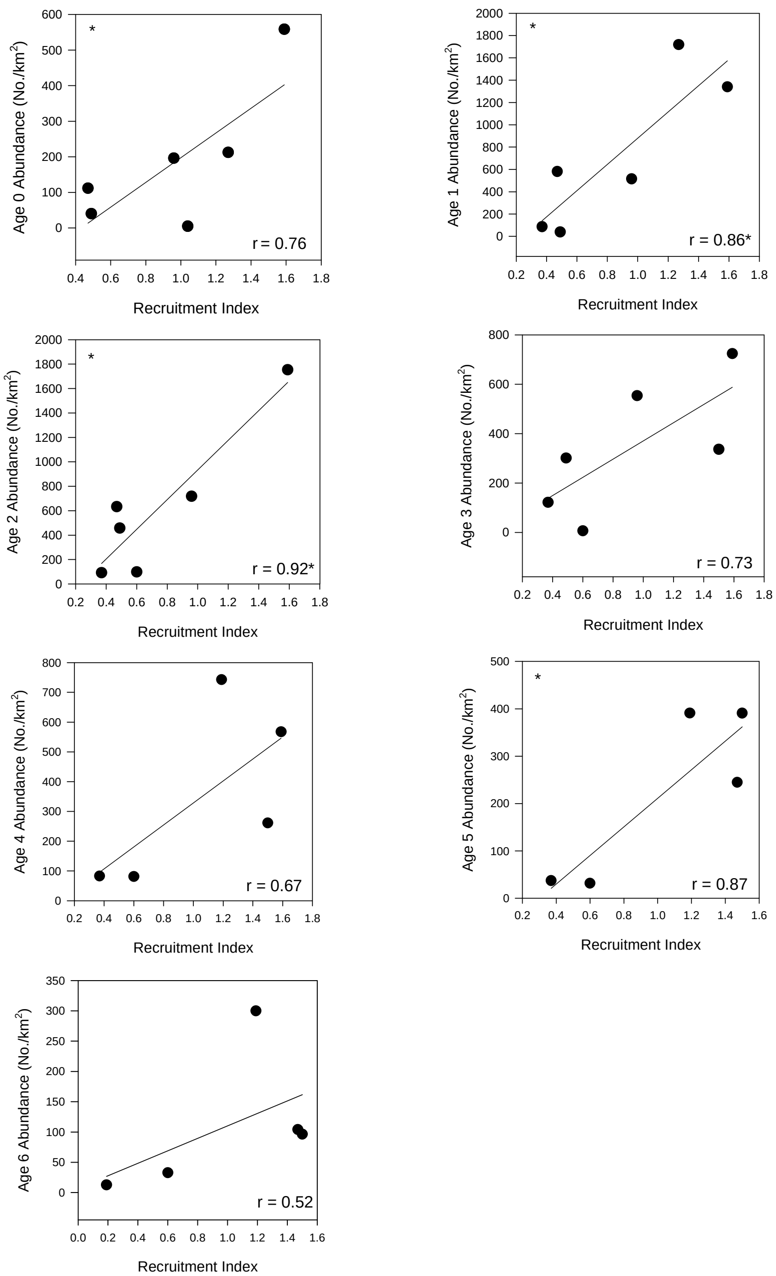


Figure 11. Estimates of age-specific adult abundance regressed against the original recruitment index for Atlantic croaker derived from the VIMS Juvenile Fish Trawl Survey. Correlation coefficients are shown in the lower right-hand corner. Asterisk indicates a significant correlation (alpha = 0.05) between the two variables.

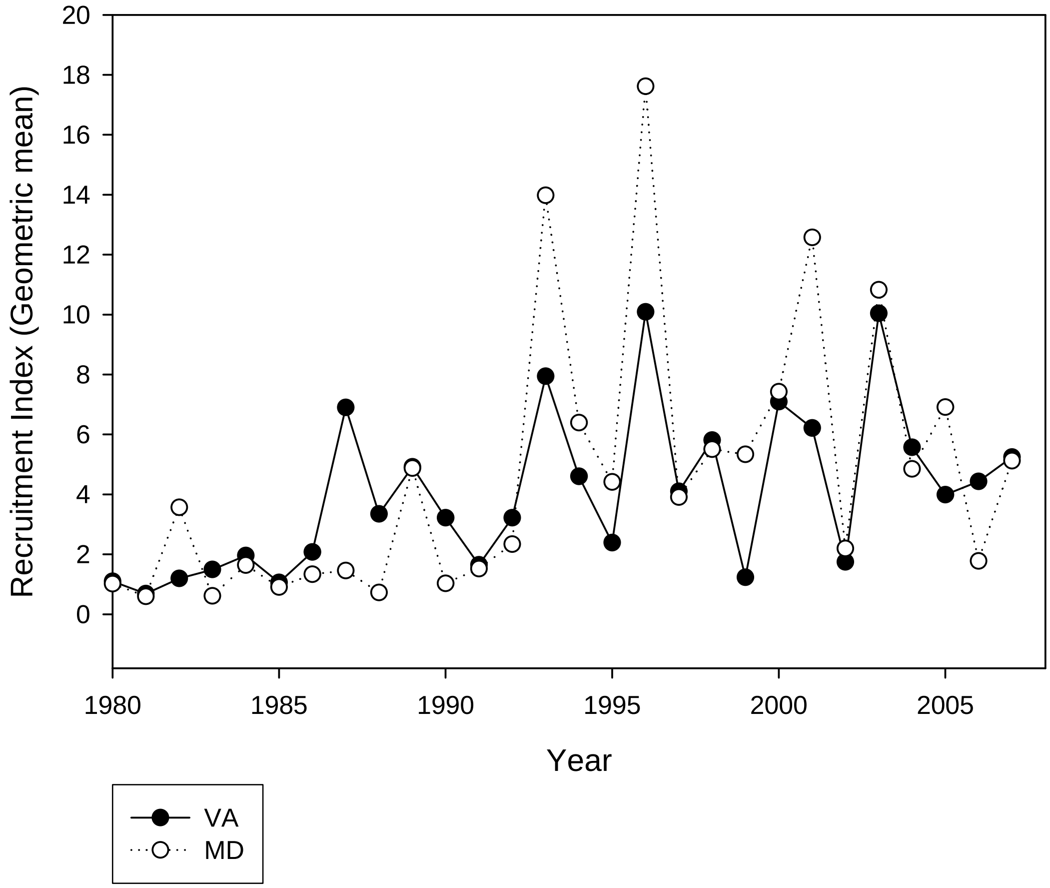


Figure 12. Striped bass recruitment indices from VA and MD for the years 1980 to 2007.

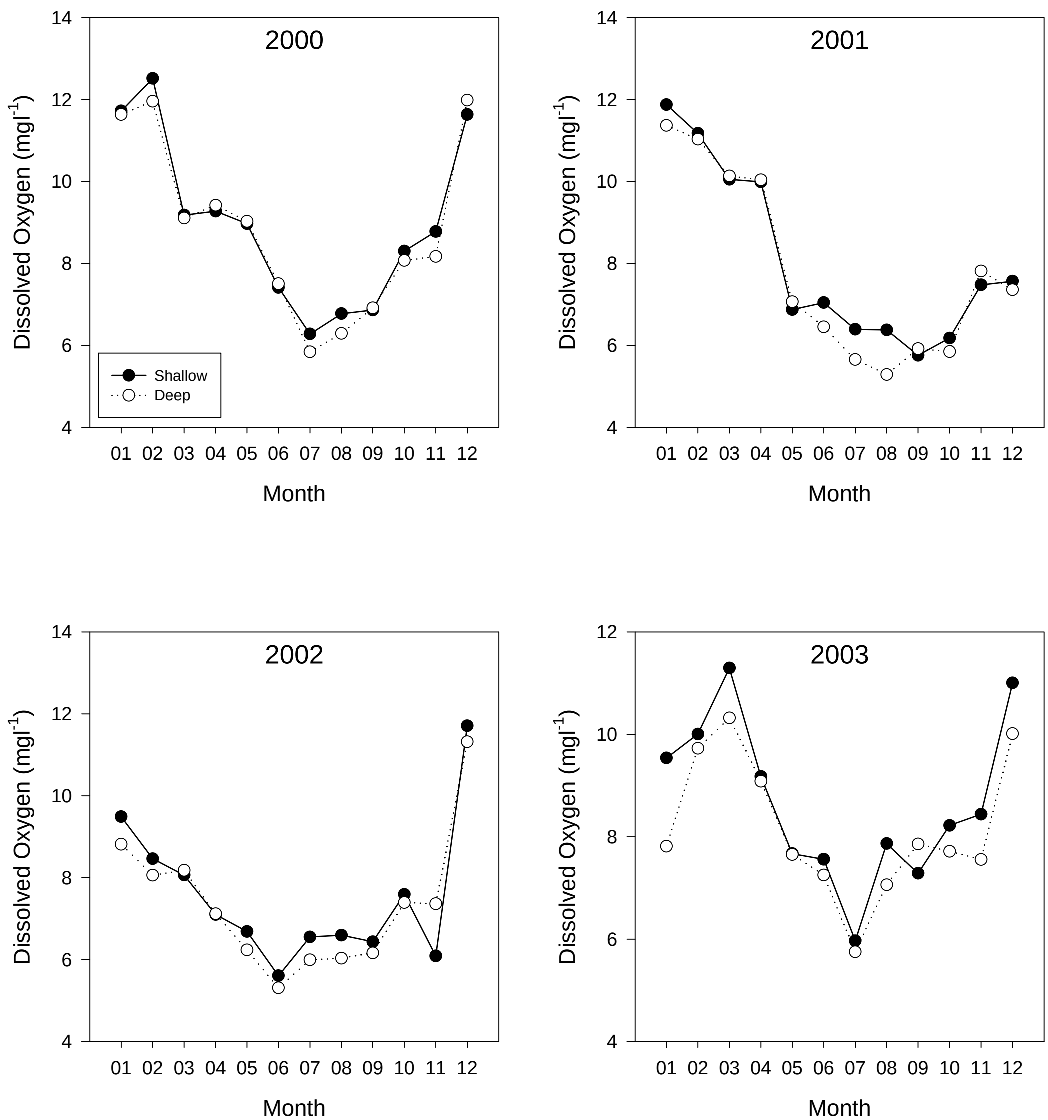


Figure 13. Average dissolved oxygen concentrations (mgl^{-1}) between shallow (≤30ft) and deep (>30ft) stations in the James River by month, 2000-2006. Dissolved oxygen concentrations were obtained using a YSI water quality sensor by the VIMS trawl survey.

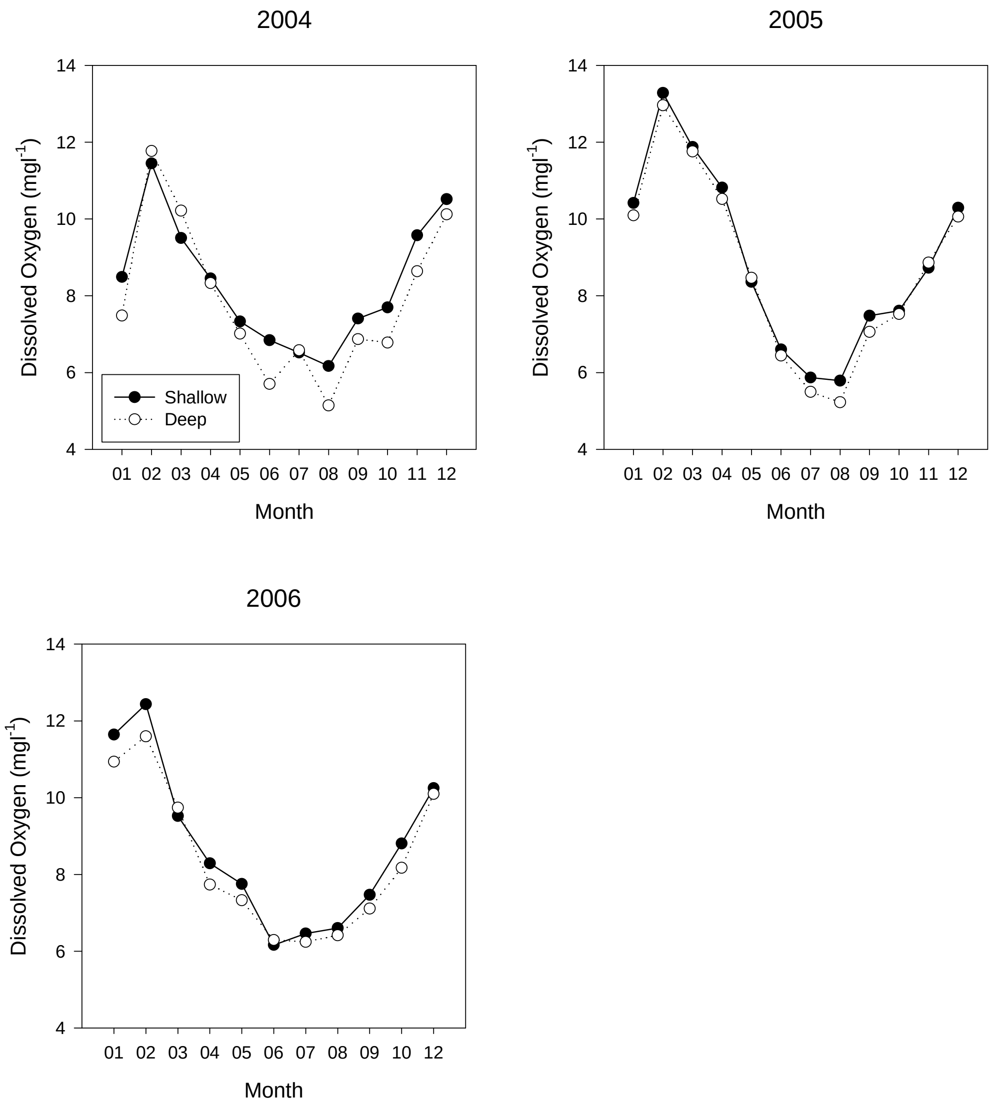


Figure 13 (cont.).

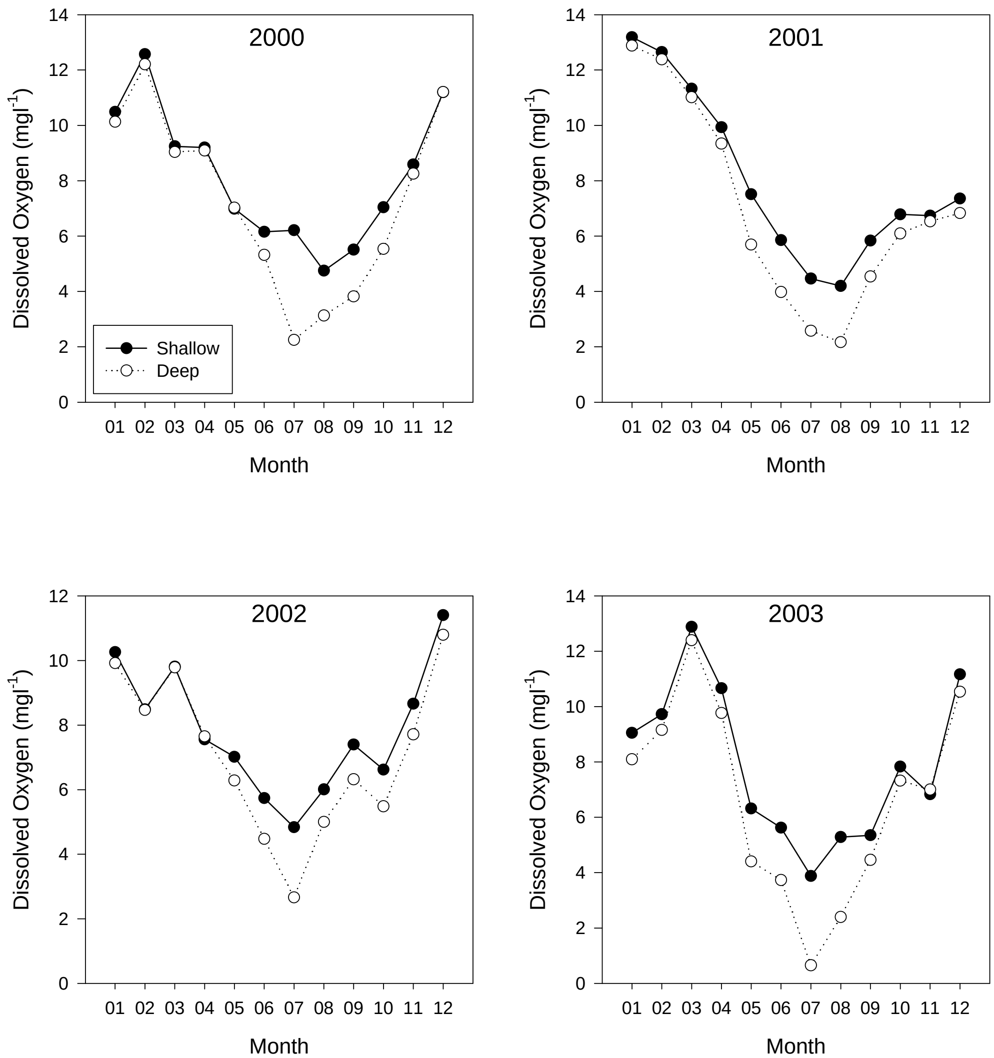


Figure 14. Average dissolved oxygen concentrations (mgl^{-1}) between shallow (≤30 ft) and deep (>30 ft) stations in the Rappahannock River by month, 2000-2006. Dissolved oxygen concentrations were obtained using a YSI water quality sensor by the VIMS trawl survey.

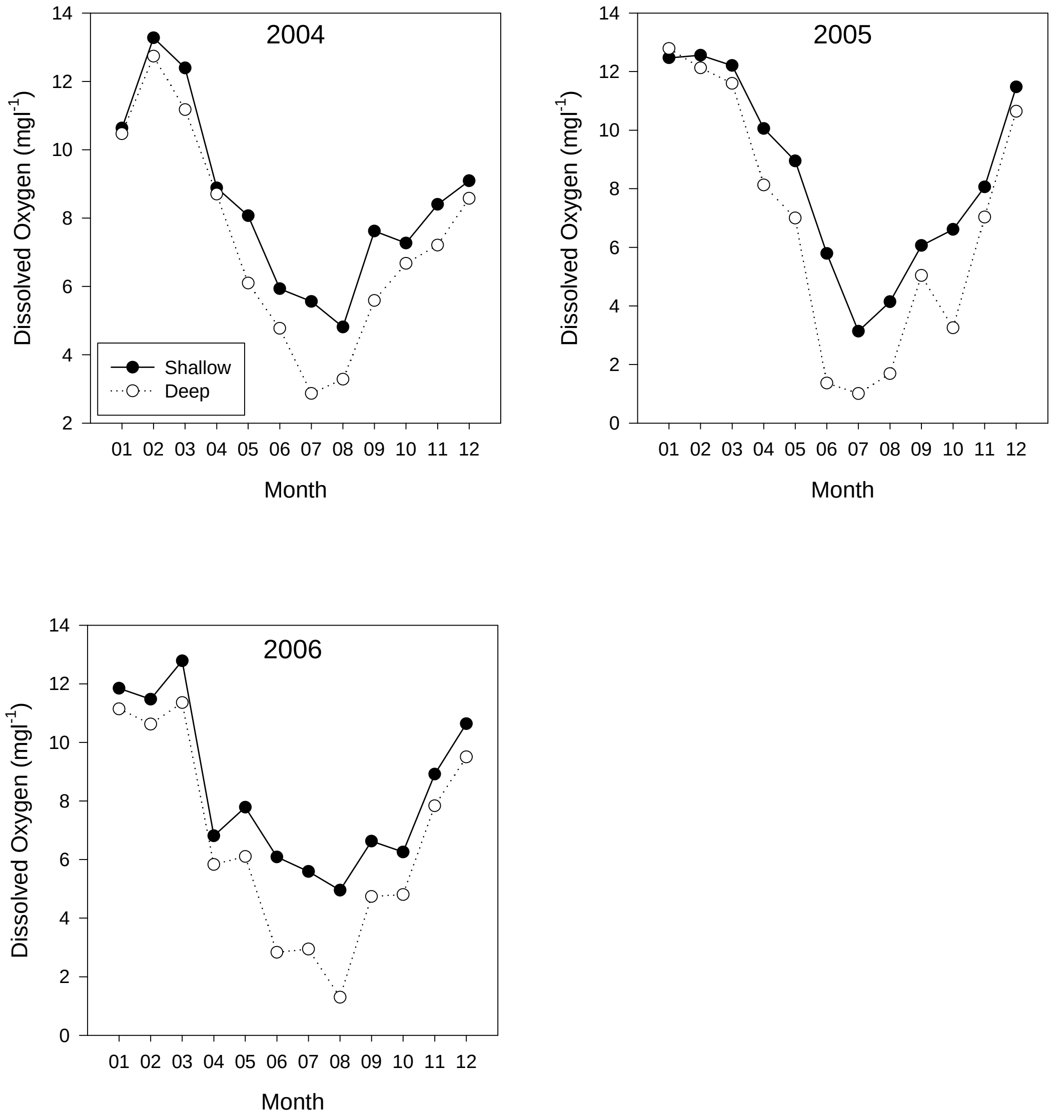


Figure 14 (cont.).

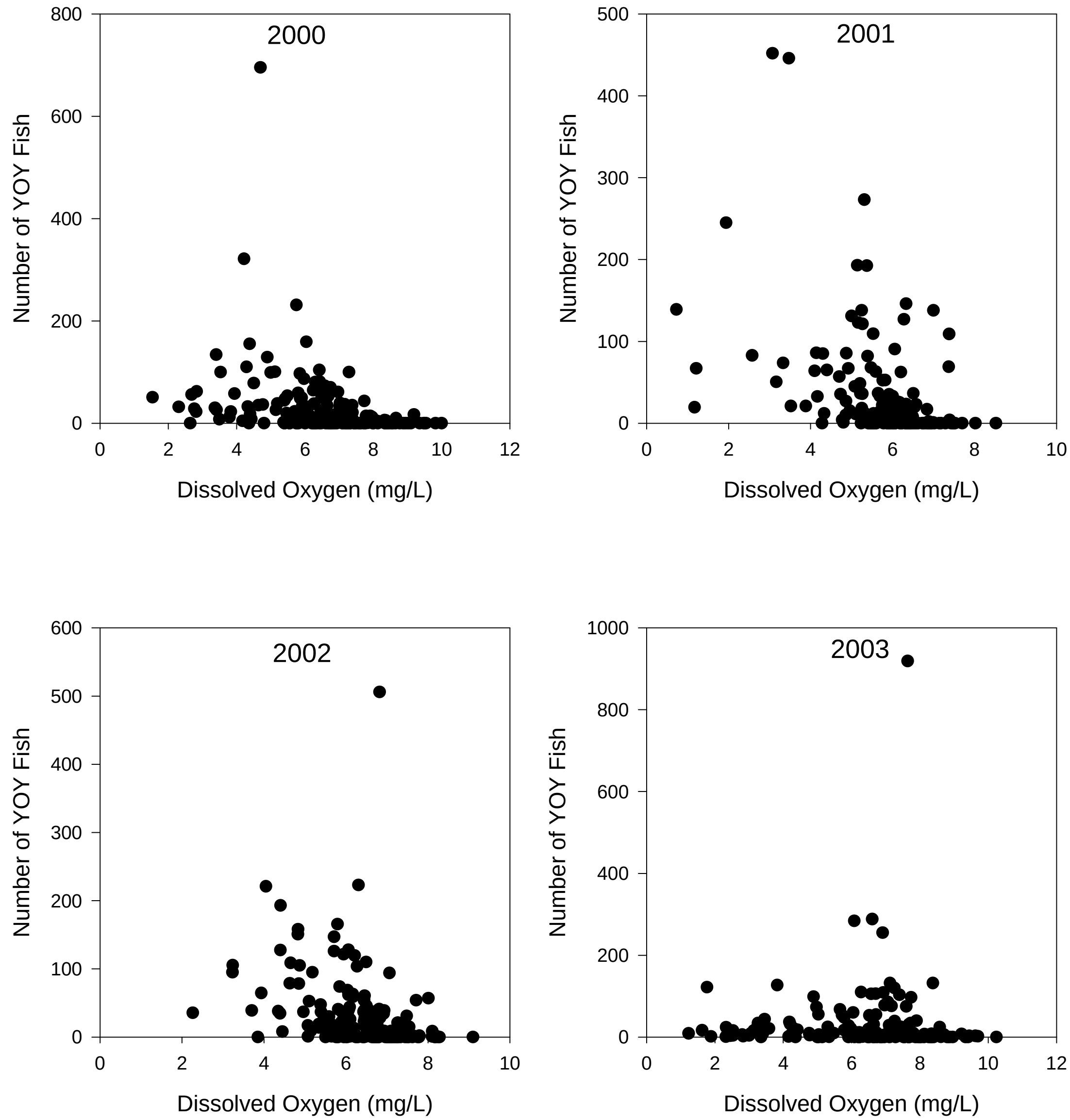


Figure 15. Average total number of YOY weakfish caught by the VIMS trawl survey during the index months (Aug.-Oct) plotted against average dissolved oxygen concentrations for each stratum, 2000-2006.

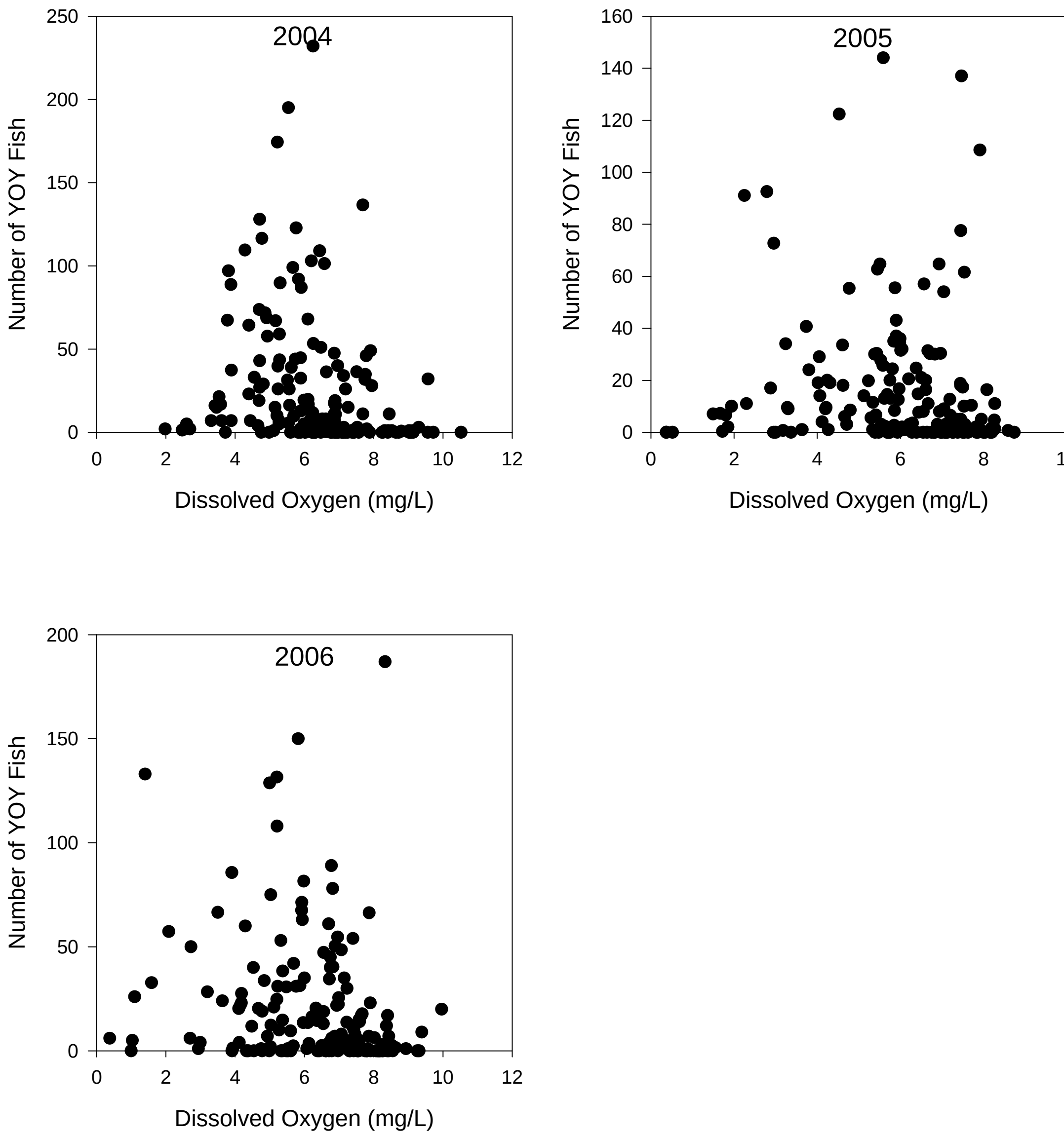


Figure 15 (cont).

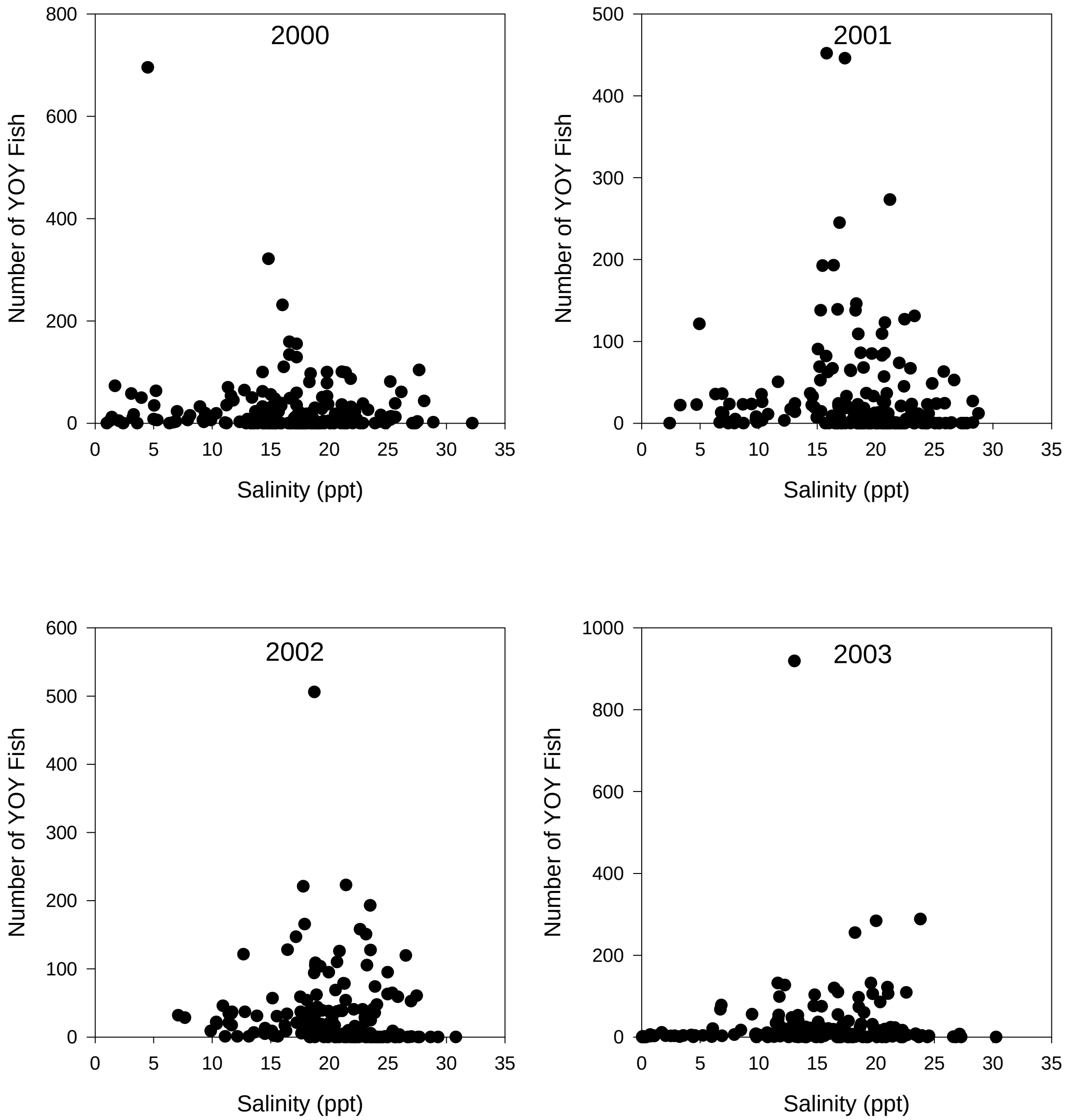


Figure 16. Average total number of YOY weakfish caught by the VIMS trawl survey during the index months (Aug.-Oct) plotted against average salinity concentrations for each stratum, 2000-2006.

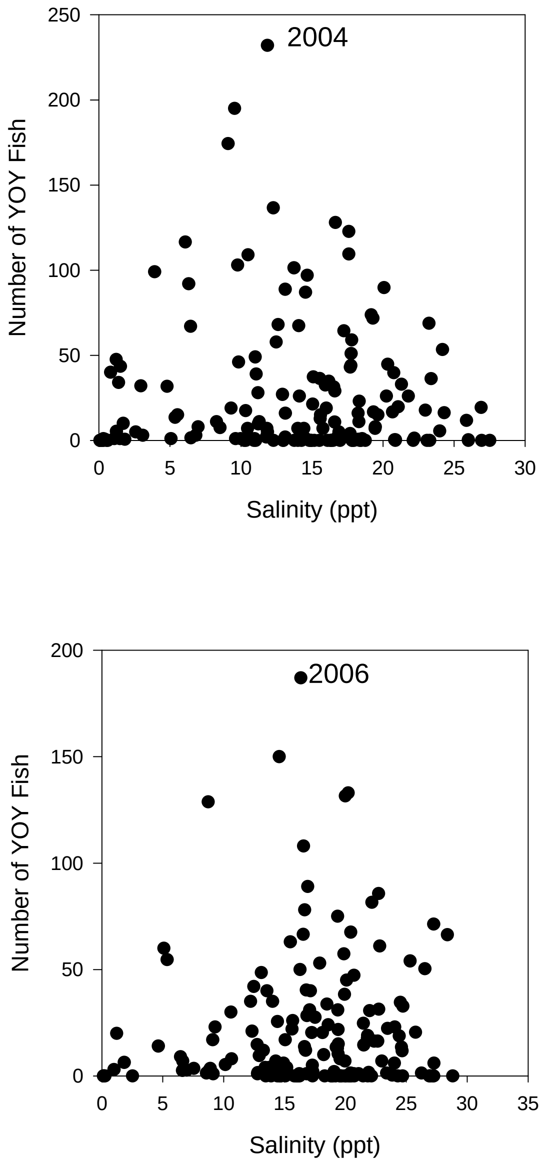


Figure 16 (cont).

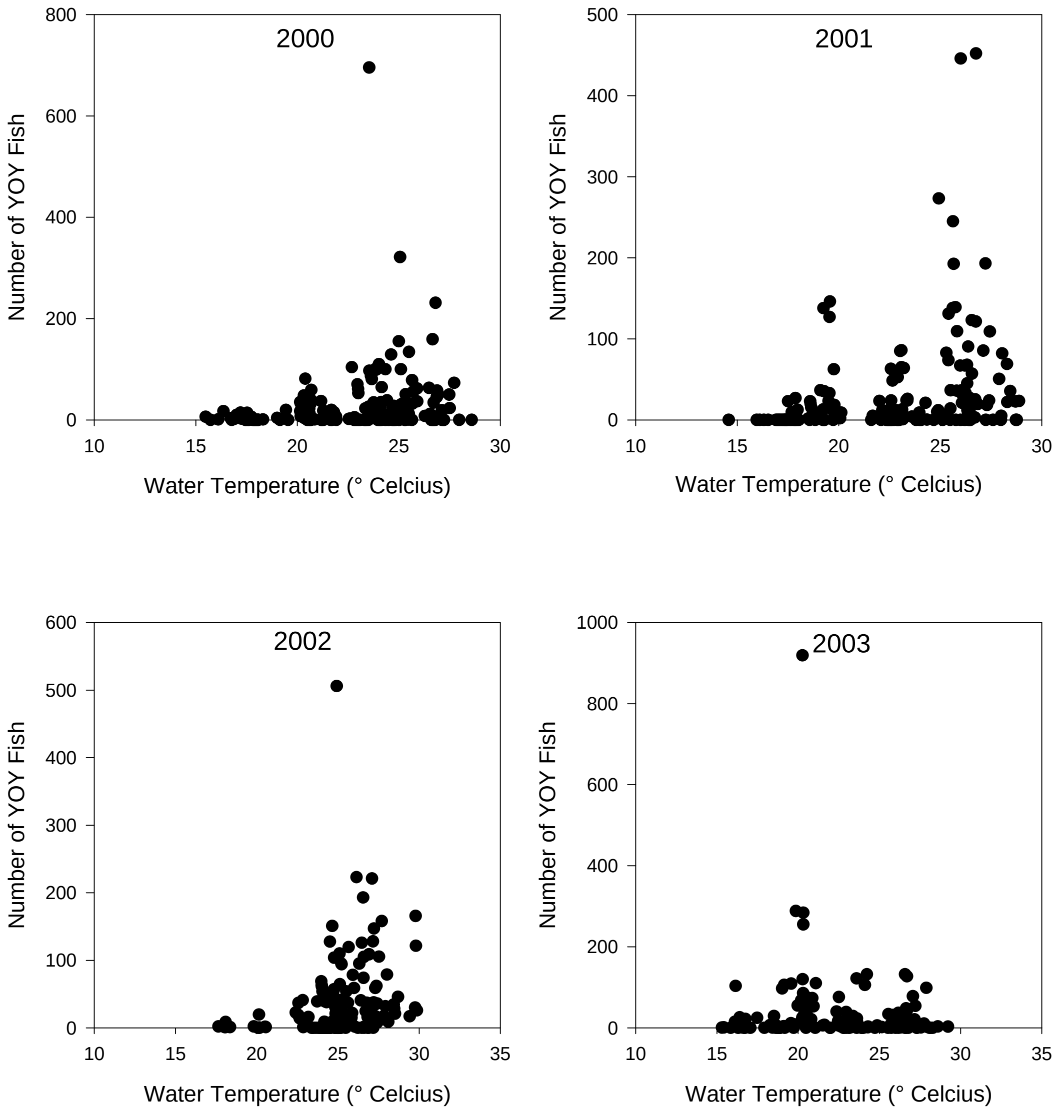
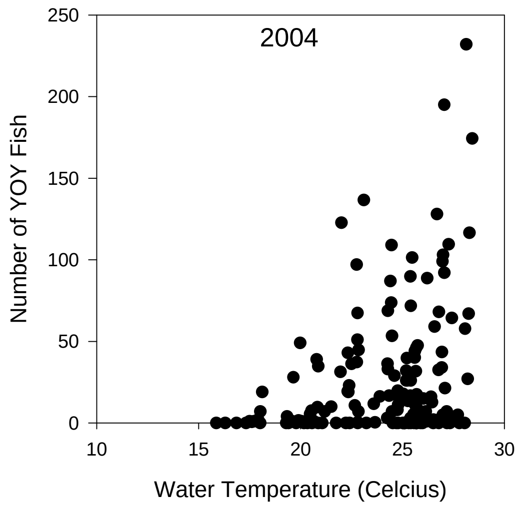
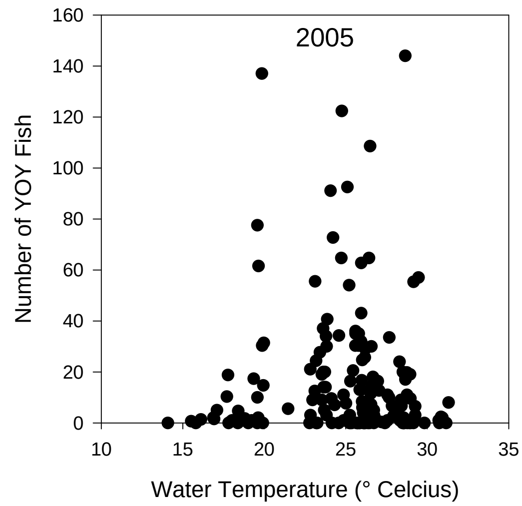


Figure 17. Average total number of YOY weakfish caught by the VIMS trawl survey during the index months (Aug.-Oct) plotted against average bottom water temperature for each stratum, 2000-2006.





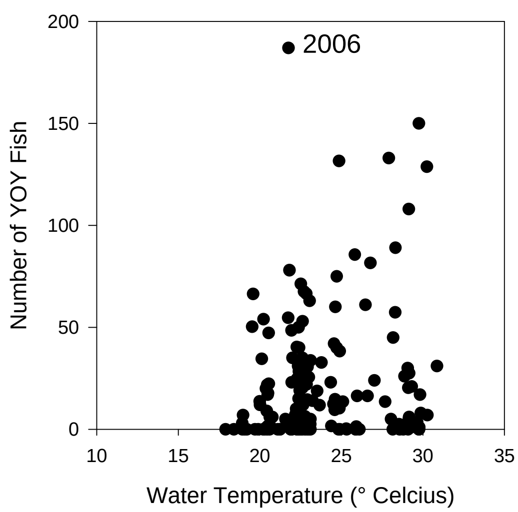


Figure 17 (cont).

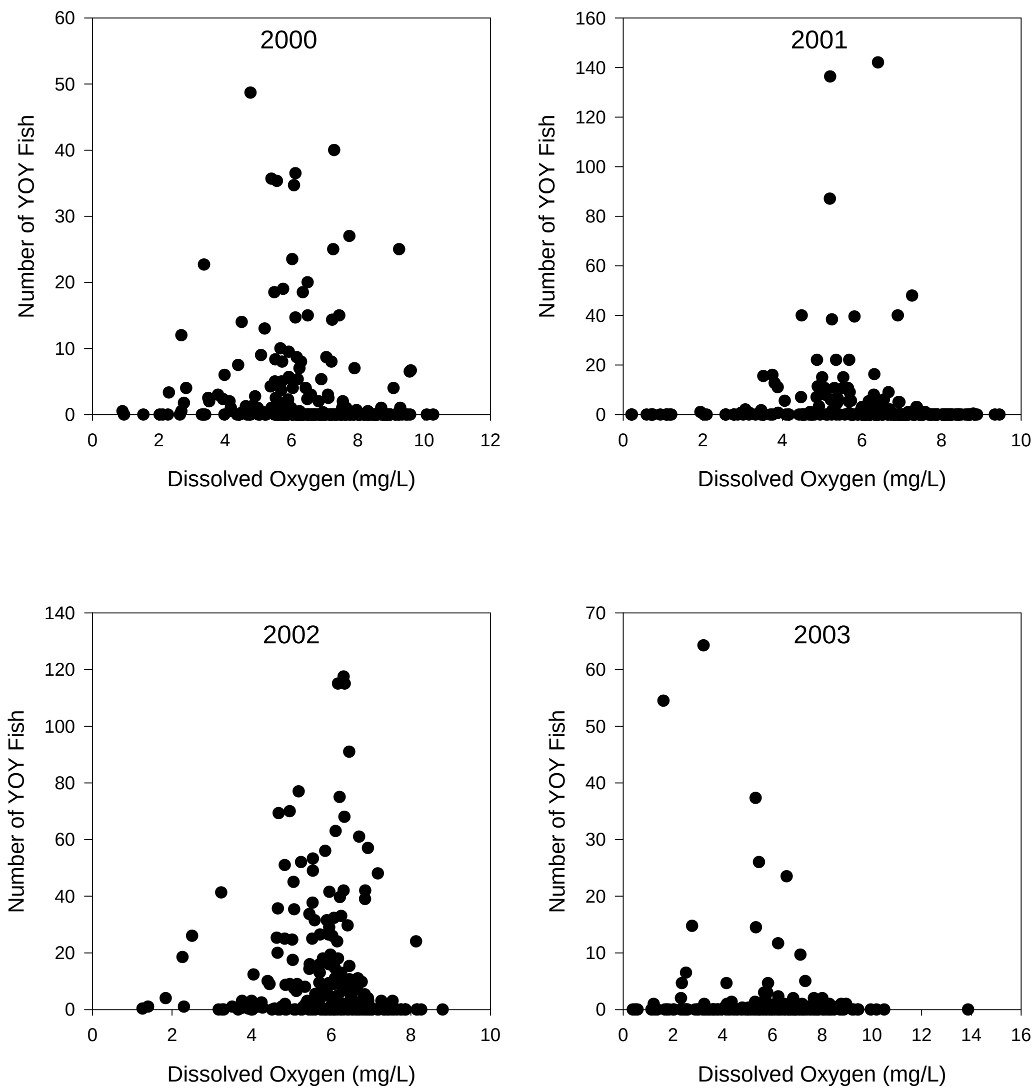


Figure 18. Average total number of YOY Atlantic croaker caught by the VIMS trawl survey during the index months (May-Aug.) plotted against average dissolved oxygen concentrations for each stratum, 2000-2006.

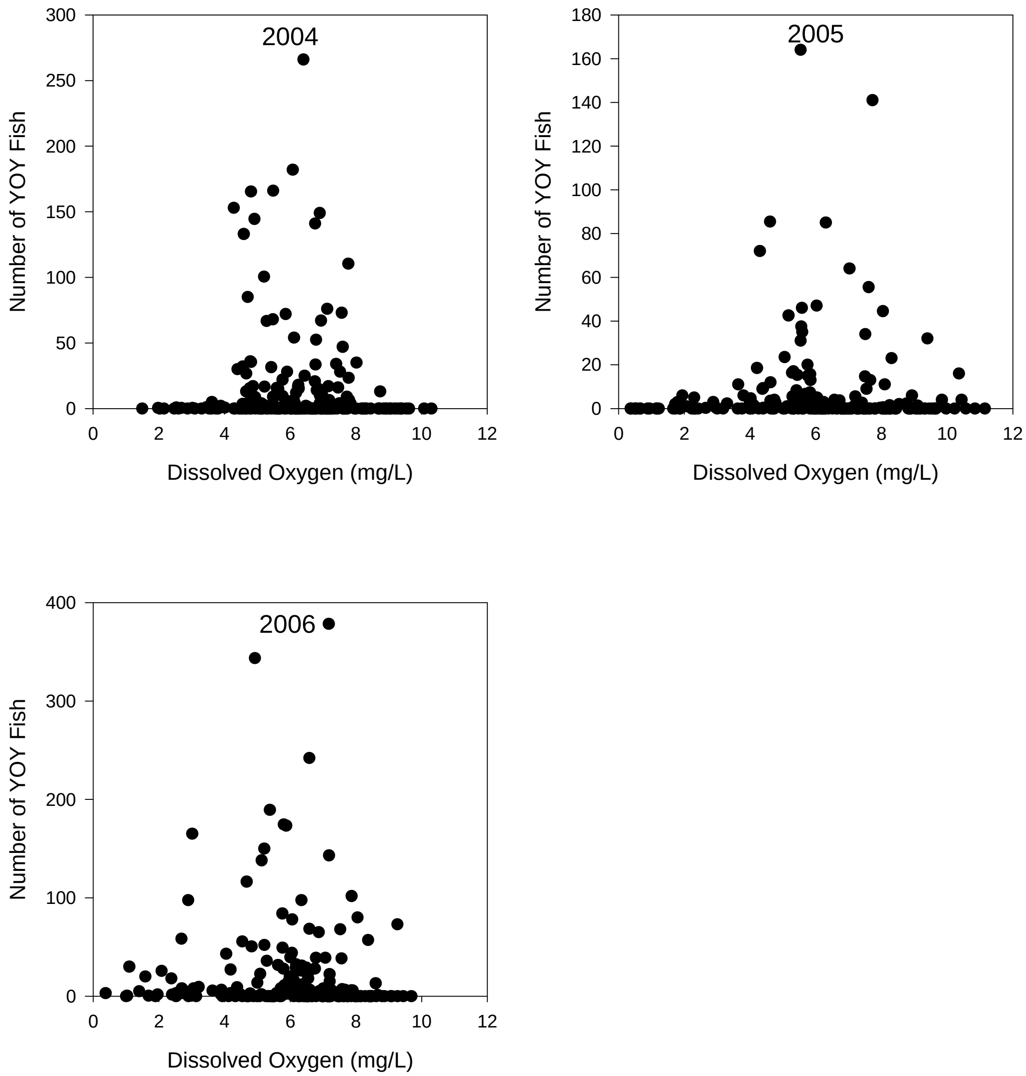


Figure 18 (cont.).

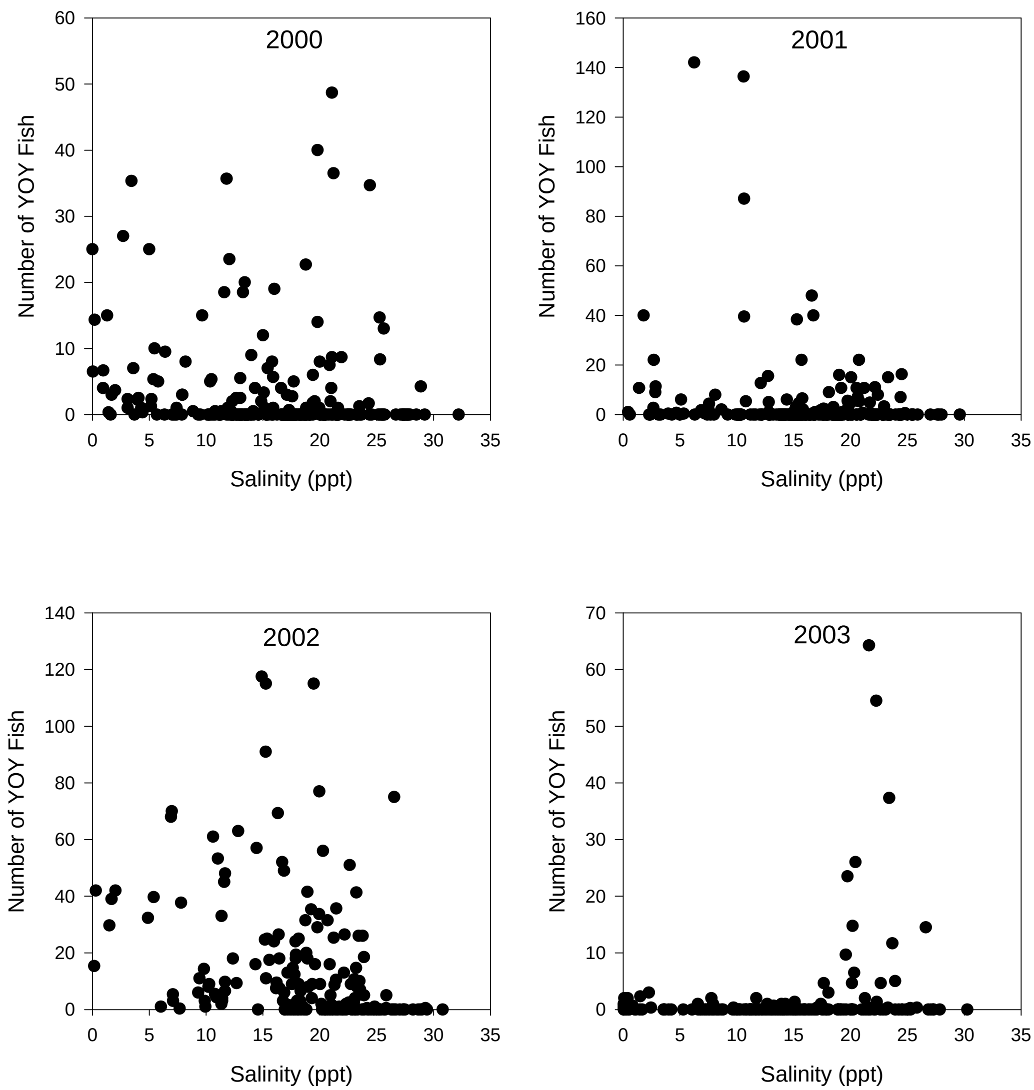


Figure 19. Average total number of YOY Atlantic croaker caught by the VIMS trawl survey during the index months (May-Aug.) plotted against average salinity concentrations for each stratum, 2000-2006.

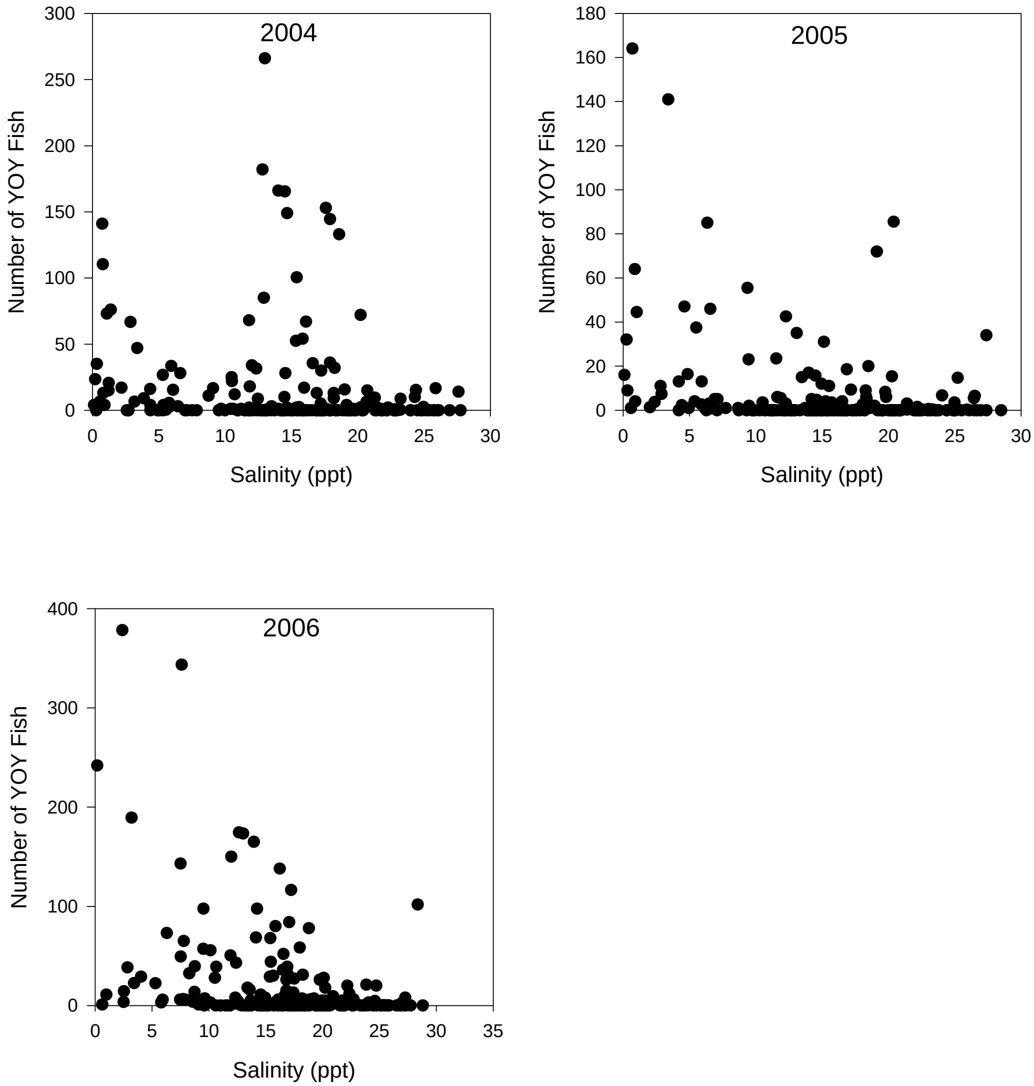


Figure 19 (cont.).

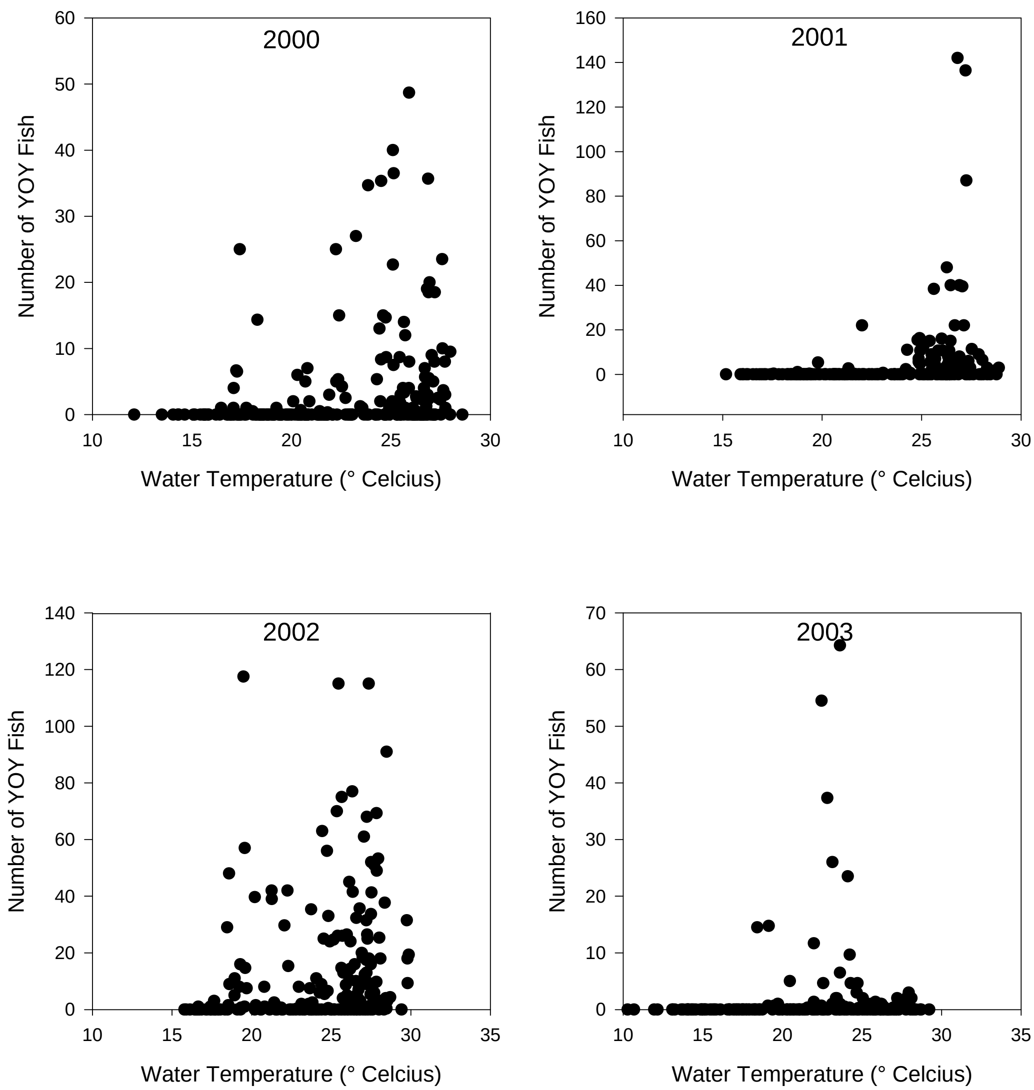


Figure 20. Average total number of YOY Atlantic croaker caught by the VIMS trawl survey during the index months (May-Aug.) plotted against average bottom water temperature for each stratum, 2000-2006.

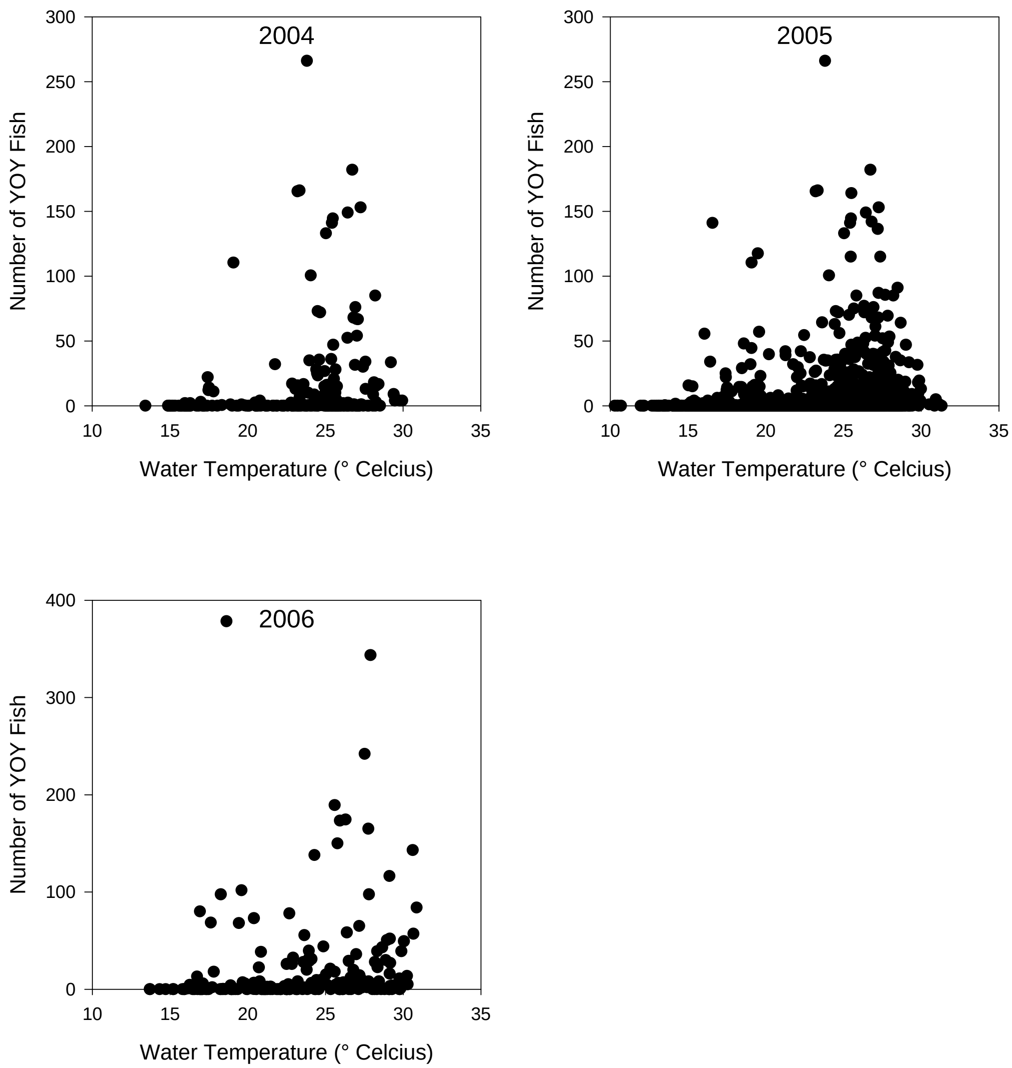


Figure 20 (cont.).

CHAPTER 2

EVALUATING LENGTH AS A PROXY FOR AGE IN YOUNG-OF-YEAR STRIPED BASS, WEAKFISH, AND ATLANTIC CROAKER

INTRODUCTION

Variability in the recruitment of fishes to the juvenile stage can have important implications for management (Fogarty *et al.* 1991). Recruitment indices, or indices of young-of-year (YOY) abundance, are useful for forecasting trends in future stock abundance (Crecco *et al.* 1983; Bailey and Spring 1992; Helle *et al.* 2000; Axenrot and Hannson 2003; Hare and Able 2007). Chesapeake Bay is a critical nursery habitat for many recreationally and commercially important fishes such as striped bass (*Morone saxatilis*), weakfish (*Cynoscion regalis*), Atlantic croaker (*Micropogonias undulatus*), and summer flounder (*Paralichthys dentatus*). Multiple fishery-independent surveys are currently in progress throughout Chesapeake Bay to monitor the abundance and distribution of juvenile fishes within their primary nursery habitat (Durell and Weeden 2007; Fabrizio and Tuckey 2008; Hewitt *et al.* 2008). Indices are derived to reflect interannual variability in recruitment to the juvenile stage; subsequently, they are used to assess the status of economically valuable stocks. Information used to develop a recruitment index should be evaluated to ensure that the index is representative of abundance at the juvenile stage and accurately reflects year-class strength. Due to the frequency of large catches, juvenile finfish research surveys often use length as a surrogate for age (Fabrizio and Tuckey 2008; Hewitt *et al.* 2008). When such methods are employed, length threshold values require verification to ensure they accurately distinguish YOY fishes from older individuals.

In this study, I evaluate the current length threshold values used to distinguish YOY fish from older individuals for striped bass, weakfish, and Atlantic croaker collected by the VIMS juvenile finfish monitoring surveys. In general, length-frequency analysis is a method of age corroboration that is most suitable for estimating growth rates of rapidly-growing fish, for which age-specific length modes are easily identified (Campana 2001). Length threshold values used by the VIMS Juvenile Fish Trawl Survey (hereafter referred to as the VIMS trawl survey) were last evaluated in 1990 (Colvocoresses and Geer 1991). Using length data from fish collected between 1955 to 1990, YOY length values were assigned based on historical composite length frequencies developed by month for weakfish and Atlantic croaker (Appendix 1). Unfortunately, there is no published description of how the length threshold value (150 mm) used to distinguish YOY striped bass from older individuals collected by the Virginia Striped Bass Seine Survey (hereafter referred to as the VA seine survey) was obtained. This value remains sufficiently high enough to include the range of lengths observed in YOY fish; nevertheless, the potential for including age-1 fish remains.

The need for validating the length threshold values for YOY fish is crucial because the use of length-frequency analysis to assign age classes does not account for the effects of variability in growth rates through time. The focus of this research is to assess whether historically-defined length threshold values accurately distinguish YOY fishes in present-day catches. Elucidating the underlying mechanisms for changes in length at age is beyond the scope of this study; however, I discuss potential reasons why the current length designations for the selected species may no longer be appropriate. Moreover, no previous studies have investigated the length-at age-relationship of presumably YOY fishes collected by the VIMS juvenile finfish surveys using a validated ageing method. My objective is to evaluate the length threshold values for YOY striped bass, weakfish, and Atlantic croaker by comparing fish length to transverse-sectioned otoliths used to determine age. The three species were selected based on the differences between their life histories (see Chapter 1). Improper ageing can ultimately lead to incorrect estimates of important age-based parameters such as growth and age-at-maturity (Beamish and McFarlane 1983), but more importantly, in this application, the use of unsuitable length values can result in inaccurate estimates of relative abundance of YOY fishes. Annulus formation in otoliths has been validated for striped bass using mark-recapture data from hatchery-reared fish that were tagged prior to release as juveniles in Chesapeake Bay and later captured as adults (Secor *et al.* 1995). Marginal increment analysis has been used to validate annual growth in transverse-sectioned otoliths of weakfish (Lowerre-Barbieri *et al.* 1994) and Atlantic croaker (Barbieri *et al.* 1994). In light of my findings, I discuss the potential for incorrectly estimating the relative abundance of YOY fishes with inappropriate length threshold values.

METHODS

Juvenile finfish monitoring programs

The VA seine survey purposely monitors the annual recruitment of striped bass from July to mid-September at fixed stations in the James, York, and Rappahannock rivers (Figure 1) using a 1.2 m x 30.5 m x 6.4 mm minnow seine (Hewitt *et al*. 2008). At index stations, striped bass measuring less than 150 mm are used to develop the recruitment index which is reported annually as a geometric mean catch-per-haul. Under the current protocol for the VA seine survey, the recruitment index is multiplied by a scaling factor of 2.28 to provide an *ad hoc* estimate that is comparable to the arithmetic mean (2.28 is the estimated ratio of the arithmetic mean to the geometric mean, calculated from historical data from the seine survey) (Austin *et al.* 1993). The scaling factor was originally included because of differences in the reported forms of the index, and because the "trigger" used by the fisheries management plan (FMP) for striped bass is based on an arithmetic mean; however, now that both states report the recruitment indices as geometric means, the scaling factor may no longer be necessary. The striped bass recruitment index reported here does not match the published recruitment index because the scaling factor was not included in my calculation of the index.

The VIMS trawl survey monitors the abundance of finfish populations on a monthly basis in the James, York, and Rappahannock River systems and portions of the lower Chesapeake Bay (Figure 2) using a lined 9.14 m semi-balloon otter trawl, with 38.1

mm stretched mesh and 6.35 mm cod liner (Fabrizio and Tuckey 2008). The survey implements a stratified random sampling design with strata defined according to depth and either latitudinal (Bay) or longitudinal regions (rivers). Each species is fully recruited to the trawl during a 3-4 month time period referred to as the 'index period.' To derive a recruitment index, the appropriate index period and strata must be identified for each species. Historically-defined length threshold values are then used to distinguish YOY fish from older individuals collected within the defined stratum. Consequently, an annual recruitment index is derived as a weighted geometric mean catch per tow using individuals that are 1) measured during the specified index period and strata and 2) are smaller than the month-specific length threshold values. Although multiple recruitment indices are calculated for each species, the random stratified converted index (RSCI) was chosen for weakfish and Atlantic croaker. The RSCI incorporates a correction factor for all gear and research vessel changes that have occurred since 1955. Additionally, for Atlantic croaker, I used the spring recruitment index (RSCI) in this analysis which reflects YOY abundance more accurately than the fall recruitment index because year-class strength is not established until the first spring (Hare and Able 2007).

Specimen collection and age determinations

Striped bass were collected between July and mid-September 2007 by the VA seine survey with about 10 individuals collected from index stations during each of five sampling rounds (Table 1). Ten weakfish and ten Atlantic croaker were collected from each region (James, York, Rappahannock Rivers and Virginia mainstem portion of Chesapeake Bay) from August to October (weakfish) and May to August (Atlantic croaker) by the VIMS trawl survey in 2007. Euthanasia was accomplished through immersion in an ice brine slurry following approved IACUC protocols. Specimens were kept on ice until they were processed immediately upon return to the laboratory. Total lengths (TL) were recorded to the nearest millimeter for weakfish and Atlantic croaker, and fork length (FL) was recorded for striped bass. Both saggital otoliths were removed and stored dry for later analysis.

Transverse sections, approximately 1-2 mm thick, were removed from the right otolith using a Buehler low-speed Isomet saw. Sections were polished on 320-grain sandpaper, mounted on glass slides using Crystalbond mounting medium, and viewed at 6x magnification. Annual marks, indicated by thin, opaque bands, were counted and recorded for each species by three independent readers (R. Johnson, M. Chattin, and J. Woodward). Final ages were assigned based on the agreement of at least two readers. The pattern of alternating narrow, opaque zones and translucent hyaline zones has been documented as annulus formation for striped bass (Secor *et al.* 1995), weakfish (Lowerre-Barbieri *et al.* 1994), and Atlantic croaker (Barbieri *et al.* 1994). Although distinguishable in striped bass and weakfish, the first annulus in Atlantic croaker is represented by a blurred, opaque band surrounding the core of the otolith and is formed during the first spring (Barbieri *et al.* 1994) when the fish are less than one year old (chronologically). Correct identification of the first annulus is imperative, with disagreements often resulting from the misidentification of the first annulus (Barbieri *et al.* 1994). Equally important, is the choice of the biological birthdate used to assign fish to appropriate age classes. In this study, I assigned January 1 as the arbitrary birthdate for all species, a practice common for assigning ages of finfishes (Devries and Frie 1996).

Precision and accuracy of age assignments

Percent agreement was used to evaluate ageing precision among readers. Using assigned ages, percent agreement between two readers is calculated as:

$$PA = \left(\frac{\#agreed}{\#read} \right) * 100 \qquad (1)$$

I did not examine more rigorous approaches for determining precision among readers given that PA was 100% for 2 out of the 3 species, and PA was at least 86% for the third species.

Following the recommendations of Campana *et al.* (1995), age bias plots were examined for Atlantic croaker to detect systematic differences, or bias, between readers. In these plots, the age assignments of one reader are presented as the mean ages and 95% confidence intervals for each of the respective ages assigned by a second reader; interpretations are then made graphically with respect to an equivalence line between the two readers (Campana *et al.* 1995). To use age bias plots, multiple year classes must be identified. Consequently, age bias plots were not constructed for striped bass and weakfish because age 1 was the maximum age identified in my samples for both species.

Assessing the relationship between mean length at age and abundance

The relationship between mean length-at-age and abundance was evaluated to investigate the possibility of density-dependent growth for striped bass, weakfish, and Atlantic croaker. Density-dependent growth may result in changes to important life-history parameters, such as growth rates which, in turn, may contribute to the uncertainty in age assignments based on length. Changes in mean length-at-age may have occurred in association with changes in stock abundance for striped bass (ASMFC 2008), weakfish

(ASMFC 2006), and Atlantic croaker (ASMFC 2006). In this study, average total length of YOY fish was regressed against the recruitment index of the same year for each species to investigate the occurrence of density-dependent growth.

A simple linear regression model was applied to the striped bass, weakfish, and Atlantic croaker abundance data. The model for a simple linear regression is:

$$L_j = \beta_0 + \beta_1 I_{YOY,j} + \varepsilon_j \qquad (2)$$

where the dependent variable, L_j, is the average length of YOY fish for the j^{th} year class, the overall mean is β_0, the slope parameter, β_1, measures the change in L_j per unit change in the independent variable, I_{YOY}, which is the recruitment index for the j^{th} year class, and ε_j is the random error associated with the j^{th} year class. The following assumptions apply when using linear regression analysis: (i) the response variable, L_j, is independent and normally distributed; (ii) the errors, ε_j, are independent and normally distributed; (iii) the expected mean value of the error term is 0 and the variance is designated as σ_ε^2; and (iv) variances of the error terms are homogeneous. Residual plots were examined for patterns, and Cook's D statistic (Cook 1977) was used to assess the influence of potential outliers on the models. If the Cook's D statistic had a value greater than 1, then this indicated the influential data. Data collected from 1988 to 2007 (n = 19 years) were used in the analysis. I chose 1988 because this was the year during which the VIMS trawl survey was expanded to include portions of the lower Chesapeake Bay.

To examine the strength of the relationship between average length of YOY fish and the recruitment index for that year, the Pearson's product-moment correlation coefficient *r,* a derived statistic from simple linear regressions, was determined for each species. A statistical test based on the t-distribution was used to test the significance of the correlation coefficient. A sample size of 20 was used based on the number of years included in the analysis (1988-2007). For n = 20 and 4 (n-2) degrees of freedom, the critical value of r in this analysis is t_{crit} = 0.42 at an alpha level of 0.05. Significant, positive correlations provided support for linear relationships between average length of YOY fish and the recruitment index and also indicated the possibility of density-dependent growth.

RESULTS

Striped bass

Six individuals were aged as 1-year old fish out of 179 collected specimens. Five of these individuals, ranging between 119 mm and 149 mm, were less than the 150 mm length threshold for YOY fish, and thus represent fish which were incorrectly assigned as YOY (Figure 3). The sixth fish was expected to be 1-year old because it was greater than the length threshold. Percent agreement between readers was 100% (Table 3).

To determine how length-based age assignments influence the magnitude of the striped bass recruitment index, I calculated the annual percentage of the catch between 100 mm and 150 mm for 2000 to 2007 (Table 2). On average, less than 1% of the catch was greater than 100 mm. Thus, the recruitment index is not likely influenced by older individuals measured as YOY fish.

I examined historical data for changes in average length coincident with changes in the recruitment index to investigate the occurrence of density-dependent growth in YOY striped bass during the last 20 years. From 1988 to 2007, average length of YOY striped bass was significantly correlated with the recruitment index providing support for the possible occurrence of density-dependent growth (Figure 4). The absence of a detectable pattern in the residual plots indicated the appropriateness of the linear regression model (Figure 5).

Weakfish

All weakfish collected in August 2007 less than the 150 mm length maximum were YOY fish (Figure 6). Although no specimens were collected between 150 mm and 190 mm in August, three individuals between 190 mm and 240 mm were aged as 1-year old fish, as expected. In September, all specimens measuring less than the 180 mm length threshold value were identified as YOY fish; however, I found five YOY individuals between 180 mm and 200 mm. The smallest 1-year old weakfish collected in September measured 198 mm. In October, six individuals greater than the 200 mm length threshold value were aged as YOY fish; however, overlapping year classes occurred at lengths between 190 mm and 200 mm. Percent agreement between readers was 100% (Table 3).

Between 1988 and 2007, average length of YOY weakfish was significantly correlated with the recruitment index providing support for the possible occurrence of density-dependent growth (Figure 7). Residual plots were examined for patterns, and Cook's D statistic was used to assess the influence of potential outliers on the model (Figure 8). The Cook's D statistic identified one observation (89) with a value greater than 1, indicating the strong influence of the outlier. However, average length of YOY weakfish was still significantly correlated with the recruitment index when the outlier was removed ($r = -0.73$).

Atlantic croaker

Eight individuals collected during May 2007 were YOY fish, and all were smaller than the 135 mm length threshold value (Figure 9). Specimens larger than 140 mm collected in May were at least 1-yr old fish. In June, only one individual (143 mm) was aged as a YOY fish. Two individuals smaller than the 160 mm length threshold value were aged as 1-yr old fish. In July, 14 YOY fish were smaller than the 180 mm length threshold value with lengths ranging from 138-169 mm. Five individuals, ranging in length from 169 mm to 180 mm, were 1-year olds with one 2-year old measured at 179 mm. Lastly, for the month of August, only two out of 26 individuals less than 220 mm were aged as YOY fish, all others in this size class (n = 24) were identified as 1-year to 3-year olds and ranged in lengths between 191 mm and 220 mm. Unlike striped bass and weakfish, no relationship was observed between average total length of YOY Atlantic croaker and the recruitment index (r = 0.0) thus providing little support for the occurrence of density-dependent growth in Atlantic croaker during the past 20 years (Figure 10).

I examined age bias plots for systematic differences between Atlantic croaker age assignments among the three readers (Figures 11-13). Bias between readers is indicated by the presence of non-overlapping but parallel lines, or increasing departures from the edges of the age range (Campana *et al.* 1995). Although age bias appears to be present between reader 1 and the other readers at the upper age range (Figure 11), this is attributed to a single fish aged as a 5-year old by reader 1 but aged as a 4-year old by the other two readers. There is no evidence for systematic error between reader 2 and the other readers (Figure 12); however, there is a slight indication of bias between reader 3 and readers 1 and 2 (Figure 13). Compared with readers 1 and 2, reader 3 appears to assign older ages to younger fish. Reader 3 also appears to assign younger ages to older fish relative to reader 2. For Atlantic croaker, percent agreement was high among all readers, with an initial percent agreement of at least 86% (Table 3; Figure 14).

DISCUSSION

This is the first study to use a validated ageing method to verify the appropriateness of length threshold values for age designations of specimens collected from the VIMS juvenile finfish surveys. I compared fish lengths to ages based on transverse-sectioned otoliths to evaluate the length designations currently used to partition YOY fish from older individuals for striped bass, weakfish, and Atlantic croaker. For the three species collected from the VIMS juvenile finfish surveys, year-class assignments should not be based exclusively on length. For all species collected by the surveys, I recommend the use of ageing studies to corroborate length threshold values obtained from length frequency analyses.

Using length to demarcate YOY fishes from older individuals can be problematic due to annual variations in length-at-age that occur during the early life stages. Variability in length-at-age results in the potential for overlapping ages at the lower and upper length ranges of a year class. Assigning a conservative length designation value will eliminate slow-growing, smaller individuals of the previous year's cohort from being considered as YOY fish at the expense of excluding the fast-growing, larger individuals from the current year's cohort. Therefore, validated ageing methods should be used to assign the length designations as the largest length at which no overlap between year classes occurs. Of the three species I examined, Atlantic croaker exhibited the greatest variability in length-at-age. This is commonly observed among members of the family

Sciaenidae (Jones and Wells 1998; Lowerre-Barbieri *et al.* 1996; Piner and Jones 2004) and has been attributed to the protracted spawning seasons of these species. Accordingly, length is an inadequate predictor of age for Atlantic croaker, particularly beyond the second year (Barbieri *et al.* 1994; Nixon and Jones 1997). In this study, I encountered a substantial amount of overlap in lengths of individuals from different year classes for Atlantic croaker which further illustrates the importance of evaluating the length threshold values used to differentiate YOY fish from older individuals.

Length threshold values for striped bass should be reassigned to ensure that the recruitment index accurately reflects YOY abundance. The current length threshold value (150 mm) for striped bass may be about 30 mm too high. However, given that less than 1% of the total catch during the index months was between 100-150 mm over the last seven years, the inclusion of potential age-1 fish that were classified as YOY has not greatly influenced the striped bass recruitment index. The recruitment index for Atlantic croaker appears to have been overestimated in recent years because older individuals are being counted as YOY fish.

Several recommendations can be made concerning length designations for striped bass and Atlantic croaker. The results for weakfish are equivocal; thus, I recommend repeating the study and increasing the total sample size for weakfish from 40 (in this study) to at least 80. For striped bass, I advise reducing the length threshold to 120 mm. Although the current recruitment index for striped bass is not likely influenced by the small number of 1-year olds measured as YOY fish, reducing the length threshold value will ensure that only YOY fish are included in the recruitment index. For Atlantic croaker, length threshold values for the early portion of the index period (May, June) appear appropriate. However, results indicate that values used for the latter half of the index period (July, August) are too high, allowing for older individuals to be considered YOY when clearly most of them are not. Therefore, I advise reducing the length thresholds to 170mm and 190mm for July and August.

I speculate that the underlying changes in mean length-at-age for striped bass and Atlantic croaker are associated with changes in stock abundance that have occurred since the length threshold values were established in the early 1990's. My hypothesis is based on observed increases in population sizes of striped bass and Atlantic croaker over the past two decades. Approaching 90,000 metric tons in 2006, estimates of total spawning stock biomass for striped bass doubled since 1991 (ASMFC 2008). Estimates of spawning stock biomass for Atlantic croaker increased from 60,000 metric tons in 1991 to approximately 80,000 metric tons in 2002 (ASMFC 2006). Density-dependent effects, mediated by changes in population size, may influence important life-history parameters, such as individual growth rates. Increases in abundance of adult fishes and consequently increases in abundance of YOY fishes may augment intra-specific competition for resources particularly during the early life stages, resulting in slower growth rates and smaller lengths-at-age of YOY fish. Consequently, the length at which the first annulus is formed can be modified through compensatory growth. I speculate that the current length designations for striped bass and possibly Atlantic croaker may no longer be appropriate due to the occurrence of density-dependent growth at the juvenile stage during the last eighteen years. Although further collections are needed to evaluate the length threshold values for weakfish, the results suggest that density-dependent growth may also occur in this species. Estimated weakfish spawning stock biomass increased from approximately 15 million pounds in 1990 to a maximum of 60 million pounds in 1998; however, since then, estimated spawning stock biomass has diminished to less than 10 million pounds in recent years (ASMFC 2006).

Changes in size-at-age relationships have been associated with stock size fluctuations for many species including northern rock sole (*Lepidopsetta bilineata*) (Walters and Wilderbuer 2000), haddock (*Melanogrammus aeglefinus)* (Marshall and Frank 1999), burbot (*Lota lota*) (Kjellman and Hudd 1996), and juvenile Arcto-norwegian cod (*Gadus morhua*) (Ottersen *et al.* 2002). Experimental evidence suggests that juvenile spot (*Leiostomus xanthurus*), a member of the Sciaenid family like Atlantic croaker, experience density-dependent growth (Craig *et al.* 2007). An inverse relationship was identified between average specimen length and recruitment index for striped bass between the years 1988 and 2007 which supports the hypothesis that compensatory growth has been occurring during this time period. For Atlantic croaker, however, there was no apparent relationship between average length and the recruitment index. I cannot discount the possible occurrence of density-dependent growth, however, there is little evidence from this study to support it. Because the growth of Atlantic croaker is extremely variable to begin with, it may be difficult to distinguish density-dependent contributions to growth separately from density-independent effects. For example, population outbursts of Atlantic croaker along the east coast of the U.S. have been linked to climatic effects, specifically, increased juvenile survival due to warmer winter temperatures (Hare and Able 2007). Partitioning out the interactive effects of density-dependent and density-independent factors may be difficult for this species. Nonetheless, Sinclair *et al.* (2002) emphasize the importance of considering alternative mechanisms, such as size-selective mortality, temperature, and population density, and their influence on growth in fish populations. Here, I considered only the effects of changes in population size on growth and examined patterns between the relative abundance and size of YOY fishes. Additional research is needed to determine how environmental variables, such as temperature or river flow, may influence growth of YOY fishes, and ultimately, annual year-class strength.

The main limitation of this study was the lack of a sufficient number of samples within 5-10 mm of the length threshold values (e.g., weakfish collected in August). There are two plausible explanations for this. In the early index months, it is possible that there are few individuals reaching those lengths that are present in the bay and rivers, which is why they were not reflected in the samples. The alternative, and perhaps more likely explanation, concerns the collection protocol: individuals in that size range may have been captured and measured on board the research vessel but returned to the water because specimens within the desirable size range had already been collected from a particular region for a given month.

Another minor, yet notable, constraint of this study is the collection of samples from only one year class. Ideally, to further substantiate the recommendations for reviewing length designation values, sampling should be conducted across year classes. In light of these limitations, however, this study can be used as a baseline for identifying suitable sample sizes and length ranges for future collections.

Length threshold values should be revisited frequently to account for changes that may influence length-at-age relationships. I recommend re-examining these values at least every 4-5 years when using otoliths to assign age, or as deemed necessary depending on discernable changes in stock structure or abundance. If length frequency analysis is to be used, then a validated ageing method should also be applied periodically to confirm length threshold values.

The results indicate the importance of applying these methods to other species collected by the VIMS juvenile finfish surveys for which a recruitment index is calculated. Priority should be given to recreationally and commercially important species, such as summer flounder, followed by additional members of the family Sciaenidae, such as spot (*Leiostomus xanthurus*), and silver perch (*Bairdiella chrysoura*) which also exhibit variability in length-at-age. Recruitment indices are critical sources of information used to evaluate and predict the response of fish stocks to different levels of fishing pressure. Therefore, routine examination of the information used to derive recruitment indices is necessary to ensure that the best available scientific information is being used to support policy development and management regulations.

LITERATURE CITED

ASMFC (Atlantic States Marine Fisheries Commission). 2006. 2006 review of the ASMFC fishery management plan for Atlantic croaker (*Micropogonias undulatus*). ASMFC, Washington, D.C.

ASMFC (Atlantic States Marine Fisheries Commission). 2006. 2006 weakfish stock assessment. ASMFC, Washington, D.C.

ASMFC (Atlantic States Marine Fisheries Commission). 2008. 46th Northeast Regional Stock Assessment Workshop (46th SAW) Part A. Assessment Report for Striped Bass. National Oceanic and Atmospheric Association. NMFS Northeast Fisheries Science Center. Woods Hole, Mass.

Austin, H. M., J. A. Colvocoresses, and T. A. Mosca III. 1993. Developing a Chesapeake Bay-wide young-of-the-year striped bass index. Final Report, CBSAC Cooperative Agreement NA16FU0393-01, 59 p.

Axenrot, T., and S. Hannson. 2003. Predicting herring recruitment from young-of-the-year densities, spawning stock biomass, and climate. Limnology and Oceanography 48(4): 1716-1720.

Bailey, K.M., and S.M. Spring. 1992. Comparison of larval, age-0 juvenile and age-2 recruit abundance indices of walleye pollock (*Theragra chalcogramma*), in the western Gulf of Alaska. ICES Journal of Marine Science 49: 297-304.

Barbieri, L. R., M. E. Chittenden Jr., and C. M. Jones. 1994. Age, growth, and mortality of Atlantic croaker, *Micropogonias undulatus*, in the Chesapeake Bay region, with a discussion of apparent geographic changes in population dynamics. Fishery Bulletin 92: 1-12.

Beamish, R. J., and G. A. McFarlane. 1983. The forgotten requirement for age validation in fisheries biology. Transactions of the American Fisheries Society 112: 735-743.

Campana, S. E. 2001. Accuracy, precision and quality control in age determination, including a review of the use and abuse of age validation methods. Journal of Fish Biology 59: 197-242.

Campana, S. E., M. C. Annand, and J. I. McMillan. 1995. Graphical and statistical methods for determining the consistency of age determinations. Transactions of the American Fisheries Society 124: 131-138.

Colvocoresses, J. A. and P. J. Geer. 1991. Estimation of relative abundance of recreationally important finfish in the Virginia portion of Chesapeake Bay. U. S. Fish and Wildlife Service Sportfish Restoration Project F104R1, July 1990-June 1991. Annual Progress Report to the Virginia Marine Resources Commission.

Cook, R. D. 1977. Detection of influential observation in linear regression. Technometrics 19(1): 15-18.

Craig, J. K., J. A. Rice, L. B. Crowder, and D. A. Nadeau. 2007. Density-dependent growth and mortality in an estuarine-dependent fish: an experimental approach with juvenile spot *Leiostomus xanthurus*. Marine Ecology Progress Series: 343: 251-262.

Crecco, V., T. Savoy, and L. Gunn. 1983. Daily mortality rates of larval and juvenile American shad (*Alosa sapidissima*) in the Connecticut River with changes in year-class strength. Canadian Journal of Fisheries and Aquatic Sciences 40(10): 1719-1728.

Devries, D. R., and R. V. Frie. 1996. Determination of age and growth. Pages 483-512 *in* B. R. Murphy and D. W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Durell, E.Q., and C. Weedon. 2007. Striped bass seine survey juvenile index web page. http://www.dnr.state.md.us/fisheries/juvindex/index.html. Maryland Department of Natural Resources, Fisheries Service.

Fabrizio, M. C., and T. D. Tuckey. 2008. Estimating relative abundance of ecologically important finfish in the Virginia portion of Chesapeake Bay. Annual report to Virginia Marine Resources Commission Project F-104-R-12. Virginia Institute of Marine Science, Gloucester Pt., VA 23062. 84 p.

Fogarty, M. J. M. P. Sissenwine, and E. B. Cohen. 1991. Recruitment variability and the dynamics of exploited marine populations. Trends in Ecology and Evolution 6(8): 241-246.

Hare, J. A. and K. W. Able. 2007. Mechanistic links between climate and fisheries along the east coast of the United States: explaining population outbursts of Atlantic croaker (*Micropogonias undulatus*). Fisheries Oceanography 16(1): 31-45.

Helle, K., B. Bogstad, C. T. Marshall, K. Michalsen, G. Ottersen, and M. Pennington. 2000. An evaluation of recruitment indices for Arcto-Norwegian cod (*Gadus morhua* L.). Fisheries Research (Amsterdam) 48(1):55-67.

Hewitt, A. H., L. S. Machut, and M. C. Fabrizio. 2008. Estimation of juvenile striped bass relative abundance in the Virginia portion of Chesapeake Bay. Annual Report 2007. Virginia Institute of Marine Science, Gloucester Point, VA. 28 p.

Jones, C. M., and B. Wells. 1998. Age, growth, and mortality of black drum, *Pogonias cromis,* in the Chesapeake Bay region. Fishery Bulletin 96(3): 451-461.

Kjellman, J., and R. Hudd. 1996. Changed length-at-age of burbot, *Lota lota*, from an acidified estuary in the Gulf of Bothnia. Environmental Biology of Fishes 45(1): 65-73.

Lowerre-Barbieri. S. K., M. E. Chittenden, Jr., and C. M. Jones. 1994. A comparison of a validated otolith method to age weakfish, *Cynoscion regalis*, with the traditional scale method. Fishery Bulletin 92: 555-568.

Lowerre-Barbieri, S. K., M. E. Chittenden, Jr., and L.R. Barbieri. 1996. The multiple spawning pattern of weakfish in the Chesapeake Bay and Middle Atlantic Bight. Journal of Fish Biology 48: 1139-1163.

Nixon, S. W. and C. M. Jones. 1997. Age and growth of larval and juvenile Atlantic croaker, *Micropogonias undulatus*, from the Middle Atlantic Bight and estuarine waters of Virginia. Fishery Bulletin 95: 773-784.

Ottersen, G., K. Helle, and B. Bogstad. 2002. Do abiotic mechanisms determine interannual variability in length-at-age of juvenile Arcto-Norwegian cod? Canadian Journal of Fisheries and Aquatic Sciences 59: 57-65.

Piner, K. R., and C. M. Jones. 2004. Age, growth, and the potential for growth overfishing of spot (*Leiostomus xanthurus*) from the Chesapeake Bay, eastern USA. Marine and Freshwater Research 55: 553-560.

Secor, D. H., T. M. Trice, and H. T. Hornick. 1995. Validation of otolith-based ageing and a comparison of otolith and scale-based ageing in mark-recaptured Chesapeake Bay striped bass, *Morone saxatilis*. Fishery Bulletin 93: 186-190.

Sinclair, A. F., D. P. Swain, and J. M. Hanson. 2002. Disentangling the effects of size-selective mortality, density, and temperature on length-at-age. Canadian Journal of Fisheries and Aquatic Sciences 59: 372-382.

Walters, G. E., and T. K. Wilderbuer. 2000. Decreasing length at age in a rapidly expanding population of northern rock sole in the eastern Bering Sea and its effect on management advice. Journal of Sea Research 44: 17-26.

Table 1. Number of specimens collected monthly for striped bass, weakfish, and Atlantic croaker and the associated length threshold values for each index month. Length threshold values are used to distinguish YOY fish from older individuals.

Species	Survey	Index months	Length threshold value (mm)	Number of specimens collected
Striped bass	VIMS seine survey	July through mid-September	150	179
Weakfish	VIMS trawl survey	August	150	46
		September	180	30
		October	200	41
Atlantic croaker	VIMS trawl survey	May	135	49
		June	160	29
		July	180	48
		August	220	41

Table 2. Percentage of total catch of striped bass between 100 mm and 150 mm from 2000 to 2007 and mean over the eight years.

Year	Percentage of total catch between 100 mm and 150 mm
2000	0.6
2001	0.4
2002	2.3
2003	0.2
2004	0.4
2005	0.0
2006	0.3
2007	1.1
Mean	0.7

Table 3. Overall percent agreement between three independent readers for Atlantic croaker. Atlantic croaker specimens were collected from May to August of 2007. Transverse sectioned otoliths were used for age determination. The total sample size was 167 individuals.

Readers	**Percent Agreement**	**n**	**Percent Agreement +/- 1 year**
3, 1	92.2	145	100
3, 2	91	154	100
2, 1	86.8	152	100

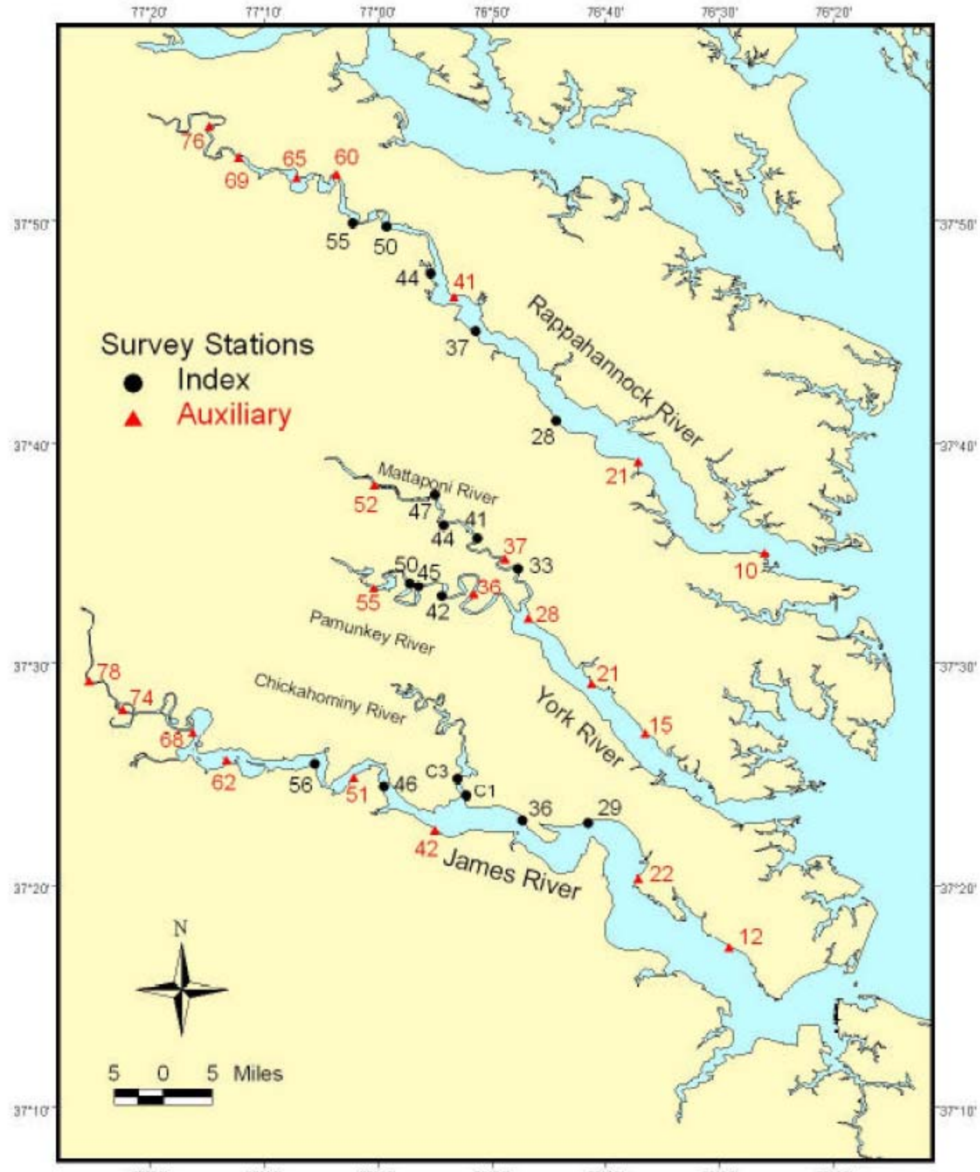


Figure 1. Sampling locations of the VA Juvenile Striped Bass Seine Survey. Data collected from index stations only are used in the striped bass recruitment index. Numbers indicate the number of river miles from the mouth of the river (Hewitt *et al.* 2008).

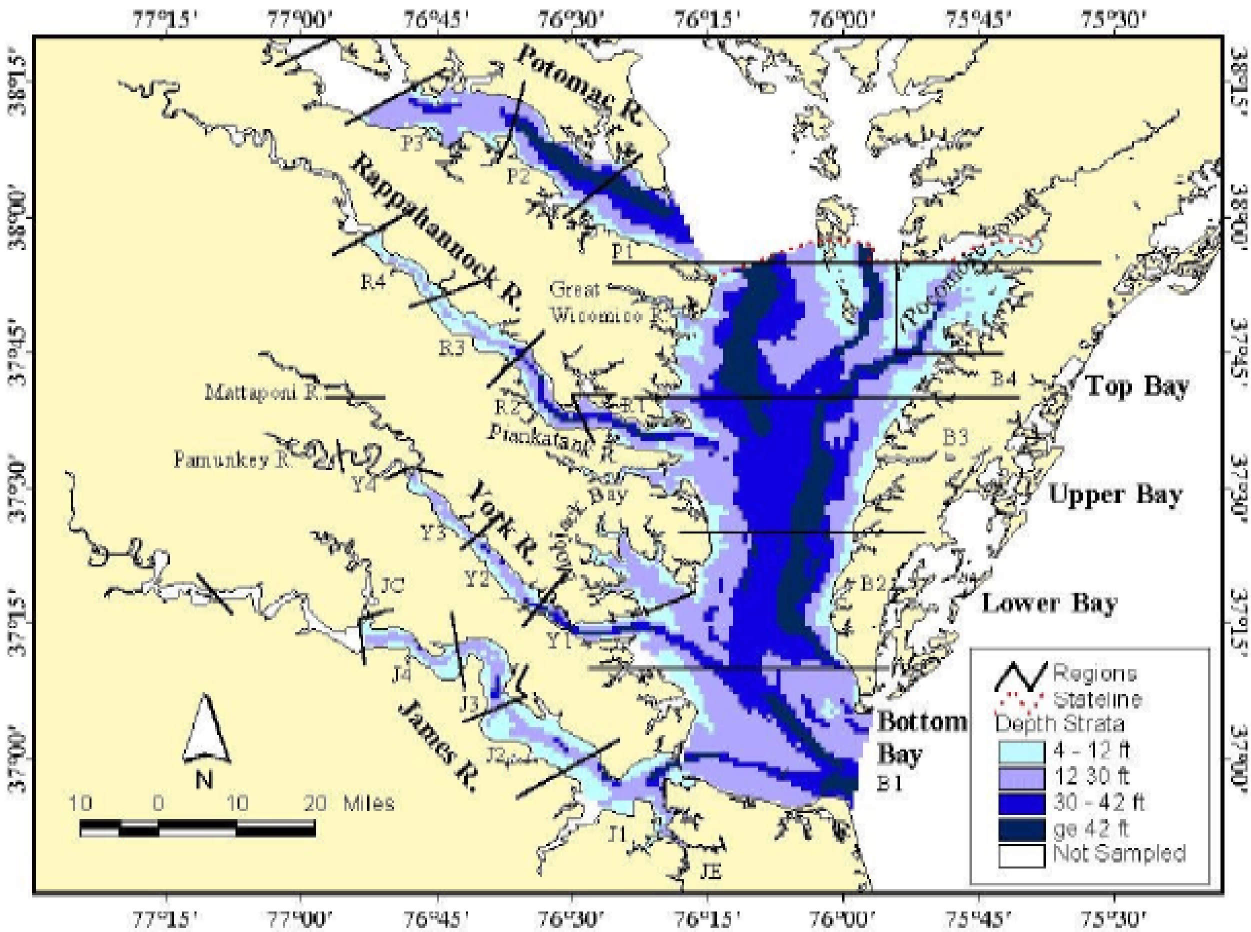


Figure 2. Stratified random sampling design for the VIMS Juvenile Fish Trawl Survey (Fabrizio and Tuckey 2008). The four regions include the James, York, and Rappahannock Rivers, and the Virginia mainstem portion of Chesapeake Bay.

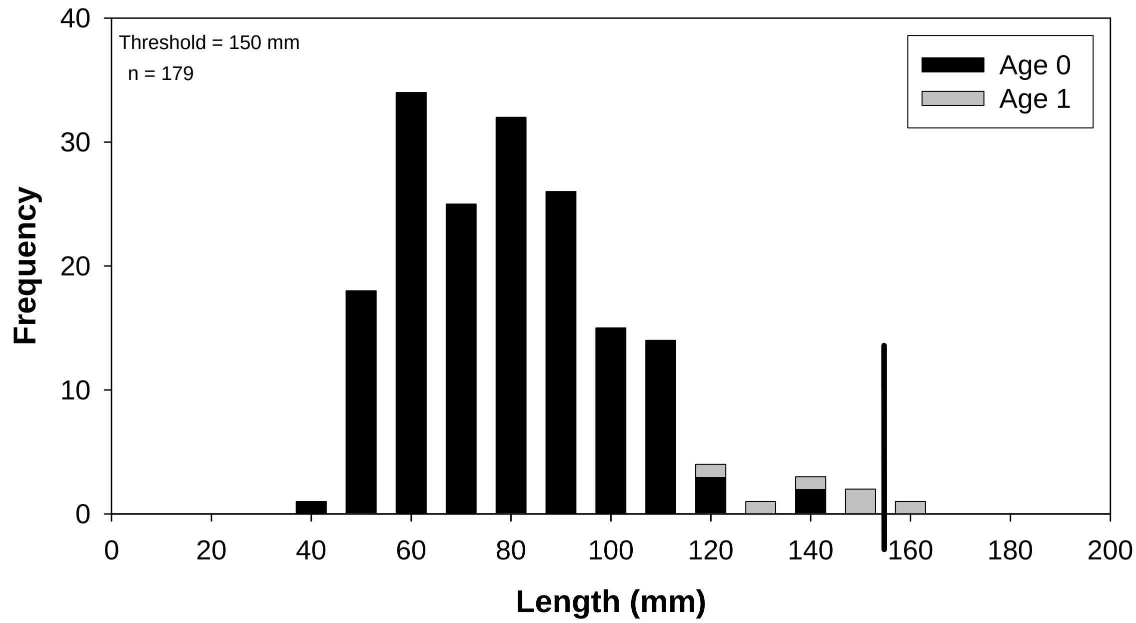


Figure 3. Length frequency histogram for striped bass collected from July to mid-September in 2007. Length data are binned in increments of 10 mm, e.g., “160 mm” includes fishing ranging in size from 151 mm to 160 mm. Solid black line indicates length threshold value for YOY fish.

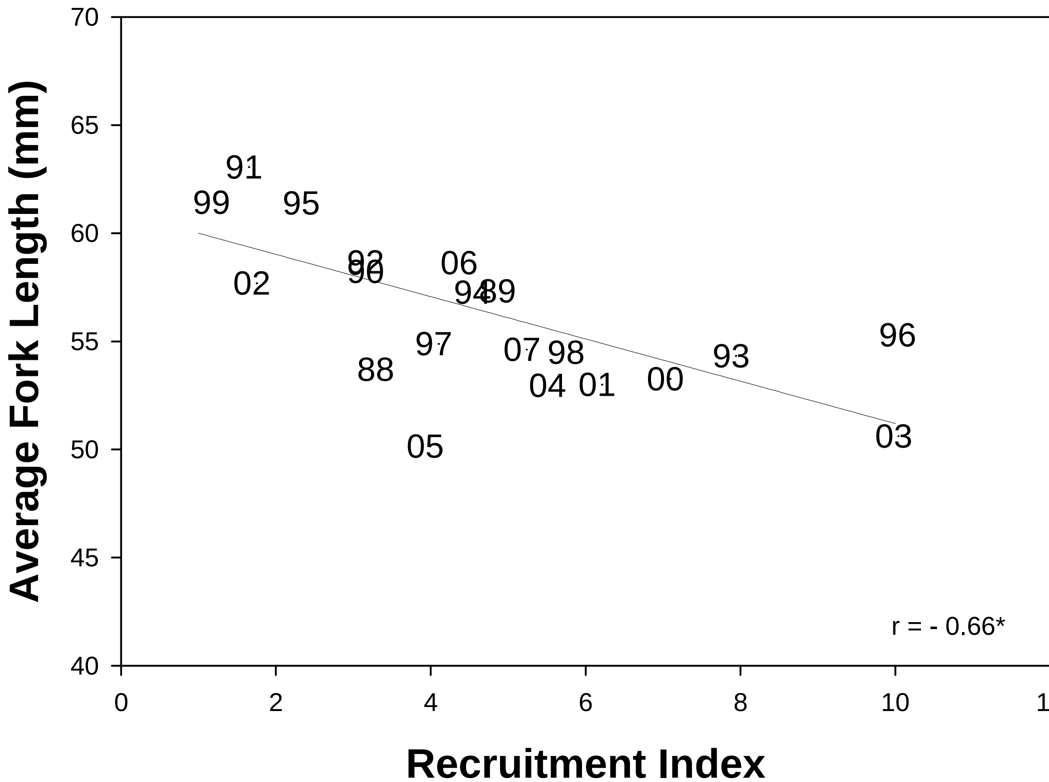


Figure 4. Average length of all individual YOY striped bass measured in a sampling season plotted against the recruitment index of the same year. Symbols are represented by year. Recruitment index values shown here do not match published values because the scaling factor (2.28) was not applied to the data. Asterisk indicates a significant correlation between average fork length of YOY striped bass and the recruitment index.

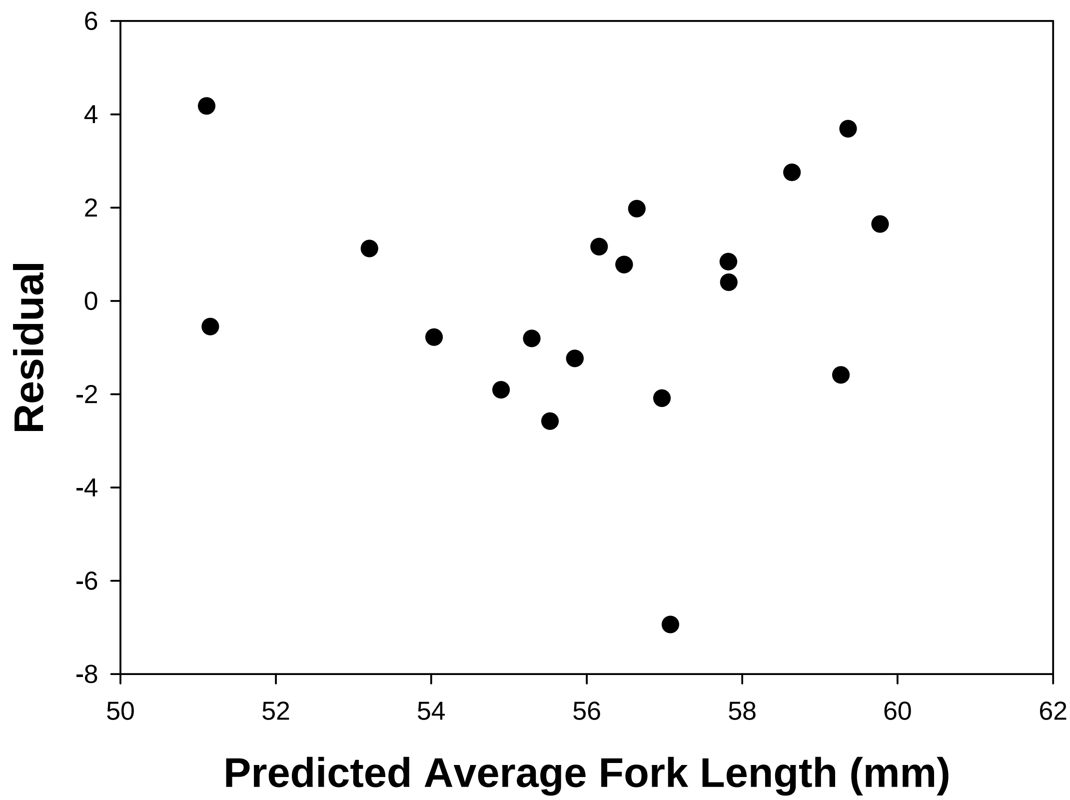


Figure 5. Scatterplots of residuals against predicted average length (mm) of YOY striped bass.

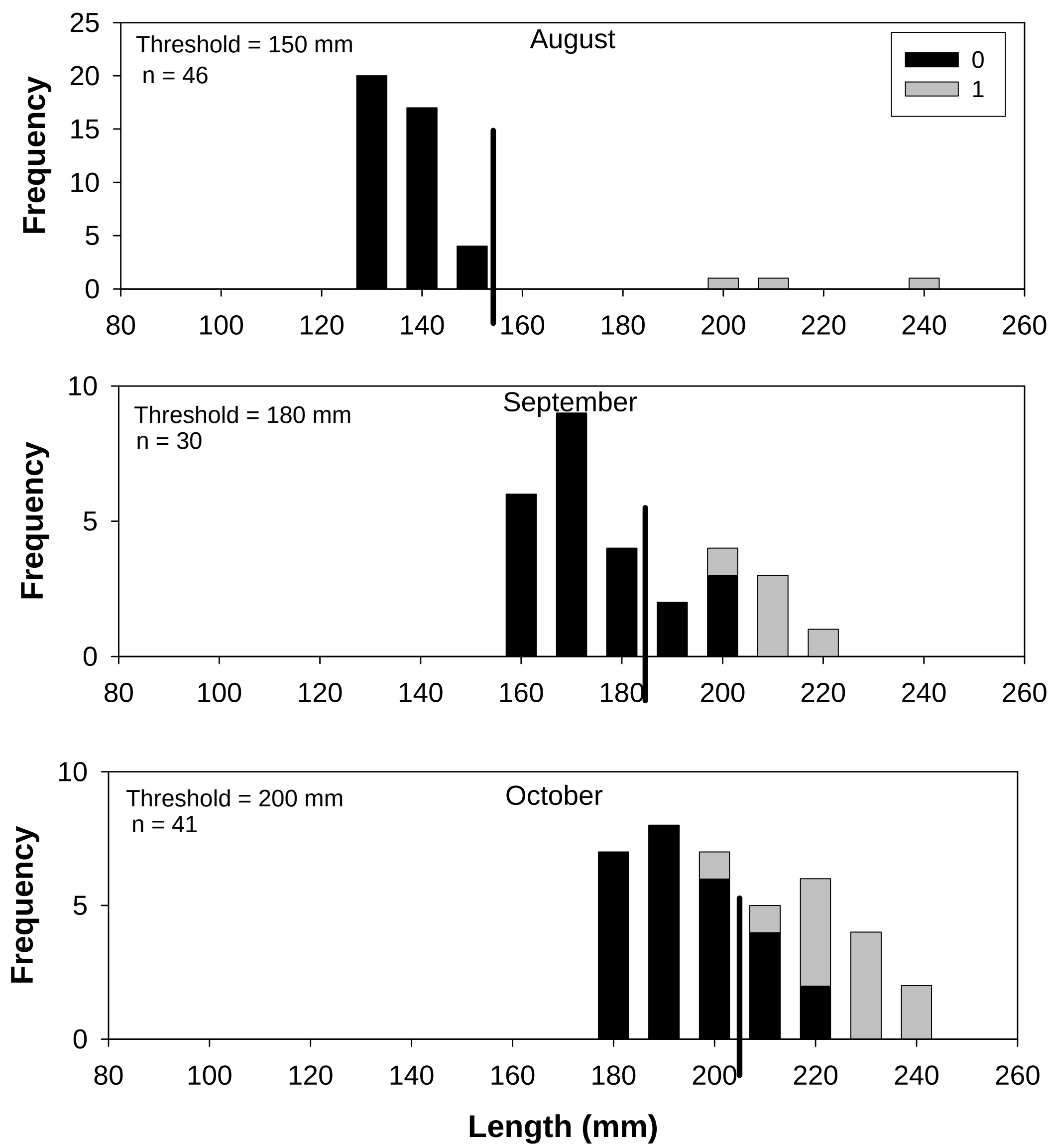


Figure 6. Length frequency histograms by month for weakfish collected from August to October in 2007. Length data are binned in increments of 10 mm, e.g., "160 mm" includes fish ranging in size from 151 mm to 160 mm. Solid black lines indicate length threshold values for YOY fish.

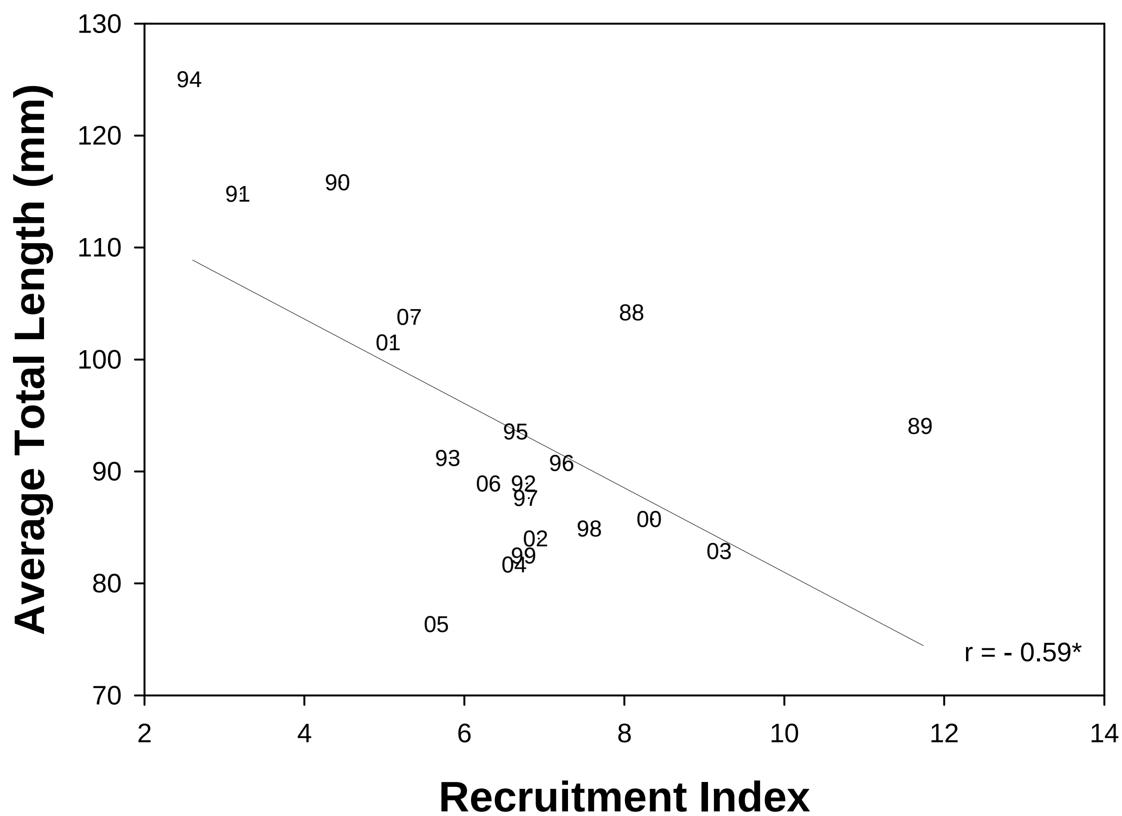


Figure 7. Average length of all individual YOY weakfish measured in a sampling season plotted against the recruitment index (RSCI) of the same year. Symbols are represented by year. Asterisk indicates a significant correlation between average total length of YOY weakfish and the recruitment index.

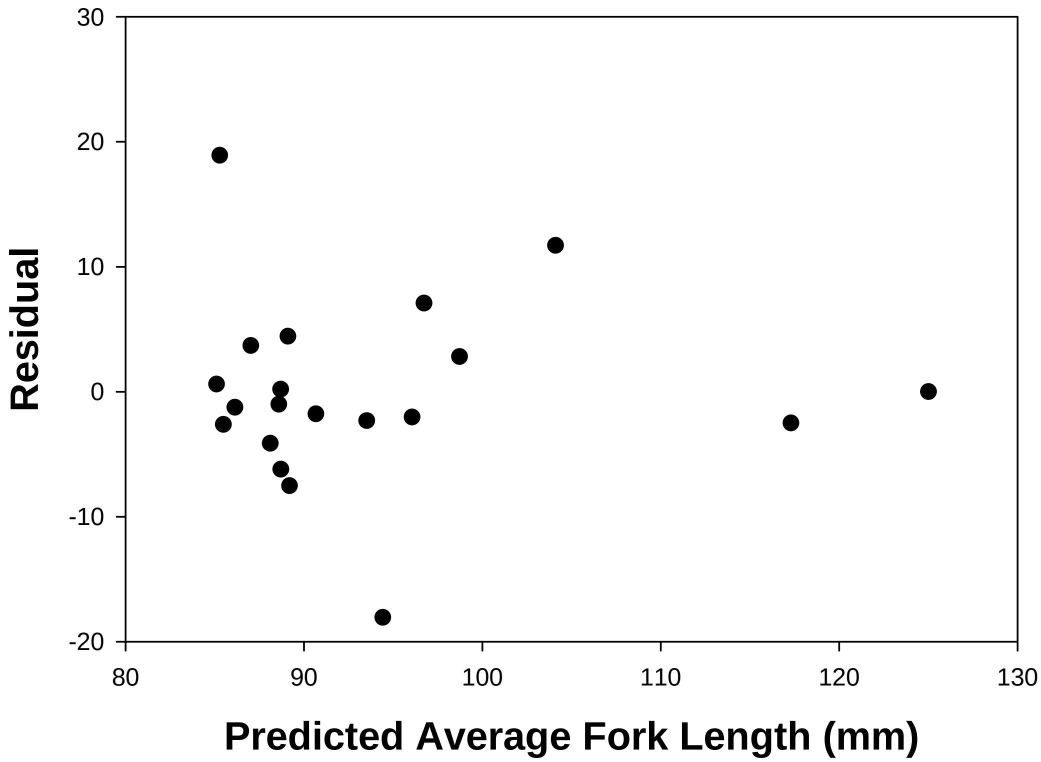


Figure 8. Scatterplots of residuals against predicted average length (mm) for YOY weakfish.

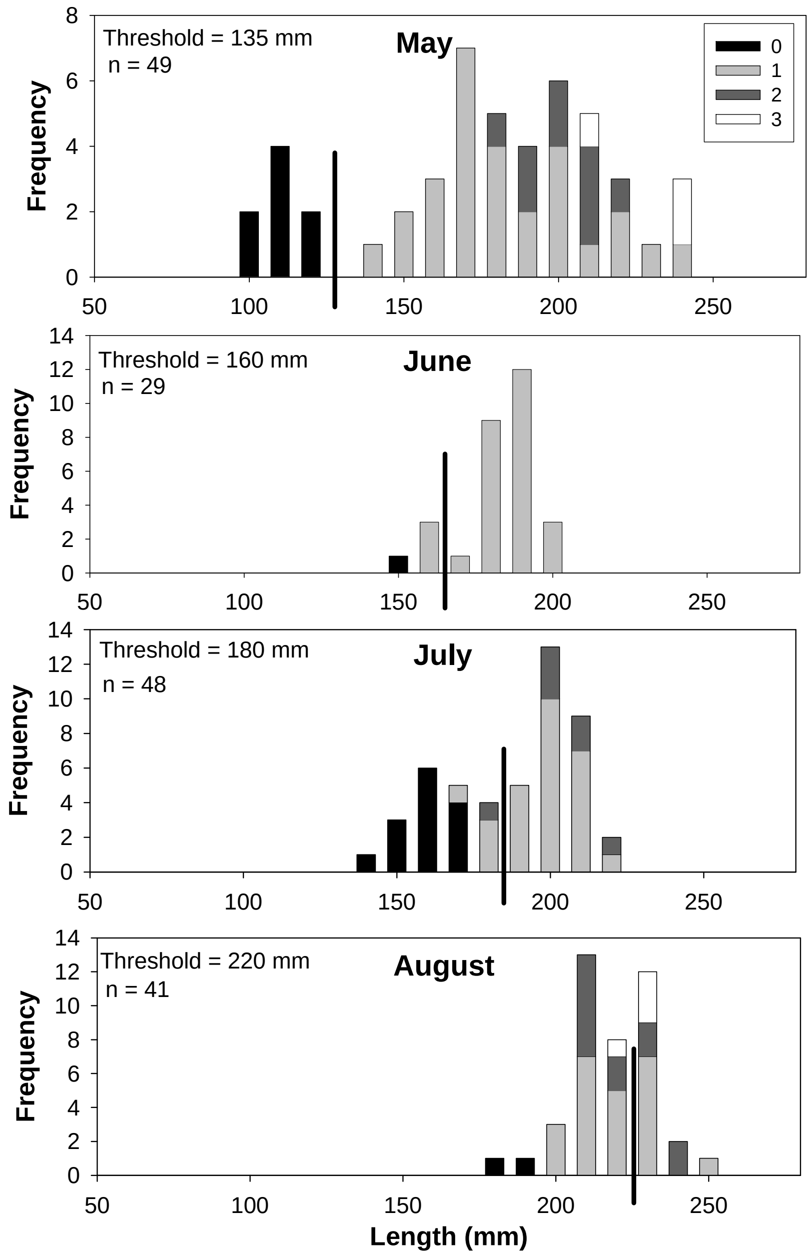


Figure 9. Length frequency histograms by month for Atlantic croaker collected from May to August in 2007. Length data are binned in increments of 10 mm, e.g., "160 mm" includes fish ranging in size from 151 mm to 160 mm. Solid black lines indicate length threshold values for YOY fish.

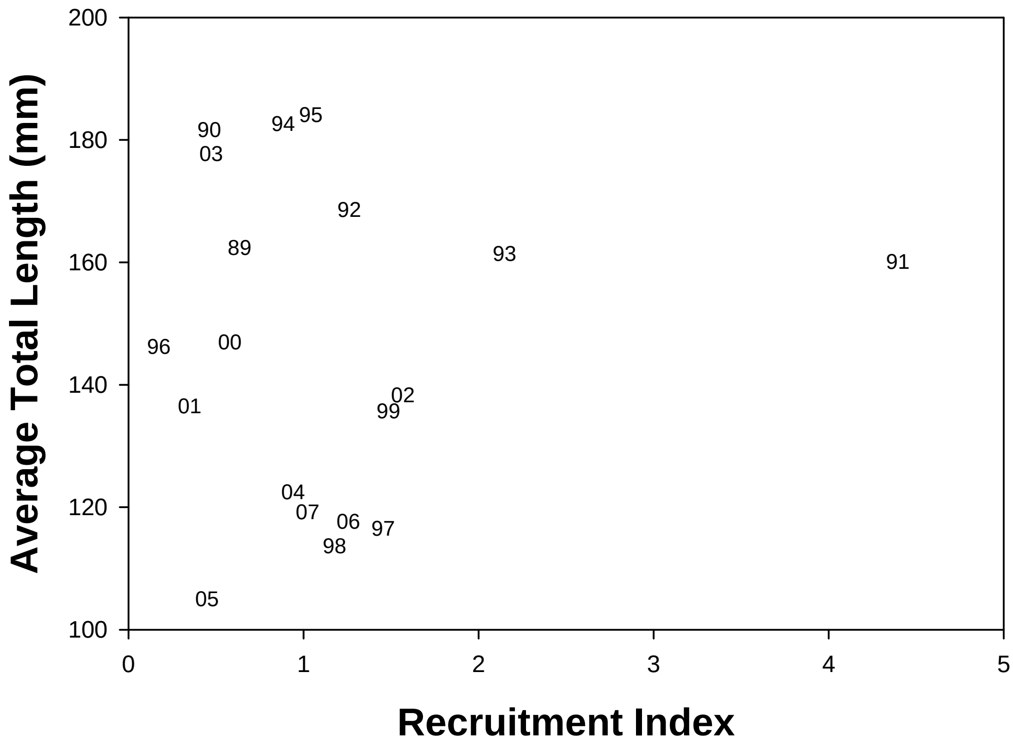


Figure 10. Average total length of individual YOY Atlantic croaker measured each year plotted against the recruitment index (RSCI) of the same year. Symbols represent year. No relationship was detected between average total length and the recruitment index (r = 0).

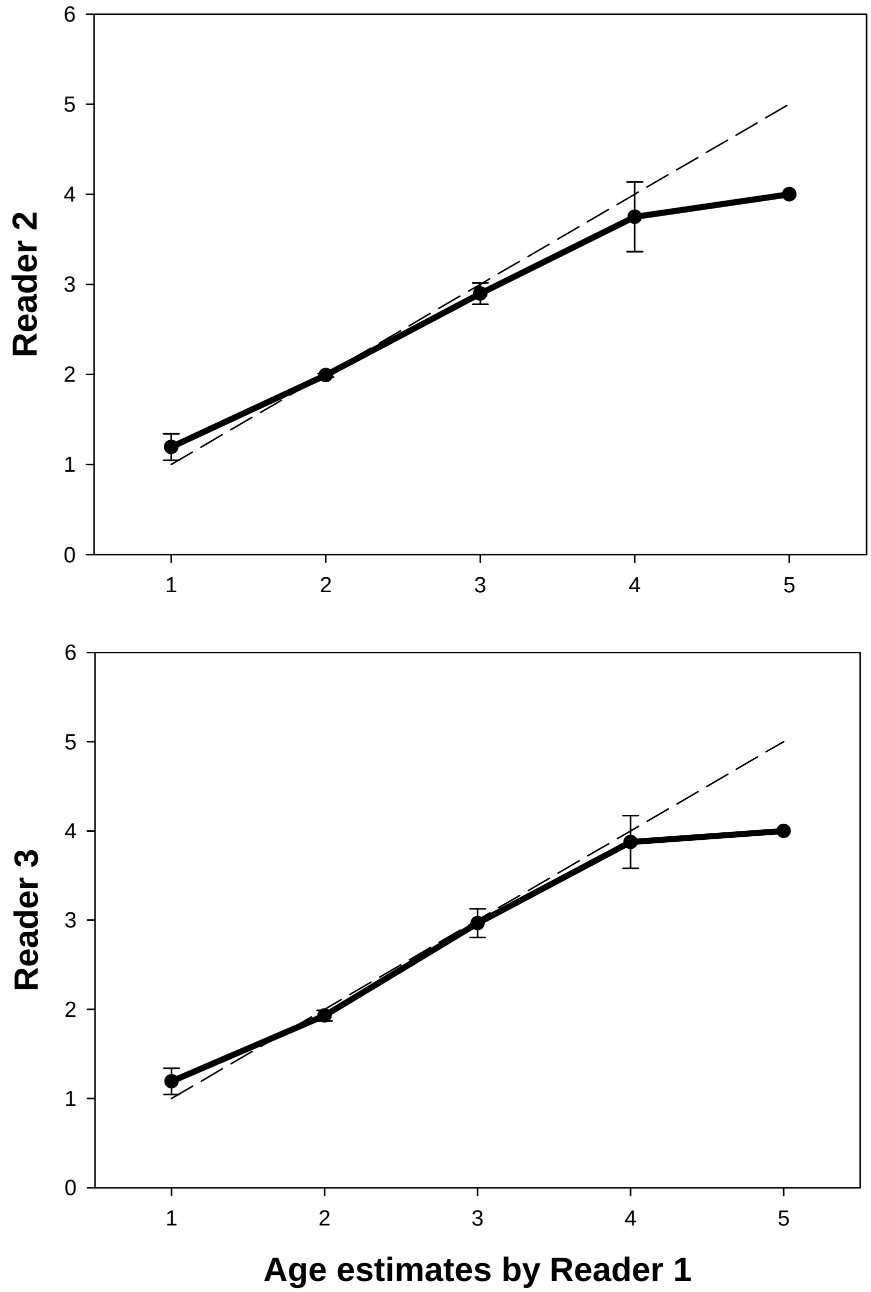


Figure 11. Age bias plots for Reader 1 with 95% confidence intervals. The dashed line represents the one-to-one equivalence line. Atlantic croaker specimens were collected from May to August of 2007 by the VIMS trawl survey.

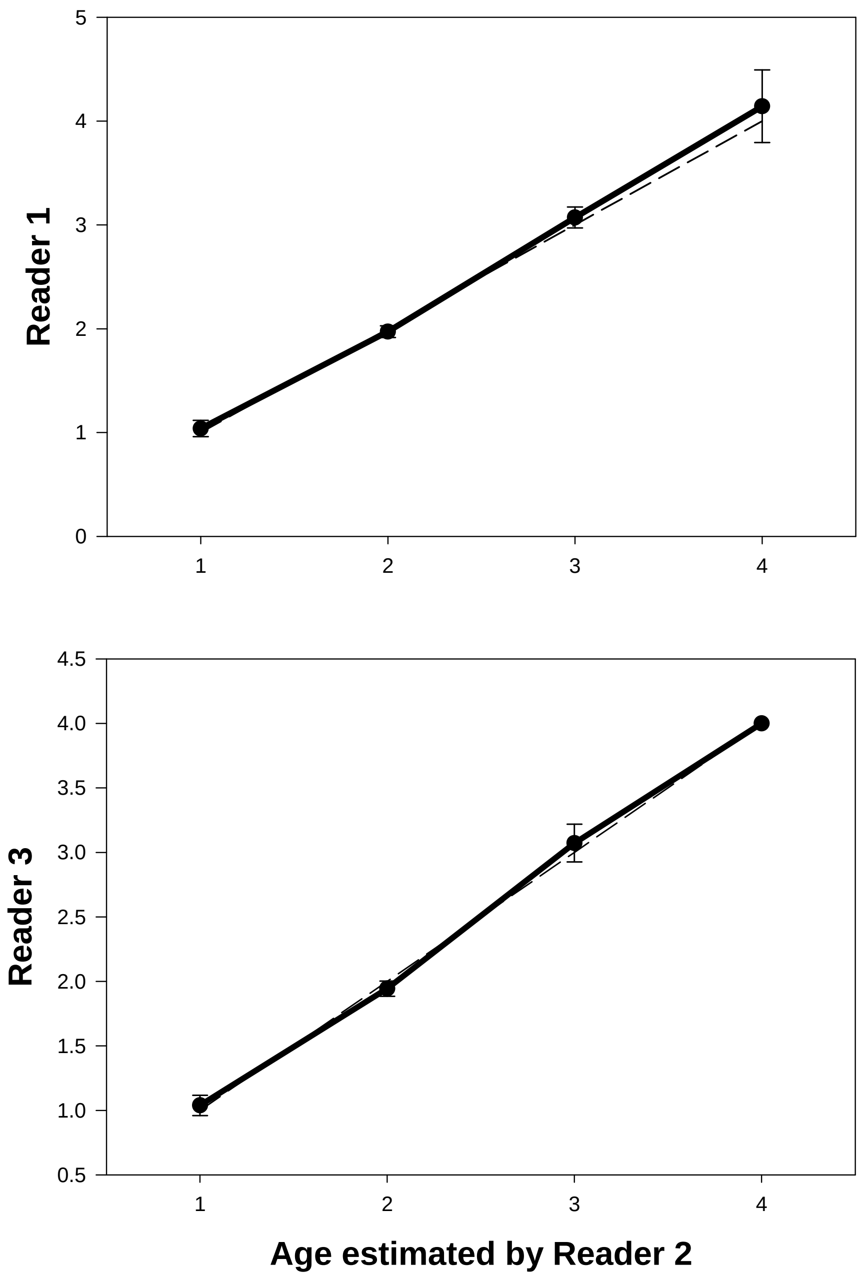


Figure 12. Age bias plots for Reader 2 with 95% confidence intervals. The dashed line represents the one-to-one equivalence line. Atlantic croaker specimens were collected from May to August of 2007 by the VIMS trawl survey.

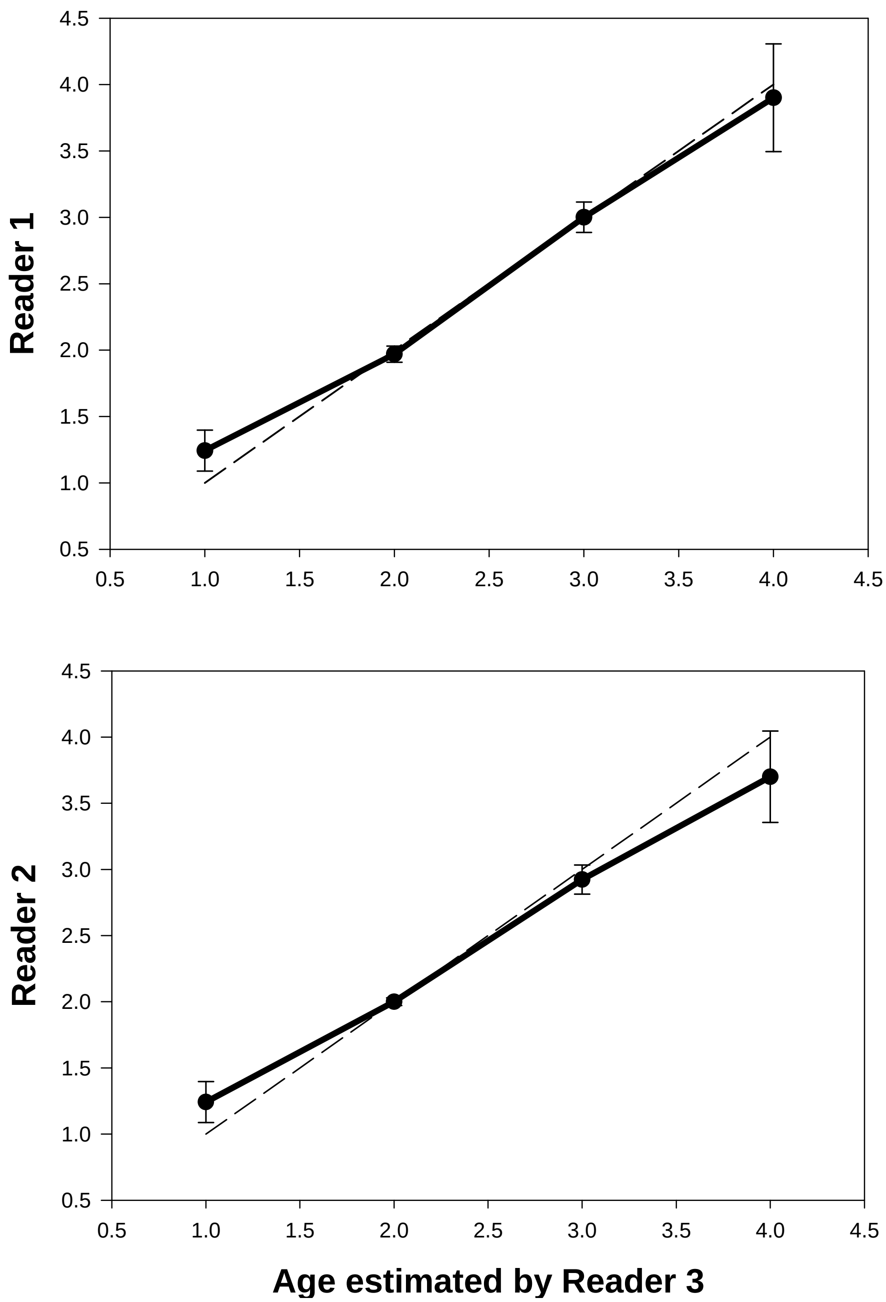


Figure 13. Age bias plots for Reader 3 with 95% confidence intervals. The dashed line represents the one-to-one equivalence line. Atlantic croaker specimens were collected from May to August of 2007 by the VIMS trawl survey.

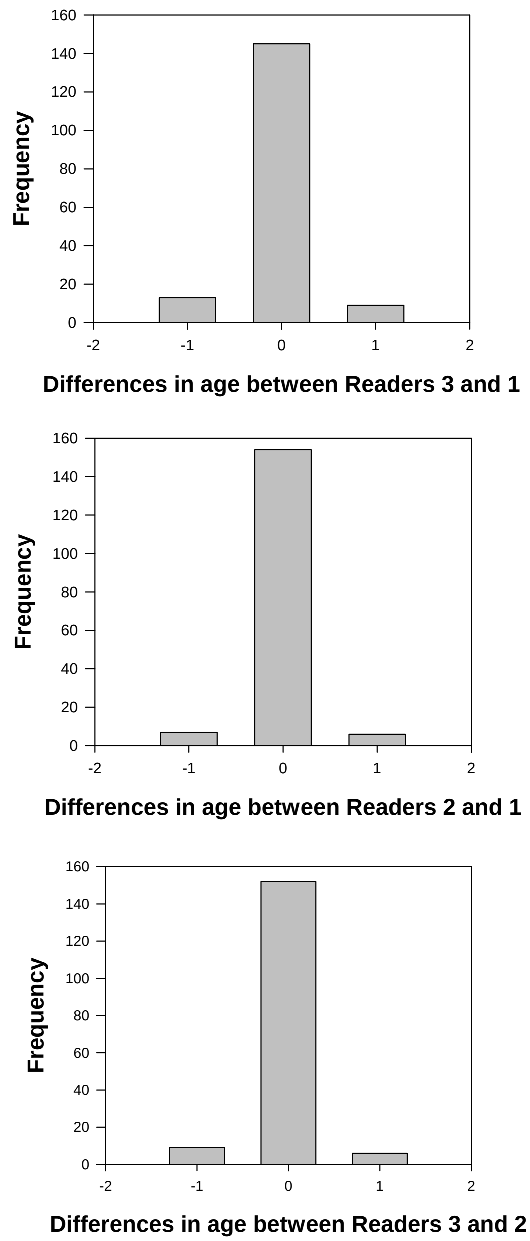
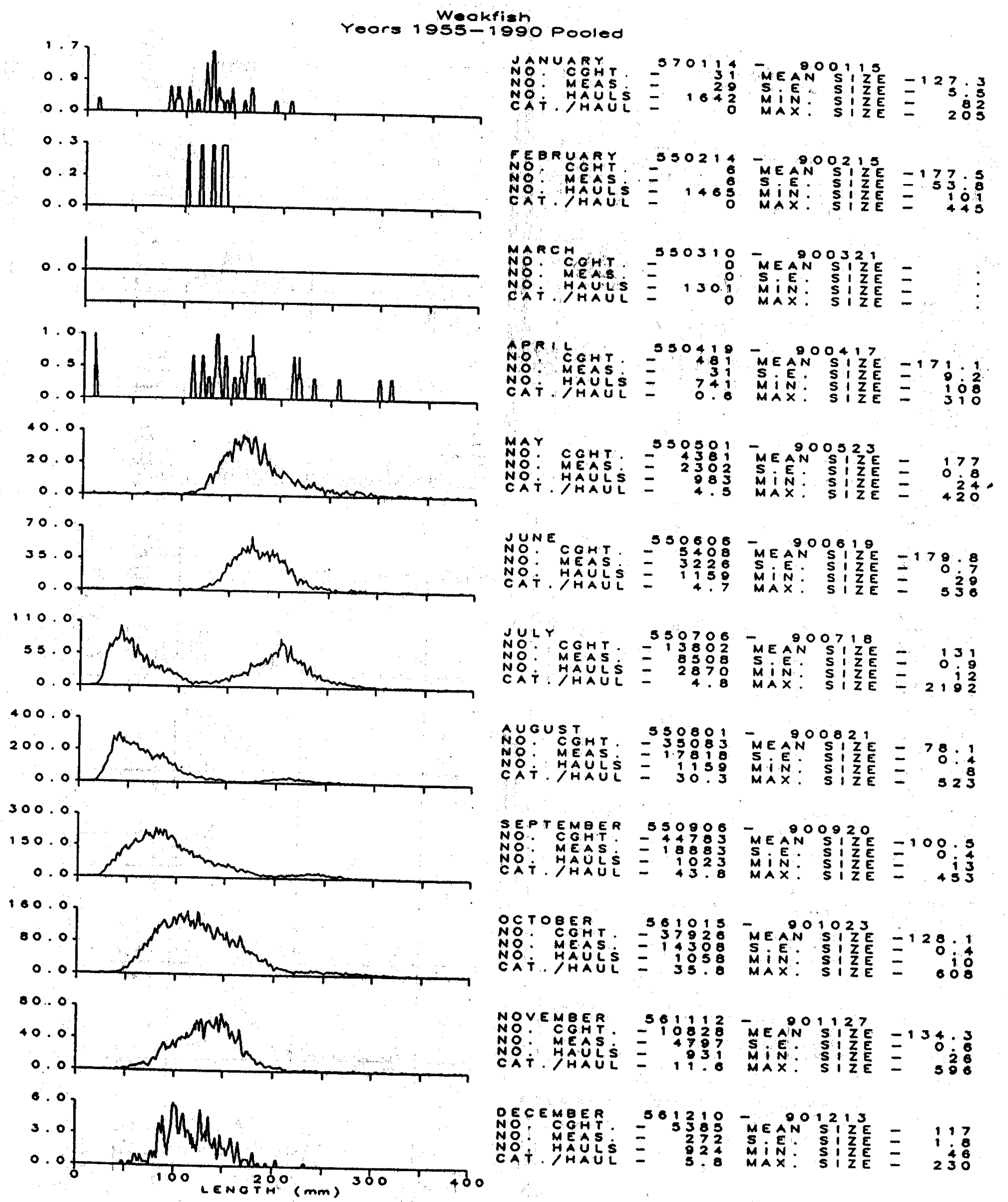
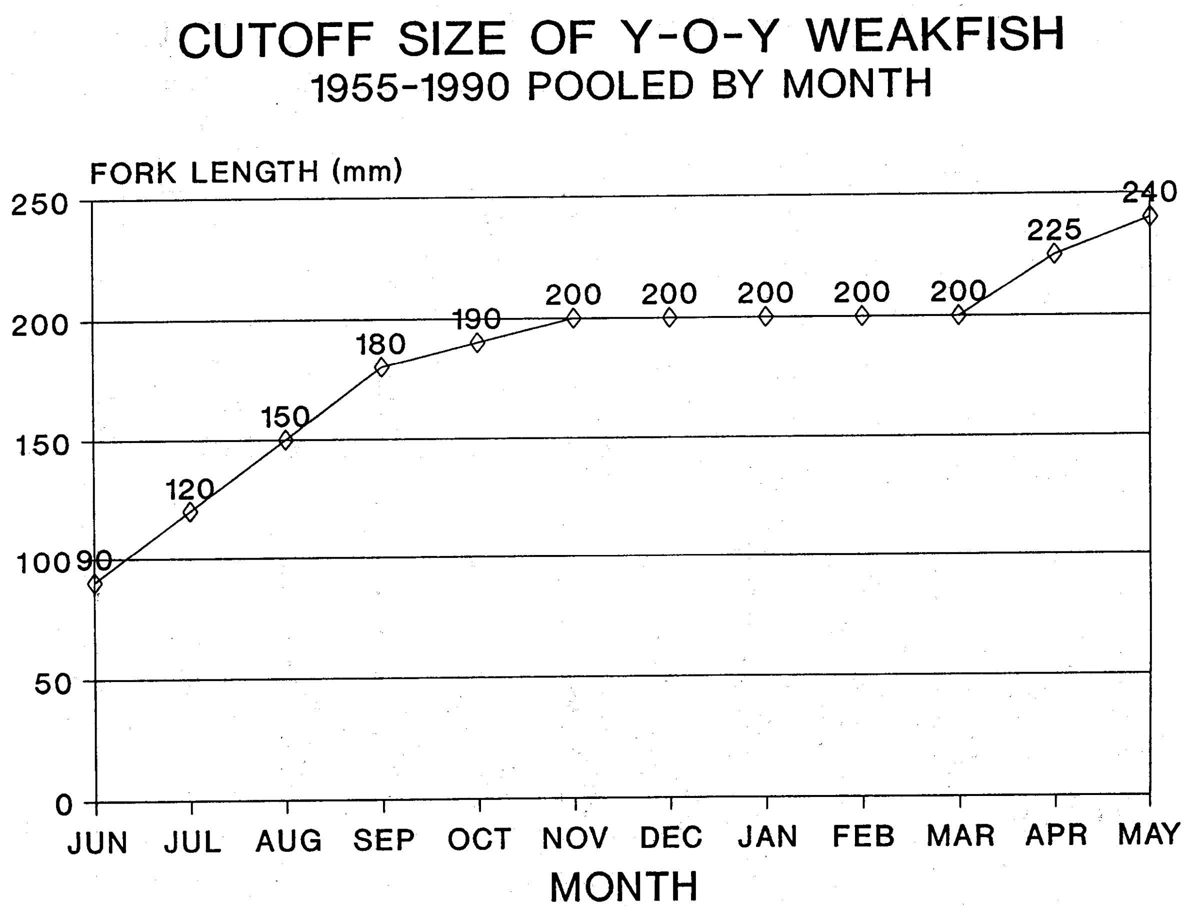


Figure 14. Frequency of agreement between three independent readers for Atlantic croaker assigned ages. Atlantic croaker specimens were collected from May to August of 2007 by the VIMS trawl survey.

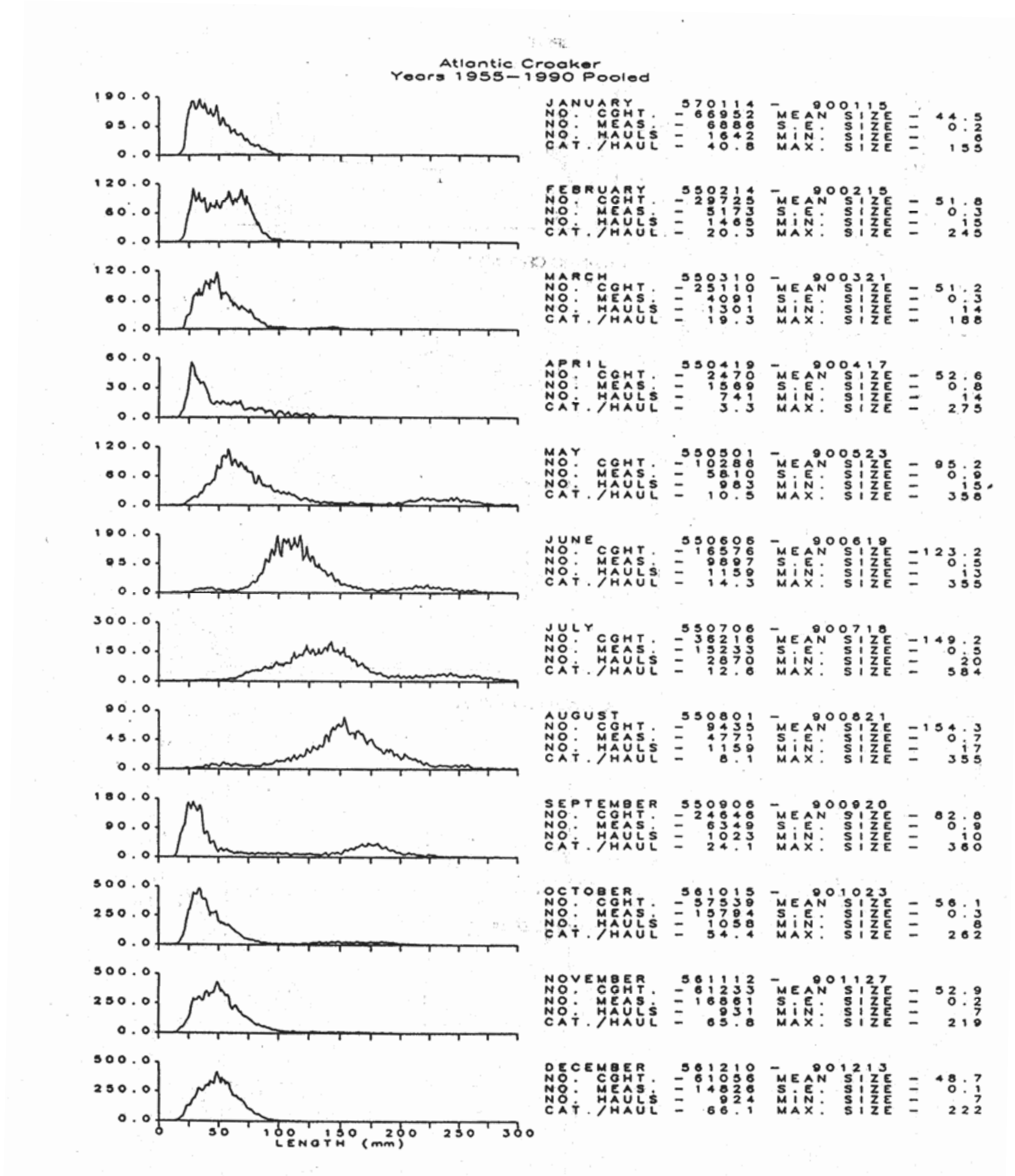
Appendix 1a. Composite length frequencies by month for weakfish, VIMS trawl survey data base, 1955-1990 (Colvocoresses and Geer 1991).



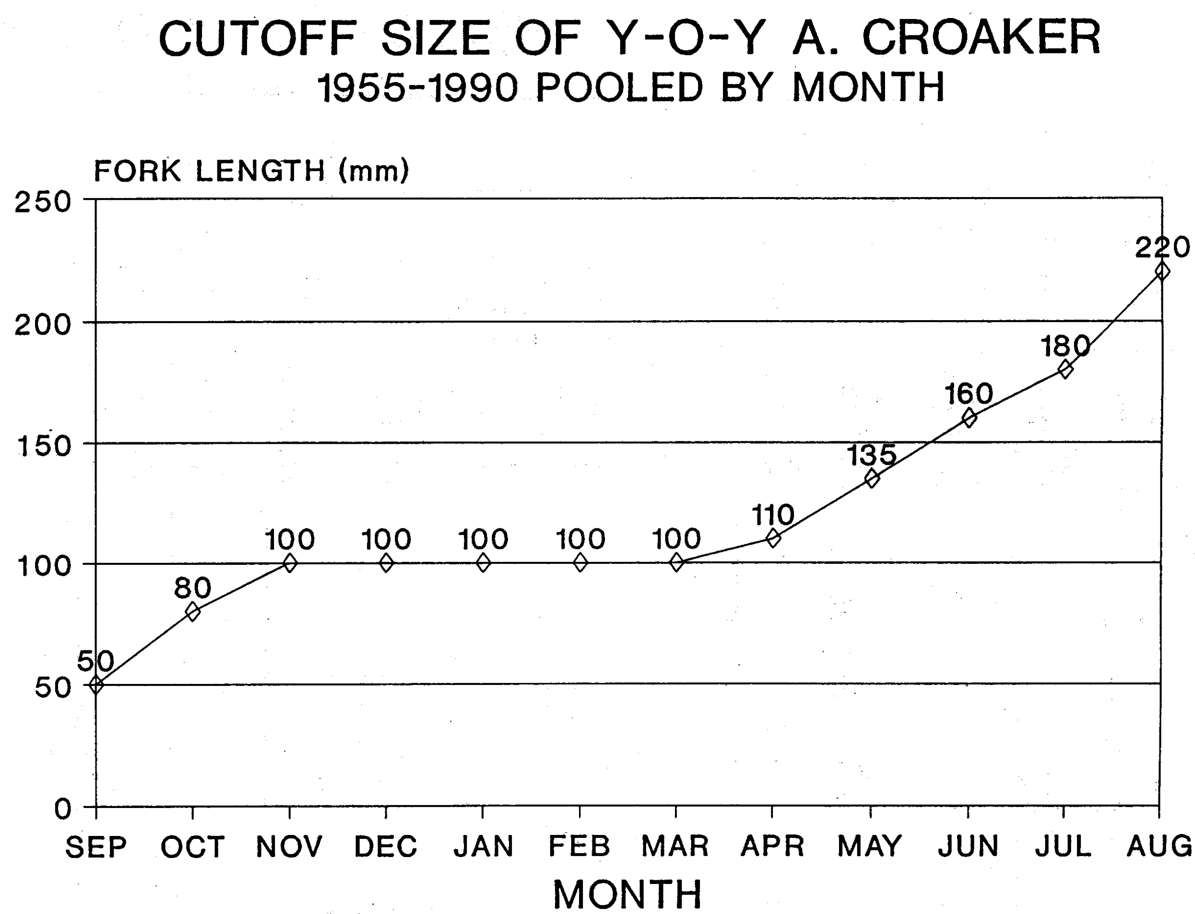
Appendix 1b. Length designation values used to separate young-of-year weakfish from older cohorts (Colvocoresses and Geer 1991).



Appendix 1c. Composite length frequencies by month for Atlantic croaker, VIMS trawl survey data base, 1955-1990 (Colvocoresses and Geer 1991). Index months include May through August.



Appendix 1d. Length designation values used to separate young-of-year Atlantic croaker from older year cohorts (Colvocoresses and Geer 1991).



VITA

Justine Rhea Woodward

Born in Denver, Colorado on 27 August 1981. Graduated from Princess Anne High School in Virginia Beach, Virginia in 1999. Graduated *suma cum laude* from Virginia Tech with a Bachelor of Science in Biology and a minor in Chemistry in May 2003. Entered the Master of Science program at the School of Marine Science, Virginia Institute of Marine Science, at The College of William and Mary in 2005.